# Ground motion prediction equations 1964–2023 (*incomplete*)

John Douglas
Department of Civil and Environmental Engineering
University of Strathclyde
James Weir Building
75 Montrose Street
Glasgow
G1 1XJ
United Kingdom
john.douglas@strath.ac.uk
https://www.strath.ac.uk/staff/douglasjohndr/

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# Contents

# Synopsis

This online resource summarizes all empirical ground-motion prediction equations (GMPEs), to estimate earthquake peak ground acceleration (PGA) and elastic response spectral ordinates, published between 1964 and 2023 (inclusive)[1]. This resource replaces: the Imperial College London reports of Douglas (2001b), Douglas (2002) and Douglas (2004a), which provide a summary of all GMPEs from 1964 until the end of 2003; the BRGM report of Douglas (2006), which summarizes all GMPEs from 2004 to 2006 (plus some earlier models); the report of Douglas (2008), concerning GMPEs published in 2007 and 2008 (plus some earlier models); and the report of Douglas (2011), which superseded all these reports and covered the period up to 2010. It is planned to continually update this website when new GMPEs are published or errors/omissions are discovered. In addition, this resource lists published GMPEs derived from simulations, although details are not given since the focus here is on empirical models. Studies that only present graphs are only listed, as are those non-parametric formulations that provide predictions for different combinations of distance and magnitude because these are more difficult to use for seismic hazard analysis than those which give a single formula. Equations for single earthquakes or for earthquakes of approximately the same size are excluded due to their limited usefulness. Those relations based on conversions from macroseismic intensity are only listed. Finally, conditional ground-motion models (e.g. Sung et al., 2021), which provide predictions for a secondary intensity measure conditional on a primary measure, are excluded due to a lack of resources to identify and summarise these models.

This website summarizes, in total, the characteristics of 505 empirical GMPEs for the prediction of PGA and 324 empirical models for the prediction of elastic response spectral ordinates. In addition, 91 simulation-based models to estimate PGA and elastic response spectral ordinates are listed but no details are given. 53 complete stochastic models, 45 GMPEs derived in other ways, 41 non-parametric models and 20 backbone (Atkinson et al., 2014a; Douglas, 2018a) models are also listed. Finally, the table provided by Douglas (2012) is expanded and updated to include the general characteristics of empirical GMPEs for the prediction of: Arias intensity (34 models), cumulative absolute velocity (14 models), Fourier spectral amplitudes (20 models), maximum absolute unit elastic input energy (6 models), inelastic response spectral ordinates (6 models), Japanese Meterological Agency seismic intensity (5 models), macroseismic intensity (52 models, commonly called intensity prediction equations), mean period (6 models), peak ground velocity (155 models), peak ground displacement (38 models), relative significant duration (23 models) and vertical-to-horizontal response spectral ratio (15 models).

It should be noted that the size of this resource means that it may contain some errors or omissions. The boundaries between empirical, simulation-based and non-parametric ground-motion models are not always clear so I may classify a study differently than expected. No discussion of the merits, ranges of applicability or limitations of any of the relationships is included herein except those mentioned by the authors or inherent in the data used. This compendium is *not* a critical review of the models.

This compilation was made when I was employed at: Imperial College London, University of Iceland, BRGM and University of Strathclyde. I thank: my current and former employers for their support, many people for references, suggestions and encouragement while producing this resource, and the developers of LaTeXand associated packages, without whom this report would never have been written.

If required, you can cite this resource in the following way:

Douglas, J. (2024), Ground motion prediction equations 1964–2023, `http://www.gmpe.org.uk`.

[1]Please note that this version is incomplete. I hope to complete it later this year. JD, 2nd April 2024.

# Chapter 1

# Introduction

ESEE Report 01-1 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)' (Douglas, 2001b) was completed and released in January 2001. A report detailing errata of this report and additional studies was released in October 2002 (Douglas, 2002). These two reports were used by Douglas (2003) as a basis for a review of previous ground-motion prediction equations (GMPEs). Following the release of these two reports, some further minor errors were found in the text and tables of the original two reports, and additional studies were found in the literature that were not included in ESEE 01-1 or the follow-on report. Also some new studies were published. Rather than produce another report listing errata and additions it was decided to produce a new report that included details on all the studies listed in the first two reports (with the corrections made) and also information on the additional studies. This report was published as a research report of Imperial College London at the beginning of 2004 (Douglas, 2004a). At the end of 2006 a BRGM report was published (Douglas, 2006) detailing studies published in 2004–2006 plus a few earlier models that had been missed in previous reports. Finally, at the end of 2008 another BRGM report was published (Douglas, 2008) containing summaries of GMPEs from 2007 and 2008 and some additional earlier models that had been recently uncovered.

Because of the large number of new GMPEs published in 2009 and 2010 and the discovery of some additional earlier studies and various errors in the previous reports, it was decided to publish a new comprehensive report to replace the previous reports (Douglas, 2001b, 2002, 2004a, 2006, 2008) containing all previous reports plus additional material rather than publish yet another addendum to the 2004 report. It was also decided that, for completeness and due to the lack of another comprehensive and public source for this information, to include a list of GMPEs developed using other methods than regression of strong-motion data, e.g. simulation-based models (e.g. Douglas and Aochi, 2008). However, due to the complexity of briefly summarizing these models it was decided not to provide details but only references. This report was published as Douglas (2011).

In order to make the compendium easier to use and to update in the future it was decided to port the entire report to `html` using the LaTeXTeX 4ht package as well as add models from 2011 to 2021 and some older GMPEs that were recently found. Finally, GMPEs for intensity measures other than PGA and elastic response spectral ordinates are listed but details are not given (although some of these correspond to models for PGA and elastic spectral ordinates and hence they are summarized elsewhere in this compendium).

This report summarizes, in total, the characteristics of 505 empirical GMPEs for the prediction of peak ground acceleration (PGA) and 324 models for the prediction of elastic response spectral ordinates as well as 34 models for the prediction of Arias intensity, 14 models for cumulative absolute velocity, 20 models for Fourier spectral amplitudes, 6 models for maximum absolute unit elastic input energy, 6 models for inelastic response spectral ordinates, 5 models for Japanese Meterological Agency seismic intensity, 52 models[1] (intensity prediction equations) for macroseismic intensity, 6 models for mean period, 155 for peak ground velocity, 38 for peak ground displacement, 23 for relative significant duration and 15 models for vertical-to-horizontal response spectral ratio. With this many GMPEs available it is important to have criteria available for the selection of

[1]Only those models using magnitude rather than epicentral intensity are listed.

appropriate models for seismic hazard assessment in a given region — Cotton et al. (2006) and, more recently, Bommer et al. (2010) suggest selection requirements for the choice of models. For the selection of GMPEs routinely applicable to state-of-the-art hazard analyses of ground motions from shallow crustal earthquakes Bommer et al. (2010) summarize their criteria thus.

1. Model is derived for an inappropriate tectonic environment (such as subduction-zone earthquakes or volcanic regions).
2. Model not published in a Thomson Reuters ISI-listed peer-reviewed journal (although an exception can be made for an update to a model that did meet this criterion).
3. The dataset used to derive the model is not presented in an accessible format; the minimum requirement would be a table listing the earthquakes and their characteristics, together with the number of records from each event.
4. The model has been superseded by a more recent publication.
5. The model does not provide spectral predictions for an adequate range of response periods, chosen here to be from 0 to 2 s.
6. The functional form lacks either non-linear magnitude dependence or magnitude-dependent decay with distance.
7. The coefficients of the model were not determined with a method that accounts for inter-event and intra-event components of variability; in other words, models must be derived using one- or two-stage maximum likelihood approaches or the random effects approach.
8. Model uses inappropriate definitions for explanatory variables, such as $M_L$ or $r_{epi}$, or models site effects without consideration of $V_{s,30}$.
9. The range of applicability of the model is too small to be useful for the extrapolations generally required in PSHA: $M_{\min} > 5$, $M_{\max} < 7$, $R_{\max} < 80$ km.
10. Model constrained with insufficiently large dataset: fewer than 10 earthquakes per unit of magnitude or fewer than 100 records per 100 km of distance.

Similar criteria could be developed for other types of earthquakes (e.g. subduction). For example, the reader is referred to Stewart et al. (2015) for a discussion of the selection of GMPEs for hazard assessments for the three principal tectonic regimes. Application of such criteria would lead to a much reduced set of models. The aim of this report, however, is not to apply these, or any other, criteria but simply to summarize all models that have been published. Bommer et al. (2010) also note that: '[i]f one accepts the general approach presented in this paper, then it becomes inappropriate to develop and publish GMPEs that would subsequently be excluded from use in PSHA [probabilistic seismic hazard analysis] on the basis of not satisfying one or more of the requirements embodied in the criteria.'

Predictions of median ground motions from GMPEs show great dispersion (Douglas, 2010a,b, 2012) demonstrating the large epistemic uncertainties involved in the estimation of earthquake shaking. This uncertainty should be accounted for within seismic hazard assessments by, for example, logic trees (e.g. Bommer and Scherbaum, 2008).

## 1.1 Other summaries and reviews of GMPEs

A number of reviews of GMPEs have been made in the past that provide a good summary of the methods used, the results obtained and the problems associated with such relations. Trifunac and Brady (1975a, 1976) provide a brief summary and comparison of published relations. McGuire (1976) lists numerous early relations. Idriss (1978) presents a comprehensive review of published attenuation relations up until 1978, including a number which are not easily available elsewhere. Hays (1980) presents a good summary of ground-motion estimation procedures up to 1980. Boore and Joyner (1982) provide a review of attenuation studies published in 1981 and they comment on empirical prediction of strong ground motion in general. Campbell (1985) contains a full survey of attenuation equations up until 1985. Joyner and Boore (1988) give an excellent analysis of ground motion prediction methodology in general, and attenuation relations in particular; Joyner and Boore (1996) update this by including more recent studies. Ambraseys and Bommer (1995) provide an overview of relations that are used for seismic design in Europe although they do not provide details about methods used. Recent reviews include those by Campbell (2003c,a) and Bozorgnia and Campbell (2004a), which provide the coefficients for a number of commonly-used equations for peak ground acceleration and spectral ordinates, and Douglas (2003). Bommer (2006) discusses some pressing problems in the field of empirical ground-motion estimation. The International Institute of Seismology and Earthquake Engineering provides a useful online resource `http://iisee.kenken.go.jp/eqflow/reference/Start.htm` summarising a number of GMPEs (particularly those from Japan) and providing coefficients and an Excel spreadsheet for their evaluation. A recent discussion of current and future trends in ground-motion prediction is provided by Douglas and Edwards (2016). Aldea et al. (2022) provide an overview of published GMPEs for the Vrancea (Romania) intermediate-depth seismic source.

Summaries and reviews of published ground-motion models for the estimation of strong-motion parameters other than PGA and elastic response spectral ordinates are available[2]. For example: Bommer and Martínez-Pereira (1999), Alarcón (2007) and Bommer et al. (2009) review predictive equations for strong-motion duration; Tromans (2004) summarizes equations for the prediction of PGV and displacement (PGD); Bommer and Alarcón (2006) provide a more recent review of GMPEs for PGV; Hancock and Bommer (2005) discuss available equations for estimating number of effective cycles; Stafford et al. (2009) briefly review GMPEs for Arias intensity; Rathje et al. (2004) summarize the few equations published for the prediction of frequency-content parameters (e.g. predominant frequency); and Cua et al. (2010) review various intensity prediction equations.

## 1.2 GMPEs summarised here

Equations for single earthquakes (e.g. Bozorgnia et al., 1995) or for earthquakes of approximately the same size (e.g. Seed et al., 1976; Sadigh et al., 1978b) are excluded because they lack a magnitude-scaling term and, hence, are of limited use. Also excluded are those originally developed to yield the magnitude of an earthquake (e.g. Espinosa, 1980), i.e. the regression is performed the other way round, which should not be used for the prediction of ground motion at a site. The model of Kim and Shin (2017) is not included because it is based on the ratio of the magnitude of the mainshock to an aftershock rather than the magnitude directly. The model of Zhao and Gerstenberger (2010) is not summarised since it uses recorded motions to estimate motions at sites without observations, within a rapid-response system. Models such as that by Olszewska (2006) and Golik and Mendecki (2012), who use 'source energy logarithms' to characterize mining-induced events, have been excluded because such a characterization of event size is rare in standard seismic hazard assessments. Similarly, equations derived using data from nuclear tests, such as those reported by Mickey (1971); Hays (1980), are not included. Finally, conditional ground-motion models (e.g. Sung et al., 2021), which provide predictions for a secondary intensity measure conditional on a primary measure, are excluded due to a lack of resources to identify and summarise these models.

Those based on simulated ground motions from stochastic source models (e.g Atkinson and Boore, 1990) and other types of simulations (e.g. Megawati et al., 2005), those derived using the hybrid empirical technique (e.g Campbell, 2003b; Douglas et al., 2006), those relations based on intensity measurements (e.g. Battis, 1981) and backbone models (Atkinson et al., 2014a; Douglas, 2018a) are listed in Chapter 6 but no details are given because the focus here is on empirical models derived from ground-motion data. Studies using simulation techniques

[2]Note that a number of the models summarized in this report also provide coefficients for peak ground velocity (PGV).

other than the classic stochastic method and which do not provide a closed-form GMPE (e.g. Medel-Vera and Ji, 2016) are not listed as they are often difficult to use. Studies which provide graphs to give predictions (e.g. Schnabel and Seed, 1973) are only listed and not summarized as are those non-parametric formulations that give predictions for different combinations of distance and magnitude (e.g. Anderson, 1997), both of which are generally more difficult to use for seismic hazard analysis than those which report a single formula. For similar reasons, models derived using neural networks (e.g. Güllü and Erçelebi, 2007) are only listed.

GMPEs for the prediction of PGA are summarized in Chapters 2 and 3 and those for spectral ordinates are summarized in Chapters 4 and 5. Chapter 6 lists other ground-motion models that are not detailed in the previous chapters. The final chapter (Chapter 7) provides the general characteristics of GMPEs for intensity measures other than PGA and elastic spectral ordinates. All the studies that present the same GMPE are mentioned at the top of the section and in the tables of general characteristics (Illustrations 3.1 & 5.1). The information contained within each section, and within tables, is the sum of information contained within each of the publications, i.e. not all the information may be from a single source. Note that GMPEs are ordered in chronological order both in the section titles and the order of the sections. Therefore, a well-known model presented in a journal article may not be listed where expected since it had previously been published in a conference proceedings or technical report. To find a given model it is recommended to examine the table of content carefully or apply a keyword search to the PDF. Some models (e.g. Abrahamson and Silva, 1997) provide GMPEs for spectral accelerations up to high frequencies (e.g. 100 Hz) but do not explicitly state that these equations can be used for the prediction of PGA. Therefore, they are only listed in the chapters dealing with GMPEs for the prediction of spectral ordinates (Chapters 4 and 5) and their coefficients are not given. This should be considered when searching for a particular model.

To make it easier to understand the functional form of each GMPE the equations are given with variable names replacing actual coefficients and the derived coefficients and the standard deviation, $\sigma$, are given separately (for PGA equations). These coefficients are given only for completeness and if an equation is to be used then the original reference should be consulted. If a coefficient is assumed before the analysis is performed then the number is included directly in the formula.

Obviously all the details from each publication cannot be included in this report because of lack of space but the most important details of the methods and data used are retained. The style is telegraphic and hence phrases such as 'Note that ...' should be read 'The authors [of the original model] note that ...'. The number of records within each site and source mechanism category are given if this information was reported by the authors of the study. Sometimes these totals were found by counting the numbers in each category using the tables listing the data used and, therefore, they may be inaccurate.

This report contains details of all studies for PGA and response spectra that could be found in the literature (journals, conference proceedings, technical reports and some Ph.D. theses) although some may have been inadvertently missed[3]. Some of the studies included here have not been seen but are reported in other publications and hence the information given here may not be complete or correct. Since this resource has been written in many distinct periods over almost two decades (2000–2021), the amount of information given for each model varies, as does the style.

In the equations unless otherwise stated, $D$, $d$, $R$, $r$, $X$, $\Delta$ or similar are distance and $M$ or similar is magnitude and all other independent variables are stated. PGA is peak ground acceleration, PGV is peak ground velocity and PSV is relative pseudo-velocity.

In Tables 3.1, 5.1 and 7.1 the gross characteristics of the data used and equation obtained are only given for the main equation in each study. The reader should refer to the section on a particular publication or the original reference for information on other equations derived in the study.

In earlier reports the name 'attenuation relation(ships)' is used for the models reported. The current *de facto* standard is to refer to such models as 'ground motion prediction equations' (GMPEs) and, therefore, this terminology is adopted here. However, as discussed by Boore and Atkinson (2007, Appendix A) there is

[3] Generally GMPEs from technical reports and Ph.D. theses are only summarized if they have been cited in journal or conference articles.

some debate over the best name for these models (e.g. 'ground-motion model' or 'ground motion estimation equations') and some people disagree with the use of the word 'prediction' in this context.

No discussion of the merits, ranges of applicability or limitations of any of the relationships is included herein except those mentioned by the authors or inherent in the data used. This report is *not* a critical review of the models. The ground-motion models are generally reported in the form given in the original references. The boundaries between empirical, simulation-based and non-parametric ground-motion models are not always clear so I may classify a study differently than expected. Note that the size of this report means that it may contain some errors or omissions — the reader is encouraged to consult the original reference if a model is to be used.

# Chapter 2

# Summary of published GMPEs for PGA

## 2.1 Esteva and Rosenblueth (1964)

- Ground-motion model is:

$$a = c \exp(\alpha M) R^{-\beta}$$

where $a$ is in cm/s$^2$, $c = 2000$, $\alpha = 0.8$ and $\beta = 2$ ($\sigma$ is not given).

## 2.2 Kanai (1966)

- Ground-motion model is:

$$\begin{aligned} a &= \frac{a_1}{\sqrt{T_G}} 10^{a_2 M - P \log_{10} R + Q} \\ P &= a_3 + a_4/R \\ Q &= a_5 + a_6/R \end{aligned}$$

where $a$ is in cm/s$^2$, $a_1 = 5$, $a_2 = 0.61$, $a_3 = 1.66$, $a_4 = 3.60$, $a_5 = 0.167$ and $a_6 = -1.83$ ($\sigma$ is not given).

- $T_G$ is the fundamental period of the site.

## 2.3 Milne and Davenport (1969)

- Ground-motion model is:

$$A = \frac{a_1 \mathrm{e}^{a_2 M}}{a_3 \mathrm{e}^{a_4 M} + \Delta^2}$$

where $A$ is in percentage of g, $a_1 = 0.69$, $a_2 = 1.64$, $a_3 = 1.1$ and $a_4 = 1.10$ ($\sigma$ not given).

- Use data from Esteva and Rosenblueth (1964).

## 2.4 Esteva (1970)

- Ground-motion model is:

$$a = c_1 \mathrm{e}^{c_2 M} (R + c_3)^{-c_4}$$

where $a$ is in cm/s$^2$, $c_1 = 1230$, $c_2 = 0.8$, $c_3 = 25$, $c_4 = 2$ and $\sigma = 1.02$ (in terms of natural logarithm).

- Records from soils comparable to stiff clay or compact conglomerate.
- Records from earthquakes of moderate duration.

## 2.5 Denham and Small (1971)

- Ground-motion model is:

$$\log Y = b_1 + b_2 M + b_3 \log R$$

  where $Y$ is in g, $b_1 = -0.2$, $b_2 = 0.2$ and $b_3 = -1.1$ ($\sigma$ not given).

- Records from near dam on recent unconsolidated lake sediments which are $\geq 50$ m thick.

- Note need for more points and large uncertainty in $b_1$, $b_2$ and $b_3$.

## 2.6 Davenport (1972)

- Ground-motion model is:

$$A = \alpha e^{\beta m} R^{-\gamma}$$

  where $A$ is in g, $\alpha = 0.279$, $\beta = 0.80$, $\gamma = 1.64$ and $\sigma = 0.74$ (in terms of natural logarithms).

## 2.7 Denham et al. (1973)

- Ground-motion model is:

$$\log Y_a = a_1 + a_2 M_L + b_3 \log R$$

  where $Y_a$ is in cm/s$^2$, $a_1 = 2.91$, $a_2 = 0.32$ and $a_3 = -1.45$ ($\sigma$ is not given).

- Use records from Yonki station (20 records) which is on 50 m of recent alluvium and from Paguna station (5 records) which is on unconsolidated volcanic rock.

- Question validity of combining data at the two sites because of differences in geological foundations.

- Note large standard errors associated with coefficients preclude accurate predictions of ground motions.

- Also derive equation for Yonki station separately.

## 2.8 Donovan (1973)

- Ground-motion model is:

$$y = b_1 e^{b_2 M} (R + 25)^{-b_3}$$

  where $y$ is in gal, $b_1 = 1080$, $b_2 = 0.5$, $b_3 = 1.32$ and $\sigma = 0.71$. 25 adopted from Esteva (1970).

- 214 (32%) records from San Fernando (9/2/1971) earthquake and 53% of records with PGA less than 0.5 m/s$^2$.

- Considers portions of data and finds magnitude dependence increases with increasing distance from source and more small accelerations increase magnitude dependence. Thus magnitude and distance cannot be considered independent variables.

## 2.9 Esteva and Villaverde (1973) & Esteva (1974)

- Ground-motion model is:

$$Y_c = b_1 e^{b_2 M} (R + b_4)^{-b_3}$$

  where $Y_c$ is in cm/s$^2$, $b_1 = 5600$, $b_2 = 0.8$, $b_3 = 2$, $b_4 = 40$ and $\sigma = 0.64$ (in terms of natural logarithm).

## 2.10 Katayama (1974)

- Ground-motion model is:

$$\log A = c_1 + c_2 \log(R + c_3) + c_4 M$$

where $A$ is in cm/s$^2$, $c_1 = 2.308$, $c_2 = -1.637$, $c_3 = 30$ and $c_4 = 0.411$ ($\sigma$ not reported[1]). Also derive equation using $r_{epi}$: $c_1 = 0.982$, $c_2 = -0.129$, $c_3 = 0$ and $c_4 = 0.466$ ($\sigma$ not reported[2]).

## 2.11 McGuire (1974) & McGuire (1977)

- Ground-motion model is:

$$E[v] = a10^{bM}(R + 25)^{-c}$$

where $E$ indicates expectation, $v$ is in gal, $a = 472$, $b = 0.278$, $c = 1.301$.

- Excludes records for which significant soil amplification established but makes no distinction between rock and soil sites.
- Focal depths between 9 and 70 km with most about 10 km. Most records from earthquakes with magnitudes about 6.5 and most distances less than 50 km. Uses records from 21 different sites.
- Notes that physical laws governing ground motion near the source are different than those governing motion at greater distances therefore excludes records with epicentral distance or distance to fault rupture smaller than one-half of estimated length of rupture.
- Examines correlation among the records but find negligible effect.

## 2.12 Orphal and Lahoud (1974)

- Ground-motion model is:

$$A = \lambda 10^{\alpha M} R^{\beta}$$

where $A$ is in g, $\lambda = 6.6 \times 10^{-2}$, $\alpha = 0.40$, $\beta = -1.39$ and $\sigma = 1.99$ (this is multiplication factor).

- Use 113 records with distances between 15 to 350 km from San Fernando earthquake to find distance dependence, $\beta$.
- Use 27 records of Wiggins (1964) from El Centro and Ferndale areas, with magnitudes between 4.1 and 7.0 and distances between 17 and 94 km (assuming focal depth of 15 km), to compute magnitude dependent terms assuming distance dependence is same as for San Fernando.

## 2.13 Ahorner and Rosenhauer (1975)

- Ground-motion model is:

$$A = c_1 \exp(c_2 M)(R + c_3)^{-c_4}$$

where $A$ is in cm/s$^2$, $c_1 = 1230$, $c_2 = 0.8$, $c_3 = 13$ and $c_4 = -2$ ($\sigma$ is not reported).

[1] Reports coefficient of variation of 0.942 which could be the value of $\sigma$ in terms of natural logarithms.

[2] Report coefficient of variation of 0.877 which could be the value of $\sigma$ in terms of natural logarithms.

## 2.14 Ambraseys (1975b), Ambraseys (1975a) & Ambraseys (1978a)

- Ground-motion model is:

$$\log Y = b_1 + b_2 M_L + b_3 \log R$$

where $Y$ is in $\mathrm{cm/s^2}$, $b_1 = 0.46$, $b_2 = 0.63$, $b_3 = -1.10$ and $\sigma = 0.32$[3]

- Ambraseys and Bommer (1995) state that uses earthquakes with maximum focal depth of 15 km.

## 2.15 Shah and Movassate (1975)

- Ground-motion model is:

$$A = c_1 \exp(c_2 M)(R + c_3)^{-c_4}$$

where $A$ is in $\mathrm{cm/s^2}$, $c_1 = 5000$, $c_2 = 0.8$, $c_3 = 40$ and $c_4 = -2$ ($\sigma$ is not reported).

## 2.16 Trifunac and Brady (1975a), Trifunac (1976a) & Trifunac and Brady (1976)

- Ground-motion model is:

$$\begin{aligned}
\log_{10} a_{\max} &= M + \log_{10} A_0(R) - \log_{10} a_0(M, p, s, v) \\
\log_{10} a_0(M, p, s, v) &= \begin{cases} ap + bM + c + ds + ev + fM^2 - f(M - M_{\max})^2 & \text{for} \quad M \geq M_{\max} \\ ap + bM + c + ds + ev + fM^2 & \text{for} \quad M_{\max} \geq M \geq M_{\min} \\ ap + bM_{\min} + c + ds + ev + fM_{\min}^2 & \text{for} \quad M \leq M_{\min} \end{cases}
\end{aligned}$$

where $a_{\max}$ is in $\mathrm{cm/s^2}$, $\log_{10} A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of $M_L$, $p$ is confidence level and $v$ is component direction ($v = 0$ for horizontal and 1 for vertical). Coefficients are: $a = -0.898$, $b = -1.789$, $c = 6.217$, $d = 0.060$, $e = 0.331$, $f = 0.186$, $M_{\min} = 4.80$ and $M_{\max} = 7.50$ ($\log_{10} A_0(R)$ not given here due to lack of space).

- Use three site categories:

  $s = 0$ Alluvium or other low velocity 'soft' deposits: 63% of records.

  $s = 1$ 'Intermediate' type rock: 23% of records.

  $s = 2$ Solid 'hard' basement rock: 8% of records.

- Exclude records from tall buildings.

- Do not use data from other regions because attenuation varies with geological province and magnitude determination is different in other countries.

- Records baseline and instrument corrected. Accelerations thought to be accurate between 0.07 and 25 Hz or between 0.125 and 25 Hz for San Fernando records.

- Most records (71%) from earthquakes with magnitudes between 6.0–6.9, 22% are from 5.0–5.9, 3% are from 4.0–4.9 and 3% are from 7.0–7.7 (note barely adequate data from these two magnitude ranges). 63% of data from San Fernando earthquake.

[3]From Ambraseys and Bommer (1995).

- Note that for large earthquakes, i.e. long faults, $\log_{10} A_0(R)$ would have a tendency to flatten out for small epicentral distances and for low magnitude shocks curve would probably have a large negative slope. Due to lack of data $\lesssim 20$ km this is impossible to check.

- Note difficulty in incorporating anelastic attenuation because representative frequency content of peak amplitudes change with distance and because relative contribution of digitization noise varies with frequency and distance.

- Note that $\log_{10} A_0(R)$ may be unreliable for epicentral distances less than 10 km because of lack of data.

- Change of slope in $\log_{10} A_0(R)$ at $R = 75$ km because for greater distances main contribution to strong shaking from surface waves, which are attenuated less rapidly ($\sim 1/R^{1/2}$) than near-field and intermediate-field ($\sim 1/R^{2-4}$), or far-field body waves ($\sim 1/R$).

- Note lack of data to reliably characterise $\log_{10} a_0(M, p, s, v)$ over a sufficiently broad range of their arguments. Also note high proportion of San Fernando data may bias results.

- Firstly partition data into four magnitude dependent groups: 4.0–4.9, 5.0–5.9, 6.0–6.9 and 7.0–7.9. Subdivide each group into three site condition subgroups (for $s = 0$, 1 and 2). Divide each subgroup into two component categories (for $v = 0$ and 1). Calculate $\log_{10} a_0(M, p, s, v) = M + \log_{10} A_0(R) - \log_{10} a_{\max}$ within each of the 24 parts. Arrange each set of $n$ $\log_{10} a_0$ values into decreasing order with increasing $n$. Then $m$th data point (where $m$ equals integer part of $pn$) is estimate for upper bound of $\log_{10} a_0$ for $p$% confidence level. Then fit results using least squares to find $a, \ldots f$.

- Check number of PGA values less than confidence level for $p = 0.1, \ldots, 0.9$ to verify adequacy of bound. Find simplifying assumptions are acceptable for derivation of approximate bounds.

## 2.17 Blume (1977)

- Ground-motion model is:
$$a = b_1 \mathrm{e}^{b_2 M_L} (R + 25)^{-b_3}$$
where $a$ is in gal, for $M_L \leq 6\frac{1}{2}$ $b_1 = 0.318 \times 29^{1.14\bar{b}}$, $b_2 = 1.03$, $b_3 = 1.14\bar{b}$ and $\sigma = 0.930$ (in terms of natural logarithm) and for $M_L > 6\frac{1}{2}$ $b_1 = 26.0 \times 29^{1.22\bar{b}}$, $b_2 = 0.432$, $b_3 = 1.22\bar{b}$ and $\sigma = 0.592$ (in terms of natural logarithm).

- Assumes all earthquakes have focal depth of 8 km.

- Makes no distinction for site conditions in first stage where uses only earthquake records.

- Studies effects of PGA cutoff (no cutoff, 0.01, 0.02 and 0.05 m/s$^2$), distance cutoff (no cutoff and $< 150$ km) and magnitude cutoff (all, $\geq 5\frac{1}{2}$, $\geq 6$, $\geq 6\frac{1}{2}$, $\geq 6\frac{3}{4}$ and $\leq 6\frac{1}{2}$).

- Selects $6\frac{1}{2}$ as optimum magnitude cutoff but uses all data to derive equation for $M_L \leq 6\frac{1}{2}$ because not much difference and dispersion is slightly lower (in terms of $\pm 1$ standard deviation have 2.53 and 2.61).

- In second stage uses only records from underground nuclear explosions, consistent with natural earthquake records, to derive site factor.

- Uses 1911 alluvium and 802 rock records and derive PGA ratio of alluvium to rock assuming their PGAs equal at 4 km.

- Finds site impedance $\rho V_s$, where $\rho$ is density and $V_s$ is shear-wave velocity under site, is best measure of site condition. Use 2000 fps (600 m/s) as shear-wave velocity of alluvium stations.

- Multiplies equation (after taking logarithms) by $\bar{b} = \frac{1}{2}\log_{10}(\rho V_s)$ and normalise to 4 km.
- Notes may not be a good model for other regions.

## 2.18 Gürpinar (1977)

- Ground-motion model is:

$$\ln y = \ln a_1 + a_2 \ln M + a_3 \ln R$$

  where $y$ is in cm/s$^2$; $a_1 = 0.15$, $a_2 = 4.84$ and $a_3 = -0.68$ ($\sigma$ not reported) for site class I; $a_1 = 9.80$, $a_2 = 3.57$ and $a_3 = -1.12$ ($\sigma$ not reported) for site class II; and $a_1 = 0.0022$, $a_2 = 8.31$ and $a_3 = -1.31$ ($\sigma$ not reported) for site class III.

- Use 3 site classes (based on Caltech classification):

  I Soft alluvium. 128 components.

  II Stiff soil. 68 components.

  III Hard rock. 26 components.

- Only uses data from $20 < r_{epi} < 70$ km because of large dispersion in data for closer distances.
- Uses F-values to test goodness of fit.

## 2.19 Milne (1977)

- Ground-motion model is:

$$\text{ACC} = a_1 \mathrm{e}^{a_2 M} R^{a_3}$$

  where ACC is in g, $a_1 = 0.04$, $a_2 = 1.00$ and $a_3 = -1.4$.

## 2.20 Saeki et al. (1977)

- Ground-motion model is:

$$\log A = c_1 + c_2 M + c_3 \log(\Delta)$$

  where $A$ is in cm/s$^2$, for class I: $c_1 = 1.455$, $c_2 = 0.207$ and $c_3 = -0.598$; for class II: $c_1 = 1.121$, $c_2 = 0.330$ and $c_3 = -0.806$; for class III: $c_1 = 1.507$,

  $c_2 = 0.254$ and $c_3 = -0.757$; for class IV: $c_1 = 0.811$, $c_2 = 0.430$ and $c_3 = -0.977$; and for all sites: $c_1 = 1.265$, $c_2 = 0.302$ and $c_3 = -0.800$. $\sigma$ not reported.

- Use 4 site classes:

Class I 29 records

Class II 74 records

Class III 127 records

Class IV 68 records

## 2.21 Ambraseys (1978b)

- Ground-motion model is:

$$\bar{a} = a_1 \bar{R}^{a_2} \exp(a_3 \bar{M})$$

  where $\bar{a}$ is in cm/s$^2$, $a_1 = 1.31$, $a_2 = -0.92$ and $a_3 = 1.455$ ($\sigma$ is not given).

- Uses data from former USSR, former Yugoslavia, Portugal, Italy, Iran, Greece and Pakistan.

- Peak ground accelerations have either been taken from true-to-scale accelerograms or have been supplied by local networks. Records have not been high- or low-pass filtered because it was found not to work with short records.

- Believes body-wave or local magnitude are the appropriate magnitude scales because interested in the high-frequency range of spectra, which are seen and sampled by strong-motion instruments, and most engineering structures have high natural frequencies.

- Most of the magnitudes were recalculated using P-waves of periods of not more than 1.2 s because it was found that the magnitude was dependent on the period of the P-waves used for its determination.

- Groups data into intervals of 0.5 magnitude units by 10 km in which the mean and standard deviations of the PGAs is calculated. This grouping minimises distance and magnitude-dependent effects. Notes that the number of observations is barely sufficient to allow a statistical treatment of the data and hence only test general trend. Notes that scatter is significant and decreases with increasing magnitude.

## 2.22 Donovan and Bornstein (1978)

- Ground-motion model is:

$$\begin{aligned} y &= b_1 e^{b_2 M} (R + 25)^{-b_3} \\ \text{where} \quad b_1 &= c_1 R^{-c_2} \\ b_2 &= d_1 + d_2 \log R \\ b_3 &= e_1 + e_2 \log R \end{aligned}$$

  where $y$ is in gal, $c_1 = 2,154,000$, $c_2 = 2.10$, $d_1 = 0.046$, $d_2 = 0.445$, $e_1 = 2.515$, $e_2 = -0.486$, for $y = 0.01$ g $\sigma = 0.5$, for $y = 0.05$ g $\sigma = 0.48$, for $y = 0.10$ g $\sigma = 0.46$ and for $y = 0.15$ g $\sigma = 0.41$ (in terms of natural logarithm).

  Use 25 because assume energy centre of Californian earthquakes to be at depth 5 km.

- Consider two site conditions but do not model:
  1. Rock: (21 records)
  2. Stiff soil: (38 records)

- 32% of records from San Fernando (9/2/1971) but verifies that relationship is not significantly biased by this data.

- Most records within 50 km and most from earthquakes with magnitudes of about 6.5.

- Recognises that magnitude and distance are not independent variables.

- Find $b_1$, $b_2$ and $b_3$ by dividing data according to distance and computing $b$ parameters for each set using least squares. Find a distinct trend with little scatter.

## 2.23 Faccioli (1978)

- Ground-motion model is:

$$y = a10^{bM}(R + 25)^{-c}$$

where $y$ is in gal, $a = 108.60$, $b = 0.265$, $c = 0.808$ and $\sigma = 0.236$ (in terms of logarithm to base 10).

- Records from sites underlain by cohesive or cohesionless soils with shear-wave velocities less than about 100 m/s and/or standard penetration resistance $N \leq 10$ in uppermost 10 m with layers of considerably stiffer materials either immediately below or at depths not exceeding a few tens of metres.

- Focal depths between 9 and 100 km.

- Free-field accelerograms, to minimize soil-structure interaction.

- Excludes records with PGA $< 0.4\,\mathrm{m/s^2}$.

- 21 Japanese records processed with frequency cutoffs of bandpass filter, for baseline correction, adjusted so as to account for length and mean sampling rate of records and response characteristics of SMAC-2. 4 of remaining 7 records processed in same way.

## 2.24 Goto et al. (1978)

- Ground-motion model is:

$$\log A = c_1 + c_2 M + c_3 \log(\Delta + 30)$$

where $A$ is in $\mathrm{cm/s^2}$, $c_1 = 2.610$, $c_2 = 0.160$ and $c_3 = -0.752$ ($\sigma$ not reported[4]).

- Data from alluvial sites

- All PGAs $> 50$ gal.

## 2.25 McGuire (1978a)

- Ground-motion model is:

$$\ln x = b_1 + b_2 M + b_3 \ln R + b_4 Y_s$$

where $x$ is in $\mathrm{cm/s^2}$, $b_1 = 3.40$, $b_2 = 0.89$, $b_3 = -1.17$, $b_4 = -0.20$ and $\sigma = 0.62$.

- Uses two site categories:

$Y_s = 0$ Rock: sedimentary or basement rock or soil less than 10 m thick, 11 records.

$Y_s = 1$ Soil: alluvium or other soft material greater than 10 m thick, 59 records.

- Uses records from basement of buildings or from 'free-field'. Uses no more than seven records from same earthquake and no more than nine from a single site to minimize underestimation of calculated variance. Retains records which give a large distance and magnitude range.

- Notes that near-field ground motion governed by different physical laws than intermediate and far field so excludes near-field data, for example El Centro (19/5/1940) and Cholame-2, from Parkfield earthquake (28/6/1966)

- Considers a distance dependent site term but not statistically significant. Also uses a magnitude dependent site term and although it was statistically significant it did not reduce the scatter and also since largest magnitude for a rock site is 6.5, result may be biased.

[4]Report coefficient of variation of 0.443 which could be the value of $\sigma$ in terms of natural logarithms.

## 2.26 A. Patwardhan, K. Sadigh, I.M. Idriss, R. Youngs (1978) reported in Idriss (1978)

- Ground-motion model is:
$$\ln y = \ln A + BM_s + E\ln[R + d\exp(fM_s)]$$
where $y$ is in $\mathrm{cm/s^2}$, $d = 0.864$ and $f = 0.463$ and for path A (rock): $A = 157$ (for median), $A = 186$ (for mean), $B = 1.04$ and $E = -1.90$, for path A (stiff soil): $A = 191$ (for median), $A = 224$ (for mean), $B = 0.823$ and $E = -1.56$ and for path B (stiff soil): $A = 284$ (for median), $A = 363$ (for mean), $B = 0.587$ and $E = -1.05$ ($\sigma$ not given).

- Separate equations for two types of path:

  A Shallow focus earthquakes (California, Japan, Nicaragua and India), 63 records.

  B Subduction (Benioff) zone earthquakes (Japan and South America), 23 earthquakes, $5.3 \leq M_s \leq 7.8$, 32 records.

- Use two site categories for path A earthquakes for which derive separate equations:

  1. Rock: 21 records.
  2. Stiff soil: 42 records.

  Use only stiff soil records for deriving subduction zone equation.

- Most earthquakes for path A have $5 \leq M_s \leq 6.7$.

- All data corrected. PGA for corrected Japanese and South American records much higher than uncorrected PGA.

## 2.27 Cornell et al. (1979)

- Ground-motion model is:
$$\ln A_p = a + bM_L + c\ln(R + 25)$$
where $A_p$ is in $\mathrm{cm/s^2}$, $a = 6.74$, $b = 0.859$, $c = -1.80$ and $\sigma = 0.57$.

- No more than 7 records from one earthquake to avoid biasing results.

- Records from basements of buildings or free-field.

## 2.28 Faccioli (1979)

- Ground-motion model is:
$$\log y = b_1 + b_2M + b_3\log(R + 25)$$
where $y$ is in $\mathrm{cm/s^2}$, $b_1 = 0.44$, $b_2 = 0.33$, $b_3 = -2.66$ and $\sigma = 0.12$.

- Uses data from three sedimentary rock sites (Somplago, San Rocco and Robic) because aim of study to provide zoning criteria as free as possible from influence of local conditions.

- Compares predictions and observations and find close fit, possibly because of restricted distance range.

- Note that use of simple functional form and $r_{hypo}$ acceptable approximation because of short rupture lengths.

## 2.29 Faccioli and Agalbato (1979)

- Ground-motion model is:

$$\log y = b_1 + b_2 M + b_3 \log(R + \alpha)$$

where $y$ is in cm/s$^2$, $b_1 = 1.59 \pm 0.69$, $b_2 = 0.25 \pm 0.03$, $b_3 = -0.79 \pm 0.12$, $\alpha = 0$ and $\sigma = 0.25$ for horizontal PGA and $b_1 = 1.38 \pm 1.89$, $b_2 = 0.24 \pm 0.09$, $b_3 = -0.78 \pm 0.25$ and $\sigma = 0.25$ for vertical PGA.

- Use two site classes:

Soil Includes alluvium and moraine deposits of varying thicknesses and characteristics.

Rock-like Includes limestone, dolomite, flysch and cemented conglomerates, even if heavily fractured, overlain by not more than 4–5 m of alluvium.

Use published and unpublished material for classification.

- Focal depths between 6 and 11 km.
- Use data from Friuli 1976 mainshock and subsequent earthquakes from four networks including temporary stations (ENEL, CNEN, IZIIS and CEA/DSN). Data from ENEL, CNEN and IZIIS from RFT-250 and SMA-1 instruments and data from CEA/DSN from short-period seismographs. Some records not available in digital form so used reported PGAs.
- Almost all records from free-field stations.
- 58 PGAs from $r_{hypo} \leq 20$ km.
- $13\,\mathrm{cm/s^2} \leq PGA \leq 515\,\mathrm{cm/s}$ with 93% above $30\,\mathrm{cm/s^2}$.
- Best-recorded earthquake (mainshock) contributed 24 PGAs.
- One station contributed 17 PGAs.
- Also regresses just using data from mainshock.
- $\alpha$ is either 0 or 25 in regression. Prefer results with $\alpha = 0$ because smaller standard errors in $b_3$.
- Statistical tests show $b_2$ and $b_3$ are significantly different than 0.
- Also present coefficients for rock-like stations only and soil stations only. Find that effect of selection by site class does not greatly affect coefficients.
- Process a smaller set of records available in digitized form (76 horizontal components) using high-pass filter (cut-off and roll-off of 0.4–0.8 Hz) based on digitization noise. Note difficulty in standard processing due to high-frequency content and short durations. Use sampling rate of 100 Hz. Find that corrected horizontal PGAs are on average 6% lower than uncorrected PGAs and 15% show difference larger than 10%. For vertical PGAs average difference is 12%. Develop equations based on this subset (for horizontal PGA $b_1 = 1.51 \pm 0.77$, $b_2 = 0.24 \pm 0.04$, $b_3 = 0.70 \pm 0.21$ and $\sigma = 0.24$). Note similarity to results for uncorrected PGAs.
- Also derive equation using only 39 PGAs from $r_{hypo} \leq 20$ km and note weak magnitude and distance dependence. Compare to data from shallow soil sites at Forgaria-Cornino and Breginj and note that local site conditions can significantly modify bedrock motions even at close distances.

## 2.30 Aptikaev and Kopnichev (1980)

- Ground-motion model is:

$$\log A_e = a_1 M + a_2 \log R + a_3$$

where $A_e$ is in cm/s$^2$, for $A_e \geq 160\,\text{cm/s}^2$ $a_1 = 0.28$, $a_2 = -0.8$ and $a_3 = 1.70$ and for $A_e < 160\,\text{cm/s}^2$ $a_1 = 0.80$, $a_2 = -2.3$ and $a_3 = 0.80$ ($\sigma$ not given).

- As a rule, PGA corresponds to S-wave.

- Use five source mechanism categories (about 70 records, 59 earthquakes from W. N. America including Hawaii, Guatemala, Nicaragua, Chile, Peru, Argentina, Italy, Greece, Romania, central Asia, India and Japan):

  1. Contraction faulting (uplift and thrust), about 16 earthquakes.
  2. Contraction faulting with strike-slip component, about 6 earthquakes.
  3. Strike-slip, about 17 earthquakes.
  4. Strike-slip with dip-slip component, about 6 earthquakes.
  5. Dip-slip, about 9 earthquakes.

- Use these approximately 70 records to derive ratios of mean measured, $A_0$, to predicted PGA, $A_e$, $\log(A_0/A_e)$, and for ratios of mean horizontal to vertical PGA, $\log A_h/A_v$, for each type of faulting. Use every earthquake with equal weight independent of number of records for each earthquake.

- Results are:

| | Category 1 | Category 2 | Category 3 | Category 4 | Category 5 |
|---|---|---|---|---|---|
| $\log A_0/A_e$ | $0.35 \pm 0.13$ (16) | $0.11 \pm 0.17$ (5) | $0.22 \pm 0.08$ (17) | $0.06 \pm 0.13$ (6) | $-0.06 \pm 0.20$ (9) |
| $\log A_h/A_v$ | $0.32 \pm 0.13$ (12) | $0.32 \pm 0.08$ (5) | $0.27 \pm 0.07$ (12) | $0.18 \pm 0.10$ (5) | $0.17 \pm 0.11$ (5) |

where $\pm$ gives 0.7 confidence intervals and number in brackets is number of earthquakes used.

- Also calculate mean envelope increasing speed for P-wave amplitudes, $A$, obtained at teleseismic distances: $n = \mathrm{d} \ln A/\mathrm{d}t$, where $t$ is time for P-wave arrival and try to relate to ratios for each type of faulting.

## 2.31 Blume (1980)

- Ground-motion model is:

$$a = b_1 \mathrm{e}^{b_2 M} (R + k)^{-b_3}$$

where $a$ is in gal, for method using distance partitioning $b_1 = 18.4$, $b_2 = 0.941$, $b_3 = 1.27$ and $k = 25$ and for ordinary one-stage method $b_1 = 102$, $b_2 = 0.970$, $b_3 = 1.68$ and $k = 25$ ($\sigma$ not given).

- Does not use PGA cutoff because PGA is, by itself, a poor index of damage in most cases.

- Mean magnitude is 5.4 and mean distance is 84.4 km.

- Notes problem of regression leverage for some attenuation studies. Lots of data in fairly narrow distance band, e.g. records from San Fernando earthquake, can dominate regression and lead to biased coefficients.

- Divides data into ten distance bands (A-J) which are 10 km wide up to 60 km and then 60-99.9 km, 100–139.9 km, 140–199.9 km and $\geq 200$ km. Fits $\log_{10} a = bM - c$ to data in each band and fits Ground-motion model to selected point set in $M$, $R$ and $a$.

- Also fits equation using all data using normal least squares.

- Adds 52 records ($3.2 \leq M \leq 6.5$, $5 \leq R \leq 15$ km) and repeats; finds little change.

## 2.32 Iwasaki et al. (1980)

- Ground-motion model is:

$$\mathrm{PGA} = a_1 10^{a_2 M} (\Delta + 10)^{a_3}$$

  where PGA is in gal, for type I sites $a_1 = 46.0$, $a_2 = 0.208$ and $a_3 = -0.686$ , for type II sites $a_1 = 24.5$, $a_2 = 0.333$ and $a_3 = -0.924$, for type III sites $a_1 = 59.0$, $a_2 = 0.261$ and $a_3 = -0.886$, for type IV sites $a_1 = 12.8$, $a_2 = 0.432$, $a_3 = -1.125$ and for all sites $a_1 = 34.1$, $a_2 = 0.308$ and $a_3 = -0.925$ ($\sigma$ not given).

- Use four site categories:

Type I Tertiary or older rock (defined as bedrock) or diluvium with depth to bedrock, $H < 10$ m, 29 records.

Type II Diluvium with $H \geq 10$ m or alluvium with $H < 10$ m, 74 records.

Type III Alluvium with $H < 25$ m including soft layer (sand layer vulnerable to liquefaction or extremely soft cohesive soil layer) with thickness $< 5$ m, 130 records.

Type IV Other than above, usually soft alluvium or reclaimed land, 68 records.

- Select earthquakes with Richter magnitude $\geq 5.0$, hypocentral depth $\leq 60$ km and which include at least one record with PGA $\geq 50$ gals ($0.5\,\mathrm{m/s^2}$). Exclude records with PGA $< 10$ gals ($0.1\,\mathrm{m/s^2}$).

- All records for $M \geq 7.0$ are from distance $> 60$ km.

- Do regression separately for each soil category and also for combined data.

## 2.33 Matuschka (1980)

- Ground-motion model is:

$$Y_c = b_1 \mathrm{e}^{b_2 M} (R + b_4)^{-b_3}$$

  Coefficients unknown.

## 2.34 Ohsaki et al. (1980b)

- Ground-motion model is:

$$A = 10^{a_1 M - a_2 \log x + a_3}$$

  where $A$ is in $\mathrm{cm/s^2}$, for horizontal PGA $a_1 = 0.440$, $a_2 = 1.381$ and $a_3 = 1.04$ and for vertical PGA $a_1 = 0.485$, $a_2 = 1.85$ and $a_3 = 1.38$ ($\sigma$ not given).

- All records from free-field bedrock sites.

## 2.35 TERA Corporation (1980)

- Ground-motion model is:

$$\mathrm{PGA} = a \exp(bM)[R + c_1 \exp(c_2 M)]^{-d}$$

  where PGA is in g, for constrained model $a = 0.0782$, $b = 1.10$, $c_1 = 0.343$, $c_2 = 0.629$, $d = 1.75$ and $\sigma = 0.457$ (in terms of natural logarithm).

- Similar to Campbell (1981) (see Section 2.36) but different data.

## 2.36 Campbell (1981)

- Ground-motion model is:

$$\mathrm{PGA} = a \exp(bM)[R + c_1 \exp(c_2 M)]^{-d}$$

  where PGA is in g, for unconstrained model $a = 0.0159$, $b = 0.868$, $c_1 = 0.0606$, $c_2 = 0.700$, $d = 1.09$ and $\sigma = 0.372$ (on natural logarithm) and for constrained model $a = 0.0185$, $b = 1.28$, $c_1 = 0.147$, $c_2 = 0.732$, $d = 1.75$ and $\sigma = 0.384$ (in terms of natural logarithm).

  Uses this functional form because capable of modelling possible nonlinear distance scaling in near field and because distance at which transition from near field to far field occurs probably proportional to fault rupture zone size.

- Considers six site classifications but does not model:

  A Recent alluvium: Holocene Age soil with rock $\geq 10$ m deep, 71 records.

  B Pleistocene deposits: Pleistocene Age soil with rock $\geq 10$ m deep, 22 records.

  C Soft rock: Sedimentary rock, soft volcanics, and soft metasedimentary rock, 14 records.

  D Hard rock: Crystalline rock, hard volcanics, and hard metasedimentary rock, 9 records.

  E Shallow soil deposits: Holocene or Pleistocene Age soil $< 10$ m deep overlying soft or hard rock, 17 records. Not used in analysis.

  F Soft soil deposits: extremely soft or loose Holocene Age soils, e.g. beach sand or recent floodplain, lake, swamp, estuarine, and delta deposits, 1 record. Not used in analysis.

- Notes that data from areas outside western USA may be substantially different than those from western USA due to tectonics and recording practices but far outweighed by important contribution these data can make to understanding of near-source ground motion.

- Notes use of only near-source data has made differences in anelastic attenuation negligible to inherent scatter from other factors.

- Selects data from shallow tectonic plate boundaries generally similar to western N. America, deep subduction events excluded because of differences in travel paths and stress conditions.

- Selects data from instruments with similar dynamic characteristics as those used in USA to avoid bias, therefore excludes data from SMAC accelerographs in Japan.

- Selects data which meet these criteria:

  1. Epicentres known with an accuracy of 5 km or less, or accurate estimate of closest distance to fault rupture surface known.
  2. Magnitudes accurate to within 0.3 units.
  3. Distances were within 20, 30, and 50 km for magnitudes less than 4.75 between 4.75 and 6.25 and greater than 6.25 respectively. Only uses data from earthquakes with magnitude $\geq 5.0$ because of greatest concern for most design applications.
  4. Hypocentres or rupture zones within 25 km of ground surface.
  5. PGA$\geq 0.2\,\mathrm{m/s^2}$ for one component, accelerographs triggered early enough to capture strong phase of shaking.
  6. Accelerograms either free-field, on abutments of dams or bridges, in lowest basement of buildings, or on ground level of structures without basements. Excluded Pacoima Dam record, from San Fernando (9/2/1971) earthquake due to topographic, high-frequency resonance due to large gradation in wave propagation velocities and amplification due to E-W response of dam.

- Well distributed data, correlation between magnitude and distance only 6%.
- Uses PGA from digitised, unprocessed accelerograms or from original accelerograms because fully processed PGAs are generally smaller due to the 0.02 s decimation and frequency band-limited filtering of records.
- Uses mean of two horizontal components because more stable peak acceleration parameter than either single components taken separately or both components taken together.
- Magnitude scale chosen to be generally consistent with $M_w$. Division point between using $M_L$ and $M_s$ varied between 5.5 and 6.5; finds magnitudes quite insensitive to choice.
- Notes $r_{rup}$ is a statistically superior distance measure than epicentral or hypocentral and is physically consistent and meaningful definition of distance for earthquakes having extensive rupture zones.
- Does not use all data from San Fernando earthquake to minimize bias due to large number of records.
- Uses seven different weighting schemes, to control influence of well-recorded earthquakes (e.g. San Fernando and Imperial Valley earthquakes). Giving each record or each earthquake equal weight not reasonable representation of data. Uses nine distance dependent bins and weights each record by a relative weighting factor $1/n_{i,j}$, where $n_{i,j}$ is total number of recordings from $i$th earthquake in $j$th interval.
- Finds unconstrained coefficients and all coefficients statistically significant at 99%.
- Finds coefficients with $d$ constrained to 1.75 (representative of far-field attenuation of PGA) and $c_2 = b/d$, which means PGA is independent of magnitude at the fault rupture surface. All coefficients statistically significant at 99%. Notes similarity between two models.
- Plots normalised weighted residuals against distance, magnitude[5] and predicted acceleration[5]. Finds that residuals uncorrelated, at 99%, with these variables.
- Normal probability plots, observed distribution of normalised weighted residuals and Kolmogorov-Smirnov test, at 90%, confirms that PGA can be accepted as being lognormally distributed.
- Finds effects of site geology, building size, instrument location and mechanism to be extensively interrelated so selects only records from free-field or small structures.
- Analyses all selected data, find sites of classes E and F significantly higher PGA , at 90% level, so removes records from E and F.
- Finds differences in PGA from other site categories to be negligible but notes that it cannot be extended to PGV, PGD, spectral ordinates or smaller magnitudes or further distances.
- Distribution with mechanism is: 69 from strike-slip, 40 from reverse, 5 from normal and 2 records from oblique. Finds that reverse fault PGAs are systematically higher, significant at 90%, than those from other fault types although size of bias is due to presence of data from outside N. America.
- Considers soil (A and B) records from small buildings (115 components) and in free-field and those obtained in lowest basement of large buildings (40 components). Finds PGA significantly lower, at 90% level, in large buildings.
- Finds topographic effects for 13 components used in final analysis (and for 11 components from shallow soil stations) to be significantly higher, at 90%, although states size of it may not be reliable due to small number of records.

[5]Not shown in paper.

- Removes Imperial Valley records and repeats analysis. Finds that saturation of PGA with distance is not strongly dependent on this single set of records. Also repeats analysis constraining $c_2 = 0$, i.e. magnitude independent saturation, and also constraining $c_1 = c_2 = 0$, i.e. no distance saturation, finds variance when no distance saturation is significantly higher, at 95%, than when there is saturation modelled.
- Finds that magnitude saturation effects in modelling near-source behaviour of PGA is important and $c_2$ is significantly greater than zero at levels of confidence exceeding 99%. Also variance is reduced when $c_2 \neq 0$ although not at 90% or above.
- Repeats analysis using distance to surface projection of fault, finds reduced magnitude saturation but similar magnitude scaling of PGA for larger events.

## 2.37 Chiaruttini and Siro (1981)

- Ground-motion model is:

$$\log a = b_0 + b_{AN} X_{AN} + b_{AB} X_{AB} + b_M M_L + b_d \log d$$

  where $a$ is in g/100, $b_0 = 0.04$, $b_{AN} = 0.24$, $b_{AB} = 0.23$, $b_M = 0.41$ and $b_d = -0.99$ ($\sigma$ not given).

- Use three site categories for Friuli records, although note that information is rather superficial:

  ThA Alluvium with depth $> 20$ m, 36 records.

  RI Rock-like: hard rock or stiff soil, 24[6] records.

  thA Alluvium-like with depth $\leq 20$ m: includes sites for which thickness of deposit is reported to be very small which accounts for a few metres of weathering of underlying bedrock, 60 records.

  Alpide belt records divided into two categories: rock-like (25 records) and alluvium-like (40 records).

- Use data from free-field instruments or from instruments in basements of small structures and divide data into three regions: those from 1976 Friuli shocks (120 records) $\Rightarrow X_{AN} = X_{AB} = 0$, those from 1972 Ancona swarm (40 records) $\Rightarrow X_{AN} = 1$ & $X_{AB} = 0$ and those from Alpide Belt (Azores to Pakistan excluding those from Friuli and Ancona) (64 records) $\Rightarrow X_{AN} = 0$ & $X_{AB} = 1$. Exclude records with PGA $< 0.15\,\mathrm{m/s^2}$ to avoid possible bias at low acceleration values.
- Assume average focal depth of 6 km.
- Note some PGA values derived from velocity records which are retained because compatible with other data. No instrument corrections applied to Friuli records because correction does not substantially alter PGA.
- Use $M_L$ because determined at short distances and allows homogenous determination from lowest values up to saturation at $M_L = 7.0$ and it is determined at frequencies of nearly 1 Hz, close to accelerographic band.
- Perform regression on PGAs from each of the three regions and each soil types considered within that region.
- Group rock-like (R) and thick alluvium (ThA) records together for Friuli. Find $b_d$ for Friuli equations derived for thin alluvium-like and rock and thick alluvium not significantly different but $b_M$ is significantly different, at 95% level. Repeat analysis using only Tolmezzo records because of large scatter in residuals but decide it is in thA category.

[6] Typographic error in their Table 1 because only 14 records are listed for rock-like sites

- For Alpide belt equations find $b_M$ is almost the same for Rl and Al records and the difference in $b_d$ is less than standard error, thus repeat analysis using a dummy variable $X_{Al}$ which equals 0 for Rl and 1 for Al records.

## 2.38 Goto et al. (1981)

- Ground-motion model is:

$$\log A = b_0 + b_1 M + b_2 \log(\Delta + b_3)$$

  where $A$ is in cm/s$^2$, $b_0 = 2.305$, $b_1 = 0.178$, $b_2 = -0.666$ and $b_3 = 30$ ($\sigma$ not reported[7]).

- Use $N$-value profiles from standard penetration tests (SPTs) to characterise sites. Use data from alluvial and diluvial sites. Exclude data from rock and very soft soils. Define $S_n$ as a weighting function for SPT profile to characterise softness of surface layers. Plot residuals from model against $S_n$ and find correlation. Derive site correction factors for model. Find coefficient of variation decreases after applying correction.

- Use 346 uncorrected components (magnitudes from 5 to about 7.8 and $r_{epi}$ from about 7 to 500 km) to derive preliminary model without site term: $\bar{A} = b_0 10^{b_1 M}/(r_{epi} + 30)^{b_2}$. Derive models using different data selections: all data, $M < 6.6$, $M \geq 6.6$, $r_{epi} \leq 119$ km, $r_{epi} > 119$ km, $M$-$r_{epi}$ region where expected PGA (from model using all data) $\geq 39$ cm/s$^2$ or expected PGA $< 39$ cm/s$^2$ (these selected divide data into two equal halves). Examine scaling of the various models in 3D plots. Based on this analysis, conclude that model depends on $M$-$r_{epi}$ range used for data selection. Because of engineering interest in PGA$>$ 10 gal believe model should be derived using $M$-$r_{epi}$ region defined by expected PGA.

- 18 records from 1978 Off Miyagi earthquakes and 6 records from 1978 Izu-oshima-kinkai earthquake.

- Strong correlation between $M$ and $r_{epi}$ with almost all data from $M > 7$ being from $r_{epi} > 100$ km.

- Try different $b_3$ values but find influence on coefficient of variation minimal so fix to 30 km.

- For final model use corrected accelerograms (PGAs generally 10% to 30% higher than uncorrected values). Most data from SMAC instruments.

- Plot residuals w.r.t. $r_{epi}$ and $M$ and find no trends.

## 2.39 Joyner and Boore (1981)

- Ground-motion model is:

$$\begin{aligned} \log y &= \alpha + \beta \mathbf{M} - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2} \end{aligned}$$

  where $y$ is in g, $\alpha = -1.02$, $\beta = 0.249$, $b = -0.00255$, $h = 7.3$ and $\sigma = 0.26$.

- Use two site categories (not all records have category):

  $S = 0$ Rock: sites described as granite, diorite, gneiss, chert, greywacke, limestone, sandstone or siltstone and sites with soil material less than 4 to 5 m thick overlying rock, 29 records. Indicate caution in applying equations for $\mathbf{M} > 6.0$ due to limited records.

  $S = 1$ Soil: sites described as alluvium, sand, gravel, clay, silt, mud, fill or glacial outwash except where soil less than 4 to 5 m thick, 96 records.

[7]Report coefficient of variation of 0.578 which could be the value of $\sigma$ in terms of natural logarithms.

- Restrict data to western North American shallow earthquakes, depth less than 20 km, with $\mathbf{M} > 5.0$. Most records from earthquakes with magnitudes less than 6.6.
- Exclude records from base of buildings three or more storeys high and from abutments of dams.
- Exclude records associated with distances which had an uncertainty greater than 5 km.
- Exclude records from distances greater than or equal to the shortest distance to an instrument which did not trigger.
- Six earthquakes recorded at only one station so not included in second stage regression.
- Include quadratic dependence term, $\gamma\mathbf{M}^2$, but not significant at 90% level so omitted.
- Include site term, $cS$, but not significant so omitted.
- Examine residuals against distance for difference magnitude ranges, no obvious differences in trends are apparent among the different magnitude classes.
- Consider a magnitude dependent $h = h_1 \exp(h_2[\mathbf{M} - 6.0])$ but reduction in variance not significant. Also prefer magnitude independent $h$ because requires fewer parameters.
- Examine effect of removing records from different earthquakes from data.
- Examine effect of different $h$ on residuals and $b$. Note coupling between $h$ and $b$.
- Note coincidence of anelastic coefficient, $b$, and measured $Q$ values. Also note similarity between $h$ and proportions of depth of seismogenic zone in California.

## 2.40 Bolt and Abrahamson (1982)

- Ground-motion model is:
$$y = a\{(x+d)^2 + 1\}^c \mathrm{e}^{-b(x+d)}$$
where $y$ is in g, for $5 \leq \mathbf{M} < 6$ $a = 1.2$, $b = 0.066$, $c = 0.033$, $d = 23$ and standard error for one observation of 0.06 g, for $6 \leq \mathbf{M} < 7$ $a = 1.2$, $b = 0.044$, $c = 0.042$, $d = 25$ and standard error for one observation of 0.10 g, for $7 \leq \mathbf{M} \leq 7.7$ $a = 0.24$ $b = 0.022$, $c = 0.10$, $d = 15$ and standard error for one observation of 0.05 g and for $6 \leq \mathbf{M} \leq 7.7$ $a = 1.6$, $b = 0.026$, $c = -0.19$, $d = 8.5$ and standard error for one observation of 0.09 g.
- Use data of Joyner and Boore (1981).
- Form of equation chosen to satisfy plausible physical assumptions but near-field behaviour is not determined from overwhelming contributions of far-field data.
- Apply nonlinear regression on $y$ not on $\log y$ to give more weight to near-field values.
- Split data into four magnitude dependent groups: $5 \leq \mathbf{M} < 6$, $6 \leq \mathbf{M} < 7$, $7 \leq \mathbf{M} \leq 7.7$ and $6 \leq \mathbf{M} \leq 7.7$.
- Use form of equation and regression technique of Joyner and Boore (1981), after removing 25 points from closer than 8 km and find very similar coefficients to Joyner and Boore (1981). Conclude from this experiment and their derived coefficients for the four magnitude groups that using their form of equation predicted near-field accelerations are not governed by far-field data.
- Find no evidence of systematic increase in PGA near the source as a function of magnitude and that the large scatter prevents attaching significance to differences in near-field PGA which are predicted using their attenuation relations for different magnitude ranges.

## 2.41 Joyner and Boore (1982b) & Joyner and Boore (1988)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta(M-6) + \gamma(M-6)^2 - p\log r + br + cS \\ r &= (d^2+h^2)^{1/2}\end{aligned}$$

  where $y$ is in g, $\beta = 0.23$, $\gamma = 0$, $p = 1$, $b = -0.0027$, $c = 0$, $h = 8.0$ and $\sigma = 0.28$ and for randomly oriented component $\alpha = 0.43$ and for larger component $\alpha = 0.49$.

- Use same data and method as Joyner and Boore (1981), see Section 2.39, for PGA.

- Use data from shallow earthquakes, defined as those for which fault rupture lies mainly above a depth of 20 km.

## 2.42 PML (1982)

- Ground-motion model is:

$$\ln(a) = C_1 + C_2M + C_3\ln[R + C_4\exp(C_5M)]$$

  where $a$ is in g, $C_1 = -1.17$, $C_2 = 0.587$, $C_3 = -1.26$, $C_4 = 2.13$, $C_5 = 0.25$ and $\sigma = 0.543$.

- Use data from Italy (6 records, 6 earthquakes), USA (18 records, 8 earthquakes), Greece (13 records, 9 earthquakes), Iran (3 records, 3 earthquakes), Pakistan (3 records, 1 earthquake), Yugoslavia (3 records, 1 earthquake), USSR (1 record, 1 earthquake), Nicaragua (1 record, 1 earthquake), India (1 record, 1 earthquake) and Atlantic Ocean (1 record, 1 earthquake).

- Develop for use in UK.

## 2.43 Schenk (1982)

- Ground-motion model is:

$$\log A_{\mathrm{mean}} = aM - b\log R + c$$

  where $A_{\mathrm{mean}}$ is in cm/s$^2$, $a = 1.1143$, $b = 1.576$ and $c = 2.371$ ($\sigma$ not given).

- Fits equation by eye because least squares method is often strictly dependent on marginal observations, particularly for little pronounced dependence.

## 2.44 Brillinger and Preisler (1984)

- Ground-motion model is:

$$A^{1/3} = a_1 + a_2M + a_3\ln(d^2 + a_4^2)$$

  where $A$ is in g, $a_1 = 0.432(0.072)$, $a_2 = 0.110(0.012)$, $a_3 = -0.0947(0.0101)$, $a_4 = 6.35(3.24)$, $\sigma_1 = 0.0351(0.0096)$ (inter-event) and $\sigma_2 = 0.0759(0.0042)$ (intra-event), where numbers in brackets are the standard errors of the coefficients.

- Use exploratory data analysis (EDA) and alternating conditional expectations (ACE) techniques.

- Firstly sought to determine functions $\theta(A)$, $\phi(M)$ and $\psi(d)$ so that $\theta(A) \doteq \phi(M) + \psi(d)$, i.e. an approximately additive relationship. Prefer additivity because of linearity, ease of interpolation and interpretation and departures from fit are more easily detected.

- Use ACE procedure to find model. For set of data, with response $y_i$ and predictors $w_i$ and $x_i$ find functions to minimize: $\sum_{i=1}^{n}[\theta(y_i) - \phi(w_i) - \psi(x_i)]^2$ subject to $\sum \phi(w_i) = 0$, $\sum \psi(x_i) = 0$, $\sum \theta(y_i) = 0$ and $\sum \theta(y_i)^2 = n$. Search amongst unrestricted curves or unrestricted monotonic curves. Use EDA to select specific functional forms from the estimates of $\theta$, $\phi$ and $\psi$ at each data point.
- Do not use weighting because does not seem reasonable from statistical or seismological points of view.
- Do not want any individual earthquake, e.g. one with many records, overly influencing results.
- Note that because each earthquake has its own source characteristics its records are intercorrelated. Therefore use 'random effects model' which accounts for perculiarities of individual earthquakes and correlation between records from same event.
- On physical grounds, restrict $\theta$, $\phi$ and $\psi$ to be monotonic and find optimal transformation of magnitude is approximately linear, optimal transformation of distance is logarithmic and cube root is optimal for acceleration transformation.
- Note that need correlations between coefficients, which are provided, to attach uncertainties to estimated PGAs.
- Provide method of linearization to give 95% confidence interval for acceleration estimates.
- Also provide a graphical procedure for estimating accelerations that does not rely on an assumed functional form.
- Examine residual plots (not shown) and found a candidate for an outlying observation (the record from the Hollister 1974 earthquake of 0.011 g at 17.0 km).
- Find that assumption of normality after transformation seems reasonable.

## 2.45 Campbell (1984) & K.W. Campbell (1988) reported in Joyner and Boore (1988)

- Ground-motion model is:

$$\begin{aligned}\ln y &= a + bM + d\ln[r + h_1\exp(h_2 M)] + s\\ \text{where } s &= e_1K_1 + e_2K_2 + e_3K_3 + e_4K_4 + e_5K_5 + e_6(K_4 + K_5)\tanh(e_7 r)\end{aligned}$$

  where $y$ is in g, $a = -2.817$, $b = 0.702$, $d = -1.20$, $h_1 = 0.0921$, $h_2 = 0.584$, $e_1 = 0.32$, $e_2 = 0.52$, $e_3 = 0.41$, $e_4 = -0.85$, $e_5 = -1.14$, $e_6 = 0.87$, $e_7 = 0.068$ and $\sigma = 0.30$.[8]

- Uses two site categories:

$K_3 = 1$ Soils $\leq 10$ m deep.

$K_3 = 0$ Other.

- Uses three embedment categories:

$K_4 = 1$, $K_5 = 0$ Basements of buildings 3–9 storeys.

$K_5 = 1$, $K_4 = 0$ Basements of buildings $\geq 10$ storeys.

$K_4 = 0$, $K_5 = 0$ Other.

[8]Thenhaus et al. (1989) summarise a model by K.W. Campbell (1984, 1987) where: $a = -3.303$, $b = 0.85$, $d = -1.25$, $h_1 = 0.0872$, $h_2 = 0.678$, $e_1 = 0.34$ and includes an anelastic term $-0.0059r$ ($\sigma$ is not reported), which they use for western Saudi Arabia.

- Selects data using these criteria:
  1. Largest horizontal component of peak acceleration was $\geq 0.02$ g [$\geq 0.2$ m/s$^2$].
  2. Accelerograph triggered early enough to record strongest phase of shaking.
  3. Magnitude of earthquake was $\geq 5.0$.
  4. Closest distance to seismogenic rupture was $< 30$ or $< 50$ km, depending on whether magnitude of earthquake was $< 6.25$ or $> 6.25$.
  5. Shallowest extent of seismogenic rupture was $\leq 25$ km.
  6. Recording site located on unconsolidated deposits.
- Excludes records from abutments or toes of dams.
- Derives two equations: unconstrained (coefficients given above) and constrained which includes a anelastic decay term $kr$ which allows equation to be used for predictions outside near-source zone (assumes $k = -0.0059$ for regression, a value appropriate for region of interest should be chosen).
- Uses two source mechanism categories:

$K_1 = 0$ Strike-slip.

$K_1 = 1$ Reverse.

- Uses two directivity categories:

$K_2 = 1$ Rupture toward site.

$K_2 = 0$ Other.

## 2.46 Joyner and Fumal (1984), Joyner and Fumal (1985) & Joyner and Boore (1988)

- Ground-motion model is:

$$
\begin{aligned}
\log y &= c_0 + c_1(\mathbf{M} - 6) + c_2(\mathbf{M} - 6)^2 + c_3 \log r + c_4 r + S \\
\text{where } r &= (d^2 + h^2)^{1/2} \\
\text{and: } S &= \begin{cases} 0 & \text{for rock site} \\ c_6 \log \frac{V}{V_0} & \text{for soil site} \end{cases}
\end{aligned}
$$

  where $y$ is in g, coefficients $c_0$ to $c_4$, $h$ and $\sigma$ are from Joyner and Boore (1981) and $c_6$ and $V_0$ are not significant at 90% level so do not report them.
- Use data of Joyner and Boore (1981).
- Continuous site classification for soil sites in terms of shear-wave velocity, $V$, to depth of one quarter wavelength of waves of period of concern. $V$ measured down to depths of at least 30 m and then extrapolated using geological data. $V$ known for 33 stations.
- Soil amplification factor based on energy conservation along ray tubes, which is a body wave argument and may not hold for long periods for which surface waves could be important. Does not predict resonance effects.
- Regress residuals, $R_{ij}$, w.r.t. motion predicted for rock sites on $\log R_{ij} = P_i + c_6 V_j$, where $j$ corresponds to $j$th station and $i$ to $i$th earthquake. Decouples site effects variation from earthquake-to-earthquake variation. Find unique intercept by requiring average site effect term calculated using shear-wave velocity to be same as that calculated using rock/soil classification.

- No significant, at 90%, correlation between residuals and $V$ for PGA.

- Repeat regression on residuals using $V$ and depth to underlying rock (defined as either shear-wave velocity $> 750$ m/s or $> 1500$ m/s). Find no correlation.

## 2.47 Kawashima et al. (1984) & Kawashima et al. (1986)

- Ground-motion model is:

$$X(M, \Delta, \mathrm{GC}_i) = a(\mathrm{GC}_i) 10^{b(\mathrm{GC}_i)M} (\Delta + 30)^c$$

  where $X(M, \Delta, \mathrm{GC}_i)$ is in gal, $c = -1.218$, for group 1 sites $a(\mathrm{GC}_1) = 987.4$, $b(\mathrm{GC}_1) = 0.216$ and $\sigma = 0.216$, for group 2 sites $a(\mathrm{GC}_2) = 232.5$, $b(\mathrm{GC}_2) = 0.313$ and $\sigma = 0.224$ and for group 3 sites $a(\mathrm{GC}_3) = 403.8$, $b(\mathrm{GC}_3) = 0.265$ and $\sigma = 0.197$.

- Use three site categories:

Group 1 Tertiary or older rock (defined as bedrock) or diluvium with $H < 10$ m or fundamental period $T_G < 0.2$ s.

Group 2 Diluvium with $H \geq 10$ m, alluvium with $H < 10$ m or alluvium with $H < 25$ m including soft layer with thickness $< 5$ m or fundamental period $0.2 < T_G < 0.6$ s.

Group 3 Other than above, normally soft alluvium or reclaimed land.

- Only includes free-field records with $M_{\mathrm{JMA}} \geq 5.0$ and focal depths $D_p < 60$ km. Excludes records from structures with first floor or basement.

- Records instrument corrected, because Japanese instruments substantially suppress high frequencies, considering accuracy of digitization for frequencies between $\frac{1}{3}$ and 12 Hz.

- Note that $M_{\mathrm{JMA}}$ and $\Delta$ not necessarily most suitable parameters to represent magnitude and distance but only ones for all records in set.

- Note lack of near-field data for large magnitude earthquakes, approximately $\frac{3}{4}$ of records from $M_{\mathrm{JMA}} < 7.0$.

- Use 30 km in distance dependence term because focal depth of earthquakes with magnitudes between 7.5 and 8.0 are between 30 and 100 km so 30 is approximately half the fault length.

- Try equation: $\log X = f_1 + f_2 M + f_3 \log(\Delta + 30) + f_4 D_p + f_5 M \log(\Delta + 30) + f_6 M D_p + f_7 D_p \log(\Delta + 30) + f_8 M^2 + f_9 \{\log(\Delta + 30)\}^2 + f_{10} D_p^2$ where $f_i$ are coefficients to be found considering each soil category separately. Apply multiple regression analysis to 36 combinations of retained coefficients, $f_i$, and compute multiple correlation coefficient, $R$, and adjusted multiple correlation coefficient, $R^*$. Find that inclusion of more than three coefficients does not give significant increase in $R^*$, and can lead to unrealistic results. Conclude due to insufficient data.

- Consider $a$, $b$ and $c$ dependent and independent of soil type and examine correlation coefficient, $R$, and adjusted correlation coefficient, $R^*$. Find that $c$ is not strongly dependent on soil type.

- Find match between normal distribution and histograms of residuals.

## 2.48 McCann Jr. and Echezwia (1984)

- Four Ground-motion models:

$$\begin{aligned}
\log_{10} Y &= a + bM + d\log_{10}[(R^2+h^2)^{1/2}] \quad \text{Model I}\\
\log_{10} Y &= a + bM + d\log_{10}[R + c_1\exp(c_2 M)] \quad \text{Model II}\\
\log_{10} Y &= a + bM + d\log_{10}\left[\frac{c_1}{R^2} + \frac{c_2}{R}\right] + eR \quad \text{Model III}\\
\log_{10} Y &= a + bM + d\log_{10}[R + 25] \quad \text{Model IV}
\end{aligned}$$

  where $Y$ is in g, for model I $a = -1.320$, $b = 0.262$, $d = -0.913$, $h = 3.852$ and $\sigma = 0.158$, for model II $a = -1.115$, $b = 0.341$, $c_1 = 1.000$, $c_2 = 0.333$, $d = -1.270$ and $\sigma = 0.154$, for model III $a = -2.000$, $b = 0.270$, $c_1 = 0.968$, $c_2 = 0.312$, $d = 0.160$, $e = -0.0105$ and $\sigma = 0.175$ and for model IV $a = 1.009$, $b = 0.222$, $d = -1.915$ and $\sigma = 0.174$.

- Note 25 in Model IV should not be assumed but should be found by regression.
- Note tectonics and travel paths may be different between N. American and foreign records but consider additional information in near field more relevant.
- Selection procedure composite of Campbell (1981) and Joyner and Boore (1981). Exclude data from buildings with more than two storeys.
- Weighted least squares, based on distance, applied to control influence of well recorded events (such as San Fernando and Imperial Valley). Similar to Campbell (1981)
- Test assumption that logarithm of residuals are normally distributed. Cannot disprove assumption.
- Variability between models not more than $\pm 20\%$ at distances $> 10$ km but for distances $< 1$ km up to $\pm 50\%$.

## 2.49 Schenk (1984)

- Ground-motion model is:

$$\log A_{\text{mean}} = aM - b\log R + c$$

  where $A_{\text{mean}}$ is in cm/s$^2$, $a = 0.37$, $b = 1.58$ and $c = 2.35$ ($\sigma$ not given).

- Considers two site conditions but does not model:
  1. Solid
  2. Soft
- Fits equation by eye.
- States applicable approximately for: $R_{\text{lower}} \le R \le R_{\text{upper}}$ where $\log R_{\text{lower}} \doteq 0.1M + 0.5$ and $\log R_{\text{upper}} \doteq 0.35M + 0.4$, due to distribution of data.
- Notes great variability in recorded ground motions up to $R = 30$ km due to great influence of different site conditions.
- Notes for $M \le 4$ source can be assumed spherical but for $M > 4$ elongated (extended) shape of focus should be taken into account.

## 2.50 Xu et al. (1984)

- Ground-motion model is:

$$\mathrm{PGA} = a_1 \exp(a_2 M)(R + a_3)^{-a_4}$$

  where PGA is in g, $a_1 = 0.1548$, $a_2 = 0.5442$, $a_3 = 8$ and $a_4 = 1.002$ ($\sigma$ not given).

- All records from aftershocks of 1975 Haicheng earthquake and from 1976 Tangshan earthquake and aftershocks.

- Most records from earthquakes with magnitude less than 5.8 and from distances $< 30$ km.

- Exclude records with PGA $< 0.5\,\mathrm{m/s^2}$ to avoid too much contribution from far field.

- Due to small number of records simple regression technique justified.

- States valid for $4 \leq M \leq 6.5$ and $R \leq 100$ km.

- Also use 158 records from western N. America to see whether significantly different than N. Chinese data. Derive equations using both western N. American and N. Chinese data and just western N. American data and find that predicted PGAs are similar, within uncertainty.

- Insufficient data to find physically realistic anelastic term.

## 2.51 Brillinger and Preisler (1985)

- Ground-motion model is:

$$\begin{aligned} \log A &= a_1 + a_2 M - \log r + a_3 r \\ \text{where} \quad r^2 &= d^2 + a_4^2 \end{aligned}$$

  where $A$ is in g, $a_1 = -1.229(0.196)$, $a_2 = 0.277(0.034)$, $a_3 = -0.00231(0.00062)$, $a_4 = 6.650(2.612)$, $\sigma_1 = 0.1223(0.0305)$ (inter-event) and $\sigma = 0.2284(0.0127)$ (intra-event), where numbers in brackets are the standard errors of the coefficients.

- Provide algorithm for random effects regression.

- Note that the functional form adopted in Brillinger and Preisler (1984) is strictly empirical and hence repeat analysis using functional form of Joyner and Boore (1981), which is based on physical reasoning.

- Note that need correlations between coefficients, which are provided, to attach uncertainties to estimated PGAs.

## 2.52 Kawashima et al. (1985)

- Use very similar data to Kawashima et al. (1984); do not use some records because missing due to recording and digitizing processes. Use equation and method (although do not check all 36 combinations of forms of equation) used by Kawashima et al. (1984), see section 2.47.

- $X(M, \Delta, \mathrm{GC}_i)$ is in gal. Coefficients are: $c = -1.190$ and for ground group 1 $a = 117.0$ and $b = 0.268$ and for ground group 2 $a = 88.19$ and $b = 0.297$ and for group ground 3 $a = 13.49$ and $b = 0.402$ with $\sigma = 0.253$.

## 2.53 Makropoulos and Burton (1985) & Makropoulos (1978)

- Ground-motion model is:

$$A = b_1 \exp(b_2 M)(R + h)^{-b_3}$$

where $A$ is in cm/s$^2$, $b_1 = 2164$, $b_2 = 0.7 \pm 0.03$, $h = 20$ and $b_3 = -1.8 \pm 0.02$ ($\sigma$ is not reported).

- Derived by averaging (at $M = 7.5$) eight previous models: Donovan (1973), Orphal and Lahoud (1974), Esteva (1974), Katayama (1974) and Trifunac (1976a).
- Check predictions against eight Greek accelerograms and find agreement.

## 2.54 Peng et al. (1985b)

- Ground-motion model is:

$$\log_{10} a = A + BM + C \log_{10} R + DR$$

where $a$ is in cm/s$^2$, for N.E. China $A = -0.474$, $B = 0.613$, $C = -0.873$ and $D = -0.00206$ ($\sigma$ not given) and for S.W. China $A = 0.437$, $B = 0.454$, $C = -0.739$ and $D = -0.00279$ ($\sigma$ not given).

- Consider two site conditions for NE records but do not model:
  1. Rock: 28 records.
  2. Soil: 45 records.
- Consider all records to be free-field.
- Note that Chinese surface-wave magnitude, $M$, is different than $M_s$ and may differ by 0.5 or more. Use $m_b$ or $M_s$ and find larger residuals.
- Most records from $M \leq 5.8$.
- Note isoseismals are not elongated for these earthquakes so use of another distance measure will not change results by much.
- Also derives equation for SW China ($3.7 \leq M \leq 7.2$, $6.0 \leq R \leq 428.0$ km all but one record $\leq 106.0$ km , 36 records from 23 earthquakes) and note difference between results from NE China although use less data.
- Note that some scatter may be due to radiation pattern.
- Note that data is from limited distance range so need more data to confirm results.

## 2.55 Peng et al. (1985a)

- Ground-motion model is:

$$\begin{aligned} \log A_m &= a_1 + a_2 M - \log R - a_3 R \\ R &= \sqrt{d^2 + h^2} \end{aligned}$$

where $A_m$ is g, $a_1 = -1.49$, $a_2 = 0.31$, $a_3 = 0.0248$, $h = 9.4$ km and $\sigma = 0.32$ (for horizontal components) and $a_1 = -1.92$, $a_2 = 0.29$, $a_3 = 0.0146$, $h = 6.7$ km and $\sigma = 0.36$ (for vertical components).

- Data from experimental strong-motion array consisting of 12 Kinemetrics PDR-1 instruments deployed in the epicentral area of the $M_s = 7.8$ Tangshan earthquake of 28th July 1976. Provide details of site geology at each station; most stations are on soil.
- Records from earthquakes recorded by only one station were excluded from analysis.
- Note that equations are preliminary and more refined equations await further studies of magnitudes and distances used in analysis.
- Note that high anelastic attenuation coefficient may be due to biases introduced by the distribution in magnitude-distance space and also because of errors in magnitude and distances used.

## 2.56 PML (1985)

- Ground-motion model is:

$$\ln(a) = C_1 + C_2 M + C_3 \ln[R + C_4 \exp(C_5 M)] + C_6 F$$

where $a$ is in g, $C_1 = -0.855$, $C_2 = 0.46$, $C_3 = -1.27$, $C_4 = 0.73$, $C_5 = 0.35$, $C_6 = 0.22$ and $\sigma = 0.49$.

- Use data from Italy (47 records, 9 earthquakes), USA (128 records, 18 earthquakes), Greece (11 records, 8 earthquakes), Iran (2 records, 2 earthquakes), Yugoslavia (7 records, 2 earthquake), Nicaragua (1 record, 1 earthquake), New Zealand (3 records, 3 earthquakes), China (2 records, 2 earthquakes) and Canada (2 records, 1 earthquake).
- Develop for use in UK.
- Select earthquakes with $M_s < 7$ and $R \leq 40$ km.
- Focal depths $< 40$ km.
- Use two source mechanism categories (40 records have no source mechanism given):

$F = 0$ Strike-slip and normal, 85 records.

$F = 1$ Thrust, 78 records.

- Also derive equation not considering source mechanism, i.e. $C_6 = 0$.

## 2.57 McCue (1986)

- Ground-motion model is:

$$A = a_1 (e^{a_2 M_L})(d_h)^{a_3}$$

where $A$ is in g, $a_1 = 0.00205$, $a_2 = 1.72$ and $a_3 = -1.58$ ($\sigma$ not given).

## 2.58 C.B. Crouse (1987) reported in Joyner and Boore (1988)

- Ground-motion model is:

$$\ln y = a + bM_s + cM_s^2 + d\ln(r + 1) + kr$$

where $y$ is in gal, $a = 2.48456$, $b = 0.73377$, $c = -0.01509$, $d = -0.50558$, $k = -0.00935$ and $\sigma = 0.58082$.

- Records from deep soil sites (generally greater than 60 m in thickness).
- Data from shallow crustal earthquakes.

## 2.59 Krinitzsky et al. (1987) & Krinitzsky et al. (1988)

- Ground-motion model is (for shallow earthquakes):

  $$\log A = a_1 + a_2 M - \log r + a_3 r$$

  where A is in $\mathrm{cm/s^2}$, $a_1 = 1.23$ (for hard sites), $a_1 = 1.41$ (for soft sites), $a_2 = 0.385$ and $a_3 = -0.00255$ ($\sigma$ is not given).

  Ground-motion model is (for subduction zone earthquakes):

  $$\log A = b_1 + b_2 M - \log \sqrt{r^2 + 100^2} + b_3 r$$

  where $A$ is in $\mathrm{cm/s^2}$, $b_1 = 2.08$ (for hard sites), $b_1 = 2.32$ (for soft sites), $b_2 = 0.35$ and $b_3 = -0.0025$ ($\sigma$ is not given).

- Use four site categories:

  1 Rock

  2 Stiff soil

  3 Deep cohesionless soil ($\geq 16\,\mathrm{m}$)

  4 Soft to medium stiff clay ($\geq 16\,\mathrm{m}$)

  Categories 1 and 2 are combined into a hard (H) class and 3 and 4 are combined into a soft (S) class. This boundary established using field evidence at a shear-wave velocity of $400\,\mathrm{m/s}$ and at an SPT N count of 60.

- Use data from ground floors and basements of small or low structures (under 3 stories) because believe that small structures have little effect on recorded ground motions.

- Separate earthquakes into shallow ($h \leq 19\,\mathrm{km}$) and subduction ($h \geq 20\,\mathrm{km}$) because noted that ground motions have different characteristics.

- Use epicentral distance for Japanese data because practical means of representing deep subduction earthquakes with distant and imprecise fault locations.

- Do not use rupture distance or distance to surface projection of rupture because believe unlikely that stress drop and peak motions will occur with equal strength along the fault length and also because for most records fault locations are not reliably determinable.

- Note that there is a paucity of data but believe that the few high peak values observed (e.g. Pacoima Dam and Morgan Hill) cannot be dismissed without the possibility that interpretations will be affected dangerously.

- For subduction equations, use records from Japanese SMAC instruments that have not been instrument corrected, even though SMAC instruments show reduced sensitivity above $10\,\mathrm{Hz}$, because ground motions $> 10\,\mathrm{Hz}$ are not significant in subduction earthquakes. Do not use records from SMAC instruments for shallow earthquakes because high frequency motions may be significant.

- Examine differences between ground motions in extensional (strike-slip and normal faulting) and compressional (reverse) regimes for shallow earthquakes but do not model. Find that the extensional ground motions seem to be higher than compressional motions, which suggest is because rupture propagation comes closer to ground surface in extensional faults than in compressional faults.

- Group records into $1\,M$ unit intervals and plot ground motions against distance. When data is numerous enough the data points are encompassed in boxes (either one, two or three) that have a range equal to the distribution of data. The positions of the calculated values within the boxes were used as guides for shaping appropriate curves. Initially curves developed for $M = 6.5$ were there is most data and then these were extended to smaller and larger magnitudes.

## 2.60 Sabetta and Pugliese (1987)

- Ground-motion model is:

$$\log y = a + bM - \log(R^2 + h^2)^{1/2} + eS$$

  where $y$ is in g and for distance to surface projection of fault $a = -1.562$, $b = 0.306$, $e = 0.169$, $h = 5.8$ and $\sigma = 0.173$.

- Use two site categories:

$S = 0$ Stiff and deep soil: limestone, sandstone, siltstone, marl, shale and conglomerates ($V_s > 800\,\text{m/s}$) or depth of soil, $H$, $> 20\,\text{m}$, 74 records.

$S = 1$ Shallow soil: depth of soil, $H$, $5 \leq H \leq 20\,\text{m}$, 21 records.

- Select records which satisfy these criteria:
  1. Reliable identification of the triggering earthquake.
  2. Magnitude greater than 4.5 recorded by at least two stations.
  3. Epicentres determined with accuracy of 5 km or less.
  4. Magnitudes accurate to within 0.3 units.
  5. Accelerograms from free-field. Most are from small electric transformer cabins, 4 from one- or two-storey buildings with basements and 5 from near abutments of dams.

- Depths between 5.0 and 16.0 km with mean 8.5 km.

- Focal mechanisms are: normal and oblique (7 earthquakes, 48 records), thrust (9 earthquakes, 43 records) and strike-slip (1 earthquake, 4 records).

- Notes lack of records at short distances from large earthquakes.

- Records baseline-, instrument-corrected and filtered with cutoff frequencies determined by visual inspection in order to maximise signal to noise ratio within band. Cutoff frequencies ranged from 0.2 to 0.4 Hz and from 25 to 35 Hz. This correction routine thought to provide reliable estimates of PGA so uncorrected PGA do not need to be used.

- For well separated multiple shocks, to which magnitude and focal parameters refer, use only first shock.

- Magnitude scale assures a linear relationship between logarithm of PGA and magnitude and avoids saturation effects of $M_L$.

- Distance to surface projection of fault rupture thought to be a more physically consistent definition of distance for earthquakes having extensive rupture zones and is easier to predict for future earthquakes. Also reduces correlation between magnitude and distance.

- Use Exploratory Data Analysis using the ACE procedure to find transformation functions of distance, magnitude and PGA.

- Include anelastic attenuation term but it is positive and not significant.

- Include magnitude dependent $h$ equal to $h_1 \exp(h_2 M)$ but find $h_2$ not significantly different than zero. Note distribution of data makes test not definitive.
- Find geometric attenuation coefficient, $c$, is close to $-1$ and highly correlated with $h$ so constrain to $-1$ so less coefficients to estimate.
- Consider deep soil sites as separate category but find difference between them and stiff sites is not significant.
- Also use two-stage method but coefficients and variance did not change significantly with respect to those obtained using one-stage method, due to uniform distribution of recordings among earthquakes.
- Find no significant trends in residuals, at 99% level and also no support for magnitude dependent shape for attenuation curves.
- Exclude records from different seismotectonic and geological regions and repeat analysis. Find that predicted PGA are similar.
- Plot residuals from records at distances 15 km or less against magnitude; find no support for magnitude dependence of residuals.
- Note some records are affected by strong azimuthal effects, but do not model them because they require more coefficients to be estimated, direction of azimuthal effect different from region to region and azimuthal effects have not been used in other relationships.

## 2.61 K. Sadigh (1987) reported in Joyner and Boore (1988)

- Ground-motion model is:

$$\ln y = a + b\mathbf{M} + c_1(8.5 - \mathbf{M})^{c_2} + d \ln[r + h_1 \exp(h_2\mathbf{M})]$$

  where $y$ is in g. For strike-slip earthquakes: $b = 1.1$, $c_1 = 0$, $c_2 = 2.5$, for PGA at soil sites $a = -2.611$ and $d = -1.75$, for $\mathbf{M} < 6.5$ $h_1 = 0.8217$, $h_2 = 0.4814$ and for $\mathbf{M} \geq 6.5$ $h_1 = 0.3157$ and $h_2 = 0.6286$, for PGA at rock sites $a = -1.406$ and $d = -2.05$, for $\mathbf{M} < 6.5$ $h_1 = 1.353$ and $h_2 = 0.406$ and for $\mathbf{M} \geq 6.5$ $h_1 = 0.579$ and $h_2 = 0.537$. For reverse-slip increase predicted values by 20%. For $\mathbf{M} < 6.5$ $\sigma = 1.26 - 0.14\mathbf{M}$ and for $\mathbf{M} \geq 6.5$ $\sigma = 0.35$.

- Uses two site categories:

  1. Soil
  2. Rock

- Use two source mechanism categories:

  1. Strike-slip
  2. Reverse-slip

- Supplement data with significant recordings of earthquakes with focal depths < 20 km from other parts of world.
- Different equations for $\mathbf{M} < 6.5$ and $\mathbf{M} \geq 6.5$.

## 2.62 Singh et al. (1987)

- Ground-motion model is:

$$\log y_{\max} = \alpha M_s - c \log R + \beta$$

  where $y_{\max}$ is in cm/s$^2$, $\alpha = 0.429$, $c = 2.976$, $\beta = 5.396$ and $\sigma = 0.15$.

  More complicated functional form unwarranted due to limited distance range.

- Depths between 15 and 20 km.

- Only use data from a single firm site (Ciudad Universitaria), on a surface layer of lava flow or volcanic tuff.

- Only records from coastal earthquakes.

- Residuals plotted against distance, no trends seen.

- Give amplification factor for lake bed sites (25 to 80 m deposit of highly compressible, high water content clay underlain by resistant sands), but note based on only a few sites so not likely to be representative of entire lake bed.

## 2.63 Algermissen et al. (1988)

- Ground-motion model is:

$$\ln(A) = a_1 + a_2 M_s + a_3 \ln(R) + a_4 R$$

  where $A$ is in g, $a_1 = -1.987$, $a_2 = 0.604$, $a_3 = -0.9082$, $a_4 = -0.00385$ and $\sigma = 0.68$.

## 2.64 Annaka and Nozawa (1988)

- Ground-motion model is:

$$\log A = C_m M + C_h H - C_d \log(R + A \exp BM) + C_o$$

  where $A$ is in cm/s$^2$, $A$ and $B$ so PGA becomes independent of magnitude at fault rupture, $H$ is depth of point on fault plane when $R$ becomes closest distance to fault plane, $C_m = 0.627$, $C_h = 0.00671$, $C_d = 2.212$, $C_o = 1.711$ and $\sigma = 0.211$.

- Focal depths $< 100$ km.

- Convert records from sites with $V_s < 300$ m/s into records from sites with $V_s > 300$ m/s using 1-D wave propagation theory.

- Introduce term $C_h H$ because it raises multiple correlation coefficient for PGA.

- Note equations apply for site where $300 \leq V_s \leq 600$ m/s.

## 2.65 Fukushima et al. (1988) & Fukushima and Tanaka (1990)

- Ground-motion model is:

$$\log A = aM - \log(R + c10^{aM}) - bR + d$$

  where $A$ is in cm/s$^2$, $a = 0.41$, $b = 0.0034$, $c = 0.032$, $d = 1.30$ and $\sigma = 0.21$.

- Use four site categories for some Japanese stations (302 Japanese records not classified):
  1. Rock: 41 records
  2. Hard: ground above Tertiary period or thickness of diluvial deposit above bedrock $< 10$ m, 44 records.
  3. Medium: thickness of diluvial deposit above bedrock $> 10$ m, or thickness of alluvial deposit above bedrock $< 10$ m, or thickness of alluvial deposit $< 25$ m and thickness of soft deposit is $< 5$ m, 66 records.
  4. Soft soil: other soft ground such as reclaimed land, 33 records.
- Use 1100 mean PGA values from 43 Japanese earthquakes ($6.0 \leq M_{\mathrm{JMA}} \leq 7.9$, focal depths $\leq 30$ km) recorded at many stations to investigate one and two-stage methods. Fits $\log A = c - b \log X$ (where $X$ is hypocentral distance) for each earthquake and computes mean of $b$, $\bar{b}$. Also fits $\log A = aM - b^* \log X + c$ using one-stage method. Find that $\bar{b} > b^*$ and shows that this is because magnitude and distance are strongly correlated (0.53) in data set. Find two-stage method of Joyner and Boore (1981) very effective to overcome this correlation and use it to find similar distance coefficient to $\bar{b}$. Find similar effect of correlation on distance coefficient for two other models: $\log A = aM - b \log(\Delta + 30) + c$ and $\log A = aM - \log X - bX + c$, where $\Delta$ is epicentral distance.
- Japanese data selection criteria: focal depth $< 30$ km, $M_{\mathrm{JMA}} > 5.0$ and predicted PGA $\geq 0.1\,\mathrm{m/s^2}$. US data selection criteria: $d_r \leq 50$ km, use data from Campbell (1981).
- Because $a$ affects distance and magnitude dependence, which are calculated during first and second steps respectively use an iterative technique to find coefficients. Allow different magnitude scaling for US and Japanese data.
- For Japanese data apply station corrections before last step in iteration to convert PGAs from different soil conditions to standard soil condition using residuals from analysis.
- Two simple numerical experiments performed. Firstly a two sets of artificial acceleration data was generated using random numbers based on attenuation relations, one with high distance decay and which contains data for short distance and one with lower distance decay, higher constant and no short distance data. Find that the overall equation from regression analysis has a smaller distance decay coefficient than individual coefficients for each line. Secondly find the same result for the magnitude dependent coefficient based on similar artificial data.
- Exclude Japanese data observed at long distances where average acceleration level was predicted (by using an attenuation relation derived for the Japanese data) to be less than the trigger level (assume to be about $0.05\,\mathrm{m/s^2}$) plus one standard deviation (assume to be 0.3), i.e. $0.1\,\mathrm{m/s^2}$, to avoid biasing results and giving a lower attenuation rate.
- Use the Japanese data and same functional form and method of Joyner and Boore (1981) to find an attenuation relation; find the anelastic coefficient is similar so conclude attenuation rate for Japan is almost equal to W. USA.
- Find difference in constant, $d$, between Japanese and W. USA PGA values.
- Plot residuals against distance and magnitude and find no bias or singularity.

## 2.66 Gaull (1988)

- Ground-motion model is:

$$\log \mathrm{PGA} = [(a_1 \log R + a_2)/a_3](M_L - a_4) - a_5 \log R - a_6 R + a_7$$

where PGA is in $\mathrm{m/s^2}$, $a_1 = 5$, $a_2 = 3$, $a_3 = 20$, $a_4 = 6$, $a_5 = 0.77$, $a_6 = 0.0045$ and $a_7 = 1.2$ ($\sigma$ not given).

- Considers three site categories but does not model:
  1. Rock: 6 records
  2. Alluvium: 5 records
  3. Average site: 10 records
- Most records from earthquakes with magnitudes about 3 and most from distances below about 20 km.
- Band pass filter records to get PGA associated with waves with periods between 0.1 and 0.5 s because high frequency PGA from uncorrected records not of engineering significance.
- Adds 4 near source ($5 \leq R \leq 10$ km) records from US, Indian and New Zealand earthquakes with magnitudes between 6.3 and 6.7 to supplement high magnitude range.
- Add some PGA points estimated from intensities associated with 14/10/1968 $M_L = 6.9$ Meckering earthquake in Western Australia.
- Plot 6 records from one well recorded event with $M_L = 4.5$ and fit an attenuation curve of form $\log \mathrm{PGA} = b_1 - b_2 \log R - b_3 R$ by eye. Plot PGA of all records with $2 \leq R \leq 20$ km against magnitude, fit an equation by eye. Use these two curves to normalise all PGA values to $M_L = 4.5$ and $R = 5$ km from which estimates attenuation relation.

## 2.67 McCue et al. (1988)

- Ground-motion model is:

$$A = a(\exp(bM)) \left( \frac{R}{R_0} + c \right)^{-d}$$

  where $A$ is in g, $\ln a = -5.75$, $b = 1.72$, $c = 0$, $d = 1.69$ and $R_0 = 1$ ($\sigma$ not given).
- Few records from free-field, most are in dams or special structures.,
- Because only 62 records, set $R_0 = 1$ and $c = 0$.
- Most records from earthquakes with $M_L$ between 1.5 and 2.0.
- Maximum PGA in set $3.05\,\mathrm{m/s^2}$.
- Nonuniform distribution of focal distances. One quarter of records from same hypocentral distance. Therefore plot PGA of these records against magnitude ($1.2 \lesssim M_L \lesssim 4.3$ most less than 2.1) to find $b$. Then plot $bM - \ln A$ against $\ln(R/R_0)$ for all records to find $a$ and $d$.
- Notes limited data.

## 2.68 Petrovski and Marcellini (1988)

- Ground-motion model is:

$$\ln(a) = b_1' + b_2 M + b_3 \ln(R + c)$$

  where $a$ is in $\mathrm{cm/s^2}$, $b_1' = 6.4830$, $b_2 = 0.5438$, $b_3 = -1.3330$, $c = 20$ km and $\sigma = 0.6718$ (for horizontal PGA) and $b_1 = 5.6440$, $b_2 = 0.5889$, $b_3 = -1.3290$, $c = 20$ km and $\sigma = 0.6690$ (for vertical PGA) (also give coefficients for other choices of $c$).

- Data from 'moderate' soil conditions.
- Data mainly from SMA-1s but 17 from RFT-250s.
- Data from northern Greece (5 records, 4 stations, 3 earthquakes), northern Italy (45 records, 18 stations, 20 earthquakes) and former Yugoslavia (70 records, 42 stations, 23 earthquakes).
- Data from free-field or in basements of structures.
- Select records from earthquakes with $3 \leq M \leq 7$. Most earthquakes with $M \leq 5.5$. 4 earthquakes (4 records) with $M \leq 3.5$, 20 (27 records) with $3.5 < M \leq 4.5$, 13 (25 records) with $4.5 < M \leq 5.5$, 8 (50 records) with $5.5 < M \leq 6.5$ and 1 (14 records) with $M > 6.5$.
- Select records from earthquakes with $h \leq 40$ km. Most earthquakes with $h \leq 10$ km. 6 earthquakes with $h \leq 5$ km, 30 with $5 < h \leq 10$ km, 5 with $10 < h \leq 20$ km, 4 with $20 < h \leq 30$ km and 1 with $h > 30$.
- Select records that satisfied predetermined processing criteria so that their amplitude would be such as to give negligible errors after processing.
- Select records to avoid concentration of records w.r.t. certain sites, magnitudes, hypocentral distances or earthquakes. Most well-recorded earthquakes is 15/4/1979 Montenegro earthquake with 14 records.
- Try values of $c$ between 0 and 40 km. Find standard deviation does not vary much for different choices.
- Test assumption of the log-normal probability distribution of data using graph in a coordinate system for log-normal distribution of probability, by $\chi^2$ test and by the Kolmogorov-Smirnov test (not shown). Find assumption is acceptable.

## 2.69 PML (1988)

- Ground-motion model is:
$$\ln y = C_0 + C_1 M_s + C_2 \ln R$$
where $y$ is in cm/s$^2$, $C_0 = 4.75$, $C_1 = 0.52$, $C_2 = -1.00$ and $\sigma = 0.53$ for hard ground and horizontal; $C_0 = 3.77$, $C_1 = 0.70$, $C_2 = -1.24$ and $\sigma = 0.64$ for hard ground and vertical; $C_0 = 4.37$, $C_1 = 0.57$, $C_2 = -0.91$ and $\sigma = 0.52$ for medium ground and horizontal; $C_0 = 3.20$, $C_1 = 0.75$, $C_2 = -1.07$ and $\sigma = 0.55$ for medium ground and vertical; $C_0 = 4.68$, $C_1 = 0.55$, $C_2 = -0.99$ and $\sigma = 0.54$ for soft ground and horizontal; and $C_0 = 3.53$, $C_1 = 0.71$, $C_2 = -1.10$ and $\sigma = 0.66$ for soft ground and vertical.
- Use 3 site classes (and develop independent models for each):

Hard Equivalent to rock. 57 records.

Medium Soil depth < 20 m or 'shallow'. Includes sites described as 'medium'.53 records.

Soft Soil depth > 20 m or 'deep'. Includes sites described as 'soft' or 'alluvium'. 53 records.

Notes that difficult to classify due to lack of information for some stations (particularly for soft and medium sites).

- Extends models of PML (1982, 1985) to spectral ordinates.
- Develop for use in the UK.
- Use earthquakes with focal depths $\leq 30$ km.

- Prioritize data away from well-defined plate-boundaries, e.g. central and eastern North America (Miramichi, Nahanni, New Madrid), mainland China (e.g. Tangshan) and the Alpide Belt (Ancona, Friuli, Irpinia, Cephalonia, Koyna, Montenegro, Imotski, Gazli, Tabas), over data from California. When Californian data is required use near-field records so that model not affected by specific attenuation of California. California data was required for soft ground model because of lack of near-field data from other areas.
- Vast majority of data from $M_w4$ to 7 and from $\leq 100$ km.
- Because of limited information on stress field and diversity of focal mechanisms in the UK do not consider style of faulting when selecting data.
- Correct data for instrument response and apply elliptic filter for majority of data (some data already processed using similar schemes). Note that differences below 0.04 s between records corrected in different ways are minor.
- Use PGAs from processed data, which note may be slightly lower than those from uncorrected records.

## 2.70 Tong and Katayama (1988)

- Ground-motion model is:

$$\log \bar{A} = \alpha M - \beta \log(\Delta + 10) + \gamma T + \delta$$

  where $\bar{A}$ is in gal, $T$ is predominant period of site, $\alpha = 0.509$, $\beta = 2.32$, $\gamma = 0.039$ and $\delta = 2.33$ ($\sigma$ not given).
- Correlation coefficient between magnitude and distance is 0.84, so magnitude and distance cannot be considered independent, so attenuation rate, $\beta$, is difficult to find.
- First step fit $\log \bar{A} = -\beta_i \log(\Delta + 10) + \delta_i$ to each earthquake. Define reliability parameter, $\psi_i = N_i R_i^2$, where $N_i$ is degrees of freedom for $i$ earthquake and $R_i$ is correlation coefficient. Plot $\psi_i$ against $\beta_i$ and find attenuation rate scattered, between $-6$ and 9, for $\psi_i < 1$ (Group B) and for $\psi_1 > 1$ attenuation rate converges (Group U).
- Group B includes earthquakes with focal depths $> 388$ km, earthquakes with small magnitudes and records from distances $\approx 100$ km, earthquakes with records from great distances where spread of distances is small, earthquakes recorded by only 3 stations and earthquakes with abnormal records. Exclude these records.
- Apply multiple regression on Group U to find $\alpha$, $\beta$, $\gamma$ and $\delta$ simultaneously. Also fix $\beta = \sum \psi_i \beta_i / \sum \psi_i$ and find $\alpha$, $\gamma$ and $\delta$. Find different coefficients but similar correlation coefficient. Conclude due to strong correlation between $M$ and $\Delta$ so many regression planes exist with same correlation coefficient.
- Perform Principal Component Analysis (PCA) on $\log A$, $M$, $\log(\Delta + 10)$, $T$ and $\log \bar{A}/A$ and find that equation found by fixing $\beta$ is not affected by ill-effect of correlation between $M$ and $\Delta$.
- Omit $T$ from regression and find little effect in estimation.

## 2.71 Yamabe and Kanai (1988)

- Ground-motion model is:

$$\begin{aligned} \log_{10} a &= \beta - \nu \log_{10} x \\ \text{where } \beta &= b_1 + b_2 M \\ \text{and: } \nu &= c_1 + c_2 M \end{aligned}$$

  where $a$ is in gal, $b_1 = -3.64$, $b_2 = 1.29$, $c_1 = -0.99$ and $c_2 = 0.38$ ($\sigma$ not given).

- Focal depths between 0 and 130 km.
- Regress recorded PGA of each earthquake, $i$, on $\log_{10} a = \beta_i - \nu_i \log_{10} x$, to find $\beta_i$ and $\nu_i$. Then find $b_1$ and $b_2$ from $\beta = b_1 + b_2 M$ and $c_1$ and $c_2$ from $\nu = c_1 + c_2 M$.
- Also consider $\nu = d_1 \beta$.
- Find $\beta$ and $\nu$ from 6 earthquakes (magnitudes between 5.4 and 6.1) from Tokyo-Yokohama area are much higher than for other earthquakes, so ignore them. Conclude that this is due to effect of buildings on ground motion.

## 2.72 Youngs et al. (1988)

- Ground-motion model is:

$$\ln(a_{\max}) = C_1 + C_2 M_w - C_3 \ln[R + C_4 \exp(C_5 M_w)] + B Z_t$$

where $a_{\max}$ is in g, $C_1 = 19.16$, $C_2 = 1.045$, $C_3 = 4.738$, $C_4 = 205.5$, $C_5 = 0.0968$, $B = 0.54$ and $\sigma = 1.55 - 0.125 M_w$.

- Use only rock records to derive equation but use some (389 records) for other parts of study. Classification using published shear-wave velocities for some sites.
- Exclude data from very soft lake deposits such as those in Mexico City because may represent site with special amplification characteristics.
- Data from subduction zones of Alaska, Chile, Peru, Japan, Mexico and Solomon Islands.
- Use two basic types of earthquake:

$Z_t = 0$ Interface earthquakes: low angle, thrust faulting shocks occurring on plate interfaces.

$Z_t = 1$ Intraslab earthquakes: high angle, predominately normal faulting shocks occurring within down going plate.

Classification by focal mechanisms or focal depths (consider earthquakes with depths $> 50$ km to be intraslab). Note that possible misclassification of some intraslab shocks as interface events because intraslab earthquakes do occur at depths $< 50$ km.

- Plots PGA from different magnitude earthquakes against distance; find near-field distance saturation.
- Originally include anelastic decay term $-C_6 R$ but $C_6$ was negative (and hence nonphysical) so remove.
- Plot residuals from original PGA equation (using rock and soil data) against $M_w$ and $R$; find no trend with distance but reduction in variance with increasing $M_w$. Assume standard deviation is a linear function of $M_w$ and find coefficients using combined rock and soil data (because differences in variance estimation from rock and soil are not significant).
- Use derived equation connecting standard deviation and $M_w$ for weighted (weights inversely proportional to variance defined by equation) nonlinear regression in all analyses.
- Plot residuals from original PGA equation; find that hypothesis that coefficients of equations for interface and intraslab earthquakes are the same can be rejected (using likelihood ratio test for nonlinear regression models) at 0.05 percentile level for both soil and rock. Try including a term proportional to depth of rupture into equation (because intraslab deeper than interface events) but find no significant reduction in standard error. Introduce $BZ_t$ term into equation; find $B$ is significant at 0.05 percentile level. Try including rupture type dependence into other coefficients but produces no further decrease in variance so reject.

- Use only data from sites with multiple recordings of both interface and intraslab earthquakes and include dummy variables, one for each site, to remove differences due to systematic site effects. Fix $C_1$ to $C_5$ to values from entire set and find individual site terms and $B$; find $B$ is very similar to that from unconstrained regression.

- Examine residuals for evidence of systematic differences between ground motion from different subduction zones; find no statistically significant differences in PGA among different subduction zones.

- Use geometric mean of two horizontal components to remove effect of component-to-component correlations that affect validity of statistical tests assuming individual components of motion represent independent measurements of ground motion. Results indicate no significant difference between estimates of variance about median relationships obtained using geometric mean and using both components as independent data points.

- Extend to $M_w > 8$ using finite difference simulations of faulting and wave propagation modelled using ray theory. Method and results not reported here.

## 2.73 Abrahamson and Litehiser (1989)

- Ground-motion model is:

$$\log_{10} a = \alpha + \beta M - \bar{c}\log_{10}[r + \exp(h_2 M)] + F\phi + Ebr$$

  where $F = 1$ for reverse or reverse oblique events and 0 otherwise and $E = 1$ for interplate events and 0 otherwise, $a$ is in g, for horizontal PGA $\alpha = -0.62$, $\beta = 0.177$, $\bar{c} = 0.982$, $h_2 = 0.284$, $\phi = 0.132$, $b = -0.0008$ and $\sigma = 0.277$ and for vertical PGA $\alpha = -1.15$, $\beta = 0.245$, $\bar{c} = 1.096$, $h_2 = 0.256$, $\phi = 0.096$, $b = -0.0011$ and $\sigma = 0.296$.

- Consider three site classifications, based on Joyner and Boore (1981):

  1. Rock: corresponds to C, D & E categories of Campbell (1981), 159 records.
  2. Soil: corresponds to A,B & F categories of Campbell (1981), 324 records.
  3. Unclassified: 102 records.

  Use to examine possible dependence in residuals not in regression because of many unclassified stations.

- Data based on Campbell (1981).

- Fault mechanisms are: strike-slip (256 records from 28 earthquakes), normal (14 records from 7 earthquakes), normal oblique (42 records from 12 earthquakes), reverse (224 records from 21 earthquakes) and reverse oblique (49 records from 8 earthquakes). Grouped into normal-strike-slip and reverse events. Weakly correlated with magnitude (0.23), distance (0.18) and tectonic environment (0.03).

- Tectonic environments are: interplate (555 records from 66 earthquakes) and intraplate (30 records from 10 earthquakes) measurements. Weakly correlated with magnitude (−0.26), distance (−0.17) and fault mechanism (0.03).

- Depths less than 25 km.

- Use array average (37 instruments are in array) from 10 earthquakes recorded at SMART 1 array in Taiwan.

- Most records from distances less than 100 km and magnitude distribution is reasonably uniform but correlation between magnitude and distance of 0.52.

- Try two-stage technique and model (modified to include fault mechanism and tectonic environment parameters) of Joyner and Boore (1981), find inadmissable positive anelastic coefficient, so do not use it.

- Use a hybrid regression technique based on Joyner and Boore (1981) and Campbell (1981). A method to cope with highly correlated magnitude and distance is required. First step: fit data to $f_2(r) = \bar{c}\log_{10}(r+h)$ and have separate constants for each earthquake (like in two-stage method of Joyner and Boore (1981)). Next holding $\bar{c}$ constant find $\alpha$, $\beta$, $b$ and $h_2$ from fitting $h = \exp(h_2 M)$. Weighting based on Campbell (1981) is used.

- Form of $h$ chosen using nonparametric function, $H(M)$, which partitions earthquakes into 0.5 unit bins. Plot $H(M)$ against magnitude. Find that $H(M) = h_1 \exp(h_2 M)$ is controlled by Mexico (19/9/1985) earthquake and $h_1$ and $h_2$ are highly correlated, 0.99, although does given lower total variance. Choose $H(M) = \exp(h_2 M)$ because Mexico earthquake does not control fit and all parameters are well-determined, magnitude dependent $h$ significant at 90%.

- Try removing records from single-recorded earthquakes and from shallow or soft soil but effect on predictions and variance small ($< 10\%$).

- Plot weighted residuals within 10 km no significant, at 90%, trends are present.

- Find no significant effects on vertical PGA due to site classification.

## 2.74 Campbell (1989)

- Ground-motion model is:

$$\ln \mathrm{PHA} = a + bM_L - 1.0\ln[R + c_1]$$

  where PHA is in g, $a = -2.501$, $b = 0.623$, $c_1 = 7.28$ and $\sigma = 0.506$.

- Selects records from deep soil ($> 10$ m). Excludes data from shallow soil ($\leq 10$ m) and rock sites and those in basements of buildings or associated with large structures, such as dams and buildings taller than two storeys. Selects records with epicentral distances $\leq 20$ km for $M_L < 4.75$ and distances $\leq 30$ km for $M_L \geq 4.75$ to minimize regional differences in anelastic attenuation and potential biases associated with nontriggering instruments and unreported PGAs.

- Focal depths, $H$, between 1.8 and 24.3 km with mean of 8.5 km.

- PGAs scaled from either actual or uncorrected accelerograms in order to avoid potential bias due to correction.

- Uses weighted nonlinear least squares technique of Campbell (1981).

- Tries two other forms of equation: $\ln \mathrm{PHA} = a + bM_L - 1.0\ln[R + c_1] + e_1 H$ and $\ln \mathrm{PHA} = a + bM_L - 1.0\ln[R+c_1]+e_2\ln H$ for epicentral and hypocentral distance. Allows saturation of PGA for short distances but finds nonsignificant coefficients, at 90%. Also tries distance decay coefficient other than $-1.0$ but finds instability in analysis.

- Examines normalised weighted residuals against focal depth, $M_L$ and distance. Finds that although residuals seem to be dependent on focal depth there are probably errors in focal depth estimation for deep earthquakes in the study so the dependence may not be real. Finds residuals not dependent on magnitude or distance.

- Uses 171 records ($0.9 \leq R \leq 28.1$ km) from 75 earthquakes ($2.5 \leq M_L \leq 5.0$, $0.7 \leq H \leq 24.3$ km) excluded from original analysis because they were on shallow soil, rock and/or not free-field, to examine importance of site geology and building size. Considers difference between PGA from records grouped according to instrument location, building size, embedment, and site geology and the predicted PGA using the attenuation equation to find site factors, $S$. Groups with nonsignificant, at 90%, values of $S$ are grouped together. Finds two categories: embedded alluvial sites from all building sizes (38 records) and shallow-soil (depth of soil $\leq 10$ m) sites (35 records) to have statistically significant site factors.
- Performs regression analysis on all records (irrespective of site geology or building size) from Oroville (172 records from 32 earthquakes) and Imperial Valley (71 records from 42 earthquakes) to find individual sites that have significant influence on prediction of PGA (by using individual site coefficients for each station). Finds equations predict similar PGA to those predicted by original equation. Finds significant differences between PGA recorded at different stations in the two regions some related to surface geology but for some finds no reason.
- Uses 27 records ($0.2 \leq R \leq 25.0$ km) from 19 earthquakes ($2.5 \leq M_{bLG} \leq 4.8$, $0.1 \leq H \leq 9$ km) from E. N. America to examine whether they are significantly different than those from W. N. America. Finds residuals significantly, at 99% level, higher than zero and concludes that it is mainly due to site effects because most are on shallow soils or other site factors influence ground motion. Correcting the recorded PGAs using site factors the difference in PGA between E. N. America and W. N. America is no longer significant although notes may not hold for all of E. N. America.

## 2.75 Huo (1989)

- Ground-motion model is:

$$\log Y = c_1 + c_2 M + c_4 \log[R + c_5 \exp(c_6 M)]$$

  where $Y$ is in cm/s$^2$, $c_1 = 0.207$, $c_2 = 0.808$, $c_4 = -2.026$, $c_5 = 0.183$, $c_6 = 0.703$ and $\sigma = 0.247$ (for rock sites) and $c_1 = 0.716$, $c_2 = 0.647$, $c_4 = -1.706$, $c_5 = 0.187$, $c_6 = 0.703$ and $\sigma = 0.251$ (for soil sites).

- Use 2 site classes and derive separate models:

Rock

Soil

## 2.76 Ordaz et al. (1989)

- Ground-motion model is unknown.

## 2.77 Alfaro et al. (1990)

- Ground-motion model for near field is:

$$\log(A) = a_1 + a_2 M_s - \log(r^2 + a_3^2)^{\frac{1}{2}}$$

  where $A$ is in g, $a_1 = -1.116$, $a_2 = 0.312$, $a_3 = 7.9$ and $\sigma = 0.21$.

  Ground-motion model for far field is:

$$\log(A) = b_1 + b_2 M_s + b_3 \log(r^2 + b_4^2)^{\frac{1}{2}}$$

  where $A$ is in g, $b_1 = -1.638$, $b_2 = 0.438$, $b_3 = -1.181$, $b_4 = 70.0$ and $\sigma = 0.21$.

- Separate crustal and subduction data because of differences in travel path and stress conditions:

  1. Near field
  2. Far field, 20 records from San Salvador, 20 earthquakes, $4.2 \leq M_s \leq 7.2$, depths between 36 and 94 km, $31 \leq r \leq 298$ km.

## 2.78 Ambraseys (1990)

- Ground-motion model is:

$$\begin{aligned} \log y &= \alpha + \beta M_w - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2} \end{aligned}$$

  where $y$ is in g, $\alpha = -1.101$, $\beta = 0.2615$, $b = -0.00255$, $h = 7.2$ and $\sigma = 0.25$.

- Uses data and method of Joyner and Boore (1981) but re-evaluates $M_w$ for all earthquakes. Finds some large changes, e.g. Santa Barbara changes from $M_w = 5.1$ to $M_w = 5.85$. Uses $M_L$ for 2 earthquakes ($M_L = 5.2$, 6.2).

- Find effect of uncertainty in $M_w$ causes less than 10% change in $\sigma$.

- Also calculates equation using $M_s$ instead of $M_w$.

- Finds assumption $M_s = M_w$ introduces bias, particularly for small magnitude shocks, on unsafe side, and this can be significant in cases where there is a preponderance of small earthquakes in set.

## 2.79 Campbell (1990)

- Ground-motion model is:

$$\begin{aligned} \ln(Y) &= a + bM + d\ln[R + c_1 \exp(c_2 M)] + eF + f_1 \tanh[f_2(M + f_3)] \\ &\quad + g_1 \tanh(g_2 D) + h_1 K_1 + h_2 K_2 + h_3 K_3 \end{aligned}$$

  where $Y$ is in g, $a = -2.245$, $b = 1.09$, $c_1 = 0.361$, $c_2 = 0.576$, $d = -1.89$, $e = 0.218$, $f_1 = 0$, $f_2 = 0$, $f_3 = 0$, $g_1 = 0$, $g_2 = 0$, $h_1 = -0.137$, $h_2 = -0.403$ and $h_3 = 0$. $\sigma = 0.517$ for $M \leq 6.1$ and $\sigma = 0.387$ for $M \geq 6.2$. Also given is $\sigma = 0.450$ for $M \geq 4.7$.

- Records from firm soil and soft rock sites. Characterises site conditions by depth to basement rock (sediment depth) in km, $D$.

- Records from different size buildings. $K_1 = 1$ for embedded buildings 3–11 storeys, $K_2 = 1$ for embedded buildings with >11 storeys and $K_3 = 1$ for non-embedded buildings >2 storeys in height. $K_1 = K_2 = K_3 = 0$ otherwise.

- Uses two fault mechanisms:

$F = 0$ Strike-slip

$F = 1$ Reverse

## 2.80 Dahle et al. (1990b) & Dahle et al. (1990a)

- Ground-motion model is:

$$\begin{aligned}\ln A &= c_1 + c_2 M + c_4 R + \ln G(R, R_0)\\ \text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \leq R_0\\ \text{and: } G(R, R_0) &= R_0^{-1}\left(\frac{R_0}{R}\right)^{5/6} \quad \text{for} \quad R > R_0\end{aligned}$$

  where $A$ is in $\mathrm{m/s^2}$, $c_1 = -1.471$, $c_2 = 0.849$, $c_4 = -0.00418$ and $\sigma = 0.83$.

- Use records from rock sites (presumably with hard rock or firm ground conditions).

- Assume intraplate refers to area that are tectonically stable and geologically more uniform than plate boundary areas. Select records from several 'reasonably' intraplate areas (eastern N. America, China, Australia, and some parts of Europe), due to lack of data.

- Select records which are available unprocessed and with sufficient information on natural frequency and damping of instrument.

- Use $M_s$, when available, because reasonably unbiased with respect to source dimensions and there is globally consistent calculation method.

- Most (72%) records from earthquakes with $M \leq 5.5$. Tangshan and Friuli sequence comprise a large subset. Correlation coefficient between magnitude and distance is 0.31.

- Instrument correct records and elliptical filter with pass band 0.25 to 25.0 Hz.

- If depth unknown assume 15 km.

- Choose $R_0 = 100$ km although depends on crustal structure and focal depth. It is distance at which spherical spreading for S waves overtaken by cylindrical spreading for Lg waves.

- PGA attenuation relation is pseudo-acceleration equation for 0.025 s period and 5% damping.

- Plot residuals against magnitude and distance.

- Note 'first order' results, because data from several geological regions and use limited data base.

## 2.81 Jacob et al. (1990)

- Ground-motion model is:

$$A = 10^{(a_1 + a_2 M + a_3 \log d + a_4 d)}$$

  where $A$ is in g, $a_1 = -1.43$, $a_2 = 0.31$, $a_3 = -0.62$ and $a_4 = -0.0026$ ($\sigma$ not given).

- Note equation only for hard rock sites.

- Equation from a composite of two separate regressions: one using data from 6 earthquakes, $4.7 \leq M \leq 6.4$ and $d$ primarily between 40 and 820 km and one using the same data supplemented with data from 2 earthquakes with $M = 1.8$ and $M = 3.2$ and $d \leq 20$ km to extend results to smaller $M$ and $d$. Give no details of this composite regression.

- Note regressions are preliminary and should be tested against more data.

- Note careful assessment of uncertainties is required.

## 2.82 Sen (1990)

- Ground-motion model is:

$$\ln \mathrm{PGA} = a + bM + c\ln(r + h) + \phi F$$

  where PGA is in $\mathrm{cm/s^2}$, $a = 1.375$, $b = 1.672$, $c = -1.928$ and $\phi = 0.213$ ($h$ not given). Standard deviation is composed of two parts, inter-site $\tau = 0.261$ and intra-site $\sigma = 0.653$. $F = 1$ for thrust mechanism and 0 otherwise.

- Computes theoretical radiation pattern and finds a linear trend between residuals and radiation pattern but does not model.

## 2.83 Sigbjörnsson (1990)

- Ground-motion model is:

$$a_{\mathrm{peak}} = \alpha_0 \exp(\alpha_1 M) \exp(-\alpha_2 R) R^{-\alpha} P$$

  where $P = 1$.

- Notes that data are very limited and any definite conclusions should, therefore, be avoided.

- Does not give coefficients, only predictions.

## 2.84 Tsai et al. (1990)

- Ground-motion model is:

$$\ln y = C_0 + C_1 M + C_2(8.5 - M)^{2.5} + C_3 \ln[D + C_4 \exp(C_5 M)]$$

  where $y$ is in g, $C_3 = -2.1$, $C_4 = 0.616$, $C_5 = 0.524$ and for $M \geq 6.5$ $C_0 = -1.092$, $C_1 = 1.10$, $C_2 = 0$ and $\sigma = 0.36$ and for $M < 6.5$ $C_0 = -0.442$, $C_1 = 1.0$, $C_2 = 0$ and $\sigma = 1.27 - 0.14M$.

- All records from rock or rock-like sites.

- Separate equation for $M < 6.5$ and $M \geq 6.5$.

- Use only shallow crustal thrust earthquakes.

- Use another database of rock and soil site records and simulated acceleration time histories to find conversion factors to predict strike-slip and oblique ground motions from the thrust equation given above. For strike-slip conversion factor is 0.83 and for oblique conversion factor is 0.91.

- Standard deviation, $\sigma$, for $M \geq 6.5$ from regression whereas $\sigma$ for $M < 6.5$ from previous results. Confirm magnitude dependence of standard deviation using 803 recordings from 124 earthquakes, $3.8 \leq M_w \leq 7.4$, $D < 100\,\mathrm{km}$.

## 2.85 Ambraseys and Bommer (1991) & Ambraseys and Bommer (1992)

- Ground-motion model is:

$$\begin{aligned} \log a &= \alpha + \beta M - \log r + br \\ \text{where } r &= (d^2 + h_0^2)^{1/2} \\ \text{or: } r &= (d^2 + h^2)^{1/2} \end{aligned}$$

where $a$ is in g, for horizontal PGA $\alpha = -1.09$, $\beta = 0.238$, $b = -0.00050$, $h = 6.0$ and $\sigma = 0.28$ and for vertical PGA $\alpha = -1.34$, $\beta = 0.230$, $b = 0$, $h = 6.0$ and $\sigma = 0.27$. When use focal depth explicitly: for horizontal PGA $\alpha = -0.87$, $\beta = 0.217$, $b = -0.00117$ and $\sigma = 0.26$ and for vertical PGA $\alpha = -1.10$, $\beta = 0.200$, $b = -0.00015$ and $\sigma = 0.26$.

- Consider two site classifications (without regard to depths of deposits) but do not model:
  1. Rock
  2. Alluvium
- Select records which have: $M_s \geq 4.0$ and standard deviation of $M_s$ known and reliable estimates of source-site distance and focal depth, $h \leq 25$ km, regardless of local soil conditions from free-field and bases of small buildings. No reliable data or outliers excluded. Records from instruments at further distances from the source than the closest non-triggered instrument were non-excluded because of non-homogeneous and irregularly spaced networks and different and unknown trigger levels.
- Most data, about 70%, with distances less than 40 km. Note strong bias towards smaller values of magnitude and PGA.
- PGA read from analogue and digitised data, with different levels of processing. Differences due to different processing usually below 5%, but some may be larger.
- Errors in distances for small shocks may be large.
- Prefer one-stage technique because second step of two-stage method would ignore records from singly-recorded earthquakes which compose over half the events, also find more realistic, $b$, and $h_0$ using one-stage method. Do not use weighting because involves assumptions which are difficult to verify.
- Find inadmissable and positive $b$ for vertical PGA so remove and repeat.
- Remove records from distances less than or equal to half their focal depth and also less than or equal to their focal depth, find that $h_0$ is governed by near-field data.
- Use focal depth explicitly, by replacing $r = (d^2 + h_0^2)^{1/2}$ by $r = (d^2 + h^2)^{1/2}$. Find lower standard deviation and that it is very significant.
- Repeat analysis on subsets of records grouped by focal depth. Find no correlation between $h_0$ and focal depth of subset. Use $h_0$ equal to mean focal depth in each subset and find similar results to when focal depth used explicitly.
- Repeat analysis with geometric attenuation coefficient equal to $-0.83$, corresponding to the Airy phase, as opposed to $-1.0$.
- Find small dependence of horizontal PGA on site classification, note due to level of information available.

## 2.86 Crouse (1991)

- Ground-motion model is:

$$\ln \mathrm{PGA} = p_1 + p_2 M + p_4 \ln[R + p_5 \exp(p_6 M)] + p_7 h$$

  where PGA is in gal, using all PGA values $p_1 = 6.36$, $p_2 = 1.76$, $p_4 = -2.73$, $p_5 = 1.58$, $p_6 = 0.608$, $p_7 = 0.00916$ and $\sigma = 0.773$.

- Use data from stiff soil sites (depth of soil $< 25$ m).

- Include data from any zones with strong seismic coupling, such as the younger subduction zones (S.W. Japan, Alaska, C. America (Mexico), C. Chile, Peru and northern Honshu and Kuril subduction zones in Japan) unless compelling reasons to exclude data. Do this because lack of data from Cascadia. Most ($> 70\%$) are from Japan.
- Focal depths, $h$, between 0 and 238 km.
- Compare Japanese and Cascadia PGA values for earthquakes with similar magnitude and depths and find similar.
- Do not exclude data from buildings or which triggered on S-wave. Note could mean some PGAs are underestimated.
- Plot ground motion amplitude (PGA and also some maximum displacements from seismograms) against distance for a number of large magnitude shocks (including some data from rock sites which not included in set for regression). Find that rate of attenuation becomes smaller for shorter distances and process is magnitude dependent. Also plot Japanese PGA data, from earthquakes with $h \leq 50$ km, split into three distance groups (between 50 and 75 km, between 100 and 150 km and between 250 and 300 km) find as distance increases magnitude scaling becomes larger and possible saturation in PGA for large magnitudes. Fit $\ln \text{PGA} = p_1 + p_2 \ln(R + C)$ to some PGA values from large magnitude shocks for $C = 0$ and $C > 0$, find lower standard deviation for $C > 0$.
- Fit $\ln \text{PGA} = a + bM$ and $\ln \text{PGA} = a + bM + cM^2$ to Japanese data split into the three distance groups (mentioned above); find $b$ increases with increasing distance range but both equations fit data equally well.
- Constrain $p_4$ to negative value and $p_5$ and $p_6$ to positive values.
- Include quadratic magnitude term, $p_3 M^2$, but find equal to zero.
- Plot residuals against $M$; find uniformly distributed and evidence for smaller residuals for larger $M$.
- Plot residuals against $R$[9] and find decreasing residuals for increasing $R$.
- Give equation using only those records available in digital form (235 records).

## 2.87 Garcìa-Fernàndez and Canas (1991) & Garcia-Fernandez and Canas (1995)

- Ground-motion model is:

$$\ln \text{PGA} = \ln C_0 + C_1 M - 0.5 \ln r - \gamma r$$

  where PGA is in cm/s$^2$, for Iberian Peninsula $\ln C_0 = -5.13$, $C_1 = 2.12$ and $\gamma = 0.0039$, for NE region $\ln C_0 = -4.74$, $C_1 = 2.07$ and $\gamma = 0.0110$ and for SSE region $\ln C_0 = -5.30$, $C_1 = 2.21$ and $\gamma = 0.0175$ ($\sigma$ is not given).

- Derive equations for two regions:

  SSE South south-east part of the Iberian peninsula, from the Guadalquivir basin to the Mediterranean Sea, including the Betic Cordillera, 140 records from 5 stations.

  NE North-east part of the Iberian peninsula, including the Pyrenees, the Catalan Coastal Ranges, the Celtiberian chain and the Ebro basin, 107 records from 3 stations.

[9]Not shown in paper.

- Use vertical-component short-period analogue records of Lg-waves (which are believed to have the largest amplitudes for the period range 0.1 to 1$s$) from regional earthquakes in Iberian Peninsula.
- Processing procedure is: digitise seismogram using irregular sampling rate to get better sampling at peaks and 'kinks', select baseline, apply cubic spline interpolation and compare original and digitised seismograms. Next the Fourier amplitude spectrum is computed and the instrument amplitude response is removed.
- Estimate PGA using the maximum value of pseudo-absolute acceleration obtained from Fourier amplitude spectra. Derived equations are for characteristic frequency of 5 Hz.
- Compare estimated PGAs with observed PGAs from five earthquakes and find good agreement.
- Use 5 Hz $\gamma$ values from Garcia-Fernandez and Canas (1992) and Vives and Canas (1992).

## 2.88 Geomatrix Consultants (1991), Sadigh et al. (1993) & Sadigh et al. (1997)

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln\left(r_{\mathrm{rup}} + C_4 \mathrm{e}^{C_5 M}\right) + C_6 Z_T$$

  where PGA is in g, for horizontal PGA, rock sites and strike-slip faulting $C_3 = 0$ and $C_4 = -2.100$, for $M \leq 6.5$ $C_1 = -0.624$, $C_2 = 1.0$, $C_5 = 1.29649$ and $C_6 = 0.250$ and for $M > 6.5$, $C_1 = -1.274$, $C_2 = 1.1$, $C_5 = -0.48451$ and $C_6 = 0.524$. For reverse and thrust earthquakes multiply strike-slip prediction by 1.2. $\sigma = 1.39 - 0.14M$ for $M < 7.21$ and $\sigma = 0.38$ for $M \geq 7.21$. For horizontal PGA and deep soil $C_2 = 1.0$, $C_3 = 1.70$ and $C_6 = 0$, for strike-slip faulting $C_1 = -2.17$ and for reverse or thrust faulting $C_1 = -1.92$, for $M \leq 6.5$ $C_4 = 2.1863$ and $C_5 = 0.32$ and for $M > 6.5$ $C_4 = 0.3825$ and $C_5 = 0.5882$. $\sigma = 1.52 - 0.16M$ for $M \leq 7$ and $\sigma = 0.40$ for $M = 7$.

  For vertical PGA, rock sites and strike-slip faulting $C_3 = 0$ and $C_4 = -2.300$, for $M \leq 6.5$ $C_1 = -0.430$, $C_2 = 1.0$, $C_5 = 1.2726$ and $C_6 = 0.228$ and for $M > 6.5$, $C_1 = -1.080$, $C_2 = 1.1$, $C_5 = -0.3524$ and $C_6 = 0.478$. For reverse and thrust earthquakes multiply strike-slip prediction by 1.1 and for oblique faulting multiply by 1.048. $\sigma = 0.48$ for $M \geq 6.5$, $\sigma = 3.08 - 0.40M$ for $6 < M < 6.5$ and $\sigma = 0.68$ for $M \leq 6$.

- Use two site categories (for horizontal motion):

  1. Rock: bedrock within about a metre of surface. Note that many such sites are soft rock with $V_s \leq 750$ m/s and a strong velocity gradient because of near-surface weathering and fracturing, 274 records.
  2. Deep soil: greater than 20 m of soil over bedrock. Exclude data from very soft soil sites such as those from San Francisco bay mud, 690 records.

  Vertical equations only for rock sites.

- Crustal earthquakes defined as those that occur on faults within upper 20 to 25 km of continental crust.
- Use source mechanism: RV=reverse (26+2) $\Rightarrow Z_T = 1$ and SS=strike-slip (and some normal) (89+0) $\Rightarrow Z_T = 0$. Classified as RV if rake$> 45°$ and SS if rake$< 45°$. Find peak motions from small number of normal faulting earthquakes not to be significantly different than peak motions from strike-slip events so were including in SS category.

- Records from instruments in instrument shelters near ground surface or in ground floor of small, light structures.
- 4 foreign records (1 from Gazli and 3 from Tabas) supplement Californian records.
- Separate equations for $M_w < 6.5$ and $M_w \geq 6.5$ to account for near-field saturation effects and for rock and deep soil sites.

## 2.89 Huo and Hu (1991)

- Ground-motion model is (case II):

$$\log y = C_1 + C_2 M - C_4 \log[R + C_5 \exp(C_6 M)]$$

  where $y$ is in gal, $C_5 = 0.231$ and $C_6 = 0.626$, for rock $C_1 = 0.894$, $C_2 = 0.563$, $C_4 = 1.523$ and $\sigma = 0.220$ and for soil $C_1 = 1.135$, $C_2 = 0.462$, $C_4 = 1.322$ and $\sigma = 0.243$ (these coefficients are from regression assuming $M$ and $R$ are without error).

- Use two site categories:
  1. Rock
  2. Soil
- Supplement western USA data in large magnitude range with 25 records from 2 foreign earthquakes with magnitudes 7.2 and 7.3.
- Note that there are uncertainties associated with magnitude and distance and these should be considered in derivation of attenuation relations.
- Develop method, based on weighted consistent least-square regression, which minimizes residual error of all random variables not just residuals between predicted and measured ground motion. Method considers ground motion, magnitude and distance to be random variables and also enables inverse of attenuation equation to be used directly.
- Note prediction for $R > 100$ km may be incorrect due to lack of anelastic attenuation term.
- Use both horizontal components to maintain their actual randomness.
- Note most data from moderate magnitude earthquakes and from intermediate distances therefore result possibly unreliable outside this range.
- Use weighted analysis so region of data space with many records are not overemphasized. Use $M$-$R$ subdivisions of data space: for magnitude $M < 5.5$, $5.5 \leq M \leq 5.9$, $6.0 \leq M \leq 6.4$, $6.5 \leq M \leq 6.9$, $7.0 \leq M \leq 7.5$ and $M > 7.5$ and for distance $R < 3$, $3 \leq R \leq 9.9$, $10 \leq R \leq 29.9$, $30 \leq R \leq 59.9$, $60 \leq R \leq 99.9$, $100 \leq R \leq 300$ and $R > 300$ km. Assign equal weight to each subdivision, and any data point in subdivision $i$ containing $n_i$ data has weight $1/n_i$ and then normalise.
- To find $C_5$ and $C_6$ use 316 records from 7 earthquakes ($5.6 \leq M \leq 7.2$) to fit $\log Y = \sum_{i=1}^{m} C_{2,i} E_i - C_4 \log[r + \sum_{i=1}^{m} R_{0,i} E_i]$, where $E_i = 1$ for $i$th earthquake and 0 otherwise. Then fit $R_0 = C_5 \exp(C_6 M)$ to results.
- Also try equations: $\log y = C_1 + C_2 M - C_4 \log[R + C_5]$ (case I) and $\log y = C_1 + C_2 M - C_3 M^2 - C_4 \log[R + C_5 \exp(C_6 M)]$ (case III) for $M \leq M_c$, where impose condition $C_3 = (C_2 - C_4 C_6/\ln 10)/(2M_c)$ so ground motion is completely saturated at $M = M_c$ (assume $M_c = 8.0$).
- Find equations for rock and soil separately and for both combined.

## 2.90 I.M. Idriss (1991) reported in Idriss (1993)

- Ground-motion model is:

$$\ln(Y) = [\alpha_0 + \exp(\alpha_1 + \alpha_2 M)] + [\beta_0 - \exp(\beta_1 + \beta_2 M)] \ln(R + 20) + aF$$

  where $Y$ is in g, $a = 0.2$, for $M \leq 6$ $\alpha_0 = -0.150$, $\alpha_1 = 2.261$, $\alpha_2 = -0.083$, $\beta_0 = 0$, $\beta_1 = 1.602$, $\beta_2 = -0.142$ and $\sigma = 1.39 - 0.14M$ and for $M > 6$ $\alpha_0 = -0.050$, $\alpha_1 = 3.477$, $\alpha_2 = -0.284$, $\beta_0 = 0$, $\beta_1 = 2.475$, $\beta_2 = -0.286$ and for $M < 7\frac{1}{4}$ $\sigma = 1.39 - 0.14M$ and for $M \geq 7\frac{1}{4}$ $\sigma = 0.38$.

- Records from rock sites.

- Uses three fault mechanisms:

| | |
|---|---|
| F=0 | Strike slip |
| F=0.5 | Oblique |
| F=1 | Reverse |

- Separate equations for $M \leq 6$ and $M > 6$.

- Examines residuals for PGA. Finds average residual almost zero over entire distance range; trend reasonable up to about 60 km but beyond 60 km relationship would underestimate recorded PGA.

- Finds standard deviation to be linear function of magnitude.

## 2.91 Loh et al. (1991)

- Ground-motion model is:

$$a = b_1 \mathrm{e}^{b_2 M} (R + b_4)^{-b_3}$$

  where $a$ is in g, $b_1 = 1.128$, $b_2 = 0.728$, $b_3 = 1.743$, $b_4 = 32$ km and $\sigma = 0.563$ (in terms of ln).

- Use only data from rock sites.

- Focal depths, $h$, between 0.2 and 97.4 km. Most records from $h < 30$ km.

- Also derive equations for PGA using $\log_{10}(a) = b_1 + b_2 M + b_3 \log \sqrt{R^2 + b_5^2}$ and $a = b_1 \mathrm{e}^{b_2 M}(R + b_4 \mathrm{e}^{b_5 M})^{-b_3}$ in order to have diversity in the characterisation of ground motion.

- Use $r_{hypo}$ because no clear fault ruptures identified for Taiwanese earthquakes.

- All data from SMA-1s.

- PGAs between 7.3 and 360.2 cm/s$^2$.

## 2.92 Matuschka and Davis (1991)

- Exact functional form unknown but based on those of Campbell (1981), Fukushima and Tanaka (1990) and Abrahamson and Litehiser (1989).

- Use three site classes.

- Develop separate equations for each site class. Only possible for two classes. Therefore, modify equation derived for site class C to obtain coefficients for other two classes.

- Digitization sampling rate of records used is 50 Hz. Most data low-pass filtered at 24.5 Hz.
- Most data high-pass filtered with cut-offs above 0.25 Hz.
- Due to limited data, advise caution when using model.

## 2.93 Niazi and Bozorgnia (1991)

- Ground-motion model is:
$$\ln Y = a + bM + d\ln[R + c_1 e^{c_2 M}]$$
where $Y$ is in g, for horizontal PGA $a = -5.503$, $b = 0.936$, $c_1 = 0.407$, $c_2 = 0.455$, $d = -0.816$ and $\sigma = 0.461$ and for vertical PGA $a = -5.960$, $b = 0.989$, $c_1 = 0.013$, $c_2 = 0.741$, $d = -1.005$ and $\sigma = 0.551$.
- All records from SMART-1 array so essentially identical site conditions and travel paths.
- All records from free-field instruments mounted on 4inch (10 cm) thick concrete base mats, approximately 2 by 3 feet (60 by 90 cm) across.
- Select earthquakes to cover a broad range of magnitude, distance and azimuth and ensuring thorough coverage of the array. Criteria for selection is: at least 25 stations recorded shock, focal depth $< 30$ km, hypocentral distance $< 50$ km except for two large earthquakes from beyond 50 km to constrain distance dependence.
- Focal depths between 0.2 and 27.2 km with all but one $\leq 13.9$ km.
- Azimuths between 60° and 230°.
- Most records (78%) have magnitudes between 5.9 and 6.5. Note magnitude and distance are not independent (correlation coefficient is 0.6).
- Records have sampling interval of 0.01 s. Processed using trapezoidal band passed filter with corner frequencies 0.07, 0.10, 25.0 and 30.6 Hz.
- Not enough information to use distance to rupture zone.
- Source mechanisms of earthquakes are: 4 normal, 2 reverse, 1 reverse oblique and 1 normal oblique with 4 unknown. Do not model source mechanism dependence because of 4 unknown mechanisms.
- Use weighted regression, give equal weight to recordings from each earthquake within each of 10 distance bins ($<$ 2.5, 2.5–5.0, 5.0–7.5, 7.5–10.0, 10.0–14.1, 14.1–20.0, 20–28.3, 28.3–40.0, 40.0–56.6 and 56.6–130 km). Do this so earthquakes with smaller number of recordings are not overwhelmed by those with a larger coverage and also to give additional weight to shocks recorded over multiple distance bins. Apply two-stage regression, because of high correlation between magnitude and distance, excluding 3 earthquakes ($M = 3.6$, 5.0, 7.8) with 162 records from first stage to reduce correlation between $M$ and $R$ to 0.1. Also do one-stage regression although do not give coefficients.
- Use mean horizontal component because reduces uncertainty in prediction.
- Examine coefficient of variation for each earthquake using median and normalized standard deviation of recordings in inner ring of array. Find evidence for magnitude dependent uncertainty (large magnitude shocks show less uncertainty). Find that main contribution to scatter is inter-event variations again by examining coefficient of variation; although note may be because using dense array data.

- Examine mean residuals of observations from each earthquake. Find evidence for higher than predicted vertical PGA from reverse faulting earthquakes and lower than predicted vertical PGA from normal faulting earthquakes, although due to lack of information for 4 earthquakes note that difficult to draw any conclusions.

- Examine mean residuals of observations from each station in inner ring. Find mean residuals are relatively small compared with standard deviation of regression so variation between stations is less than variation between earthquakes. Find for some stations some large residuals.

## 2.94 Rogers et al. (1991)

- Ground-motion model is:

$$\log a_p = a_1 + 0.36M - 0.002R + a_2 \log R + a_3 S_1 + a_4 S_1 \log R + a_5 S_5 + a_6 S_5 \log R + a_7 S_6 \log R$$

  where $a_p$ is in g, $a_1 = -1.62$, $a_2 = -1.01$, $a_3 = 0.246$, $a_4 = 0.212$, $a_5 = 0.59$, $a_6 = -0.29$, $a_7 = 0.21$ and $\sigma = 0.29$.

- Use six local site classifications:

  $S_1$ Holocene

  $S_2$ Pleistocene soil

  $S_3$ Soft rock

  $S_4$ Hard rock

  $S_5$ Shallow ($< 10$ m depth) soil

  $S_6$ Soft soil (e.g. bay mud)

- Data from about 800 different stations.

- Note that inclusion of subduction-zone events in analysis may affect results with unmodelled behaviour, particularly with regard to distance scaling although believe use of $r_{rup}$ partially mitigates this problem.

- Firstly compute an equation does not include site coefficients. Conduct regression analysis on site-condition subsets of the residuals using $M$ or $\log R$ as dependent variable. Find several regressions are not statistically significant at the 5% level and/or the predicted effects are small at the independent variable extremes. Find strongest effects and most significant results are for shallow soil sites and soft soil sites although because of the high correlation between $M$ and $\log R$ in the set used it is difficult to construct unbiased models.

- Use a stochastic random-vibration approach to find theoretical equations for estimating PGA that include the effect of local site conditions as distance-dependent terms. Using the results from this analysis construct equation based on the observed PGAs. Try including terms for $S_1$, $S_2$, $S_5$, $S_6$ and corresponding $\log R$ terms for each site type but iterate to retain only the significant terms.

- Fix magnitude scaling ($0.36M$) and anelastic attenuation ($0.002R$). Do not try to optimise the fit other than using fixed values similar to those given by the stochastic analysis.

- Note that anelastic coefficient may be too low but it produces an acceptable geometric spreading term.

- Note that because Moho critical reflections can increase amplitudes beyond about 50 km the effects of anelastic or geometric attenuation may be masked.

- Allowing all the coefficients in the equation to be free produces a smaller magnitude scaling coefficient, a smaller geometric spreading coefficient, and a non-significant anelastic attenuation term.
- Note that data from $S_5$ and $S_6$ are sparse.
- Compare estimated PGAs with data from within small magnitude ranges. Find that PGAs from Morgan Hill earthquake are overestimated, which believe is due to the unilateral rupture of this earthquake masking the effect of the local site conditions.

## 2.95 Stamatovska and Petrovski (1991)

- Ground-motion model is:

$$\text{Acc} = b_1 \exp(b_2 M)(R_h + c)^{b_3}$$

Acc is in cm/s$^2$, $b_1 = 534.355$, $b_2 = 0.46087$, $b_3 = -1.14459$, $c = 25$ and $\sigma_{\ln \text{Acc}} = 0.72936$.

- Data from 141 different sites, which are considered to have average soil conditions.
- Data from Yugoslavia (23 earthquakes), Italy (45 earthquakes), northern Greece (3 earthquakes), Romania (1 earthquake), Mexico (1 earthquake) and the USA (5 earthquakes). Select earthquakes to have range of magnitudes and focal depths.
- Data processed using standard procedure.
- Conduct Pearson $\chi^2$ and Kolmogorov-Smirnov tests to test acceptability of log-normal assumption using a 5% significance level. Conclude that assumption is justified.
- Note the strong influence of the data used on results and the need to improve it.

## 2.96 Abrahamson and Youngs (1992)

- Ground-motion model is:

$$\ln y = a + bM + d \ln(r + c) + eF$$

where $a = 0.0586$, $b = 0.696$, $c = 12.0$, $d = -1.858$, $e = 0.205$, $\sigma = 0.399$ (intra-event) and $\tau = 0.201$ (inter-event) (units of $y$ are not given but probably g).

- $F$ is fault type (details not given).
- Develop new algorithm for one-stage maximum-likelihood regression, which is more robust than previous algorithms.

## 2.97 Ambraseys et al. (1992)

- Ground-motion model is:

$$\begin{aligned}\log(a) &= c_1 + c_2 M + c_3 r + c_4 \log r \\ r &= (d^2 + h_0^2)^{\frac{1}{2}}\end{aligned}$$

where $a$ is in g, $c_1 = -1.038$, $c_2 = 0.220$, $c_3 = -0.00149$, $c_4 = -0.895$, $h_0 = 5.7$ and $\sigma = 0.260$.

- Investigate equations of PML (1982) and PML (1985) using criteria:

1. Is the chosen data set of earthquake strong-motion records suitable to represent the UK seismic environment?
2. Are the associated seismological and geophysical parameters used in these reports reliable and consistent?
3. Is the methodology used to derive attenuation laws and design spectra from the data set reliable?

- Investigate effect of different Ground-motion model, one and two-stage regression technique, record selection technique and recalculation of associated parameters. Find these choice cause large differences in predictions.
- Coefficients given above are for PML (1985) data with recalculated magnitudes and distances and addition of extra records from some earthquakes.

## 2.98 Huo and Hu (1992)

- Ground-motion model is[10]:

$$\ln Y = a_1 + a_2 M + a_3 \ln[R + a_4 \exp(a_5 M)]$$

where $Y$ is in gal, $a_1 = 0.1497$, $a_2 = 1.9088$, $a_3 = -2.049$, $a_4 = 0.1818$ and $a_5 = 0.7072$ ($\sigma$ is unknown).

- Use macroseismic intensities and strong-motion data to derive model. Details unknown.
- There is another model by these authors Huo and Hu (1991) (see Section 2.89) to which this model is probably similar.

## 2.99 Kamiyama et al. (1992) & Kamiyama (1995)

- Ground-motion model is (note that there is a typographical error in Kamiyama et al. (1992); Kamiyama (1995) because $r_t$ has been replaced by $r_c$ in equations):

$$\begin{aligned}
\log_{10} a_{\max} &= -1.64 R_0 + b_1 R_1 + b_2 R_2 + c_a + \sum_{i=1}^{N-1} A_i S_i \\
R_0 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ \log_{10} r - \log_{10} r_c & \text{for} \quad r > r_t \end{cases} \\
R_1 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ 1 & \text{for} \quad r > r_t \end{cases} \\
R_2 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ M & \text{for} \quad r > r_t \end{cases}
\end{aligned}$$

where $S_i = 1$ for $i$ station, $S_0 = 0$ otherwise, $a_{\max}$ is in $\mathrm{cm/s^2}$, $b_1 = -1.164$, $b_2 = 0.358$, $c_a = 2.91$, $r_c = 5.3\,\mathrm{km}$ and $\sigma = 0.247$ ($A_i$ given in publications but not reported here due to lack of space).

- Instrument correct records and filter with pass band between 0.24 and 11 Hz.
- Model individual soil conditions at each site as amplification factors, $\mathrm{AMP}_i$, as described by Kamiyama and Yanagisawa (1986).

[10] In the source for this model (Zhang et al., 1999) there is an additional $-2.049M^2$ term but as this is the same coefficient as the geometric decay term and with this quadratic magnitude term the model predictions very small PGAs it is thought that it is a typographic mistake.

- Most records are from hypocentral distances between 30 and 200 km.
- Focal depths between 0 and 130 km.
- Models peak ground accelerations independent of magnitude and distance in a fault zone, $r_t$, where $r_t = r_c 10^{(b_1+b_2M)/1.64}$.
- Constrain decay with distance in far field to $-1.64$ using results from other studies to avoid problems due to correlation between $M$ and $\log_{10} r$.
- Use trial and error method to find $r_c$ so that resulting values of $r_t$ are consistent with empirical estimates of fault length from past studies.
- Also give expression using shortest distance to fault plane (rupture distance), $R$, by replacing the expression for $r \leq r_c$ and $r > r_c$ by one expression given by replacing $r$, hypocentral distance, by $R + r_c$ in expression for $r > r_c$. This gives PGA independent of magnitude at distance $R = 0$ km.
- Note that use of $r_{hypo}$ is not necessarily best choice but use it due to simplicity.
- Check residual plots; find no trends so conclude adequate from statistical point of view.

## 2.100 Sigbjörnsson and Baldvinsson (1992)

- Ground-motion model is:

$$\begin{aligned} \log A &= \alpha + \beta M - \log R + bR \\ \text{with: } R &= \sqrt{d^2 + h^2} \end{aligned}$$

  where $A$ is in g, for average horizontal PGA and $4 < M < 6$ $\alpha = -1.98$, $\beta = 0.365$, $b = -0.0039$ and $\sigma = 0.30$, for larger horizontal PGA and $4 < M < 6$ $\alpha = -1.72$, $\beta = 0.327$, $b = -0.0043$ and $\sigma = 0.30$ and for both horizontal PGAs and $2 < M < 6$ $\alpha = -2.28$, $\beta = 0.386$, $b = 0$ and $\sigma = 0.29$.
- Find that Icelandic data does not fit other published relations.
- Find equation using only records with $M \geq 4.0$, $h$ equal to focal depth and both the horizontal components.
- Find equation using only records with $M \geq 4.0$, $h$ equal to focal depth and larger horizontal component.
- Also repeated with all data. Anelastic coefficient constrained to zero because otherwise positive.
- Also done with $h$ free.
- Note that large earthquakes have $h \approx 10$ km while small events have $h \approx 5$ km.

## 2.101 Silva and Abrahamson (1992)

- Ground-motion model is:

$$\ln \text{pga} = c_1 + 1.2M + c_3 \ln(r + 20) + 0.25F$$

  where pga is in g, $c_1 = -3.27$, $c_3 = -1.79$ and $\sigma_{total} = 0.46$ for deep soil and $c_1 = -3.56$, $c_3 = -1.67$ and $\sigma_{total} = 0.46$ for rock/shallow soil.
- Originally use five site classes (chosen based on site response analyses using broad categories and generic site profiles):

1. Rock. 66 records
2. Shallow soil ($< 250$ ft. 6 records.)
3. Intermediate depth soil (250–1000 ft). 2 records.
4. Deep soil ($> 1000$ ft). 51 records.
5. Alluvium of unknown depth. 10 records.

but insufficient records in shallow and intermediate classes to evaluate separately so combine rock and shallow classes and intermediate, deep and unknown depth categories to leave two classes: $< 250$ ft and $> 250$ ft.

- Use two faulting mechanisms:

$F = 0$ Strike-slip

$F = 1$ Reverse or oblique

- Process data by: 1) interpolation of uncorrected unevenly sampled records to 400 samples per second; 2) frequency domain low-pass filtering using a causal five-pole Butterworth filter with corner frequencies selected based on visual examination of Fourier amplitude spectrum; 3) removal of instrument response; 4) decimation to 100 or 200 samples per second depending on low-pass filter corner frequencies; and 5) application of time-domain baseline correction, using polynomials of degrees zero to ten depending on integrated displacements, and final high-pass filter chosen based on integrated displacements that is flat at corner frequency and falls off proportional to frequency on either side, which is applied in the time domain twice (forward and backwards) to result in zero phase shift.
- Note that due to limited magnitude range of data, magnitude dependence is not well constrained nor is dependency on mechanism. Hence these coefficients are fixed based on previous studies.
- Plot residuals w.r.t. distance. Find slight increase at 70–100 km. To test if due to Moho bounce repeat regression assuming functional form that is flat between 70 and 90 km but this produced a smaller likelihood. Conclude that data does not support significant flattening at $< 100$ km.
- Note that model is preliminary.

## 2.102 Taylor Castillo et al. (1992)

- Ground-motion model is:

$$\ln(A) = a_1 + a_2 M_s + a_3 \ln(R) + a_4 R$$

where $A$ is in m/s$^2$, $a_1 = 0.339$, $a_2 = 0.455$, $a_3 = -0.67$, $a_4 = -0.00207$ and $\sigma = 0.61$.

## 2.103 Tento et al. (1992)

- Ground-motion model is:

$$\begin{aligned} \ln \mathrm{PGA} &= b_1 + b_2 M + b_3 R - \ln R \\ \text{where } R &= (d^2 + h^2)^{1/2} \end{aligned}$$

where PGA is in gal, $b_1 = 4.73$, $b_2 = 0.52$, $b_3 = -0.00216$, $h$ is mean focal depth of group into which each earthquake is classified and $\sigma = 0.67$.

- Most records from distances between 10 km and 40 km.

- Correction technique based on uniform Caltech correction procedure. Most (125) were automatically digitised, rest were manually digitised. Roll-on and cutoff frequencies of Ormsby filter were selected by adopting a record dependent criteria. Cutoff frequencies range between 0.13 Hz and 1.18 Hz with a median of 0.38 Hz.
- Records included from analysis were from free-field stations. Excluded those not complete (e.g. started during strong-motion phase). Excluded those with epicentral distances greater than that of first nontriggered station.
- Note relatively small influence of form of equation adopted although two step method seems preferable.
- Note correction procedure plays a relevant role in analysis.
- Note using $d$ instead of $R$ causes greater scatter in data.
- Note moderate underestimation for low magnitude in near field and for high magnitude in far field.

## 2.104 Theodulidis and Papazachos (1992)

- Ground-motion model is:
$$\ln Y = C_1 + C_2 M + C_3 \ln(R + R_0) + C_4 S$$
where $Y$ is in $\mathrm{cm/s^2}$, $C_1 = 3.88$, $C_2 = 1.12$, $C_3 = -1.65$, $R_0 = 15$, $C_4 = 0.41$ and $\sigma = 0.71$.
- Use two site categories (mean opinion of seven specialists who classified sites into three categories: soft alluvium, crystalline rock and intermediate):
  - S=1 Rock: 34+4 records. Japanese sites have diluvium with depth to bedrock $H < 10$ m. Alaskan sites have PGV/PGA $\approx 66 \pm 7\,\mathrm{cms^{-1}g^{-1}}$.
  - S=0 Alluvium: 71+12 records. Japanese sites have diluvium $H > 10$ m or alluvium $H < 10$ m, and alluvium with $H < 25$ m as well as soft layers with thickness $< 5$ m. Alaskan sites have PGV/PGA $> 66 \pm 7\,\mathrm{cms^{-1}g^{-1}}$.
- 70% of records from ground level or basement of buildings with two storeys or less. Rest from buildings with up to eight storeys.
- Some (16) Greek records manually digitized and baseline corrected, some (22) Greek records manually digitized and filtered and rest of the Greek records automatically digitized and filtered.
- Due to lack of data for $7.0 < M_s < 7.5$ include shallow subduction data from other regions with similar seismotectonic environments (Japan and Alaska) using criteria i) depth $< 35$ km, ii) $M_w$ or $M_{\mathrm{JMA}}$ between 7.0 and 7.5, iii) instruments triggered before S-wave, iv) free-field recording, v) surface geology known at station. Note $M_s$, $M_w$ and $M_{\mathrm{JMA}}$ are equivalent between 6.0 and 8.0.
- Focal depths between 0 km (13 km) and 18 km (31 km).
- Most data from $M_s < 5.5$ and from $R < 50$ km.
- Use four step regression procedure. First step use only Greek data from $M_s > 6.0$ ($9 \leq R \leq 128$ km, 14 records) for which distances are more reliable (use both hypocentral and epicentral distance find epicentral distance gives smaller standard deviation) to find geometrical coefficient $C_{31}$ and $R_0$ ignoring soil conditions. Next find constant ($C_{12}$), magnitude ($C_{22}$) and soil ($C_{42}$) coefficients using all data. Next recalculate geometrical ($C_{33}$) coefficient using only Greek data with $M_s > 6.0$. Finally find constant ($C_{14}$), magnitude ($C_{24}$) and soil ($C_{44}$) coefficients using all the data; final coefficients are $C_{14}$, $C_{24}$, $C_{33}$ and $C_{44}$.
- Plot residuals against $M_s$ and $R$ and find no apparent trends. Find residuals (binned into 0.2 intervals) fit normal distribution.

## 2.105 Abrahamson and Silva (1993)

- Ground-motion model is:

$$\begin{aligned}\ln \mathrm{pga}_{rock} &= \theta_1 + \theta_2 M + \theta_3 \ln[r + \exp(\theta_4 + \theta_5 M)] + \theta_{11} F_1 \\ \ln \mathrm{pga}_{soil} &= \theta_6 + \theta_7 M + \theta_8 \ln[r + \exp(\theta_9 + \theta_{10})] + \theta_{11} F_1\end{aligned}$$

  where pga is in g, $\theta_1 = -4.364$, $\theta_2 = 1.016$, $\theta_3 = -1.285$, $\theta_4 = -3.34$, $\theta_5 = 0.79$, $\theta_6 = -8.698$, $\theta_7 = 1.654$, $\theta_8 = -1.166$, $\theta_9 = -6.80$, $\theta_{10} = 1.40$, $\theta_{11} = 0.17$, $\sigma = 0.44$, $\tau = 0.00$ (sic) and $\sigma_{total} = 0.44$.

- Originally use five site classes (chosen based on site response analyses using broad categories and generic site profiles):

  1. Rock. 78 records
  2. Shallow soil ($< 250$ ft. 25 records.)
  3. Intermediate depth soil (250–1000 ft). 5 records.
  4. Deep soil ($> 1000$ ft). 62 records.
  5. Alluvium of unknown depth. 31 records.

  but insufficient records in shallow and intermediate classes to evaluate separately so combine rock and shallow classes and intermediate, deep and unknown depth categories to leave two classes: $< 250$ ft and $> 250$ ft.

- Use two faulting mechanisms:

$F_1 = 0$ Strike-slip or normal

$F_1 = 1$ Reverse

- Based on Silva and Abrahamson (1992) (see Section 2.101.

- Only use Nahanni records for spectral ordinates and not PGA because more representative of eastern US rock than western US rock.

## 2.106 Boore et al. (1993), Boore et al. (1997) & Boore (2005)

- Ground-motion model is:

$$\begin{aligned}\log Y &= b_1 + b_2(\mathbf{M} - 6) + b_3(\mathbf{M} - 6)^2 + b_4 r + b_5 \log r + b_6 G_B + b_7 G_C \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  where $Y$ is in g, for randomly-oriented horizontal component (or geometrical mean) $b_1 = -0.105$, $b_2 = 0.229$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.778$, $b_6 = 0.162$, $b_7 = 0.251$, $h = 5.57$ and $\sigma = 0.230$ (for geometrical mean $\sigma = 0.208$) and for larger horizontal component $b_1 = -0.038$, $b_2 = 0.216$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.777$, $b_6 = 0.158$, $b_7 = 0.254$, $h = 5.48$ and $\sigma = 0.205$.

- Due to an error in Equation (3) of Boore et al. (1994a) and Equation (6) of Boore et al. (1997) $\sigma_c$ reported in Boore et al. (1994a, 1997) are too large by a factor of $\sqrt{2}$. Therefore correct values of standard deviations are: $\sigma_f = 0.431$, $\sigma_c = 0.160$, $\sigma_r = 0.460$, $\sigma_s = 0.184$ and $\sigma_{\ln Y} = 0.495$.

- Use three site categories:

Class A $V_{s,30} > 750$ m/s, some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 0, G_C = 0$, 48 records

Class B $360 < V_{s,30} \leq 750$ m/s, some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 1, G_C = 0$, 118 records.

Class C $180 < V_{s,30} \leq 360$ m/s,some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 0, G_C = 1$, 105 records.

where $V_{s,30}$ is average shear-wave velocity to 30 m.

- Define shallow earthquakes as those for which fault rupture lies mainly above a depth of 20 km.
- Peak acceleration scaled directly from accelerograms, in order to avoid bias from sparsely sampled older data.
- Do not use data from structures three storeys or higher, from dam abutments or from base of bridge columns. Do not use data from more than one station with the same site condition within a circle of radius 1 km (note that this is a somewhat arbitrary choice).
- Exclude records triggered by S wave.
- Do not use data beyond cutoff distance which is defined as equal to lesser of distance to the first record triggered by S wave and closest distance to an operational nontriggered instrument.
- Note that little data beyond 80 km.
- Due to positive values of $b_4$ when $b_5 = -1$, set $b_4$ to zero and let $b_5$ vary.

## 2.107 Campbell (1993)

- Ground-motion model is:

$$\begin{aligned}\ln(Y) &= \beta_0 + a_1 M + \beta_1 \tanh[a_2(M - 4.7)] - \ln(R^2 + [a_3 \exp(a_1 M)]^2)^{1/2} \\ &\quad - (\beta_4 + \beta_5 M)R + a_4 F + [\beta_2 + a_5 \ln(R)]S + \beta_3 \tanh(a_6 D)\end{aligned}$$

where $Y$ is in g, $\beta_0 = -3.15$, $\beta_1 = 0$, $\beta_2 = 0$, $\beta_3 = 0$, $\beta_4 = 0.0150$, $\beta_5 = -0.000995$, $a_1 = 0.683$, $a_2 = 0.647$, $a_3 = 0.0586$, $a_4 = 0.27$, $a_5 = -0.105$, $a_6 = 0.620$ and $\sigma = 0.50$.

- Uses two site categories:

S=0 Quaternary deposits (soil).

S=1 Tertiary or older sedimentary, metamorphic, and igneous deposits (rock).

Also includes depth to basement rock ( km), $D$.

- Uses two fault mechanisms:

F=0 Strike-slip.

F=1 Reverse, reverse-oblique, thrust, and thrust-oblique.

Recommends use $F = 0.5$ for normal or unknown mechanisms.

- Gives estimates of average minimum depths to top of seismogenic rupture zone.
- Uses stochastic simulation model to find anelastic coefficients $\beta_4$ and $\beta_5$ because uses only near-source records.
- Uses weighted nonlinear regression method based on Campbell (1981) to control dominance of well-recorded earthquakes.

## 2.108 Dowrick and Sritharan (1993)

- Ground-motion model is:

$$\begin{aligned} \log y &= \alpha + \beta\mathbf{M} - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2} \end{aligned}$$

  Coefficients are unknown.

- Data from earthquakes occurring between 1987 and 1991.

## 2.109 Gitterman et al. (1993)

- Ground-motion model is:

$$\log Y = a + bM - \log\sqrt{r^2 + h^2} - cr$$

  where $Y$ is in g, $a = -5.026$, $b = 0.989$, $h = 2.7$ and $c = 0.00443$ ($\sigma$ not reported).

- Some data from velocity sensors have been used, after differentiation, to increase amount of data at moderate and long distances.

## 2.110 McVerry et al. (1993) & McVerry et al. (1995)

- Ground-motion model is (Type A):

$$\log_{10}\mathrm{PGA} = a + bM_w - cr - d\log_{10} r$$

  where $PGA$ is in g, $a = -1.434 \pm 0.339$, $b = 0.209 \pm 0.036$, $c = 0.00297 \pm 0.00093$, $d = -0.449 \pm 0.186$ and $\sigma = 0.276$.

- Find that ground motions in previous earthquakes were significantly higher than the motions predicted by equations derived from W. N. America data.

- Only include records from earthquakes for which $M_w$ is known because of poor correlation between $M_L$ and $M_w$ in New Zealand.

- Focal depths, $h_e \leq 122$ km.

- 140 records from reverse faulting earthquakes.

- Divide records into crustal and deep earthquakes.

- Only use records for which reliable event information is available, regardless of their distances with respect to untriggered instruments.

- Only use records which triggered on the P-wave.

- Also derive separate equations for shallow, upper crustal earthquakes ($h_e \leq 20$ km, 102 records, $5.1 \leq M_w \leq 7.3$, $13 \leq r \leq 274$ km) and crustal earthquakes ($h_e \leq 50$ km, 169 records, $5.1 \leq M_w \leq 7.3$, $13 \leq r \leq 274$ km).

- Also try equations of form: $\log_{10}\text{PGA} = a+bM_w-d\log_{10}r$ (Type B) and $\log_{10}\text{PGA} = a+bM_w-cr-\log_{10}r$ (Type C) because of large standard errors and highly correlated estimates for some of the coefficients (particularly $c$ and $d$). Find Type B usually gives much reduced standard errors for $d$ than Type A model and have lowest correlation between coefficients, but are sceptical of extrapolating to distance ranges shorter and longer than the range of data. Type C usually has similar standard deviations to Type A. Find that usually all three models give similar predictions over distance range of most of the data, but sometimes considerably different values at other distances.
- Derive separate equations for reverse faulting earthquakes only and usually find similar results to the combined equations.
- Find deep earthquakes produce significantly higher PGAs than shallow earthquakes for similar $r$.

## 2.111 Midorikawa (1993a)

- Ground-motion model is:

$$\log y = c_1 M - \log(d + c_2 10^{c_1 M}) + c_3 d + c_4$$

where $y$ is in $\text{cm/s}^2$, $c_1 = 0.42$, $c_2 = 0.025$, $c_3 = -0.0033$ and $c_4 = 1.22$ ($\sigma$ unknown).

## 2.112 Quijada et al. (1993)

- Ground-motion model is unknown.
- Used by Tanner and Shedlock (2004).

## 2.113 Singh et al. (1993)

- Ground-motion model is:

$$\begin{aligned}\log(A) &= a_1 + a_2 M + a_3 \log[G(R_0)] + a_4 R_0 \\ \text{where } R_0^2 &= R^2 + (\mathrm{e}^{a_5 M})^2 \\ G(R_0) &= R_0 \text{ for: } R_0 \leq 100\,\text{km} \\ \text{and: } G(R_0) &= \sqrt{(100 R_0)} \text{ for: } R_0 > 100\,\text{km}\end{aligned}$$

where $A$ is in $\text{cm/s}^2$, $a_1 = 2.74$, $a_2 = 0.212$, $a_3 = -0.99$, $a_4 = -0.000943$, $a_5 = 0.47$ and $\sigma = 0.26$.

- Use same data as Taylor Castillo et al. (1992).
- Employ several different regression techniques.
- Select equation found by Bayesian method (given above) for hazard study.

## 2.114 Steinberg et al. (1993)

- Ground-motion model is:

$$\log(A_{\max}) = a_1 M + a_2 \log(D + a_3) + a_4$$

where $A_{\max}$ is in $\text{cm/s}^2$, $a_1 = 0.54$, $a_2 = -1.5$, $a_3 = 10$ and $a_4 = 1.25$ ($\sigma$ not reported).

## 2.115 Sun and Peng (1993)

- Ground-motion model is:

$$\ln A = a + bM - c\ln(R + h) + dT_s$$

  where $A$ is in cm/s$^2$, $a = 7.7$, $b = 0.49$, $c = 1.45$, $d = 0.19$, $h = 25.0$ and $\sigma = 0.46$.

- Model soil using its fundamental period of the overburden soil, $T_s$. Thickness of deposit defined as depth to rock base, defined either as $V_s > 800$ m/s or when ratio of shear-wave velocity in $i$th layer to shear-wave velocity in $i-1$th layer is greater than 2 (only calculate period to 100 m because only have important effect on structure). For outcropping rock, $T_s = 0.05$ s.

- Eight distance intervals used for weighting, five 10 km wide up to 50 km, 50–69.9 km, 70–99.9 km and 100–200 km. Within each interval each earthquake received equal weight, inversely proportional to number of records from that earthquake in interval.

- Use resolve accelerations in direction, $\theta$, which gives largest value. Find scatter is lower than for larger horizontal component.

- Many (27) earthquakes only have one record associated with them and 60 records are from San Fernando.

## 2.116 Ambraseys and Srbulov (1994)

- Ground-motion model is:

$$\begin{aligned}\log a &= b_1 + b_2 M_s + b_3 r + b_4 \log r \\ \text{where } r &= (d^2 + h_0^2)^{0.5}\end{aligned}$$

  where $a$ is in g, $b_1 = -1.58$, $b_2 = 0.260$, $b_3 = -0.00346$, $b_4 = -0.625$, $h_0 = 4$ and $\sigma = 0.26$.

- Do not consider effect of site geology but expect it to be statistically insignificant for PGA.

- Focal depths, $h < 25$ km. Mean focal depth is $10 \pm 4$ km.

- Mean magnitude of earthquakes considered is $6.0 \pm 0.7$.

- Most records from $d < 100$ km.

- Only use records with PGA $> 0.01$ g.

- Records mainly from SMA-1s located at ground floor or in basements of buildings and structures and free-field sites regardless of topography.

- Records from thrust earthquakes (46% of total), normal earthquakes (26%) and strike-slip earthquakes (28%).

- Baseline correct and low-pass filter records. Select cut-offs from visual examination of Fourier amplitude spectrum of uncorrected time-histories and choose cut-off below which the Fourier amplitude spectrum showed an unrealistic energy increase due to digitization noise and instrument distortions.

- Find (from reprocessing about 300 records) that with very few exceptions differences in PGAs arising from different methods of processing are not significant, remaining below 3%.

- Also derive equation which includes focal depth explicitly.

## 2.117 Boore et al. (1994a) & Boore et al. (1997)

- Based on Boore et al. (1993) see Section 2.106
- Ground-motion model is:

$$\begin{aligned}\log Y &= b_1 + b_2(\mathbf{M}-6) + b_3(\mathbf{M}-6)^2 + b_4 r + b_5 \log r + b_V(\log V_S - \log V_A)\\ \text{where } r &= (d^2+h^2)^{1/2}\end{aligned}$$

  where $Y$ is in g, $b_1$ to $b_5$, $h$ and $\sigma$ are same as for Boore et al. (1993) (see Section 2.106) and for randomly oriented component $b_V = -0.371$ and $V_A = 1400$ and for larger horizontal component $b_V = -0.364$ and $V_A = 1390$.

- Model site effect as a continuous function of average shear-wave velocity to 30 m deep, $V_S$.
- Coefficients $b_1$, $b_2$, $b_3$,$b_4$ and $b_5$ from Boore et al. (1993).
- Find no basis for different magnitude scaling at different distances.
- Find evidence for magnitude dependent uncertainty.
- Find evidence for amplitude dependent uncertainty.
- Find marginal statistical significance for a difference between strike-slip (defined as those with a rake angle within 30° of horizontal) and reverse-slip motions but do not model it. Modelled in Boore et al. (1994b) (by replacing $b_1$ by $b_{SS}G_{SS} + b_{RS}G_{RS}$ where $G_{SS} = 1$ for strike-slip shocks and 0 otherwise and $G_{RS} = 1$ for reverse-slip shocks and 0 otherwise) and reported in Boore et al. (1997). Coefficients for randomly oriented horizontal component are: $b_{SS} = -0.136$ and $b_{RS} = -0.051$[11].
- Analysis done using one and two-stage maximum likelihood methods; note that results are very similar.
- Earthquakes with magnitudes below 6.0 are poorly represented.
- Note that few Class A records.
- Note that $V_S$ does not model all the effects of site because it does not model effect of the thickness of attenuating material on motion.
- Note that ideally would like to model site in terms of average shear-wave velocity to one-quarter wavelength.
- Note lack measurements from distances greater than 100 km so that weak-motion data from seismographic stations maybe should be used.
- Note that use of cutoff distances independent of geology or azimuth may be over strict but it is simple and objective. Note that methods based on data from nontriggered stations or using seismogram data may be better.

## 2.118 El Hassan (1994)

- Ground-motion model is:

$$\log a = C_1 + C_2 M + C_3 \log(R + C_4)$$

  where $a$ is in cm/s$^2$, $C_1 = 8.65$, $C_2 = 0.71$, $C_3 = -1.6$, $C_4 = 40$ and $\sigma = 0.6$.

- May not be an empirical GMPE but derived through a intensity-PGA relations.

[11] These are taken from Table 8 of Boore et al. (1997) which uses natural logarithms so they were converted into terms of logarithms to base 10.

## 2.119 Fat-Helbary and Ohta (1994)

- Ground-motion model is:

$$\ln A = a_1 M + a_2 \ln \Delta + a_3$$

where $A$ is in gal, $a_1 = 1.812$, $a_2 = -0.796$, $a_3 = -3.616$ and $\sigma = 0.558$.

- Use velocity data recorded at GRW. Differentiate to acceleration. Use frequency range 1 to 6 Hz.

## 2.120 Fukushima et al. (1994) & Fukushima et al. (1995)

- Ground-motion model is:

$$\log Y = aM + bX - \log X + \sum \delta_i c_i$$

where $Y$ is in cm/s$^2$, $\delta_i = 1$ at $i$th receiver and 0 otherwise, for horizontal PGA $a = 0.918$ and $b = -0.00846$ ($\sigma$ not given) and for vertical PGA $a = 0.865$ and $b = -0.00741$ ($\sigma$ not given). $c_i$ given in paper but are not reported here due to lack of space.

- Data from three vertical arrays in Japan so predictions at surface and at different depths down to 950 m.
- Different definition of $M_{\mathrm{JMA}}$ for focal depths > 60 km so exclude such data. Focal depths between 2 and 60 km.
- Exclude data from earthquakes $M < 5.0$ because errors are larger for smaller events.
- Exclude data for which predicted, using a previous attenuation relation, PGV < 0.1 cm/s in order to find precise attenuation rate.
- Most data from earthquakes with $M \leq 6.0$ and most from $X \leq 100$ km.
- Records low-pass filtered with cutoff frequency 25 Hz for records from 2 sites and 30 Hz for records from 1 site.
- Use two-stage method because positive correlation between $M$ and $X$. Also apply one step; find it is biased and two-stage method is most effective method to correct bias.
- Check residuals (not shown) against $M$ and $X$ find no remarkable bias.

## 2.121 Lawson and Krawinkler (1994)

- Ground-motion model is:

$$\log Y = a + b(M-6) + c(M-6)^2 + d\sqrt{R^2+h^2} + e \log \sqrt{R^2+h^2} + fS_B + gS_C$$

- Use three site categories:

  A Firm to hard rock: granite, igneous rocks, sandstones and shales with close to widely spaced fractures, $750 \leq V_{s,30} \leq 1400$ m/s $\Rightarrow S_B = 0$, $S_C = 0$.

  B Gravelly soils and soft to firm rocks: soft igneous rocks, sandstones and shales, gravels and soils with > 20% gravel, $360 \leq V_{s,30} \leq 750$ m/s $\Rightarrow S_B = 1$ , $S_C = 0$.

  C Stiff clays and sandy soils: loose to very dense sands, silt loams and sandy clays, and medium stiff to hard clay and silty clays ($N > 5$ blows/ft), $180 \leq V_{s,30} \leq 360$ m/s $\Rightarrow S_B = 0$, $S_C = 1$.

- For shallow (fault rupture within 20 km of earth surface) crustal earthquakes.

- Use free-field records. Records not significantly contaminated by structural feedback, excludes records from structures with >2 stories.
- Chooses Ground-motion model because of simplicity. Note that other possible forms of equation may have significant effect on results, but including more terms complicates relationships without reducing variability.
- Do not give coefficients only predictions.

## 2.122 Lungu et al. (1994)

- Ground-motion model is:

$$\ln \mathrm{PGA} = c_1 + c_2 M_w + c_3 \ln R + c_4 h$$

where PGA is in g, $c_1 = -2.122$, $c_2 = 1.885$, $c_3 = -1.011$, $c_4 = -0.012$ and $\sigma = 0.502$.
- Focal depth, $h$, between 79 and 131 km.
- Consider to separate areas of 90° to investigate variation with respect to azimuth; find azimuthal dependence.
- Find individual attenuation equations for three earthquakes. Note faster attenuation for smaller magnitude and faster attenuation for deeper events.

## 2.123 Musson et al. (1994)

- Ground-motion model is (model 1):

$$\ln A = a + bM - \ln(R) + dR$$

where $A$ is in cm/s$^2$, $a = 2.11$, $b = 1.23$ and $d = -0.014$.

Ground-motion model is (model 2):

$$\begin{aligned} \ln A &= c_1 + c_2 M + c_4 R + \ln G(R, R_0) \\ \text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \leq R_0 \\ \text{and: } G(R, R_0) &= R_0^{-1} \frac{R_0}{R}^{5/6} \quad \text{for} \quad R > R_0 \end{aligned}$$

where $A$ is in m/s$^2$, $c_1$ and $c_2$ are from Dahle et al. (1990b), $c_4 = -0.0148$ and $\sigma$ is recommended as 0.65 (although this is from an earlier study and is not calculated in regression).
- Use data from Canada (Saguenay earthquake and Nahanni sequence) and Belgium (Roermond earthquake).
- Focal depths, $h$, between 1 and 30 km with average 14.4 km.
- Assume peak ground acceleration equals pseudo-acceleration at 30 Hz due to few unclipped horizontal UK records and because instrument response of UK instruments means records unreliable above 30 Hz. Use only digital VME records for 30 Hz model.
- Note poorness of data due to UK data and other data being widely separated thus preventing a comparison between the two sets. Also means straightforward regression methods would be inadequate as there would be little control on shape of curves derived.
- Note earlier models over predict UK data.

- Use two-stage least squares method to give model 1. First stage fit only UK/Belgian data to find $b$, in second stage use this value of $b$ and use all data to find $a$ and $d$.

- Do not recommend model 1 for general use because too influenced by limitations of data to be considered reliable. Canadian data probably insufficient to anchor curves at small $R$/large $M$ and extremely high Saguenay earthquake records carry undue weight.

- Use model of Dahle et al. (1990b) to get model 2. Fix $c_1$ and $c_2$ to those of Dahle et al. (1990b) and find $c_4$. Prefer this model.

## 2.124 Radu et al. (1994), Lungu et al. (1995a) & Lungu et al. (1996)

- Ground-motion model is:

$$\ln \mathrm{PGA} = c_1 + c_2 M + c_3 \ln R + c_4 h$$

  where PGA is in $\mathrm{cm/s^2}$, $c_1 = 5.432$, $c_2 = 1.035$, $c_3 = -1.358$, $c_4 = -0.0072$ and $\sigma = 0.397$.

- Sites have different soil conditions, some medium and stiff sites and some very soft soil sites.

- Use some records from Moldova and Bulgaria.

- Focal depths, $h$, between 91 and 133 km.

- Records from free-field or from basements of buildings.

- Originally include data from a shallower (focal depth 79 km), smaller magnitude ($M_L = 6.1$, $M_w = 6.3$) earthquake with shorter return period than other three earthquakes, but exclude in final analysis.

- Originally do attenuation analysis for two orthogonal directions N45E (which is in direction of fault plane) and N35E (which is normal to fault plane). From this define 3 90° circular sectors based roughly on tectonic regions, and calculate attenuation relations for each of these sectors as well as for all data. Find azimuthal dependence.

- Remove 1 to 3 anomalous records per sector.

- Remove the only record from the 4/3/1977 earthquake, because it has a strong influence on results, and repeat analysis using model $\ln \mathrm{PGA} = b_1 + b_2 M + b_3 \ln R$, find lower predicted PGA.

- Find slower attenuation in direction of fault plane compared with normal to fault plane.

- Find faster attenuation and larger standard deviation (by finding attenuation equations for two different earthquakes) for deeper focus and larger magnitude shocks.

## 2.125 Ramazi and Schenk (1994)

- Ground-motion model is:

$$\begin{aligned} a_h &= a_1 (a_2 + d + H)^{a_5} \exp(a_6 M_s) \\ H &= |d - a_3|^{a_4} \end{aligned}$$

  where for horizontal peak acceleration $a_h$ is in $\mathrm{cm/s^2}$, $a_1 = 4000$, $a_2 = 20$, $a_3 = 16$ and $a_4 = 0.63$ for soil sites $a_5 = -2.02$ and $a_6 = 0.8$ and for rock sites $a_5 = -2.11$ and $a_6 = 0.79$ ($\sigma$ not given). For vertical peak acceleration on soil sites $a_v$ is in $\mathrm{cm/s^2}$ $a_1$ to $a_3$ are same as horizontal and $a_4 = 0.48$, $a_5 = -1.75$ and $a_6 = 0.53$ ($\sigma$ not given).

- Use two site categories (from original of four) for which derive two separate equations:
  1. Rock: mainly category (2) a) loose igneous rocks (tuffs), friable sedimentary rocks, foliated metamorphic rock and rocks which have been loosened by weathering, b) conglomerate beds, compacted sand and gravel and stiff clay (argillite) beds where soil thickness $> 60$ m from bed rock. 29 records.
  2. Soil: mainly category (4) a) soft and wet deposits resulting from high level of water table, b) gravel and sand beds with weak cementation and/or uncementated unindurated clay (clay stone) where soil thickness $> 10$ m from bed rock. 54 records.
- Focal depths between 10 and 69 km.
- Find equations using hypocentral distance but find that poor fit for Rudbar (Manjil) earthquake ($M_s = 7.7$) which conclude due to use of hypocentral rather than rupture distance.
- Find equations using rupture distance[12] for Rudbar (Manjil) earthquake and hypocentral distances for other earthquakes. Coefficients given above. They conclude that it is important that equations are derived using rupture distance rather than hypocentral distance because most destructive earthquakes rupture surface in Iran.
- Do not know physical meaning of $H$ term but find that it causes curves to fit data better.

## 2.126 Xiang and Gao (1994)

- Ground-motion model is:
$$A_p = a e^{bM_s}(R + \Delta)^c$$
where $A_p$ is in cm/s$^2$ and for combined Yunnan and W. N. American data $a = 1291.07$, $b = 0.5275$, $c = -1.5785$, $\Delta = 15$ and $\sigma = 0.5203$ (in terms of natural logarithm).
- All records from basement rock.
- Most Yunnan data from main and aftershocks of Luquan and Luncang-Gengma earthquakes.
- Records from Lancang-Gengma sequence corrected.
- Most Yunnan records with $3 \leq M_s \leq 5$ and $10 \leq R \leq 40$ km.
- To overcome difficulty due to shortage of large magnitude records and sample heterogeneous distribution in near and far fields use W. N. America data, because intensity attenuation is similar.
- Fit curves to Yunnan and Yunnan with W. N. American data. Find curve for combined data has lower variance and fit to observation data for large magnitudes is better (by plotting predicted and observed PGA).

## 2.127 Aman et al. (1995)

- Ground-motion model is:
$$\log(a^{1/M}) = b_1 - b_3 \log(R)$$
where $a$ is in cm/s$^2$, $b_1 = 0.433$, $b_3 = 0.073$ and $\sigma = 0.037$.
- Data from three earthquakes with $M_B$ of 5.7, one of $M_B$ of 5.8 and the other $M_B$ of 7.2.
- Compare predicted and observed ground motions for 20/10/1991 Uttarkashi earthquake ($M$6.1) and find good fit.

[12] They state it is '...closest distance from the exposure of ruptured part of the fault ...' so may not be rupture distance.

## 2.128 Ambraseys (1995)

- Ground-motion model is:

$$\begin{aligned}\log a &= A + BM_s + Cr + D\log r\\ \text{where } r^2 &= d^2 + h_0^2\end{aligned}$$

  where $a$ is in g, for $4.0 \leq M \leq 7.4$: for horizontal PGA not including focal depth $A = -1.43$, $B = 0.245$, $C = -0.0010$, $D = -0.786$, $h_0 = 2.7$ and $\sigma = 0.24$, for vertical PGA not including focal depth $A = -1.72$, $B = 0.243$, $C = -0.00174$, $D = -0.750$, $h_0 = 1.9$ and $\sigma = 0.24$, for horizontal PGA including focal depth $A = -1.06$, $B = 0.245$, $C = -0.00045$, $D = -1.016$, $h_0 = h$ and $\sigma = 0.25$ and for vertical PGA including focal depth $A = -1.33$, $B = 0.248$, $C = -0.00110$, $D = -1.000$, $h_0 = h$ and $\sigma = 0.25$.

- Reviews and re-evaluates distances, focal depths, magnitudes and PGAs because data from variety of sources with different accuracy and reliability. For $M_s > 6.0$ distances have acceptable accuracy but for $M_s < 6.0$ distance, depths and magnitudes are poorly known. Errors in locations for $M_s < 6.0$ still large with no foreseeable means of improving them. Use of $r_{epi}$ for $M_s < 6.0$ justified because difference between $r_{jb}$ and $r_{epi}$ for small earthquakes is not larger than uncertainty in epicentre. Check and redetermine station locations; find large differences in excess of 15 km for some stations.

- Focal depths poorly determined. Revises 180 depths using S-start times (time between P and S-wave arrival).

- Focal depths $h < 26$ km; most (60%+) between 4 and 14 km.

- Does not use $M_L$ because no $M_L$ values for Algeria, Iran, Pakistan, Turkey and former USSR and unreliable for other regions. Does not use magnitude calculated from strong-motion records because magnitude calculation requires point source approximation to be valid. Conversion from $M_L$ to $M_s$ should not be done because of uncertainty in conversion which should be retained.

- Notes that $M_s$ results in nonlinear scaling on PGA with $M_w$ due to nonlinear relationship between $\log M_0$ and $M_s$.

- Uses PGAs in four forms: maximum values from accelerograms read by others (34%), from corrected records (30%), scaled directly from accelerograms (13%) and from digitised plots (23%). Notes potential bias in using both corrected and uncorrected PGAs but neglects it because small difference ($\lesssim 4\%$ for those checked). Excludes PGAs near trigger level because processing errors can be large. Some unfiltered digital records which require additional processing to simulate SMA-1 could be associated with larger differences ($\lesssim 10\%$).

- Excludes records from basements and ground floors of structures with more than 3 levels. Retains the few records from dam abutments and tunnel portals.

- Excludes records generated by close small magnitude earthquakes triggered by S-wave.

- Does not exclude records obtained at distances greater than shortest distance to an operational but not triggered instrument because of non-constant or unknown trigger levels and possible malfunctions of instruments.

- Uses weighted regression of Joyner and Boore (1988) for second stage.

- Splits data into five magnitude dependent subsets: $2.0 \leq M_s \leq 7.3$ (1260 records from 619 shocks), $3.0 \leq M_s \leq 7.3$ (1189 records from 561 shocks), $4.0 \leq M_s \leq 7.3$ (830 records from 334 shocks), , $5.0 \leq M_s \leq 7.3$ (434 records from 107 shocks), and $3.0 \leq M_s \leq 6.0$ (976 records from 524 shocks). Calculates coefficients for each subset. Finds only small differences ±15% over distance range 1–200 km between predictions and uncertainties. Concludes results stable. Prefers results from subset with $4.0 \leq M_s \leq 7.3$.

- Finds it difficult to obtain some vertical accelerations due to low ground motion so ignores data from $> 100$ km with PGA $< 1\%$g ($0.1\,\mathrm{m/s^2}$).

- Repeats regression using $r^2 = d^2 + h^2$. Finds depth important.

- Calculates using one-stage method; finds very similar results for $10 < d < 100$ km.

- Considers magnitude dependent function: $\log a = b_1 + b_2 M_s + b_3 r + b_4[r + b_5 \exp(b_6 M_s)]$. Finds $b_5$ is zero so drops $b_3$ and repeats. Finds $b_5$ close to zero so magnitude dependent function not valid for this dataset.

- Local shear-wave velocity, $V_s$, profiles known for 44 stations (268 records from 132 earthquakes between 2.5 and 7.2) although only 14 from $> 40$ km so barely sufficient to derive equation. Use 145 records from 50 earthquakes with $M_s > 4.0$ to fit $\log a = A + BM_s + Cr + D\log r + E\log V_{s30}$, where $V_{s30}$ is average shear-wave velocity to reference depth of 30 m. Finds $C$ positive so constrain to zero. Find no reduction in standard deviation.

- Uses residuals from main equation to find $E$. Notes that should not be used because of small number of records. Considers different choices of reference depth; finds using between 5 and 10 m leads to higher predicted amplifications. Notes better to use $V_{s30}$ because no need for subjective selection of categories.

## 2.129 Dahle et al. (1995)

- Ground-motion model is:

$$\begin{aligned}\ln A &= c_1 + c_2 M_w + c_3 \ln R + c_4 R + c_5 S \\ \text{with: } R &= \sqrt{r^2 + r_h^2}\end{aligned}$$

  where $A$ is in $\mathrm{m/s^2}$, $c_1 = -1.579$, $c_2 = 0.554$, $c_3 = -0.560$, $c_4 = -0.0032$, $c_5 = 0.326$, $r_h = 6$ and $\sigma = 0.3535$

- Use records from Costa Rica, Mexico, Nicaragua and El Salvador. Only Mexican earthquakes with $M_w \geq 6.5$ were used.

- Use two site categories:

  $S = 0$ Rock: 92 records

  $S = 1$ Soil: 88 records

- Use a Bayesian one-stage regression method (Ordaz et al., 1994) to yield physically possible coefficients.

- Consider tectonic type: subduction or shallow crustal but do not model.

- Find no significant difference between Guerrero (Mexico) and other data.

- Find no significant difference between subduction and shallow crustal data.

## 2.130 Lee et al. (1995)

- Ground-motion models are (if define site in terms of local geological site classification):

$$\log a_{\max} = M + \mathrm{Att}(\Delta/L, M, T) + b_1 M + b_2 s + b_3 v + b_4 + b_5 M^2 + \sum_i b_6^i S_L^i + b_{70} rR + b_{71}(1-r)R$$

or (if define site in terms of depth of sediment):

$$\log a_{\max} = M + \mathrm{Att}(\Delta/L, M, T) + b_1 M + b_2 h + b_3 v + b_4 + b_5 M^2 + \sum_i b_6^i S_L^i + b_{70} rR + b_{71}(1-r)R$$

where:

$$\begin{aligned}
\mathrm{Att}(\Delta, M, T) &= \begin{cases} b_0 \log_{10} \Delta & \text{for} \quad R \leq R_{\max} \\ b_0 \log_{10} \Delta_{\max} - (R - R_{\max})/200 & \text{for} \quad R > R_{\max} \end{cases} \\
\Delta &= S \left( \ln \frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2} \right)^{-1/2} \\
\Delta_{\max} &= \Delta(R_{\max}, H, S) \\
R_{\max} &= \frac{1}{2}(-\beta + \sqrt{\beta^2 - 4H^2})
\end{aligned}$$

$S_0$ is correlation radius of source function and can be approximated by $S_0 \sim \beta T/2$ (for PGA assume $T \approx 0.1$ s so use $S_0 = 0.1$ km), $\beta$ is shear-wave velocity in source region, $T$ is period, $S$ is 'source dimension' approximated by $S = 0.2$ for $M < 3$ and $S = -25.34 + 8.51M$ for $3 \leq M \leq 7.25$, $L$ is rupture length of earthquake approximated by $L = 0.01 \times 10^{0.5M}$ km and $v$ is component direction ($v = 0$ for horizontal 1 for vertical). Different $b_0$, $b_{70}$ and $b_{71}$ are calculated for five different path categories. Coefficients are not reported here due to lack of space.

- Use four types of site parameter:
  - Local geological site classification (defined for all records):
    - $s = 0$ Sites on sediments.
    - $s = 1$ Intermediate sites.
    - $s = 2$ Sites on basement rock.
  - Depth of sediments from surface to geological basement rock beneath site, $h$ (defined for 1675 records out of 1926).
  - Local soil type parameter describes average soil stiffness in top 100–200 m (defined for 1456 records out of 1926):
    - $s_L = 0$ 'Rock' soil sites $\Rightarrow S_L^1 = 1$, $S_L^2 = 0$ and $S_L^3 = 0$. Characterises soil up to depth of less than 10 m.
    - $s_L = 1$ Stiff soil sites $\Rightarrow S_L^1 = 1$, $S_L^2 = 0$ and $S_L^3 = 0$ (shear-wave velocities $< 800$ m/s up to depth of 75–100 m).
    - $s_L = 2$ Deep soil sites $\Rightarrow S_L^2 = 1$, $S_L^1 = 0$ and $S_L^3 = 0$. (shear-wave velocities $< 800$ m/s up to depth of 150–200 m).
    - $s_L = 3$ Deep cohesionless soil sites $\Rightarrow S_L^3 = 1$, $S_L^1 = 0$ and $S_L^2 = 0$ (only use for one site with 10 records).
  - Average soil velocity in top 30 m, $v_L$ (if unavailable then use soil velocity parameter, $s_T$) (defined for 1572 records out of 1926):
    - Soil type A $v_L > 750$ m/s.
    - Soil type B 360 m/s $< v_L \leq 750$ m/s.
    - Soil type C 180 m/s $< v_L \leq 360$ m/s.
    - Soil type D $v_L \leq 180$ m/s.
- Only include records for which significant subset of site parameters ($s$, $h$, $s_L$, $v_L$) exist.
- Almost all earthquakes have focal depths $H \leq 15$ km; all focal depths $H \leq 43$ km.
- Use records from 138 aftershocks of Imperial Valley earthquake (15/10/1979), which contribute most of $M \leq 3$ records.

- Use records from 109 earthquakes with $M \leq 3$.
- Use free-field records.
- Characterise path by two methods:
  - Fraction of wave path travelled through geological basement rock measured at surface, from epicentre to station, $0 \leq r \leq 1$.
  - Generalised path type classification:
    1. Sediments to sediments.
    2. Rock-to-sediments, vertically.
    3. Rock-to-sediments, horizontally.
    4. Rock-to-rock.
    5. Rock-to-rock through sediments, vertically.
    6. Rock-to-sediments through rock and sediments, vertically.
    7. Rock-to-sediments though rock and sediments, horizontally.
    8. Rock-to-rock through sediments, horizontally.

    Due to lack of data combine path types 2 and 6 in new category 2', combine path types 3 and 7 in new category 3', combine path types 4, 5 and 8 in new category 4' (when $r \neq 1$) and combine 4, 5 and 8 in new category 5' (when $r = 1$).
- Plot PGA against magnitude and distance to get surface by interpolation. Plot without smoothing and with light and intense smoothing. Find for small magnitude ($M \approx 3$–4) earthquakes attenuation is faster than for large magnitude ($M \approx 6$–7) earthquakes.
- Use a multi-step residue regression method. First fit $\log a_{\max} = M + \mathrm{Att}(\Delta, M, T) + b_1 M + b_2 s + b_3 v + b_4 + b_5 M^2$ (or $\log a_{\max} = M + \mathrm{Att}(\Delta, M, T) + b_1 M + b_2 h + b_3 v + b_4 + b_5 M^2$) and calculate residuals $\epsilon = \log a_{\max} - \log \hat{a}_{\max}$ where $a_{\max}$ is estimated PGA and $\hat{a}_{\max}$ is recorded PGA. Fit $\epsilon = b_7^{(-1)} S_L^{(-1)} + b_7^{(0)} S_L^{(0)} + b_7^{(1)} S_L^{(1)} + b_7^{(2)} S_L^{(2)} + b_7^{(3)} S_L^{(3)}$ where $S_L^{(i)} = 1$ if $s_L = i$ and $S_L^{(i)} = 0$ otherwise. Find significant dependence. Try including $v_L$ both as a continuous and discrete parameter in model but not significant at 5% significance level. Next calculate residuals from last stage and fit $\epsilon = b'_0 \log_{10}(\Delta/L) + b'_4 + b_{60} r R + b_{61}(1-r)R$ for each of the five path type groups (1' to 5'). Lastly combine all the individual results together into final equation.
- Note that $b_{70}$ and $b_{71}$ can only be applied for $R \lesssim 100$ km where data is currently available. For $R \gtrsim 100$ km the predominant wave type changes to surface waves and so $b_{70}$ and $b_{71}$ do not apply.

## 2.131 Lungu et al. (1995b)

- Study almost identical to Radu et al. (1994), see Section 2.124, but different coefficients given: $c_1 = 3.672$, $c_2 = 1.318$, $c_3 = -1.349$, $c_4 = -0.0093$ and $\sigma = 0.395$.

## 2.132 Molas and Yamazaki (1995)

- Ground-motion model is:

$$\log y = b_0 + b_1 M + b_2 r + b_3 \log r + b_4 h + c_i$$

  where $y$ is in cm/s$^2$, $b_0 = 0.206$, $b_1 = 0.477$, $b_2 = -0.00144$, $b_3 = -1$, $b_4 = 0.00311$, $\sigma = 0.276$ and $c_i$ is site coefficient for site $i$ (use 76 sites), given in paper but are not reported here due to lack of space.

- Records from accelerometers on small foundations detached from structures; thus consider as free-field.
- Exclude records with one horizontal component with PGA $< 1\,\mathrm{cm/s^2}[0.01\,\mathrm{m/s^2}]$ because weaker records not reliable due to resolution ($\pm 0.03\,\mathrm{cm/s^2}[0.0003\,\mathrm{m/s^2}]$) of instruments.
- Exclude earthquakes with focal depths equal to 0 km or greater than 200 km, due to lack of such data. Depths (depth of point on fault plane closest to site), $h$, between about 1 km to 200 km.
- Apply a low-cut filter with cosine-shaped transition from 0.01 to 0.05 Hz.
- Positive correlation between magnitude and distance so use two-stage method.
- Note different definition for $M_{\mathrm{JMA}}$ for focal depths $> 60$ km.
- Firstly do preliminary analysis with $b_4 = 0$ and no site coefficients; find $b_2$ is positive so constrain to 0 but find $b_3 < -1.0$ so constrain $b_3$ to $-1.0$ and unconstrain $b_2$. Find linear dependence in residuals on $h$ especially for $h < 100$ km. Find significant improvement in coefficient of determination, $R^2$, using terms $b_4 h$ and $c$.
- Find singularity in matrices if apply two-stage method, due to number of coefficients, so propose a iterative partial regression method.
- Also separate data into five depth ranges (A: $h = 0.1$ to 30 km, 553 records from 111 earthquakes; B: $h = 30$ to 60 km, 778 records from 136 earthquakes; C: $h = 60$ to 90 km, 526 records from 94 earthquakes; D: $h = 90$ to 120 km, 229 records from 31 earthquakes; E: $h = 120$ to 200 km, 112 records from 19 earthquakes) and find attenuation equations for each range. Note results from D & E may not be reliable due to small number of records. Find similar results from each group and all data together.
- Find weak correlation in station coefficients with soil categories, as defined in Iwasaki et al. (1980), but note large scatter.

## 2.133 Sarma and Free (1995)

- Ground-motion model is:

$$\begin{aligned} \log(a_h) &= C_1 + C_2 M + C_3 M^2 + C_4 \log(R) + C_5 R + C_6 S \\ \text{where } R &= \sqrt{d^2 + h_0^2} \end{aligned}$$

  where $a_h$ is in g, $C_1 = -3.4360$, $C_2 = 0.8532$, $C_3 = -0.0192$, $C_4 = -0.9011$, $C_5 = -0.0020$, $C_6 = -0.0316$, $h_0 = 4.24$ and $\sigma = 0.424$.

- Use two site categories:

$S = 0$ Rock

$S = 1$ Soil

- Use one-stage method because of the predominance of earthquakes with single recordings in the set.
- Note that it is very important to choose a functional form based as much as possible on physical grounds because the data is sparse or non-existent for important ranges of distance and magnitude.
- Carefully verify all the distances in set.
- Use focal depths from (in order of preference): special reports (such as aftershock monitoring), local agencies and ISC and NEIS determinations. Focal depths $< 30$ km.

- Do not use $M_L$ or $m_b$ because of a variety of reasons. One of which is the saturation of $M_L$ and $m_b$ at higher magnitudes ($M_L, m_b > 6$).
- If more than one estimate of $M_w$ made then use average of different estimates.
- Use PGAs from: a) digital or digitised analogue records which have been baseline corrected and filtered, b) data listings of various agencies and c) other literature. Difference between PGA from different sources is found to be small.
- Also derive equations assuming $C_3 = 0$ (using rock and soil records and only soil records) and $C_3 = 0$, $C_4 = -1$ and $C_6 = 0$ (using only rock records).
- Include records from Nahanni region and find similar results.
- Also derive equations for Australia (115 records from 86 earthquakes, $2.4 \leq M_w \leq 6.1$, $1 \leq d_e \leq 188$ km) and N. E. China (Tangshan) (193 records from 64 earthquakes, $3.5 \leq M_w \leq 7.5$, $2 \leq d_e \leq 199$ km) . Find considerable difference in estimated PGAs using the equations for the three different regions.

## 2.134 Ambraseys et al. (1996) & Simpson (1996)

- Ground-motion model is:

$$\begin{aligned} \log y &= C_1' + C_2 M + C_4 \log r + C_A S_A + C_S S_S \\ \text{where } r &= \sqrt{d^2 + h_0^2} \end{aligned}$$

  where $y$ is in g, $C_1' = -1.48$, $C_2 = 0.266$, $C_4 = -0.922$, $C_A = 0.117$, $C_S = 0.124$, $h_0 = 3.5$ and $\sigma = 0.25$.

- Use four site conditions but retain three (because only three records from very soft (L) soil which combine with soft (S) soil category):

  R Rock: $V_s > 750$ m/s, $\Rightarrow S_A = 0, S_S = 0$, 106 records.
  A Stiff soil: $360 < V_s \leq 750$ m/s, $\Rightarrow S_A = 1, S_S = 0$, 226 records.
  S Soft soil: $180 < V_s \leq 360$ m/s, $\Rightarrow S_A = 0, S_S = 1$, 81 records.
  L Very soft soil: $V_s \leq 180$ m/s, $\Rightarrow S_A = 0, S_S = 1$, 3 records.

- Lower limit of $M_s = 4.0$ because smaller earthquakes are generally not of engineering significance.
- Focal depths less than 30 km, 81% between 5 and 15 km.
- Note for some records distances have uncertainty of about 10 km.
- Most records from distances less than about 40 km.
- For some small events need to estimate $M_s$ from other magnitude scales.
- Most records from free-field stations although some from basements or ground floors of relatively small structures, and tunnel portals. Do not exclude records from instruments beyond cutoff distance because of limited knowledge about triggered level.
- All uncorrected records plotted, checked and corrected for spurious points and baseline shifts.
- Uniform correction procedure was applied for all records. For short records ($< 5$ s) a parabolic adjustment was made, for long records ($> 10$ s) filtering was performed with pass band 0.20 to 25 Hz and for intermediate records both parabolic and filtering performed and the most realistic record was chosen. Instrument correction not applied due to limited knowledge of instrument characteristics.
- Also analyze using one-stage method, note results comparable.

## 2.135 Ambraseys and Simpson (1996) & Simpson (1996)

- Based on Ambraseys et al. (1996), see Section 2.134.
- Coefficients are: $C_1' = -1.74$, $C_2 = 0.273$, $C_4 = -0.954$, $C_A = 0.076$, $C_S = 0.058$, $h_0 = 4.7$ and $\sigma = 0.26$.

## 2.136 Aydan et al. (1996) & Aydan (2001)

- Ground-motion model is:

$$a_{\max} = a_1[\exp(a_2 M_s)\exp(a_3 R) - a_4]$$

  where $a_{\max}$ is in gal, $a_1 = 2.8$, $a_2 = 0.9$, $a_3 = -0.025$ and $a_4 = 1$ ($\sigma$ is not given).
- Most records from $r_{hypo} > 20$ km.
- Note that data from Turkey is limited and hence equation may be refined as amount of data increases.
- Also give equation to estimate ratio of vertical PGA ($a_v$) to horizontal PGA ($a_h$): $a_v/a_h = 0.217+0.046M_s$ ($\sigma$ is not given).

## 2.137 Bommer et al. (1996)

- Ground-motion model is:

$$\ln(A) = a + bM + d\ln(R) + qh$$

  where $h$ is focal depth, $A$ is in g, $a = -1.47$, $b = 0.608$, $d = -1.181$, $q = 0.0089$ and $\sigma = 0.54$.
- Only use subduction earthquakes.
- Do not recommend equation used for hazard analysis, since derive it only for investigating equations of Climent et al. (1994).

## 2.138 Crouse and McGuire (1996)

- Ground-motion model is:

$$\ln Y = a + bM + d\ln(R + c_1\exp\{c_2 M\}) + eF$$

  where $Y$ is in g, for site category B: $a = -2.342699$, $b = 1.091713$, $c_1 = 0.413033$, $c_2 = 0.623255$, $d = -1.751631$, $e = 0.087940$ and $\sigma = 0.427787$ and for site category C: $a = -2.353903$, $b = 0.838847$, $c_1 = 0.305134$, $c_2 = 0.640249$, $d = -1.310188$, $e = -0.051707$ and $\sigma = 0.416739$.
- Use four site categories, $\bar{V}_s$ is shear-wave velocity in upper 100 ft (30 m):

  A Rock: $\bar{V}_s \geq 2500$ fps ($\bar{V}_s \geq 750$ m/s), 33 records

  B Soft rock or stiff soil: $1200 \leq \bar{V}_s \leq 2500$ fps ($360 \leq \bar{V}_s < 750$ m/s), 88 records

  C Medium stiff soil: $600 \leq \bar{V}_s < 1200$ fps ($180 \leq \bar{V}_s < 360$ m/s), 101 records

  D Soft clay: $\bar{V}_s < 600$ fps ($\bar{V}_s < 180$ m/s), 16 records
- Use two source mechanisms: reverse (R): $\Rightarrow F = 1$, 81 records and strike-slip (S) $\Rightarrow F = 0$, 157 records. Most (77) reverse records from $M_s \leq 6.7$.

- Most (231) records from small building (up to 3 storeys in height) or from instrument shelters to reduce effect of soil-structure interaction. 6 records from 6 storey buildings and 1 record from a 4 storey building, included because lack of data in site or distance range of these records. Structures thought not to appreciably affect intermediate or long period and at large distances short period ground motion more greatly diminished than long period so less effect on predictions.

- Exclude records from Eureka-Ferndale area in N. California because may be associated with subduction source, which is a different tectonic regime than rest of data. Also excluded Mammoth Lake records because active volcanic region, atypical of rest of California.

- Include one record from Tarzana Cedar Hills although exclude a different record from this station due to possible topographic effects.

- Most records between $6 \leq Ms \leq 7.25$ and $10 \leq R \leq 80$ km.

- Apply weighted regression separately for site category B and C. Data space split into 4 magnitude (6.0–6.25, 6.25–6.75, 6.75–7.25, 7.25+) and 5 distance intervals ($\leq 10$ km, 10–20 km, 20–40 km, 40–80 km, 80 km+). Each recording within bin given same total weight.

- So that $Y$ is increasing function of $M$ and decreasing function of $R$ for all positive $M$ and $R$ apply constraints. Define $g = b/d$ and $h = -(g + c_2)$, then rewrite equation $\ln Y = a + d\{gM + \ln[R + c_1 \exp(c_2 M)]\} + eF$ and apply constraints $g \leq 0$, $d \leq 0$, $c \geq 0$, $c_2 \geq 0$ and $h \geq 0$.

- Check plots of residuals (not shown in paper), find uniform distribution.

- Find $e$ not significantly different than 0 and inconsistency in results between different soil classes make it difficult to attach any significance to fault type.

- Lack of records for A and D site categories. Find scale factors $k_1 = 0.998638$ and $k_2 = 1.200678$ so that $Y_A = k_1 Y_B$ and $Y_D = k_2 Y_C$, where $Y_S$ is predicted ground motion for site class $S$. Find no obvious dependence of $k_1$ or $k_2$ on acceleration from examining residuals. Find $k_1$ and $k_2$ not significantly different than 1.

- Note limited data for $R < 10$ km, advise caution for this range.

- Note equation developed to estimate site-amplification factors not for seismic hazard analysis.

## 2.139 Free (1996) & Free et al. (1998)

- Ground-motion model is:

$$\begin{aligned}\log(Y) &= C_1 + C_2\mathbf{M} + C_3\mathbf{M}^2 + C_4\log(R) + C_5(R) + C_6(S) \\ R &= \sqrt{d^2 + h_0^2}\end{aligned}$$

where $Y$ is in g, for $\mathbf{M} > 1.5$ using acceleration and velocity records, for horizontal PGA $C_1 = -4.2318$, $C_2 = 1.1962$, $C_3 = -0.0651$, $C_4 = -1$, $C_5 = -0.0019$, $C_6 = 0.261$, $h_0 = 2.9$ and $\sigma = 0.432$ and for vertical PGA $C_1 = -4.1800$, $C_2 = 1.0189$, $C_3 = -0.0404$, $C_4 = -1$, $C_5 = -0.0019$, $C_6 = 0.163$, $h_0 = 2.7$ and $\sigma = 0.415$.

- Use two site categories:

$S = 0$ Rock, H: 470 records, V: 395 records.

$S = 1$ Soil, H: 88 records, V: 83 records.

Note that not most accurate approach but due to lack of site information consider this technique makes most consistent use of available information.

- Select data using these criteria:
  1. Epicentre and recording station must be within the stable continental region boundaries defined by Johnston et al. (1994) because a) such regions form end of spectrum of regions described by 'intraplate' and hence allows differences with interplate regions to be seen, b) they are clearly delineated regions and c) intraplate oceanic crust is excluded.
  2. Minimum magnitude level $\mathbf{M} = 1.5$.
  3. Use records from dam abutments and downstream free-field sites but excludes records from crests, slopes, toes, galleries, or basements.
  4. Use records from acceleration and velocity instruments.
  5. Specify no minimum PGA.
  6. Specify no maximum source distance. Do not exclude records from distances greater than shortest distance to a non-triggered station.
- Data from Australia, N.W. Europe, Peninsular India and E. N. America.
- Focal depths, $2 \leq h \leq 28$ km.
- Most records from $\mathbf{M} < 4.0$.
- Visually inspect all records including integrated velocities and displacements, identify and remove traces dominated by noise, identify and correct transient errors (spikes, ramps, linear sections, back time steps and clipped peaks), identify scaling errors, identify and remove multiple event records. Linear baseline correct and elliptically filter with cut-off 0.25 to 0.5 Hz (determine frequency by visual inspection of adjusted record) and 33 to 100 Hz (generally pre-determined by Nyquist frequency).
- Large proportion of records from velocity time histories which differentiate to acceleration. Test time domain method (central difference technique) and frequency domain method; find very similar results. Use time domain method.
- Distribution with respect to magnitude did not allow two-stage regression technique.
- In many analyses distribution of data with respect to distance did not allow simultaneous determination of coefficients $C_4$ and $C_5$, for these cases constrain $C_4$ to $-1$.
- Test effect of minimum magnitude cut-off for two cut-offs $\mathbf{M} = 1.5$ and $\mathbf{M} = 3.5$. Find if include data from $\mathbf{M} < 3.5$ then there is substantial over prediction of amplitudes for $d < 10$ km for large magnitudes unless include $C_3$ term. $C_3$ effectively accounts for large number of records from small magnitudes and so predictions using the different magnitude cut-offs are very similar over broad range of $\mathbf{M}$ and $d$.
- Try including focal depth, $h$, explicitly by replacing $h_0$ with $h$ because $h_0$ determined for whole set (which is dominated by small shocks at shallow depths) may not be appropriate for large earthquakes. Find improved fit at small distances but it does not result in overall improvement in fit ($\sigma$ increases); this increase thought due to large errors in focal depth determination.
- Find larger standard deviations than those found in previous studies which note may be due to intrinsic differences between regional subsets within whole set. Repeat analysis separately for Australia (for horizontal and vertical), N. America (for horizontal and vertical) and N.W. Europe (horizontal); find reduced standard deviations (although still large), $C_5$ varies significantly between 3 regions.
- Repeat analysis excluding velocity records.
- Also repeat analysis using only rock records.

## 2.140 Inan et al. (1996)

- Ground-motion model is:

$$\log \text{PGA} = aM + b \log R + c$$

where PGA is in an unknown unit but it is probably in gal, $a = 0.65$, $b = -0.9$ and $c = -0.44$ ($\sigma$ not reported).

## 2.141 Ohno et al. (1996)

- Ground-motion model is:

$$\log S(T) = a(T)M - \log X_{eq} - b(T)X_{eq} + c(T) + q\Delta s(T)$$

where $S(0.02)$ is in gal, $a(0.02) = 0.318$, $b(0.02) = 0.00164$ and $c(0.02) = 1.597$ ($\Delta s(0.02)$ and $\sigma$ only given in graphs).

- Use two site conditions:

$q = 0$ Pre-Quaternary: Rock (sandstone, siltstone, shale, granite, mudstone, etc.); thickness of surface soil overlying rock is less than 10 m; shallow soil or thin alluvium, 160 records. S-wave velocities $> 600$ m/s.

$q = 1$ Quaternary: Soil (alluvium, clay, sand, silt, loam, gravel, etc.), 336 records. S-wave velocities $\leq 600$ m/s.

Exclude records from very soft soil such as bay mud or artificial fill because few such records and ground motions may be strongly affected by soil nonlinearity.

- Use equivalent hypocentral distance, $X_{eq}$, because strong motion in near-source region affected from points other than nearest point on fault plane.
- Use portion of record after initial S-wave arrival.
- Approximates PGA by spectral acceleration for period of 0.02 s and 5% damping.
- Plot the amplitude factors from first stage against $M_w$; find well represented by linear function.

## 2.142 Romeo et al. (1996)

- Ground-motion model is:

$$\log \text{PHA} = a_1 + a_2 M_w - \log(d^2 + h^2)^{1/2} + a_3 S$$

where PHA is in g, $a_1 = -1.870 \pm 0.182$, $a_2 = 0.366 \pm 0.032$, $a_3 = 0.168 \pm 0.045$, $h = 6$ km and $\sigma = 0.173$ for $r_{jb}$ and $a_1 = -2.238 \pm 0.200$, $a_2 = 0.438 \pm 0.035$, $a_3 = 0.195 \pm 0.049$, $h = 5$ km and $\sigma = 0.190$ for $r_{epi}$.

- Use two site categories:

$S = 0$ Rock or stiff soils and deep alluvium.

$S = 1$ All other sites.

- Use data and functional form of Sabetta and Pugliese (1987) but use $M_w$ instead of magnitudes used by Sabetta and Pugliese (1987).

## 2.143 Sarma and Srbulov (1996)

- Ground-motion model is:

$$\begin{aligned}\log(A_p/\mathrm{g}) &= b_1 + b_2 M_s + b_3 \log r + b_4 r \\ \text{where } r &= (d^2 + h_0^2)^{0.5}\end{aligned}$$

  where $A_p$ is in g, using both horizontal components $b_1 = -1.617$, $b_2 = 0.248$, $b_3 = -0.5402$, $b_4 = -0.00392$, $h_0 = 3.2$ and $\sigma = 0.26$ and for larger horizontal component $b_1 = -1.507$, $b_2 = 0.240$, $b_3 = -0.542$, $b_4 = -0.00397$, $h_0 = 3.0$ and $\sigma = 0.26$.

- Consider two soil categories but do not model:

  1. Rock
  2. Soil

  Classify sites without regard to depth and shear-wave velocity of deposits.

- Most records from W. USA but many from Europe and Middle East.

- Focal depths between 2 and 29 km.

- Records from instruments on ground floor or in basements of buildings and structures up to 3 storeys and at free-field sites, regardless of topography.

- Records baseline corrected and low-pass filtered using elliptic filter.

## 2.144 Singh et al. (1996)

- Ground-motion model is:

$$\log_{10} \mathrm{AGM} = b_1 + 0.31M - b_3 \log R$$

  where AGM is in cm/s$^2$, $b_1 = 1.14$ and $b_3 = 0.615$ ($\sigma$ is not given). Note there are typographical errors in the abstract.

- Data from three earthquakes with $m_b = 5.7$, one with $m_b = 5.8$ and one with $m_b = 7.2$.

- Adopt magnitude scaling coefficient (0.31) from Boore (1983).

## 2.145 Spudich et al. (1996) & Spudich et al. (1997)

- Ground-motion model is:

$$\begin{aligned}\log_{10} Y &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_4 R + b_5 \log_{10} R + b_6 \Gamma \\ \text{where } R &= \sqrt{r_{jb}^2 + h^2}\end{aligned}$$

  where $Y$ is in g, $b_1 = 0.156$, $b_2 = 0.229$, $b_3 = 0$, $b_4 = 0$, $b_5 = -0.945$, $b_6 = 0.077$, $h = 5.57$, $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$ where $\sigma_1 = 0.216$, $\sigma_2 = 0$, for randomly orientated component $\sigma_3 = 0.094$ and for geometric mean $\sigma_3 = 0$.

- Use two site categories (following classification of Joyner and Boore (1981)):

$\Gamma = 0$ Rock: 35 records

$\Gamma = 1$ Soil: 93 records

- Applicable for extensional regimes, i.e. those regions where lithosphere is expanding areally.
- Reject records from structures of more than two storeys or from deeply embedded basements or those which triggered on S wave.
- Include records from those instruments beyond cutoff distance, i.e. beyond first instrument which did not trigger.
- Correction technique based on uniform correction and processing. Determine passband for filtering based on visual inspection of Fourier amplitude spectra and doubly-integrated displacements. Apply instrument correction.
- Not enough data to be able to find all coefficients so use $b_2$ and $b_3$ from Boore et al. (1994a)
- Note that should only be used in distance range 0 to 70 km because further away ground motions tend to be over predicted.

## 2.146 Stamatovska and Petrovski (1996)

- Ground-motion model is:

$$\begin{aligned}
\text{Acc} &= \exp(b)\exp(b_M)(R_h + C)^{b_R} \\
\text{where } R_h^2 &= (R_e/\rho)^2 + h^2 \\
\text{and } \rho &= \sqrt{\frac{1 + tg^2\alpha}{a^{-2} + tg^2\alpha}}
\end{aligned}$$

  where Acc is in $\text{cm/s}^2$, $\alpha$ is the azimuth of the site with respect to energy propagation pattern, $b = 3.49556$, $b_M = 1.35431$, $C = 30$, $b_R = -1.58527$, $a = 1.2$ and $\sigma = 0.48884$ (definitions of $t$ and $g$ are not given).

- Correct PGAs for local site effects so that PGAs used correspond to a site with a shear-wave velocity of 700 m/s. Do not state how this is performed.
- Most records from SMA-1s.
- Not all records from free-field.
- Records from strong intermediate depth earthquakes in Vrancea region.
- Focal depths, $89.1 \leq h \leq 131$ km.
- For each of the four earthquakes, calculate coefficents in equation $\ln \text{Acc} = b_0 + b_1 \ln(R_e/\rho)$, the main direction of energy propagation and the relation between the semi-axes of the ellipse in two orthogonal directions ($a : b$).
- Also calculate coefficents in equation $\ln \text{Acc} = b + b_M M + b_R \ln(R_h + C)$ for different azimuth by normalising the values of $R_e/\rho$ by the azimuth. Give coefficients for Bucharest, Valeni and Cerna Voda.
- Note that uncertainty is high and suggest this is because of distribution of data with respect to $M$, $R_e$ and $h$, the use of data processed in different ways, soil-structure interaction and the use of an approximate correction method for local site effects.

## 2.147 Ansal (1997)

- Ground-motion model is:

$$\log A_p = a_1 M + a_2 R + a_3 \log R + a_4$$

where $A_p$ is in gal, $a_1 = 0.329$, $a_2 = -0.00327$, $a_3 = -0.792$ and $a_4 = 1.177$ ($\sigma$ is not known).

## 2.148 Campbell (1997), Campbell (2000), Campbell (2001) & Campbell and Bozorgnia (1994)

- Ground-motion model (horizontal component) is:

$$\begin{aligned}\ln A_H &= a_1 + a_2 M + a_3 \ln\sqrt{R_{\mathrm{SEIS}}^2 + [a_4 \exp(a_5 M)]^2} \\ &\quad + [a_6 + a_7 \ln R_{\mathrm{SEIS}} + a_8 M]F + [a_9 + a_{10} \ln R_{\mathrm{SEIS}}]S_{\mathrm{SR}} \\ &\quad + [a_{11} + a_{12} \ln R_{\mathrm{SEIS}}]S_{\mathrm{HR}} + f_A(D) \\ f_A(D) &= \begin{cases} 0 & \text{for} \quad D \geq 1\,\mathrm{km} \\ \{[a_{11} + a_{12} \ln(R_{\mathrm{SEIS}})] - [a_9 + a_{10} \ln(R_{\mathrm{SEIS}})]S_{\mathrm{SR}}\}(1-D)(1-S_{\mathrm{HR}}) & \text{for} \quad D < 1\,\mathrm{km} \end{cases}\end{aligned}$$

where $A_H$ is in g, $a_1 = -3.512$, $a_2 = 0.904$, $a_3 = -1.328$, $a_4 = 0.149$, $a_5 = 0.647$, $a_6 = 1.125$, $a_7 = -0.112$, $a_8 = -0.0957$, $a_9 = 0.440$, $a_{10} = -0.171$, $a_{11} = 0.405$, $a_{12} = -0.222$, $\sigma = 0.55$ for $A_H < 0.068\,\mathrm{g}$, $\sigma = 0.173 - 0.140 \ln(A_H)$ for $0.068\,\mathrm{g} \leq A_H \leq 0.21\,\mathrm{g}$ and $\sigma = 0.39$ for $A_H > 0.21\,\mathrm{g}$ (when expressed in terms of acceleration) and $\sigma = 0.889 - 0.0691M$ for $M < 7.4$ and $\sigma = 0.38$ for $M \geq 7.4$ (when expressed in terms of magnitude).

Ground-motion model (vertical component) is:

$$\begin{aligned}\ln A_V &= \ln A_H + b_1 + b_2 M + b_3 \ln[R_{\mathrm{SEIS}} + b_4 \exp(b_5 M)] \\ &\quad + b_6 \ln[R_{\mathrm{SEIS}} + b_7 \exp(b_8 M)] + b_9 F\end{aligned}$$

where $A_V$ is in g, $b_1 = -1.58$, $b_2 = -0.10$, $b_3 = -1.5$, $b_4 = 0.079$, $b_5 = 0.661$, $b_6 = 1.89$, $b_7 = 0.361$, $b_8 = 0.576$, $b_9 = -0.11$ and $\sigma_V = \sqrt{\sigma^2 + 0.36^2}$ (where $\sigma$ is standard deviation for horizontal PGA prediction).

- Uses three site categories:

$S_{\mathrm{SR}} = 0, S_{\mathrm{HR}} = 1$ Hard rock: primarily Cretaceous and older sedimentary deposits, metamorphic rock, crystalline rock and hard volcanic deposits (e.g. basalt).

$S_{\mathrm{SR}} = 1, S_{\mathrm{HR}} = 0$ Soft rock: primarily Tertiary sedimentary deposits and soft volcanic deposits (e.g. ash deposits).

$S_{\mathrm{SR}} = 0, S_{\mathrm{HR}} = 0$ Alluvium or firm soil: firm or stiff Quaternary deposits with depths greater than 10 m.

Also includes sediment depth ($D$) as a variable.

- Restricts to near-source distances to minimize influence of regional differences in crustal attenuation and to avoid complex propagation effects that have been observed at longer distances.

- Excludes recordings from basement of buildings greater than two storeys on soil and soft rock, greater than five storeys on hard rock, toe and base of dams and base of bridge columns. Excludes recordings from shallow and soft soil because previous analyses showed such sites have accelerations significantly higher than those on deep, firm alluvium. Include records from dam abutments because comprise a significant number of rock recordings and due to stiff foundations are expected to be only minimally affected by dam. Some of these could be strongly affected by local topography.

- Includes earthquakes only if they had seismogenic rupture within shallow crust (depths less than about 25 km). Includes several large, shallow subduction interface earthquakes because previous studies found similar near-source ground motions to shallow crustal earthquakes.
- Includes only earthquakes with $M$ about 5 or larger to emphasize those ground motions of greatest engineering interest and limit analysis to more reliable, well-studied earthquakes.
- Notes that distance to seismogenic rupture is a better measure than distance to rupture or distance to surface projection because top layer of crust is non-seismogenic and will not contribute to ground motion. Give estimates for average depth to top of seismogenic rupture for hypothetical earthquakes.
- Considers different focal mechanisms: reverse (H:6, V:5), thrust (H:9, V:6), reverse-oblique (H:4, V:2) and thrust-oblique (0), total (H:19, V:13) $\Rightarrow F = 1$ (H:278 records, V:116 records) (reverse have a dip angle greater than or equal to 45°), strike-slip (H:27, V:13) $\Rightarrow F = 0$ (H:367 records, V:109 records) (strike-slip have an absolute value of rake less than or equal to 22.5° from the horizontal as measured along fault plane). There is only one normal faulting earthquakes in set of records (contributing four horizontal records) so difference is not modelled although $F = 0.5$ given as first approximation (later revised to $F = 0$).
- Mostly W. USA with 20 records from Nicaragua(1) Mexico (5), Iran (8), Uzbekistan (1), Chile (3), Armenia (1) and Turkey (1).
- Does regression firstly with all data. Selects distance threshold for each value of magnitude, style of faulting and local site condition such that the 16th percentile estimate of $A_H$ was equal to 0.02 g (which corresponds to a vertical trigger of about 0.01 g). Repeats regression repeated only with those records within these distance thresholds. Avoids bias due to non-triggering instruments.
- Finds dispersion (uncertainty) to be dependent on magnitude and PGA, models as linear functions. Finds better fit for PGA dependency.

## 2.149 Munson and Thurber (1997)

- Ground-motion model is:

$$\begin{aligned}\log_{10} \mathrm{PGA} &= b_0 + b_1(M-6) + b_2 r - \log_{10} r + b_4 S \\ \text{where } r &= \sqrt{d^2+h^2}\end{aligned}$$

  PGA is in g, $b_0 = 0.518$, $b_1 = 0.387$, $b_2 = -0.00256$, $b_4 = 0.335$, $h = 11.29$ and $\sigma = 0.237$.

- Use two site categories:

$S = 0$ Lava: 38 records

$S = 1$ Ash: $60 \lesssim V_s \lesssim 200$ m/s, 13 records

- Depths between 4 and 14 km with average 9.6 km (standard deviation 2.3 km). Limit of 15 km chosen to differentiate between large tectonic earthquakes and deeper mantle events.
- Attenuation greater than for western USA due to highly fractured volcanic pile.
- Peak acceleration measured directly from accelerograms. Check against one from corrected records, small difference.
- Excludes records triggered on S-wave and those beyond cutoff distance (the distance to first nontriggered instrument).
- Does weighted and unweighted least squares analysis; find some differences.

## 2.150 Pancha and Taber (1997)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta \mathbf{M} - \log r + br \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  Coefficients are unknown.

- Also develop model using functional form of Molas and Yamazaki (1995).
- All data from rock sites.
- Data from seismographs of New Zealand National Seismograph Network and temporary deployments on East Cape of the North Island, the Marlborough region of the South Island and the central volcanic zone of the North Island.
- Most data from more than 100 km from the source.

## 2.151 Rhoades (1997)

- Ground-motion model is:

$$\begin{aligned}\log_{10} a &= \alpha + \beta M - \log_{10} r + \gamma r \\ \text{where } r &= (d^2 + h^2)^{1/2}\end{aligned}$$

  where $a$ is in g, $\alpha = -1.237 \pm 0.254$, $\beta = 0.278 \pm 0.043$, $\gamma = -0.00220 \pm 0.00042$, $h = 6.565 \pm 0.547$, $\tau^2 = 0.00645 \pm 0.00382$ and $\sigma^2 = 0.0527 \pm 0.00525$ (where $\tau^2$ is the inter-earthquake variance and $\sigma^2$ is the intra-earthquake variance and $\pm$ signifies the standard error of the estimate.

- Notes that errors in magnitude determination are one element that contributes to the between-earthquake component of variance and could thus cause apparent differences between earthquakes, even if none existed.
- Develops a method to explicitly include consideration of magnitude uncertainties in a random earthquake effects model so that the between-earthquake component of variance can be split into the part that is due only to magnitude uncertainty (and is therefore of no physical consequence) and the part for which a physical explanation may be sought.
- Applies method to data of Joyner and Boore (1981). Assume two classes of magnitude estimates: those with estimates of $M_w$, which assumes to be associated with a standard error of 0.1, and those for which $M_L$ was used as a surrogate for $M_w$, which assumes to be associated with a standard error of 0.3. Find that the inter-earthquake variance is much lower than that computed assuming that the magnitudes are exact but that other coefficients are similar. Believes that the high inter-earthquake variance derived using the exact magnitudes model is largely explained by the large uncertainties in the magnitude estimates using $M_L$.

## 2.152 Schmidt et al. (1997)

- Ground-motion model is:

$$\begin{aligned}\ln A &= c_1 + c_2 M + c_3 \ln r + c_4 r + c_5 S_1 + c_6 S_2 \\ \text{where } r &= \sqrt{R^2 + 6^2}\end{aligned}$$

where $A$ is in m/s$^2$, $c_1 = -1.589$, $c_2 = 0.561$, $c_3 = -0.569$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.80$ (for all earthquakes), $c_1 = -1.725$, $c_2 = 0.687$, $c_3 = -0.742$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.83$ (for shallow crustal earthquakes) and $c_1 = -0.915$, $c_2 = 0.543$, $c_3 = -0.692$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.74$ (for subduction zone earthquakes).

- Use three site categories:

$S_1 = 0, S_2 = 0$ Rock, 54 records.

$S_1 = 1, S_2 = 0$ Hard soil, 63 records.

$S_1 = 0, S_2 = 1$ Soft soil, 83 records.

- Most records from SMA-1s with 6 records from SSA-2.
- Use PSA at 40 Hz (0.025 s) as peak ground acceleration.
- Records instrument corrected and bandpass filtered with cut-offs of 0.2 and 20 Hz.
- Use data from shallow crustal earthquakes (133 records) and subduction zone earthquakes (67 records).
- Perform regression on combined shallow crustal and subduction zone records, on just the shallow crustal records using $r_{hypo}$ and using $r_{epi}$ and on just subduction zone records.
- Note that distribution w.r.t. distance improves in the near field when epicentral distance is used but only possible to use $r_{epi}$ for shallow crustal earthquakes because for subduction zone earthquakes hypocentral distance is much greater than epicentral distance so should use $r_{hypo}$ instead.
- For $4 \leq M \leq 6$ distribution w.r.t. epicentral distance is quite good but for $M > 6$ no records from $d_e < 40$ km.
- Use a two step procedure. Firstly use entire set and both horizontal components and compute two soil terms (one for hard and one for soft soil). In second step use soil terms to correct motions for rock conditions and then repeat regression.
- Use Bayesian analysis (Ordaz et al., 1994) so that derived coefficients comply with physics of wave propagation because include *a priori* information on the coefficients to avoid physically unrealistic values. Choose initial values of coefficients based on theory and previous results
- Cannot find coefficient in $r$ by regression so adopt 6 km from previous study.
- Examine residuals w.r.t. distance and magnitude and find no trends.

## 2.153 Youngs et al. (1997)

- Ground-motion model for soil is:

$$\begin{aligned}
\ln \mathrm{PGA} &= C_1^* + C_2\mathbf{M} + C_3^* \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{C_4^* - \frac{C_2}{C_3^*}\mathbf{M}}\right] + C_5 Z_t + C_9 H + C_{10} Z_{ss} \\
\text{with: } C_1^* &= C_1 + C_6 Z_r \\
C_3^* &= C_3 + C_7 Z_r \\
C_4^* &= C_4 + C_8 Z_r
\end{aligned}$$

where PGA is in g, $C_1 = -0.6687$, $C_2 = 1.438$, $C_3 = -2.329$, $C_4 = \ln(1.097)$, $C_5 = 0.3643$, $C_9 = 0.00648$ and $\sigma = 1.45 - 0.1\mathbf{M}$ (other coefficients in equation not needed for prediction on deep soil and are not given in paper).

Ground-motion model for rock is:

$$\begin{aligned}\ln \mathrm{PGA} &= C_1^* + C_2\mathbf{M} + C_3^* \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{C_4^* - \frac{C_2}{C_3^*}\mathbf{M}}\right] + C_5 Z_{ss} + C_8 Z_t + C_9 H \\ \text{with: } C_1^* &= C_1 + C_3 C_4 - C_3^* C_4^* \\ C_3^* &= C_3 + C_6 Z_{ss} \\ C_4^* &= C_4 + C_7 Z_{ss}\end{aligned}$$

where PGA is in g, $C_1 = 0.2418$, $C_2 = 1.414$, $C_3 = -2.552$, $C_4 = \ln(1.7818)$, $C_8 = 0.3846$, $C_9 = 0.00607$ and $\sigma = 1.45 - 0.1\mathbf{M}$ (other coefficients in equation not needed for prediction on rock and are not given in paper).

Use different models to force rock and soil accelerations to same level in near field.

- Use three site categories to do regression but only report results for rock and deep soil:

$Z_r = 1, Z_{ds} = 0, Z_{ss} = 0$ Rock: Consists of at most about a metre of soil over weathered rock, 96 records.

$Z_{ds} = 1, Z_r = 0, Z_{ss} = 0$ Deep soil: Depth to bedrock is greater than 20 m, 284 records.

$Z_{ss} = 1, Z_{ds} = 0, Z_r = 0$ Shallow soil: Depth to bedrock is less than 20 m and a significant velocity contrast may exist within 30 m of surface, 96 records.

- Use free-field recordings, i.e. instruments in basement or ground-floor of buildings less than four storeys in height. Data excluded if quality of time history poor or if portion of main shaking not recorded.
- Consider tectonic type: interface (assumed to be thrust) (98 records) $\Rightarrow Z_t = 0$, intraslab (assumed to be normal) (66 records) $\Rightarrow Z_t = 1$
- Focal depths, $H$, between 10 and 229 km
- Not enough data to perform individual regression on each subset so do joint regression analysis.
- Both effect of depth and tectonic type significant.
- Large differences between rock and deep soil.
- Note differences between shallow crustal and interface earthquake primarily for very large earthquakes.
- Assume uncertainty to be linear function of magnitude.

## 2.154 Zhao et al. (1997)

- Ground-motion model (Model 1) is:

$$\log_{10} \mathrm{PGA} = A_1 M_w + A_2 \log_{10} \sqrt{r^2 + d^2} + A_3 h_c + A_4 + A_5 \delta_R + A_6 \delta_A + A_7 \delta_I$$

where PGA is in $\mathrm{m/s^2}$, $\delta_R = 1$ for crustal reverse 0 otherwise, $\delta_A = 1$ for rock 0 otherwise, $\delta_I = 1$ for interface 0 otherwise, $A_1 = 0.298$, $A_2 = -1.56$, $A_3 = 0.00619$, $A_4 = -0.365$, $A_5 = 0.107$, $A_6 = -0.186$, $A_7 = -0.124$, $d = 19$ and $\sigma = 0.230$.

- Models also given for soil sites only (Model 2), unspecified site (Model 3), focal mechanism and tectonic type unknown (Model 4) and only magnitude, depth and distance known (Model 5)
- Records from ground or base of buildings. 33 from buildings with more than 3 storeys; find no significant differences.

- Retain two site categories:
  1. Rock: Topographic effects expected, very thin soil layer ($\leq 3$ m) overlying rock or rock outcrop.
  2. Soil: everything else
- Use depth to centroid of rupture, $h_c$, $4 \leq h_c \leq 149$. Only nine are deeper than 50 km. Exclude records from deep events which travelled through mantle.
- Consider tectonic type: C=crustal (24+17 records), I=interface (7+0 records) and S=slab (20+0 records)
- Consider source mechanism: N=normal (15+1 records), R=reverse (22+5 records) and S=strike-slip (12+11 records). Classify mixed mechanisms by ratio of components $\geq 1.0$.
- For only five records difference between the distance to rupture surface and the distance to centroid could be more than 10%.
- 66 foreign near-source records ($d_r \leq 10$ km) from 17 crustal earthquakes supplement NZ data. Mainly from western North America including 17 from Imperial Valley and 12 from Northridge.
- Exclude one station's records (Atene A) due to possible topographical effects.
- Exclude records which could have been affected by different attenuation properties in the volcanic region.
- Note regional difference between Fiordland and volcanic region and rest of country but do model.
- Retain coefficients if significant at $\alpha = 0.05$.
- Anelastic term not significant.

## 2.155 Baag et al. (1998)

- Ground-motion model is:

$$\begin{aligned} \ln \mathrm{PGA} &= a_1 + a_2 M + a_3 \ln R + a_4 R \\ \text{where} \quad R &= \sqrt{R_{\mathrm{epi}}^2 + a_5^2} \end{aligned}$$

  where PGA is in cm/s$^2$, $a_1 = 0.4$, $a_2 = 1.2$, $a_3 = -0.76$, $a_4 = -0.0094$ and $a_5 = 10$ ($\sigma$ not given).
- This article has not been seen. The model presented may not be a fully empirical model.

## 2.156 Bouhadad et al. (1998)

- Ground-motion model is:

$$A = c \exp(\alpha M)[R^k + a]^{-\beta - \gamma R}$$

- Coefficients not given, only predictions.

## 2.157 Costa et al. (1998)

- Ground-motion model is:

$$\log(A) = a + bM + c\log(r)$$

where $A$ is in g, $a = -1.879$, $b = 0.431$ and $c = -1.908$ (for vertical components) and $a = -2.114$, $b = 0.480$ and $c = -1.693$ (for horizontal components).

- All records from digital instruments.

- Try including a term $d\log(M)$ but tests show that $d$ is negligible with respect to $a$, $b$ and $c$.

## 2.158 Manic (1998)

- Ground-motion model is:

$$\begin{aligned}\log(A) &= c_1 + c_2M + c_3\log(D) + c_4D + c_5S \\ D &= (R^2 + d_0^2)^{1/2}\end{aligned}$$

where $A$ is in g, $c_1 = -1.664$, $c_2 = 0.333$, $c_3 = -1.093$, $c_4 = 0$, $c_5 = 0.236$, $d_0 = 6.6$ and $\sigma = 0.254$.

- Uses four site categories (following Ambraseys et al. (1996)) but only two have data within them:

$S = 0$ Rock (R): $v_s > 750$ m/s, 92 records.

$S = 1$ Stiff soil (A): $360 < v_s \leq 750$ m/s, 184 records.

where $v_s$ is average shear-wave velocity in upper 30 m.

- Uses both horizontal components to get a more reliable set of data.

- Tries using $M_L$ rather than $M_s$, epicentral distance rather than hypocentral distance and constraining anelastic decay coefficient, $c_4$, to zero. Chooses combination which gives minimum $\sigma$.

## 2.159 Reyes (1998)

- Ground-motion model is:

$$\ln \mathrm{Sa} = \alpha_1 + \alpha_2(M-6) + \alpha_3(M-6)^2 + \alpha_4\ln R + \alpha_5R$$

where Sa is in cm/s$^2$, $\alpha_1 = 5.8929$, $\alpha_2 = 1.2457$, $\alpha_3 = -9.7565\times10^{-2}$, $\alpha_4 = -0.50$, $\alpha_5 = -6.3159\times10^{-3}$ and $\sigma = 0.420$.

- Use data from one station, University City (CU) in Mexico City, a relatively firm site.

## 2.160 Rinaldis et al. (1998)

- Ground-motion model is:

$$\ln Y = C_{14} + C_{22}M + C_{31}\ln(R+15) + C_{43}S + C_{54}F$$

where $Y$ is in cm/s$^2$, $C_{14} = 5.57$, $C_{22} = 0.82$, $C_{31} = -1.59$, $C_{43} = -0.14$, $C_{54} = -0.18$ and $\sigma = 0.68$. Assume 15 km inside $\ln(R + \ldots)$ from Theodulidis and Papazachos (1992).

- Use two site categories:

$S = 0$ Rock: includes stiff sites.

$S = 1$ Alluvium: includes both shallow and deep soil sites.

- Use two source mechanism categories:

$F = 0$ Thrust and strike-slip earthquakes.

$F = 1$ Normal earthquakes.

- Use epicentral distance because in Italy and Greece the surface geology does not show any evident faulting, consequently it is impossible to use a fault distance definition.

- Good distribution and coverage of data with respect to site category and source mechanism.

- Consider six strong-motion records (three Italian and three Greek) with different associated distances, magnitudes and record length and apply the different processing techniques of ENEA-ENEL and ITSAK to check if data from two databanks can be merged. Digitise six records using same equipment. ITSAK technique: subtract the reference trace (either fixed trace or trace from clock) from uncorrected accelerogram and select band-pass filter based on either Fourier amplitude spectra of acceleration components or selected using a different technique. ENEA-ENEL technique: subtract the reference trace from uncorrected accelerogram and select band-pass filter by comparing Fourier amplitude spectra of acceleration components with that of fixed trace. Find small differences in PGA, PGV, PGD so can merge Italian and Greek data into one databank.

- Use four step regression procedure, similar to that Theodulidis and Papazachos (1992) use. First step use only data with $M \geq 6.0$ ($7 \leq R \leq 138$ km) for which distances are more accurate to find geometrical coefficient $C_{31}$. Next find constant ($C_{12}$) and magnitude ($C_{22}$) coefficients using all data. Next find constant ($C_{13}$) and soil ($C_{43}$) coefficients using all data. Finally find constant ($C_{14}$) and source mechanism ($C_{54}$) coefficients using data with $M \geq 6.0$ for which focal mechanism is better constrained; final coefficients are $C_{14}$, $C_{22}$, $C_{31}$, $C_{43}$ and $C_{54}$. Investigate influence of distance on $C_{54}$ by subdividing data in final step into three categories with respect to distance ($7 \leq R \leq 140$ km, $7 \leq R \leq 100$ km and $7 \leq R \leq 70$ km).

- Equation intended as first attempt to obtain attenuation relations from combined databanks and site characteristics and fault rupture properties could and should be taken into account.

## 2.161 Sadigh and Egan (1998)

- Based on Sadigh et al. (1997), see Section 2.88.

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln[r_{\mathrm{rup}} + \exp(C_4 + C_5 M)]$$

where PGA is in g, for $M < 6.5$ $C_4 = 1.29649$ and $C_5 = 0.25$ and for $M \geq 6.5$ $C_4 = -0.48451$ and $C_5 = 0.524$. For rock sites: $C_3 = -2.100$, for strike-slip mechanism and $M < 6.5$ $C_1 = -0.949$ and $C_2 = 1.05$, for strike-slip mechanism and $M \geq 6.5$ $C_1 = -1.274$ and $C_2 = 1.10$, for reverse-slip and $M < 6.5$ $C_1 = 0.276$ and $C_2 = 0.90$ and for reverse-slip and $M \geq 6.5$ $C_1 = -1.024$ and $C_2 = 1.10$. For soil sites: $C_3 = -1.75$, for strike-slip mechanism and $M < 6.5$ $C_1 = -1.1100$ and $C_2 = 0.875$, for strike-slip mechanism and $M \geq 6.5$ $C_1 = -1.3830$ and $C_2 = 0.917$, for reverse-slip mechanism and $M < 6.5$ $C_1 = -0.0895$ and $C_2 = 0.750$ and for reverse-slip mechanism and $M \geq 6.5$ $C_1 = -1.175$ and $C_2 = 0.917$ ($\sigma$ not given).

- Use two site categories:

1. Rock: bedrock within about a metre of surface. Note that many such sites are soft rock with $V_s \leq 750$ m/s and a strong velocity gradient because of near-surface weathering and fracturing, 274 records.
2. Deep soil: greater than 20 m of soil over bedrock. Exclude data from very soft soil sites such as those from San Francisco bay mud, 690 records.

- Define crustal earthquakes as those that occur on faults within upper 20 to 25 km of continental crust.
- Consider source mechanism: RV=reverse (26+2) and SS=strike-slip (and some normal) (89+0). Classified as RV if rake> 45° and SS if rake< 45°. Find peak motions from small number of normal faulting earthquakes not to be significantly different than peak motions from strike-slip events so include in SS category.
- Separate equations for $M_w < 6.5$ and $M_w \geq 6.5$ to account for near-field saturation effects, for rock and deep soil sites and reverse and strike-slip earthquakes.
- Records from instruments in instrument shelters near ground surface or in ground floor of small, light structures.
- 4 foreign records (1 from Gazli and 3 from Tabas) supplement Californian records.

## 2.162 Sarma and Srbulov (1998)

- Ground-motion model is:

$$\log(a_p/g) = C_1 + C_2 M_s + C_3 d + C_4 \log d$$

  where $a_p$ is in g, for soil sites $C_1 = -1.86$, $C_2 = 0.23$, $C_3 = -0.0062$, $C_4 = -0.230$ and $\sigma = 0.28$ and for rock sites $C_1 = -1.874$, $C_2 = 0.299$, $C_3 = -0.0029$, $C_4 = -0.648$ and $\sigma = 0.33$.

- Use two site categories because of limited available information (based on nature of top layer of site regardless of thickness) for which derive separate equations:

  1. Soil
  2. Rock

- Use record from free-field or in basements of buildings $\leq 3$ storeys high.
- Use $M_s$ because better represents size of shallow earthquakes and is determined from teleseismic readings with much smaller standard errors than other magnitude scales and also saturates at higher magnitudes than all other magnitude scales except $M_w$ which is only available for relatively small portion of earthquakes. For some small earthquakes convert to $M_s$ from other magnitude scales.
- For very short records, $\leq 5$ s long, correct using parabolic baseline, for records $> 10$ s long correct using elliptical filter and for records between 5 and 10 s long both parabolic correction and filtering applied and select best one from appearance of adjusted time histories.
- Equations not any more precise than other attenuation relations but are simply included for completeness and for a comparison of effects of dataset used with other dataset. Data did not allow distinction between different source mechanisms.

## 2.163 Sharma (1998)

- Ground-motion model is:

$$\log A = c_1 + c_2 M - b \log(X + e^{c_3 M})$$

  where $A$ is in g, $c_1 = -1.072$, $c_2 = 0.3903$, $b = 1.21$, $c_3 = 0.5873$ and $\sigma = 0.14$.

- Considers two site categories but does not model:

  R Rock: generally granite/quartzite/sandstone, 41 records.

  S Soil: exposed soil covers on basement, 25 records.

- Focal depths between 7.0 and 50.0 km.

- Most records from distances > 50 km. Correlation coefficient between $M$ and $X$ is 0.63.

- Does not include source mechanism as parameter because not well defined and including many terms may lead to errors. Also neglects tectonic type because set is small and small differences are expected.

- Fit $\log A = -b \log X + c$ to data from each earthquake separately and find average $b$ equal to 1.292. Then fit $\log A = aM - b \log X + c$ to data from all earthquakes and find $b = 0.6884$. Fit $\log A = -b \log X + \sum d_i l_i$ to all data, where $l_i = 1$ for $i$th earthquake and 0 otherwise and find $b = 1.21$, use this for rest of analysis.

- Use weighted regression, due to nonuniform sampling over all $M$ and $X$. Divide data into distance bins 2.5 km wide up to 10 km and logarithmically dependent for larger distances. Within each bin each earthquake is given equal weight by assigning a relative weight of $1/n_{j,l}$, where $n_{j,l}$ is the number of recordings for $j$th earthquake in $l$th distance bin, then normalise so that sum to total number of recordings.

- Original data included two earthquakes with focal depths 91.0 km and 119.0 km and $M = 6.8$ and 6.1 which caused large errors in regression parameters due to large depths so excluded them.

- Check capability of data to compute coefficients by deleting, in turn, $c_1$, $c_2$ and $c_3$, find higher standard deviation.

- Makes one coefficient at a time equal to values given in Abrahamson and Litehiser (1989), finds sum of squares increases.

- Notes lack of data could make relationship unreliable.

## 2.164 Smit (1998)

- Ground-motion model is:

$$\log Y = a + bM - \log R + dR$$

  where $Y$ is in nm/s$^2$, $b = 0.868$, $d = -0.001059$, $\sigma = 0.35$, for horizontal PGA $a = 5.230$ and for vertical PGA $a = 5.054$.

- Most records from rock sites.

- Focal depths between 0 and about 27 km (most less than 10 km).

- Most records from $M_L < 3.5$.

- Most earthquakes have strike-slip mechanism.

- Uses records from high gain short period seismographs and from strong-motion instruments.

- Records are instrument corrected.
- Eliminates some far-field data from small magnitude earthquakes using signal to noise ratio criterion.
- Records cover entire azimuthal range.
- Notes that need more data in near field.
- Notes that care must be taken when using equations for prediction of ground motion in strong earthquakes ($M \approx 6$) because of lack of data.

## 2.165 Theodulidis (1998)

- Ground-motion models are (using $r_{hypo}$):

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln R$$

where PGA is in cm/s$^2$, $C_1 = 0.47$, $C_2 = 1.15$, $C_3 = -1.22$ and $\sigma = 0.64$; and (using $r_{epi}$):

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln(r + R_0)$$

where $C_1 = 2.18$, $C_2 = 1.19$, $C_3 = -1.64$, $R_0 = 10$ and $\sigma = 0.63$.

- Data from 7 free-field surface stations (STE, STC, FRM, TST, GRA, GRB and PRO) of the EuroSeisTest 3D array, which is located in an alluvial valley, recorded from April 1994 to January 1997.
- Believes model corresponds to intermediate soil.
- Data from ETNA and SSA-16 instruments.
- Focal depths from 0 to 15 km.
- Most data from $< 40$ km.
- Examines site effects by re-calculating $C_1$ for each station, called $C_{sta}$, but keeping $C_2$ and $C_3$ fixed. Report $C_{sta}$ for each station in graph. Find effect of soil is negigible ($-0.22 \leq C_{sta} \leq 0.33$).
- Prefers model with $r_{hypo}$ as focal depths highly accurate.
- Compares observations normalized to 20 km against predictions and total residuals w.r.t. $r_{hypo}$ and $M_w$. Finds no trends.

## 2.166 Theodulidis et al. (1998)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M + C_3 \ln(\Delta + 15) + 0.31 S$$

where $Y$ is in cm/s$^2$, $C_1 = 4.85$, $C_2 = 1.02$, $C_3 = -1.90$ and $\sigma = 0.50$ (the coefficients 15 and 0.31 were taken from Theodulidis and Papazachos (1992) since they cannot be determined by the data).

- Use 2 site classes:

$S = 0$ Bedrock

$S = 1$ Alluvium

- Use data from mainshock and aftershocks of 13 May 1995 Kozani-Grevena earthquake.

- Use a four-step approach: derive relation between PGA and intensity (using only data from largest events), assess decay of PGA with distance, adjust PGA to a fixed distance using this equation and finally regression to find remaining coefficients[13].
- Adjust all data to $M_w6.6$ and compare observed and predicted PGAs. Find reasonable fit.

## 2.167 Cabañas et al. (1999), Cabañas et al. (2000), Benito et al. (2000) & Benito and Gaspar-Escribano (2007)

- Ground-motion model is:

$$\ln A = C_1 + C_2 M + C_3(R + R_0) + C_4 \ln(R + R_0) + C_5 S$$

where $A$ is in $\mathrm{cm/s^2}$, $C_1 = 0$, $C_2 = 0.664$, $C_3 = 0.009$, $C_4 = -2.206$, $R_0 = 20$, $C_5 = 8.365$ (for S1), $C_5 = 8.644$ (for S2), $C_5 = 8.470$ (for S3) and $C_5 = 8.565$ (for S4) for horizontal PGA using $r_{epi}$ and $M_s$ and all Mediterranean data, $C_1 = 0$, $C_2 = 0.658$, $C_3 = 0.008$, $C_4 = -2.174$, $R_0 = 20$, $C_5 = 7.693$ (for S1), $C_5 = 7.915$ (for S2) and $C_5 = 7.813$ (for S4) ($C_5$ not derived for S3) for vertical PGA using $r_{epi}$ and $M_s$ and all Mediterranean data. $\sigma$ is not given ($R^2$ is reported).

- Use four site categories:

  S1 Hard basement rock.

  S2 Sedimentary rock and conglomerates.

  S3 Glacial deposits.

  S4 Alluvium and consolidated sediments.

- Derive separate equations using data from Mediterranean region and also just using data from Spain.
- Equations for Spain derived using $m_{bLg}$.
- Spanish data all from earthquakes with $2.5 \leq m_{bLg} \leq 6.0$ and $0 \leq r_{hypo} \leq 300$ km.

## 2.168 Chapman (1999)

- Ground-motion model is:

$$\log_{10} Y = a + b(M - 6) + c(M - 6)^2 + d \log(r^2 + h^2)^{1/2} + eG_1 + fG_2$$

where $Y$ is in $\mathrm{cm/s^2}$, $a = 3.098$, $b = 0.3065$, $c = -0.07570$, $d = -0.8795$, $h = 6.910$, $e = 0.1452$, $f = 0.1893$ and $\sigma = 0.2124$.

- Use three site categories:

A & B $V_{s,30} > 760$ m/s, 24 records $\Rightarrow G_1 = 0, G_2 = 0$.

C $360 < V_{s,30} \leq 760$ m/s, 116 records $\Rightarrow G_1 = 1, G_2 = 0$.

D $180 < V_{s,30} \leq 360$ m/s, 164 records $\Rightarrow G_1 = 0, G_2 = 1$.

- Uses records from ground level or in basements of structures of two stories or less, and excludes records from dam or bridge abutments.

[13]The procedure is not entirely clear.

- Selects records which include major motion portion of strong-motion episode, represented by S wavetrain. Excludes records triggered late on S wave or those of short duration terminating early in coda.
- Most records already corrected. Some records instrument corrected and 4-pole causal Butterworth filtered (corner frequencies 0.1 and 25 Hz). Other records instrument corrected and 4-pole or 6-pole causal Butterworth bandpass filtered (corner frequencies 0.2 and 25 Hz). All data filtered using 6-pole causal high-pass Butterworth filter with corner frequency 0.2 Hz and velocity and displacement curves examined.
- Uses method of Campbell (1997) to reduce bias due to non-triggered instruments, for some recent shocks. Firstly uses all data to determine minimum distances (which are functions of magnitude and site condition) at which 16th percentile values of PGA are $< 0.02\,\mathrm{g}[0.2\,\mathrm{m/s}]$ (corresponding to $0.01\,\mathrm{g}[0.1\,\mathrm{m/s}]$ vertical component trigger threshold). Next delete records from larger distances and repeat regression.
- Check residuals against distance and magnitude for each site class; find no obvious non-normal magnitude or distance dependent trends.

## 2.169 Cousins et al. (1999)

- Based on Zhao et al. (1997) see Section 2.154
- Ground-motion model is:

$$\begin{aligned}\log_{10}\mathrm{PGA} &= A_1M_w + A_2\log_{10}R + A_3h_c + A_4 + A_5 + A_6 + A_7R + A_8M_w + A_9\\ &\quad + A_{10}R_v\end{aligned}$$

  where PGA is in $\mathrm{m/s^2}$, $R = \sqrt{r^2 + d^2}$ and $R_v$ is distance travelled by direct seismic wave through volcanic region. $A_5$ only for crustal reverse, $A_6$ only for interface, $A_7$ only for strong and weak rock, $A_8$ only for strong rock, $A_9$ only for strong rock, $A_1 = 0.2955$, $A_2 = -1.603$, $A_3 = 0.00737$, $A_4 = -0.3004$, $A_5 = 0.1074$, $A_6 = -0.1468$, $A_7 = -0.00150$, $A_8 = 0.3815$, $A_9 = -2.660$, $A_{10} = -0.0135$, $d = 19.0$ and $\sigma = 0.24$.
- Originally considers five site categories but retain three:
  1. Strong rock: $V_s > 700\,\mathrm{m/s}$
  2. Weak rock: $375 \leq V_s \leq 700\,\mathrm{m/s}$ and category AV those sites with a very thin layer ($\leq 3\,\mathrm{m}$) overlying rock
  3. Soil: everything else
- Depth to centroid of rupture, $h_c$, used, $4 \leq h_c \leq 94\,\mathrm{km}$.
- 60% on soil, 40% on rock
- Consider tectonic type: C=Crustal (12+17), I=Interface (5+0) and S=Slab(8+0)
- Consider source mechanism: N=normal (6+1), R=reverse (12+5) and S=strike-slip (7+11). Mixed classified by ratio of components $\geq 1.0$.
- Mixture of analogue and digital accelerograms (72%) and seismograms (28%)
- Accelerograms sampled at 100–250 samples/sec. Bandpass frequencies chosen by analysis of Fourier amplitude spectrum compared with noise spectrum. $f_{\min}$ between 0.15 and 0.5 Hz and $f_{\max}$ equal to 25 Hz. Instrument correction applied to analogue records.

- Seismograms sampled at 50–100 samples/sec. Differentiated once. Instrument corrected and high pass filtered with $f_{\min} = 0.5$ Hz. No low pass filter needed.
- Clipped seismograms usually retained.
- Directional effect noticed but not modelled.
- Most records from more than 100 km away. Note lack of near-source data.
- Records from accelerograms further away than first operational non-triggering digital accelerograph, which had a similar triggering level, were excluded.
- Models difference between high attenuating volcanic and normal regions.

## 2.170 Gallego and Ordaz (1999) & Gallego (2000)

- No details known.

## 2.171 Ólafsson and Sigbjörnsson (1999)

- Ground-motion model is:

$$\log(a_{\max}) = \phi_1 + \phi_2 \log M_0 - \phi_3 \log(R)$$

  where $a_{\max}$ is in cm/s$^2$, $M_0$ is in dyn cm and $R$ is in cm, $\phi_1 = 0.0451$, $\phi_2 = 0.3089$, $\phi_3 = 0.9642$ and $\sigma = 0.3148$.
- Instruments in basement of buildings located on rock or very stiff ground.
- Records from 21 different stations.
- Focal depths between 1 and 11 km.
- Most records from digital instruments with 200 Hz sampling frequency and high dynamic range.
- Seismic moments calculated using the strong-motion data.
- Most data from $M_0 \leq 5 \times 10^{23}$dyn cm and from $d_e \leq 40$ km.

## 2.172 Si and Midorikawa (1999, 2000)

- Ground-motion model for rupture distance is:

$$\log A = aM_w + hD + \sum d_i S_i + e - \log(X + c_1 10^{c_2 M_w}) - kX$$

  where $A$ is in cm/s$^2$, $a = 0.50$, $h = 0.0036$, $d_1 = 0$, $d_2 = 0.09$, $d_3 = 0.28$, $e = 0.60$, $k = 0.003$ and $\sigma = 0.27$ ($c_1$ and $c_2$ are not given).

  Ground-motion model for equivalent hypocentral distance (EHD) is:

$$\log A = aM_w + hD + \sum d_i S_i + e - \log X_{eq} - kX_{eq}$$

  where $A$ is in cm/s$^2$, $a = 0.50$, $h = 0.0043$, $d_1 = 0$, $d_2 = 0.01$, $d_3 = 0.22$, $e = 0.61$, $k = 0.003$ and $\sigma = 0.28$.
- Use two site categories for most records following Joyner and Boore (1981):

1. Rock
2. Soil

- Records from free-field or small buildings where soil-structure interaction effects are negligible.
- Records from three different type of instrument so instrument correct. Filter with corner frequencies, chosen according to noise level, a) 0.08 & 0.15 Hz, b) 0.10 & 0.20 Hz or c) 0.15 to 0.33 Hz.
- Exclude records obviously affected by soil liquefaction.
- Focal depth (defined as average depth of fault plane), $D$, between 6 and 120 km; most less than 40 km.
- Select records satisfying: distances $< 300$ km for $M_w > 7$, distances $< 200$ km for $6.6 \leq M_w \leq 7$, distances $< 150$ km for $6.3 \leq M_w \leq 6.5$ and distances $< 100$ km for $M_w < 6.3$.
- Fix $k = 0.003$.
- Multiply rock PGAs by 1.4 to get soil PGA based on previous studies.
- Use three fault types: crustal (<719 records from 9 earthquakes) $\Rightarrow S_1 = 1, S_2 = 0, S_3 = 0$, inter-plate (<291 records from 7 earthquakes) $\Rightarrow S_2 = 1, S_1 = 0, S_3 = 0$ and intra-plate (<127 records from 5 earthquakes) $\Rightarrow S_3 = 1, S_1 = 0, S_2 = 0$.
- Use weighted regression giving more weight to near-source records (weight factor of 8 for records $< 25$ km, 4 for records between 20 and 50 km, 2 for records between 50 and 100 km and 1 for records $> 100$ km). Use only three earthquakes with sufficient near-source data to find $c_1$ and $c_2$ then use all earthquakes to find $a$, $h$, $d_i$, $e$ in second stage using weighted regression dependent on number of recordings for each earthquake (weight factor of 3 for >83 records, 2 for between 19 and 83 records, 1 for <19 records.
- Note that $M_w$ and $D$ are positively correlated so $a$ and $h$ may not be correctly determined when using rupture distance. Constrain $a$ for rupture distance model to that obtained for EHD and constrain PGA to be independent of magnitude at 0 km and repeat regression. Coefficients given above.

## 2.173 Spudich et al. (1999) & Spudich and Boore (2005)

- Update of Spudich et al. (1997) see Section 2.145.
- Ground-motion model is:

$$\begin{aligned}\log_{10} Z &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \log_{10} D + b_6\Gamma \\ \text{with: } D &= \sqrt{r_{jb}^2 + h^2}\end{aligned}$$

  where $Z$ is in g, $b_1 = 0.299$, $b_2 = 0.229$, $b_3 = 0$, $b_5 = -1.052$, $b_6 = 0.112$, $h = 7.27$ and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$ where $\sigma_1 = 0.172$, $\sigma_2 = 0.108$ and for randomly oriented horizontal component $\sigma_3 = 0.094$ and for larger horizontal component $\sigma_3 = 0$.

- Values of $\sigma_3$ (used to compute standard deviation for a randomly orientated component) reported in Spudich et al. (1999) are too large by a factor of $\sqrt{2}$.
- Use two site categories (could not use more or $V_{s,30}$ because not enough data):

$\Gamma = 0$ Rock: includes hard rock (12 records) (plutonic igneous rocks, lava flows, welded tuffs and metamorphic rocks unless severely weathered when they are soft rock), soft rock (16 records) (all sedimentary rocks unless there was some special characteristic noted in description, such as crystalline limestone or massive cliff-forming sandstone when they are hard rock) and unknown rock (8 records). 36 records in total.

$\Gamma = 1$ Soil (alluvium, sand, gravel, clay, silt, mud, fill or glacial outwash of more than 5 m deep): included shallow soil (8 records) (5 to 20 m deep), deep soil (77 records) (> 20 m deep) and unknown soil (21 records). 106 records in total.

- Applicable for extensional regimes, i.e. those regions where lithosphere is expanding areally. Significantly different ground motion than non-extensional areas.
- Criteria for selection of records is: $M_w \geq 5.0$, $d_f \leq 105$ km. Reject records from structures of more than two storeys or from deeply embedded basements or those which triggered on S wave. Also reject those close to dams which may be affected by dam. Also only use records already digitised.
- Include records from those instrument beyond cutoff distance, i.e. beyond first instrument which did not trigger, because of limited records and lack of data on non-triggering.
- Not enough data to be able to find all coefficients so use $b_2$ and $b_3$ from Boore et al. (1993) and $b_6$ from Boore et al. (1994a).
- One-stage maximum likelihood method used because many events used which only have one record associated with them and the two-stage method underestimates the earthquake-to-earthquake component of variation in that case.
- Correction technique based on uniform correction and processing using upper, $f_h$, and lower, $f_l$, frequencies for passband based on a visual inspection of Fourier amplitude spectrum and baseline fitting with a polynomial of degree 5.
- Check to see whether normal and strike-slip earthquakes give significantly different ground motions. No significant difference.

## 2.174 Wang et al. (1999)

- Ground-motion model is:

$$\log A = a + bM_s + c \log R + dR$$

where $A$ is in cm/s$^2$, using just soil records $a = 0.430$, $b = 0.428$, $c = -0.764$, $d = -0.00480$ and $\sigma = 0.271$.

- Use records from aftershocks of Tangshan earthquake.
- Focal depths between 5.7 and 12.9 km.
- Note $M_s$ values used may have some systematic deviation from other regions and errors, which decrease with increasing magnitude, can reach $\pm 0.5$.
- Errors in epicentral locations not less than 2 km. Reject 3 records because have $R < 2$ km, if include then find standard deviation increases and $c$ obtained is unreasonable.
- Fit equation to all data (both rock and soil) but note that only for reference. Also fit equation to soil data only ($2.1 \leq R \leq 41.3$ km, $3.7 \leq M_s \leq 4.9$, 33 records from 6 earthquakes).
- Remove all four earthquakes with $M_s < 4.0$, for which error in magnitude determination is large, and fit equation to soil data only ($2.8 \leq R \leq 41.1$ km, $4.5 \leq M_s \leq 4.9$, 13 records from 2 earthquakes). Find smaller uncertainties.
- Also fit data to $\log A = a + bM_s - c \log(R + R_0)$; find similar results.
- Also use resultant of both horizontal components; find similar results to using larger component.

- Also fit eastern North America data ($3.9 \leq R \leq 61.6$ km, $2.3 \leq M_s \leq 3.8$, 7 records from 3 earthquakes); find similar attenuation characteristics.
- All equations pass F-tests.

## 2.175 Zaré et al. (1999)

- Ground-motion model is:

$$\log A = aM - bX - d\log X + c_i S_i$$

where units of $A$ not given (but probably m/s$^2$), for vertical PGA $a = 0.362$, $b = 0.0002$, $c_1 = -1.124$, $c_2 = -1.150$, $c_3 = -1.139$, $c_4 = -1.064$, $d = 1$ and $\sigma = 0.336$ and for horizontal PGA $a = 0.360$, $b = 0.0003$, $c_1 = -0.916$, $c_2 = -0.862$, $c_3 = -0.900$, $c_4 = -0.859$, $d = 1$ and $\sigma = 0.333$.

- Use four site categories, which were based on $H/V$ receiver function (RF) measurements (use geotechnical measurements at 50 sites and strong-motion accelerograms at other sites):

Site class 1 RF does not exhibit any significant amplification below 15 Hz. Corresponds to rock and stiff sediment sites with average S-wave velocity in top 30 m ($V_{s,30}$) $> 700$ m/s. Use $c_1$.

Site class 2 RF exhibits a fundamental peak exceeding 3 at a frequency between 5 and 15 Hz. Corresponds to stiff sediments and/or soft rocks with $500 < V_{s,30} \leq 700$ m/s. Use $c_2$.

Site class 3 RF exhibits peaks between 2 and 5 Hz. Corresponds to alluvial sites with $300 < V_{s,30} \leq 500$ m/s. Use $c_3$.

Site class 4 RF exhibits peaks for frequencies $< 2$ Hz. Corresponds to thick soft alluvium. Use $c_4$.

- Only 100 records are associated with earthquakes with known focal mechanisms, 40 correspond to strike-slip/reverse, 31 to pure strike-slip, 24 to pure reverse and 4 to a pure vertical plane. Note that use of equations should be limited to sources with such mechanisms.
- Use only records for which the signal to noise ratio was acceptable.
- Source parameters from teleseismic studies available for 279 records.
- Calculate source parameters directly from the strong-motion records for the remaining 189 digital records using a source model. Hypocentral distance from S-P time and seismic moment from level of acceleration spectra plateau and corner frequency.
- Focal depths from 9 to 133 km but focal depth determination is very imprecise and majority of earthquakes are shallow.
- Suggest that whenever estimation of depth of earthquake is impossible use distance to surface projection of fault rather than hypocentral distance because differences between hypocentral and epicentral distances are not significant for shallow earthquakes.
- Also derive equations based only on data from the Zagros thrust fault zone (higher seismic activity rate with many earthquakes with $4 \leq M \leq 6$) and based only on data from the Alborz-Central Iran zone (lower seismic activity rate but higher magnitude earthquakes). Find some differences between regions.
- Investigate fixing $d$ to 1 (corresponding to body waves) and to 0.5 (corresponding to surface waves).
- Note that there are very few (only two) near-field (from less than 10 km from surface fault rupture) records from earthquakes with $M_w > 6.0$ and so results are less certain for such combinations of magnitude and distance.

## 2.176 Ambraseys and Douglas (2000), Douglas (2001a) & Ambraseys and Douglas (2003)

- Ground-motion model is:

$$\log y = b_1 + b_2 M_s + b_3 d + b_A S_A + b_S S_S$$

  where $y$ is in $\mathrm{m/s^2}$, for horizontal PGA $b_1 = -0.659$, $b_2 = 0.202$, $b_3 = -0.0238$, $b_A = 0.020$, $b_S = 0.029$ and $\sigma = 0.214$ and for vertical PGA $b_1 = -0.959$, $b_2 = 0.226$, $b_3 = -0.0312$, $b_A = 0.024$, $b_S = 0.075$ and $\sigma = 0.270$.

  Assume decay associated with anelastic effects due to large strains and cannot use both $\log d$ and $d$ because highly correlated in near field.

- Use four site categories (often use shear-wave velocity profiles):

  L Very soft soil: approximately $V_{s,30} < 180$ m/s, (combine with category S) $\Rightarrow S_A = 0, S_S = 1$, 4 records.

  S Soft soil: approximately $180 \leq V_{s,30} < 360$ m/s $\Rightarrow S_A = 0, S_S = 1$, 87 records.

  A Stiff soil: approximately $360 \leq V_{s,30} < 750$ m/s $\Rightarrow S_A = 1, S_S = 0$, 68 records.

  R Rock: approximately $V_{s,30} > 750$ m/s $\Rightarrow S_A = 0, S_S = 0$, 23 records.

  where $V_{s,30}$ is average shear-wave velocity to 30 m. Know no site category for 14 records.

- Use only records from 'near field' where importance of vertical acceleration is greatest. Select records with $M_s \geq 5.8$, $d \leq 15$ km and focal depth $h \leq 20$ km. Do not use magnitude dependent definition to avoid correlation between magnitude and distance for the records.

- Focal depths, $1 \leq h \leq 19$ km.

- Majority (133 records, 72%) of records from W. N. America, 40 records (22%) from Europe and rest from Canada, Nicaragua, Japan and Taiwan.

- Consider three source mechanisms but do not model:

  1. Normal, 8 earthquakes, 16 records.
  2. Strike-slip, 18 earthquakes, 72 records.
  3. Thrust, 16 earthquakes, 98 records.

- Use only free-field records using definition of Joyner and Boore (1981), include a few records from structures which violate this criterion but feel that structure did not affect record in period range of interest.

- Records well distributed in magnitude and distance so equations are well constrained and representative of entire dataspace. Note lack of records from normal earthquakes. Correlation coefficient between magnitude and distance is −0.10.

- Use same correction procedure (elliptical filter with pass band 0.2 to 25 Hz, roll-off frequency 1.001 Hz, sampling interval 0.02 s, ripple in pass-band 0.005 and ripple in stop-band 0.015 with instrument correction) for almost all records. Use 19 records available only in corrected form as well because in large magnitude range. Think different correction procedures will not affect results.

- Try both one-stage and two-stage regression method for horizontal PGA; find large differences in $b_2$ but very similar $b_3$. Find that (by examining cumulative frequency distribution graphs for magnitude scaling of one-stage and two-stage methods) that two-stage better represents large magnitude range than one-stage method. Examine plot of amplitude factors from first stage of two-stage method against $M_s$; find that amplitude factor of the two Kocaeli ($M_s = 7.8$) records is far below least squares line through the amplitude factors. Remove the two Kocaeli records and repeat analysis; find $b_2$ from two-stage method is changed by a lot but $b_2$ from one-stage method is not. Conclude two-stage method is too greatly influenced by the two records from Kocaeli and hence use one-stage method.

- Find $b_2$ and $b_3$ significantly different than 0 at 5% level but $b_A$ and $b_S$ not significant.

## 2.177 Bozorgnia et al. (2000)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= c_1 + c_2 M_w + c_3(8.5 - M_w)^2 \\ &\quad + c_4 \ln(\{R_s^2 + [(c_5 S_{HS} + c_6\{S_{PS} + S_{SR}\} + c_7 S_{HR}) \\ &\quad \exp(c_8 M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10} F_{SS} + c_{11} F_{RV} + c_{12} F_{TH} \\ &\quad + c_{13} S_{HS} + c_{14} S_{PS} + c_{15} S_{SR} + c_{16} S_{HR}\end{aligned}$$

- Use four site categories:

  HS Holocene soil: recent alluvium $\Rightarrow S_{HS} = 1, S_{PS} = 0, S_{SR} = 0, S_{HR} = 0$.

  PS Pleistocene soil: older alluvium $\Rightarrow S_{PS} = 1, S_{HS} = 0, S_{SR} = 0, S_{HR} = 0$.

  SR Soft rock $\Rightarrow S_{SR} = 1, S_{HS} = 0, S_{PS} = 0, S_{HR} = 0$.

  HR Hard rock $\Rightarrow S_{HR} = 1, S_{HS} = 0, S_{PS} = 0, S_{SR} = 0$.

- Consider all records to be free-field.

- All earthquakes occurred in shallow crustal tectonic environment.

- Consider three source mechanisms: strike-slip ($F_{SS} = 1, F_{RV} = 0, F_{TH} = 0$) 20+ earthquakes (including 1+ normal faulting shock), reverse ($F_{RV} = 1, F_{SS} = 0, F_{TH} = 0$) 7+ earthquakes and thrust ($F_{TH} = 1, F_{SS} = 0, F_{RV} = 0$) 6+ earthquakes.

- Coefficients not given, only predictions.

## 2.178 Campbell and Bozorgnia (2000)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= c_1 + c_2 M_w + c_3(8.5 - M_w)^2 + c_4 \ln(\{R_s^2 + [(c_5 + c_6\{S_{PS} + S_{SR}\} + c_7 S_{HR}) \\ &\quad \exp(c_8 M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10} F_{SS} + c_{11} F_{RV} + c_{12} F_{TH} \\ &\quad + c_{13} S_{HS} + c_{14} S_{PS} + c_{15} S_{SR} + c_{16} S_{HR}\end{aligned}$$

  where $Y$ is in g, for horizontal uncorrected PGA $c_1 = -2.896$, $c_2 = 0.812$, $c_3 = 0$, $c_4 = -1.318$, $c_5 = 0.187$, $c_6 = -0.029$, $c_7 = -0.064$, $c_8 = 0.616$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.179$, $c_{12} = 0.307$, $c_{13} = 0$, $c_{14} = -0.062$, $c_{15} = -0.195$, $c_{16} = -0.320$ and $\sigma = 0.509$, for horizontal corrected PGA $c_1 = -4.033$, $c_2 = 0.812$, $c_3 = 0.036$, $c_4 = -1.061$, $c_5 = 0.041$, $c_6 = -0.005$, $c_7 = -0.018$, $c_8 = 0.766$, $c_9 = 0.034$, $c_{10} = 0$, $c_{11} = 0.343$, $c_{12} = 0.351$, $c_{13} = 0$, $c_{14} = -0.123$, $c_{15} = -0.138$, $c_{16} = -0.289$ and $\sigma = 0.465$, for vertical uncorrected PGA $c_1 = -2.807$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.391$, $c_5 = 0.191$, $c_6 = 0.044$, $c_7 = -0.014$, $c_8 = 0.544$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.091$, $c_{12} = 0.223$, $c_{13} = 0$, $c_{14} = -0.096$, $c_{15} = -0.212$, $c_{16} = -0.199$ and $\sigma = 0.548$ and for vertical corrected PGA $c_1 = -3.108$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.287$, $c_5 = 0.142$, $c_6 = 0.046$, $c_7 = -0.040$, $c_8 = 0.587$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.253$, $c_{12} = 0.173$, $c_{13} = 0$, $c_{14} = -0.135$, $c_{15} = -0.138$, $c_{16} = -0.256$ and $\sigma = 0.520$.

- Use four site categories:

  HS Holocene soil: soil deposits of Holocene age (11,000 years or less), generally described on geological maps as recent alluvium, approximate average shear-wave velocity in top 30 m is 290 m/s $\Rightarrow S_{HS} = 1, S_{PS} = 0, S_{SR} = 0, S_{HR} = 0$.

  PS Pleistocene soil: soil deposits of Pleistocene age (11,000 to 1.5 million years) , generally described on geological maps as older alluvium or terrace deposits, approximate average shear-wave velocity in top 30 m is 370 m/s $\Rightarrow S_{PS} = 1, S_{HS} = 0, S_{SR} = 0, S_{HR} = 0$.

  SR Soft rock: primarily includes sedimentary rock deposits of Tertiary age (1.5 to 100 million years), approximate average shear-wave velocity in top 30 m is 420 m/s $\Rightarrow S_{SR} = 1, S_{HS} = 0, S_{PS} = 0, S_{HR} = 0$.

  HR Hard rock: primarily includes older sedimentary rock deposits, metamorphic rock and crystalline rock, approximate average shear-wave velocity in top 30 m is 800 m/s $\Rightarrow S_{HR} = 1, S_{HS} = 0, S_{PS} = 0, S_{SR} = 0$.

- Earthquakes from shallow crustal active tectonic regions.

- Most earthquakes with $6 \leq M_w \leq 7$.

- Use three source mechanism categories:

  SS Strike-slip: primarily vertical or near-vertical faults with predominantly lateral slip (includes only normal faulting earthquake in set), $\Rightarrow F_{SS} = 1, F_{RV} = 0, F_{TH} = 0$.

  RV Reverse: steeply dipping faults with either reverse or reverse-oblique slip, $\Rightarrow F_{RV} = 1, F_{SS} = 0, F_{TH} = 0$.

  TH Thrust: shallow dipping faults with predominantly thrust slip including blind-thrust shocks, $\Rightarrow F_{TH} = 1, F_{SS} = 0, F_{RV} = 0$.

- Consider all records to be free-field. Records from ground level in instrument shelter or a building <3 storeys high (<7 if located on hard rock). Include records from dam abutments to increase number of rock records. Exclude data from basements of buildings of any size or at toe or base of dams.

- Exclude data from $R_s > 60$ km to avoid complicating problems related to arrival of multiple reflections from lower crust. Distance range is believed to include most ground shaking amplitudes of engineering interest, except for possibly long period spectral accelerations on extremely poor soil.

- Equations for uncorrected (Phase 1 standard level of processing) and corrected (Phase 2 standard level of processing).

- Find sediment depth (depth to basement rock) has significant effect on amplitude of ground motion and should be taken into account; it will be included once its mathematical form is better understood.

## 2.179 Field (2000)

- Ground-motion model is:

$$\mu(M, r_{\mathrm{jb}}, V_s) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln[(r_{\mathrm{jb}}^2 + h^2)^{0.5}] + b_v \ln(V_s/V_a)$$

  $\mu(M, r_{\mathrm{jb}}, V_s)$ is natural logarithm of ground-motion parameter (e.g. ln(PGA) where PGA is in g), $b_{1,ss} = 0.853 \pm 0.28$, $b_{1,rv} = 0.872 \pm 0.27$, $b_2 = 0.442 \pm 0.15$, $b_3 = -0.067 \pm 0.16$, $b_5 = -0.960 \pm 0.07$, $b_v = -0.154 \pm 0.14$, $h = 8.90$ km, $V_a = 760$ m/s, $\sigma = 0.47 \pm 0.02$ (intra-event) and $\tau = 0.23$ (inter-event). Also gives overall $\sigma = (0.93 - 0.10M_w)^{0.5}$ for $M_w \leq 7.0$ and overall $\sigma = 0.48$ for $M_w > 7.0$.

- Uses six site classes (from Wills et al. (2000)):

  B $760 \leq V_s \leq 1500$ m/s. Uses $V_s = 1000$ m/s in regression. 12 records.

  BC Boundary between B and C. Uses $V_s = 760$ m/s in regression. 36 records.

  C $360 \leq V_s \leq 760$ m/s. Uses $V_s = 560$ m/s in regression. 16 records.

  CD Boundary between C and D. Uses $V_s = 360$ m/s in regression. 166 records.

  D $180 \leq V_s \leq 360$ m/s. Uses $V_s = 270$ m/s in regression. 215 records.

  DE Boundary between D and E. Uses $V_s = 180$ m/s in regression. 2 records.

- Uses data from the SCEC Phase III strong-motion database.

- Uses three faulting mechanism classes:

Strike-slip Use $b_{1,ss}$. 14 earthquakes, 103 records.

Reverse Use $b_{1,rv}$. 6 earthquakes, 300 records.

Oblique Use $0.5(b_{1,ss} + b_{1,rv})$. 8 earthquakes, 46 records.

- Notes that data is unbalanced in that each earthquake has a different number of records for each site type hence it is important to correct observations for the inter-event terms before examining residuals for site effects.

- Plots average site class residuals w.r.t. BC category and the residuals predicted by equation and finds good match.

- Uses 197 records with basin-depth estimates (depth defined to the 2.5 km/s shear-wave velocity isosurface) to examine dependence of inter-event corrected residuals w.r.t. basin depth. Plots residuals against basin depth and fits linear function. Finds that all slopes are significantly different than zero by more than two sigmas. Finds a significant trend in subset of residuals where basin-depths are known w.r.t. magnitude hence needs to test whether basin-depth effect found is an artifact of something else. Hence derives Ground-motion models (coefficients not reported) using only subset of data for which basin-depth estimates are known and examines residuals w.r.t. basin-depth for this subset. Finds similar trends as before hence concludes found basin effect is truly an effect of the basin. Notes that basin-depth coefficients should be derived simultaneously with other coefficients but because only a subset of sites have a value this could not be done.

- Tests for nonlinearity by plotting residuals for site class D w.r.t. predicted ground motion for BC boundary. Fits linear equation. Finds slope for PGA is significantly different than zero.

- Notes that due to large number of class D sites site nonlinearity could have affected other coefficients in equation leading to less of a trend in residuals. Tests for this by plotting residuals for site classes B and BC combined w.r.t. predicted ground motion for BC boundary. Fits linear equation. Finds non-significant slopes. Notes that nonlinearity may lead to rock ground motions being underestimated by model but not enough data to conclude.

- Investigates inter-event variability estimate through Monte Carlo simulations using 250 synthetic databases because uncertainty estimate of $\tau$ was considered unreliable possibly due to limited number of events. Find that there could be a problem with the regression methodology adopted w.r.t. the estimation of $\tau$.

- Plots squared residuals w.r.t. magnitude and fits linear equations. Finds significant trends. Notes that method could be not statistically correct because squared residuals are not Gaussian distributed.

- Plots squared residuals w.r.t. $V_s$ and does not find a significant trend.

- Provides magnitude-dependent estimates of overall $\sigma$ up to $M_w7.0$ and constant overall $\sigma$ for larger magnitudes.
- Tests normality of residuals using Kolmogorov-Smirnov test and finds that the null hypothesis cannot be rejected. Also examines theoretical quantile-quantile plots and finds nothing notable.

## 2.180 Jain et al. (2000)

- Ground-motion model is:
$$\ln(\text{PGA}) = b_1 + b_2 M + b_3 R + b_4 \ln(R)$$
where PGA is in g, for central Himalayan earthquakes $b_1 = -4.135$, $b_2 = 0.647$, $b_3 = -0.00142$, $b_4 = -0.753$ and $\sigma = 0.59$ and for non-subduction earthquakes in N.E. India $b_1 = -3.443$, $b_2 = 0.706$, $b_3 = 0$, $b_4 = -0.828$ and $\sigma = 0.44$ (coefficients of other equations not given here because they are for a particular earthquake).
- Data from strong-motion accelerographs (SMA) and converted from structural response recorders (SRR), which consist of six seismoscopes with natural periods 0.40, 0.75 and 1.25 s and damping levels 5 and 10%. Conversion achieved by deriving spectral amplification factors (ratio of response ordinate and PGA) using SMA recordings close to SRR, checking that these factors were independent of distance. The mean of the six estimates of PGA (from the six spectral ordinates) from each SRR are then used as PGA values. Check quality of such PGA values through statistical comparisons and discard those few which appear inconsistent.
- Data split into four categories for which derive separate equations:
  a Central Himalayan earthquakes (thrust): (32 SMA records, 117 SRR records), 3 earthquakes with $5.5 \leq M \leq 7.0$, focal depths $10 \leq h \leq 33$ km and $2 \leq R \leq 322$ km.
  b Non-subduction earthquakes in NE India (thrust): (43 SMA records, 0 SRR records), 3 earthquakes with $5.2 \leq M \leq 5.9$, focal depths $33 \leq h \leq 49$ km and $6 \leq R \leq 243$ km.
  c Subduction earthquakes in NE India: (33 SMA records, 104 SRR records), 1 earthquake with $M = 7.3$, focal depth $h = 90$ km and $39 \leq R \leq 772$ km.
  d Bihar-Nepal earthquake in Indo-Gangetic plains (strike-slip): (0 SMA records, 38 SRR records), 1 earthquake with $M = 6.8$, focal depth $h = 57$ km and $42 \leq R \leq 337$ km.
- Limited details of fault ruptures so use epicentral distance.
- Use epicentral locations which give best correlation between distance and PGA.
- Find PGA not well predicted by earlier equations.
- Simple model and regression method because of limited data.
- Remove one PGA value from category b equation because significantly affecting equation and because epicentral location only approximate.
- Constrain $b_3$ for category b equation to zero because otherwise positive.
- Category c originally contained another earthquake (14 SMA records, $M = 6.1$, $200 \leq d \leq 320$ km) but gave very small $b_2$ so exclude it.
- Equations for category c and category d have $b_2$ equal to zero because only one earthquake.
- Find considerable differences between predicted PGA in different regions.
- Note lack of data hence use equations only as first approximation.

## 2.181 Kobayashi et al. (2000)

- Ground-motion model is:

$$\log_{10} y = aM - bx - \log(x + c10^{dM}) + eh + S_k$$

where $h$ is focal depth, $y$ is in $\text{cm/s}^2$, $a = 0.578$, $b = 0.00355$, $e = 0.00661$, $S = -0.069$, $S_R = -0.210$, $S_H = -0.114$, $S_M = 0.023$, $S_S = 0.237$ and $\sigma_T = \sqrt{\sigma^2 + \tau^2}$ where $\sigma = 0.213$ and $\tau = 0.162$.

- Use four site categories (most data from medium and hard soils):

$S_k = S_R$ Rock

$S_k = S_H$ Hard soil

$S_k = S_M$ Medium soil

$S_k = S_S$ Soft soil

$S$ is the mean site coefficient, i.e. when do not consider site category.

- Records interpolated in frequency domain from 0.02 to 0.005 s interval and displacement time history calculated using a fast Fourier transform (FFT) method having perpended to beginning and appended to end at least 5 s of zeros to record. Number of samples in FFT is large enough that duration used in FFT is at least twice that of selected duration for processing window so that numerical errors are small. Bandpass Ormsby filter used, with limits 0.2 and 24.5 Hz, and displacement time history plotted. If displacement in pre- and appended portions is large then increase lower frequency limit in filter until displacements are small, using smoothed Fourier spectral amplitudes from 0.05 to 25 Hz to make choice.
- Most earthquakes are intra-slab.
- Note lack of near-field data for all magnitudes, most data from $> 100$ km, therefore use coefficients, $c$ and $d$, from an early study.
- Excludes data from distances greater than the distance at which an earlier study predicts PGA $< 0.02\,\text{m/s}^2$.
- Consider residuals of earthquakes in western Japan (a small subset of data) and find small difference in anelastic coefficient and focal depth coefficient but note may be due to small number of records or because type of source not modelled.
- Note model predicts intraslab motions well but significantly over predicts interface motions.
- Plots site correction factors (difference between individual site factor and mean factor for that category) and find rock sites have largest variation, which suggest due to hard and soft rock included.
- Examine residual plots. Find no significant bias.

## 2.182 Monguilner et al. (2000a)

- Ground-motion model is:

$$\log a_m = C_0' + C_1 M + C_2 \Delta + C_3 \log \Delta + C_4' S_r$$

where $a_m$ is in unknown unit, $\Delta = \sqrt{\text{DE}^2 + H^2 + S^2}$, DE is epicentral distance, $H$ is focal depth, $S$ is fault area and $C_0' = -1.23$, $C_1 = 0.068$, $C_2 = -0.001$ and $C_3 = -0.043$ ($\sigma$ is not given). Note that there are typographical inconsistencies in the text, namely $S_r$ maybe should be replaced by $S_{al}$.

- Use two site categories (based on Argentinean seismic code):

$S_r = 1$ Stiff soil ($\mathrm{II_A}$).

$S_r = 0$ Intermediate stiff soil ($\mathrm{II_B}$).

  Since there is no geotechnical data available, classify sites, assuming a uniform surface layer, using the predominant period of ground motions estimated using Fourier spectra to get an equivalent shear-wave velocity (mainly these are between 100 and 400 m/s).

- Records from instruments located in basements or ground floors of relatively small buildings.
- Records from SMAC and SMA-1 instruments.
- Uniform digitisation and correction procedure applied to all records to reduce noise in high and low frequency range.
- Calculate fault area using $\log S = M_s + 8.13 - 0.6667 \log(\sigma\Delta\sigma/\mu)$ where $\Delta\sigma$ is stress drop, $\sigma$ is average stress and $\mu$ is rigidity.
- Most magnitudes between 5.5 and 6.0.
- Most records from DE $< 100$ km.
- Most focal depths, $H \leq 40$ km. One earthquake with $H = 120$ km.
- Use weighted regression because of a correlation between magnitude and distance of 0.35. Weight each record by $\omega_i = (\omega_M + \omega_{\mathrm{DH}})/2$ where (note there are typographical errors in formulae in paper):

$$\begin{aligned}
\omega_M &= \frac{n_s(i_s)\Delta M(n_i) n_e(n_i, i_s)\Delta M_T}{n_{\mathrm{cat}}} \\
\omega_{\mathrm{DH}} &= \frac{n_s(i_s)\Delta \log \mathrm{DH}(n_i) n_e(n_i, i_s)\Delta \log \mathrm{DH}_T}{n_{\mathrm{cat}}} \\
\Delta M_T &= \frac{\sum \Delta M(n_i)}{n_{\mathrm{cat}}} \\
\Delta \log \mathrm{DH}_T &= \frac{\sum \Delta \log \mathrm{DH}(n_i)}{n_{\mathrm{cat}}}
\end{aligned}$$

  where $\Delta M(n_i)$ is the width of the $n_i$th magnitude interval and $\Delta \log \mathrm{DH}(n_i)$ is the width of the $n_i$th distance interval, $n_{\mathrm{cat}}$ is total number of intervals, $n_i$ the index of the interval, $n_e(n_i, i_s)$ is the number of records in interval $n_i$ from site classification $i_s$ and $n_s$ is the number of records from site classification $i_s$. Use two site classifications, three magnitude intervals and four epicentral distance intervals so $n_{\mathrm{cat}} = 2 \times 3 \times 4 = 24$.

- First do regression on $\log a_i = C_0 + C_1 M + C_2 \Delta + C_3 \log \Delta$ and then regress residuals, $\epsilon_i$, against $C_4 S_r + C_5 S_{al}$ where $S_{al} = 1$ if site is intermediate stiff soil and $S_{al} = 0$ otherwise. Then $C_0' = C_0 + C_5$ and $C_4' = C_4 + C_5$. Similar method to that used by Ambraseys et al. (1996).

## 2.183 Paciello et al. (2000)

- Ground-motion model is:

$$\ln Y = a + bM + c \ln \sqrt{R^2 + h^2} + dS_B + eS_C + g\mathrm{FM}$$

  where $Y$ is in cm/s$^2$ and when using $M_w$: $a = 0.920$, $b = 1.128$, $c = -0.997$, $h = 8.839$, $d = 0.643$, $e = 0.088$, $g = -0.196$ and $\sigma = 0.647$.

- Use 3 site classes:

  A Rock and stiff soil, $V_s > 800\,\mathrm{m/s}$. $S_B = S_C = 0$.

  B Shallow loose deposits, $V_s < 400\,\mathrm{m/s}$. $S_B = 1$, $S_C = 0$.

  C Deep medium-dense deposits, $400 \leq V_s \leq 800\,\mathrm{m/s}$. $S_C = 1$, $S_B = 0$.

- Consider 2 mechanisms:

$FM = 0$ Thrust and strike-slip faulting.

$FM = 1$ Normal faulting.

- Only select earthquakes recorded by $\geq 3$ stations.
- Exclude non-free-field stations and those with unknown site conditions.
- Use $r_{epi}$ because surface geology in Italy and Greece rarely shows evident seismogenic faults.
- Note differences in the coefficients depending on whether $M_w$ or $M_s$ is used.

## 2.184 Sharma (2000)

- Based on Sharma (1998), see 2.163.
- $A$ is in g and coefficients are: $c_1 = -2.87$, $c_2 = 0.634$, $c_3 = 0.62$, $b = 1.16$ and $\sigma = 0.142$.
- Fit $\log A = -b \log X + c$ to data from each earthquake separately and find average $b$ equal to 1.18. Then fit $\log A = aM - b \log X + c$ to data from all earthquakes and find $b = 0.405$. Fit $\log A = -b \log X + \sum d_i l_i$ to all data, where $l_i = 1$ for $i$th earthquake and 0 otherwise and find $b = 1.16$, use this for rest of analysis.

## 2.185 Smit et al. (2000)

- Ground-motion model is:

$$\begin{aligned} \log Y &= a + bM - \log R + dR \\ \text{where } R &= \sqrt{D^2 + h^2} \end{aligned}$$

  where $Y$ is in $\mathrm{cm/s^2}$, $a = 0.72$, $b = 0.44$, $d = -0.00231$, $h = 4.5$ and $\sigma = 0.28$.

- Records from soil or alluvium sites.
- All records corrected.
- Note that scatter can be reduced by increasing number of records used (especially in near field), improving all seismological and local site parameters and increasing number of variables (especially in near field and those modelling local site behaviour) but that this requires much more information than is available.

## 2.186 Takahashi et al. (2000)

- Ground-motion model is:

$$\log_{10}[y] = aM - bx - \log_{10}(x + c10^{dM}) + e(h - h_c)\delta_h + S_k$$

  where $y$ is in $\mathrm{cm/s^2}$, $a = 0.446$, $b = 0.00350$, $c = 0.012$, $d = 0.446$, $e = 0.00665$, $S = 0.941$, $S_R = 0.751$, $S_H = 0.901$, $S_M = 1.003$, $S_S = 0.995$, $\sigma_T = \sqrt{\sigma^2 + \tau^2}$ where $\sigma = 0.135$ (intra-event) and $\tau = 0.203$ (inter-event), $h_c$ is chosen as 20 km because gave positive depth term.

- Use four site categories:

$S_k = S_R$ Rock
$S_k = S_H$ Hard soil
$S_k = S_M$ Medium soil
$S_k = S_S$ Soft soil

  Note site conditions for many stations are uncertain. $S$ is the mean site term for all data.

- Note ISC focal depths, $h$, significant reduce prediction errors compared with JMA depths. $\delta_h = 1$ for $h \geq h_c$ and $\delta_h = 0$ otherwise.

- Most Japanese data from $x > 50$ km.

- Use 166 Californian and Chilean (from 2 earthquakes) records to control model in near source.

- Due to lack of multiple records from many sites and because $c$ and $d$ require near-source records use a maximum likelihood regression method of two steps. Firstly, find all coefficients using all data except those from sites with only one record associated with them and unknown site class. Next, use individual site terms for all sites so as to reduce influence of uncertainty because of approximate site classifications and find $a$, $b$, $e$ and site terms using $c$ and $d$ from first step.

- Intra-event and inter-event residuals decrease with increasing magnitude.

- Conclude variation in residuals against distance is due to small number of records at short and large distances.

- Individual site factors means prediction error propagates into site terms when number of records per station is very small.

- Note model may not be suitable for seismic hazard studies because model prediction errors are partitioned into $\sigma_T$ and mean site terms for a given site class. Suitable model can be derived when accurate site classifications are available.

## 2.187 Wang and Tao (2000)

- Ground-motion model is:

$$\log Y = C + (\alpha + \beta M)\log(R + R_0)$$

  where $Y$ is in cm/s$^2$, $C = 4.053$, $\alpha = -2.797$, $\beta = 0.251$, $R_0 = 8.84$ and $\sigma = 0.257$.

- Use same data as Joyner and Boore (1981), see Section 2.39.

- Use a two-stage method based on Joyner and Boore (1981). Firstly fit data to $\log Y = C + \sum_{i=1}^{n}(a_i E_i)\log(R_i + R_0)$, where $E_i = 1$ for records from $i$th earthquake and $E_i = 0$ otherwise, to find $C$ and $a_i$ for each earthquake. Next fit $a = \alpha + \beta M$ to find $\alpha$ and $\beta$ using $a_i$ from first stage.

## 2.188 Wang et al. (2000)

- Ground-motion model is:

$$\log A = a_1 + a_2 M + a_3 \log[R + a_4 \exp(a_5 M)]$$

  where $A$ is in cm/s$^2$, $a_1 = 2.304$, $a_2 = 0.747$, $a_3 = -2.590$, $a_4 = 2.789$ and $a_5 = 0.451$ ($\sigma$ is unknown).

## 2.189 Chang et al. (2001)

- Ground-motion model for shallow crustal earthquakes is:

$$\ln A = c_1 + c_2 M - c_3 \ln D_p - (c_4 - c_5 D_p) \ln D_e$$

  where $A$ is in $\mathrm{cm/s^2}$, $c_1 = 2.8096$, $c_2 = 0.8993$, $c_3 = 0.4381$, $c_4 = 1.0954$, $c_5 = 0.0079$ and $\sigma = 0.60$.

  Ground-motion model for subduction earthquakes is:

$$\ln A = c'_1 + c'_2 M - c'_3 \ln D_p - c'_4 \ln D_h$$

  where $A$ is in $\mathrm{cm/s^2}$, $c'_1 = 4.7141$, $c'_2 = 0.8468$, $c'_3 = 0.17451$, $c'_4 = 1.2972$ and $\sigma = 0.56$.

- Note that there is limited site information available for strong-motion stations in Taiwan so do not consider local site effects.

- Use strong-motion data from Central Weather Bureau from 1994 to 1998 because it is more numerous and of better quality than older data.

- Separate earthquakes into shallow crustal and subduction earthquakes because of different seismic attenuation and seismogenic situation for the two types of earthquake.

- Shallow crustal earthquakes are mostly due to continental deformation, shallow collision or back-arc opening or are the uppermost interface earthquakes. Focal depths depth between 1.1 and 43.7 km with most shallower than 20 km. Most records from earthquakes with $4.5 \leq M_w \leq 6.0$.

- Subduction earthquakes are located in the Wadati-Benioff zone or the deep lateral collision zone and are principally intraslab. Focal depth between 39.9 and 146.4 km.

- Do not use records from earthquakes associated with coseismic rupture because they have complex near-field source effects.

- To avoid irregularly large amplitudes at great distances reject distant data predicted to be less than trigger level plus 1 standard deviation using this threshold formula: $aM_w - b \ln D + c \geq \ln V$, where $V$ is geometric mean of PGA equal to threshold plus 1 standard deviation. For shallow crustal earthquakes: $a = 0.64$, $b = 0.83$, $c = 2.56$ and $V = 6.93$ and for subduction earthquakes: $a = 0.76$, $b = 1.07$, $c = 3.13$ and $V = 6.79$.

- For shallow crustal earthquakes examine effect of focal depth on seismic attenuation by finding geometric attenuation rate using epicentral distance, $D_e$, for earthquakes with 5 km depth intervals. Find that deeper earthquakes have slower attenuation than shallow earthquakes. Therefore assume ground motion, $A$, is product of $f_{\mathrm{source}}$ (source effects) and $f_{\mathrm{geometrical-spreading}}$ (geometrical spreading effects) where $f_{\mathrm{source}} = C_1 \exp(c_2 M)/D_p^{-c_3}$ and $f_{\mathrm{geometrical-spreading}} = D_e^{-(c_4 - c_5 D_p)}$ where $D_p$ is focal depth.

- For subduction earthquakes examine effect of focal depth in the same way as done for shallow crustal earthquakes but find no effect of focal depth on attenuation rate. Therefore use $f_{\mathrm{geometrical-spreading}} = D_h^{-c_4}$.

- Plot residuals of both equations against distance and find no trend.

- Note that it is important to separate subduction and shallow crustal earthquakes because of the different role of focal depth and attenuation characteristics.

- Plot residual maps of ground motion for Taiwan and find significant features showing the important effect of local structures on ground motion.

- Cite various published models for Taiwan[14].

[14]These are not summarised here as they are in Chinese and are not easily available.

## 2.190 Herak et al. (2001)

- Ground-motion model is:

$$\log a_{\max} = c_1 + c_2 M_L + c_3 \log \sqrt{c_4^2 + D^2}$$

  where $a_{\max}$ is in g, for horizontal PGA $c_1 = -1.300 \pm 0.192$, $c_2 = 0.331 \pm 0.040$, $c_3 = -1.152 \pm 0.099$, $c_4 = 11.8 \pm 4.8$ km and $\sigma = 0.311$ and for vertical PGA $c_1 = -1.518 \pm 0.293$, $c_2 = 0.302 \pm 0.035$, $c_3 = -1.061 \pm 0.096$, $c_4 = 11.0 \pm 5.5$ and $\sigma = 0.313$.

- Records from 39 sites. Records from instruments on ground floor or in basements of relatively small structures.

- Site information only available for a small portion of the recording sites and therefore is not considered. Believe that most sites are 'rock' or 'stiff soil'.

- All records from Kinemetrics SMA-1s.

- Select records with $M_L \geq 4.5$ and $D \leq 200$ km because of poor reliability of SMA-1 records for small earthquakes and to avoid problems related to a possible change of geometrical spreading when surface waves start to dominate over body waves at large distances.

- Bandpass filter with passbands selected for which signal-to-noise ratio is $> 1$. Widest passband is 0.07–25 Hz.

- Do not use $r_{jb}$ because do not accurately know causative fault geometry for majority of events.

- Do not include an anelastic decay term because data is inadequate to independently determine geometric and anelastic coefficients.

- Note correlation between magnitude and distance in data distribution therefore use two-stage regression. Because many earthquakes have only a few records data is divided into classes based on magnitude (details not given).

- Most data from $M_L < 5.5$, particularly data from $D < 20$ km.

- Find all coefficients significantly different than 0 at levels exceeding 0.999.

- Also regress using one-stage method and find practically equal coefficients and larger standard errors.

- Find residuals are approximately lognormally distributed with slight asymmetry showing longer tail on positive side. Relate this to site amplification at some stations balanced by larger than expected number of slightly negative residuals.

- Find no distance or magnitude dependence of residuals.

- Compute ratio between larger and average horizontal component as 1.15.

- Believe that higher than normal $\sigma$ is due to lack of consideration of site effects and due to the use of $r_{epi}$ rather than $r_{jb}$.

## 2.191 Lussou et al. (2001)

- Ground-motion model is:

$$\log \text{PSA}(f) = a(f)M + b(f)R - \log R + c(i, f)$$

where $\text{PSA}(f)$ is in $\text{cm/s}^2$, $a(f) = 3.71 \times 10^{-1}$, $b(f) = -2.54 \times 10^{-3}$, $c(A, f) = 0.617$, $c(B, f) = 0.721$, $c(C, f) = 0.845$, $c(D, f) = 0.891$ and $\sigma = 3.13 \times 10^{-1}$.

- Use four site categories, based on $V_{s,30}$ (average shear-wave velocity in top 30 m) as proposed in Eurocode 8:

  A $V_{s,30} > 800$ m/s. Use $c(A, f)$. 14 records.

  B $400 < V_{s,30} \leq 800$ m/s. Use $c(B, f)$. 856 records.

  C $200 < V_{s,30} \leq 400$ m/s. Use $c(C, f)$. 1720 records.

  D $100 < V_{s,30} \leq 200$ m/s. Use $c(D, f)$. 421 records.

- Good determination of site conditions between shear-wave velocities have been measured down to 10 to 20 m at every site. Extrapolate shear-wave velocity data to 30 m to find $V_{s,30}$. $V_{s,30}$ at stations is between about 50 m/s and about 1150 m/s.
- Use data from Kyoshin network from 1996, 1997 and 1998.
- All data from free-field sites.
- No instrument correction needed or applied.
- Use data from earthquakes with $M_{\text{JMA}} > 3.5$ and focal depth $< 20$ km because want to compare results with Ambraseys et al. (1996) and Boore et al. (1997). Also this criteria excludes data from deep subduction earthquakes and data that is not significant for seismic hazard studies.
- Homogeneous determination of JMA magnitude and hypocentral distance.
- Roughly uniform distribution of records with magnitude and distance.
- Assume pseudo-spectral acceleration for 5% damping at 0.02 s equals PGA.
- Note equation valid for $3.5 \leq M_{\text{JMA}} \leq 6.3$ and $10 \leq r_{hypo} \leq 200$ km.
- Find inclusion of site classification has reduced standard deviation.

## 2.192 Sanchez and Jara (2001)

- Ground-motion model is:

$$\log(A_{\max}) = aM_s + b \log R + c$$

where the units of $A_{\max}$ are not given[15], $a = 0.444$, $b = -2.254$ and $c = 4.059$ ($\sigma$ is not given).

- Use one site category: firm ground.

[15] There could be a typographical error in the article since the use of common (base ten) logarithms leads to very large ground motions — the authors may mean natural logarithms.

## 2.193 Wu et al. (2001)

- Ground-motion model is:

$$\log_{10}(Y) = C_1 + C_2 M_w - \log_{10}(r_{\text{rup}} + h) + C_3 r_{\text{rup}}$$

  where $Y$ is in $\text{cm/s}^2$, $C_1 = 0.00215$, $C_2 = 0.581$, $C_3 = -0.00414$, $h = 0.00871 \times 10^{0.5M_w}$ from the square root of the expected rupture area and $\sigma = 0.79$ (in terms of natural logarithms not common logarithms).

- Select data from events with $M_L > 5$ and focal depths $< 35$ km to restrict interest to large shallow earthquakes, which cause most damage.

- Focal depths between 1.40 and 34.22 km.

- Relocate events using available data.

- Develop empirical relationship to convert $M_L$ to $M_w$.

- Develop relation for use in near real-time (within 2 min) mapping of PGA following an earthquake.

- Select records from the Taiwan Rapid Earthquake Information Release System (TREIRS) and records from the TSMIP if $r_{\text{rup}} < 30$ km so as not to bias the results at larger distances by untriggered instruments.

- Most data from $50 \leq d_r \leq 200$ km and $5 \leq M_w \leq 6$.

- Compute site correction factors for TSMIP stations (since these sites have not been well classified), $S$, by averaging residuals between observed and predicted values. After applying these site amplifications in regression analysis obtain reduced $\sigma$ of 0.66.

- Display inter-event residuals w.r.t. $M_w$ before and after site correction.

## 2.194 Chen and Tsai (2002)

- Ground-motion model is:

$$\log_{10} \text{PGA} = \theta_0 + \theta_1 M + \theta_2 M^2 + \theta_3 R + \theta_4 \log_{10}(R + \theta_5 10^{\theta_6 M})$$

  where PGA is in $\text{cm/s}^2$, $\theta_0 = -4.366 \pm 2.020$, $\theta_1 = 2.540 \pm 0.714$, $\theta_2 = -0.172 \pm 0.0611$, $\theta_3 = 0.00173 \pm 0.000822$, $\theta_4 = -1.845 \pm 0.224$, $\theta_5 = 0.0746 \pm 0.411$, $\theta_6 = 0.221 \pm 0.405$, $\sigma_e^2 = 0.0453 \pm 0.0113$ (earthquake-specific variance), $\sigma_s^2 = 0.0259 \pm 0.00699$ (site-specific variance) and $\sigma_r^2 = 0.0297 \pm 0.00235$ (record-specific variance). $\pm$ signifies the estimated standard errors.

- Records from 45 stations on rock and firm soil. All sites have more than two records.

- Use a new estimation procedure where the residual variance is decomposed into components due to various source of deviations. Separate variance into earthquake-to-earthquake variance, site-to-site variance and the remainder.

- Proposed method does not require additional regression or searching procedures.

- Perform a simulation study and find proposed procedure yields estimates with smaller biases and take less computation time than do other similar regression techniques.

- Visually examine the equation for various magnitude values before regressing.

## 2.195 Gregor et al. (2002a)

- Ground-motion model is (their model D):

$$\begin{aligned}\ln \mathrm{GM} &= \theta_1 + \theta_2 M + (\theta_3 + \theta_4 M)\ln[D + \exp(\theta_5)] + \theta_6(1 - S) + \theta_7(M - 6)^2 + \theta_8 F \\ &\quad + \theta_9/\tanh(D + \theta_{10})\end{aligned}$$

  where GM is in g, $\theta_1 = 4.31964$, $\theta_2 = -0.00175$, $\theta_3 = -2.40199$, $\theta_4 = 0.19029$, $\theta_5 = 2.14088$, $\theta_6 = 0.09754$, $\theta_7 = -0.21015$, $\theta_8 = 0.38884$, $\theta_9 = -2.29732$, $\theta_{10} = 448.88360$, $\sigma = 0.5099$ (intra-event) and $\tau = 0.4083$ (inter-event) for horizontal PGA using the static dataset without the Chi-Chi data and $\theta_1 = 1.50813$, $\theta_2 = 0.15024$, $\theta_3 = -2.52562$, $\theta_4 = 0.17143$, $\theta_5 = 2.12429$, $\theta_6 = 0.10517$, $\theta_7 = -0.16655$, $\theta_8 = 0.22243$, $\theta_9 = -0.11214$, $\theta_{10} = 19.85830$, $\sigma = 0.5141$ (intra-event) and $\tau = 0.4546$ (inter-event) for vertical PGA using the static dataset without the Chi-Chi data. Coefficients are also given for the three other models and for both the dynamic and the static datasets but are not reported here due to lack of space.

- Use two site categories:

  $S = 0$ Soil: includes sites located on deep broad and deep narrow soil deposits.

  $S = 1$ Rock: includes sites that are located on shallow stiff soil deposits;

- Use three rupture mechanism categories:

  $F = 0$ Strike-slip, 39 earthquakes, 387 records;

  $F = 0.5$ Reverse/oblique, 13 earthquakes, 194 records;

  $F = 1$ Thrust, 16 earthquakes, 412 records.

- Process records using two procedures as described below.

  1. Use the standard PEER procedure with individually chosen filter cut-offs.
  2. Fit the original integrated velocity time-history with three different functional forms (linear in velocity; bilinear, piecewise continuous function; and quadratic in velocity). Choose the 'best-fit' result and view it for reasonableness. Differentiate the velocity time-history and then low-pass filter with a causal Butterworth filter with cut-offs about 50 Hz.

- PGA values from the two processing techniques are very similar.

- Investigate using a nonlinear model for site response term but the resulting models did not improve the fit.

- Also try three other functional forms:

$$\begin{aligned}\ln(\mathrm{GM}) &= \theta_1 + \theta_2 M + \theta_3 \ln[D + \theta_4 \exp(\theta_5 M)] + \theta_6(1 - S) + \theta_7 F \\ \ln(\mathrm{GM}) &= \theta_1 + \theta_2 M + (\theta_3 + \theta_4 M)\ln[D + \exp(\theta_5)] + \theta_6(1 - S) + \theta_7(M - 6)^2 + \theta_8 F \\ \ln(\mathrm{GM}) &= \theta_1 + \theta_2 M + \theta_3 \ln[D + \exp(\theta_5 M)] + \theta_6(1 - S) + \theta_7 F + \theta_8/\tanh(D + \theta_9)\end{aligned}$$

  which all give similar standard deviations and predictions but prefer model D.

- Models oversaturate slightly for large magnitudes at close distances. Therefore recommend that the PGA equations are not used because this oversaturation is based on very little data.

- Because the Chi-Chi short period ground motions may be anomalous relative to California they develop equations including and excluding the Chi-Chi data, which only affects predictions for large magnitudes ($M > 7.5$).

## 2.196 Gülkan and Kalkan (2002)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln(V_S/V_A)\\ \text{where } r &= (r_{\mathrm{cl}}^2 + h^2)^{1/2}\end{aligned}$$

  where $Y$ is in g, $b_1 = -0.682$, $b_2 = 0.253$, $b_3 = 0.036$, $b_5 = -0.562$, $b_V = -0.297$, $V_A = 1381$, $h = 4.48$ and $\sigma = 0.562$.

- Use three site categories:

| | |
|---|---|
| Soft soil | Average shear-wave velocity, $V_S$, is 200 m/s. 40 records. |
| Soil | Average shear-wave velocity, $V_S$, is 400 m/s. 24 records. |
| Rock | Average shear-wave velocity, $V_S$, is 700 m/s. 29 records. |

  Actual shear-wave velocities and detailed site descriptions are not available for most stations in Turkey. Therefore estimate site classification by analogy with information in similar geologic materials. Obtain type of geologic material in number of ways: consultation with geologists at Earthquake Research Division of Ministry of Public Works and Settlement, various geological maps, past earthquake reports and geological references prepared for Turkey.

- Only used records from small earthquakes recorded at closer distances than large earthquakes to minimize the influence of regional differences in attenuation and to avoid the complex propagation effects coming from longer distances.

- Only use records from earthquakes with $M_w \gtrsim 5.0$ to emphasize ground motions of engineering significance and to limit analysis to more reliably recorded earthquakes.

- During regression lock magnitudes within $\pm 0.25$ magnitude unit bands centred at halves or integer magnitudes to eliminate errors coming from magnitude determination.

- Note that use of epicentral distance for small earthquakes does not introduce significant bias because dimensions of rupture area of small earthquakes are usually much smaller than distance to recording stations.

- Examine peak ground motions from the small number of normal- (14 records) and reverse-faulting (6 records) earthquakes in set and find that they were not significantly different from ground motions from strike-slip earthquakes (73 records). Therefore combine all data.

- Records mainly from small buildings built as meteorological stations up to three stories tall. Note that this modifies the recorded accelerations and hence increases the uncertainty.

- Exclude data from aftershocks (mainly of the Kocaeli and Duzce earthquakes) because it was from free-field stations and did not want to mix it with the data from the non-free-field records.

- Exclude a few records for which PGA of mainshock is $\lesssim 0.04$ g.

- Note that there is limited data and the data is poorly distributed. Also note that there is near-total lack of knowledge of local geology and that some of the records could be affected by the building in which the instrument was housed.

- More than half the records (49 records, 53% of total) are from two $M_w > 7$ earthquakes (Kocaeli and Duzce) so the results are heavily based on the ground motions recorded in these two earthquakes.

## 2.197 Iglesias et al. (2002)

- Ground-motion model is:

$$\log A_{max} = a_1 + a_2 M_w - \log R + a_3 R$$

where $A_{max}$ is in gal, $a_1 = -0.148$, $a_2 = 0.623$, $a_3 = -0.0032$ and $\sigma = 0.273$.

- Focal depths between 40 and 65 km.
- Compare predictions with data from Copalillo ($M_w$5.9) earthquake and find good match.
- Compare predictions and observations at Ciudad Universitaria station and find good match (bias of $-0.013$ and standard deviation of 0.25 for $\log A_{max}$.

## 2.198 Khademi (2002)

- Ground-motion model is:

$$Y = C_1 \exp(C_2 M)((R + C_3 \exp(C_4 M))^{C_5}) + C_6 S$$

where $Y$ is in g, $C_1 = 0.040311$, $C_2 = 0.417342$, $C_3 = 0.001$, $C_4 = 0.65$, $C_5 = -0.351119$ and $C_6 = -0.035852$ for horizontal PGA and $C_1 = 0.0015$, $C_2 = 0.8548$, $C_3 = 0.001$, $C_4 = 0.4$, $C_5 = -0.463$ and $C_6 = 0.0006$ for vertical PGA.

- Uses two site categories:

$S = 0$ Rock, site categories I and II of Iranian building code.

$S = 1$ Soil, site categories III and IV of Iranian building code.

- Selection criteria are: i) causative earthquake, earthquake fault (if known) and respective parameters are determined with reasonable accuracy, ii) PGA of at least one component $> 50$ gal, iii) records from free-field conditions or ground level of low-rise buildings ($<$ three stories), iv) some aftershocks have been eliminated to control effect of a few large earthquakes and v) records have been processed with acceptable filter parameters.
- Regresses directly on $Y$ not on logarithm of $Y$. Therefore does not calculate standard deviation in normal way. Considers the deviation of individual records from predictive equations as being PGA dependent. Finds that a sigmoidal model fits the data well. Therefore $Y = (ab + cx^d)/(b + x^d)$ where $Y$ is the error term and $x$ is the predicted ground motion, $a = 0.038723$, $b = 0.00207$, $c = 0.29094$ and $d = 4.97132$ for horizontal PGA and $a = 0.00561$, $b = 0.0164$, $c = 0.1648$ and $d = 1.9524$ for vertical PGA.

## 2.199 Margaris et al. (2002b) & Margaris et al. (2002a)

- Ground-motion model is:

$$\ln Y = c_0 + c_1 M_w + c_2 \ln(R + R_0) + c_3 S$$

where $Y$ is in cm/s$^2$, $c_0 = 4.16$, $c_1 = 0.69$, $c_2 = -1.24$, $R_0 = 6$, $c_3 = 0.12$ and $\sigma = 0.70$.

- Use three site categories:

$S = 0$ NEHRP and UBC category B. 145 records.

$S = 1$ NEHRP and UBC category C. 378 records.

$S = 2$ NEHRP and UBC category D. 221 records.

- Selection criteria are: a) earthquake has $M_w \geq 4.5$, b) PGA $\geq 0.05$ g and c) PGA $< 0.05$ g but another record from same earthquake has PGA $\geq 0.05$ g.
- Records mainly from normal faulting earthquakes.
- Exclude data recorded in buildings with four stories or higher.
- Automatically digitize records and process records homogenously, paying special attention to the filters used.
- Correlation between $M_w$ and $R$ in set of records used. For $4.5 \leq M_w \leq 5.0$ records exist at $R \leq 40$ km and for larger magnitudes records exist at intermediate and long distances. For $M_w > 6.0$ there is a lack of records for $R < 20$ km.
- Use a two step regression method. In first step use all records to find $c_1$. In second step use records from earthquakes with $M_w \geq 5.0$ to find $c_0$, $c_2$ and $c_3$.
- Adopt $R_0 = 6$ km because difficult to find $R_0$ via regression due to its strong correlation with $c_2$. This corresponds to average focal depth of earthquakes used.
- Also try Ground-motion model: $\ln Y = c_0' + c_1' M_w + c_2' \ln(R^2 + h_0^2)^{1/2} + c_3' S$. Coefficients are: $c_0' = 3.52$, $c_1' = 0.70$, $c_2' = -1.14$, $h_0 = 7$ km (adopted), $c_3' = 0.12$ and $\sigma = 0.70$.
- Find no apparent trends in residuals w.r.t. distance.
- Due to distribution of data, equations valid for $5 \leq R \leq 120$ km and $4.5 \leq M_w \leq 7.0$.

## 2.200 Saini et al. (2002)

- Ground-motion model is unknown.

## 2.201 Schwarz et al. (2002)

- Ground-motion model is:

$$\begin{aligned}\log_{10} a_{H(V)} &= c_1 + c_2 M_L + c_4 \log_{10}(r) + c_R S_R + c_A S_A + c_S S_S \\ \text{where } r &= \sqrt{R_e^2 + h_0^2}\end{aligned}$$

where $a_{H(V)}$ is in g, $c_1 = -3.0815$, $c_2 = 0.5161$, $c_4 = -0.9501$, $c_R = -0.1620$, $c_A = -0.1078$, $c_S = 0.0355$, $h_0 = 2.0$ and $\sigma = 0.3193$ for horizontal PGA and $c_1 = -2.8053$, $c_2 = 0.4858$, $c_4 = -1.1842$, $c_R = -0.1932$, $c_A = -0.0210$, $c_S = 0.0253$, $h_0 = 2.5$ and $\sigma = 0.3247$ for vertical PGA.

- Use three site categories:

R Rock, subsoil classes A1, (A2) $V_s > 800$ m/s (according to E DIN 4149) or subsoil class B (rock) $760 < V_s \leq 1500$ m/s (according to UBC 97). $S_R = 1$, $S_A = 0$, $S_S = 0$. 59 records.

A Stiff soil, subsoil classes (A2), B2, C2 $350 \leq V_s \leq 800$ m/s (according to E DIN 4149) or subsoil class C (very dense soil and soft rock) $360 < V_s \leq 760$ m/s (according to UBC 97). $S_A = 1$, $S_R = 0$, $S_S = 0$. 88 records.

S Soft soil, subsoil classes A3, B3, C3 $V_s < 350$ m/s (according to E DIN 4149) or subsoil class D (stiff clays and sandy soils) $180 < V_s \leq 360$ m/s (according to UBC 97). $S_S = 1$, $S_R = 0$, $S_A = 0$. 536 records.

KOERI stations classified using UBC 97 and temporary stations of German TaskForce classified using new German code E DIN 4149. Classify temporary stations of German TaskForce using microtremor H/V spectral ratio measurements by comparing shapes of H/V spectral ratios from microtremors to theoretical H/V spectral ratios as well as with theoretical transfer functions determined for idealized subsoil profiles.

- Use Kocaeli aftershock records from temporary German TaskForce stations (records from earthquakes with $1 \lesssim M_L < 4.9$ and distances $R_e < 70$ km, 538 records) and from mainshock and aftershocks records from Kandilli Observatory (KOERI) stations ($4.8 \leq M_L \leq 7.2$ and distances $10 \leq R_e \leq 250$ km, 145 records).
- Visually inspect all time-histories and only use those thought to be of sufficiently good quality.
- Baseline correct all records.
- Use technique of Ambraseys et al. (1996) to find the site coefficients $c_R$, $c_A$ and $c_S$, i.e. use residuals from regression without considering site classification.
- Note that equations may not be reliable for rock and stiff soil sites due to the lack of data and that equations probably only apply for $2 \leq M_L \leq 5$ due to lack of data from large magnitude earthquakes.

## 2.202 Stamatovska (2002)

- Ground-motion model is:

$$\ln \mathrm{PGA} = b' + b_M M + b_R \ln \left\{ \left[ \left( \frac{R_e}{\rho} \right)^2 + h^2 \right]^{1/2} + C \right\}$$

where PGA is in cm/s$^2$. For Bucharest azimuth $b' = -0.21056$, $b_M = 1.29099$, $b_R = -0.80404$, $C = 40$ and $\sigma = 0.52385$, for Valeni azimuth $b' = -1.52412$, $b_M = 1.42459$, $b_R = -0.70275$, $C = 40$ and $\sigma = 0.51389$ and for Cherna Voda $b' = 4.16765$, $b_M = 1.11724$, $b_R = -1.44067$, $C = 40$ and $\sigma = 0.47607$.

- Focal depths, $h$, between 89 and 131 km.
- Incomplete data on local site conditions so not included in study.
- Some strong-motion records are not from free-field locations.
- Uses $\rho$ to characterise the non-homogeneity of region. Includes effect of instrument location w.r.t. the main direction of propagation of seismic energy, as well as the non-homogeneous attenuation in two orthogonal directions. $\rho = \sqrt{(1 + tg^2\alpha)/(a^{-2} + tg^2\alpha)}$ where $\alpha$ is angle between instrument and main direction of seismic energy or direction of fault projection on surface and $a$ is parameter defining the non-homogeneous attenuation in two orthogonal directions, or relation between the semi-axes of the ellipse of seismic field.
- Uses a two step method. In first step derive equations for each earthquake using $\ln \mathrm{PGA} = b_0' + b_1 \ln(R_e/\rho)$. In the second step the complete Ground-motion model is found by normalizing separately for each earthquake with a value of $\rho$ defined for that earthquake according to the location for which the equation was defined.
- Notes that there is limited data so coefficients could be unreliable.
- Strong-motion records processed by different institutions.

## 2.203 Tromans and Bommer (2002)

- Ground-motion model is:

$$\begin{aligned}\log y &= C_1 + C_2 M_s + C_4 \log r + C_A S_A + C_S S_S \\ \text{where } r &= \sqrt{d^2 + h_0^2}\end{aligned}$$

  where $y$ is in cm/s$^2$, $C_1 = 2.080$, $C_2 = 0.214$, $h_0 = 7.27$, $C_4 = -1.049$, $C_A = 0.058$, $C_S = 0.085$ and $\sigma = 0.27$.

- Use three site categories:

  S Soft soil, $V_{s,30} \leq 360$ m/s. $S_S = 1$, $S_A = 0$. 25% of records.

  A Stiff soil, $360 < V_{s,30} < 750$ m/s. $S_A = 1$, $S_S = 0$. 50% of records.

  R Rock, $V_{s,30} \geq 750$ m/s. $S_S = 0$, $S_A = 0$. 25% of records.

  If no $V_{s,30}$ measurements at station then use agency classifications.

- Supplement dataset of Bommer et al. (1998) with 66 new records using same selection criteria as Bommer et al. (1998) with a lower magnitude limit of $M_s = 5.5$. Remove 3 records from Bommer et al. (1998) with no site classifications.

- Roughly uniform distribution of records w.r.t. magnitude and distance. New data contributes significantly to large magnitude and near-field ranges.

- Correct records using an elliptical filter selecting an appropriate low-frequency cut-off, $f_L$, individually for each record using the criterion of Bommer et al. (1998).

- Plot PGA against $f_L$ for two pairs of horizontal components of ground motion from the BOL and DZC stations from the Duzce earthquake (12/11/1999). Record from BOL was recorded on a GSR-16 digital accelerograph and that from DZC was recorded on a SMA-1 analogue accelerograph. Find PGA is stable for low-frequency cut-offs up to at least 0.4 Hz for the selected records.

## 2.204 Zonno and Montaldo (2002)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM + c\log_{10}(R^2 + h^2)^{1/2} + e\Gamma$$

  where $Y$ is in g, $a = -1.632$, $b = 0.304$, $c = -1$, $h = 2.7$, $e = 0$ and $\sigma = 0.275$.

- Use two site categories:

  Soil $V_{s,30} \leq 750$ m/s, $\Gamma = 0$.

  Rock $V_{s,30} > 750$ m/s, $\Gamma = 1$.

- Note that amount of data available for the Umbria-Marche area in central Italy is sufficiently large to perform statistical analysis at regional scale.

- Focal depths between 2 and 8.7 km. Exclude data from an earthquake that occurred at 47 km.

- Select only records from earthquakes with $M_L \geq 4.5$ recorded at less than 100 km.

- Exclude data from Nocera Umbra station because it shows a strong amplification effect due to the presence of a sub-vertical fault and to highly fractured rocks.

- Uniformly process records using BAP (Basic strong-motion Accelerogram Processing software). Instrument correct records and band-pass filter records using a high-cut filter between 23 and 28 Hz and a bi-directional Butterworth low-cut filter with corner frequency of 0.4 Hz and rolloff parameter of 2.
- Note that can use $M_L$ because it does not saturate until about 6.5 and largest earthquake in set is $M_L = 5.9$.
- More than half of records are from earthquakes with $M_L \leq 5.5$.
- State that equations should not be used for $M_L > 6$ because of lack of data.
- Use similar regression method as Ambraseys et al. (1996) to find site coefficient, $e$.

## 2.205 Alarcón (2003)

- Ground-motion model is (his model 2):

$$\log(a) = A + BM + Cr + D\log(r)$$

where $a$ is in gal, $A = 5.5766$, $B = 0.06052$, $C = 0.0039232$, $D = -2.524849$ and $\sigma = 0.2597$.

- Due to lack of information classify stations as soil or rock (stations with $\leq 10$ m of soil). Only derives equation for rock.
- Uses data from National Accelerometer Network managed by INGEOMINAS from 1993 to 1999.
- Exclude data from subduction zone, focal depths $h > 60$ km.
- Focal depths, $11.4 \leq h \leq 59.8$ km.
- Exclude data from earthquakes with $M_L < 4.0$.
- Exclude data with PGA $< 5$ gal. $5 \leq$ PGA $\leq 100.1$ gal.
- Derive equations using four different models:

$$\begin{aligned} a &= C_1 \mathrm{e}^{C_2 M}(R + C_3)^{-C_4} \\ \log(a) &= A + BM + Cr + D\log(r) \\ \log(y) &= C_0 + C_1(M-6) + C_2(M-6) + C_3\log(r) + C_4 r \\ \ln(a) &= a + bM + d\ln(R) + qh \end{aligned}$$

## 2.206 Alchalbi et al. (2003)

- Ground-motion model is:

$$\log A = b_0 + b_1 M_c + b_r \log r$$

where $A$ is in g, $b_0 = -1.939$, $b_1 = 0.278$, $b_2 = -0.858$ and $\sigma = 0.259$ for horizontal PGA and $b_0 = -2.367$, $b_1 = 0.244$, $b_2 = -0.752$ and $\sigma = 0.264$ for vertical PGA.

- Use two site categories: bedrock ($S = 0$) and sediments ($S = 1$) but found the coefficient $b_3$ in the term $+b_3 S$ is close to zero so repeat analysis constraining $b_3$ to 0.
- Records from SSA-1 instruments.
- Carefully inspect and select records.

- Do not use record from the Aqaba ($M = 7.2$) earthquake because it is very far and was only recorded at one station.
- Do not use records from buildings or dams because they are affected by response of structure.
- Instrument correct records. Apply bandpass filter (0.1 to 25 Hz) to some low-quality records.
- Do regression using only records from earthquakes with $4.8 \leq M \leq 5.8$ and also using only records from earthquakes with $3.5 \leq M \leq 4.5$.
- Most data from $M \leq 5$ and $r \leq 100$ km.
- Note that use a small set of records and so difficult to judge reliability of derived equation.

## 2.207 Atkinson and Boore (2003)

- Ground-motion model is:

$$\begin{aligned}
\log Y &= c_1 + c_2\mathbf{M} + c_3 h + c_4 R - g\log R + c_5 \mathrm{sl} S_C + c_6 \mathrm{sl} S_D + c_7 \mathrm{sl} S_E \\
\text{where } R &= \sqrt{D_{\text{fault}}^2 + \Delta^2} \\
\Delta &= 0.00724\, 10^{0.507\mathbf{M}} \\
\mathrm{sl} &= \begin{cases} 1 & \text{for} \quad \mathrm{PGA}_{rx} \leq 100\,\mathrm{cm/s or} f \leq 1\,\mathrm{Hz} \\ 1 - \frac{(f-1)(\mathrm{PGA}_{rx}-100)}{400} & \text{for} \quad 100 < \mathrm{PGArx} < 500\,\mathrm{cm/s\&}1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\ 1-(f-1) & \text{for} \quad \mathrm{PGA}_{rx} \geq 500\,\mathrm{cm/s\&}1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\ 1 - \frac{\mathrm{PGA}_{rx}-100}{400} & \text{for} \quad 100 < \mathrm{PGArx} < 500\,\mathrm{cm/s\&} f \geq 2\,\mathrm{Hz} \\ 0 & \text{for} \quad \mathrm{PGA}_{rx} \geq 500\,\mathrm{cm/s\&} f \geq 2\,\mathrm{Hz}) \end{cases}
\end{aligned}$$

  where $Y$ is in cm/s$^2$, $f$ is frequency of interest, $\mathrm{PGA}_{rx}$ is predicted PGA on NEHRP B sites, $c_1 = 2.991$, $c_2 = 0.03525$, $c_3 = 0.00759$, $c_4 = -0.00206$, $\sigma_1 = 0.20$ (intra-event) and $\sigma_2 = 0.11$ (inter-event) for interface events and $c_1 = -0.04713$, $c_2 = 0.6909$, $c_3 = 0.01130$, $c_4 = -0.00202$, $\sigma_1 = 0.23$ and $\sigma_2 = 0.14$ for in-slab events and $c_5 = 0.19$, $c_6 = 0.24$, $c_7 = 0.29$ for all events. $g = 10^{1.2-0.18\mathbf{M}}$ for interface events and $g = 10^{0.301-0.01\mathbf{M}}$ for in-slab events. Recommended revised $c_1$ for interface events in Cascadia is 2.79 and in Japan 3.14, recommended revised $c_1$ for in-slab events in Cascadia is $-0.25$ and in Japan 0.10.

- Use four site categories:

  B NEHRP site class B, $V_{s,30} > 760$ m/s. $S_C = 0$, $S_D = 0$ and $S_E = 0$.

  C NEHRP site class C, $360 < V_{s,30} \leq 760$ m/s. $S_C = 1$, $S_D = 0$ and $S_E = 0$.

  D NEHRP site class D, $180 \leq V_{s,30} \leq 360$ m/s. $S_D = 1$, $S_C = 0$ and $S_E = 0$.

  E NEHRP site class E, $V_{s,30} < 180$ m/s. $S_E = 1$, $S_C = 0$ and $S_D = 0$.

  Stations in KNET were classified using shear-wave velocity profiles using an statistical method to extrapolate measured shear-wave velocities to depths up to 10–20 m to 30 m. Stations in Guerrero array assumed to be on rock, i.e. site class B. Broadband stations in Washington and British Columbia sited on rock ($V_{s,30} \approx 1100$ m/s), i.e. site class B. Strong-motion stations in Washington classified using map of site classes based on correlations between geology and $V_{s,30}$ in Washington, and verified at 8 stations using actual borehole measurements. Converted Youngs et al. (1997) Geomatrix classifications by assuming Geomatrix A=NEHRP B, Geomatrix B=NEHRP C, Geomatrix C/D=NEHRP D and Geomatrix E=NEHRP E using shear-wave velocity and descriptions of Geomatrix classification.

- Note that cannot develop equations using only Cascadia data because not enough data. Combine data of Crouse (1991) and Youngs et al. (1997) with additional data from Cascadia (strong-motion and broadband seismographic records), Japan (KNET data), Mexico (Guerrero array data) and El Salvador data.
- Classify event by type using focal depth and mechanism as:

In-slab All earthquakes with normal mechanism. Earthquakes with thrust mechanism at depths $> 50$ km or if occur on steeply dipping planes.

Interface Earthquakes with thrust mechanism at depths $< 50$ km on shallow dipping planes.

Exclude events of unknown type.

- Exclude events with focal depth $h > 100$ km.
- Exclude events that occurred within crust above subduction zones.
- Use many thousands of extra records to explore various aspects of ground motion scaling with $M$ and $D_{\text{fault}}$.
- Data relatively plentiful in most important $M$-$D_{\text{fault}}$ ranges, defined according to deaggregations of typical hazard results. These are in-slab earthquakes of $6.5 \leq \mathbf{M} \leq 7.5$ for $40 \leq D_{\text{fault}} \leq 100$ km and interface earthquakes of $\mathbf{M} \geq 7.5$ for $20 \leq D_{\text{fault}} \leq 200$ km.
- Data from KNET from moderate events at large distances are not reliable at higher frequencies due to instrumentation limitations so exclude KNET data from $\mathbf{M} < 6$ at $D_{\text{fault}} > 100$ km and for M $\geq 6$ at $D_{\text{fault}} > 200$ km. Excluded data may be reliable at low frequencies.
- Estimate $D_{\text{fault}}$ for data from Crouse (1991) and for recent data using fault length versus $\mathbf{M}$ relations of Wells and Coppersmith (1994) to estimate size of fault plane and assuming epicentre lies above geometric centre of dipping fault plane. Verified estimates for several large events for which fault geometry is known.
- Perform separate regressions for interface and in-slab events because analyses indicated extensive differences in amplitudes, scaling and attenuation between two types.
- Experiment with a variety of functional forms. Selected functional form allows for magnitude dependence of geometrical spreading coefficient, $g$; the observed scaling with magnitude and amplitude-dependent soil nonlinearity.
- For $h > 100$ km use $h = 100$ km to prevent prediction of unrealistically large amplitudes for deeper earthquakes.
- $R$ is approximately equal to average distance to fault surface. $\Delta$ is defined from basic fault-to-site geometry. For a fault with length and width given by equations of Wells and Coppersmith (1994), the average distance to the fault for a specified $D_{\text{fault}}$ is calculated (arithmetically averaged from a number of points distributed around the fault), then used to determine $\Delta$. Magnitude dependence of $R$ arises because large events have a large spatial extent, so that even near-fault observation points are far from most of the fault. Coefficients in $\Delta$ were defined analytically, so as to represent average fault distance, not be regression. Although coefficients in $\Delta$ were varied over a wide range but did not improve accuracy of model predictions.
- Determine magnitude dependence of $g$ by preliminary regressions of data for both interface and in-slab events. Split data into 1 magnitude unit increments to determine slope of attenuation as a function of magnitude using only 1 and 2 s data and records with $50 \leq D_{\text{fault}} \leq 300$ km (50 km limit chosen to avoid near-source distance saturation effects). Within each bin regression was made to a simple functional form: $\log Y' = a_1 + a_2\mathbf{M} - g \log R + a_3 S$ where $Y' = Y \exp(0.001R)$, i.e. $Y$ corrected for curvature due to anelasticity, and $S = 0$ for NEHRP A or B and 1 otherwise. $g$ is far-field slope determined for each magnitude bin.

- Nonlinear soil effects not strongly apparent in database on upon examination of residuals from preliminary regressions, as most records have PGA $< 200\,\text{cm/s}^2$, but may be important for large $M$ and small $D_{\text{fault}}$. To determine linear soil effects perform separate preliminary regressions for each type of event to determine $c_5$, $c_6$ and $c_7$ assuming linear response. Smooth these results (weighted by number of observations in each subset) to fix $c_5$, $c_6$ and $c_7$ (independent of earthquake type) for subsequent regressions. sl was assigned by looking at residual plots and from consideration of NEHRP guidelines. Conclude that there is weak evidence for records with $\text{PGA}_{rx} > 100\,\text{cm/s}^2$, for NEHRP E sites at periods $< 1\,\text{s}$. Use these observations to fix sl for final regression.

- Final regression needs to be iterated until convergence because of use of $\text{PGA}_{rx}$ in definition of dependent variable.

- To optimize fit for $M$-$D_{\text{fault}}$ range of engineering interest limit final regression to data within: $5.5 \leq \mathbf{M} < 6.5$ and $D_{\text{fault}} \leq 80\,\text{km}$, $6.5 \leq \mathbf{M} < 7.5$ and $D_{\text{fault}} \leq 150\,\text{km}$ and $\mathbf{M} \geq 7.5$ and $D \leq 300\,\text{km}$ for interface events and $6.0 \leq \mathbf{M} < 6.5$ and $D_{\text{fault}} \leq 100\,\text{km}$ and $\mathbf{M} \geq 6.5$ and $D_{\text{fault}} \leq 200\,\text{km}$ for in-slab events. These criteria refined by experimentation until achieved an optimal fit for events that are important for seismic hazard analysis. Need to restrict $M$-$D_{\text{fault}}$ for regression because set dominated by records from moderate events and from intermediate distances whereas hazard is from large events and close distances.

- Lightly smooth coefficients (using a weighted 3-point scheme) over frequency to get smooth spectral shape and allows for reliable linear interpolation of coefficients for frequencies not explicitly used in regression.

- In initial regressions, use a $\mathbf{M}^2$ term as well as a $\mathbf{M}$ term leading to a better fit over a linear magnitude scaling but lead to a positive sign of the $\mathbf{M}^2$ rather than negative as expected. Therefore to ensure the best fit in the magnitude range that is important for hazard and constrained by data quadratic source terms refit to linear form. Linear model constrained to provide same results in range $7.0 \leq \mathbf{M} \leq 8.0$ for interface events and $6.5 \leq \mathbf{M} \leq 7.5$ for in-slab events. To ensure that non-decreasing ground motion amplitudes for large magnitudes: for $\mathbf{M} > 8.5$ use $\text{M} = 8.5$ for interface events and for $\mathbf{M} > 8.0$ use $\text{M} = 8.0$ for in-slab events.

- Calculate $\sigma$ based on records with $\mathbf{M} \geq 7.2$ and $D_{\text{fault}} \leq 100\,\text{km}$ for interface events and $\mathbf{M} \geq 6.5$ and $D_{\text{fault}} \leq 100\,\text{km}$ for in-slab events. These magnitude ranges selected to obtain the variability applicable for hazard calculations. Do not use KNET data when computing $\sigma$ because data appear to have greater high-frequency site response than data from same soil class from other regions, due to prevalence of sites in Japan with shallow soil over rock.

- Determine $\sigma_1$ using data for several well-recorded large events and determining average value. Then calculate $\sigma_2$ assuming $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$.

- Examine residuals w.r.t. $D_{\text{fault}}$ using all data from $\mathbf{M} \geq 5.5$ and $D_{\text{fault}} \leq 200\,\text{km}$ and $\mathbf{M} \geq 6.5$ and $D_{\text{fault}} \leq 300\,\text{km}$. Find large variability but average residuals near 0 for $D_{\text{fault}} \leq 100\,\text{km}$.

- Find significantly lower variability for $\mathbf{M} \geq 7.2$ events ($\sigma = 0.2$–$0.35$ for larger events and $\sigma = 0.25$–$0.4$ for smaller events).

- Examine graphs and statistics of subsets of data broken down by magnitude, soil type and region. Find significant positive residuals for $\mathbf{M} < 6.6$ due to use of linear scaling with magnitude. Accept positive residuals because small magnitudes do not contribute strongly to hazard.

- Find large positive residuals for class C sites for interface events (most records are from Japan) whereas residuals for class C sites for in-slab events (which are from both Japan and Cascadia) do not show trend. No other overwhelming trends. Differences in residuals for Japan and Cascadia class C sites likely due to differences in typical soil profiles in the two regions within the same NEHRP class. Sites in Japan are typically shallow soil over rock, which tend to amplify high frequencies, whereas in Cascadia most soil sites represent relatively deep layers over rock or till. Provide revised $c_1$ coefficients for Japan and Cascadia to model these differences.

- Note that debate over whether 1992 Cape Mendocino earthquake is a subduction zone or crustal earthquake. Excluding it from regressions has a minor effect on results, reducing predictions for interface events for $\mathbf{M} < 7.5$.

## 2.208 Boatwright et al. (2003)

- Ground-motion model is:

$$\begin{aligned}
\log \mathrm{PGA} &= \psi(\mathbf{M}) - \log g(r) - \eta'(\mathbf{M})r \\
\text{where} & \\
\psi(\mathbf{M}) &= \psi_1 + \psi_2(\mathbf{M} - 5.5) \quad \text{for} \quad \mathbf{M} \leq 5.5 \\
&= \psi_1 + \psi_3(\mathbf{M} - 5.5) \quad \text{for} \quad \mathbf{M} > 5.5 \\
\eta'(\mathbf{M}) &= \eta_1 \quad \text{for} \quad \mathbf{M} \leq 5.5 \\
&= \eta_1 \times 10^{\rho(\mathbf{M}-5.5)} \quad \mathbf{M} > 5.5 \\
g(r) &= r \quad \text{for} \quad r \leq r_0 = 27.5\,\mathrm{km} \\
&= r_0(r/r_0)^{0.7} \quad \text{for} \quad r > r_0 = 27.5\,\mathrm{km}
\end{aligned}$$

where PGA is in $\mathrm{m/s^2}$, $\psi_1 = 1.45 \pm 0.24$, $\psi_2 = 1.00 \pm 0.01$, $\psi_3 = 0.31 \pm 0.09$, $\eta_1 = 0.0073 \pm 0.0003$, $\rho = -0.30 \pm 0.06$, $\sigma_e = 0.170$ (inter-earthquake) and $\sigma_r = 0.361$ (intra-earthquake).

- Classify station into four classes using the NEHRP categories using geological maps:

  B Rock. Amplification from category C 0.79.

  C Soft rock or stiff soil. Amplification from category C 1.00.

  D Soft soil. Amplification from category C 1.35.

  E Bay mud. Amplification from category D 1.64.

  The amplifications (from Boore et al. (1997)) are used to correct for site effects.

  For some stations in the broadband Berkeley Digital Seismic Network, which are in seismic vaults and mine adits and therefore have low site amplifications, use one-half the above site amplifications.

- Use data from August 1999 and December 2002 from the northern California ShakeMap set of data. Extend set to larger earthquakes by adding data from nine previous large northern California earthquakes.

- Focal depths, $0.1 \leq h \leq 28..8\,\mathrm{km}$.

- Use hypocentral distance because this distance is available to ShakeMap immediately after an earthquake. Note that this is a poor predictor of near-field ground motion from extended faults.

- Plot decay of PGA with distance for two moderate earthquakes ($\mathbf{M} = 4.9$, $\mathbf{M} = 3.9$) and find decay is poorly fit by a power-law function of distance and that fitting such an equation who require PGA $\propto r^{-2}$, which they believe is physically unrealistic for body-wave propagation.

- Find that PGAs flatten or even increase at large distances, which is believed to be due to noise. Hence use a magnitude-dependent limit of $r_{\max} = 100(\mathbf{M} - 2) \leq 400\,\mathrm{km}$, determined by inspecting PGA and PGV data for all events, to exclude problem data.

- Fit data from each event separately using $\log \mathrm{PGA} = \psi - \eta r - \log g(r) + \log s_{\mathrm{BJF}}$. Find $\eta$ varies between four groups: events near Eureka triple junction, events within the Bay Area, events near San Juan Bautista and those in the Sierras and the western Mojave desert.
- Use a numerical search to find the segmentation magnitude $\mathbf{M}'$. Choose $\mathbf{M}' = 5.5$ as the segmentation magnitude because it is the lowest segmentation magnitude within a broad minimum in the $\chi^2$ error for the regression.
- Fit magnitude-dependent part of the equation to the PGA values scaled to 10 km and site class C.
- Note that the PGAs predicted are significantly higher than those given by equations derived by Joyner and Boore (1981) and Boore et al. (1997) because of use of hypocentral rather than fault distance.
- Recompute site amplifications relative to category C as: for B $0.84 \pm 0.03$, for D $1.35 \pm 0.05$ and for E $2.17 \pm 0.15$.

## 2.209 Bommer et al. (2003)

- Ground-motion model is:

$$\log y = C_1 + C_2 M + C_4 \log(\sqrt{r^2 + h^2}) + C_A S_A + C_S S_S + C_N F_N + C_R F_R$$

  where $y$ is in g, $C_1 = -1.482$, $C_2 = 0.264$, $C_4 = -0.883$, $h = 2.473$, $C_A = 0.117$, $C_S = 0.101$, $C_N = -0.088$, $C_R = -0.021$, $\sigma_1 = 0.243$ (intra-event) and $\sigma_2 = 0.060$ (inter-event).

- Use four site conditions but retain three (because only three records from very soft (L) soil which combine with soft (S) soil category):

  R Rock: $V_s > 750$ m/s, $\Rightarrow S_A = 0, S_S = 0$, 106 records.

  A Stiff soil: $360 < V_s \leq 750$ m/s, $\Rightarrow S_A = 1, S_S = 0$, 226 records.

  S Soft soil: $180 < V_s \leq 360$ m/s, $\Rightarrow S_A = 0, S_S = 1$, 81 records.

  L Very soft soil: $V_s \leq 180$ m/s, $\Rightarrow S_A = 0, S_S = 1$, 3 records.

- Use same data as Ambraseys et al. (1996).
- Use three faulting mechanism categories:

  S Strike-slip: earthquakes with rake angles ($\lambda$) $-30 \leq \lambda \leq 30°$ or $\lambda \geq 150°$ or $\lambda \leq -150°$, $\Rightarrow F_N = 0, F_R = 0$, 47 records.

  N Normal: earthquakes with $-150 < \lambda < -30°$, $\Rightarrow F_N = 1, F_R = 0$, 146 records.

  R Reverse: earthquakes with $30 < \lambda < 150°$, $\Rightarrow F_R = 1, F_N = 0$, 229 records.

  Earthquakes classified as either strike-slip or reverse or strike-slip or normal depending on which plane is the main plane were included in the corresponding dip-slip category. Some records (137 records, 51 normal, 10 strike-slip and 76 reverse) from earthquakes with no published focal mechanism (80 earthquakes) were classified using the mechanism of the mainshock or regional stress characteristics.

- Try using criteria of Campbell (1997) and Sadigh et al. (1997) to classify earthquakes w.r.t. faulting mechanism. Also try classifying ambiguously classified earthquakes as strike-slip. Find large differences in the faulting mechanism coefficients with more stricter criteria for the rake angle of strike-slip earthquakes leading to higher $C_R$ coefficients.

- Note that distribution of records is reasonably uniform w.r.t. to mechanism although significantly fewer records from strike-slip earthquakes.
- Try to use two-stage maximum-likelihood method as employed by Ambraseys et al. (1996) but find numerical instabilities in regression.
- Also rederive mechanism-independent equation of Ambraseys et al. (1996) using one-stage maximum-likelihood method.

## 2.210 Campbell and Bozorgnia (2003d,a,b,c) & Bozorgnia and Campbell (2004b)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= c_1 + f_1(M_w) + c_4 \ln \sqrt{f_2(M_w, r_{\mathrm{seis}}, S)} + f_3(F) + f_4(S) \\
&\quad + f_5(\mathrm{HW}, F, M_w, r_{\mathrm{seis}}) \\
\text{where} \quad f_1(M_w) &= c_2 M_w + c_3 (8.5 - M_w)^2 \\
f_2(M_w, r_{\mathrm{seis}}, S) &= r_{\mathrm{seis}}^2 + g(S)^2 (\exp[c_8 M_w + c_9 (8.5 - M_w)^2])^2 \\
g(S) &= c_5 + c_6 (S_{VFS} + S_{SR}) + c_7 S_{FR} \\
f_3(F) &= c_{10} F_{RV} + c_{11} F_{TH} \\
f_4(S) &= c_{12} S_{VFS} + c_{13} S_{SR} + c_{14} S_{FR} \\
f_5(\mathrm{HW}, F, M_w, r_{\mathrm{seis}}) &= \mathrm{HW} f_{\mathrm{HW}}(M_w) f_{\mathrm{HW}}(r_{\mathrm{seis}}) (F_{\mathrm{RV}} + F_{\mathrm{TH}}) \\
\mathrm{HW} &= \begin{cases} 0 & \text{for} \quad r_{\mathrm{jb}} \geq 5\,\mathrm{km} \text{ or } \delta > 70^\circ \\ (S_{VFS} + S_{SR} + S_{FR})(5 - r_{\mathrm{jb}})/5 & \text{for} \quad r_{\mathrm{jb}} < 5\,\mathrm{km} \;\&\; \delta \leq 70^\circ \end{cases} \\
f_{\mathrm{HW}}(M_w) &= \begin{cases} 0 & \text{for} \quad M_w < 5.5 \\ M_w - 5.5 & \text{for} \quad 5.5 \leq M_w \leq 6.5 \\ 1 & \text{for} \quad M_w > 6.5 \end{cases} \\
f_{\mathrm{HW}}(r_{\mathrm{seis}}) &= \begin{cases} c_{15}(r_{\mathrm{seis}}/8) & \text{for} \quad r_{\mathrm{seis}} < 8\,\mathrm{km} \\ c_{15} & \text{for} \quad r_{\mathrm{seis}} \geq 8\,\mathrm{km} \end{cases}
\end{aligned}
$$

where $Y$ is in g, $r_{\mathrm{jb}}$ is the distance to the surface projection of rupture and $\delta$ is the dip of the fault; for uncorrected horizontal PGA: $c_1 = -2.896$, $c_2 = 0.812$, $c_3 = 0.0$, $c_4 = -1.318$, $c_5 = 0.187$, $c_6 = -0.029$, $c_7 = -0.064$, $c_8 = 0.616$, $c_9 = 0$, $c_{10} = 0.179$, $c_{11} = 0.307$, $c_{12} = -0.062$, $c_{13} = -0.195$, $c_{14} = -0.320$, $c_{15} = 0.370$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.964$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132 \ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.263$; for corrected horizontal PGA: $c_1 = -4.033$, $c_2 = 0.812$, $c_3 = 0.036$, $c_4 = -1.061$, $c_5 = 0.041$, $c_6 = -0.005$, $c_7 = -0.018$, $c_8 = 0.766$, $c_9 = 0.034$, $c_{10} = 0.343$, $c_{11} = 0.351$, $c_{12} = -0.123$, $c_{13} = -0.138$, $c_{14} = -0.289$, $c_{15} = 0.370$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.920$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132 \ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.219$; for uncorrected vertical PGA: $c_1 = -2.807$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.391$, $c_5 = 0.191$, $c_6 = 0.044$, $c_7 = -0.014$, $c_8 = 0.544$, $c_9 = 0$, $c_{10} = 0.091$, $c_{11} = 0.223$, $c_{12} = -0.096$, $c_{13} = -0.212$, $c_{14} = -0.199$, $c_{15} = 0.630$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 1.003$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132 \ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.302$; and for corrected vertical PGA: $c_1 = -3.108$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.287$, $c_5 = 0.142$, $c_6 = 0.046$, $c_7 = -0.040$, $c_8 = 0.587$, $c_9 = 0$, $c_{10} = 0.253$, $c_{11} = 0.173$, $c_{12} = -0.135$, $c_{13} = -0.138$, $c_{14} = -0.256$, $c_{15} = 0.630$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.975$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132 \ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.274$.

- Use four site categories:

Firm soil Generally includes soil deposits of Holocene age (less than 11,000 years old) described on geological maps as recent alluvium, alluvial fans, or undifferentiated Quaternary deposits. Approximately corresponds to $V_{s,30} = 298 \pm 92$ m/s and NEHRP soil class D. Uncorrected PGA: 534 horizontal records and 525 vertical records and corrected PGA: 241 horizontal records and 240 vertical records. $S_{VFS} = 0$, $S_{SR} = 0$ and $S_{FR} = 0$.

Very firm soil Generally includes soil deposits of Pleistocene age (11,000 to 1.5 million years old) described on geological maps as older alluvium or terrace deposits. Approximately corresponds to $V_{s,30} = 368 \pm 80$ m/s and NEHRP soil class CD. Uncorrected PGA: 168 horizontal records and 166 vertical records and corrected PGA: 84 horizontal records and 83 vertical records. $S_{VFS} = 1$, $S_{SR} = 0$ and $S_{FR} = 0$.

Soft rock Generally includes sedimentary rock and soft volcanic deposits of Tertiary age (1.5 to 100 million years old) as well as 'softer' units of the Franciscan Complex and other low-grade metamorphic rocks generally described as melange, serpentine and schist. Approximately corresponds to $V_{s,30} = 421 \pm 109$ m/s and NEHRP soil class CD. Uncorrected PGA: 126 horizontal records and 124 vertical records and corrected PGA: 63 horizontal records and 62 vertical records. $S_{SR} = 1$, $S_{VFS} = 0$ and $S_{FR} = 0$.

Firm rock Generally include older sedimentary rocks and hard volcanic deposits, high-grade metamorphic rock, crystalline rock and the 'harder' units of the Franciscan Complex generally described as sandstone, greywacke, shale, chert and greenstone. Approximately corresponds to $V_{s,30} = 830 \pm 339$ m/s and NEHRP soil class BC. Uncorrected PGA: 132 horizontal records and 126 vertical records and corrected PGA: 55 horizontal records and 54 vertical records. $S_{FR} = 1$, $S_{VFS} = 0$ and $S_{SR} = 0$.

Note that for generic soil (approximately corresponding to $V_{s,30} = 310$ m/s and NEHRP site class D) use $S_{VFS} = 0.25$, $S_{SR} = 0$, $S_{FR} = 0$ and for generic rock (approximately corresponding to $V_{s,30} = 620$ m/s and NEHRP site class C) use $S_{SR} = 0.50$, $S_{FR} = 0.50$ and $S_{VFS} = 0$.

- Use four fault types but only model differences between strike-slip, reverse and thrust:

Normal Earthquakes with rake angles between 202.5° and 337.5°. 4 records from 1 earthquake.

Strike-slip Includes earthquakes on vertical or near-vertical faults with rake angles within 22.5° of the strike of the fault. Also include 4 records from 1975 Oroville normal faulting earthquake. Uncorrected PGA: 404 horizontal records and 395 vertical records and corrected PGA: 127 horizontal and vertical records. $F_{RV} = 0$ and $F_{TH} = 0$

Reverse Steeply dipping earthquakes with rake angles between 22.5° and 157.5°. Uncorrected PGA: 186 horizontal records and 183 vertical records and corrected PGA: 58 horizontal records and 57 vertical records. $F_{RV} = 1$ and $F_{TH} = 0$.

Thrust Shallow dipping earthquakes with rake angles between 22.5° and 157.5°. Includes some blind thrust earthquakes. Uncorrected PGA: 370 horizontal records and 363 vertical records and corrected PGA: 258 horizontal records and 255 vertical records. $F_{TH} = 1$ and $F_{RV} = 0$.

Note that for generic (unknown) fault type use $F_{RV} = 0.25$ and $F_{TH} = 0.25$.

- Most records from $5.5 \leq M_w \leq 7.0$.

- Note that equations are an update to equations in Campbell (1997) because they used a somewhat awkward and complicated set of Ground-motion models because there used a mixture of functional forms. Consider that the new equations supersede their previous studies.

- Uncorrected PGA refers to the standard level of accelerogram processing known as Phase 1. Uncorrected PGAs are either scaled directly from the recorded accelerogram or if the accelerogram was processed, from the baseline and instrument-corrected Phase 1 acceleration time-history.

- Corrected PGA measured from the Phase 1 acceleration time-history after it had been band-pass filtered and decimated to a uniform time interval.

- Restrict data to within 60 km of seismogenic rupture zone ($r_{seis} \leq 60$ km) of shallow crustal earthquakes in active tectonic regions which have source and near-source attenuation similar to California. Most data from California with some from Alaska, Armenia, Canada, Hawaii, India, Iran, Japan, Mexico, Nicaragua, Turkey and Uzbekistan. Note some controversy whether this is true for all earthquakes (e.g. Gazli and Nahanni). Exclude subduction-interface earthquakes.

- Restrict earthquakes to those with focal depths < 25 km.

- Exclude data from subduction-interface earthquakes, since such events occur in an entirely different tectonic environment that the other shallow crustal earthquakes, and it has not been clearly shown that their near-source ground motions are similar to those from shallow crustal earthquakes.

- Restrict to $r_{seis} \leq 60$ km to avoid complications related to the arrival of multiple reflections from the lower crust. Think that this distance range includes most ground-motion amplitudes of engineering interest.

- All records from free-field, which define as instrument shelters or non-embedded buildings < 3 storeys high and < 7 storeys high if located on firm rock. Include records from dam abutments to enhance the rock records even though there could be some interaction between dam and recording site. Exclude records from toe or base of dam because of soil-structure interaction.

- Do preliminary analysis, find coefficients in $f_3$ need to be constrained in order to make $Y$ independent on $M_w$ at $r_{seis} = 0$, otherwise $Y$ exhibits 'oversaturation' and decreases with magnitude at close distances. Therefore set $c_8 = -c_2/c_4$ and $c_9 = -c_3/c_4$.

- Functional form permits nonlinear soil behaviour.

- Do not include sediment depth (depth to basement rock) as a parameter even though analysis of residuals indicated that it is an important parameter especially at long periods. Do not think its exclusion is a serious practical limitation because sediment depth is generally not used in engineering analyses and not included in any other widely used attenuation relation.

- Do not apply weights during regression analysis because of the relatively uniform distribution of records w.r.t. magnitude and distance.

- To make regression analysis of corrected PGA more stable set $c_2$ equal to value from better-constrained regression of uncorrected PGAs.

- Examine normalised residuals $\delta_i = (\ln Y_i - \ln \bar{Y})/\sigma_{\ln(\text{Unc.PGA}}$ where $\ln Y_i$ is the measured acceleration, $\bar{Y}$ is the predicted acceleration and $\sigma_{\ln(\text{Unc.PGA}}$ is the standard deviation of the uncorrected PGA equation. Plot $\delta_i$ against magnitude and distance and find models are unbiased.

- Consider equations valid for $M_w \geq 5.0$ and $r_{seis} \leq 60$ km. Probably can be extrapolated to a distance of 100 km without serious compromise.

- Note that should use equations for uncorrected PGA if only an estimate of PGA is required because of its statistical robustness. If want response spectra and PGA then should use corrected PGA equation because the estimates are then consistent.

- Note that should include ground motions from Kocaeli (17/8/1999, $M_w = 7.4$), Chi-Chi (21/9/1999, $M_w = 7.6$), Hector Mine (16/10/1999, $M_w = 7.1$) and Duzce (12/11/1999, $M_w = 7.1$) earthquakes but because short-period motions from these earthquakes was significantly lower than expected their inclusion could lead to unconservative estimated ground motions for high magnitudes.

- Prefer the relationship for $\sigma$ in terms of PGA because statistically more robust. Note that very few records to constrain value of $\sigma$ for large earthquakes but many records to constrain $\sigma$ for PGA $\geq 0.25$ g.
- Find that Monte Carlo simulation indicates that all regression coefficients statistically significant at 10% level.

## 2.211 Halldórsson and Sveinsson (2003)

- Ground-motion models are:

$$\log A = aM - b\log R + c$$

where $A$ is in g, $a = 0.484$, $b = 1.4989$, $c = -2.1640$ and $\sigma = 0.3091$, and:

$$\log A = aM - \log R - bR + c$$

$a = 0.4805$, $b = 0.0049$, $c = -2.6860$ and $\sigma = 0.3415$.

- Vast majority of data from south Iceland (18 earthquakes in SW Iceland and 4 in N Iceland).
- Most data from less than 50 km and $M < 5.5$. 76% of data is from 5 to 50 km.
- Examine residual plots against distance and find no trends.
- Recommend first equation.
- Most data from five earthquakes (04/06/1998, 13/11/1998, 27/09/1999, 17/06/2000 and 21/06/2000).

## 2.212 Li et al. (2003)

- Ground-motion model is:

$$A_{max} = a10^{bM}(\Delta + r)^c$$

where $A_{max}$ is in cm/s$^2$, $a = 459.0$, $b = 0.198$ and $c = -1.175$ ($\sigma$ is not reported). $r$ can be 5, 10 or 15 km.

- Data from Lancang-Gengma 1989 ($M7.6$) earthquake.

## 2.213 Nishimura and Horike (2003)

- Ground-motion model is:

$$\log \mathrm{PGA} = a_1 + a_2M + a_3D - \log(R + a_4 10^{a_5 M_{JMA}}) + a_6 RD^{a_6} + S_j$$

where PGA is in m/s$^2$, $a_1 = -1.579$, $a_2 = 0.739$, $a_3 = 0.022$, $a_4 = 0.0006$, $a_5 = 0.69$, $a_6 = -0.0025$ and $a_7 = 0.263$ ($\sigma$ is unknown).

- Use unknown number of site classes, $S_j$
- $D$ is focal depth.
- Use data from K-Net.

## 2.214 Shi and Shen (2003)

- Ground-motion model is:

$$\log \mathrm{PGA} = a_1 + a_2 M_s + a_3 \log[R + a_4 \exp(a_5 M_s)]$$

where PGA is in cm/s$^2$, $a_1 = 1.3012$, $a_2 = 0.6057$, $a_3 = -1.7216$, $a_4 = 1.126$ and $a_5 = 0.482$ ($\sigma$ not reported).

## 2.215 Sigbjörnsson and Ambraseys (2003)

- Ground-motion model is:

$$\begin{aligned}\log_{10}(\mathrm{PGA}) &= b_0 + b_1 M - \log_{10}(R) + b_2 R \\ R &= \sqrt{D^2 + h^2}\end{aligned}$$

where PGA is in g, $b_0 = -1.2780 \pm 0.1909$, $b_1 = 0.2853 \pm 0.0316$, $b_2 = -1.730 \times 10^{-3} \pm 2.132 \times 10^{-4}$ and $\sigma = 0.3368$ ($\pm$ indicates the standard deviation of the coefficients). $h$ was fixed arbitrarily to 8 km.

- Use data from ISESD (Ambraseys et al., 2004). Select using $d_e < 1000$ km, $5 \leq M \leq 7$ (where $M$ is either $M_w$ or $M_s$).
- Focal depths $< 20$ km.
- Only use data from strike-slip earthquakes.
- Note that coefficient of variation for $b$ coefficients is in range 11 to 15%.
- Note that $b_0$ and $b_1$ are very strongly negatively correlated (correlation coefficient of $-0.9938$), believed to be because PGA is governed by $b_0 + b_1 M$ as $D$ approaches zero, but they are almost uncorrelated with $b_2$ (correlation coefficients of $-0.0679$ and $-0.0076$ for $b_0$ and $b_1$ respectively), believed to be because of zero correlation between $M$ and $D$ in the data used.
- Also derive equation using $\log_{10}(\mathrm{PGA}) = b_0 + b_1 M + b_2 R + b_3 \log_{10}(R)$ (do not report coefficients) and find slightly smaller residuals but similar behaviour of the $b$ parameters.
- Plot distribution of residuals (binned into intervals of 0.25 units) and the normal probability density function.

## 2.216 Skarlatoudis et al. (2003)

- Ground-motion model is:

$$\log Y = c_0 + c_1 M + c_2 \log(R^2 + h^2)^{1/2} + c_3 F + c_5 S$$

where $Y$ is in cm/s$^2$, $c_0 = 0.86$, $c_1 = 0.45$, $c_2 = -1.27$, $c_3 = 0.10$, $c_5 = 0.06$ and $\sigma = 0.286$.

- Use three site classes (from NEHRP):

$S = 0$ B: 19 stations plus 6 stations between A and B

$S = 1$ C: 68 stations

$S = 2$ D: 25 stations

No stations in NEHRP class A or E. Use geotechnical information where available and geological maps for the other stations.

- Focal depths, $h$, between 0.0 and 30.1 km.
- Classify earthquakes into three faulting mechanism classes:

$F = 0$ Normal, 101 earthquakes

$F = 1$ Strike-slip, 89 earthquakes

$F = 1$ Thrust, 35 earthquakes

but only retain two categories: normal and strike-slip/thrust. Classify using plunges of P and T axes and also knowledge of the geotectonic environment. Have fault-plane solutions for 67 earthquakes.

- Choose data that satisfies at least one of these criteria:
  - from earthquake with $M_w \geq 4.5$;
  - record has PGA $\geq 0.05$ g, independent of magnitude;
  - record has PGA $< 0.05$ g but at least one record from earthquake has PGA $\geq 0.05$ g.
- Relocate all earthquakes.
- Redigitise all records using a standard procedure and bandpass filter using cut-offs chosen by a comparison of the Fourier amplitude spectrum (FAS) of the record to the FAS of the digitised fixed trace. Find that PGAs from uncorrected and filtered accelerograms are almost identical.
- Convert $M_L$ to $M_w$, for earthquakes with no $M_w$, using a locally derived linear equation
- Most data from earthquakes with $M_w < 6$ and $r_{hypo} < 60$ km.
- Note correlation in data between $M_w$ and $r_{hypo}$.
- Note lack of near-field data ($R < 20$ km) for $M_w > 6.0$.
- Plot estimated distance at which instruments would not be expected to trigger and find that all data lie within the acceptable distance range for mean trigger level and only 14 records fall outside the distance range for trigger level plus one $\sigma$. Try excluding these records and find no effect. Hence conclude that record truncation would not affect results.
- Use an optimization procedure based on the least-squares technique using singular value decomposition because two-step methods always give less precise results than one-step techniques. Adopted method allows the controlling of stability of optimization and accurate determination and analysis of errors in solution. Also method expected to overcome and quantify problems arising from correlation between magnitude and distance.
- Test assumption that site coefficient for site class D is twice that for C by deriving equations with two site terms: one for C and one for D. Find that the site coefficient for D is roughly twice that of site coefficient for C.
- Test effect of focal mechanism by including two coefficients to model difference between normal, strike-slip and thrust motions. Find that the coefficients for difference between strike-slip and normal and between thrust and normal are almost equal. Hence combine strike-slip and thrust categories.
- Try including quadratic $M$ term but find inadmissible (positive) value due to lack of data from large magnitude events.

- Also derive equations using this functional form: $\log Y = c_0 + c_1 M + c_2 \log(R + c_4) + c_3 F + c_5 S$ where $c_4$ was constrained to 6 km from an earlier study due to problems in deriving reliable values of $c_2$ and $c_4$ directly by regression.

- Plot observed data scaled to $M_w 6.5$ against predictions and find good fit.

- Find no systematic variations in residuals w.r.t. remaining variables.

- Find reduction in $\sigma$ w.r.t. earlier studies. Relate this to better locations and site classifications.

## 2.217 Ulutaş and Özer (2003)

- Ground-motion model is:

$$\log A = a_1 + a_2 M - \log(R + a_3 10^{0.5M}) + a_4 R$$

where $A$ is in gal, $a_1 = 0.505171$, $a_2 = 0.537579$, $a_3 = 0.008347$ and $a_4 = -0.00242$ ($\sigma$ is not known).

## 2.218 Zhao et al. (2003)

- Ground-motion model is:

$$A_{max} = a 10^{bM} (\Delta + 10)^c$$

where $A_{max}$ is in cm/s$^2$, $a = 195.0$, $b = 0.38$ and $c = -1.97$ ($\sigma$ is not reported).

- Data from Lancang-Gengma 1989 ($M7.6$) earthquake.

## 2.219 Beauducel et al. (2004)

- Ground-motion model is:

$$\log(\text{PGA}) = aM + bR - \log(R) + c$$

where PGA is in g, $a = 0.611377$, $b = -0.00584334$, $c = -3.216674$ and $\sigma = 0.5$.

- Do not include terms for site effects due to uncertainty of site classifications (rock/soil). Suggest multiplying predictions by 3 to estimate PGA at soil sites.

- Derive model to better estimate macroseismic intensities rapidly after an earthquake.

- Select data from 21/11/2004 to 28/12/2004, which mainly come from earthquakes in the Les Saintes sequence but include some subduction events and crustal earthquakes in other locations.

- Data from 13 stations on Guadeloupe.

- Vast majority of data from $M < 4$ and $20 < d < 100$ km.

- Remove constant offset from accelerations but do not filter.

- Use resolved maximum because other definitions (e.g. larger) can underestimate PGA by up to 30%.

- Plot residuals against $M$ and find no trends. Observe some residuals of $\pm 1.5$.

- Apply model to other earthquakes from the region and find good match to observations.

## 2.220 Beyaz (2004)

- Ground-motion model is:

$$\log \mathrm{PGA} = a_1 + a_2 M_w^2 + a_3 \log(r + a_4)$$

  where PGA is in unknown unit (probably cm/s$^2$), $a_1 = 2.581$, $a_2 = 0.029$, $a_3 = -1.305$, $a_4 = 7$ and $\sigma = 0.712$[16].

- Data from rock sites.

## 2.221 Bragato (2004)

- Ground-motion model is:

$$\log_{10}(y) = a + (b + cm)m + (d + em)\log_{10}(\sqrt{r^2 + h^2})$$

  where $y$ is in g, $a = 0.46$, $b = 0.35$, $c = 0.07$, $d = -4.79$, $e = 0.60$, $h = 8.9$ km and $\sigma = 0.33$.

- Investigates effect of nontriggering stations on derivation of empirical Ground-motion model based on the assumption that the triggering level is known (or can be estimated from data) but do not know which stations triggered (called left truncated data).

- Develops mathematical theory and computational method (after trying various alternative methods) for truncated regression analysis (TRA) and randomly truncated regression analysis (RTRA) (where triggering level changes with time).

- Tests developed methods on 1000 lognormally-distributed synthetic data points simulated using the equation of Ambraseys et al. (1996) for $4 \leq M_s \leq 7$ and $1 \leq d_f \leq 100$ km. A fixed triggering threshold of 0.02 g is imposed. Regresses remaining 908 samples using TRA and RTRA. Finds a very similar equation using TRA but large differences for $d_f > 20$ km by using standard regression analysis (SRA) due to slower attenuation. Also apply TRA to randomly truncated synthetic data and find a close match to original curve, which is not found using SRA.

- Applies method to 189 records from rock sites downloaded from ISESD with $M > 4.5$ (scale not specified) and $d < 80$ km (scale not specified) using functional form: $\log_{10}(y) = a + bm + c\log_{10}(\sqrt{r^2 + h^2})$. Uses these selection criteria to allow use of simple functional form and to avoid complications due to crustal reflections that reduce attenuation. Discards the five points with PGA $< 0.01$ g (assumed threshold of SMA-1s). Applies TRA and SRA. Finds both $M$-scaling and distance attenuation are larger with TRA than with SRA because TRA accounts for larger spread in original (not truncated) data. Differences are relevant for $M < 6$ and $d > 20$ km.

- Applies method to dataset including, in addition, non-rock records (456 in total). Finds no differences between TRA and SRA results. Believes that this is due to lack of data in range possibly affected by truncation (small $M$ and large $d$). Finds similar results to Ambraseys et al. (1996).

- Applies method to NE Italian data from seven seismometric and ten accelerometric digital stations assuming: $\log_{10}(y) = a + bm + c\log_{10}(\sqrt{r^2 + h^2})$. Accelerometric stations used usually trigger at 0.001 g. Seismometric stations used trigger based on ratio of short-term and long-term averages (STA/LTA), which varies from station to station and acts like a random threshold. Firstly neglects randomness and assumes trigger level of each station equals lowest recorded PGA and applies TRA and SRA. Finds small differences for $d < 8$ km and $d > 30$ km.

[16] It is stated that common logarithms are used but this standard deviation is extremely high and hence it may actually be in terms of natural logarithms.

- Applies method using functional form above, which believes is more physically justified. SRA does not converge. Studies reason for this by regressing on data from $M$ intervals of 0.3 units wide. Finds behaviour of PGAs inverts for $M < 3$. Finds increasing $\sigma$ with decreasing $M$ for $M > 3$. TRA does converge and shows stronger magnitude saturation than SRA.
- Notes that application of RTRA to model effect of STA/LTA for used data is not realistic since probably not enough data to constrain all 23 parameters and to computational expensive using adopted maximization technique for RTRA.
- Estimates the random truncation parameters for one station (Zoufplan) and finds that the fixed threshold assumption made is acceptable since estimated random truncation parameters predict that only 14% of observations are lost at the earlier assumed fixed threshold level (the lowest PGA recorded).

## 2.222 Cantavella et al. (2004)

- Ground-motion model is:

$$\ln y = a + bM + c \ln \sqrt{r^2 + h^2}$$

where $y$ is in $\mathrm{cm/s^2}$, $a = -2.25$, $b = 1.95$, $c = -1.65$ and $h = 6$ ($\sigma$ is not known).

## 2.223 Gupta and Gupta (2004)

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln R_h + C_4 R_h + C_5 v$$

where PGA is in g, $C_1 = -7.515$, $C_2 = 1.049$, $C_3 = -0.105$, $C_4 = -0.0211$, $C_5 = -0.287$ and $\sigma = 0.511$. $v = 0$ for horizontal PGA and 1 for vertical PGA.

- Data from basalt sites (7 stations), thick hard lateritic soil underlain by basalt (1 station) and dam galleries (4 stations).
- Data from 13-station strong-motion network (AR-240 and RFT-250 instrument types) close to Koyna Dam. Exclude data from dam top. Use data from foundation gallery because believe they can be considered as ground acceleration data. Select set of 31 significant records after scrutinizing all data.
- Correct for instrument response and filter using cut-off frequencies based on a signal-to-noise ratio $> 1$.
- Use a 2-stage regression method. Firstly, find $C_1$, $C_2$ and $C_5$ (magnitude and component dependencies) and then find updated $C_1$, $C_3$ and $C_4$ (distance dependence) using residuals from first stage.
- Find that equation matches the observed data quite well.

## 2.224 Iyengar and Ghosh (2004)

- Ground-motion model is:

$$\log_{10} y = C_1 + C_2 M - B \log_{10}(r + \mathrm{e}^{C_3 M})$$

where $y$ is in g, $C_1 = -1.5232$, $C_2 = 0.3677$, $B = 1.0047$, $C_3 = 0.41$ and $\sigma = 0.2632$.

- Data from rock sites, which assume to have $760 < V_{s,30} < 1500\,\mathrm{m/s}$.
- 38 records from Sharma (1998) and 23 are new data.

## 2.225 Kalkan and Gülkan (2004a)

- Ground-motion model is:

$$\begin{aligned}\ln Y_V &= C_1 + C_2(M-6) + C_3(M-6)^2 + C_4(M-6)^3 + C_5 \ln r + C_6\Gamma_1 + C_7\Gamma_2 \\ r &= (r_{cl}^2 + h^2)^{1/2}\end{aligned}$$

  where $Y$ is in g, $C_1 = 0.055$, $C_2 = 0.387$, $C_3 = -0.006$, $C_4 = 0.041$, $C_5 = -0.944$, $C_6 = 0.277$, $C_7 = 0.030$, $h = 7.72$ km, $\sigma_{\text{rock}} = 0.629$, $\sigma_{\text{soil}} = 0.607$ and $\sigma_{\text{softsoil}} = 0.575$.

- Use three site classes:

$\Gamma_1 = 0$, $\Gamma_2 = 0$ Rock: average $V_s = 700$ m/s, 27 records

$\Gamma_1 = 1$, $\Gamma_2 = 0$ Soil: average $V_s = 400$ m/s, 26 records

$\Gamma_1 = 0$, $\Gamma_2 = 1$ Soft soil: average $V_s = 200$ m/s, 47 records

  Classify using approximate methods due to lack of available information. Note that correspondence between average $V_s$ values for each site class and more widely accepted soil categories is tenuous.

- Focal depths from 0 to 111.0 km. State that all earthquakes were shallow crustal events. Only 4 records come from earthquakes with reported focal depths $> 33$ km.

- Expand with data from after 1999 and update database of Gülkan and Kalkan (2002).

- Faulting mechanism distribution is: normal (12 earthquakes, 14 records), strike-slip (33 earthquakes, 81 records) and reverse (2 earthquakes, 5 records). Note that poor distribution w.r.t. mechanism does not allow its effect to be modelled.

- Use only records from earthquakes with $M_w \geq 4.5$ to emphasize motions having greatest engineering interest and to include only more reliably recorded events. Include data from one $M_w$4.2 earthquake because of high vertical acceleration (31 mg) recorded.

- Data reasonably well distribution w.r.t. $M$ and $d$ for $d < 100$ km.

- Data mainly recorded in small and medium-sized buildings $\leq 3$ storeys. Note that these buildings modify recorded motions and this is an unavoidable uncertainty of the study.

- Data from main shocks. Exclude data from aftershocks, in particular that from the 1999 Kocaeli and Düzce aftershocks because these records are from free-field stations, which do not want to commingle with non-free-field data.

- Exclude a few records for which PGA caused by main shock is $< 10$ mg. Exclude data from aftershocks from the same stations.

- Note that data used is of varying quality and could be affected by errors.

- Include cubic term for $M$ dependence to compensate for the controversial effects of sparsity of Turkish data. Find that it gives a better fit.

- Use two-step method of Ambraseys et al. (1996) to find site coefficients $C_6$ and $C_7$ after exploratory analysis to find regression method that gives the best estimates and the lowest $\sigma$.

- State equations can be used for $4.5 \leq M_w \leq 7.4$ and $d_f \leq 200$ km.

- Find no significant trends in residuals w.r.t. $M$ or $d$ for all data and for each site category except for a few high residuals for soil and soft soil records at $d_f > 100$ km.

- Compute individual $\sigma$s for each site class.
- Find that observed ground motions for the Kocaeli earthquake are well predicted.

## 2.226 Kalkan and Gülkan (2004b) and Kalkan and Gülkan (2005)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln(V_S/V_A) \\ r &= (r_{cl}^2 + h^2)^{1/2}\end{aligned}$$

where $Y$ is in g, $b_1 = 0.393$, $b_2 = 0.576$, $b_3 = -0.107$, $b_5 = -0.899$, $b_V = -0.200$, $V_A = 1112\,\mathrm{m/s}$, $h = 6.91\,\mathrm{km}$ and $\sigma = 0.612$.

- Use three site classes:

Rock Average $V_s = 700\,\mathrm{m/s}$, 23 records

Soil Average $V_s = 400\,\mathrm{m/s}$, 41 records

Soft soil Average $V_s = 200\,\mathrm{m/s}$, 48 records

Use $V_s$ measurements where available (10 stations, 22 records) but mainly classify using approximate methods. Note that correspondence between average $V_s$ values for each site class and more widely accepted soil categories is tenuous.

- Focal depths from 0 to 111.0 km. State that all earthquakes were shallow crustal events. Only 4 records come from earthquakes with reported focal depths $> 33$ km.
- Expand with data from after 1999 and update database of Gülkan and Kalkan (2002).
- Faulting mechanism distribution is: normal (12 earthquakes, 14 records), strike-slip (34 earthquakes, 82 records), reverse (2 earthquakes, 5 records), unknown (9 earthquakes, 11 records). Note that poor distribution w.r.t. mechanism does not allow its effect to be modelled.
- Use only records from earthquakes with $M_w \geq 4.0$ to include only more reliably recorded events.
- Data reasonably well distribution w.r.t. $M$ and $d$ for $d < 100$ km.
- Data from main shocks. Exclude data from aftershocks, in particular that from the 1999 Kocaeli and Düzce aftershocks because of high nonlinear soil behaviour observed during the mainshocks near the recording stations.
- Data mainly recorded in small and medium-sized buildings $\leq 3$ storeys. Note that these buildings modify recorded motions and this is an unavoidable uncertainty of the study.
- State equations can be used for $4.0 \leq M_w \leq 7.5$ and $d_f \leq 250$ km.
- Find no significant trends in residuals w.r.t. $M$ or $d$ for all data and for each site category.
- Find that observed ground motions for the Kocaeli earthquake are well predicted.

## 2.227 Lubkowski et al. (2004)

- Ground-motion model is not reported. Use six functional forms.
- Use four site categories:

| | |
|---|---|
| Very soft soil | $V_{s,30} < 180$ m/s. 0 records. |
| Soft soil | $180 \leq V_{s,30} < 360$ m/s. 1 record. |
| Stiff soil | $360 \leq V_{s,30} < 750$ m/s. 34 records. |
| Rock | $V_{s,30} \geq 750$ m/s. 93 records. |

  Site conditions are unknown for 35 records. Classify mainly using description of local site conditions owing to unavailability of $V_s$ measurements.

- Exclude data from $M_w < 3.0$ to exclude data from earthquakes that are likely to be associated with large uncertainties in their size and location and because ground motions from smaller earthquakes are likely to be of no engineering significance.
- Exclude data from multi-storey buildings, on or in dams or on bridges.
- Most data from $M_w < 5.5$ so believe use of $r_{epi}$ is justified.
- Records from: eastern N America (78 records), NW Europe (61 including 6 from UK) and Australia (24).
- Locations from special studies, ISC/NEIC or local network determinations.
- Note distinct lack of data from $< 10$ km for $M_w > 5$.
- Only retain good quality strong-motion data. No instrument correction applied because of the lack of instrument characteristics for some records. Individually bandpass filter each record with a Butterworth filter with cut-offs at 25 Hz and cut-off frequencies chosen by examination of signal-to-noise ratio and integrated velocity and displacement traces.
- Find use of different functional forms has significant influence on predicted PGA.
- Regression on only rock data generally reduced PGA.
- Predictions using the functional forms with quadratic $M$-dependence were unreliable for $M_w > 5.5$ because they predict decrease PGA with increasing $M$ since there was insufficient data from large magnitude earthquakes to constrain the predictions.
- Find different regression methods predict similar PGAs with differences of $< 5\%$ for a $M_w 5$ event at 5 km when all records were used but differences up to 63% when using only rock data. Prefer the one-stage maximum-likelihood method since allows for correlation between $M$ and $d$ in dataset and does not ignore earthquakes recorded by only a single station (25% of data).
- Find, from analysis of residuals, that equation generally underpredicts PGA of data from eastern N America and Australia but overpredicts motions from Europe and UK.
- Find no trends in residuals w.r.t. amplitude, distance, magnitude or fault mechanism.
- Believe that large $\sigma$s found are due to: lack of data from close to large magnitude earthquakes, use of data from different regions with varying source and path characteristics and use of much data from small earthquakes that are probably associated with higher uncertainty w.r.t. magnitude and location since such earthquakes have not been as well studied as large earthquakes and there is a lack of data with high signal-to-noise ratio from which relocations can be made.
- Do not recommend equations for practical use due to large uncertainties.

## 2.228 Marin et al. (2004)

- Ground-motion model is:

$$\log_{10}\mathrm{PGA} = a_1 + a_2 M_L + a_3 \log_{10} R$$

where PGA is in g, $a_1 = -3.93$, $a_2 = 0.78$, $a_3 = -1.5$ and $\sigma = 0.55$.

- All records from stiff bedrock. Shear-wave velocities estimated from geology gives: 1200–2000 m/s for carbonated formations and > 2500 m/s for eruptive formations (majority of data).

- Derive equation since find previous equations are not consistent with recent data recorded in France and because of differences between $M_L$ of LDG and other $M_L$ scales.

- Use data from the Alps, the Pyrenees and Armorican Massif recorded by LDG network of vertical seismometers between 1995 and 1996. Convert vertical PGAs to horizontal PGAs using empirical relation of Smit (1998).

- Focal depths between 2 and 12 km.

- 11 records from $3 \leq d_e \leq 50$ km, 34 from $50 < d_e \leq 200$ km and 18 from $d_e > 200$ km (all from two largest earthquakes with $M_L 5.3$ and $M_L 5.6$).

- Plot predictions and data from rock sites of all French earthquakes with $M_L \geq 4$ recorded by RAP network (largest three earthquakes have $M_L 5.5$, $M_L 5.7$ and $M_L 5.9$) and find good agreement. State that this agreement shows that equation can be extrapolated to strongest earthquakes considered for France.

- Note that it will be possible to establish a more robust equation using increasing number of data from RAP, especially from near field and large magnitudes.

## 2.229 Midorikawa and Ohtake (2004)

- Ground-motion models are:

$$\begin{aligned}
\log A &= b - \log(X + c) - kX \quad \text{for } D \leq 30\,\text{km} \\
\log A &= b + 0.6\log(1.7D + c) - 1.6\log(X + c) - kX \quad \text{for } D > 30\,\text{km} \\
\text{where} \quad b &= aM_w + hD + d_i S_i + e
\end{aligned}$$

where $A$ is in gal, $a = 0.59$, $c = 0.0060 \times 10^{0.5M_w}$ (adopted from Si and Midorikawa (2000)), $d_1 = 0.00$ (for crustal earthquakes), $d_2 = 0.08$ (for inter-plate earthquakes), $d_3 = 0.30$ (for intra-plate earthquakes), $e = 0.02$, $h = 0.0023$, $k = 0.003$ [adopted from Si and Midorikawa (2000)], $\sigma_{\text{intra-event}} = 0.27$ and $\sigma_{\text{inter-event}} = 0.16$.

- Use two site categories [definitions of Joyner and Boore (1981)]:

Rock

Soil

Use $V_{s,30}$ where available. Multiply PGA values from rock sites by 1.4 to normalise them w.r.t. PGA at soil sites.

- All records from the free-field or small buildings where soil-structure interaction is negligible.

- Data from different types of instruments hence instrument correct and bandpass filter.

- Classify earthquakes into these three types:

Crustal $S_1 = 1$, $S_2 = S_3 = 0$. 12 earthquakes, 1255 records. Focal depths, $D$, between 3 and 30 km.

Inter-plate $S_2 = 1$, $S_1 = S_3 = 0$. 10 earthquakes, 640 records. $6 \leq D \leq 49$ km.

Intra-plate $S_3 = 1$, $S_1 = S_2 = 0$. 11 earthquakes, 1440 records. $30 \leq D \leq 120$ km.

- Most data from $M_w < 7$. No data between 6.9 and 7.6.
- Use separate functional forms for $D \leq 30$ km and $D > 30$ km because of significantly faster decay for deeper earthquakes.
- Plot histograms of residuals and conclude that they are lognormally distributed.
- Compute $\sigma$ for 4 $M$ ranges: 5.5–5.9, 6.0–6.5, 6.6–6.9 and 7.6–8.3. Find slight decrease in $\sigma$ w.r.t. $M$.
- Compute $\sigma$ for ranges of 20 km. Find significantly smaller $\sigma$s for distances $< 50$ km and almost constant $\sigma$s for longer distances.
- Compute $\sigma$ for ranges of PGA of roughly 50 km. Find much larger $\sigma$s for small PGA than for large PGA.
- Believe that main cause of $M$-dependent $\sigma$ is that stress-drop is $M$-dependent and that radiation pattern and directivity are not likely to be significant causes.
- Believe that distance-dependent $\sigma$ is likely to be due to randomness of propagation path (velocity and $Q$-structure).
- Believe site effects do not contribute greatly to the variance.
- Plot PGA versus distance and observe a saturation at several hundred cm/s$^2$, which suggest may be due to nonlinear soil behaviour.
- Plot $\sigma$ w.r.t. PGA for three site categories: $100 \leq V_{s,30} \leq 300$ m/s, $300 \leq V_{s,30} \leq 600$ m/s and $600 \leq V_{s,30} \leq 2600$ m/s. Find $\sigma$ lower for soft soils than for stiff soils, which believe may demonstrate that nonlinear soil response is a cause of PGA-dependent $\sigma$.
- Note that because inter-event $\sigma$ is significantly smaller than intra-event $\sigma$, source effects are unlikely to be the main cause for observed $\sigma$ dependencies.

## 2.230 Özbey et al. (2004)

- Ground-motion model is:

$$\log(Y) = a + b(M-6) + c(M-6)^2 + d\log\sqrt{R^2+h^2} + eG_1 + fG_2$$

  where $Y$ is in cm/s$^2$, $a = 3.287$, $b = 0.503$, $c = -0.079$, $d = -1.1177$, $e = 0.141$, $f = 0.331$, $h = 14.82$ km and $\sigma = 0.260$.

- Use three site classes:

$G_1 = 0$, $G_2 = 0$ A: shear-wave velocity $> 750$ m/s, 4 records, and B: shear-wave velocity 360–750 m/s, 20 records.

$G_1 = 1$, $G_2 = 0$ C: shear-wave velocity 180–360 m/s, 35 records.

$G_1 = 0$, $G_2 = 1$ D: shear-wave velocity $< 180$ m/s, 136 records.

  Originally A and B were separate but combine due to lack of data for site class A.

- Focal depths between 5.4 and 25.0 km.

- Use $M_w$ for $M > 6$ to avoid saturation effects.
- Assume $M_L = M_w$ for $M \leq 6$.
- Select records from earthquakes with $M \geq 5.0$.
- Most (15 earthquakes, 146 records) data from earthquakes with $M \leq 5.8$.
- Only use data from the Earthquake Research Department of General Directorate of Disaster Affairs from $d_f \leq 100$ km.
- Exclude record from Bolu because of possible instrument error.
- Use mixed effects model to account for both inter-event and intra-event variability.
- Find that the mixed effects model yields $\sigma$s lower than fixed effects model.
- Compare predictions with observed data from the Kocaeli and Düzce earthquakes and find reasonable fit.
- Plot coefficients and $\sigma$s against frequency and find dependence on frequency.
- Plot inter-event and intra-event residuals against distance and magnitude and find not systematic trends.
- Find intra-event residuals are significantly larger than inter-event residuals. Suggest that this is because any individual event's recordings used to develop model follow similar trends with associated parameters.
- Recommend that equations are only used for ground-motion estimation in NW Turkey.

## 2.231 Pankow and Pechmann (2004) and Pankow and Pechmann (2006)

- Ground-motion model is:

$$\begin{aligned}\log_{10}(Z) &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \log_{10} D + b_6\Gamma \\ D &= (r_{jb}^2 + h^2)^{1/2}\end{aligned}$$

  where $Z$ is in g, $b_1 = 0.237$, $b_2 = 0.229$, $b_3 = 0$, $b_5 = -1.052$, $b_6 = 0.174$, $h = 7.27$ km and $\sigma_{\log Z} = 0.203$ (see Spudich and Boore (2005) for correct value of $\sigma_3$ for use in calculating $\sigma$ for randomly-orientated component).

- Use two site classes:

$\Gamma = 0$ Rock: sites with soil depths of $< 5$ m.

$\Gamma = 1$ Soil

- Use data of Spudich et al. (1999).
- Correct equations of Spudich et al. (1999) for 20% overprediction of motions for rock sites, which was due either to underestimation of shear-wave velocities for rock sites for extensional regimes (believed to be more likely) or an overestimation of shear-wave velocities at soil sites. Correction based on adjusting $b_1$ and $b_6$ to eliminate bias in rock estimates but leave soil estimates unchanged.
- Verify that adjustment reduces bias in rock estimates.
- Do not change $\sigma_{\log Z}$ because changes to $b_1$ and $b_6$ have a negligible influence on $\sigma_{\log Z}$ w.r.t. errors in determining $\sigma_{\log Z}$.

## 2.232 Skarlatoudis et al. (2004)

- Ground-motion model is:

$$\log Y = c_0 + c_1 M + c_2 \log(R^2 + h^2)^{1/2}$$

  where $Y$ is in $\mathrm{cm/s^2}$, $c_0 = 1.03$, $c_1 = 0.32$, $c_2 = -1.11$, $h = 7\,\mathrm{km}$ and $\sigma = 0.34$.

- Classify stations into four NEHRP categories: A, B, C and D (through a site coefficient, $c_4$) but find practically no effect so neglect.

- Aim to investigate scaling of ground motions for small magnitude earthquakes.

- Most earthquakes have normal mechanisms from aftershock sequences.

- Records from permanent and temporary stations of ITSAK network. Many from EuroSeisTest array.

- Records from ETNA, K2, SSA-1 and SSA-2 plus very few SMA-1 instruments.

- Filter records based on a consideration of signal-to-noise ratio. For digital records use these roll-off and cut-off frequencies based on magnitude (after studying frequency content of records and applying different bandpass filters): for $2 \leq M_w < 3$ $f_r = 0.95\,\mathrm{Hz}$ and $f_c = 1.0\,\mathrm{Hz}$, for $3 \leq M_w < 4$ $f_r = 0.65\,\mathrm{Hz}$ and $f_c = 0.7\,\mathrm{Hz}$ and for $4 \leq M_w < 5$ $f_r = 0.35$ and $f_c = 0.4\,\mathrm{Hz}$. Find that this method adequately removes the noise from the accelerograms used.

- Use source parameters computed from high-quality data from local networks. Note that because focal parameters are from different institutes who use different location techniques may mean data set is inhomogeneous.

- Note that errors in phase picking in routine location procedures may lead to less accurate locations (especially focal depths) for small earthquakes as opposed to large earthquakes due to indistinct first arrivals.

- To minimize effects of focal parameter uncertainties, fix $h$ as $7\,\mathrm{km}$, which corresponds to average focal depth in Greece and also within dataset used.

- Exclude data from $d_e > 40\,\mathrm{km}$ because only a few (3% of total) records exist for these distances and also to exclude far-field records that are not of interest.

- Most records from $d_e < 20\,\mathrm{km}$ and $2.5 \leq M_w \leq 4.5$.

- Also derive equations using this functional form: $\log Y = c_0 + c_1 M + c_2 \log(R + c_3)$ where $c_3$ was constrained to $6\,\mathrm{km}$ from an earlier study due to problems in deriving reliable values of $c_2$ and $c_3$ directly by regression.

- Use singular value decomposition for regression following Skarlatoudis et al. (2003).

- Combined dataset with dataset of Skarlatoudis et al. (2003) and regress. Find significant number of data outside the $\pm 1\sigma$ curves. Also plot average residual at each $M$ w.r.t. $M$ and find systematically underestimation of PGA for $M_w \geq 5$. Conclude that this shows the insufficiency of a common relation to describe both datasets.

- Find no trends in the residuals w.r.t. magnitude or distance.

- Find that the predominant frequencies of PGAs are $< 15\,\mathrm{Hz}$ so believe results not affected by low-pass filtering at 25–27 Hz.

## 2.233 Sunuwar et al. (2004)

- Ground-motion model is:

$$\log Y(T) = b_1(T) + b_2(T)M_{\mathrm{J}} - b_3(T)D - b_4(T)\log(R)$$

  where $Y(T)$ is in cm/s$^2$, $b_1(0) = 1.1064$, $b_2(0) = 0.2830$, $b_3(0) = 0.0076$, $b_4(0) = 0.6322$ and $\sigma = 0.303$ for horizontal PGA and $b_1(0) = 0.7134$, $b_2(0) = 0.3091$, $b_3(0) = 0.0069$, $b_4(0) = 0.7421$ and $\sigma = 0.301$ for vertical PGA.

- Records from 225 stations of K-Net network with $39.29 \leq V_{s,30} \leq 760.25$ m/s (mean $V_{s,30} = 330.80$ m/s.

- Select earthquakes that occurred within the region of the boundary of the Okhotsk-Amur plates (NE Japan bordering Sea of Japan) defined by its horizontal location and vertically, to exclude earthquakes occurring in other plates or along other boundaries.

- Focal depths, $D$, between 8 and 43 km with mean depth of 20.8 km.

- Mean value of $M$ is 4.72.

- Mean $r_{epi}$ is 84.67 km.

- State that exclude records with PGA $< 5$ cm/s$^2$ (although ranges of PGAs given include records with PGA $< 5$ cm/s$^2$).

- Horizontal PGA range: 4.15–411.56 cm/s$^2$. Vertical PGA range: 0.50–163.11 cm/s$^2$.

- Originally use this form: $\log Y(T) = b_1(T) + b_2(T)M - b_3(T)D - \log(R) + b_5(T)R$ but find $b_5(T) > 0$. Regress using the 379 records from sites with $V_{s,30} > 300$ m/s and still find $b_5(T) > 0$ but report results for investigating site effects.

- Plot residuals w.r.t. $r_{hypo}$ and find mean of residuals is zero but find some high residuals.

- Note that need to refine model to consider site effects.

## 2.234 Ulusay et al. (2004)

- Ground-motion model is:

$$\mathrm{PGA} = a_1 \mathrm{e}^{a_2(a_3 M_w - R_e + a_4 S_A + a_5 S_B)}$$

  where PGA is in gal, $a_1 = 2.18$, $a_2 = 0.0218$, $a_3 = 33.3$, $a_4 = 7.8427$, $a_5 = 18.9282$ and $\sigma = 86.4$.

- Use three site categories:

$S_A = 0$, $S_B = 0$ Rock, 55 records.

$S_A = 1$, $S_B = 0$ Soil, 94 records.

$S_A = 0$, $S_B = 1$ Soft soil, 72 records.

  Classify by adopting those given by other authors, selecting the class reported by more than one source.

- Most data from instruments in small buildings.

- Use records with PGA $> 20$ gal to avoid bias due to triggering.

- PGAs of records between 20 and 806 gal.

- Use records from earthquakes with $M_w \geq 4$ because smaller earthquakes are generally not of engineering significance.
- Derive linear conversion formulae (correlation coefficients $> 0.9$) to transform $M_s$ (39), $m_b$ (18), $M_d$ (10) and $M_L$ (6) to $M_w$ (73 events in total).
- Note that rupture surfaces have not been accurately defined for most events therefore use $r_{epi}$.
- Note that accurate focal depths are often difficult to obtain and different data sources provide different estimates therefore do not use $r_{hypo}$.
- Use records from $\geq 5$ km because of assumed average error in epicentral locations.
- Use records from $\leq 100$ km because this is the distance range where engineering significant ground motions occur.
- Most data from $M_w \leq 6$ and $d_e \leq 50$ km.
- Do not consider faulting mechanism because focal mechanism solutions for most earthquakes not available.
- Plot observed versus predicted PGA and find that a few points fall above and below the lines with slopes 1 : 0.5 and 1 : 2 but most are between these lines.
- Note that to improve precision of equation site characterisation based on $V_s$ measurements should be included. Also note that directivity, fault type and hanging wall effects should be considered when sufficient data is available.

## 2.235 Yu and Wang (2004)

- Ground-motion model is:

$$\log S_a = C_1 + C_2 M + C_3 M^2 + C_4 \log[R + C_5 \exp(C_6 M)]$$

  where $S_a$ is in cm/s$^2$, $C_1 = -1.276$, $C_2 = 1.442$, $C_3 = -0.067$, $C_4 = -1.884$, $C_5 = 1.046$, $C_6 = 0.451$ and $\sigma = 0.232$.
- Almost all data from $r_{epi} < 100$ km.
- Assume saturation at $M = 8$ and find $C_5$ and $C_6$. Once these coefficients are fixed find other coefficients by regression.

## 2.236 Adnan et al. (2005)

- Ground-motion model is unknown.
- Data from generic rock sites, equivalent to NEHRP class B.

## 2.237 Ambraseys et al. (2005a)

- Ground-motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 M_w) \log \sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

  where $y$ is in m/s$^2$, $a_1 = 2.522$, $a_2 = -0.142$, $a_3 = -3.184$, $a_4 = 0.314$, $a_5 = 7.6$, $a_6 = 0.137$, $a_7 = 0.050$, $a_8 = -0.084$, $a_9 = 0.062$, $a_{10} = -0.044$, $\sigma_1 = 0.665 - 0.065 M_w$ (intra-event) and $\sigma_2 = 0.222 - 0.022 M_w$ (inter-event).

- Use three site categories:

$S_S = 1$, $S_A = 0$ Soft soil (S), $180 < V_{s,30} \leq 360$ m/s. 143 records.

$S_S = 0$, $S_A = 1$ Stiff soil (A), $360 < V_{s,30} \leq 750$ m/s. 238 records.

$S_S = 0$, $S_A = 0$ Rock (R), $V_{s,30} > 750$ m/s. 203 records.

  Originally include a fourth category, very soft soil ($V_{s,30} \leq 180$ m/s), but only included 11 records so combined with soft soil records. Note that measured $V_{s,30}$ only exist for 89 of 338 stations contributing 161 records so use descriptions of local site conditions to classify stations. Exclude records from stations with unknown site conditions because could not be handled by chosen regression method.

- Use only data from Europe and Middle East because believe their databank is reasonably complete for moderate and large earthquakes that occurred in region. Also these data have been carefully reviewed in previous studies. Finally based on a previous study believe motions in California could be significantly higher than those in Europe. Note that including these data would increase the quantity of high-quality near-source data available.

- Combine data from all seismically active parts of Europe and the Middle East into a common dataset because a previous study shows little evidence for regional differences between ground motions in different regions of Europe.

- Only use earthquakes with a $M_0$ estimate for which to calculate $M_w$. Do not convert magnitudes from other scales because this increases the uncertainty in the magnitude estimates. Exclude records from earthquakes with $M_w < 5$ in order to have a good distribution of records at all magnitudes. Note that this also excludes records from small earthquakes that are unlikely to be of engineering significance.

- Use $r_{jb}$ because does not require a depth estimate, which can be associated with a large error.

- Exclude records from $> 100$ km because: excludes records likely to be of low engineering significance, reduces possible bias due to non-triggering instruments, reduces effect of differences in anelastic decay in different regions and it gives a reasonably uniform distribution w.r.t. magnitude and distance, which reduces likelihood of problems in regression analysis.

- Use only earthquakes with published focal mechanism in terms of trends and plunges of T, B and P axes because estimating faulting type based on regional tectonics or to be the same as the associated mainshock can lead to incorrect classification. Classify earthquakes using method of Frohlich and Apperson (1992):

  Thrust Plunge of T axis $> 50°$. 26 earthquakes, 91 records, $F_T = 1$, $F_N = 0$, $F_O = 0$.

  Normal Plunge of P axis $> 60°$. 38 earthquakes, 191 records, $F_T = 0$, $F_N = 1$, $F_O = 0$.

  Strike-slip Plunge of B axis $> 60°$. 37 earthquakes, 160 records, $F_T = 0$, $F_N = 0$, $F_O = 0$.

  Odd All other earthquakes. 34 earthquakes, 153 records, $F_T = 0$, $F_N = 0$, $F_O = 1$.

  Use this method because does not require knowledge of which plane is the main plane and which the auxiliary.

- Do not exclude records from ground floors or basements of large buildings because of limited data.

- Exclude records from instruments that triggered late and those that were poorly digitised.

- Instrument correct records and then apply a low-pass filter with roll-off and cut-off frequencies of 23 and 25 Hz for records from analogue instruments and 50 and 100 Hz for records from digital instruments. Select cut-off frequencies for high-pass bidirectional Butterworth filtering based on estimated signal-to-noise ratio and also by examining displacement trace. For records from digital instruments use pre-event portion of records as noise estimate. For those records from analogue instruments with an associated digitised fixed trace these were used to estimate the cut-offs. For records from analogue instruments without a fixed trace examine Fourier amplitude spectrum and choose the cut-offs based on where the spectral amplitudes do not tend to zero at low frequencies. Note that there is still some subjective in the process. Next choose a common cut-off frequency for all three components. Use a few records from former Yugoslavia that were only available in corrected form.

- Only use records with three usable components in order that ground-motion estimates are unbiased and that mutually consistent horizontal and vertical equations could be derived.

- Note lack of data from large ($M_w > 6.5$) earthquakes particularly from normal and strike-slip earthquakes.

- Data from: Italy (174 records), Turkey (128), Greece (112), Iceland (69), Albania (1), Algeria (3), Armenia (7), Bosnia & Herzegovina (4), Croatia (1), Cyprus (4), Georgia (14), Iran (17), Israel (5), Macedonia (1), Portugal (4), Serbia & Montenegro (24), Slovenia (15), Spain (6), Syria (5) and Uzbekistan (1).

- Note that much strong-motion data could not be used due to lack of local site information.

- Select one-stage maximum-likelihood regression method because accounts for correlation between ground motion from same earthquake whereas ordinary one-stage method does not. Note that because there is little correlation between $M_w$ and distance in the data used (correlation coefficient of 0.23) ordinary one-stage and one-stage maximum-likelihood methods give similar coefficients. Do not use two-stage maximum-likelihood method because underestimates $\sigma$ for sets with many singly-recorded earthquakes (35 earthquakes were only recorded by one station). Do not use method that accounts for correlation between records from same site because records are used from too many different stations and consequently method is unlikely to lead to an accurate estimate of the site-to-site variability (196 stations contribute a single record). Do not use methods that account for uncertainty in magnitude determination because assume all magnitude estimates are associated with the same uncertainty since all $M_w$ are derived from published $M_0$ values.

- Apply pure error analysis of Douglas and Smit (2001). Divide dataspace into $0.2M_w$ units by 2 km intervals and compute mean and unbiased standard deviation of untransformed ground motion in each bin. Fit a linear equation to graphs of coefficient of variation against ground motion and test if slope of line is significantly different (at 5% significance level) than zero. If it is not then the logarithmic transformation is justified. Find that slope of line is not significantly different than zero so adopt logarithmic transformation of ground motion.

- Use pure error analysis to compute mean and unbiased standard deviation of logarithmically transformed ground motion in each $0.2M_w \times 2$ km bin. Plot the standard deviations against $M_w$ and fit linear equation. Test significance (5% level) of slope. Find that it is significantly different than zero and hence magnitude-independent standard deviation is not justified. Use the reciprocals of fitted linear equations as weighting functions for regression analysis.

- Using the standard deviations computed by pure error analysis for each bin estimate lowest possible $\sigma$ for derived equations.

- Investigate possible magnitude-dependence of decay rate of ground motions using ten best-recorded earthquakes (total number of records between 13 and 26). Fit PGAs for each earthquake with equation of form: $\log y = a_1 + a_2 \log \sqrt{d^2 + a_3^2}$. Plot decay rates ($a_2$) against $M_w$ and fit a linear equation. Find that the fitted line has a significant slope and hence conclude that data supports a magnitude-dependent decay rate. Assume a linear dependence between decay rate and $M_w$ due to limited data.

- Try including a quadratic magnitude term in order to model possible differences in scaling of ground motions for earthquakes that rupture entire seismogenic zone. Find that term is not significant at 5% level so drop.
- Could not simultaneously find negative geometric and anelastic decay coefficients so assume decay attributable to anelastic decay is incorporated into geometric decay coefficient.
- Test significance of all coefficients at 5% level. Retain coefficients even if not significant.
- Note that there is not enough data to model possible distance dependence in effect of faulting mechanism or nonlinear soil effects.
- Compute median amplification factor (anti-logarithm of mean residual) for the 16 stations that have recorded more than five earthquakes. Find that some stations show large amplifications or large deamplifications due to strong site effects.
- Compute median amplification factor for the ten best recorded earthquakes. Find that most earthquakes do not show significant overall differences but that a few earthquakes do display consistently lower or higher ground motions.
- Plot residual plots w.r.t. weighted $M_w$ and weighted distance and find no obvious dependence of scatter on magnitude or distance.
- Plot histograms of binned residuals.
- Compare predicted and observed PGAs from the 2004 Parkfield earthquake and find a close match. Note that this may mean that the exclusion of data from California based on possible differences in ground motions was not justified.

## 2.238 Ambraseys et al. (2005b)

- Ground-motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 M_w) \log \sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

  where $y$ is in $\mathrm{m/s^2}$, $a_1 = 0.835$, $a_2 = 0.083$, $a_3 = -2.489$, $a_4 = 0.206$, $a_5 = 5.6$, $a_6 = 0.078$, $a_7 = 0.046$, $a_8 = -0.126$, $a_9 = 0.005$, $a_{10} = -0.082$, $\sigma_1 = 0.262$ (intra-event) and $\sigma_2 = 0.100$ (inter-event).

- Based on Ambraseys et al. (2005a). See Section 2.237.

## 2.239 Bragato (2005)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = c_1 + c_2 M_s + c_3 r$$

  where PGA is in $\mathrm{m/s^2}$, $c_1 = -2.09$, $c_2 = 0.47$, $c_3 = -0.039$ and $\sigma = 0.3$ (note that the method given in the article must be followed in order to predict the correct accelerations using this equation).

- Uses data (186 records) of Ambraseys and Douglas (2000, 2003) for $M_s \geq 5.8$. Add 57 records from ISESD (Ambraseys et al., 2004) for $5.0 \leq M_s \leq 5.7$.
- Investigates whether 'magnitude-dependent attenuation', i.e. PGA saturation in response to increasing magnitude, can be explained by PGA approaching an upper physical limit through an accumulation of data points under an upper limit.

- Proposes model with: a magnitude-independent attenuation model and a physical mechanism that prevents PGA from exceeding a given threshold. Considers a fixed threshold and a threshold with random characteristics.
- Develops the mathematical models and regression techniques for the truncated and the randomly clipped normal distribution.
- Reduces number of parameters by not considering site conditions or rupture mechanism. Believes following results of Ambraseys and Douglas (2000, 2003) that neglecting site effects is justified in the near-field because they have little effect. Believes that the distribution of data w.r.t. mechanism is too poor to consider mechanism.
- Performs a standard one-stage, unweighted regression with adopted functional form and also with form: $\log_{10}(\mathrm{PGA}) = c_1 + c_2M + c_3r + c_4Mr + c_5M^2 + c_6r^2$ and finds magnitude saturation and also decreasing standard deviation with magnitude.
- Performs regression with the truncation model for a fixed threshold with adopted functional form. Finds almost identical result to that from standard one-stage, unweighted regression.
- Performs regression with the random clipping model. Finds that it predicts magnitude-dependent attenuation and decreasing standard deviation for increasing magnitude.
- Investigates the effect of the removal of high-amplitude ($\mathrm{PGA} = 17.45\,\mathrm{m/s^2}$) record from Tarzana of the 1994 Northridge earthquake. Finds that it has little effect.

## 2.240 Bragato and Slejko (2005)

- Ground-motion model is:

$$\begin{aligned}\log_{10}(Y) &= a + (b + cM)M + (d + eM^3)\log_{10}(r) \\ r &= \sqrt{d^2 + h^2}\end{aligned}$$

  where $Y$ is in g, $a = -3.27$, $b = 1.95$, $c = -0.202$, $d = -3.11$, $e = 0.00751$, $h = 8.9$ km and $\sigma = 0.399$ for horizontal PGA and $r_{epi}$, $a = -3.37$, $b = 1.93$, $c = -0.203$, $d = -3.02$, $e = 0.00744$, $h = 7.3$ km and $\sigma = 0.358$ for horizontal PGA and $r_{jb}$, $a = -2.96$, $b = 1.79$, $c = -0.184$, $d = -3.26$, $e = 0.00708$, $h = 11.3$ km and $\sigma = 0.354$ for vertical PGA and $r_{epi}$ and $a = -3.18$, $b = 1.80$, $c = -0.188$, $d = -3.13$, $e = 0.00706$, $h = 9.1$ km and $\sigma = 0.313$ for vertical PGA and $r_{jb}$.
- Believe relation valid for rather rigid soil.
- Use data from the Seismometric Network of Friuli-Venezia Giulia (SENF) (converted to acceleration), the Friuli Accelerometric Network (RAF), data from the 1976 Friuli sequence and data from temporary seismometric (converted to acceleration) and accelerometric stations of Uprava RS za Geofiziko (URSG) of the 1998 Bovec sequence.
- Data from 1976 Friuli sequence is taken from ISESD. Records have been bandpass filtered with cut-offs of 0.25 and 25 Hz. No instrument correction has been applied. Data from other networks has been instrument corrected and high-pass filtered at 0.4 Hz.
- Hypocentral locations and $M_L$ values adopted from local bulletins and studies.
- Use running vectorial composition of horizontal time series because horizontal vector is the actual motion that intersects seismic hazard. Find that on average running vectorial composition is 8% larger than the larger horizontal peak and 27% larger than the geometric mean. Find that using other methods to

combine horizontal components simply changes $a$ by about 0.1 downwards and does not change the other coefficients.

- Use data from 19 earthquakes with $M_L \geq 4.5$ (161 vertical records, 130 horizontal records).
- Note that distribution w.r.t. magnitude of earthquakes used roughly follows log-linear Gutenberg-Richter distribution up to about $M_L \geq 4.5$.
- Few records available for $d < 10$ km and $M_L > 3$.
- Focal depths between 1.0 and 21.6 km. Average depth is $11.4 \pm 3.6$ km.
- Apply multi-linear multi-threshold truncated regression analysis (TRA) of Bragato (2004) to handle the effect of nontriggering stations using the simplification that for SENF and URSG data the random truncation level can be approximated by the lowest value available in the data set for that station. For data from the 1976 Friuli sequence use a unique truncation level equal to the minimum ground motion for that entire network in the dataset. Use same technique for RAF data.
- Develop separate equations for $r_{epi}$ and $r_{jb}$ (available for 48 records in total including all from $M_L > 5.8$). Note that physically $r_{jb}$ is a better choice but that $r_{epi}$ is more similar to geometric distance used for seismic hazard assessment.
- Use $M_L$ because available for regional earthquakes eastern Alps since 1972.
- Conduct preliminary tests and find that weak-motion data shows higher attenuation than strong-motion data. Investigate horizontal PGA using entire data set and data for 0.5-wide magnitude classes. Find that attenuation is dependent on magnitude and it is not useful to include a coefficient to model anelastic attenuation.
- Since data is not uniformly distributed with magnitude, inversely weight data by number of records within intervals of 0.1 magnitude units wide.
- Because correlation between magnitude and distance is very low (0.03 and 0.02 for vertical and horizontal components, respectively) apply one-stage method.
- Note that large differences between results for $r_{epi}$ and $r_{jb}$ are due to magnitude-dependent weighting scheme used.
- Plot predicted and observed ground motions binned into 0.3 magnitude intervals and find close match.
- Plot residuals w.r.t. focal depth, $r_{jb}$ and $M_L$. Find that it appears equation over-estimates horizontal PGA for $d_f > 80$ km, $M_L < 3$ and focal depths $> 15$ km but note that this is due to the truncation of low amplitude data. Check apparent trend using TRA and find no significant trend.
- Note that difficult to investigate importance of focal depth on attenuation due to unreliability of depths particularly for small earthquakes. Find that focal depths seem to be correlated to magnitude but believe that this is an artifact due to poor location of small earthquakes. Try regression using $r_{hypo}$ and find larger $\sigma$ hence conclude that depth estimates are not accurate enough to investigate effect of depth on ground motions.
- Investigate methods for incorporation of site effect information using their ability to reduce $\sigma$ as a criteria.
- Note that largest possible reduction is obtained using individual average station residuals for each site but that this is not practical because this method cannot be used to predict ground motions at arbitrary site and that it requires sufficient number of observations for each station. Using just those stations that recorded at least five earthquakes obtain estimate of lowest possible $\sigma$ by adopting this method.

- Try using a classification of stations into three site categories: rock (16 stations, 1020 records), stiff soil (9 stations, 117 records) and soft soil (4 stations, 27 records) and find no reduction in $\sigma$, which believe is due to the uneven distribution w.r.t. site class. Find that the strong site effects at Tolmezzo has a significant effect on the obtained site coefficients.

- Use Nakamura (H/V) ratios from ambient noise for a selection of stations by including a term $g(S) = c_{\mathrm{HV}} N(S)$, where $N(S)$ is the Nakamura ratio at the period of interest (0.125–1 s for PGA), in the equation. Find large reductions in $\sigma$ and high correlations between Nakamura ratios and station residuals.

- Use receiver functions from earthquake recordings in a similar way to Nakamura ratios. Find that it is reduces $\sigma$ more than site classification technique but less than using the Nakamura ratios, which note could be because the geometry of the source affects the computed receiver functions so that they are not representative of the average site effects.

- Believe equation is more appropriate than previous equations for $M_L < 5.8$ and equivalent to the others up to $M_L 6.3$. Discourage extrapolation for $M_L > 6.3$ because it overestimates PGA in the far-field from about $M_L 6.5$.

## 2.241 Frisenda et al. (2005)

- Ground-motion model is:
$$\log(Y) = a + bM + cM^2 + d\log(R) + eS$$
where $Y$ is in g, $a = -3.19 \pm 0.02$, $b = 0.87 \pm 0.01$, $c = -0.042 \pm 0.002$, $d = -1.92 \pm 0.01$, $e = 0.249 \pm 0.005$ and $\sigma = 0.316$.

- Use two site classes, because lack local geological information (e.g. average $V_s$):

$S = 0$ Rock, eight stations, 3790 records.

$S = 1$ Soil, seven stations, 3109 records.

Classify station using geological reports, $M_L$ station corrections and H/V spectral ratios computed over a 30 s wide time window of S waves for entire waveform data set.

- Data from Regional Seismic Network of Northwestern Italy and Regional Seismic Network of Lunigiana-Garfagnana (ten Lennartz LE3D-5s and five Guralp CMG-40 sensors with Lennartz Mars88/MC recording systems). Sampling rate either 62.5 or 125 samples/s. Records from broadband and enlarged band seismometers converted to acceleration by: correcting for instrument response, bandpass filtering between 1 and 20 Hz and then differentiating. Accuracy of conversion verified by comparing observed and derived PGA values at one station (STV2), which was equipped with both a Kinemetrics K2 accelerometer and a Guralp CMG-40 broadband sensor.

- Find strong attenuation for short distances ($< 50$ km) and small magnitudes ($M_L < 3.0$).

- $M_L$ calculated using a calibration formula derived for northwestern Italy using a similar dataset.

- Compute signal-to-noise (S/N) ratio for the S phase using windows of 3 s wide and find that data is good quality (85% of windows have S/N ratio greater than 10 dB. Only use records with S/N ratio $> 20$ dB.

- Most earthquakes are from SW Alps and NW Apennines.

- Most records from earthquakes with $1 \leq M_L \leq 3$, small number from larger earthquakes particularly those with $M_L > 4$. $M_L < 1$: 1285 records, $1 \leq M_L < 2$: 2902 records, $2 \leq M_L < 3$: 1737 records, $3 \leq M_L < 4$: 693 records and $M_L \geq 4$: 282 records.

- Data shows strong magnitude-distance correlation, e.g. records from earthquakes with $M_L < 1$ are from $0 \leq R \leq 100$ km and those from earthquakes with $M_L > 4$ are mainly from $R > 50$ km. Distribution is uniform for $2 \leq M_L \leq 4$ and $0 \leq R \leq 200$ km.

- Originally include an anelastic decay term ($d_1 R$) in addition but the value of $d_1$ was positive and not statistically significantly different than zero so it was removed.

- Regression in two-steps: firstly without site effect coefficient ($e$) and then with $e$ added.

- Compare data to estimated decay within one magnitude unit intervals and find predictions are good up to $M_L = 4.0$.

- Find no systematic trends in the residuals.

## 2.242 García et al. (2005)

- Ground-motion model is:

$$
\begin{aligned}
\log Y &= c_1 + c_2 M_w + c_3 R - c_4 \log R + c_5 H \\
R &= \sqrt{R_{\text{cld}}^2 + \Delta^2} \\
\Delta &= 0.00750 \times 10^{0.507 M_w}
\end{aligned}
$$

  where $Y$ is in cm/s$^2$, for horizontal PGA: $c_1 = -0.2$, $c_2 = 0.59$, $c_3 = -0.0039$, $c_4 = 1$, $c_5 = 0.008$, $\sigma_r = 0.27$, $\sigma_e = 0.10$ and for vertical PGA: $c_1 = -0.4$, $c_2 = 0.60$, $c_3 = -0.0036$, $c_4 = 1$, $c_5 = 0.006$, $\sigma_r = 0.25$ and $\sigma_e = 0.11$ where $\sigma_r$ is the intra-event standard deviation and $\sigma_e$ is the inter-event standard deviation.

- All data from 51 hard (NEHRP B) sites.

- All stations in the Valley of Mexico omitted.

- All data from free-field stations: small shelters, isolated from any building, dam abutment, bridge, or structure with more than one storey.

- Focal depths: $35 \leq H \leq 138$ km, most records (13 earthquakes, 249 records) from $35 \leq H \leq 75$ km.

- Exclude data from $M_w < 5.0$ and $R > 400$ km.

- Exclude data from deep earthquakes where wave paths cross the mantle edge.

- All data from normal-faulting earthquakes.

- Use about 27 records from velocity records from broadband seismograph network that were differentiated to acceleration.

- Adopt $\Delta$ from Atkinson and Boore (2003).

- Investigate a number of functional forms. Inclusion of $\Delta$ substantially improves fit, leading to a decrease in random variability at close distances, and an increase in $c_2$ and $c_3$ coefficients. Find worse correlation when add a quadratic magnitude term. A magnitude-dependent $c_4$ leads to higher $\sigma$s. Find unrealistically high ground motions at close distances using the form of $c_4$ used by Atkinson and Boore (2003).

- If exclude three deep earthquakes then little dependence on $H$.

- Do not find any noticeable bias in residuals w.r.t. distance, magnitude or depth (not shown).

- Note that decrease in variability w.r.t. magnitude is only apparent for frequencies $< 1$ Hz.
- Discuss observed dependence of, particularly high-frequency, ground motions on focal depth.

## 2.243 Liu and Tsai (2005)

- Ground-motion model is:
$$\ln Y = a\ln(X+h) + bX + cM_w + d$$
where $Y$ is in $\mathrm{cm/s^2}$ for horizontal PGA (for whole Taiwan) $a = -0.852$, $b = -0.0071$, $c = 1.027$, $d = 1.062$, $h = 1.24$ km and $\sigma = 0.719$ and for vertical PGA (for whole Taiwan) $a = -1.340$, $b = -0.0036$, $c = 1.101$, $d = 1.697$, $h = 1.62$ km and $\sigma = 0.687$. Also report coefficients for equations derived for three different sub-regions.
- Do not differentiate site conditions.
- Focal depths, $h$, between 2.72 and 29.98 km.
- Data from high-quality digital strong-motion networks of Taiwan Strong Motion Instrumentation Program (TSMIP) and Central Mountain Strong Motion Array (CMSMA).
- Select data from earthquakes with $h \leq 30$ km and with records from $\geq 6$ stations at $d_e \leq 20$ km.
- Select events following the 1999 Chi-Chi earthquake ($M_w$7.7) with $M_L > 6$.
- Do not use data from the Chi-Chi earthquake because: a) earlier analysis of Chi-Chi data showed short-period ground motion was significantly lower than expected and b) the Chi-Chi rupture triggered two $M6$ events on other faults thereby contaminating the ground motions recorded at some stations.
- Data uniformly distributed for $M_w \leq 6.5$ and $20 \leq r_{hypo} \leq 100$ km. Significant number of records for $r_{hypo} > 100$ km.
- Use data from the Chi-Chi earthquake and the 2003 Cheng-Kung earthquake ($M_w$6.8) for testing applicability of developed equations.
- For 32 earthquakes (mainly with $M_w < 5.3$) convert $M_L$ to $M_w$ using empirical equation developed for Taiwan.
- Develop regional equations for three regions: CHY in SW Taiwan (16 earthquakes, 1382 records), IWA in NE Taiwan (14 earthquakes, 2105 records) and NTO in central Taiwan (13 earthquakes, 3671 records) and for whole Taiwan to compare regional differences of source clustering in ground-motion characteristics.
- Use $M_w$ since corresponds to well-defined physical properties of the source, also it can be related directly to slip rate on faults and avoids saturation problems of other $M$-scales.
- Use relocated focal depths and epicentral locations.
- Do not use $r_{jb}$ or $r_{rup}$ because insufficient information on rupture geometries, particularly those of small earthquakes, even though believe such distance metrics are justified. However, for small earthquakes do not think using $r_{hypo}$ rather than $r_{rup}$ will introduce significant bias into the equations. Also use $r_{hypo}$ because it is quickly determined after an earthquake hence early ground-motion maps can be produced.
- From equations derived for different sub-regions and from site residual contour maps that ground motions in CHY are about four times higher than elsewhere due to thick, recent alluvial deposits.
- Find predictions for Chi-Chi and Cheng-Kung PGAs are close to observations.

- Plot contour maps of residuals for different sites and relate the results to local geology (alluvial plains and valleys and high-density schist).

- Divide site residuals into three classes: $> 0.2\sigma$, $-0.2$–$0.2\sigma$ and $< -0.2\sigma$ for four NEHRP-like site classes. Find the distribution of residuals is related to the site class particularly for the softest class. Find residuals for C (very dense soil and soft rock) and D (stiff soil) are similar so suggest combining them. Believe geomorphology may also play an important role in site classification because a geomorphologic unit is often closely related to a geologic unit.

## 2.244 McGarr and Fletcher (2005)

- Ground-motion model is:

$$\log(y) = a + bM + d\log(R) + kR + s_1 + s_2$$

  where $y$ is in $\mathrm{cm/s^2}$, $a = -0.9892$, $b = 0.8824$, $d = -1.355$, $k = -0.1363$, $s_1 = 0.337$ (for stations on surface), $s_2 = 0$ (for station at depth) and $\sigma = 0.483$.

- Use data from seven stations, one of which (TU1) is located underground within the mine. Determine site factors (constrained to be between 0 and 1) from PGV data. Originally group into three site categories: one for stations with close to horizontal straight-line ray paths, one for stations with steeper ray paths and one for underground station. Find site factors for first two categories similar so combine, partly because there is no precedent for topographic site factors in empirical ground-motion estimation equations. Believe that low site factors found are because stations are on solid rock $V_s > 1.5\,\mathrm{km/s}$.

- Most data from Trail Mountain coal mine from between 12/2000 and 03/2001 (maximum $M_{CL}2.17$). Supplement with data (2 records) from a $M4.2$ earthquake at Willow Creek mine to provide data at much higher magnitude.

- Most data from $M_w < 1.7$.

- Lower magnitude limit dictated by need for adequate signal-to-noise ratio.

- Focal depths between 50 and 720 m (relative to the ground surface).

- Note that although data may be poorly suited to determine both $d$ and $k$ simultaneously they are retained because both attenuation mechanisms must be operative. State that $d$ and $k$ should be solely considered as empirical parameters due to trade-offs during fitting.

- Do not include a quadratic $M$ term because it is generally of little consequence.

- Use $r_{hypo}$ because earthquakes are small compared to distances so can be considered as point sources.

- Selected events using these criteria:

  - event was recorded by $\geq 6$ stations;
  - data had high signal-to-noise ratio;
  - to obtain the broadest $M$-range as possible; and
  - to have a broad distribution of epicentral locations.

- Find that $M_w$ (estimated for 6 events) does not significantly differ from $M_{CL}$.

- Find that constrains must be applied to coefficients. Constrain $k$ to range $-2$–$0$ because otherwise find small positive values. Believe that this is because data inadequate for independently determining $d$ and $k$.

## 2.245 Nath et al. (2005a)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M - C_3 \ln r - C_4 r$$

where $Y$ is in g, $C_1 = -3.6$, $C_2 = 0.72$, $C_3 = 1.08$ and $C_4 = -0.007$ (SIC) ($\sigma$ is not given).

- Do not consider site effects but note that sediment cover is very thin.
- Data from 9 stations (1 K2 and 8 Etna instruments) established by Indian Institute of Technology, Kharagpur in 1998.
- Focal depths from 3.01 to 34.27 km.
- Use data with signal-to-noise ratios $\geq 3$.
- Instrument and baseline correct data and bandpass filter with cut-offs of 0.1 and 30 Hz.

## 2.246 Nowroozi (2005)

- Ground-motion model is:

$$\ln(A) = c_1 + c_2(M - 6) + c_3 \ln(\sqrt{\text{EPD}^2 + h^2}) + c_4 S$$

where $A$ is in cm/s$^2$, $c_1 = 7.969$, $c_2 = 1.220$, $c_3 = -1.131$, $c_4 = 0.212$, $h = 10$ km (fixed after tests) and $\sigma = 0.825$ for horizontal PGA and $c_1 = 7.262$, $c_2 = 1.214$, $c_3 = -1.094$[17], $c_4 = 0.103$, $h = 10$ km (fixed after tests) and $\sigma = 0.773$ for vertical PGA.

- Uses four site categories ($S$ equals number of site category):

  1. Rock. 117 records.
  2. Alluvial. 52 records.
  3. Gravel and sandy. 70 records.
  4. Soft. 39 records.

  Does analysis combining 1 and 2 together in a firm rock category ($S = 0$) and 3 and 4 in a soft soil category ($S = 1$) and for all site categories combined. Reports coefficients for these two tests.

- Focal depths between 9 and 73 km. Most depths are shallow (depths fixed at 33 km) and majority are about 10 km. Does not use depth as independent parameter due to uncertainties in depths.
- Uses $M_w$ because nearly all reported Ground-motion models use $M_w$.
- Uses macroseismic distance for three events since no $r_{epi}$ reported.
- Believes that methods other than vectorial sum of both horizontal PGAs underestimates true PGA that acts on the structure. Notes that vectorial sum ideally requires that PGAs on the two components arrive at the same time but due to unknown or inaccurate timing the occurrence time cannot be used to compute the resolved component.
- Does not consider faulting mechanism due to lack of information for many events.
- Most records from $M_w \leq 5$.

[17] There is a typographical error in Equation 12 of Nowroozi (2005) since this coefficient is reported as $-1094$.

- Originally includes terms $c_5(M-6)^2$ and $c_6$EPD but finds them statistically insignificant so drops them.
- Notes that all coefficients pass the $t$-test of significance but that the site coefficients are not highly significant, which relates to poor site classification for some stations.
- Compares observed and predicted PGAs with respect to distance. Notes that match to observations is relatively good.
- Compares observed PGAs during Bam 2003 earthquake to those predicted and finds good match.

## 2.247 Ruiz and Saragoni (2005) & Saragoni et al. (2004)

- Ground-motion model is:

$$x = \frac{A\mathrm{e}^{BM}}{(R+C)^D}$$

where $x$ is in cm/s$^2$, $A=4$, $B=1.3$, $C=30$ and $D=1.43$ for horizontal PGA, hard rock sites and thrust earthquakes; $A=2$, $B=1.28$, $C=30$ and $D=1.09$ for horizontal PGA, rock and hard soil sites and thrust earthquakes; $A=11$, $B=1.11$, $C=30$, $D=1.41$ for vertical PGA, hard rock sites and thrust earthquakes; $A=18$, $B=1.31$, $C=30$, $D=1.65$ for vertical PGA, rock and hard soil sites and thrust earthquakes; $A=3840$, $B=1.2$, $C=80$ and $D=2.16$ for horizontal PGA, rock and hard soil sites and intermediate-depth earthquakes; and $A=66687596$, $B=1.2$, $C=80$ and $D=4.09$ for vertical PGA, rock and hard soil sites and intermediate-depth earthquakes.

- Use two site categories:

Hard rock $V_s > 1500$ m/s. 8 records.

Rock & hard soil $360 < V_s < 1500$ m/s. 41 records.

- Focal depths between 28.8 and 50.0 km.
- Develop separate equations for interface and intraslab (intermediate-depth) events.
- Baseline correct and bandpass filter (fourth-order Butterworth) with cut-offs 0.167 and 25 Hz.
- 8 records from between $M_s$6.0 and 7.0, 13 from between 7.0 and 7.5 and 20 from between 7.5 and 8.0.
- Values of coefficient $D$ taken from previous studies.

## 2.248 Takahashi et al. (2005), Zhao et al. (2006) and Fukushima et al. (2006)

- Ground-motion model is:

$$\begin{aligned}\log_e(y) &= aM_w + bx - \log_e(r) + e(h-h_c)\delta_h + F_R + S_I + S_S + S_{SL}\log_e(x) + C_k \\ \text{where} \quad r &= x + c\exp(dM_w)\end{aligned}$$

where $y$ is in cm/s$^2$, $\delta_h = 1$ when $h \geq h_c$ and 0 otherwise, $a=1.101$, $b=-0.00564$, $c=0.0055$, $d=1.080$, $e=0.01412$, $S_R=0.251$, $S_I=0.000$, $S_S=2.607$, $S_{SL}=-0.528$, $C_H=0.293$, $C_1=1.111$, $C_2=1.344$, $C_3=1.355$, $C_4=1.420$, $\sigma=0.604$ (intra-event) and $\tau=0.398$ (inter-event). Use $h_c=15$ km because best depth effect for shallow events.

- Use five site classes ($T$ is natural period of site):

Hard rock NEHRP site class A, $V_{s,30} > 1100$ m/s. 93 records. Use $C_H$.

SC I Rock, NEHRP site classes A+B, $600 < V_{s,30} \leq 1100$ m/s, $T < 0.2$ s. 1494 records. Use $C_1$.

SC II Hard soil, NEHRP site class C, $300 < V_{s,30} \leq 600$ m/s, $0.2 \leq T < 0.4$ s. 1551 records. Use $C_2$.

SC III Medium soil, NEHRP site class D, $200 < V_{s,30} \leq 300$ m/s, $0.4 \leq T < 0.6$ s. 629 records. Use $C_3$.

SC IV Soft soil, NEHRP site classes E+F, $V_{s,30} \leq 200$ m/s, $T \geq 0.6$ s. 989 records. Use $C_4$.

Site class unknown for 63 records.

- Focal depths, $h$, between about 0 and 25 km for crustal events, between about 10 and 50 km for interface events, and about 15 and 162 km for intraslab events. For earthquakes with $h > 125$ km use $h = 125$ km.
- Classify events into three source types:

  1. Crustal.
  2. Interface. Use $S_I$.
  3. Slab. Use $S_S$ and $S_{SL}$.

  and into four mechanisms using rake angle of $\pm 45°$ as limit between dip-slip and strike-slip earthquakes except for a few events where bounds slightly modified:

  1. Reverse. Use $F_R$ if also crustal event.
  2. Strike-slip
  3. Normal
  4. Unknown

  Distribution of records by source type, faulting mechanism and region is given in following table.

| Region | Focal Mechanism | Crustal | Interface | Slab | Total |
|---|---|---|---|---|---|
| Japan | Reverse | 250 | 1492 | 408 | 2150 |
| | Strike-slip | 1011 | 13 | 574 | 1598 |
| | Normal | 24 | 3 | 735 | 762 |
| | Unknown | | | 8 | 8 |
| | Total | 1285 | 1508 | 1725 | 4518 |
| Iran and Western USA | Reverse | 123 | 12 | | 135 |
| | Strike-slip | 73 | | | 73 |
| | Total | 196 | 12 | | 208 |
| All | Total | 1481 | 1520 | 1725 | 4726 |

- Exclude data from distances larger than a magnitude-dependent distance (300 km for intraslab events) to eliminate bias introduced by untriggered instruments.
- Only few records from $< 30$ km and all from $< 10$ km from 1995 Kobe and 2000 Tottori earthquake. Therefore add records from overseas from $< 40$ km to constrain near-source behaviour. Note that could affect inter-event error but since only 20 earthquakes (out of 269 in total) added effect likely to be small.
- Do not include records from Mexico and Chile because Mexico is characterised as a 'weak' coupling zone and Chile is characterised as a 'strong' coupling zone (the two extremes of subduction zone characteristics), which could be very different than those in Japan.
- Note reasonably good distribution w.r.t. magnitude and depth.
- State that small number of records from normal faulting events does not warrant them between considered as a separate group.

- Note that number of records from each event varies greatly.
- Process all Japanese records in a consistent manner. First correct for instrument response. Next low-pass filter with cut-offs at 24.5 Hz for 50 samples-per-second data and 33 Hz for 100 samples-per-second data. Find that this step does not noticeably affect short period motions. Next determine location of other end of usable period range. Note that this is difficult due to lack of estimates of recording noise. Use the following procedure to select cut-off:

  1. Visually inspect acceleration time-histories to detect faulty recordings, S-wave triggers or multiple events.
  2. If record has relatively large values at beginning (P wave) and end of record, the record was mirrored and tapered for 5 s at each end.
  3. Append 5 s of zeros at both ends and calculate displacement time-history in frequency domain.
  4. Compare displacement amplitude within padded zeros to peak displacement within the record. If displacement in padded zeros was relatively large, apply a high-pass filter.
  5. Repeat using high-pass filters with increasing corner frequencies, $f_c$, until the displacement within padded zeros was 'small' (subjective judgement). Use $1/f_c$ found as maximum usable period.

  Verify method by using K-Net data that contains 10 s pre-event portions.
- Conduct extensive analysis on inter- and intra-event residuals. Find predictions are reasonably unbiased w.r.t. magnitude and distance for crustal and interface events and not seriously biased for slab events.
- Do not smooth coefficients.
- Do not impose constraints on coefficients. Check whether coefficient is statistically significant.
- Note that the assumption of the same anelastic attenuation coefficient for all types and depths of earthquakes could lead to variation in the anelastic attenuation rate in a manner that is not consistent with physical understanding of anelastic attenuation.
- Derive $C_H$ using intra-event residuals for hard rock sites.
- Residual analyses show that assumption of the same magnitude scaling and near-source characteristics for all source types is reasonable and that residuals not not have a large linear trend w.r.t. magnitude. Find that introducing a magnitude-squared term reveals different magnitude scaling for different source types and a sizable reduction in inter-event error. Note that near-source behaviour mainly controlled by crustal data. Derive correction function from inter-event residuals of each earthquake source type separately to avoid trade-offs. Form of correction is: $\log_e(S_{MSst}) = P_{st}(M_w - M_C) + Q_{st}(M_w - M_C)^2 + W_{st}$. Derive using following three-step process:

  1. Fit inter-event residuals for earthquake type to a quadratic function of $M_w - M_C$ for all periods.
  2. Fit coefficients $P_{st}$ for $(M_w - M_C)$ and $Q_{st}$ for $(M_w - M_C)^2$ (from step 1) where subscript $st$ denotes source types, to a function up to fourth oder of $\log_e(T)$ to get smoothed coefficients.
  3. Calculate mean values of differences between residuals and values of $P_{st}(M_w - M_C) + Q_{st}(M_w - M_C)^2$ for each earthquake, $W_{st}$, and fit mean values $W_{st}$ to a function of $\log_e(T)$.

  For PGA $Q_C = W_C = Q_I = W_I = 0$, $\tau_C = 0.303$, $\tau_I = 0.308$, $P_S = 0.1392$, $Q_S = 0.1584$, $W_S = -0.0529$ and $\tau_S = 0.321$. Since magnitude-square term for crustal and interface is not significant at short periods when coefficient for magnitude-squared term is positive, set all coefficients to zero. Find similar predicted motions if coefficients for magnitude-squared terms derived simultaneously with other coefficients even though the coefficients are different than those found using the adopted two-stage approach.

- Compare predicted and observed motions normalized to $M_w7$ and find good match for three source types and the different site conditions. Find model overpredicts some near-source ground motions from SC III and SC IV that is believed to be due to nonlinear effects.

## 2.249 Wald et al. (2005)

- Ground-motion model is:

$$\begin{aligned}\log_{10}(Y) &= B_1 + B_2(M-6) - B_5 \log_{10} R \\ \text{where} \quad R &= \sqrt{R_{jb}^2 + 6^2}\end{aligned}$$

where $Y$ is in cm/s$^2$, $B_1 = 4.037$, $B_2 = 0.572$, $B_5 = 1.757$ and $\sigma = 0.836$.

## 2.250 Atkinson (2006)

- Ground-motion model is:

$$\begin{aligned}\log Y &= c0 + c1(\mathbf{M}-5) + c2(\mathbf{M}-5)^2 + c3\log R + c4R + S_i \\ R &= \sqrt{d^2 + h^2}\end{aligned}$$

where $Y$ is in m/s$^2$, $c0 = 2.007$, $c1 = 0.567$, $c2 = 0.0311$, $c3 = -1.472$, $c4 = 0.00000$, $h = 5$ km [from Boore et al. (1997)], $\sigma(\text{BJF}) = 0.309$, $\sigma(\text{emp}-\text{amp}) = 0.307$ and $\sigma(\text{NoSiteCorr}) = 0.305$. Individual station: with empirical-corrected amplitudes $\sigma = 0.269$ and with BJF-corrected amplitudes $\sigma = 0.268$.

- Uses data from 21 TriNet stations with known $V_{s,30}$ values. $190 \leq V_{s,30} \leq 958$ m/s. Uses two approaches for site term $S_i$. In first method (denoted 'empirically-corrected amplitudes', emp − amp) uses empirical site amplification factors from previous study of TriNet stations (for PGA uses site factor for PSA at 0.3 s because correction for PGA is unavailable). In second method [denoted 'Boore-Joyner-Fumal (BJF)-corrected amplitudes', BJF] uses amplification factors based on $V_{s,30}$ from Boore et al. (1997) to correct observations to reference (arbitrarily selected) $V_{s,30} = 760$ m/s.

- Uses only data with amplitudes $> 0.01\%$ g (100 times greater than resolution of data, $0.0001\%$ g).

- States that developed relations not intended for engineering applications due to lack of data from large events and from short distances. Equations developed for investigation of variability issues for which database limitations are not crucial.

- Many records from Landers mainshock and aftershocks.

- Uses standard linear regression since facilitates comparisons using regressions of different types of datasets, including single-station datasets.

- Notes possible complications to functional form due to effects such as magnitude-dependent shape are not important due to small source size of most events.

- Truncates data at 300 km to get dataset that is well distributed in distance-amplitude space.

- Notes that small differences between $\sigma$s when no site correction is applied and when site correction is applied could be due to complex site response in Los Angeles basin.

- Fits trend-lines to residuals versus distance for each station and finds slope not significantly different from zero at most stations except for Osito Audit (OSI) (lying in mountains outside the geographical area defined by other stations), which has a significant positive trend.

- Finds empirical-amplification factors give better estimate of average site response (average residuals per station closer to zero) than $V_{s,30}$-based factors at short periods but the reverse for long periods. Notes $V_{s,30}$ gives more stable site-response estimates, with residuals for individual stations less than factor of 1.6 for most stations.
- Finds standard deviations of station residuals not unusually large at sites with large mean residual, indicating that average site response estimates could be improved.
- Plots standard deviation of station residuals using $V_{s,30}$-based factors and the average of these weighted by number of observations per station. Compares with standard deviation from entire databank. Finds that generally standard deviations of station residuals slightly lower (about 10%) than for entire databank.
- Examines standard deviations of residuals averaged over 0.5-unit magnitude bins and finds no apparent trend for **M**3.5 to **M**7.0 but notes lack of large magnitude data.
- Restricts data by magnitude range (e.g. $4 \leq \mathbf{M} \leq 6$) and/or distance (e.g. $\leq 80$ km) and find no reduction in standard deviation.
- Finds no reduction in standard deviation using one component rather than both.
- Performs separate analysis of residuals for Landers events (10 stations having $\geq 20$ observations) recorded at $> 100$ km. Notes that due to similarity of source and path effects for a station this should represent a minimum in single-station $\sigma$. Finds $\sigma$ of $0.18 \pm 0.06$.

## 2.251 Beyer and Bommer (2006)

- Exact functional form of Ground-motion model is not given but note includes linear and quadratic terms of magnitude and a geometric spreading term. Coefficients not given but report ratios of $\sigma$ using different definitions w.r.t. $\sigma$ using geometric mean.
- Distribution w.r.t. NEHRP site classes is:

| | |
|---|---|
| A | 8 records |
| B | 37 records |
| C | 358 records |
| D | 534 records |
| E | 11 records |
| Unspecified | 1 record |

- Use data from Next Generation Attenuation (NGA) database.
- Distribution w.r.t. mechanism is:

| | |
|---|---|
| Strike-slip | 333 records, 51 earthquakes |
| Normal | 36 records, 12 earthquakes |
| Reverse | 329 records, 21 earthquakes |
| Reverse-oblique | 223 records, 9 earthquakes |
| Normal-oblique | 25 records, 7 earthquakes |
| Undefined | 3 records, 3 earthquakes |

- Exclude records from Chi-Chi 1999 earthquake and its aftershocks to avoid bias due to over-representation of these data ($> 50\%$ of 3551 records of NGA databank).

- Exclude records with PGA (defined using geometric mean) $< 0.05$ g to focus on motions of engineering significance and to avoid problems with resolution of analogue records.
- Exclude records with maximum usable period $< 0.5$ s.
- Exclude records without hypocentral depth estimate since use depth in regression analysis.
- Earthquakes contribute between 1 and 138 accelerograms.
- Note data is from wide range of $M$, $d$, mechanism, site class and instrument type.
- State aim was not to derive state-of-the-art Ground-motion models but to derive models with the same data and regression method for different component definitions.
- Assume ratios of $\sigma$s from different models fairly insensitive to assumptions made during regression but that these assumptions affect $\sigma$ values themselves.
- Find ratios of $\sigma$s from using different definitions close to 1.
- Note that results should be applied with caution to subduction and stable continental regions since have not been checked against these data.

## 2.252 Bindi et al. (2006)

- Ground-motion model is for $r_{epi}$:

  $$\log(y) = a + bM + c \log \sqrt{(R^2 + h^2)} + e_1 S_1 + e_2 S_2 + e_3 S_3 + e_4 S_4$$

  where $y$ is in g, $a = -2.487$, $b = 0.534$, $c = -1.280$, $h = 3.94$, $e_1 = 0$, $e_2 = 0.365$, $e_3 = 0.065$, $e_4 = 0.053$, $\sigma_{\text{event}} = 0.117$ and $\sigma_{\text{record}} = 0.241$ (or alternatively $\sigma_{\text{station}} = 0.145$ and $\sigma_{\text{record}} = 0.232$). For $r_{hypo}$:

  $$\log(y) = a + bM + c \log R_h + e_1 S_1 + e_2 S_2 + e_3 S_3 + e_4 S_4$$

  where $y$ is in g, $a = -2.500$, $b = 0.544$, $c = -1.284$ and $\sigma = 0.292$ (do not report site coefficients for $r_{hypo}$).

- Use four site classes:

  $A_C$ Lacustrine and alluvial deposits with thickness $> 30$ m ($180 \leq V_{s,30} < 360$ m/s). Sites in largest lacustrine plains in Umbria region. $S_4 = 1$ and others are zero.

  $B_C$ Lacustrine and alluvial deposits with thickness 10–30 m ($180 \leq V_{s,30} < 360$ m/s). Sites in narrow alluvial plains or shallow basins. $S_3 = 1$ and others are zero.

  $C_E$ Shallow debris or colluvial deposits (3–10 m) overlaying rock (surface layer with $V_s < 360$ m/s). Sites located on shallow colluvial covers or slope debris (maximum depth 10 m) on gentle slopes. $S_2 = 1$ and others are zero.

  $D_A$ Rock ($V_{s,30} > 800$ m/s). Sites on outcropping rock, or related morphologic features, such as rock crests and cliffs. $S_1 = 1$ and others are zero.

  Base classifications on recently collected detailed site information from site investigations, census data, topographic maps, data from previous reports on depth of bedrock, and data from public and private companies. Subscripts correspond to classification in Eurocode 8.

- Focal depths between 1.1 and 8.7 km except for one earthquake with depth 47.7 km.

- Nearly all earthquakes have normal mechanism, with a few strike-slip earthquakes.
- Select earthquakes with $M_L \geq 4.0$ and $d < 100$ km.
- Use $M_L$ since available for all events.
- Fault geometries only available for three events so use $r_{epi}$ and $r_{hypo}$ rather than $r_{jb}$. Note that except for a few records differences between $r_{epi}$ and $r_{jb}$ are small.
- Correct for baseline and instrument response and filter analogue records to remove high- and low-frequency noise by visually selecting a suitable frequency interval: average range was 0.5–25 Hz. Filter digital records with bandpass of, on average, 0.3–40 Hz.
- For $M_L < 5$ no records from $d_e > 50$ km.
- Use maximum-likelihood regression with event and record $\sigma$s and also one with station and record $\sigma$s. Perform each regression twice: once including site coefficients and once without to investigate reduction in $\sigma$s when site information is included.
- Investigate difference in residuals for different stations when site coefficients are included or not. Find significant reductions in residuals for some sites, particularly for class $C_E$.
- Note that some stations seem to display site-specific amplifications different than the general trend of sites within one site class. For these sites the residuals increase when site coefficients are introduced.
- Find large negative residuals for records from the deep earthquake.
- Find similar residuals for the four earthquakes not from the 1997–1998 Umbria-Marche sequence.

### 2.253 Campbell and Bozorgnia (2006a) and Campbell and Bozorgnia (2006b)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= f_1(M) + f_2(R) + f_3(F) + f_4(\mathrm{HW}) + f_5(S) + f_6(D) \\
f_1(M) &= \begin{cases} c_0 + c_1 M & M \leq 5.5 \\ c_0 + c_1 M + c_2(M-5.5) & 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M-5.5) + c_3(M-6.5) & M > 6.5 \end{cases} \\
f_2(R) &= (c_4 + c_5 M)\ln(\sqrt{r_{\mathrm{rup}}^2 + c_6^2}) \\
f_3(F) &= c_7 F_{\mathrm{RV}} f_F(H) + c_8 F_N \\
f_F(H) &= \begin{cases} H & H < 1\,\mathrm{km} \\ 1 & H \geq 1\,\mathrm{km} \end{cases} \\
f_4(\mathrm{HW}) &= c_9 F_{\mathrm{RV}} f_{\mathrm{HW}}(M) f_{\mathrm{HW}}(H) \\
f_{\mathrm{HW}}(R) &= \begin{cases} 1 & r_{\mathrm{jb}} = 0\,\mathrm{km} \\ 1 - (r_{\mathrm{jb}}/r_{\mathrm{rup}}) & r_{jb} > 0\,\mathrm{km} \end{cases} \\
f_{\mathrm{HW}}(M) &= \begin{cases} 0 & M \leq 6.0 \\ 2(M-6.0) & 6.0 < M < 6.5 \\ 1 & M \geq 6.5 \end{cases} \\
f_{\mathrm{HW}}(H) &= \begin{cases} 0 & H \geq 20\,\mathrm{km} \\ 1 - (H/20) & H < 20\,\mathrm{km} \end{cases} \\
f_5(S) &= \begin{cases} c_{10}\ln\left(\frac{V_{s30}}{k_1}\right) + k_2\left\{\ln\left[\mathrm{PGA}_r + c\left(\frac{V_{s30}}{k_1}\right)^n\right] - \ln[\mathrm{PGA}_r + c]\right\} & V_{s30} < k_1 \\ (c_{10} + k_2 n)\ln\left(\frac{V_{s30}}{k_1}\right) & V_{s30} \geq k_1 \end{cases} \\
f_6(D) &= \begin{cases} c_{11}(D-1) & D < 1\,\mathrm{km} \\ 0 & 1 \leq D \leq 3\,\mathrm{km} \\ c_{12}\{k_3[0.0000454 - \exp(-3.33D)] + k_4[0.472 - \exp(-0.25D)]\} & D > 3\,\mathrm{km} \end{cases}
\end{aligned}
$$

  Do not report coefficients, only display predicted ground motions. $H$ is the depth to top of coseismic rupture in km, $\mathrm{PGA}_r$ is the reference value of PGA on rock with $V_{s30} = 1100\,\mathrm{m/s}$, $D$ is depth to $2.5\,\mathrm{km/s}$ shear-wave velocity horizon (so-called sediment or basin depth) in km.

- Use $V_{s30}$ (average shear-wave velocity in top 30 m in m/s) to characterise site conditions.

- Model developed as part of PEER Next Generation Attenuation (NGA) project.

- State that model is not final and articles should be considered as progress reports.

- NGA database only includes records that represent free-field conditions (i.e. records from large buildings are excluded).

- Include earthquake if: 1) it occurred within the shallow continental lithosphere, 2) it was in a region considered to be tectonically active, 3) it had enough records to establish a reasonable source term and 4) it had generally reliable source parameters.

- Exclude records from earthquakes classified as poorly recorded defined by: $M < 5.0$ and $N < 5$, $5.0 \leq M < 6.0$ and $N < 3$ and $6.0 \leq M < 7.0$, $r_{\mathrm{rup}} > 60\,\mathrm{km}$ and $N < 2$ where $N$ is number of records. Include singly-recorded earthquakes with $M \geq 7.0$ and $r_{\mathrm{rup}} \leq 60\,\mathrm{km}$ because of importance in constraining near-source estimates.

- Include records if: 1) it was from or near ground level, 2) it had negligible structural interaction effects and 3) it had generally reliable site parameters.

- Find two-step regression technique was much more stable than one-step method and allows the independent evaluation and modelling of ground-motion scaling effects at large magnitudes. Find random effects regression analysis gives very similar results to two-step method.

- Use classical data exploration techniques including analysis of residuals to develop functional forms. Develop forms using numerous iterations to capture observed trends. Select final forms based on: 1) their simplicity, although not an overriding factor, 2) their seismological bases, 3) their unbiased residuals and 4) their ability to be extrapolated to parameter values important for engineering applications (especially probabilistic seismic hazard analysis). Find that data did not always allow fully empirical development of functional form therefore apply theoretical constraints [coefficients $n$ and $c$ (period-independent) and $k_i$ (period-dependent)].

- Use three faulting mechanisms:

$F_{\mathrm{RV}} = 1$, $F_{\mathrm{N}} = 0$ Reverse and reverse-oblique faulting,$30^\circ < \lambda < 150^\circ$, where $\lambda$ is the average rake angle.

$F_{\mathrm{N}} = 1$, $F_{\mathrm{RV}} = 1$ Normal and normal-oblique faulting, $-150^\circ < \lambda < -30^\circ$.

$F_{\mathrm{RV}} = 0$, $F_{\mathrm{RV}} = 0$ Strike-slip, other $\lambda$s.

- Find slight tendency for over-saturation of short-period ground motions at large magnitudes and short distances. Find other functional forms for magnitude dependence too difficult to constrain empirically or could not be reliably extrapolated to large magnitudes.

- Note transition depth for buried rupture (1 km) is somewhat arbitrary.

- Find weak but significant trend of increasing ground motion with dip for both reverse and strike-slip faults. Do not believe that seismological justified therefore do not include such a term.

- Nonlinear site model constrained by theoretical studies since empirical data insufficient to constrain complex nonlinear behaviour.

- Use depth to 2.5 km/s horizon because it showed strongest correlation with shallow and deep sediment-depth residuals.

- Believe that aspect ratio (ratio of rupture length to rupture width) has promise as a source parameter since it shows high correlation with residuals and could model change in ground-motion scaling at large magnitudes.

- Do not find standard deviations are magnitude-dependent. Believe difference with earlier conclusions due to larger number of high-quality intra-event recordings for both small and large earthquakes.

- Find standard deviation is dependent on level of ground shaking at soft sites.

## 2.254 Costa et al. (2006)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = c_0 + c_1 M + c_2 M^2 + (c_3 + c_4 M)\log(\sqrt{d^2 + h^2}) + c_S S$$

where PGA is in g, $c_0 = -3.879$, $c_1 = 1.178$, $c_2 = -0.068$, $c_3 = -2.063$, $c_4 = 0.102$, $c_S = 0.411$, $h = 7.8$ and $\sigma = 0.3448$ (for larger horizontal component), $c_0 = -3.401$, $c_1 = 1.140$, $c_2 = -0.070$, $c_3 = -2.356$, $c_4 = 0.150$, $c_S = 0.415$, $h = 8.2$ and $\sigma = 0.3415$ (for horizontal component using vectorial addition), $c_0 = -3.464$, $c_1 = 0.958$, $c_2 = -0.053$, $c_3 = -2.224$, $c_4 = 0.147$, $c_S = 0.330$, $h = 6.1$ and $\sigma = 0.3137$ (for vertical).

- Use two site classes (since do not have detailed information on geology at all considered stations):

$S = 0$ Rock

$S = 1$ Soil

- Use selection criteria: $3.0 \leq M \leq 6.5$ and $1 \leq d_e \leq 100$ km.

- Bandpass filter with cut-offs between 0.1 and 0.25 Hz and between 25 and 30 Hz.

- Compute mean ratio between recorded and predicted motions at some stations of the RAF network. Find large ratios for some stations on soil and for some on rock.

## 2.255 Gómez-Soberón et al. (2006)

- Ground-motion model is:

$$\ln a = \alpha_0 + \alpha_1 M + \alpha_2 M^2 + \alpha_3 \ln R + \alpha_5 R$$

where $a$ is in cm/s$^2$, $\alpha_0 = 1.237$, $\alpha_1 = 1.519$, $\alpha_2 = -0.0313$, $\alpha_3 = -0.844$, $\alpha_5 = -0.004$ and $\sigma = 0.780$.

- Exclude records from soft soil sites or with previously known site effects (amplification or deamplification).

- Focal depths between 5 and 80 km.

- Also derive equation using functional form $\ln a = \alpha_0 + \alpha_1 M + \alpha_2 \ln R + \alpha_4 R$.

- Select records from stations located along the seismically active Mexican Pacific coast.

- Only use records from earthquakes with $M > 4.5$.

- Exclude data from normal faulting earthquakes using focal mechanisms, focal depths, location of epicentre and characteristics of records because subduction zone events are the most dominant and frequent type of earthquakes.

- Use $M_w$ because consider best representation of energy release.

- Visually inspect records to exclude poor quality records.

- Exclude records from dams and buildings.

- Exclude records from 'slow' earthquakes, which produce smaller short-period ground motions.

- Correct accelerations by finding quadratic baseline to minimize the final velocity then filter using most appropriate bandpass filter (low cut-off frequencies between 0.05 and 0.4 Hz and high cut-off frequency of 30 Hz).

- Use data from 105 stations: 7 in Chiapas, 6 in Oaxaca, 6 in Colima, 19 in Jalisco, 49 in Guerrero, 14 in Michoacán and 6 near the Michoacán-Guerrero border.

## 2.256 Hernandez et al. (2006)

- Ground-motion model is:

$$\log(y) = aM_L - \log(X) + bX + c_j$$

where $y$ is in cm/s$^2$, $a = 0.41296$, $b = 0.0003$, $c_1 = 0.5120$, $c_2 = 0.3983$, $c_3 = 0.2576$, $c_4 = 0.1962$, $c_5 = 0.1129$ and $\sigma = 0.2331$.

- Data from ARM1 and ARM2 vertical borehole arrays of the Hualien LSST array at: surface (use $c_1$), 5.3 m (use $c_2$), 15.8 m (use $c_3$), 26.3 m (use $c_4$) and 52.6 m (use $c_5$). Surface geology at site is massive unconsolidated poorly bedded Pleistocene conglomerate composed of pebbles varying in diameter from 5 to 20 cm, following 5 m is mainly composed of fine and medium sand followed by a gravel layer of 35 m.
- Apply these criteria to achieve uniform data: $M_L > 5$, focal depth $< 30$ km and $0.42M_L - \log(X + 0.02510^{0.42M_L} - 0.0033X + 1.22 > \log 10$ from a previous study.
- Most records from $M_L < 6$.
- Bandpass filter records with cut-offs at 0.08 and 40 Hz.
- Propose $M_s = 1.154M_L - 1.34$.
- Some comparisons between records and predicted spectra are show for four groups of records and find a good match although for the group $M_L 6.75$ and $X = 62$ km find a slight overestimation, which believe is due to not modelling nonlinear magnitude dependence.
- Coefficients for vertical equations not reported.

## 2.257 Jaimes et al. (2006)

- Ground-motion model is:
$$\ln \mathrm{Sa}_{\mathrm{CU}} = \alpha_1 + \alpha_2(M_w - 6) + \alpha_3 \ln R + \alpha_4 R$$
where $\mathrm{Sa}_{\mathrm{CU}}$ is in cm/s$^2$, $\alpha_1 = 5.6897$, $\alpha_2 = 1.1178$, $\alpha_3 = -0.50$ and $\alpha_4 = -0.0060$ ($\sigma$ is not reported).
- Only use data from Ciudad Universitaria (CU) station, which is the reference site in the hill zone (rock) of Mexico City. Also derive models for Secretaria de Comunicaciones y Transportes (SCT) and Central de Abastos (CD), which are in lakebed zone, using same approach.
- Weight data so large and small earthquakes equally represented in regression.
- Use Bayesian regression where prior probability distributions of coefficients are assigned based on $\omega^2$ model for source, frequency-dependent attenuation parameters and duration from previous studies and random vibration theory. Coefficients are updated using the records.
- Compare observed and predicted spectra. Find match acceptable except for event 13 (Ometepec, 25/04/1989, $M_w 6.9$), which was an anomalously intense earthquake.
- Derive model for comparison with less direct ways of estimating motions.

## 2.258 Jean et al. (2006)

- Ground-motion model is:
$$\ln Y_s = C_0 + C_1\{B_1 + b_2 M - b_3 \ln[R + b_4 \exp(b_5 M)]\}$$
Coefficients not reported. $\sigma = 0.78$ for hard-site model.
- Use data from hard sites ($760 \le V_s \le 1500$ m/s) to develop hard-site model (term in curly brackets) and develop site terms for about 450 stations based on residuals w.r.t. rock model for >3000 records from >242 events.
- Develop model for use in early warning system.

- Use data from two networks of Central Weather Bureau. Select all data from Real-Time Digital network and, to account for lack of near-source records, data with $r_{hypo} < 25$ km from Taiwan Strong-Motion Instrumentation Program network.

- Compare observed and predicted hard-site PGAs grouped into magnitude ranges.

## 2.259 Kanno et al. (2006)

- Ground-motion model is for $D \leq 30$ km:

$$\log \mathrm{pre} = a_1 M_w + b_1 X - \log(X + d_1 10^{0.5M_w}) + c_1$$

  and for $D > 30$ km:

$$\log \mathrm{pre} = a_2 M_w + b_2 X - \log(X) + c_2$$

  where pre is in cm/s$^2$, $a_1 = 0.56$, $b_1 = -0.0031$, $c_1 = 0.26$, $d_1 = 0.0055$, $a_2 = 0.41$, $b_2 = -0.0039$, $c_2 = 1.56$, $\sigma_1 = 0.37$ and $\sigma_2 = 0.40$.

- Use $V_{s,30}$ to characterise site effects using correction formula: $G = \log(\mathrm{obs/pre}) = p \log V_{s,30} + q$. Derive $p$ and $q$ by regression analysis on residuals averaged at intervals of every 100 m/s in $V_{s,30}$. $p = -0.55$ and $q = 1.35$ for PGA. Note that the equation without site correction predicts ground motions at sites with $V_{s,30} \approx 300$ m/s.

- Focal depths, $D$, for shallow events between 0 km and 30 km and for deep events between 30 km and about 180 km.

- Note that it is difficult to determine a suitable model form due to large variability of strong-motion data, correlation among model variables and because of coupling of variables in the model. Therefore choose a simple model to predict average characteristics with minimum parameters.

- Introduce correction terms for site effects and regional anomalies.

- Originally collect 91731 records from 4967 Japanese earthquakes.

- Include foreign near-source data (from California and Turkey, which are compressional regimes similar to Japan) because insufficient from Japan.

- High-pass filter records with cut-off of 0.1 Hz. Low-pass filter analogue records using cut-offs selected by visual inspection.

- Choose records where: 1) $M_w \geq 5.5$, 2) data from ground surface, 3) two orthogonal horizontal components available, 4) at least five stations triggered and 5) the record passed this $M_w$-dependent source distance criterion: $f(M_w, X) \geq \log 10$ (for data from mechanical seismometer networks) or $f(M_w, X) \geq \log 2$ (for data from other networks) where $f(M_w, X) = 0.42M_w - 0.0033X - \log(X + 0.025 10^{0.43M_w}) + 1.22$ (from a consideration of triggering of instruments).

- Examine data distributions w.r.t. amplitude and distance for each magnitude. Exclude events with irregular distributions that could be associated with a particular geological/tectonic feature (such as volcanic earthquakes).

- Do not include data from Chi-Chi 1999 earthquake because have remarkably low amplitudes, which could be due to a much-fractured continental margin causing different seismic wave propagation than normal.

- Data from 2236 different sites in Japan and 305 in other countries.

- Note relatively few records from large and deep events.
- Note that maybe best to use stress drop to account for different source types (shallow, interface or intraslab) but cannot use since not available for all earthquakes in dataset.
- Investigate effect of depth on ground motions and find that ground-motions amplitudes from earthquakes with $D > 30$ km are considerably different than from shallower events hence derive separate equations for shallow and deep events.
- Select 0.5 within function from earlier study.
- Weight regression for shallow events to give more weight to near-source data. Use weighting of 6.0 for $X \leq 25$ km, 3.0 for $25 < X \leq 50$ km, 1.5 for $50 < X \leq 75$ km and 1.0 for $X > 75$ km. Note that weighting scheme has no physical meaning.
- Note that amplitude saturation at short distances for shallow model is controlled by crustal events hence region within several tens of kms of large ($M_w > 8.0$) interface events falls outside range of data.
- Note standard deviation decreases after site correction term is introduced.
- Introduce correction to model anomalous ground motions in NE Japan from intermediate and deep earthquakes occurring in the Pacific plate due to unique $Q$ structure beneath the island arc. Correction is: $\log(\text{obs}/\text{pre}) = (\alpha R_{\text{tr}} + \beta)(D - 30)$ where $R_{\text{tr}}$ is shortest distance from site to Kuril and Izu-Bonin trenches. $\alpha$ and $\beta$ are derived by regression on subset fulfilling criteria: hypocentre in Pacific plate, station E of 137° E and station has $V_{s,30}$ measurement. For PGA $\alpha = -6.73 \times 10^{-5}$ and $\beta = 2.09 \times 10^{-2}$. Find considerable reduction in standard deviation after correction. Note that $R_{\text{tr}}$ may not be the best parameter due to observed bias in residuals for deep events.
- Examine normalised observed ground motions w.r.t. predicted values and find good match.
- Examine residuals w.r.t. distance and predicted values. Find residuals decrease with increasing predicted amplitude and with decreasing distance. Note that this is desirable from engineering point of view, however, note that it may be due to insufficient data with large amplitudes and from short distances.
- Examine total, intra-event and inter-event residuals w.r.t. $D$ for $D > 30$ km. When no correction terms are used, intra-event residuals are not biased but inter-event residuals are. Find mean values of total error increase up to $D = 70$ km and then are constant. Find depth correction term reduces intra-event residuals considerably but increases inter-event error slightly. Overall bias improves for $D < 140$ km. Find site corrections have marginal effect on residuals.
- Find no bias in residuals w.r.t. magnitude.

## 2.260 Kataoka et al. (2006)

- Ground-motion model is:

$$\log_{10} Y = a_1 M_w - bX + c_0 - \log_{10}(X + d10^{0.5M_w}) + c_j$$

where $Y$ is in cm/s$^2$, $a_1 = 0.595$, $b = 0.00395$, $c_0 = 0.03$, $d = 0.0065$, $\sigma_{intra} = 0.129$, $\sigma_{inter} = 0.110$ and $\sigma_{total} = 0.169$.

- Data from stations in site classes I, II and III, for which derive correction factors w.r.t. overall model.
- Also derive models using data from 136 subduction earthquakes (5882 records).

- Also present models using focal depth and short period level of acceleration source spectrum as additional variables.
- Find that including short period level of acceleration source spectrum significantly reduces inter-event $\sigma$.

## 2.261 Laouami et al. (2006)

- Ground-motion model is:

$$y = c\exp(\alpha M_s)[D^k + a]^{-\beta-\gamma R}$$

where $D$ is $r_{hypo}$ and $R$ is $r_{epi}$, $y$ is in m/s$^2$, $c = 0.38778$, $\alpha = 0.32927$, $k = 0.29202$, $a = 1.557574$, $\beta = 1.537231$, $\gamma = 0.027024$ and $\sigma = 0.03$ (note that this $\sigma$ is additive).

- All records except one at 13 km from distances of 20 to 70 km so note that lack information from near field.
- Compare predictions to records from the 2003 Boumerdes ($M_w$6.8) earthquake and find that it underpredicts the recorded motions, which note maybe due to local site effects.

## 2.262 Luzi et al. (2006)

- Ground-motion model is:

$$\log_{10} Y = a + bM + c\log_{10} R + s_{1,2}$$

$Y$ is in g, $a = -4.417$, $b = 0.770$, $c = -1.097$, $s_1 = 0$, $s_2 = 0.123$, $\sigma_{\text{event}} = 0.069$ and $\sigma_{\text{record}} = 0.339$ (for horizontal PGA assuming intra-event $\sigma$), $a = -4.367$, $b = 0.774$, $c = -1.146$, $s_1 = 0$, $s_2 = 0.119$, $\sigma_{\text{station}} = 0.077$ and $\sigma_{\text{record}} = 0.337$ (for horizontal PGA assuming intra-station $\sigma$), $a = -4.128$, $b = 0.722$ ,$c = -1.250$, $s_1 = 0$, $s_2 = 0.096$, $\sigma_{\text{event}} = 0.085$ and $\sigma_{\text{record}} = 0.338$ (for vertical PGA assuming intra-event $\sigma$), $a = -4.066$, $b = 0.729$, $c = -1.322$, $s_1 = 0$, $s_2 = 0.090$, $\sigma_{\text{station}} = 0.105$ and $\sigma_{\text{record}} = 0.335$ (for vertical PGA assuming intra-station $\sigma$).

- Use two site classes:
  1. Rock, where $V_s > 800$ m/s. Use $s_1$.
  2. Soil, where $V_s < 800$ m/s. This includes all kinds of superficial deposits from weak rock to alluvial deposits. Use $s_2$.

  Can only use two classes due to limited information.

- Use 195 accelerometric records from 51 earthquakes ($2.5 \leq M_L \leq 5.4$) from 29 sites. Most records are from rock or stiff sites. Most data from $r_{hypo} < 50$ km with few from $> 100$ km. Also use data from velocimeters (Lennartz 1 or 5 s sensors and Guralp CMG-40Ts). In total 2895 records with $r_{hypo} < 50$ km from 78 events and 22 stations available, most from $20 \leq r_{hypo} \leq 30$ km.
- For records from analogue instruments, baseline correct, correct for instrument response and bandpass filter with average cut-offs at 0.5 and 20 Hz (after visual inspection of Fourier amplitude spectra). For records from digital instruments, baseline correct and bandpass filter with average cut-offs at 0.2 and 30 Hz. Sampling rate is 200 Hz. For records from velocimeters, correct for instrument response and bandpass filter with average cut-offs at 0.5 and 25 Hz. Sampling rate is 100 Hz.
- Select records from 37 stations with $10 \leq r_{hypo} \leq 50$ km.
- Compare predictions and observations for $M_L$4.4 and find acceptable agreement. Also find agreement between data from accelerometers and velocimeters.

## 2.263 Mahdavian (2006)

- Ground-motion model is:

$$\log(y) = a + bM + c\log(R) + dR$$

where $y$ is in cm/s$^2$. For horizontal PGA: $a = 1.861$, $b = 0.201$, $c = -0.554$, $d = -0.0091$ and $\sigma = 0.242$ (for Zagros, rock sites and $M_s \geq 4.5$ or $m_b \geq 5.0$), $a = 1.831$, $b = 0.208$, $c = -0.499$, $d = -0.0137$ and $\sigma = 0.242$ (for Zagros, rock sites and $3 < M_s < 4.6$ or $4.0 \leq m_b < 5.0$), $a = 2.058$, $b = 0.243$, $c = -1.02$, $d = -0.000875$ and $\sigma = 0.219$ (for central Iran and rock sites), $a = 2.213$, $b = 0.225$, $c = -0.847$, $d = -0.00918$ and $\sigma = 0.297$ (for Zagros and soil sites), $a = 1.912$, $b = 0.201$, $c = -0.790$, $d = -0.00253$ and $\sigma = 0.204$ (for central Iran and soil sites). For vertical PGA: $a = 2.272$, $b = 0.115$, $c = -0.853$, $d = -0.00529$ and $\sigma = 0.241$ (for Zagros, rock sites and $M_s \geq 4.5$ or $m_b \geq 5.0$), $a = 2.060$, $b = 0.147$[18], $c = -0.758$, $d = -0.00847$ and $\sigma = 0.270$ (for Zagros, rock sites and $M_s \geq 3.0$ or $m_b \geq 4.0$), $a = 1.864$, $b = 0.232$, $c = -1.049$, $d = -0.000372$ and $\sigma = 0.253$ (for central Iran and rock sites), $a = 2.251$, $b = 0.140$[19], $c = -0.822$, $d = -0.00734$ and $\sigma = 0.290$[20] (for Zagros and soil sites) and $a = 1.76$, $b = 0.232$[21], $c = -1.013$, $d = -0.000551$ and $\sigma = 0.229$ (for central Iran and soil sites).

- Uses two site classes:

  1. Sedimentary. 55 records.
  2. Rock. 95 records.

  Bases classification on geological maps, station visits, published classifications and shape of response spectra from strong-motion records. Notes that the classification could be incorrect for some stations. Uses only two classes to reduce possible errors.

- Divides Iran into two regions: Zagros and other areas.

- Select data with $M_s$ or $m_b$ where $m_b > 3.5$. Notes that only earthquakes with $m_b > 5.0$ are of engineering concern for Iran but since not enough data (especially for Zagros) includes smaller earthquakes.

- Use $M_s$ when $m_b \geq 4$.

- Records bandpass filtered using Ormsby filters with cut-offs and roll-offs of 0.1–0.25 Hz and 23–25 Hz.

- Notes that some data from far-field.

- Notes that some records do not feature the main portion of shaking.

- To be consistent, calculates $r_{hypo}$ using S-P time difference. For some records P wave arrival time is unknown so use published hypocentral locations. Assumes focal depth of 10 km for small and moderate earthquakes and 15 km for large earthquakes.

- Does not recommend use of relation for Zagros and soil sites due to lack of data (15 records) and large $\sigma$.

- Compares recorded and predicted motions for some ranges of magnitudes and concludes that they are similar.

[18] Assume that 147 reported in paper is a typographical error.
[19] Assume that 0140 reported in paper is a typographical error.
[20] Assume that 0290 reported in paper is a typographical error.
[21] Assume that 0232 reported in paper is a typographical error.

## 2.264 McVerry et al. (2006)

- Ground-motion model for crustal earthquakes is:

$$\begin{aligned}\ln \mathrm{SA}'_{A/B}(T) &= C'_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C'_5(T)r \\ &\quad + [C'_8(T) + C_{6AS}(M-6)] \ln \sqrt{r^2 + C^2_{10AS}(T)} + C'_{46}(T) r_{VOL} \\ &\quad + C_{32}\mathrm{CN} + C_{33AS}(T)\mathrm{CR} + F_{HW}(M,r)\end{aligned}$$

  Ground-motion model for subduction earthquakes is:

$$\begin{aligned}\ln \mathrm{SA}'_{A/B}(T) &= C'_{11}(T) + \{C_{12Y} + [C'_{15}(T) - C'_{17}(T)]C_{19Y}\}(M-6) \\ &\quad + C_{13Y}(T)(10-M)^3 + C'_{17}(T)\ln[r + C_{18Y}\exp(C_{19Y}M)] + C'_{20}(T)H_c \\ &\quad + C'_{24}(T)\mathrm{SI} + C'_{46}(T) r_{VOL}(1-\mathrm{DS})\end{aligned}$$

  where $C'_{15}(T) = C_{17Y}(T)$. For both models:

$$\ln \mathrm{SA}'_{C,D}(T) = \ln \mathrm{SA}'_{A/B}(T) + C'_{29}(T)\delta_C + [C_{30AS}(T)\ln(\mathrm{PGA}'_{A/B} + 0.03) + C'_{43}(T)]\delta_D$$

  where $\mathrm{PGA}'_{A/B} = \mathrm{SA}'_{A/B}(T=0)$. Final model given by:

$$\mathrm{SA}_{A/B,C,D}(T) = \mathrm{SA}'_{A/B,C,D}(T)(\mathrm{PGA}_{A/B,C,D}/\mathrm{PGA}'_{A/B,C,D})$$

  where $\mathrm{SA}_{A/B,C,D}$ is in g, $r_{VOL}$ is length in km of source-to-site path in volcanic zone and $F_{HW}(M,r)$ is hanging wall factor of Abrahamson and Silva (1997). Coefficients for PGA (larger component) are: $C_1 = 0.28815$, $C_3 = 0$, $C_4 = -0.14400$, $C_5 = -0.00967$, $C_6 = 0.17000$, $C_8 = -0.70494$, $C_{10} = 5.60000$, $C_{11} = 8.68354$, $C_{12} = 1.41400$, $C_{13} = 0$, $C_{15} = -2.552000$, $C_{17} = -2.56727$, $C_{18} = 1.78180$, $C_{19} = 0.55400$, $C_{20} = 0.01550$, $C_{24} = -0.50962$, $C_{29} = 0.30206$, $C_{30} = -0.23000$, $C_{32} = 0.20000$, $C_{33} = 0.26000$, $C_{43} = -0.31769$, $C_{46} = -0.03279$, $\sigma_{M6} = 0.4865$, $\sigma_{slope} = -0.1261$, where $\sigma = \sigma_{M6} + \sigma_{slope}(M_w - 6)$ for $5 < M_w < 7$, $\sigma = \sigma_{M6} - \sigma_{slope}$ for $M_w < 5$ and $\sigma = \sigma_{M6} + \sigma_{slope}$ for $M_w > 7$ (intra-event), and $\tau = 0.2687$ (inter-event). Coefficients for PGA′ (larger component) are: $C_1 = 0.18130$, $C_3 = 0$, $C_4 = -0.14400$, $C_5 = -0.00846$, $C_6 = 0.17000$, $C_8 = -0.75519$, $C_{10} = 5.60000$, $C_{11} = 8.10697$, $C_{12} = 1.41400$, $C_{13} = 0$, $C_{15} = -2.552000$, $C_{17} = -2.48795$, $C_{18} = 1.78180$, $C_{19} = 0.55400$, $C_{20} = 0.01622$, $C_{24} = -0.41369$, $C_{29} = 0.44307$, $C_{30} = -0.23000$, $C_{32} = 0.20000$, $C_{33} = 0.26000$, $C_{43} = -0.29648$, $C_{46} = -0.03301$, $\sigma_{M6} = 0.5035$, $\sigma_{slope} = -0.0635$ and $\tau = 0.2598$.

- Use site classes (combine A and B together and do not use data from E):

  A Strong rock. Strong to extremely-strong rock with: a) unconfined compressive strength $> 50$ MPa, and b) $V_{s,30} > 1500$ m/s, and c) not underlain by materials with compressive strength $< 18$ MPa or $V_s < 600$ m/s.

  B Rock. Rock with: a) compressive strength between 1 and 50 MPa, and b) $V_{s,30} > 360$ m/s, and c) not underlain by materials having compressive strength $< 0.8$ MPa or $V_s < 300$ m/s.

  C $\delta_C = 1$, $\delta_D = 0$. Shallow soil sites. Sites that: a) are not class A, class B or class E sites, and b) have low-amplitude natural period, $T$, $\leq 0.6$ s, or c) have soil depths $\leq$ these depths:

| | Soil type and description | Maximum soil depth ( m) |
|---|---|---|
| Cohesive soil | Representative undrained shear strengths ( kPa) | |
| Very soft | < 12.5 | 0 |
| Soft | 12.5–25 | 20 |
| Firm | 25–50 | 25 |
| Stiff | 50–100 | 40 |
| Very stiff or hard | 100–200 | 60 |
| Cohesionless soil | Representative SPT N values | |
| Very loose | < 6 | 0 |
| Loose dry | 6–10 | 40 |
| Medium dense | 10–30 | 45 |
| Dense | 30–50 | 55 |
| Very dense | > 50 | 60 |
| Gravels | > 30 | 100 |

D $\delta_D = 1$, $\delta_C = 0$. Deep or soft soil sites. Sites that: a) are not class A, class B or class E sites, and b) have a low-amplitude $T > 0.6$ s, or c) have soil depths > depths in table above, or c) are underlain by < 10 m of soils with an undrained shear-strength < 12.5 kPa or soils with SPT N-values < 6.

E Very soft soil sites. Sites with: a) > 10 m of very soft soils with undrained shear-strength < 12.5 kPa, b) > 10 m of soils with SPT N values < 6, c) > 10 m of soils with $V_s < 150$ m/s, or d) > 10 m combined depth of soils with properties as described in a), b) and c).

Categories based on classes in existing New Zealand Loadings Standard but modified following statistical analysis. Note advantage of using site categories related to those in loading standards. Site classifications based on site periods but generally categories from site descriptions.

- Classify earthquakes in three categories:

Crustal Earthquakes occurring in the shallow crust of overlying Australian plate. 24 earthquakes. Classify into:

Strike-slip $-33 \leq \lambda \leq 33°$, $147 \leq \lambda \leq 180°$ or $-180 \leq \lambda \leq -147°$ where $\lambda$ is the rake. 6 earthquakes. Centroid depths, $H_c$, $4 \leq H_c \leq 13$ km. $5.20 \leq M_w \leq 6.31$. CN = 0, CR = 0.

Normal $-146 \leq \lambda \leq -34°$. 7 earthquakes. $7 \leq H_c \leq 17$ km. $5.27 \leq M_w \leq 7.09$. CN = −1, CR = 0.

Oblique-reverse $33 \leq \lambda \leq 66°$ or $124 \leq \lambda \leq 146°$. 3 earthquakes. $5 \leq H_c \leq 19$ km. $5.75 \leq M_w \leq 6.52$. CR = 0.5, CN = 0.

Reverse $67 \leq \lambda \leq 123°$. 8 earthquakes. $4 \leq H_c \leq 13$ km. $5.08 \leq M_w \leq 7.23$. CR = 1, CN = 0.

Interface Earthquake occurring on the interface between Pacific and Australian plates with $H_c < 50$ km. 5 reserve and 1 strike-slip with reverse component. Use data with $15 \leq H_c \leq 24$ km. Classify using location in 3D space. 6 earthquakes. $5.46 \leq M_w \leq 6.81$. SI = 1, DS = 0.

Slab Earthquakes occurring in slab source zone within the subducted Pacific plate. Predominant mechanism changes with depth. 19 earthquakes. $26 \leq H_c \leq 149$ km. Split into shallow slab events with $H_c \leq 50$ km (9 normal and 1 strike-slip, $5.17 \leq M_w \leq 6.23$) and deep slab events with $H_c > 50$ km (6 reverse and 3 strike-slip, $5.30 \leq M_w \leq 6.69$). SI = 0, DS = 1 (for deep slab events).

Note seismicity cross sections not sufficient to distinguish between interface and slab events, also require source mechanism.

- Find that mechanism is not a significant extra parameter for motions from subduction earthquakes.

- State that model is not appropriate for source-to-site combinations where the propagation path is through the highly attenuating mantle wedge.
- Note magnitude range of New Zealand is limited with little data for large magnitudes and from short distances. Most data from $d > 50$ km and $M_w < 6.5$.
- Only include records from earthquakes with available $M_w$ estimates because correlations between $M_L$ and $M_w$ are poor for New Zealand earthquakes. Include two earthquakes without $M_w$ values ($M_s$ was converted to $M_w$) since they provide important data for locations within and just outside the Central Volcanic Region.
- Only include data with centroid depth, mechanism type, source-to-site distance and a description of site conditions.
- Only include records with PGA above these limits (dependent on resolution of instrument):
  1. Acceleroscopes (scratch-plates): 0.02 g
  2. Mechanical-optical accelerographs: 0.01 g
  3. Digital 12-bit accelerographs: 0.004 g
  4. Digital 16-bit accelerographs: 0.0005 g
- Exclude data from two sites: Athene A (topographic effect) and Hanmer Springs (site resonance at 1.5–1.7 Hz) that exhibit excessive amplifications for their site class.
- Exclude data from sites of class E (very soft soil sites with $\gtrsim 10$ m of material with $V_s < 150$ m/s) to be consistent with Abrahamson and Silva (1997) and Youngs et al. (1997). Not excluded because of large amplifications but because spectra appear to have site-specific characteristics.
- Exclude records from bases of buildings with $> 4$ storeys because may have been influenced by structural response.
- Exclude data from very deep events with travel paths passing through the highly attenuating mantle were excluded.
- Only use response spectral ordinates for periods where they exceed the estimated noise levels of the combined recording and processing systems.
- Lack of data from near-source. Only 11 crustal records from distances $< 25$ km with 7 of these from 3 stations. To constrain model at short distances include overseas PGA data using same criteria as used for New Zealand data. Note that these data were not intended to be comprehensive for 0–10 km range but felt to be representative. Note that it is possible New Zealand earthquakes may produce PGAs at short distances different that those observed elsewhere but feel that it is better to constrain the near-source behaviour rather than predict very high PGAs using an unconstrained model.
- In order to supplement limited data from moderate and high-strength rock and from the volcanic region, data from digital seismographs were added.
- Data corrected for instrument response.
- Derive model from 'base models' (other Ground-motion models for other regions). Select 'base model' using residual analyses of New Zealand data w.r.t. various models. Choose models of Abrahamson and Silva (1997) for crustal earthquakes and Youngs et al. (1997). Link these models together by common site response terms and standard deviations to get more robust coefficients.

- Apply constraints using 'base models' to coefficients that are reliant on data from magnitude, distance and other model parameters sparsely represented in the New Zealand data. Coefficients constrained are those affecting estimates in near-source region, source-mechanism terms for crustal earthquakes and hanging-wall terms. Eliminate some terms in 'base models' because little effect on measures of fit using Akaike Information Criterion (AIC).
- Apply the following procedure to derive model. Derive models for PGA and SA using only records with response spectra available (models with primed coefficients). Next derive model for PGA including records without response spectra (unprimed coefficients). Finally multiply model for SA by ratio between the PGA model using all data and that using only PGA data with corresponding response spectra. Apply this method since PGA estimates using complete dataset for some situations (notably on rock and deep soil and for near-source region) are higher than PGA estimates using reduced dataset and are more in line with those from models using western US data. This scaling introduces a bias in final model. Do not correct standard deviations of models for this bias.
- Use $r_{rup}$ for 10 earthquakes and $r_c$ for rest. For most records were $r_c$ was used, state that it is unlikely model is sensitive to use $r_c$ rather than $r_{rup}$. For five records discrepancy likely to be more than 10%.
- Free coefficients are: $C_1$, $C_{11}$, $C_8$, $C_{17}$, $C_5$, $C_{46}$, $C_{20}$, $C_{24}$, $C_{29}$ and $C_{43}$. Other coefficients fixed during regression. Coefficients with subscript AS are from Abrahamson and Silva (1997) and those with subscript Y are from Youngs et al. (1997). Try varying some of these fixed coefficients but find little improvement in fits.
- State that models apply for $5.25 \leq M_w \leq 7.5$ and for distances $\leq 400$ km, which is roughly range covered by data.
- Note possible problems in applying model for $H_c > 150$ km therefore suggest $H_c$ is fixed to 150 km if applying model to deeper earthquakes.
- Note possible problems in applying model for $M_w < 5.25$.
- Apply constraints to coefficients to model magnitude- and distance-saturation.
- Try including an anelastic term for subduction earthquakes but find insignificant.
- Investigate possibility of different magnitude-dependence and attenuation rates for interface and slab earthquakes but this required extra parameters that are not justified by AIC.
- Investigate possible different depth dependence for interface and slab earthquakes but extra parameters not justified in terms of AIC.
- Try adding additive deep slab term but not significant according to AIC.
- Cannot statistically justify nonlinear site terms. Believe this could be due to lack of near-source records.
- Find that if a term is not included for volcanic path lengths then residuals for paths crossing the volcanic zone are increasingly negative with distance but this trend is removed when a volcanic path length term is included.
- Compare predictions to observed ground motions in 21/08/2003 Fiordland interface ($M_w$7.2) earthquake and its aftershocks. Find ground motions, in general, underestimated.

## 2.265 Moss and Der Kiureghian (2006)

- Ground-motion model is [adopted from Boore et al. (1997)]:

$$\ln(Y) = \theta_1 + \theta_2(M_w - 6) + \theta_3(M_w - 6)^2 - \theta_4 \ln(\sqrt{R_{jb}^2 + \theta_5^2}) - \theta_6 \ln(V_{s,30}/\theta_7)$$

- Use $V_{s,30}$ to characterize site.
- Use data of Boore et al. (1997).
- Develop Bayesian regression method to account for parameter uncertainty in measured accelerations (due to orientation of instrument) (coefficient of variation of $\sim 0.30$, based on analysis of recorded motions) and magnitudes (coefficient of variation of $\sim 0.10$, based on analysis of reported $M_w$ by various agencies) to better understand sources of uncertainty and to reduce model variance.
- Do not report coefficients. Only compare predictions with observations and with predictions by model of Boore et al. (1997) for $M_w 7.5$ and $V_{s,30} = 750\,\mathrm{m/s}$. Find slightly different coefficients than Boore et al. (1997) but reduced model standard deviations.

## 2.266 Pousse et al. (2006)

- Ground-motion model is:

$$\log_{10}(\mathrm{PGA}) = a_{\mathrm{PGA}} M + b_{\mathrm{PGA}} R - \log_{10}(R) + S_{\mathrm{PGA},k}, k = 1, 2, \ldots, 5$$

  where PGA is in $\mathrm{cm/s^2}$, $a_{\mathrm{PGA}} = 0.4346$, $b_{\mathrm{PGA}} = -0.002459$, $S_{\mathrm{PGA},1} = 0.9259$, $S_{\mathrm{PGA},2} = 0.9338$, $S_{\mathrm{PGA},3} = 0.9929$, $S_{\mathrm{PGA},4} = 0.9656$, $S_{\mathrm{PGA},5} = 0.9336$ and $\sigma = 0.2966$.

- Use five site categories (from Eurocode 8):

  A $V_{s,30} > 800\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},1}$. 43 stations, 396 records.

  B $360 < V_{s,30} < 800\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},2}$. 399 stations, 4190 records.

  C $180 < V_{s,30} < 360\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},3}$. 383 stations, 4108 records.

  D $V_{s,30} < 180\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},4}$. 65 stations, 644 records.

  E Site D or C underlain in first 20 m with a stiffer layer of $V_s > 800\,\mathrm{m/s}$. Use $S_{\mathrm{PGA},5}$. 6 stations, 52 records.

  Use statistical method of Boore (2004) with parameters derived from KiK-Net profiles in order to extend $V_s$ profiles down to 30 m depth.

- Records from K-Net network whose digital stations have detailed geotechnical characterisation down to 20 m depth.
- Retain only records from events whose focal depths $< 25$ km.
- Convert $M_{\mathrm{JMA}}$ to $M_w$ using empirical conversion formula to be consist with other studies.
- Apply magnitude-distance cut-off to exclude distant records.
- Bandpass filter all records with cut-offs 0.25 and 25 Hz. Visually inspect records for glitches and to retain only main event if multiple events recorded.
- Find that one-stage maximum likelihood regression gives almost the same results.
- Also derive equations for other strong-motion parameters.

## 2.267 Souriau (2006)

- Ground-motion model is:

$$\log_{10}(\text{PGA}) = a + bM + c\log_{10} R$$

where $y$ is in m/s$^2$, $a = -2.50 \pm 0.18$, $b = 0.99 \pm 0.05$ and $c = -2.22 \pm 0.08$ when $M = M_{\text{LDG}}$ and $a = -2.55 \pm 0.19$, $b = 1.04 \pm 0.05$ and $c = -2.17 \pm 0.08$ when $M = M_{\text{ReNass}}$ ($\sigma$ is not given although notes that 'explained variance is of the order of 84%').

- Focal depths between 0 and 17 km.

- Most data from $R < 200$ km.

- Uses PGAs from S-waves.

- Finds that introducing an anelastic attenuation term does not significantly improve explained variance because term is poorly constrained by data due to trade offs with geometric term and travel paths are short. When an anelastic term is introduced finds: $\log_{10}(\text{PGA}) = -3.19(\pm 0.25) + 1.09(\pm 0.05)M_{\text{ReNass}} - 1.83(\pm 0.12)\log_{10} R - 0.0013(\pm 0.0004)R$.

## 2.268 Tapia (2006) & Tapia et al. (2007)

- Ground-motion model is:

$$\begin{aligned}\log y &= a + bM + c\log r + dr \\ r &= \sqrt{r^2 + h^2}\end{aligned}$$

where $y$ is in g, $a = -1.8$, $b = 0.45$, $c = -1.6$, $d = -0.0013$, $h = 10$ and $\sigma = 0.426$.

- Use data from networks of IGC/ICC and IGN (Spain), RAP (France), SSN-ENEL (Italy) and CRECIT (Andorra). Umbria-Marche 1997–1998 sequence contributes 144 records from 8 earthquakes, SE Spain 56 records from 13 events, France 32 records from 1 event and the Pyrenees 102 records from 9 events.

- Data reasonably uniform up to about 100 km. Believe model can be used up to $M5.2$.

- Records filtered with cut-offs of 0.25 and 25 Hz.

- Examine residuals w.r.t. magnitude and distance.

- Compare predictions and observations for Alhucemas (24/2/2004, $M_L6.5$), Lourdes (17/11/2006, $M_L5.1$) and San Vicente (12/2/2007, $M_w6.1$) earthquakes.

## 2.269 Tsai et al. (2006)

- Ground-motion model is:

$$\log \text{PGA} = \theta_0 + \theta_1 M + \theta_2 M^2 + \theta_3 R + \theta_4 \log(R + \theta_5 10^{\theta_6 M})$$

where PGA is in cm/s$^2$, $\theta_0 = 0.4063$, $\theta_1 = 0.7936$, $\theta_2 = -0.02146$, $\theta_3 = 0.0004183$, $\theta_4 = -1.7056$, $\theta_5 = 5.7814$, $\theta_6 = -0.05656$, $\sigma_e = 0.17561$ (inter-event), $\sigma_s = 0.17065$ (inter-site), $\sigma_r = 0.19925$ (residual) and $\sigma_T = 0.31569$ (total).

- Use data from 204 sites.

- Use regression approach of Chen and Tsai (2002) to separate variance into 3 components: inter-event, inter-site and residual.
- Plot inter-event residuals (event terms) of shallow (focal depth $\leq 30$ km) earthquakes w.r.t. $M_L$ and on map. Find residuals are independent of magnitude and not correlated with location.
- Plot inter-site residuals (site terms) on map. Find that these are more coherent in space, which are generally consistent with local geology (e.g. positive terms for alluvium sites.).
- Plot direct travel paths from all shallow earthquakes to associated sites. Expect that variability of path-to-path component of error would be similar to event terms or at least not smaller than site terms. Hence assume $\sigma_P = 0.17321$ (path component) and compute refined $\sigma$s.
- Show that by specifying *a priori* the variability of path-to-path component that this can be removed from residual.

## 2.270 Zare and Sabzali (2006)

- Ground-motion model is:

$$\log \mathrm{Sa}(T) = a_1(T)M + a_2(T)M^2 + b(T)\log(R) + c_i(T)S_i$$

where Sa is in g, $a_1 = 0.5781$, $a_2 = -0.0317$, $b = -0.4352$, $c_1 = -2.6224$, $c_2 = -2.5154$, $c_3 = -2.4654$, $c_4 = -2.6213$ and $\sigma = 0.2768$ (for horizontal PGA), $a_1 = 0.5593$, $a_2 = -0.0258$, $b = -0.6119$, $c_1 = -2.6261$, $c_2 = -2.6667$, $c_3 = -2.5633$, $c_4 = -2.7346$ and $\sigma = 0.2961$ (for vertical PGA).

- Use four site classes based on fundamental frequency, $f$, from receiver functions:

Class 1 $f > 15$ Hz. Corresponds to rock and stiff sediment sites with $V_{s,30} > 700$ m/s. 22 records. $S_1 = 1$ and other $S_i = 0$.

Class 2 $5 < f \leq 15$ Hz. Corresponds to stiff sediments and/or soft rocks with $500 < V_{s,30} \leq 700$ m/s. 16 records. $S_2 = 1$ and other $S_i = 0$.

Class 3 $2 < f \leq 5$ Hz. Corresponds to alluvial sites with $300 < V \leq 500$ m/s. 25 records. $S_3 = 1$ and other $S_i = 0$.

Class 4 $f \leq 2$ Hz. Corresponds to thick soft alluvium. 26 records. $S_4 = 1$ and other $S_i = 0$.

- Separate records into four mechanisms: reverse (14 records), reverse/strike-slip (1 record), strike-slip (26 records) and unknown (48 records).
- Select records that have PGA $> 0.05$ g on at least one component and are of good quality in frequency band of 0.3 Hz or less.
- Find results using one- or two-step regression techniques are similar. Only report results from one-step regression.
- $M_w$ for earthquakes obtained directly from level of acceleration spectra plateau of records used.
- $r_{hypo}$ for records obtained from S-P time difference.
- Most data from $r_{hypo} < 60$ km.
- Bandpass filter records with cut-offs of between 0.08 and 0.3 Hz and between 16 and 40 Hz.
- Note that the lack of near-field data is a limitation.

## 2.271 Akkar and Bommer (2007b)

- Ground-motion model is:

$$\log y = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M) \log \sqrt{R_{\mathrm{jb}}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

  where $y$ is in $\mathrm{cm/s^2}$, $b_1 = 1.647$, $b_2 = 0.767$, $b_3 = -0.074$, $b_4 = -3.162$, $b_5 = 0.321$, $b_6 = 7.682$, $b_7 = 0.105$, $b_8 = 0.020$, $b_9 = -0.045$, $b_{10} = 0.085$, $\sigma_1 = 0.557 - 0.049M$ (intra-event) and $\sigma_2 = 0.189 - 0.017M$ (inter-event) when $b_3$ is unconstrained and $b_1 = 4.185$, $b_2 = -0.112$, $b_4 = -2.963$, $b_5 = 0.290$, $b_6 = 7.593$, $b_7 = 0.099$, $b_8 = 0.020$, $b_9 = -0.034$, $b_{10} = 0.104$, $\sigma_1 = 0.557 - 0.049M$ (intra-event) and $\sigma_2 = 0.204 - 0.018M$ (inter-event) when $b_3$ is constrained to zero (to avoid super-saturation of PGA).

- Use three site categories:

Soft soil $S_S = 1$, $S_A = 0$.

Stiff soil $S_A = 1$, $S_S = 0$.

Rock $S_S = 0$, $S_A = 0$.

- Use three faulting mechanism categories:

Normal $F_N = 1$, $F_R = 0$.

Strike-slip $F_N = 0$, $F_R = 0$.

Reverse $F_R = 1$, $F_N = 0$.

- Use same data as Akkar and Bommer (2007a), which is similar to that used by Ambraseys et al. (2005a).
- Individually process records using well-defined correction procedure to select the cut-off frequencies (Akkar and Bommer, 2006).
- Use pure error analysis to determine magnitude dependence of inter- and intra-event variabilities before regression analysis.

## 2.272 Amiri et al. (2007a) & Amiri et al. (2007b)

- Ground-motion model is:

$$\ln y = C_1 + C_2 M_s + C_3 \ln[R + C_4 \exp(M_s)] + C_5 R$$

  where $y$ is in $\mathrm{cm/s^2}$, $C_1 = 4.15$, $C_2 = 0.623$, $C_3 = -0.96$ and $\sigma = 0.478$ for horizontal PGA, rock sites and Alborz and central Iran; $C_1 = 3.46$, $C_2 = 0.635$, $C_3 = -0.996$ and $\sigma = 0.49$ for vertical PGA, rock sites and Alborz and central Iran; $C_1 = 3.65$, $C_2 = 0.678$, $C_2 = -0.95$ and $\sigma = 0.496$ for horizontal PGA, soil sites and Alborz and central Iran; $C_1 = 3.03$, $C_2 = 0.732$, $C_3 = -1.03$ and $\sigma = 0.53$ for vertical PGA, soil sites and Alborz and central Iran; $C_1 = 5.67$, $C_2 = 0.318$, $C_3 = -0.77$, $C_5 = -0.016$ and $\sigma = 0.52$ for horizontal PGA, rock sites and Zagros; $C_1 = 5.26$, $C_2 = 0.289$, $C_3 = -0.8$, $C_5 = -0.018$ and $\sigma = 0.468$ for vertical PGA, rock sites and Zagros; $C_1 = 5.51$, $C_2 = 0.55$, $C_3 = -1.31$ and $\sigma = 0.488$ for horizontal PGA, soil sites and Zagros; and $C_1 = 5.52$, $C_2 = 0.36$, $C_3 = -1.25$ and $\sigma = 0.474$ for vertical PGA, soil sites and Zagros. Constrain $C_4$ to zero for better convergence even though $\sigma$s are higher.

- Use two site categories (derive individual equations for each):

Rock Roughly $V_s \geq 375\,\mathrm{m/s}$.

Soil Roughly $V_s < 375\,\mathrm{m/s}$.

- Divide Iran into two regions: Alborz and central Iran, and Zagros, based on tectonics and derive separate equations for each.
- Use S-P times to compute $r_{hypo}$ for records for which it is unknown.
- Exclude data from earthquakes with $M_s \leq 4.5$ to remove less accurate data and since larger earthquakes more important for seismic hazard assessment purposes.
- Most records from $r_{hypo} > 50$ km.
- Exclude poor quality records.
- Instrument, baseline correct and bandpass filter records with cut-offs depending on instrument type and site class. For SSA-2 recommend: 0.15–0.2 Hz and $30-33$ Hz for rock records and 0.07–0.2 Hz and 30–33 Hz for soil records. For SMA-1 recommend: 0.15–0.25 Hz and 20–23 Hz for rock records and 0.15–0.2 Hz and 20–23 Hz for soil records. Apply trial and error based on magnitude, distance and velocity time-history to select cut-off frequencies.
- Test a number of different functional forms.
- Often find a positive (non-physical) value of $C_5$. Therefore, remove this term. Try removing records with $r_{hypo} > 100$ km but find little difference and poor convergence due to limited data.
- Do not include term for faulting mechanism because such information not available for Iranian events.

## 2.273 Aydan (2007)

- Ground-motion model is:

$$a_{\max} = F(V_s)G(R, \theta)H(M)$$

- Characterises sites by $V_s$ (shear-wave velocity).
- Considers effect of faulting mechanism.
- Considers angle between strike and station, $\theta$.

## 2.274 Bindi et al. (2007)

- Ground-motion models are:

$$\log_{10} Y = a + bM + (c + dM)\log_{10} R_{\text{hypo}} + s_{1,2}$$

where $Y$ is in m/s$^2$, $a = -1.4580$, $b = 0.4982$, $c = -2.3639$, $d = 0.1901$, $s_2 = 0.4683$, $\sigma_{\text{eve}} = 0.0683$ (inter-event), $\sigma_{\text{sta}} = 0.0694$ (inter-station) and $\sigma_{\text{rec}} = 0.2949$ (record-to-record) for horizontal PGA; and $a = -1.3327$, $b = 0.4610$, $c = -2.4148$, $d = 0.1749$, $s_2 = 0.3094$, $\sigma_{\text{eve}} = 0.1212$ (inter-event), $\sigma_{\text{sta}} = 0.1217$ (inter-station) and $\sigma_{\text{rec}} = 0.2656$ (record-to-record) for vertical PGA.

$$\log_{10} Y = a + bM + (c + dM)\log_{10}(R_{\text{epi}}^2 + h^2)^{0.5} + s_{1,2}$$

where $Y$ is in m/s$^2$, $a = -2.0924$, $b = 0.5880$, $c = -1.9887$, $d = 0.1306$, $h = 3.8653$, $s_2 = 0.4623$, $\sigma_{\text{eve}} = 0.0670$ (inter-event), $\sigma_{\text{sta}} = 0.0681$ (inter-station) and $\sigma_{\text{rec}} = 0.2839$ (record-to-record) for horizontal PGA; and $a = -1.8883$, $b = 0.5358$, $c = -2.0869$, $d = 0.1247$, $h = 4.8954$, $s_2 = 0.3046$, $\sigma_{\text{eve}} = 0.1196$ (inter-event), $\sigma_{\text{sta}} = 0.0696$ (inter-station) and $\sigma_{\text{rec}} = 0.2762$ (record-to-record). Coefficients not reported in article but in electronic supplement.

- Use two site categories:

  $s_1$ Rock. Maximum amplification less than 2.5 (for accelerometric stations) or than 4.5 (for geophone stations). Amplification thresholds defined after some trials.

  $s_2$ Soil. Maximum amplification greater than thresholds defined above.

  Classify stations using generalized inversion technique.

- Focal depths between 5 and 15 km.
- Use aftershocks from the 1999 Kocaeli ($M_w$7.4) earthquake.
- Use data from 31 1 Hz 24-bit geophones and 23 12-bit and 16-bit accelerometers. Records corrected for instrument response and bandpass filtered (fourth order Butterworth) with cut-offs 0.5 and 25 Hz for $M_L \leq 4.5$ and 0.1 and 25 Hz for $M_L > 4.5$. Find filters affect PGA by maximum 10%.
- Only 13 earthquakes have $M_L < 1.0$. Most data between have $1.5 < M_L < 5$ and from $10 \leq d_e \leq 140$ km.
- Geophone records from free-field stations and accelerometric data from ground floors of small buildings.
- Use $r_{hypo}$ and $r_{epi}$ since no evidence for surface ruptures from Turkey earthquakes with $M_L < 6$ and no systematic studies on the locations of the rupture planes for events used.
- Since most earthquakes are strike-slip do not include style-of-faulting factor.
- Find differences in inter-event $\sigma$ when using $M_L$ or $M_w$, which relate to frequency band used to compute $M_L$ (about 1–10 Hz) compared to $M_w$ (low frequencies), but find similar intra-event $\sigma$s using the two different magnitudes, which expected since this $\sigma$ not source-related.
- Investigate influence of stress drop on inter-event $\sigma$ for horizontal PGA relations using $r_{epi}$ and $M_L$ or $M_w$. Find inter-event errors range from negative (low stress drop) to positive (high stress drop) depending on stress drop.
- Regress twice: firstly not considering site classification and secondly considering. Find site classification significantly reduces inter-station errors for velometric stations but inter-station errors for accelerometric stations less affected.

## 2.275 Bommer et al. (2007)

- Ground-motion model is:

$$\begin{aligned}\log_{10}[\mathrm{PSA}(T)] &= b_1 + b_2 M_w + b_3 M_w^2 + (b_4 + b_5 M_w)\log_{10}\sqrt{R_{jb}^2 + b_6^2} + b_7 S_S + b_8 S_A \\ &\quad + b_9 F_N + b_{10} F_R\end{aligned}$$

  where PSA($T$) is in cm/s$^2$, $b_1 = 0.0031$, $b_2 = 1.0848$, $b_3 = -0.0835$, $b_4 = -2.4423$, $b_5 = 0.2081$, $b_6 = 8.0282$, $b_7 = 0.0781$, $b_8 = 0.0208$, $b_9 = -0.0292$, $b_{10} = 0.0963$, $\sigma_1 = 0.599 \pm 0.041 - 0.058 \pm 0.008 M_w$ (intra-event) and $\sigma_2 = 0.323 \pm 0.075 - 0.031 \pm 0.014 M_w$ (inter-event).

- Use three site categories:

Soft soil $V_{s,30} < 360$ m/s. $S_S = 1$, $S_A = 1$. 75 records from $3 \leq M_w < 5$.

Stiff soil $360 < V_{s,30} < 750$ m/s. $S_A = 1$, $S_S = 0$. 173 records from $3 \leq M_w < 5$.

Rock $V_{s,30} \geq 750$ m/s. $S_S = 0$, $S_A = 0$. 217 records from $3 \leq M_w < 5$.

- Use three faulting mechanism categories:

Normal $F_N = 1$, $F_R = 0$. 291 records from $3 \leq M_w < 5$.

Strike-slip $F_N = 0$, $F_R = 0$. 140 records from $3 \leq M_w < 5$.

Reverse $F_R = 1$, $F_N = 0$. 24 records from $3 \leq M_w < 5$. 12% of all records. Note that reverse events poorly represented.

- Investigate whether Ground-motion models can be extrapolated outside the magnitude range for which they were derived.
- Extend dataset of Akkar and Bommer (2007b) by adding data from earthquakes with $3 \leq M_w < 5$. Search ISESD for records from earthquakes with $M_w < 5$, known site class and known faulting mechanism. Find one record from a $M_w 2$ event but only 11 for events with $M_w < 3$ therefore use $M_w 3$ as lower limit. Select 465 records from 158 events with $3 \leq M_w < 5$. Many additional records from Greece (mainly singly-recorded events), Italy, Spain, Switzerland, Germany and France. Few additional records from Iran and Turkey.
- Data well distributed w.r.t. magnitude, distance and site class but for $M_w < 4$ data sparse for distances $> 40$ km.
- Additional data has been uniformly processed with cut-offs at 0.25 and 25 Hz.
- Use same regression technique as Akkar and Bommer (2007b).
- Observe that equations predict expected behaviour of response spectra so conclude that equations are robust and reliable.
- Compare predicted ground motions with predictions from model of Akkar and Bommer (2007b) and find large differences, which they relate to the extrapolation of models outside their range of applicability.
- Investigate effect of different binning strategies for pure error analysis (Douglas and Smit, 2001). Derive weighting functions for published equations using bins of 2 km $\times$ 0.2 magnitude units and require three records per bin before computing $\sigma$. Repeat using 1 km $\times$ 0.1 unit bins. Find less bins allow computation of $\sigma$. Also repeat original analysis but require four or five records per bin. Find more robust estimates of $\sigma$ but note that four or five records are still small samples. Also repeating using logarithmic rather than linear distance increments for bins since ground motions shown to mainly decay geometrically. For all different approaches find differences in computed magnitude dependence depending on binning scheme. None of the computed slopes are significant at 95% confidence level.
- Repeat analysis assuming no magnitude dependence of $\sigma$. Find predictions with this model are very similar to those assuming a magnitude-dependent $\sigma$.
- Find that compared to $\sigma$s of Akkar and Bommer (2007b) that inter-event $\sigma$s has greatly increased but that intra-event $\sigma$s has not, which they relate to the uncertainty in the determination of $M_w$ and other parameters for small earthquakes.
- Repeat analysis exclude data from (in turn) Greece, Italy, Spain and Switzerland to investigate importance of regional dependence on results. Find that results are insensitive to the exclusion of individual regional datasets.
- Compute residuals with respect to $M_w$ for four regional datasets and find that only for Spain (the smallest set) is a significant difference to general results found.

- Examine total and intra-event residuals for evidence of soil nonlinearity. Find that evidence for nonlinearity is weak although the expected negative slopes are found. Conclude that insufficient data (and too crude site classification) to adjust the model for soil nonlinearity.
- Plot inter-event and intra-event residuals w.r.t. $M_w$ and find no trend and hence conclude that new equations perform well for all magnitudes.
- Do not propose model for application in seismic hazard assessments.

## 2.276 Boore and Atkinson (2007) & Boore and Atkinson (2008)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= F_M(M) + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M) \\
F_D(R_{JB}, M) &= [c_1 + c_2(M - M_{ref})] \ln(R/R_{ref}) + c_3(R - R_{ref}) \\
R &= \sqrt{R_{JB}^2 + h^2} \\
F_M(M) &= \begin{cases} e_1\mathrm{U} + e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_5(M - M_h) + \\ \quad e_6(M - M_h)^2 \quad \text{for} \quad M \leq M_h \\ e_1\mathrm{U} + e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_7(M - M_h) \quad \text{for} \quad M > M_h \end{cases} \\
F_S &= F_{LIN} + F_{NL} \\
F_{LIN} &= b_{lin} \ln(V_{S30}/V_{ref}) \\
F_{NL} &= \begin{cases} b_{nl} \ln(\text{pga\_low}/0.1) \quad \text{for} \quad \text{pga4nl} \leq a_1 \\ b_{nl} \ln(\text{pga\_low}/0.1) + c[\ln(\text{pga4nl}/a_1)]^2 + \\ \quad d[\ln(\text{pga4nl}/a_1)]^3 \quad \text{for} \quad a_1 < \text{pga4nl} \leq a_2 \\ b_{nl} \ln(\text{pga4nl}/0.1) \quad \text{for} \quad a_2 < \text{pga4nl} \end{cases} \\
c &= (3\Delta y - b_{nl}\Delta x)/\Delta x^2 \\
d &= -(2\Delta y - b_{nl}\Delta x)/\Delta x^3 \\
\Delta x &= \ln(a_2/a_1) \\
\Delta y &= b_{nl} \ln(a_2/\text{pga\_low}) \\
b_{nl} &= \begin{cases} b_1 \quad \text{for} \quad V_{S30} \leq V_1 \\ (b_1 - b_2)\ln(V_{S30}/V_2)/\ln(V_1/V_2) + b_2 \quad \text{for} \quad V_1 < V_{S30} \leq V_2 \\ b_2 \ln(V_{S30}/V_{ref})/\ln(V_2/V_{ref}) \quad \text{for} \quad V_2 < V_{S30} < V_{ref} \\ 0.0 \quad \text{for} \quad V_{ref} \leq V_{S30} \end{cases}
\end{aligned}
$$

  where $Y$ is in g, $M_h = 6.75$ (hinge magnitude), $V_{ref} = 760$ m/s (specified reference velocity corresponding to the NEHRP B/C boundary), $a_1 = 0.03$ g (threshold for linear amplifcation), $a_2 = 0.09$ g (threshold for nonlinear amplification), pga_low $= 0.06$ g (for transition between linear and nonlinear behaviour), pga4nl is predicted PGA in g for $V_{ref}$ with $F_S = 0$, $V_1 = 180$ m/s, $V_2 = 300$ m/s, $b_{lin} = -0.360$, $b_1 = -0.640$, $b_2 = -0.14$, $M_{ref} = 4.5$, $R_{ref} = 1$ km, $c_1 = -0.66050$, $c_2 = 0.11970$, $c_3 = -0.01151$, $h = 1.35$, $e_1 = -0.53804$, $e_2 = -0.50350$, $e_3 = -0.75472$, $e_4 = -0.50970$, $e_5 = 0.28805$, $e_6 = -0.10164$, $e_7 = 0.0$; $\sigma = 0.502$ (intra-event); $\tau_U = 0.265$, $\tau_M = 0.260$ (inter-event); $\sigma_{TU} = 0.566$, $\sigma_{TM} = 0.560$ (total).

- Characterise sites using $V_{S30}$. Believe equations applicable for $180 \leq V_{S30} \leq 1300$ m/s (state that equations should not be applied for very hard rock sites, $V_{S30} \geq 1500$ m/s). Bulk of data from NEHRP C and D sites (soft rock and firm soil) and very few data from A sites (hard rock). Use three equations for nonlinear amplification: to prevent nonlinear amplification increasing indefinitely as pga4nl decreases and to smooth transition from linear to nonlinear behaviour. Equations for nonlinear site amplification simplified version of those of Choi and Stewart (2005) because believe NGA database insufficient to simultaneously determine all coefficients for nonlinear site equations and magnitude-distance scaling due to trade-offs between parameters. Note that implicit trade-offs involved and change in prescribed soil response equations would lead to change in derived magnitude-distance scaling.

- Focal depths between 2 and 31 km with most $< 20$ km.
- Use data from the PEER Next Generation Attenuation (NGA) Flatfile supplemented with additional data from three small events (2001 Anza $M4.92$, 2003 Big Bear City $M4.92$ and 2002 Yorba Linda $M4.27$) and the 2004 Parkfield earthquake, which were used only for a study of distance attenuation function but not the final regression (due to rules of NGA project).
- Use three faulting mechanism categories using P and T axes:

  SS Strike-slip. Plunges of T and P axes $< 40°$. 35 earthquakes. Dips between 55 and 90°. $4.3 \leq M \leq 7.9$. SS = 1, U = 0, NS = 0, RS = 0.

  RS Reverse. Plunge of T axis $> 40°$. 12 earthquakes. Dips between 12 and 70°. $5.6 \leq M \leq 7.6$. RS = 1, U = 0, SS = 0, NS = 0.

  NS Normal. Plunge of P axis $> 40°$. 11 earthquakes. Dips between 30 and 70°. $5.3 \leq M \leq 6.9$. NS = 1, U = 0, SS = 0, RS = 0.

  Note that some advantages to using P and T axes to classify earthquakes but using categories based on rake angles with: within 30° of horizontal as strike-slip, from 30 to 150° as reverse and from $-30°$ to $-150°$ as normal, gives essentially the same classification. Also allow prediction of motions for unspecified (U = 1, SS = 0, NS = 0, RS = 0) mechanism (use $\sigma$s and $\tau$s with subscript U otherwise use $\sigma$s and $\tau$s with subscript M).
- Exclude records from obvious aftershocks because believe that spectral scaling of aftershocks could be different than that of mainshocks. Note that this cuts the dataset roughly in half.
- Exclude singly-recorded earthquakes.
- Note that possible bias due to lack of low-amplitude data (excluded due to non-triggering of instrument, non-digitisation of record or below the noise threshold used in determining low-cut filter frequencies). Distance to closest non-triggered station not available in NGA Flatfile so cannot exclude records from beyond this distance. No information available that allows exclusion of records from digital accelerograms that could remove this bias. Hence note that obtained distance dependence for small earthquakes and long periods may be biased towards a decay that is less rapid than true decay.
- Use estimated $R_{JB}$s for earthquakes with unknown fault geometries.
- Lack of data at close distances for small earthquakes.
- Three events (1987 Whittier Narrows, 1994 Northridge and 1999 Chi-Chi) contribute large proportion of records (7%, 10% and 24%).
- Note that magnitude scaling better determined for strike-slip events, which circumvent using common magnitude scaling for all mechanisms.
- Seek simple functional forms with minimum required number of predictor variables. Started with simplest reasonable form and added complexity as demanded by comparisons between predicted and observed motions. Selection of functional form heavily guided by subjective inspection of nonparametric plots of data.

- Data clearly show that modelling of anelastic attenuation required for distances $> 80$ km and that effective geometric spreading is dependent on magnitude. Therefore, introduce terms in the function to model these effects, which allows model to be used to 400 km.

- Do not include factors for depth-to-top of rupture, hanging wall/footwall or basin depth because residual analysis does not clearly show that the introduction of these factors would improve the predictive capabilities of model on average.

- Models are data-driven and make little use of simulations.

- Believe that models provide a useful alternative to more complicated NGA models as they are easier to implement in many applications.

- Firstly correct ground motions to obtain equivalent observations for reference velocity of 760 m/s using site amplification equations using only data with $R_{JB} \leq 80$ km and $V_{S30} > 360$ m/s. Then regress site-corrected observations to obtain $F_D$ and $F_M$ with $F_S = 0$. No smoothing of coefficients determined in regression (although some of the constrained coefficients were smoothed).

- Assume distance part of model applies for crustal tectonic regimes represented by NGA database. Believe that this is a reasonable initial approach. Test regional effects by examining residuals by region.

- Note that data sparse for $R_{JB} > 80$ km, especially for moderate events, and, therefore, difficult to obtain robust $c_1$ (slope) and $c_3$ (curvature) simultaneously. Therefore, use data from outside NGA database (three small events and 2004 Parkfield) to define $c_3$ and use these fixed values of $c_3$ within regression to determine other coefficients. To determine $c_3$ and $h$ from the four-event dataset set $c_1$ equal to $-0.5$, $-0.8$ and $-1.0$ and $c_2 = 0$ if the inclusion of event terms $c_0$ for each event. Use $c_3$s when $c_1 = -0.8$ since it is a typical value for this parameter in previous studies. Find that $c_3$ and $h$ are comparable to those in previous studies.

- Note that desirable to constrain $h$ to avoid overlap in curves for large earthquakes at very close distances. Do this by initially performing regression with $h$ as free parameter and then modifying $h$ to avoid overlap.

- After $h$ and $c_3$ have been constrained solve for $c_1$ and $c_2$.

- Constrain quadratic for magnitude scaling so that maximum not reached for $M < 8.5$ to prevent over-saturation. If maximum reached for $M < 8.5$ then perform two-segment regression hinged at $M_h$ with quadratic for $M \leq M_h$ and linear for $M > M_h$. If slope of linear segment is negative then repeat regression by constraining slope above $M_h$ to 0.0. Find that data generally indicates oversaturation but believe this effect is too extreme at present. $M_h$ fixed by observation that ground motions at short periods do not get significantly larger with increasing magnitude.

- Plots of event terms (from first stage of regression) against $M$ show that normal-faulting earthquakes have ground motions consistently below those of strike-slip and reverse events. Firstly group data from all fault types together and solved for $e_1$, $e_5$, $e_6$, $e_7$ and $e_8$ by setting $e_2$, $e_3$ and $e_4$ to 0.0. Then repeat regression fixing $e_5$, $e_6$, $e_7$ and $e_8$ to values obtained in first step to find $e_2$, $e_3$ and $e_4$.

- Examine residual plots and find no significant trends w.r.t. $M$, $R_{JB}$ or $V_{S30}$ although some small departures from a null residual.

- Examine event terms from first stage of regression against $M$ and conclude functional form provides reasonable fit to near-source data.

- Examine event terms from first stage of regression against $M$ for surface-slip and no-surface-slip earthquakes. Find that most surface-slip events correspond to large magnitudes and so any reduction in motions for surface-slip earthquakes will be mapped into reduced magnitude scaling. Examine event terms from strike-slip earthquakes (because both surface- and buried-slip events in same magnitude range) and find no indication of difference in event terms for surface-slip and no-surface-slip earthquakes. Conclude that no need to include dummy variables to account for this effect.

- Examine residuals for basin depth effects. Find that $V_{S30}$ and basin depth are highly correlated and so any basin-depth effect will tend to be captured by empirically-determined site amplifications. To separate $V_{S30}$ and basin-depth effects would require additional information or assumptions but since aiming for simplest equations no attempt made to break down separate effects. Examine residuals w.r.t. basin depth and find little dependence.

- Chi-Chi data forms significant fraction (24% for PGA) of data set. Repeat complete analysis without these data to examine their influence. Find that predictions are not dramatically different.

- Note that use of anelastic coefficients derived using data from four earthquakes in central and southern California is not optimal and could lead to inconsistencies in $h$s.

## 2.277 Campbell and Bozorgnia (2007), Campbell and Bozorgnia (2008b) & Campbell and Bozorgnia (2008a)

- Ground-motion model is:

$$
\begin{aligned}
\ln \hat{Y} &= f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} \\
f_{mag} &= \begin{cases} c_0 + c_1 M & \text{for} \quad M \leq 5.5 \\ c_0 + c_1 M + c_2(M - 5.5) & \text{for} \quad 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M - 5.5) + c_3(M - 6.5) & \text{for} \quad M > 6.5 \end{cases} \\
f_{dis} &= (c_4 + c_5 M) \ln(\sqrt{R_{RUP}^2 + c_6^2}) \\
f_{flt} &= c_7 F_{RV} f_{flt,Z} + c_8 F_{NM} \\
f_{flt,Z} &= \begin{cases} Z_{TOR} & \text{for} \quad Z_{TOR} < 1 \\ 1 & \text{for} \quad Z_{TOR} \geq 1 \end{cases} \\
f_{hng} &= c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta} \\
f_{hng,R} &= \begin{cases} 1 & \text{for} \quad R_{JB} = 0 \\ \{\max(R_{RUP}, \sqrt{R_{JB}^2 + 1}) - R_{JB}\}/ & \\ \quad \max(R_{RUP}, \sqrt{R_{JB}^2 + 1}) & \text{for} \quad R_{JB} > 0, Z_{TOR} < 1 \\ (R_{RUP} - R_{JB})/R_{RUP} & \text{for} \quad R_{JB} > 0, Z_{TOR} \geq 1 \end{cases} \\
f_{hng,M} &= \begin{cases} 0 & \text{for} \quad M \leq 6.0 \\ 2(M - 6.0) & \text{for} \quad 6.0 < M < 6.5 \\ 1 & \text{for} \quad M \geq 6.5 \end{cases} \\
f_{hng,Z} &= \begin{cases} 0 & \text{for} \quad Z_{TOR} \geq 20 \\ (20 - Z_{TOR})/20 & \text{for} \quad 0 \leq Z_{TOR} < 20 \end{cases} \\
f_{hng,\delta} &= \begin{cases} 1 & \text{for} \quad \delta \leq 70 \\ (90 - \delta)/20 & \text{for} \quad \delta > 70 \end{cases} \\
f_{site} &= \begin{cases} c_{10} \ln\left(\frac{V_{S30}}{k_1}\right) + k_2 \left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln(A_{1100} + c)\right\} & \text{for} \quad V_{S30} < k_1 \\ (c_{10} + k_2 n) \ln\left(\frac{V_{S30}}{k_1}\right) & \text{for} \quad k_1 \leq V_{S30} < 1100 \\ (c_{10} + k_2 n) \ln\left(\frac{1100}{k_1}\right) & \text{for} \quad V_{S30} \geq 1100 \end{cases} \\
f_{sed} &= \begin{cases} c_{11}(Z_{2.5} - 1) & \text{for} \quad Z_{2.5} < 1 \\ 0 & \text{for} \quad 1 \leq Z_{2.5} \leq 3 \\ c_{12} k_3 \mathrm{e}^{-0.75}[1 - \mathrm{e}^{-0.25(Z_{2.5} - 3)}] & \text{for} \quad Z_{2.5} > 3 \end{cases} \\
\sigma &= \sqrt{\sigma_{\ln Y}^2 + \sigma_{\ln AF}^2 + \alpha^2 \sigma_{\ln A_B}^2 + 2\alpha\rho\sigma_{\ln Y_B}\sigma_{\ln A_B}} \\
\alpha &= \begin{cases} k_2 A_{1100}\{[A_{1100} + c(V_{S30}/k_1)^n]^{-1} - (A_{1100} + c)^{-1}\} & \text{for} \quad V_{S30} < k_1 \\ 0 & \text{for} \quad V_{S30} \geq k_1 \end{cases}
\end{aligned}
$$

where $Y$ is in g, $c_0 = -1.715$, $c_1 = 0.500$, $c_2 = -0.530$, $c_3 = -0.262$, $c_4 = -2.118$, $c_5 = 0.170$, $c_6 = 5.60$, $c_7 = 0.280$, $c_8 = -0.120$, $c_9 = 0.490$, $c_{10} = 1.058$, $c_{11} = 0.040$, $c_{12} = 0.610$, $k_1 = 865$, $k_2 = -1.186$, $k_3 = 1.839$, $\sigma_{\ln Y} = 0.478$ (intra-event), $\tau_{\ln Y} = 0.219$ (inter-event), $\sigma_C = 0.166$, $\sigma_T = 0.526$ (total), $\sigma_{Arb} = 0.551$ and $\rho = 1.000$ (correlation coefficient between intra-event residuals of ground-motion parameter of interest and PGA). $\sigma_{\ln Y_B} = (\sigma_{\ln Y}^2 - \sigma_{\ln AF}^2)^{1/2}$ is standard deviation at base of site profile. Assume that $\sigma_{\ln AF} \approx 0.3$ based on previous studies for deep soil sites. $\sigma_{Arb} = \sqrt{\sigma_T^2 + \sigma_C^2}$ for estimating aleatory uncertainty of arbitrary horizontal component.

- Characterise sites using $V_{S30}$. Account for nonlinear effects using $A_{1100}$, median estimated PGA on reference rock outcrop ($V_{S30} = 1100$ m/s) in g. Linear part of $f_{site}$ is consistent with previous studies but with constraint for constant site term for $V_{S30} > 1100$ m/s (based on residual analysis) even though limited data for $V_{S30} > 1100$ m/s. When only including linear part of shallow site response term find residuals clearly exhibit bias when plotted against rock PGA, $A_{1100}$. Find that residuals not sufficient to determine functional form for nonlinear amplification so use 1D equivalent-linear site response simulations to constrain form and coefficients. Believe model applicable for $V_{S30} = 150$–$1500$ m/s.

- Also use depth to 2.5 km/s shear-wave velocity horizon (basin or sediment depth) in km, $Z_{2.5}$. Deep-basin term modelled based on 3D simulations for Los Angeles, San Gabriel and San Fernando basins (southern California) calibrated empirically from residual analysis, since insufficient observational data for fully empirical study. Shallow-sediment effects based on analysis of residuals. Note high correlation between $V_{S30}$ and $Z_{2.5}$. Provide relationships for predicting $Z_{2.5}$ based on other site parameters. Believe model applicable for $Z_{2.5} = 0$–$10$ km.

- Use three faulting mechanism categories based on rake angle, $\lambda$:

  RV Reverse and reverse-oblique. $30 < \lambda < 150°$. 17 earthquakes. $F_{RV} = 1$ and $F_{NM} = 0$.

  NM Normal and normal-oblique. $-150 < \lambda < -30°$. 11 earthquakes. $F_{NM} = 1$ and $F_{RV} = 0$.

  SS Strike-slip. All other rake angles. 36 earthquakes. $F_{RV} = 0$ and $F_{NM} = 0$.

- Use data from PEER Next Generation Attenuation (NGA) Flatfile.

- Select records of earthquakes located within shallow continental lithosphere (crust) in a region considered to be tectonically active from stations located at or near ground level and which exhibit no known embedment or topographic effects. Require that the earthquakes have sufficient records to reliably represent the mean horizontal ground motion (especially for small magnitude events) and that the earthquake and record is considered reliable.

- Exclude these data: 1) records with only one horizontal component or only a vertical component; 2) stations without a measured or estimated $V_{S30}$; 3) earthquakes without a rake angle, focal mechanism or plunge of the P- and T-axes; 4) earthquakes with the hypocentre or a significant amount of fault rupture located in lower crust, in oceanic plate or in a stable continental region; 5) LDGO records from the 1999 Düzce earthquake that are considered to be unreliable due to their spectral shapes; 6) records from instruments designated as low-quality from the 1999 Chi-Chi earthquake; 7) aftershocks but not triggered earthquakes such as the 1992 Big Bear earthquake; 8) earthquakes with too few records ($N$) in relation to its magnitude, defined as: a) $M < 5.0$ and $N < 5$, b) $5.0 \leq M < 6.0$ and $N < 3$, c) $6.0 \leq M < 7.0$, $R_{RUP} > 60$ km and $N < 2$ (retain singly-recorded earthquakes with $M \geq 7.0$ and $R_{RUP} \leq 60$ km because of their significance); 9) records considered to represent non-free-field site conditions, defined as instrument located in a) basement of building, b) below the ground surface, c) on a dam except the abutment; and 10) records with known topographic effects such as Pacoima Dam upper left abutment and Tarzana Cedar Hill Nursery.

- Functional forms developed or confirmed using classical data exploration techniques, such as analysis of residuals. Candidate functional forms developed using numerous iterations to capture the observed trends in the recorded ground motion data. Final functional forms selected according to: 1) sound seismological basis; 2) unbiased residuals; 3) ability to be extrapolated to magnitudes, distances and other explanatory variables that are important for use in engineering and seismology; and 4) simplicity, although this was not an overriding factor. Difficult to achieve because data did not always allow the functional forms of some explanatory variables to be developed empirically. Theoretical constraints were sometimes used to define the functional forms.

- Use two-stage maximum-likelihood method for model development but one-stage random-effects method for final regression.

- Also perform statistical analysis for converting between selected definition of horizontal component and other definitions.

- Include depth to top of coseismic rupture plane, $Z_{TOR}$, which find important for reverse-faulting events. Find that some strike-slip earthquakes with partial or weak surface expression appeared to have higher-than-average ground motions but other strike-slip events contradict this, which believe could be due to ambiguity in identifying coseismic surface rupture in NGA database. Therefore, believe additional study required before $Z_{TOR}$ can be used for strike-slip events. Believe model applicable for $Z_{TOR} = 0$–$15$ km.

- Include dip of rupture plane, $\delta$. Believe model applicable for $\delta = 15$–$90°$.

- Assume that $\tau$ is approximately equal to standard deviation of inter-event residuals, $\tau_{\ln Y}$, since inter-event terms are not significantly affected by soil nonlinearity. Note that if $\tau$ was subject to soil nonlinearity effects it would have only a relatively small effect on $\sigma_T$ because intra-event $\sigma$ dominates. $\sigma$ takes into account soil nonlinearity effects. Assume that $\sigma_{\ln Y}$ and $\sigma_{\ln PGA}$ represent aleatory uncertainty associated with linear site response, reflecting dominance of such records in database.

- Based on statistical tests on binned intra-event residuals conclude that intra-event standard deviations not dependent on $V_{S30}$ once nonlinear site effects are taken into account.

- Use residual analysis to derive trilinear functional form for $f_{mag}$. Piecewise linear relationship allows greater control of $M > 6.5$ scaling and decouples this scaling from that of small magnitude scaling. Demonstrate using stochastic simulations that trilinear model fits ground motions as well as quadratic model for $M \leq 6.5$. Find that large-magnitude scaling of trilinear model consistent with observed effects of aspect ratio (rupture length divided by rupture width), which was abandoned as explanatory variable when inconsistencies in NGA database for this variable found.

- Original unconstrained regression resulted in prediction of oversaturation at short periods, large magnitudes and short distances. Oversaturation not statistically significant nor is this behaviour scientifically accepted and therefore constrain $f_{mag}$ to saturate at $M > 6.5$ and $R_{RUP} = 0$ when oversaturation predicted by unconstrained regression analysis. Constraint equivalent to setting $c_3 = -c_1 - c_2 - c_5 \ln(c_6)$. Inter- and intra-event residual plots w.r.t. $M$ show predictions relatively unbiased, except for larger magnitudes where saturation constraint leads to overestimation of short-period ground motions.

- Examine inter-event residuals w.r.t. region and find some bias, e.g. find generally positive inter-event residuals at relatively long periods of $M > 6.7$ events in California but only for five events, which believe insufficient to define magnitude scaling for this region. Note that user may wish to take these dependences into account.

- Note that adopted distance-dependence term has computational advantage since it transfers magnitude-dependent attenuation term to outside square root, which significantly improves stability of nonlinear regression. Note that adopted functional form consistent with broadband simulations for 6.5 and 7.5 between 2 and 100 km and with simple theoretical constraints. Examine intra-event residuals w.r.t. distance and find that they are relatively unbiased.

- Functional form for $f_{flt}$ determined from residual analysis. Find coefficient for normal faulting only marginally significant at short periods but very significant at long periods. Believe long-period effects due to systematic differences in sediment depths rather than source effects, since many normal-faulting events in regions with shallow depths to hard rock (e.g. Italy, Greece and Basin and Range in the USA), but no estimates of sediment depth to correct for this effect. Constrain normal-faulting factor found at short periods to go to zero at long periods based on previous studies.

- Functional form for $f_{hng}$ determined from residual analysis with additional constraints to limit range of applicability so that hanging-wall factor has a smooth transition between hanging and foot walls, even for small $Z_{TOR}$. Include $f_{hng,M}$, $f_{hng,Z}$ and $f_{hng,\delta}$ to phase out hanging-wall effects at small magnitudes, large rupture depths and large rupture dips, where residuals suggest that effects are either negligible or irresolvable from data. Include hanging-wall effects for normal-faulting and non-vertical strike-slip earthquakes even those statistical evidence is weak but it is consistent with better constrained hanging-wall factor for reverse faults and it is consistent with foam-rubber experiments and simulations.

## 2.278 Danciu and Tselentis (2007a), Danciu and Tselentis (2007b) & Danciu (2006)

- Ground-motion model is:

$$\log_{10} Y = a + bM - c\log_{10}\sqrt{R^2 + h^2} + eS + fF$$

  where $Y$ is in cm/s$^2$, $a = 0.883$, $b = 0.458$, $c = 1.278$, $h = 11.515$, $e = 0.038$, $f = 0.116$, $\tau = 0.109$ (intra-event) and $\sigma = 0.270$ (inter-event).

- Use three site classes:

  B Rock, $V_{s,30} > 800$ m/s. $S = 0$. 75 records.

  C Stiff soil, $360 \leq V_s \leq 665$ m/s. $S = 1$. 197 records.

  D Soft soil, $200 \leq V_s \leq 360$ m/s. $S = 2$. 63 records.

  From initial analysis find that ground-motions on D sites are double those on C sites.

- Use three style-of-faulting categories:

  Thrust $F = 1$

  Strike-slip $F = 1$

  Normal $F = 0$

  From initial analysis find that thrust and strike-slip ground motions are similar but greater than normal motions.

- Focal depths between 0 and 30 km with mean of 10.66 km.

- Most records from earthquakes near the Ionian islands.

- Use records from free-field stations and from basements of buildings with $< 2$ storeys. Note that some bias may be introduced by records from buildings but due to lack of data from free-field stations these records must be included.

- Use corrected records from ISESD (bandpass filtered 0.25 and 25 Hz).

- Use epicentral distance because most earthquakes are offshore and those that are onshore do not display evidence of surface faulting and therefore cannot use a fault-based distance measure.

- Data from large events recorded at intermediate and long distances and small events at small distances. Correlation coefficient between magnitude and distance is 0.64.

- Recommend that equation not used outside range of data used.

- Analyse residuals normalized to have zero mean and unity variance (only display results for PGA and SA at 1 s due to similar results for all periods). Find that residuals do not show trends and are uncorrelated (at more than 99% confidence level) w.r.t. independent variables. Show normality of residuals through histograms for PGA and SA at 1 s.

- Also derive equations for various other strong-motion parameters.

## 2.279 Douglas (2007)

- Ground-motion model is:

$$\log y = a_1 + a_2 M + a_3 \log \sqrt{(d^2 + 5^2)} + a_{3+i} S_i$$

  Coefficients not reported since purpose is not to develop models for seismic hazard assessments but to derive confidence limits on median PGA and thereafter to examine possible regional dependence of ground motions.

- Rederives models of Joyner and Boore (1981), Boore et al. (1993, 1997), Ambraseys et al. (1996), Ambraseys et al. (2005a), Ulusay et al. (2004), Kalkan and Gülkan (2004b) and Sabetta and Pugliese (1987) to find their complete covariance matrices in order to compute confidence limits of the predicted median PGA.

- Uses same site classifications as original studies. $S_i = 1$ for site class $i$ and 0 otherwise.

- Adopts a simple linear functional form and standard one-stage regression method so that the covariance matrices can be easily computed.

- Assumes a fixed coefficient of 5 km (a rough average value for this coefficient for most models using adopted functional form) inside square root to make function linear.

- Examines 95% confidence limits on PGA since it is standard to use 5% significance levels when testing null hypotheses. Plots predicted median PGAs and their confidence limits for $M_w 5$, 6.5 and 8.0 up to 200 km to show effects of extrapolation outside range of applicability of models. Finds that confidence limits for models derived using limited data (Ulusay et al., 2004; Kalkan and Gülkan, 2004b; Sabetta and Pugliese, 1987) are wider than models derived using large well-distributed datasets (Joyner and Boore, 1981; Boore et al., 1993, 1997; Ambraseys et al., 1996, 2005a). Notes that for $5.5 < M_w < 7$ and $10 \leq d_f \leq 60$ km the 95%-confidence limits of the median are narrow and within bands 10–30% from the median but for other magnitudes and distances (away from the centroid of data) they are much wider (bands of 100% from the median). Notes that inclusion of data from large magnitude events decreases the width of the confidence limits of the model derived using the data of Boore et al. (1993, 1997) compared with that derived using the data of Joyner and Boore (1981) and similarly that derived with the data of Ambraseys et al. (2005a) compared with that derived using the data of Ambraseys et al. (1996).

## 2.280 Fukushima et al. (2007a)

- Ground-motion model is:

$$\log a = a_1 M + a_2 h + a_3 \log[\Delta + a_4 \exp(a_5 M)] + a_6$$

  where $a$ is in cm/s$^2$, $a_1 = 0.606$, $a_2 = 0.00459$, $a_3 = -2.136$, $a_4 = 0.334$, $a_5 = 0.653$, $a_6 = 1.730$, $\phi = 0.251$ (intra-event), $\tau = 0.192$ (inter-event) and $\sigma = 0.317$ (total).

- Select K-Net and KiK-Net data within geographical region 137–142E and 34N–38N with $M > 5$ and focal depths 200 km from 09/1996 to 07/2006. Remove inadequate records, e.g. those with small amplitudes.

- $h$ is central depth of rupture plane.

- Data from 186 stations.

## 2.281 Graizer and Kalkan (2007, 2008)

- Ground-motion model is:

$$
\begin{aligned}
\ln(Y) &= \ln(A) - 0.5\ln\left[\left(1-\frac{R}{R_0}\right)^2 + 4D_0^2\frac{R}{R_0}\right] \\
&\quad - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_1}}\right)^2 + 4D_1^2\sqrt{\frac{R}{R_1}}\right] + b_v\ln\left(\frac{V_{s,30}}{V_A}\right) \\
A &= [c_1\arctan(M+c_2)+c_3]F \\
R_0 &= c_4M + c_5 \\
D_0 &= c_6\cos[c_7(M+c_8)] + c_9
\end{aligned}
$$

  where $Y$ is in g, $c_1 = 0.14$, $c_2 = -6.25$, $c_3 = 0.37$, $c_4 = 2.237$, $c_5 = -7.542$, $c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.15$, $c_9 = 0.525$, $b_v = -0.25$, $V_A = 484.5$, $R_1 = 100$ km and $\sigma = 0.552$.

- Characterise sites by $V_{s,30}$ (average shear-wave velocity in upper 30 m). Note that approximately half the stations have measured shear-wave velocity profiles.
- Include basin effects through modification of $D_1$. For sediment depth ($Z \geq 1$ km $D_1 = 0.35$; otherwise $D_1 = 0.65$.
- Use three faulting mechanism classes:

| | |
|---|---|
| Normal | 13 records |
| Strike-slip | 1120 records. $F = 1.00$. |
| Reverse | 1450 records. $F = 1.28$ (taken from previous studies). |

  but only retain two (strike-slip and reverse) by combining normal and strike-slip categories.

- Only use earthquakes with focal depths $< 20$ km. Focal depths between 4.6 and 19 km.
- Exclude data from aftershocks.
- Use data from: Alaska (24 records), Armenia (1 record), California (2034 records), Georgia (8), Iran (7 records) Italy (10 records), Nevada (8 records), Taiwan (427 records), Turkey (63 records) and Uzbekistan (1 record).
- Most data from $5.5 \leq M_w \leq 7.5$.
- Adopt functional form to model: a constant level of ground motion close to fault, a slope of about $R^{-1}$ for $> 10$ km and $R^{-1.5}$ at greater distances ($> 100$ km) and observation (and theoretical results) that highest amplitude ground motions do not always occur nearest the fault but at distances of 3–10 km.
- Choose functional form based on transfer function of a SDOF oscillator since this has similar characteristics to those desired.
- Note that magnitude scaling may need adjusting for small magnitudes.
- Firstly regress for magnitude and distance dependency and then regress for site and basin effects.
- Examine residual w.r.t. magnitude and distance and observe no significant trends.
- Compare predictions to observations for 12 well-recorded events in the dataset and find that the observations are well predicted for near and far distances.
- Demonstrate (for the 2004 Parkfield earthquake) that it is possible to add an additional 'filter' term in order to predict ground motions at large distances without modifying the other terms.

## 2.282 Güllü and Erçelebi (2007)

- Ground-motion model is:

$$\ln \mathrm{PGA} = a_1 + a_2 M + a_3 \ln r_{epi} + a_4 r_{epi} + a_5 C_1 + a_6 C_2 + a_7 C_3$$

  where $a_1 = -4.8272$, $a_2 = 0.90061$, $a_3 = -0.28195$, $a_4 = -0.00831$, $a_5 = 0.61098$, $a_6 = 0.37342$ and $a_7 = 0.2117$ ($\sigma$ is not reported)

- Use 4 site classes (Zaré and Bard, 2002):

  1. Rock and hard alluvial sites, $f_0 > 15\,\mathrm{Hz}$, $V_s > 800\,\mathrm{m/s}$. $C_1 = C_2 = C_3 = 0$.
  2. Alluvial sites, thin soft alluvium, $5 < f_0 < 15\,\mathrm{Hz}$, $500 < V_s < 700\,\mathrm{m/s}$. $C_1 = 1$, $C_2 = C_3 = 0$.
  3. Soft gravel and sandy sites, $2 < f_0 < 5\,\mathrm{Hz}$, $300 < V_s < 500\,\mathrm{m/s}$. $C_2 = 1$, $C_1 = C_3 = 0$.
  4. Soft soil sites, thick soft alluvia, $f_0 < 2\,\mathrm{Hz}$, $V_s < 300\,\mathrm{m/s}$. $C_3 = 1$, $C_1 = C_2 = 0$.

- Derive model to compare to neural-network-based model.

## 2.283 Hong and Goda (2007) & Goda and Hong (2008)

- Ground-motion model is:

$$\ln Y = b_1 + b_2(\mathbf{M} - 7) + b_3(\mathbf{M} - 7)^2 + [b_4 + b_5(\mathbf{M} - 4.5)] \ln[(r_{\mathrm{jb}}^2 + h^2)^{0.5}] + \mathrm{AF}_s$$

  where $Y$ is in g, $b_1 = 1.096$, $b_2 = 0.444$, $b_3 = 0.0$, $b_4 = -1.047$, $b_5 = 0.038$, $h = 5.7$, $\sigma_\eta = 0.190$ (inter-event) and $\sigma_\epsilon = 0.464$ (intra-event) for geometric mean.

- $\mathrm{AF}_s$ is the amplification factor due to linear and nonlinear soil behaviour used by Atkinson and Boore (2006), which is a function of $V_{s,30}$ and expected PGA at site with $V_{s,30} = 760\,\mathrm{m/s}$, $\mathrm{PGA}_{\mathrm{ref}}$. Derive equation for $\mathrm{PGA}_{\mathrm{ref}}$ of form $\ln \mathrm{PGA}_{\mathrm{ref}} = b_1 + b_2(M - 7) + b_4 \ln((r_{jb}^2 + h^2)^{0.5})$, where $b_1 = 0.851$, $b_2 = 0.480$, $b_4 = -0.884$ and $h = 6.3\,\mathrm{km}$ for geometric mean ($\sigma$ not reported).

- Use data from the PEER Next Generation Attenuation (NGA) database.

- Investigate the spatial correlation of ground motions and their variabilities.

- Generate datasets using normally distributed values of $M$ (truncated at $\pm 2$ standard deviations that are reported in the PEER NGA database) for earthquakes and lognormally-distributed values of $V_{s,30}$ (again using standard deviations from PEER NGA database) for stations. Repeat regression analysis and find coefficients very similar to those obtained ignoring the uncertainty in $M$ and $V_{s,30}$.

## 2.284 Massa et al. (2007)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM_L + c \log(R) + dS_{\mathrm{soil}}$$

  where $Y$ is in g, $a = -3.2191 \pm 0.16$, $b = 0.7194 \pm 0.025$, $c = -1.7521 \pm 0.075$, $d = 0.1780$ and $\sigma = 0.282$.

- Originally use three site classes based on Eurocode 8:

  A Rock, $V_{s,30} > 800\,\mathrm{m/s}$. Marine clay or other rocks (Lower Pleistocene and Pliocene), volcanic rock and deposits. 11 stations. 833 records.

B Stiff soil, $360 < V_{s,30} < 800$ m/s. Colluvial, alluvial, lacustrine, beach, fluvial terraces, glacial deposits and clay (Middle-Upper Pleistocene). Sand and loose conglomerate (Pleistocene and Pliocene). Travertine (Pleistocene and Holocene). 6 stations. 163 records.

C Soft soil, $V_{s,30} < 360$ m/s. Colluvial, alluvial, lacustrine, beach and fluvial terrace deposits (Holocene). 3 stations. 67 records.

Classify stations using geological maps. Find that results obtained using this classification are not realistic because of some stations on very thick (> 1000 m) sedimentary deposits whose amplification factors are small. Therefore, use two site classes using H/V ratios both using noise and earthquake records. Confirm H/V results by computing magnitude residuals at each station.

Final site classes are:

Rock Site amplification factors < 2 at all considered frequencies from H/V analysis. 422 records. $S_{\mathrm{soil}} = 0$.

Soil Site amplification factors > 2. 641 records. $S_{\mathrm{soil}} = 1$.

- Use data from velocimeters (31 stations) and accelerometers (2 stations) from 33 sites with sampling rates of 62.5 samples/s.
- Relocate events and calculate $M_L$.
- Exclude data from $M_L < 2.5$ and $r_{hypo} > 300$ km.
- Few near-source records ($r_{hypo} < 150$ km) from $M_L > 4$ but for $M_L < 4$ distances from 0 to 300 km well represented.
- Exclude records with signal-to-noise ratios < 10 dB.
- Correct for instrument response and bandpass filter between 0.5 and 25 Hz and then the velocimetric records have been differentiated to obtain acceleration.
- Visually inspect records to check for saturated signals and noisy records.
- Compare records from co-located velocimetric and accelerometric instruments and find that they are very similar.
- Compare PGAs using larger horizontal component, geometric mean of the two horizontal components and the resolved component. Find that results are similar and that the records are not affected by bias due to orientation of sensors installed in field.
- Try including a quadratic magnitude term but find that it does not reduce uncertainties and therefore remove it.
- Try including an anelastic attenuation term but find that the coefficient is not statistically significant and that the coefficient is positive and close to zero and therefore remove this term.
- Try using a term $c \log_{10} \sqrt{R_{\mathrm{epi}}^2 + h^2}$ rather than $c \log_{10}(R)$ but find that $h$ is not well constrained and hence PGAs for distances < 50 km underpredicted.
- Find that using a maximum-likelihood regression technique leads to very similar results to the one-stage least-squares technique adopted, which relate to lack of correlation between magnitudes and distances in dataset.
- Find site coefficients via regression following the derivation of $a$, $b$ and $c$ using the 422 rock records.

- Compare observed and predicted ground motions for events in narrow (usually 0.3 units) magnitude bands. Find good match.
- Examine residuals w.r.t. magnitude and distance and find no significant trends except for slight underestimation for short distances and large magnitudes. Also check residuals for different magnitude ranges. Check for bias due to non-triggering stations.
- Compare predicted PGAs to observations for 69 records from central northern Italy from magnitudes 5.0–6.3 and find good match except for $r_{hypo} < 10$ km where ground motions overpredicted, which relate to lack of near-source data.

## 2.285 Popescu et al. (2007)

- Ground-motion model is:

$$\log A = C_1 M_w + C_2 \log R + C_3$$

where $A$ in in cm/s$^2$, $C_1 = 0.80 \pm 0.05$, $C_2 = -0.30 \pm 0.08$, $C_3 = -2.93$ and $\sigma = 0.314$ using $r_{epi}$ and $C_1 = 0.79 \pm 0.05$, $C_2 = -0.89 \pm 0.38$, $C_3 = -1.43$ and $\sigma = 0.341$ using $r_{hypo}$.

- Adjust observations by multiplicative factor $S$ to account for site conditions ($0.8 \leq S \leq 1$ for hard rocks, $0.7 \leq S \leq 0.8$ for thin sedimentary layers and $0.65 \leq S \leq 0.7$ for thick sedimentary cover.
- Focal depths between 60 and 166 km.
- Data from digital strong-motion network (K2 instruments) from 1997 to 2000 ($4 \leq M_w \leq 6$) plus data (SMA-1) from 30th August 1986 ($M_w$7.1) and 30th and 31st May 1990 ($M_w$6.9 and 6.4) earthquakes.
- Regression in two steps: a) dependence on $M_w$ found and then b) dependence on $R$ is found (details on this procedure are not given).
- Also regress using just K2 data ($\log A = 0.94 \pm 0.09 M_w - 1.01 \pm 0.42 \log R - 1.84$, $\sigma = 0.343$) and using $r_{epi}$ ($\log A = 0.89 \pm 0.09 M_w - 0.28 \pm 0.09 \log \Delta - 3.35$, $\sigma = 0.322$). Note that correlation coefficients are higher and $\sigma$s are lower when all data is used and that match (based on relative residuals) to data from 1986 and 1990 earthquakes is better when all data is used.
- Present relative residuals for sites in epicentral area and in Bucharest. Note that for 63% of earthquakes relative errors are < 50% for at least one station; for 43% of earthquake relative errors are < 30% for at least one station; and for 9 earthquakes relative errors are smaller than 10% for at least one station (BMG, the extreme site). Based on this analysis it is concluded that predictions more reliable in far-field than in epicentral area. Also find that largest absolute residuals are for MLR (stiff rock).
- Note largest relative errors are for $4 \leq M_w \leq 4.5$.

## 2.286 Sobhaninejad et al. (2007)

- Ground-motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 Mw) \log \sqrt{r_{jb}^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

where $y$ is in m/s$^2$, $a_1 = -0.703$, $a_2 = 0.392$, $a_3 = -0.598$, $a_4 = -0.100$, $a_5 = -7.063$, $a_6 = 0.186$, $a_7 = 0.125$, $a_8 = 0.082$, $a_9 = 0.012$ and $a_{10} = -0.038$ (do not report $\sigma$ but unbiased mean square error) for horizontal PGA; and $a_1 = 0.495$, $a_2 = 0.027$, $a_3 = -2.83$, $a_4 = 0.235$, $a_5 = 7.181$, $a_6 = 1.150$, $a_7 = 1.103$, $a_8 = -0.074$, $a_9 = 0.065$ and $a_{10} = -0.170$ (do not report $\sigma$ but unbiased mean square error).

- Use three site categories:

Soft soil $S_S = 1$, $S_A = 0$.
Stiff soil $S_A = 1$, $S_S = 0$.
Rock $S_S = 0$, $S_A = 0$.

- Use four faulting mechanisms:

Normal $F_N = 1$, $F_T = 0$, $F_O = 0$.
Strike-slip $F_N = 0$, $F_T = 0$, $F_O = 0$.
Thrust $F_T = 1$, $F_N = 0$, $F_O = 0$.
Odd $F_O = 1$, $F_N = 0$, $F_T = 0$.

- Use same data and functional form as Ambraseys et al. (2005a) and Ambraseys et al. (2005b) but exclude six records that were not available.

- Use genetic (global optimization) algorithm to find coefficients so as to find the global (rather than a local) minimum. Use the unbiased mean square error as the error (cost or fitness) function in the algorithm. Use 20 chromosomes as initial population, best-fitness selection for offspring generation, uniform random selection for mutation of chromosomes and heuristic crossover algorithm for generation of new offspring.

- Find smaller (by 26% for horizontal and 16.66% for vertical) unbiased mean square error than using standard regression techniques.

## 2.287 Tavakoli and Pezeshk (2007)

- Ground-motion model is:

$$\log_{10} y = \theta_1 + \theta_2 M + \theta_3 M^2 + \theta_4 R + \theta_5 \log_{10}(R + \theta_6 10^{\theta_7 M})$$

  where $y$ is in $\mathrm{cm/s^2}$, $\theta_1 = -3.4712$, $\theta_2 = 2.2639$, $\theta_3 = -0.1546$, $\theta_4 = 0.0021$, $\theta_5 = -1.8011$, $\theta_6 = 0.0490$, $\theta_7 = 0.2295$, $\sigma_r = 0.2203$ (intra-event) and $\sigma_e = 0.2028$ (inter-event).

- All records from rock sites.

- Strong correlation between magnitude and distance in dataset.

- Use a derivative-free approach based on a hybrid genetic algorithm to derive the model. Use a simplex search algorithm to reduce the search domain to improve convergence speed. Then use a genetic algorithm to obtain the coefficients and uncertainties using one-stage maximum-likelihood estimation. Believe that approach is able to overcome shortcomings of previous methods in providing reliable and stable solutions although it is slower.

- In hybrid genetic algorithm an initial population of possible solutions is constructed in a random way and represented as vectors called strings or chromosomes of length determined by number of regression coefficients and variance components. Population size is usually more than twice string length. Each value of population array is encoded as binary string with known number of bits assigned according to level of accuracy or range of each variable. Use three operations (reproduction/selection, crossover and mutation) to conduct directed search. In reproduction phase each string assigned a fitness value derived from its raw performance measure given by objective function. Probabilities of choosing a string is related to its fitness value. Crossover or mating combines pairs of strings to create improved strings in next population. In mutation one or more bits of every string are altered randomly. The process is then repeated until a termination criterion is met. Demonstrate approach using test function and find small maximum bias in results. Conclude that method is reliable.

- Use Taiwanese dataset of Chen and Tsai (2002) to demonstrate method.
- Compare results with those obtained using methods of Brillinger and Preisler (1985), Joyner and Boore (1993) and Chen and Tsai (2002). Find differences in coefficients (although predictions are very similar except at edges of dataspace) and standard deviations (slightly lower for proposed method).
- Compare predicted motions for $M_L$5.5 with observations for $M_L$5–6. Find good fit.
- Plot total residuals against magnitude and distance and find no trends.
- Note that residuals show that model is satisfactory up to 100 km but for larger distances assumption of geometric spreading of body waves in not appropriate due to presence of waves reflected off Moho.
- Note that near-source saturation should be included. Apply proposed method using a complex functional form with different equations for three distance ranges and compare results to those using simple functional form. Find differences at short and large distances.

## 2.288 Tejeda-Jácome and Chávez-García (2007)

- Ground-motion model is:

$$\ln A = c_1 + c_2 M - c_3 \ln h - c_4 \ln R$$

  where $A$ is in cm/s$^2$, $c_1 = -0.5342$, $c_2 = 2.1380$, $c_3 = 0.4440$, $c_4 = 1.4821$ and $\sigma = 0.28$ for horizontal PGA and $c_1 = -0.5231$, $c_2 = 1.9876$, $c_3 = 0.5502$, $c_4 = 1.4038$ and $\sigma = 0.27$ for vertical PGA.
- Most stations on rock or firm ground. 4 instruments (from close to coast) installed on sandy or silty-sandy soils. Not enough data to correct for site effects or derive site coefficients. Check residuals (not shown) for each station and find no systematic bias.
- Focal depths $h$ between 3.4 and 76.0 km (most $< 40$ km). No correlation between $h$ and $r_{epi}$.
- Use data from 12 (5 Etnas and 7 GSR-18s) temporary and 5 permanent strong-motion stations.
- Since data from digital instruments only apply baseline correction.
- Exclude data from 3 events only recorded at 3 stations.
- Relocate earthquakes because of poor locations given by agencies. Recompute $M_L$ from accelerograms.
- Inclusion of $h$ leads to less scatter but note need for larger database to better understand effect of $h$.
- Examine residuals w.r.t. distance and find no trend or bias.

## 2.289 Abrahamson and Silva (2008) & Abrahamson and Silva (2009)

- Ground-motion model is:

$$
\begin{aligned}
\ln \mathrm{Sa}(\mathrm{g}) &= f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) \\
&\quad + F_{HW} f_4(R_{jb}, R_{rup}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M) \\
&\quad + f_{10}(Z_{1.0}, V_{S30}) \\
f_1(M, R_{rup}) &= \begin{cases} a_1 + a_4(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for} \quad M \leq c_1 \\ a_1 + a_5(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for} \quad M > c_1 \end{cases} \\
R &= \sqrt{R_{rup}^2 + c_4^2} \\
f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) &= \begin{cases} a_{10}\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) - b\ln(\widehat{\mathrm{PGA}_{1100}} + c) & \\ +b\ln\left(\widehat{\mathrm{PGA}_{1100}} + c\left(\frac{V_{S30}^*}{V_{LIN}}\right)^n\right) & \text{for} \quad V_{S30} < V_{LIN} \\ (a_{10} + bn)\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) & \text{for} \quad V_{S30} \geq V_{LIN} \end{cases} \\
\text{where} \quad V_{S30}^* &= \begin{cases} V_{S30} & \text{for} \quad V_{S30} < V_1 \\ V_1 & \text{for} \quad V_{S30} \geq V_1 \end{cases} \\
\text{and} \quad V_1 &= \begin{cases} 1500 & \text{for} \quad T \leq 0.50\,\mathrm{s} \\ \exp[8.0 - 0.795\ln(T/0.21)] & \text{for} \quad 0.50 < T \leq 1\,\mathrm{s} \\ \exp[6.76 - 0.297\ln(T)] & \text{for} \quad 1 < T < 2\,\mathrm{s} \\ 700 & \text{for} \quad T \geq 2\,\mathrm{s} \end{cases} \\
f_4(R_{jb}, R_{rup}, \delta, Z_{TOR}, M, W) &= a_{14}T_1(R_{jb})T_2(R_x, W, \delta)T_3(R_x, Z_{TOR})T_4(M)T_5(\delta) \\
\text{where} \quad T_1(R_{jb}) &= \begin{cases} 1 - \frac{R_{jb}}{30} & \text{for} \quad R_{jb} < 30\,\mathrm{km} \\ 0 & \text{for} \quad R_{jb} \geq 30\,\mathrm{km} \end{cases} \\
T_2(R_x, W, \delta) &= \begin{cases} 0.5 + \frac{R_x}{2W\cos(\delta)} & \text{for} \quad R_x \leq W\cos(\delta) \\ 1 & \text{for} \quad R_x > W\cos(\delta) \quad \text{or} \quad \delta = 90^\circ \end{cases} \\
T_3(R_x, Z_{TOR}) &= \begin{cases} 1 & \text{for} \quad R_x \geq Z_{TOR} \\ \frac{R_x}{Z_{TOR}} & \text{for} \quad R_x < Z_{TOR} \end{cases} \\
T_4(M) &= \begin{cases} 0 & \text{for} \quad M \leq 6 \\ M - 6 & \text{for} \quad 6 < M < 7 \\ 1 & \text{for} \quad M \geq 7 \end{cases} \\
T_5(\delta) &= \begin{cases} 1 - \frac{\delta - 30}{60} & \text{for} \quad \delta \geq 30 \\ 1 & \text{for} \quad \delta < 30 \end{cases} \\
f_6(Z_{TOR}) &= \begin{cases} \frac{a_{16}Z_{TOR}}{10} & \text{for} \quad Z_{TOR} < 10\,\mathrm{km} \\ a_{16} & \text{for} \quad Z_{TOR} \geq 10\,\mathrm{km} \end{cases} \\
f_8(R_{rup}, M) &= \begin{cases} 0 & \text{for} \quad R_{rup} < 100\,\mathrm{km} \\ a_{18}(R_{rup} - 100)T_6(M) & \text{for} \quad R_{rup} \geq 100\,\mathrm{km} \end{cases} \\
\text{where} \quad T_6(M) &= \begin{cases} 1 & \text{for} \quad M < 5.5 \\ 0.5(6.5 - M) + 0.5 & \text{for} \quad 5.5 \leq M \leq 6.5 \\ 0.5 & \text{for} \quad M > 6.5 \end{cases} \\
f_{10}(Z_{1.0}, V_{S30}) &= a_{21}\ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0}(V_{S30}) + c_2}\right) + \begin{cases} a_{22}\ln\left(\frac{Z_{1.0}}{200}\right) & \text{for} \quad Z_{1.0} \geq 200 \\ 0 & \text{for} \quad Z_{1.0} < 200 \end{cases} \\
\text{where} \quad \ln[\hat{Z}_{1.0}(V_{S30})] &= \begin{cases} 6.745 & \text{for} \quad V_{S30} < 180\,\mathrm{m/s} \\ 6.745 - 1.35\ln\left(\frac{V_{S30}}{180}\right) & \text{for} \quad 180 \leq V_{S30} \leq 500\,\mathrm{m/s} \\ 5.394 - 4.48\ln\left(\frac{V_{S30}}{500}\right) & \text{for} \quad V_{S30} > 500\,\mathrm{m/s} \end{cases} \\
a_{21} &= \begin{cases} 0 & \text{for} \quad V_{S30} \geq 1000 \\ \frac{-(a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right)}{\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right)} & \text{for} \quad (a_{10} + bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right) + e_2\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right) < 0 \\ e_2 & \text{otherwise} \end{cases} \\
e_2 &= \begin{cases} 0 & \text{for} \quad T < 0.35\,\mathrm{s} \quad \text{or} \quad V_{S30} > 1000 \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{T}{0.35}\right) & \text{for} \quad 0.35 \leq T \leq 2\,\mathrm{s} \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{2}{0.35}\right) & \text{for} \quad T > 2\,\mathrm{s} \end{cases} \\
a_{22} &= \begin{cases} 0 & \text{for} \quad T < 2\,\mathrm{s} \\ 0.0625(T - 2) & \text{for} \quad T \geq 2\,\mathrm{s} \end{cases}
\end{aligned}
$$

The model for the standard deviation is:

$$
\begin{aligned}
\sigma_B(M,T) &= \sqrt{\sigma_0^2(M,T)-\sigma_{Amp}^2(T)}\\
\sigma(T,M,\widehat{\mathrm{PGA}_{1100}},V_{S30}) &= \left[\begin{array}{l}\sigma_B^2(M,T)+\sigma_{Amp}^2(T)\\ +\left(\frac{\partial\ln\mathrm{Amp}(T,\widehat{\mathrm{PGA}_{1100}},V_{S30})}{\partial\ln\mathrm{PGA}_{1100}}\right)^2\sigma_B^2(M,\mathrm{PGA})\\ +2\left(\frac{\partial\ln\mathrm{Amp}(T,\widehat{\mathrm{PGA}_{1100}},V_{S30})}{\partial\ln\mathrm{PGA}_{1100}}\right)\\ \times\sigma_B(M,T)\sigma_B(M,\mathrm{PGA})\rho_{\epsilon/\sigma}(T,\mathrm{PGA})\end{array}\right]^{1/2}\\
\frac{\partial\ln\mathrm{Amp}(T,\widehat{\mathrm{PGA}_{1100}},V_{S30})}{\partial\ln\mathrm{PGA}_{1100}} &= \begin{cases}0 \quad \text{for} \quad V_{S30}\geq V_{LIN}\\ \frac{-b(T)\widehat{\mathrm{PGA}_{1100}}}{\widehat{\mathrm{PGA}_{1100}}+c}+\frac{-b(T)\widehat{\mathrm{PGA}_{1100}}}{\widehat{\mathrm{PGA}_{1100}}+c\left(\frac{V_{S30}}{V_{LIN}}\right)^n} \quad \text{for} \quad V_{S30}<V_{LIN}\end{cases}\\
\sigma_0(M) &= \begin{cases}s_1 \quad \text{for} \quad M<5\\ s_1+\left(\frac{s_2-s_1}{2}\right)(M-5) \quad \text{for} \quad 5\leq M\leq 7\\ s_2 \quad \text{for} \quad M>7\end{cases}\\
\tau_0(M) &= \begin{cases}s_3 \quad \text{for} \quad M<5\\ s_3+\left(\frac{s_4-s_3}{2}\right)(M-5) \quad \text{for} \quad 5\leq M\leq 7\\ s_4 \quad \text{for} \quad M>7\end{cases}
\end{aligned}
$$

where Sa is in g, $\hat{\mathrm{PGA}}_{1100}$ is median peak acceleration for $V_{S30}=1100\,\mathrm{m/s}$, $\sigma_B$ and $\tau_B$ $(=\tau_0(M,T))$ are intra-event and inter-event standard deviations, $\sigma_0$ and $\tau_0$ are intra-event and inter-event standard deviations of the observed ground motions for low levels of outcrop rock motions (directly from regression), $\sigma_{amp}$ is intra-event variability of the site amplification factors (assumed equal to 0.3 for all periods based on 1D site response results), $c_1=6.75$, $c_4=4.5$, $a_3=0.265$, $a_4=-0.231$, $a_5=-0.398$, $N=1.18$, $c=1.88$, $c_2=50$, $V_{LIN}=865.1$, $b=-1.186$, $a_1=0.804$, $a_2=-0.9679$, $a_8=-0.0372$ ,$a_{10}=0.9445$, $a_{12}=0.0000$, $a_{13}=-0.0600$, $a_{14}=1.0800$, $a_{15}=-0.3500$, $a_{16}=0.9000$, $a_{18}=-0.0067$, $s_1=0.590$ and $s_2=0.470$ for $V_{S30}$ estimated, $s_1=0.576$ and $s_2=0.453$ for $V_{S30}$ measured, $s_3=0.470$, $s_4=0.300$ and $\rho(T,\mathrm{PGA})=1.000$.

- Characterise sites using $V_{S30}$ and depth to engineering rock ($V_s=1000\,\mathrm{m/s}$), $Z_{1.0}$. Prefer $V_{s,30}$ to generic soil/rock categories because it is consistent with site classification in current building codes. Note that this does not imply that 30 m is key depth range for site response but rather that $V_{s,30}$ is correlated with entire soil profile.

- Classify events in three fault mechanism categories:

Reverse(-oblique) $F_{RV}=1$, $F_{NM}=0$. Earthquakes defined by rake angles between 30 and 150°.

Normal $F_{RV}=0$, $F_{NM}=1$. Earthquakes defined by rake angles between −60 and −120°.

Strike-slip $F_{RV}=0$, $F_{NM}=0$. All other earthquakes.

- Believe that model applicable for $5\leq M_w\leq 8.5$ (strike-slip) and $5\leq M_w\leq 8.0$ (dip-slip) and $0\leq d_r\leq$ 200 km.

- Use simulations for hard-rock from 1D finite-fault kinematic source models for $6.5\leq M_w\leq 8.25$, 3D basin response simulations for sites in southern California and equivalent-linear site response simulations to constrain extrapolations beyond the limits of the empirical data.

- Select data from the Next Generation Attenuation (NGA) database (flat-file version 7.2). Include data from all earthquakes, including aftershocks, from shallow crustal earthquakes in active tectonic regions under assumption that median ground motions from shallow crustal earthquakes at $d_r<100\,\mathrm{km}$ are similar. This assumes that median stress-drops are similar between shallow crustal events in: California, Alaska, Taiwan, Japan, Turkey, Italy, Greece, New Zealand and NW China. Test assumption by comparing inter-event residuals from different regions to those from events in California. Since aim is for model for

California and since difference in crustal structure and attenuation can affect ground motions at long distances exclude data from $d_r > 100$ km from outside western USA.

- Also exclude these data: events not representative of shallow crustal tectonics, events missing key source metadata, records not representative of free-field motion, records without a $V_{s,30}$ estimate, duplicate records from co-located stations, records with missing horizontal components or poor quality accelerograms and records from western USA from $d_r > 200$ km.

- Classify earthquakes by event class: AS (aftershock) ($F_{AS} = 1$); MS (mainshock), FS (foreshock) and swarm ($F_{AS} = 0$). Note that classifications not all unambiguous.

- Use depth-to-top of rupture, $Z_{TOR}$, fault dip in degrees, $\delta$ and down-dip rupture width, $W$.

- Use $r_{jb}$ and $R_x$ (horizontal distance from top edge of rupture measured perpendicular to fault strike) to model hanging wall effects. For hanging wall sites, defined by vertical projection of the top of the rupture, $F_{HW} = 1$. $T_1$, $T_2$ and $T_3$ constrained by 1D rock simulations and the Chi-Chi data. $T_4$ and $T_5$ constrained by well-recorded hanging wall events. Only $a_{14}$ was estimated by regression. State that hanging-wall scaling is one of the more poorly-constrained parts of model[22].

- Records well distributed w.r.t. $M_w$ and $r_{rup}$.

- For four Chi-Chi events show steep distance decay than other earthquakes so include a separate coefficient for the $\ln(R)$ term for these events so they do not have a large impact on the distance scaling. Retain these events since important for constraining other aspects of the model, e.g. site response and intra-event variability.

- Only used records from $5 \leq M \leq 6$ to derive depth-to-top of rupture ($Z_{TOR}$) dependence to limit the effect on the relation of the positive correlation between $Z_{TOR}$ and $M$.

- Constrain (outside the main regression) the large distance ($R_{rup} > 100$ km) attenuation for small and moderate earthquakes ($4 \leq M \leq 5$) using broadband records of 3 small ($M4$) Californian earthquakes because limited data for this magnitude-distance range in NGA data set.

- Note difficult in developing model for distinguishing between shallow and deep soil sites due to significant inconsistencies between $V_{S30}$ and depth of soil ($Z_{1.0}$), which believe to be unreliable in NGA Flat-File. Therefore, develop soil-depth dependence based on 1D (for $Z_{1.0} < 200$ m) and 3D (for $Z_{1.0} > 200$ m) site response simulations. Motion for shallow soil sites do not fall below motion for $V_{S30} = 1000$ m/s.

- $T_D$ denotes period at which rock ($V_{S30} = 1100$ m/s) spectrum reaches constant displacement. Using point-source stochastic model and 1D rock simulations evaluate magnitude dependence of $T_D$ as $\log_{10}(T_D) = -1.25 + 0.3M$. For $T > T_D$ compute rock spectral acceleration at $T_D$ and then scale this acceleration at $T_D$ by $(T_D/T)^2$ for constant spectral displacements. The site response and soil depth scaling is applied to this rock spectral acceleration, i.e. $\mathrm{Sa}(T_D, V_{S30} = 1100)\frac{T_D^2}{T^2} + f_5(\mathrm{PG\hat{A}}_{1100}, V_{S30}, T) + f_{10}(Z_{1.0}, V_{S30}, T)$.

- Reduce standard deviations to account for contribution of uncertainty in independent parameters $M$, $R_{rup}$, $Z_{TOR}$ and $V_{S30}$.

- Note that regression method used prevents well-recorded earthquakes from dominating regression.

- Examine inter-event residuals and find that there is no systemic trend in residuals for different regions. Find that residuals for $M > 7.5$ are biased to negative values because of full-saturation constraint. Examine intra-event residuals and find no significant trend in residuals.

[22]Model for $T_5$ reported here is that given in 2009 errata. In original reference: $T_5 = 1 - (\delta - 70)/20$ for $\delta \geq 70$ and 1 otherwise).

- Although derive hanging-wall factor only from reverse-faulting data suggest that it is applied to normal-faulting events as well.

- State that should use median $\mathrm{PGA}_{1100}$ for nonlinear site amplification even if conducting a seismic hazard analysis for above median ground motions.

- State that if using standard deviations for estimated $V_{S30}$ and $V_{S30}$ is accurate to within 30% do not need to use a range of $V_{S30}$ but if using measured-$V_{S30}$ standard deviations then uncertainty in measurement of $V_{S30}$ should be estimated by using a range of $V_{S30}$ values.

- State that if do not know $Z_{1.0}$ then use median $Z_{1.0}$ estimated from equations given and do not adjust standard deviation.

## 2.290 Ágústsson et al. (2008)

- Ground-motion models are:

$$\log_{10}(\text{acceleration}) = a\log_{10}(R) + b\log_{10}(M) + c$$

where acceleration is in $\mathrm{m/s^2}$, $a = -1.95600$, $b = 9.59878$, $c = -4.87778$ and $\sigma = 0.4591$, and:

$$\log_{10}(\text{acceleration}) = a\log_{10}(R) + bM + c$$

where $a = -1.96297$, $b = 0.89343$, $c = -2.65660$ and $\sigma = 0.4596$.

- Select data from SIL database with $M_{Lw} > 3.5$ in latitude range 63.5 to 64.3°N and longitude range 18 to 23.5°W between July 1992 and April 2007.

- Exclude data where several earthquakes are superimposed and retain only ‘clean’ waveforms.

- Most data from 5 Hz Lennarz seismometers. Some from 1 Hz and long-period instruments. Sampling frequency is 100 Hz.

- Use data from SW Iceland plus data from Reykjanes Ridge and Myrdalsjokull volcano.

- Investigate decay in several individual earthquakes and fit equations of form $\log y = a\log R + b$. Note that relations are well behaved so fit entire dataset.

## 2.291 Aghabarati and Tehranizadeh (2008)

- Ground-motion model is:

$$
\begin{aligned}
\ln y &= c_1 + f_1(M_w) + f_2(M_w) f_3(R) + f_4(F) + \mathrm{FR} f_5(Z_{FR}) + \\
&\quad \mathrm{FS} f_6(Z_{FR}) + f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) + \\
&\quad f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) + f_9(V_{s,30}, Z_{1.5}) \\
\text{where for} \quad M_w \leq c_0 & \\
f_1(M_w) &= c_3(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_4(M_w - c_0) \\
\text{and for} \quad M_w > c_0 & \\
f_1(M_w) &= c_5(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_6(M_w - c_0) \\
f_3(R) &= \ln \sqrt{R_{rup}^2 + c_7(T)^2} \\
f_4(F) &= c_9(T)\mathrm{FR} + c_{10}(T)\mathrm{FS} + c_{11}(T)\mathrm{FN} \\
f_5(Z_{\mathrm{FR}}) &= \begin{cases} 0 & Z_{top} \leq 2\,\mathrm{km} \\ c_{12}(T)(Z_{top} - 2)/3 & 2 < Z_{top} \leq 5\,\mathrm{km} \\ c_{12}(T) & 5 < Z_{top} \leq 10\,\mathrm{km} \\ c_{12}(T)[1 - (Z_{top} - 10)/5] & 5 < Z_{top} \leq 10\,\mathrm{km}(sic) \\ 0 & Z_{top} > 10\,\mathrm{km} \end{cases} \\
f_6(Z_{\mathrm{FS}}) &= \begin{cases} c_{13}(T) Z_{top}/2 & 0 < Z_{top} \leq 2\,\mathrm{km} \\ c_{13}(T) & 2 < Z_{top} \leq 4\,\mathrm{km} \\ c_{13}(T)[1 - (Z_{top} - 4)/2] & 4 < Z_{top} \leq 6\,\mathrm{km} \\ 0 & Z_{top} > 6\,\mathrm{km} \end{cases} \\
g_1(R_{JB}) &= \begin{cases} 1 - R_{JB}/45 & 0 \leq R_{JB} < 15\,\mathrm{km} \\ \frac{2}{3}(2 - R_{JB}/15) & 15 \leq R_{JB} < 30\,\mathrm{km} \\ 0 & R_{JB} \geq 30\,\mathrm{km} \end{cases} \\
g_2(M_w) &= \begin{cases} 0 & M_w < 6.0 \\ 2(M_w - 6) & 6.0 \leq M_w < 6.5 \\ 1 & M_w \geq 6.5 \end{cases} \\
g_3(\mathrm{DIP}) &= \begin{cases} 1 - (\mathrm{DIP} - 70)/20 & \mathrm{DIP} \geq 70 \\ 1 & \mathrm{DIP} < 70 \end{cases} \\
f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) &= c_{14}(T)\mathrm{HW} g_1(R_{JB}) g_2(M_w) g_3(\mathrm{DIP}) \\
f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= g_4(V_{s,30}, V_{lin}) + g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) \\
g_4(V_{s,30}, V_{lin}) &= c_{15}(T)\ln(V_{s,30}/V_{lin}) \\
g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= \begin{cases} c_{16}(T)\ln(\mathrm{PGA}_{min}/0.1) & \mathrm{PGA}_{non-lin} < a_1 \\ c_{16}(T)[\ln(\mathrm{PGA}_{min}/0.1) & \\ +a\ln(\mathrm{PGA}_{non-lin}/a_1) & \\ +b(\ln(\mathrm{PGA}_{non-lin}/a_1))^2] & a_1 \leq \mathrm{PGA}_{non-lin} \leq a_2 \\ c_{16}(T)\ln(\mathrm{PGA}_{non-lin}/0.1) & \mathrm{PGA}_{non-lin} \geq a_2 \end{cases} \\
f_9(V_{s,30}, Z_{1.5}) &= g_6(V_{s,30}, Z_{1.5}, \hat{Z}) + g_7(Z_D, Z_{1.5}) \\
g_6(V_{s,30}, Z_{1.5}, \hat{Z}) &= c_{17}(T)(1/\hat{Z})\ln(V_{s,30}/1500)\ln(Z_{1.5}) \\
g_7(Z_{1.5}, Z_D) &= Z_D c_{18}(T) K_1(1 - \exp(-(Z_{1.5} - 200)/300)) + \\
&\quad Z_D c_{19}(T) K_2(1 - \exp(-(Z_{1.5} - 200)/4000))
\end{aligned}
$$

where $y$ is in g, $c_1 = 1.81$, $c_2 = -1.18$, $c_7 = 8.647$, $c_8 = -0.028$, $c_9 = -0.176$, $c_{10} = -0.266$, $c_{11} = -0.476$, $c_{12} = 0.52$, $c_{13} = -0.32$, $c_{14} = 0.4$, $c_{15} = -0.36$, $c_{17} = 0$, $c_{18} = 0$, $c_{19} = 0$, $c_{20} = 0.496$, $c_{21} = 0.427$, $K_1 = 2.260$, $K_2 = 1.04$, $V_{lin} = 760$, $\sigma = c_{20}(T) + [c_{21}(T) - c_{20}(T)]M_w$ for $5.0 \leq M_w < 7.0$ and $\sigma = c_{21}(T)$ for $M_w \geq 7.0$.

- Use $V_{s,30}$ to characterize site conditions.
- Characterize basin by depth to $V_s = 1500$ m/s, $Z_{1.5}$, since more likely to be obtained for engineering projects.
- Use three mechanism classes:
  1. Normal. 34 records. FN = 1, FS = FR = 0.
  2. Strike-slip. 184 records. FS = 1, FN = FR = 0.
  3. Reverse. Originally classify as thrust, reverse and reverse oblique but combine. 423 records. FR = 1, FN = FS = 0.

  Note lack of records from normal earthquakes.
- Use data from earthquakes with focal depths $\leq 15$ km.
- Only use data from instrument shelters, non-embedded buildings with $< 3$ stories ($< 7$ if located on firm rock) and dam abutments (to enhance database even though could be some interaction with dam).
- Not sufficient data to investigate effect of tectonic environment. Exclude data from subduction zones because that is different tectonic regime than for shallow crustal earthquakes.
- Data well distributed in magnitude-distance space so do not use special statistical procedures to decouple source and path effects. Do not use weights due to uniform distribution w.r.t. $M_w$ and distance.
- Exclude data from $> 60$ km to avoid records with multiple reflections from lower crust.
- Vast majority of data from western USA. Some from Alaska, Canada, Greece, Iran, Italy, Japan, Mexico, New Zealand and Turkey.
- Constrain $c_7(T)$ to be monotonically varying with period because otherwise can have large changes in spectral shape at very short distances.
- Note that for $M_w < 5.8$ magnitude dependence may be due to depth-to-top ($Z_{\mathrm{FR}}$ and $Z_{\mathrm{FS}}$) effects since small earthquakes have on average larger depth-to-top than larger earthquakes. Inter-event residuals from preliminary regression are functions of rake and depth-to-top (stronger than rake dependency) particularly for reverse earthquakes. These observations influence functional form of $f_5(Z)$.
- Use residuals from 1D simulations to define functional form for hanging wall effect (HW = 1).
- Coefficients for nonlinear soil effects determined from analytical results because of correlations between other parameters and nonlinearity and since analytical results better constrained at high amplitudes than empirical data. Set $a_1 = 0.04$ g, $a_2 = 0.1$ g and $\mathrm{PGA}_{min} = 0.06$ g. $\mathrm{PGA}_{non-lin}$ is expected PGA on rock ($V_{s,30} = 760$ m/s). $c_{15}(T)$, $c_{16}(T)$ and $V_{lin}$ taken from Choi and Stewart (2005) and are not determined in regression.
- Applied limited smoothing (using piecewise continuous linear fits on log period axis) to avoid variability in predicted spectral ordinates for neighbouring periods particularly at large magnitudes and short distances.
- Examine normalized inter- and intra-event residuals w.r.t. $M_w$ and distance (shown). Find no bias nor trends. Also plot against mechanism, site and other parameters and find no bias nor trends (not shown).

## 2.292 Al-Qaryouti (2008)

- Ground-motion model is:

$$\log(y) = c_1 + c_2 M + c_3 \log(R) + c_4 R$$

where $y$ is in g[23], $c_1 = -3.45092$, $c_2 = 0.49802$, $c_3 = -0.38004$, $c_4 = -0.00253$ and $\sigma = 0.313$.

- Uses data from strong-motion networks in Israel and Jordan.
- Records from analogue, PDR-1, SSA-2 and Etna instruments.
- 21 earthquakes were recorded by only one station.

## 2.293 Cauzzi and Faccioli (2008), Cauzzi (2008) & Cauzzi et al. (2008)

- Ground-motion model is:

$$\log_{10} y = a_1 + a_2 M_w + a_3 \log_{10} R + a_B S_B + a_C S_C + a_D S_D$$

where $y$ is in m/s$^2$, $a_1 = -1.296$, $a_2 = 0.556$, $a_3 = -1.582$, $a_B = 0.22$, $a_C = 0.304$, $a_D = 0.332$ and $\sigma = 0.344$ for horizontal PGA.

- Use four site categories based on Eurocode 8:

  A Rock-like. $V_{s,30} \geq 800$ m/s. $S_B = S_C = S_D = 0$.

  B Stiff ground. $360 \leq V_{s,30} < 800$ m/s. $S_B = 1$, $S_C = S_D = 0$.

  C $180 \leq V_{s,30} < 360$ m/s. $S_C = 1$, $S_B = S_D = 0$.

  D Very soft ground. $V_{s,30} < 180$ m/s. $S_D = 1$, $S_B = S_C = 0$.

  Try to retain only records from stations of known site class but keep records from stations of unknown class (4% of total), which assume are either B or C classes. Use various techniques to extend 20 m profiles of K-Net down to 30 m. Vast majority of data with $V_{s,30} \leq 500$ m/s.

- Use mechanism classification scheme of Boore and Atkinson (2007) based on plunges of P-, T- and B-axes:

Normal 16 earthquakes. $5 \leq M_w \leq 6.9$.

Strike-slip 32 earthquakes. $5 \leq M_w \leq 7.2$.

Reverse 12 earthquakes. $5.3 \leq M_w \leq 6.6$.

- Develop for use in displacement-based design.
- Select records with minimal long-period noise so that the displacement ordinates are reliable. Restrict selection to digital records because their displacement spectra are not significantly affected by correction procedure and for which reliable spectral ordinates up to at least 10 s are obtainable. Include 9 analogue records from 1980 Irpinia ($M_w$6.9) earthquake after careful scrutiny of long-period characteristics.
- Use approach of Paolucci et al. (2008) to estimate cut-off frequencies for bandpass filtering. Compute noise index $I_V$ for each record based on PGV and average value computed from coda of velocity time-history. Compare $I_V$ with curves representing as a function of $M_w$ the probability $P$ that the long-period errors in the displacement spectrum are less than a chosen threshold. Use probability $P \geq 0.9$ and drifts in displacement spectrum $< 15\%$ using $I_V$ from geometric mean. Rejections closely correlated with instrument type (less data from high-bit instruments rejected than from low-bit instruments). Process

[23]Not cm/s$^2$ as specified at some points in the article.

records by removing pre-even offset from entire time-history. Following this 57% of records satisfied criterion of Paolucci et al. (2008). Remaining records filtered using fourth-order acausal filter with cut-off 0.05 Hz after zero padding and cosine tapering. After this step records pass criterion of Paolucci et al. (2008). Note that filtering of 43% of records may affect reliability beyond 15 s.

- Use data from K-Net and Kik-Net (Japan) (84%); California (5%); Italy, Iceland and Turkey (5%); and Iran (6%). Try to uniformly cover magnitude-distance range of interest. All data from $M > 6.8$ are from events outside Japan.
- Exclude data from $M_w < 5$ because probabilistic seismic hazard deaggregation analyses show contribution to spectral displacement hazard from small events is very low.
- Exclude data from $M_w > 7.2$ because 7.2 is representative of the largest estimated magnitude in historical catalogue of Italy. Most records from $M_w \leq 6.6$.
- Exclude data from subduction zone events.
- Focal depths between 2 and 22 km. Exclude earthquakes with focal depth > 22 km to be in agreement with focal depths of most Italian earthquakes.
- Use $r_{hypo}$ for greater flexibility in seismic hazard analyses where source zones have variable depth. Exclude data from $r_{hypo} > 150$ km based on deaggregation results.
- Test regional dependence of ground motions using analysis of variance. Divide dataset into intervals of $10\,\text{km} \times 0.3 M_w$ units and consider only bins with $\geq 3$ records. Apply analysis for 18 bins on logarithmically transformed ground motions. Transform observed motions to site class A by dividing by site amplification factor derived by regression. Find no strong evidence for regional dependence.
- Apply pure error analysis to test: i) standard logarithmic transformation, ii) magnitude-dependence of scatter and iii) lower bound on standard deviation using only $M$ and $r_{hypo}$. Divide dataset into bins of $2\,\text{km} \times 0.2 M_w$ units and consider only bins with $\geq 2$ records (314 in total). Compute mean and standard deviation of untransformed ground motion and calculate coefficient of variation (COV). Fit linear equation to plots of COV against mean. Find no significant trend for almost all periods so conclude logarithmic transformation is justified for all periods. Compute standard deviation of logarithmically-transformed ground motions and fit linear equations w.r.t. $M_w$. Find that dependence of scatter on magnitude is not significant. Compute mean standard deviation of all bins and find limit on lowest possible standard deviation using only $M_w$ and $r_{hypo}$.
- Aim for simplest functional form and add complexity in steps, checking the statistical significance of each modification and its influence on standard error. Try including an anelastic term, quadratic $M_w$ dependence and magnitude-dependent decay term but find none of these is statistically significant and/or leads to a reduction in standard deviation.
- Try one-stage maximum likelihood regression but find higher standard deviation so reject it. Originally use two-stage approach of Joyner and Boore (1981).
- Find that coefficients closely match a theoretical model at long periods.
- Consider style-of-faulting by adding terms: $a_N E_N + a_R E_R + a_S E_S$ where $E_x$ are dummy variables for normal, reverse and strike-slip mechanisms. Find that reduction in standard deviation is only appreciable for limited period ranges but keep terms in final model.
- Replace terms: $a_B S_B + a_C S_C + a_D S_D$ by $b_V \log_{10}(V_{s,30}/V_a)$ so that site amplification factor is continuous. $V_{s,30}$ available for about 85% of records. To be consistent between both approaches constrain $V_a$ to equal 800 m/s. Find $b_V$ closely matches theoretical values 1 close to resonance period and 0.5 at long periods.

- Examine residuals w.r.t. $r_{hypo}$ and $M_w$. Find no trends.

## 2.294 Chen (2008)

- Ground-motion model is:

$$\log_{10} Y = a + bM + c \log_{10} \sqrt{R^2 + h^2} + eS$$

where $Y$ is in cm/s$^2$; when using $r_{epi}$: $a = 1.0028$, $b = 0.3330$, $c = -0.8842$, $h = 2.4$, $e = 0.1717$ and $\sigma = 0.3574$ (for larger), $a = 0.8947$, $b = 0.3410$, $c = -0.8834$, $h = 2.6$, $e = 0.1725$ and $\sigma = 0.3428$ (for geometric mean) and $a = 0.9050$, $b = 0.3485$, $c = -1.0803$, $h = 3.2$, $e = 0.1596$ and $\sigma = 0.3240$ (for vertical); and when using $r_{hypo}$ ($h$ is constrained to zero): $a = 1.1317$, $b = 0.3282$, $c = -0.9297$, $e = 0.1860$ and $\sigma = 0.3680$ (for larger), $a = 1.0335$, $b = 0.3365$, $c = -0.9352$, $e = 0.1865$ and $\sigma = 0.3527$ (for geometric mean) and $a = 1.0706$, $b = 0.3430$, $c = -1.1418$, $e = 0.1767$ and $\sigma = 0.3392$ (for vertical).

- Uses 2 site classes:

Rock Granite, diorite, gneiss, sandstone, limestone or siltstone. Roughly $V_s > 360$ m/s. 82 records. $S = 0$.

Soil Alluvium, sand, gravel, clay, sandy clay, silt, sandy silt or fill. 167 records. $S = 1$.

Cannot use more complex approach because of insufficient information for Chinese sites.

- Selects 129 from China (mainly SMA-1A and GDQJ-1A instruments) and Taiwan and, because there are insufficient to develop model, adds 120 records from Japan.

- Data from China corrected using unknown technique. Data from Japan uncorrected.

- Plot residuals w.r.t. $r$ and $M$ and find no significant trends.

## 2.295 Chiou and Youngs (2008)

- Ground-motion model is:

$$
\begin{aligned}
\ln(y) &= \ln(y_{ref}) + \phi_1 \min\left[\ln\left(\frac{V_{S30}}{1130}\right), 0\right] \\
&\quad + \phi_2\{e^{\phi_3[\min(V_{S30},1130)-360]} - e^{\phi_3(1130-360)}\} \ln\left(\frac{y_{ref}e^{\eta} + \phi_4}{\phi_4}\right) \\
&\quad + \phi_5\left\{1 - \frac{1}{\cosh[\phi_6 \max(0, Z_{1.0} - \phi_7)]}\right\} \\
&\quad + \frac{\phi_8}{\cosh[0.15 \max(0, Z_{1.0} - 15)]} \\
\ln(y_{ref}) &= c_1 + [c_{1a}F_{RV} + c_{1b}F_{NM} + c_7(Z_{TOR} - 4)](1 - \mathrm{AS}) \\
&\quad + [c_{10} + c_{7a}(Z_{TOR} - 4)]\mathrm{AS} + c_2(M - 6) + \frac{c_2 - c_3}{c_n} \ln[1 + e^{c_n(c_M - M)}] \\
&\quad + c_4 \ln\{R_{RUP} + c_5 \cosh[c_6 \max(M - c_{HM}, 0)]\} \\
&\quad + (c_{4a} - c_4)\ln(\sqrt{R_{RUP}^2 + c_{RB}^2}) \\
&\quad + \left\{c_{\gamma 1} + \frac{1}{\cosh[\max(M - c_{\gamma 3}, 0)]}\right\} R_{RUP} \\
&\quad + c_9 F_{HW} \tanh\left(\frac{R_X \cos^2\delta}{c_{9a}}\right)\left(1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 0.001}\right) \\
\tau &= \tau_1 + \frac{\tau_2 - \tau_1}{2} \times [\min\{\max(M, 5), 7\} - 5] \\
\sigma &= \left\{\sigma_1 + \frac{\sigma_2 - \sigma_1}{2}[\min(\max(M, 5), 7) - 5] + \sigma_4 \times \mathrm{AS}\right\} \\
&\quad \times \sqrt{(\sigma_3 F_{Inferred} + 0.7F_{Measured}) + (1 + \mathrm{NL})^2} \\
\text{where} \quad \mathrm{NL} &= \left(b\frac{y_{ref}e^{\eta}}{y_{ref}e^{\eta} + c}\right) \\
\sigma_T^2 &= (1 + \mathrm{NL}_0)^2\tau^2 + \sigma_{\mathrm{NL}_0}^2
\end{aligned}
$$

where $y$ is in g, $c_2 = 1.06$, $c_3 = 3.45$, $c_4 = -2.1$, $c_{4a} = -0.5$, $c_{RB} = 50$, $c_{HM} = 3$, $c_{\gamma 3} = 4$, $c_1 = -1.2687$, $c_{1a} = 0.1$, $c_{1b} = -0.2550$, $c_n = 2.996$, $c_M = 4.1840$, $c_5 = 6.1600$, $c_6 = 0.4893$, $c_7 = 0.0512$, $c_{7a} = 0.0860$, $c_9 = 0.7900$, $c_{9a} = 1.5005$, $c_{10} = -0.3218$, $c_{\gamma 1} = -0.00804$, $c_{\gamma 2} = -0.00785$, $\phi_1 = -0.4417$, $\phi_2 = -0.1417$, $\phi_3 = -0.007010$, $\phi_4 = 0.102151$, $\phi_5 = 0.2289$, $\phi_6 = 0.014996$, $\phi_7 = 580.0$, $\phi_8 = 0.0700$, $\tau_1 = 0.3437$, $\tau_2 = 0.2637$, $\sigma_1 = 0.4458$, $\sigma_2 = 0.3459$, $\sigma_3 = 0.8$ and $\sigma_4 = 0.0663$ ($\eta$ is the inter-event residual). $\sigma_T$ is the total variance for $\ln(y)$ and is approximate based on the Taylor series expansion of the sum of the inter-event and intra-event variances. $\sigma_{\mathrm{NL}_0}$ is the equation for $\sigma$ evaluated for $\eta = 0$. Check approximate using Monte Carlo simulation and find good (within a few percent) match to exact answer.

- Characterise sites using $V_{S30}$. $F_{Inferred} = 1$ if $V_{S30}$ inferred from geology and 0 otherwise. $F_{Measured} = 1$ if $V_{S30}$ is measured and 0 otherwise. Believe model applicable for $150 \leq V_{S30} \leq 1500$ m/s.

- Use depth to shear-wave velocity of 1.0 km/s, $Z_{1.0}$, to model effect of near-surface sediments since 1 km/s similar to values commonly used in practice for rock, is close to reference $V_{S30}$ and depth to this velocity more likely to be available. For stations without $Z_{1.0}$ use this empirical relationship: $\ln(Z_{1.0}) = 28.5 - \frac{3.82}{8}\ln(V_{S30}^8 + 378.7^8)$.

- Use PEER Next Generation Attenuation (NGA) database supplemented by data from TriNet system to provide additional guidance on functional forms and constraints on coefficients.

- Consider model to be update of Sadigh et al. (1997).

- Focal depths less than 20 km and $Z_{TOR} \leq 15$ km. Therefore note that application to regions with very thick crusts (e.g. $\gg 20$ km) is extrapolation outside range of data used to develop model.

- Develop model to represent free-field motions from shallow crustal earthquakes in active tectonic regions, principally California.

- Exclude data from earthquakes that occurred in oceanic crust offshore of California or Taiwan because these data have been found to be more consistent with ground motions from subduction zones. Include data from 1992 Cape Mendocino earthquakes because source depth places event above likely interface location. Exclude data from four 1997 NW China earthquakes because of large depths ($\geq 20$ km) and the very limited information available on these data. Exclude data from the 1979 St Elias earthquake because believe it occurred on subduction zone interface. Include data from the 1985 Nahanni and 1992 Roermond because believe that they occurred on boundary of stable continental and active tectonic regions.

- Assume that ground motions from different regions are similar and examine this hypothesis during development.

- Include data from aftershocks, because they provide additional information on site model coefficients, allowing for systematic differences in ground motions with mainshock motions. AS = 1 if event aftershock and 0 otherwise.

- Exclude data from large buildings and at depth, which removes many old records. Include sites with known topographic effects since the effect of topography has not been systematically studied for all sites so many other stations may be affected by such effects. Topographic effects are considered to be part of variability of ground motions.

- Exclude records with only a single horizontal component.

- Exclude records from more than 70 km (selected by visual inspection) to remove effects of bias in sample.

- To complete missing information in the NGA database estimate strike, dip ($\delta$) and rake ($\lambda$) and/or depth to top of rupture, $Z_{TOR}$, from other associated events (e.g. mainshock or other aftershock) or from tectonic environment. For events unassociated to other earthquake $\delta$ assigned based on known or inferred mechanisms: 90° for strike-slip, 40° for reverse and 55° for normal. For events without known fault geometries $R_{RUP}$ and $R_{JB}$ estimated based on simulations of earthquake ruptures based on focal mechanisms, depths and epicentral locations.

- Use $M_w$ since simplest measure for correlating the amount of energy released in earthquake with ground motions. Develop functional form and constrain some coefficients for magnitude dependence based on theoretical arguments on source spectra and some previous analyses. Note that data are not sufficient to distinguish between various forms of magnitude-scaling.

- Exploratory analysis indicates that reverse faulting earthquakes produce larger high-frequency motions than strike-slip events. It also shows that style-of-faulting effect is statistically significant (p-values slightly less than 0.05) only when normal faulting was restricted to $\lambda$ in range $-120$ to 60° with normal-oblique in strike-slip class. Find style-of-faulting effect weaker for aftershocks than main shocks hence effect not included for aftershocks.

- Preliminary analysis indicates statistically-significant dependence on depth to top of rupture, $Z_{TOR}$ and that effect stronger for aftershocks therefore model different depth dependence for aftershocks and main shocks. Find that aftershocks produce lower motions than main shocks hence include this in model.

- Examine various functional forms for distance-scaling and find all provide reasonable fits to data since to discriminate between them would require more data at distances $< 10$ km. Find that data shows magnitude-dependence in rate of attenuation at all distances but that at short distances due to effect of extended sources and large distances due to interaction of path $Q$ with differences in source Fourier spectra as a function of magnitude. Choose functional form to allow for separation of effect of magnitude at small and large distances.

- Examine distance-scaling at large distances using 666 records from 3 small S. Californian earthquakes (2001 Anza, $M4.92$; 2002 Yorba Linda, $M4.27$; 2003 Big Bear City, $M4.92$) by fitting ground motions to three functional forms. Find that two-slope models fit slightly better than a one-slope model with break point between 40 and 60 km. Other data and simulations also show this behaviour. Prefer a smooth transition over broad distance range between two decay rates since transition point may vary from earthquake to earthquake. Constrain some coefficients based on previous studies.

- Initially find that anelastic attenuation coefficient, $\gamma$, is 50% larger for Taiwan than other areas. Believe this (and other similar effects) due to missing data due to truncation at lower amplitudes. Experiments with extended datasets for 21 events confirm this. Conclude that regression analyses using NGA data will tend to underestimate anelastic attenuation rate at large distances and that problem cannot be solved by truncated regression. Develop model for $\gamma$ based on extended data sets for 13 Californian events.

- To model hanging-wall effect, use $R_X$, site coordinate (in km) measured perpendicular to the fault strike from the surface projection of the updip edge of the fault rupture with the downdip direction being positive and $F_{HW}$ ($F_{HW} = 1$ for $R_X \geq 0$ and 0 for $R_X < 0$. Functional form developed based on simulations and empirical data.

- Choose reference site $V_{S30}$ to be 1130 m/s because expected that no significant nonlinear site response at that velocity and very few records with $V_{S30} > 1100$ m/s in NGA database. Functional form adopted for nonlinear site response able to present previous models from empirical and simulation studies.

- Develop functional form for $Z_{1.0}$-dependence based on preliminary analyses and residual plots.

- Model variability using random variables $\eta_i$ (inter-event) and $\epsilon_{ij}$ (intra-event). Assume inter-event residuals independent and normally distributed with variance $\tau^2$. Assume intra-event error components independent and normally distributed with variances $\sigma_P^2$ (path), $\sigma_S^2$ (site) and $\sigma_X^2$ (remaining). Assume total intra-event variance to be normally distributed with variance $\sigma^2$. Show that $\sigma^2$ is function of soil nonlinearity. Note that complete model difficult to use in regression analysis due to lack of repeatedly sampled paths and limited repeatedly sampled sites and unavailability of inference method capable of handling complicated data structure introduced by path error being included as predictor of soil amplification. Therefore apply simplification to solve problem.

- Find inter-event residuals do not exhibit trend w.r.t. magnitude. Residuals for Californian and non-Californian earthquakes do not show any trends so both sets of earthquakes consistent with model. Note that inter-event term for Chi-Chi approximately $2\tau$ below population mean.

- Find intra-event residuals do not exhibit trends w.r.t. $M$, $R_{RUP}$, $V_{S30}$ or $y_{ref}$. Note that very limited data suggests slight upward trend in residuals for $V_{S30} > 1130$ m/s, which relate to lower kappa attenuation for such sites.

- Preliminary analyses based on visual inspection of residuals suggested that standard errors did not depend on $M$ but statistical analysis indicated that significant (p-values $< 0.05$) magnitude dependence is present [using test of Youngs et al. (1995)]. Find that magnitude dependence remains even when accounting for differences in variance for aftershocks and main shocks and for nonlinear site amplification.

- Note that in regions where earthquakes at distances $> 50$ km are major contribution to hazard adjustments to $c_{\gamma 1}$ and $c_{\gamma 2}$ may be warranted.

## 2.296 Cotton et al. (2008)

- Ground-motion model is:

$$\log[\mathrm{PSA}(f)] = a(f) + b(f)M_w + c(f)M^2 + d(f)R - \log_{10}[R + e(f) \times 10^{0.42M_w}] + S_i(f)$$

  where PSA($f$) is in m/s$^2$, $a = -5.08210$, $b = 2.06210$, $c = -0.11966$, $d = -0.00319$, $e = 0.00488$, $S = -0.01145$ and $\sigma = 0.32257$ for borehole stations ($S$ applies for stations at 200 m) and $a = -4.884$, $b = 2.18080$, $c = -0.12964$, $d = -0.00397$, $e = 0.01226$, $S_B = 0.16101$, $S_C = 0.27345$, $S_D = 0.45195$ and $\sigma = 0.35325$ for surface stations.

  Experiments on magnitude dependency of decay and $\sigma$ reported below conducted using:

$$\log_{10}[\mathrm{SA}_{i,j}(f)] = a(f)M_i + b(f)R_{\mathrm{rup},j} - \log_{10}(R_{\mathrm{rup},j}) + S(f)$$

  Do not report coefficients of these models.

- Use four site classes (based on Eurocode 8) for surface stations:

Class A $V_{s,30} > 800$ m/s.

Class B $360 < V_{s,30} < 800$ m/s. Use coefficient $S_B$.

Class C $180 < V_{s,30} < 360$ m/s. Use coefficient $S_C$.

Class D $V_{s,30} < 180$ m/s. Use coefficient $S_D$.

- Use data from boreholes to reduce influence of nonlinear site effects for investigating magnitude-dependent decay. Also derive models using surface records.

- Only use data from $< 100$ km.

- Only retain events with depth $< 25$ km to exclude subduction earthquakes.

- Note relatively good magnitude-distance coverage.

- Visually inspect records to retain only main event if multiple events recorded and to check for glitches. Bandpass Butterworth (four poles and two passes) filter records with cut-offs 0.25 and 25 Hz. Longest usable period of model is less than 3 s due to filtering.

- Derive equations using data from small ($M_w \leq 5$) earthquakes (3376 records from 310 events) and large ($M_w \geq 5$) earthquakes (518 records from 27 events) to examine ability of models to predict ground motions outside their magnitude range of applicability. Find ground motions from small events attenuate faster than from large events. Predict ground motions for $M_w$ 4.0, 5.0 and 6.5 and 10, 30 and 99 km. Find overestimation of ground motions for $M_w$4.0 using model derived using data from $M_w \geq 5$ and overestimation of ground motions for $M_w$6.5 using model derived using data from $M_w \leq 5$. Predictions for $M_w$5.0 are similar for both models. Also compare predictions from both models and observations for $M_w$4.1, 4.6, 5.2, 5.7, 6.5 and 7.3 and find similar results.

- Also derive models for 11 magnitude ranges: 4.0–4.2, 4.2–4.4, 4.4–4.6, 4.6–4.8, 4.8–5.0, 5.0–5.2, 5.2–5.4, 5.6–5.8, 5.8–6.8 and 6.8–7.3. Compare predictions with observations for each magnitude range and find good match. Find that decay rate depends on $M_w$ with faster decay for small events. Plot $\sigma$s from each model w.r.t. $M_w$ and find that it has a negative correlation with $M_w$.
- Examine residuals w.r.t. distance. Find slight increase at large distances, which relate to magnitude dependency of attenuation.
- Note that goal of analysis was not to compete with existing models but to compare magnitude dependency of ground motions at depth and surface.
- Examine residuals w.r.t. distance and magnitude of final model. Find no trends.
- Find that $\sigma$s for surface motions are larger (by about 9%) than those for motions at depth.

## 2.297 Güllü et al. (2008)

- Ground-motion model is:

$$\ln \mathrm{PGA} = C_0 + C_1 M_w + C_2 \ln R + C_3 R + C_4 S$$

  where PGA is in gal, $C_0 = 0.192$, $C_1 = 0.867$, $C_2 = -0.294$, $C_3 = -0.008$, $C_4 = 0.113$ and $\sigma = 0.903$.
- Use 2 site classes:

  Rock Class 1 (rock and hard alluvial with $V_{s,30} > 800\,\mathrm{m/s}$) and class 2 (thin soft alluvial with $500 \leq V_{s,30} \leq 700\,\mathrm{m}$). $S = 0$.

  Soil Class 3 (soft gravel and sandy sites with $300 \leq V_{s,30} leq 500\,\mathrm{m/s}$) and class 4 (soft soil with $V_{s,30} < 300\,\mathrm{m/s}$). $S = 1$.
- Use data of Zaré and Bard (2002).
- Select records with PGA of any component $> 0.05\,\mathrm{m/s^2}$.
- Choose functional form because it is simple and hence avoids computational difficulties.
- Use $r_{epi}$ rather than $r_{hypo}$ because of uncertainties in focal depth estimates and because almost all earthquakes have depths $\leq 35\,\mathrm{km}$.
- Originally use coefficients for each of the 4 site classes of Zaré and Bard (2002) but find that the order of predicted PGAs is not as expected (e.g. PGAs on site class 4 are smaller than those on site class 2). Therefore, combine the original classes 1 and 2 together and classes 3 and 4 together.
- Plot residuals w.r.t. predicted PGA and find no trend.

## 2.298 Humbert and Viallet (2008)

- Ground-motion model is:

$$\log(\mathrm{PGA}) = aM + bR - \log(R) + c$$

  where PGA is in $\mathrm{cm/s^2}$, $a = 0.31$, $b = -0.00091$, $c = 1.57$ and $\sigma = 0.23$.
- Use data of Berge-Thierry et al. (2003).
- Focal depths between 0 and 30 km.

- Plot $r_{hypo}$, epicentral location and $M_s$ from ISC against those used by Berge-Thierry et al. (2003). Derive standard deviation, skewness and kurtosis based on these plots.
- Account for estimated uncertainties of $M$ and $R$ in fuzzy regression and find same coefficients as standard regression but with estimated uncertainties and lower $\sigma$ than in standard regression.
- Find that epistemic uncertainties increase at edge of magnitude-distance space.

## 2.299 Idriss (2008)

- Ground-motion model is:

$$\ln[\mathrm{PSA}(T)] = \alpha_1(T) + \alpha_2(T)M - [\beta_1(T) + \beta_2(T)M] \ln(R_{rup} + 10) + \gamma(T)R_{rup} + \phi(T)F$$

  where PSA is in g, $\alpha_1 = 3.7066$ and $\alpha_2 = -0.1252$ for $M \leq 6.75$, $\alpha_1 = 5.6315$ and $\alpha_2 = -0.4104$ for $6.75 < M \leq 8.5$, $\beta_1 = 2.9832$, $\beta_2 = -0.2339$, $\gamma = 0.00047$, $\phi = 0.12$ and $\sigma = 1.28 + 0.05\ln(T) - 0.08M$. $\sigma$ for $M < 5$ equals $\sigma$ at $M5$ and $\sigma$ for $M > 7.5$ equals $\sigma$ at $M7.5$. $\sigma$ for $T < 0.05$ equals $\sigma$ for $T = 0.05$ s. Correction factor for $V_{S30} > 900$ m/s $\Delta\alpha_1(T) = \ln[(1 + 11T + 0.27T^2)/(1 + 16T + 0.08T^2)]$ for $0.05 \leq T \leq 10$ s [$\Delta\alpha_1(T)$ for $T < 0.05$ s equals $\Delta\alpha_1(0.05)$].

- Use two site classes (may derive model for $180 \leq V_{S30} < 450$ m/s in future):

  1. $V_{S30} > 900$ m/s. 45 records. Since not enough records from stations with $V_{S30} > 900$ m/s derive correction factor, $\Delta\alpha_1(T)$, to $\alpha_1$ based on residuals for these 45 records. Find no trends in residuals w.r.t. $M$, $R$ or $V_{S30}$.
  2. $450 \leq V_{S30} \leq 900$ m/s. 942 records (333 from stations with measured $V_{S30}$).

  Notes that only 29% of stations have measured $V_{S30}$; the rest have inferred $V_{S30}$s. Examine distributions of measured and inferred $V_{S30}$s and concluded no apparent bias by using inferred values of $V_{S30}$.

- Uses two mechanism categories:

Strike-slip Rake within 30° of horizontal. Includes records from normal events (rake within 30° of vertical downwards) because insufficient data to retain as separate category. $F = 0$.

Reverse Rake within 30° of vertical upwards. Includes records from reverse oblique and normal oblique events (remaining rake angles) because insufficient data to retain as separate categories. $F = 1$.

- Uses the PEER Next Generation Attenuation (NGA) database (Flat-File version 7.2).
- Excludes (to retain only free-field records): i) records from basements of any building; ii) records from dam crests, toes or abutments; and iii) records from first floor of buildings with $\geq 3$ storeys.
- Excludes records from 'deep' events, records from distances $> 200$ km and records from co-located stations.
- Only retains records with $450 \leq V_{S30} \leq 900$ m/s for regression. Notes that initial analysis indicated that ground motions not dependent on value of $V_{S30}$ in this range so do not include a dependency on $V_{S30}$.
- Uses 187 records from California (42 events), 700 records from Taiwan (Chi-Chi, 152 records, and 5 aftershocks, 548 records) and 55 records from 24 events in other regions (USA outside California, Canada, Georgia, Greece, Iran, Italy, Mexico and Turkey).
- Only 17 records from $R \leq 5$ km and 33 from $R \leq 10$ km (for $M \leq 7$ only 3 records from California for these distance ranges) (all site classes). Therefore, difficult to constrain predictions at short distances, particularly for large magnitudes.

- States that, from a geotechnical engineering perspective, use of $V_{S30}$ bins is more appropriate than use of $V_{S30}$ as an independent parameter.
- Does not investigate the influence of other parameters within the NGA Flat-File on ground motions.
- Uses PSA at 0.01 s for PGA (checked difference and generally less than 2%).
- Divides data into magnitude bins 0.5 units wide and conducts one-stage regression analysis for each. Compares observed and predicted PGAs at distances of 3, 10, 30 and 100 km against magnitude. Find that results for each magnitude bin generally well represent observations. Find oversaturation for large magnitudes due to presence of many records (152 out of 159 records for $M > 7.5$) from Chi-Chi. Does not believe that this is justified so derive $\alpha_1$ and $\alpha_2$ for $M > 6.75$ by regression using the expected magnitude dependency based on previous studies and 1D simulations.
- Examines residuals w.r.t. $M$, $R$ and $V_{S30}$ and concludes that for $5.2 \leq M \leq 7.2$ model provides excellent representation of data. Examine residuals for 5 Chi-Chi aftershocks and find that for $R > 15$ km there is no bias but for shorter distances some negative bias.
- Compares predictions to observations for Hector Mine ($M$7.1), Loma Prieta ($M$6.9), Northridge ($M$6.7) and San Fernando ($M$6.6) events w.r.t. $R$. Finds good match.
- Comments on the insufficiency of $V_{S30}$ as a parameter to characterise site response due to soil layering and nonlinear effects.

## 2.300 Lin and Lee (2008)

- Ground-motion model is:

$$\ln(y) = C_1 + C_2 M + C_3 \ln(R + C_4 \mathrm{e}^{C_5 M}) + C_6 H + C_7 Z_t$$

  where $y$ is in g, $C_1 = -2.5$, $C_2 = 1.205$, $C_3 = -1.905$, $C_4 = 0.516$, $C_5 = 0.6325$, $C_6 = 0.0075$, $C_7 = 0.275$ and $\sigma = 0.5268$ for rock sites and $C_1 = -0.9$, $C_2 = 1.00$, $C_3 = -1.90$, $C_4 = 0.9918$, $C_5 = 0.5263$, $C_6 = 0.004$, $C_7 = 0.31$ and $\sigma = 0.6277$ for soil sites.

- Use two site categories (separate equations for each):

Rock B and C type sites

Soil D and E type sites

- Use two earthquake types:

Interface Shallow angle thrust events occurring at interface between subducting and over-riding plates. Classified events using 50 km maximum focal depth for interface events. 12 events from Taiwan (819 records) and 5 from elsewhere (54 records). $Z_t = 0$.

Intraslab Typically high-angle normal-faulting events within the subducting oceanic plate. 32 events from Taiwan (3865 records) and 5 from elsewhere (85 records). $Z_t = 1$.

- Focal depths, $H$, between 3.94 and 30 km (for interface) and 43.39 and 161 km (for intraslab).
- Develop separate $M_L$-$M_w$ conversion formulae for deep ($H > 50$ km) and shallow events.
- Use data from TSMIP and the SMART-1 array.

- Lack data from large Taiwanese earthquake (especially interface events). Therefore, add data from foreign subduction events (Mexico, western USA and New Zealand). Note that future study should examine suitability of adding these data.
- Exclude poor-quality records by visual screening of available data. Baseline correct records.
- Weight data given the number of records from different sources (Taiwan or elsewhere). Focus on data from foreign events since results using only Taiwanese data are not reliable for large magnitudes. Note that should use maximum-likelihood regression method.
- Compare predicted and observed PGAs for the two best recorded events (interface $M_w 6.3$ $H = 6\,\mathrm{km}$ and intraslab $M_w 5.9$ $H = 39\,\mathrm{km}$) and find good fit.
- Examine residuals and find that a normal distribution fits them very well using histograms.
- From limited analysis find evidence for magnitude-dependent $\sigma$ but do not give details.
- Note that some events could be mislocated but that due to large distances of most data this should not have big impact on results.

## 2.301 Massa et al. (2008)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM + c\log(R^2 + h^2)^{1/2} + s_1 S_A + s_2 S_{(B+C)}$$

where $Y$ is in g; $a = -2.66$, $b = 0.76$, $c = -1.97$, $d = 10.72$, $s_1 = 0$, $s_2 = 0.13$, $\sigma_{eve} = 0.09$ (inter-event) and $\sigma_{rec} = 0.27$ (intra-event) for horizontal PGA and $M_L$; $a = -2.66$, $b = 0.76$, $c = -1.97$, $d = 10.72$, $s_1 = 0$, $s_2 = 0.13$, $\sigma_{sta} = 0.09$ (inter-site) and $\sigma_{rec} = 0.28$ (intra-site) for horizontal PGA and $M_L$; $a = -2.59$, $b = 0.69$, $c = -1.95$, $d = 11.16$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{eve} = 0.09$ (inter-event) and $\sigma_{rec} = 0.26$ (intra-event) for vertical PGA and $M_L$; $a = -2.59$, $b = 0.69$, $c = -1.95$, $d = 11.16$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{eve} = 0.08$ (inter-site) and $\sigma_{rec} = 0.26$ (intra-site) for vertical PGA and $M_L$; $a = -3.62$, $b = 0.93$, $c = -2.02$, $d = 11.71$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{eve} = 0.10$ (inter-event) and $\sigma_{rec} = 0.28$ (intra-event) for horizontal PGA and $M_w$; $a = -3.62$, $b = 0.93$, $c = -2.02$, $d = 11.71$, $s_1 = 0$, $s_2 = 0.12$, $\sigma_{sta} = 0.11$ (inter-site) and $\sigma_{rec} = 0.29$ (intra-site) for horizontal PGA and $M_w$; $a = -3.49$, $b = 0.85$, $c = -1.99$, $d = 11.56$, $s_1 = 0$, $s_2 = 0.11$, $\sigma_{eve} = 0.09$ (inter-event) and $\sigma_{rec} = 0.29$ (intra-event) for vertical PGA and $M_w$; $a = -3.49$, $b = 0.85$, $c = -1.99$, $d = 11.56$, $s_1 = 0$, $s_2 = 0.11$, $\sigma_{eve} = 0.12$ (inter-site) and $\sigma_{rec} = 0.30$ (intra-site) for vertical PGA and $M_w$.

Also use functional form: $\log_{10}(Y) = a + bM + (c + eM)\log(R^2 + h^2)^{1/2} + s_1 S_A + s_2 S_{(B+C)}$ but do not report coefficients since find small values for $e$.

- Use three site classifications based on Eurocode 8 for the 77 stations:

  A Rock, $V_{s,30} > 800\,\mathrm{m/s}$: marine clay or other rocks (Lower Pleistocene and Pliocene) and volcanic rock and deposits. 49 stations. $S_A = 1$ and $S_{(B+C)} = 0$.

  B Stiff soil, $360 < V_{s,30} < 800\,\mathrm{m/s}$: colluvial, alluvial, lacustrine, beach, fluvial terraces, glacial deposits and clay (Middle-Upper Pleistocene); sand and loose conglomerate (Pleistocene and Pliocene); and travertine (Pleistocene and Holocene). 19 stations. $S_{(B+C)} = 1$ and $S_A = 0$.

  C Soft soil, $V_s < 360\,\mathrm{m/s}$: colluvial, alluvial, lacustrine, beach and fluvial terraces deposits (Holocene). 9 stations. $S_{(B+C)} = 1$ and $S_A = 0$.

Because of limited records from class C combine classes B and C in regression. Note that the classification of some stations in class A could not be appropriate due to site amplification due to structure-soil interaction and topographic effects. Also note that class C is not appropriate for some stations on Po Plain due to deep sediments but that there are few data from these sites so no bias.

- Use data from various analogue and digital strong-motion (Episensor, K2, Etna, SSA-1 or SMA-1 instruments) and digital velocimetric (Mars-Lite, Mars88-MC, Reftek 130 or other instruments) networks in northern Italy, western Slovenia and southern Switzerland.
- Originally collect about 10 000 records but reduce by careful selection. Exclude data with $d_e > 100$ km and with $M_L < 3.5$. Consider earthquakes down to $M_L 3.5$ because such earthquakes could damage sensitive equipment in industrial zones.
- 216 components (both horizontal and vertical combined) from earthquakes with $M_L > 4.5$.
- Focal depths between 1.9 and 57.9 km. Most less than 15 km.
- Bandpass filter using fourth-order acausal Butterworth filter with cut-offs of 0.4 and 25 Hz for $M_L \leq 4.5$ and 0.2 and 25 Hz for $M_L > 4.5$. Check using some records that PGA is not affected by filtering nor are spectral accelerations in the period range of interest. Check filtering of analogue records by visually examining Fourier amplitude spectra. Check conversion of velocimetric records to acceleration is correct by examining records from co-located instruments of different types. Exclude clipped records or records affected by noise.
- Try including a quadratic magnitude term but find that the coefficient is not statistically significant.
- Try including an anelastic attenuation term but find that coefficient is not statistically significant.
- Do not use $r_{jb}$ since not sufficient information on rupture locations. Do not use $r_{hypo}$ so as not to introduce errors due to unreliable focal depths.
- Do not include style-of-faulting terms because most data from reverse-faulting earthquakes (often with strike-slip component).
- Apply simple tests to check regional dependence and do not find significant evidence for regional differences in ground motions. Since records from similar earthquakes of similar mechanisms conclude that models appropriate for whole of northern Italy (6°–15°E and 43°–47°N).
- Examine residuals (against earthquake and station indices, as box and whisker plots and against distance and magnitude) for sites A and sites B & C and for $M_L \leq 4.5$ and $M_L > 4.5$. Also compare predicted and observed ground motions for various magnitudes and events. Find good results.
- Suggest that for $d_e < 10$ km and $M_L > 5.5$ 10 km is considered the distance at which distance saturation starts (since little data with $d_e < 10$ km to constrain curves and predictions for shorter distances unrealistically high).
- Also derive equations for other strong-motion intensity parameters.

## 2.302 Mezcua et al. (2008)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M + C_3 \ln R$$

  where $Y$ is in cm/s$^2$, $C_1 = 0.125$, $C_2 = 1.286$, $C_3 = -1.133$ and $\sigma = 0.69$. Only derive equation for firm soil sites due to insufficient data for other classes. For compact rock sites propose using ratio between PGA on firm soil and rock derived by Campbell (1997).

- Use three site classifications:

  1 Compact rock. Crystalline rocks (granite and basalt), metamorphic rocks (e.g. marble, gneiss, schist and quartzite) and Cretaceous and older sedimentary deposits following criteria of Campbell (1997). Similar to Spanish building code classes I and II with $400 \leq V_s \leq 750$ m/s. 23 stations.

  2 Alluvium or firm soil. Quaternary consolidated deposits. Similar to Spanish building code class III with $200 \leq V_s \leq 400$ m/s. 29 stations.

  3 Soft sedimentary deposits. 52 stations.

  Classify using crude qualitative descriptions.

- Most stations in basements of small buildings (e.g. city council offices) and therefore records are not truly free-field.

- Only consider data with $5 \leq d_e \leq 100$ km and $M \geq 3$.

- Focal depths between 1 and 16 km.

- Most data from $3 \leq M \leq 4$ and $d_e \leq 50$ km. Only one record with $M > 5$ and $d_e < 20$ km.

- Use hypocentral distance because no information on locations of rupture planes and since using hypocentral distance automatically limits near-source ground motions.

- Do not consider style-of-faulting since no reported mechanisms are available for most events.

- Compare predicted PGA for $M_w 5$ with observations for $4.9 \leq M_w \leq 5.1$. Find reasonable fit.

## 2.303 Morasca et al. (2008)

- Ground-motion model is:

$$\log_{10} Y = a + bM + c \log_{10} R + s_{1,2}$$

  where $Y$ is in g, $a = -4.417$, $b = 0.770$, $c = -1.097$, $D = 0$, $D_1 = 0.123$, $\sigma_{\rm eve} = 0.069$ and $\sigma_{\rm rec} = 0.339$ for horizontal PGA and intra-event sigma; $a = -4.128$, $b = 0.722$, $c = -1.250$, $D = 0$, $D_1 = 0.096$, $\sigma_{\rm eve} = 0.085$ and $\sigma_{\rm rec} = 0.338$ for vertical PGA and intra-event sigma; $a = -4.367$, $b = 0.774$, $c = -1.146$, $D = 0$, $D_1 = 0.119$, $\sigma_{\rm sta} = 0.077$ and $\sigma_{\rm rec} = 0.337$ for horizontal PGA and intra-station sigma; and $a = -4.066$, $b = 0.729$, $c = -1.322$, $D = 0$, $D_1 = 0.090$, $\sigma_{\rm sta} = 0.105$ and $\sigma_{\rm rec} = 0.335$.

- Use two site categories ($s_{1,2}$) because insufficient information to use more:

  $D$ Rock. Average $V_s > 800$ m/s. 10 stations.

  $D_1$ Soil. Average $V_s < 800$ m/s. Includes all kinds of superficial deposits, from weak rocks to alluvial deposits although they are mainly shallow alluvium and soft rock (600-700 m/s) sites. 27 stations.

- Use data from the 2002–2003 Molise sequence from various agencies.

- Use data from accelerometers (SMA-1, 3 stations; RFT-250, 2 stations; Episensor, 10 stations) and velocimeters (CMG-40T, 4 stations; Lennartz 1 s, 5 stations; Lennartz 5 s, 13 stations).

- Select data with $M > 2.7$.

- Baseline and instrument correct records from analogue accelerometric instruments and filter in average bandpass 0.5–20 Hz after visual inspection of the Fourier amplitude spectra. Baseline correct records from digital accelerometric instruments and filter in average bandpass 0.2–30 Hz after visual inspection of the Fourier amplitude spectra. Instrument correct records from digital velocimetric instruments and filter in average bandpass 0.5–25 Hz after visual inspection of the Fourier amplitude spectra.

- Most data from $r_{hypo} < 40$ km and almost all velocimetric data from 20-30 km.
- Most focal depths between 10 and 30 km.
- Relocate events using manual picks of P and S phases and a local velocity model.
- Compute $M_L$s using velocimetric data.
- Note that small value of $\sigma_{\text{eve}}$ suggests that the calibrated local magnitudes and relocated hypocentral locations are accurate.
- Note that small value of $\sigma_{\text{sta}}$ suggests that the site classification is correct.
- Note that records from accelerometric and velocimetric instruments are similar.

## 2.304 Slejko et al. (2008)

- Ground-motion model is:

$$\begin{aligned} \log_{10} PGA &= a + (b + cM_s)M_s + (d + eM_s)\log_{10} r \\ \text{where} \quad r^2 &= D^2 + h^2 \end{aligned}$$

  where $PGA$ is in g, $a = -2.14$, $b = 0.98$, $c = -0.06$, $d = -1.88$, $e = 0.0009$, $h = 13.4$ and $\sigma = 0.35$.
- Only use data for $d_e < 100$ km because data from larger distances only available for large earthquakes.
- Only eight records have PGA$< 0.005$ g (standard trigger level).
- Use truncated regression analysis (Bragato, 2004) to account for bias due to non-triggering stations.

## 2.305 Srinivasan et al. (2008)

- Ground-motion model is:

$$\log(A) = c_1 + c_2 M - b\log(X + \mathrm{e}^{c_3 M})$$

  where $A$ is in cm/s$^2$, $c_1 = -1.3489$, $c_2 = 1.0095$, $b = 0.1956$, $c_3 = 0.1272$ and $\sigma = 0.20$.
- Use data from one station.
- Data from rockbursts in mines in the Kolar Gold Fields.
- Exclude records with $r_{hypo} < 1$ km due to large change in PGAs in near-source region.
- Regress data using $\log(A) = -b\log(X) + c$ for data binned in 5 0.2 magnitude unit bins from 2.0 upwards.
- Also regress data using $\log(A) = aM - b\log(X) + c$.
- Also regress using $\log(A) = c_1 + c_2 M - bc_4 \log(X + \mathrm{e}^{c_3 M})$ (sic) but find $c_4$ has a very large standard error so remove it.
- Compare predictions and observations for $M$2.1, 2.3, 2.5, 2.7 and 2.9.

## 2.306 Adnan and Suhatril (2009)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M + C_3 M_4^C + C_5 \ln[R + C_6 \exp(C_7 M)] + C_8 H$$

  where $Y$ is in gal, $C_1 = -0.469151$, $C_2 = 7.108251 \times 10^{-4}$, $C_3 = 0.456626$, $C_4 = -0.032769$, $C_5 = 2.122059 \times 10^{-3}$, $C_6 = 235088.506$, $C_7 = 0.664657$ and $C_8 = -2.860212 \times 10^{-7}$ ($\sigma$ is not given).

- Focal depths $H$ between 16.2 and 576 km.

- Data from about 11 stations of Malaysia Meteorological Department.

- Also derive various models using worldwide data.

- Records from subduction earthquakes on Sumatran arc: 3 are deep events ($289.2 \leq H \leq 576$ km) and 11 are shallow ($16.2 \leq H \leq 35$ km).

- Plot residuals w.r.t. $r_{epi}$, $M$ and $H$.

## 2.307 Aghabarati and Tehranizadeh (2009)

- Ground-motion model is:

$$
\begin{aligned}
\ln y &= c_1 + f_1(M_w) + f_2(M_w) f_3(R) + f_4(F) + \mathrm{FR} f_5(Z_{FR}) + \\
&\quad \mathrm{FS} f_6(Z_{FR}) + f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) + \\
&\quad f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) + f_9(V_{s,30}, Z_{1.5}) \\
\text{where for} \quad M_w &\leq c_0 \\
f_1(M_w) &= c_3(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_4(M_w - c_0) \\
\text{and for} \quad M_w &> c_0 \\
f_1(M_w) &= c_5(M_w - c_0) + c_8(T)(8.5 - M_w)^n \\
f_2(M_w) &= c_2(T) + c_6(M_w - c_0) \\
f_3(R) &= \ln \sqrt{R_{rup}^2 + c_7(T)^2} \\
f_4(F) &= c_9(T)\mathrm{FR} + c_{10}(T)\mathrm{FS} + c_{11}(T)\mathrm{FN} \\
f_5(Z_{\mathrm{FR}}) &= \begin{cases} 0 & Z_{top} \leq 2\,\mathrm{km} \\ c_{12}(T)(Z_{top} - 2)/3 & 2 < Z_{top} \leq 5\,\mathrm{km} \\ c_{12}(T) & 5 < Z_{top} \leq 10\,\mathrm{km} \\ c_{12}(T)[1 - (Z_{top} - 10)/5] & 10 < Z_{top} \leq 15\,\mathrm{km} \\ 0 & Z_{top} > 15\,\mathrm{km} \end{cases} \\
f_6(Z_{\mathrm{FS}}) &= \begin{cases} c_{13}(T) Z_{top}/2 & 0 < Z_{top} \leq 2\,\mathrm{km} \\ c_{13}(T) & 2 < Z_{top} \leq 4\,\mathrm{km} \\ c_{13}(T)[1 - (Z_{top} - 4)/2] & 4 < Z_{top} \leq 6\,\mathrm{km} \\ 0 & Z_{top} > 6\,\mathrm{km} \end{cases} \\
g_1(R_{JB}) &= \begin{cases} 1 - R_{JB}/45 & 0 \leq R_{JB} < 15\,\mathrm{km} \\ \frac{2}{3}(2 - R_{JB}/15) & 15 \leq R_{JB} < 30\,\mathrm{km} \\ 0 & R_{JB} \geq 30\,\mathrm{km} \end{cases} \\
g_2(M_w) &= \begin{cases} 0 & M_w < 6.0 \\ 2(M_w - 6) & 6.0 \leq M_w < 6.5 \\ 1 & M_w \geq 6.5 \end{cases} \\
g_3(\mathrm{DIP}) &= \begin{cases} 1 - (\mathrm{DIP} - 70)/20 & \mathrm{DIP} \geq 70 \\ 1 & \mathrm{DIP} < 70 \end{cases} \\
f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) &= c_{14}(T)\mathrm{HW} g_1(R_{JB}) g_2(M_w) g_3(\mathrm{DIP}) \\
f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= g_4(V_{s,30}, V_{lin}) + g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) \\
g_4(V_{s,30}, V_{lin}) &= c_{15}(T) \ln(V_{s,30}/V_{lin}) \\
g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) &= \begin{cases} c_{16}(T) \ln(\mathrm{PGA}_{min}/0.1) & \mathrm{PGA}_{non-lin} < a_1 \\ c_{16}(T)[\ln(\mathrm{PGA}_{min}/0.1) & \\ +a \ln(\mathrm{PGA}_{non-lin}/a_1) & \\ +b(\ln(\mathrm{PGA}_{non-lin}/a_1))^2] & a_1 \leq \mathrm{PGA}_{non-lin} \leq a_2 \\ c_{16}(T) \ln(\mathrm{PGA}_{non-lin}/0.1) & \mathrm{PGA}_{non-lin} \geq a_2 \end{cases} \\
f_9(V_{s,30}, Z_{1.5}) &= g_6(V_{s,30}, Z_{1.5}, \hat{Z}) + g_7(Z_D, Z_{1.5}) \\
g_6(V_{s,30}, Z_{1.5}, \hat{Z}) &= c_{17}(T)(1/\hat{Z}) \ln(V_{s,30}/1500) \ln(Z_{1.5}) \\
\hat{Z} &= \begin{cases} 7.154 & V_{s,30} \leq 360\,\mathrm{m/s} \\ 7.154 + \frac{(4.465 - 7.154)[\ln(V_{s,30}/1500) - \ln(360/1500)]}{\ln(600/1500) - \ln(360/1500)} & 360 < V_{s,30} \leq 600\,\mathrm{m/s} \\ 4.465 - \frac{(2.772 - 4.465)[\ln(V_{s,30}/1500) - \ln(600/1500)]}{\ln(600/1500)} & V_{s,30} > 600\,\mathrm{m/s} \end{cases} \\
g_7(Z_{1.5}, Z_D) &= Z_D c_{18}(T) K_1(1 - \exp(-(Z_{1.5} - 200)/300)) + \\
&\quad Z_D c_{19}(T) K_2(1 - \exp(-(Z_{1.5} - 200)/4000))
\end{aligned}
$$

where $y$ is in g and $c_0 = 6.5$; $c_1 = 2.033$, $c_2 = -1.180$, $c_7 = 8.647$, $c_8 = -0.028$, $c_9 = -0.176$, $c_{10} = -0.266$, $c_{11} = -0.476$, $c_{12} = 0.520$, $c_{13} = -0.320$, $c_{14} = 0.400$, $c_{15} = -0.360$, $c_{17} = 0$, $c_{18} = 0$, $c_{19} = 0$, $c_{20} = 0.412$, $c_{21} = 0.427$, $K_1 = 2.260$, $K_2 = 1.040$, $V_{lin} = 760$ for horizontal PGA; and $c_1 = 2.983$, $c_2 = -1.616$, $c_7 = 9.101$, $c_8 = -0.043$, $c_9 = -0.253$, $c_{10} = -0.463$, $c_{11} = -0.706$, $c_{12} = 0.132$, $c_{13} = -0.171$, $c_{14} = 0.513$, $c_{15} = -0.360$, $c_{17} = 0$, $c_{18} = 0$, $c_{19} = 0$, $c_{20} = 0.522$, $c_{21} = 0.537$, $K_1 = 2.260$, $K_2 = 1.040$, $V_{lin} = 760$ for vertical PGA; $\sigma = c_{20}(T) + [c_{21}(T) - c_{20}(T)]M_w$ for $5.0 \leq M_w < 7.0$ and $\sigma = c_{21}(T)$ for $M_w \geq 7.0$.

- Almost identical to Aghabarati and Tehranizadeh (2008) (see Section 2.291) but some coefficients are slightly different and they are also provided for the vertical components.
- Set $a_1 = 0.04$ g, $a_2 = 0.1$ g and $\text{PGA}_{min} = 0.06$ g. $\text{PGA}_{non-lin}$ is expected PGA on rock ($V_{s,30} = 760$ m/s). $c_{15}(T)$, $c_{16}(T)$ and $V_{lin}$ taken from Choi and Stewart (2005) and are not determined in regression.

## 2.308 Akyol and Karagöz (2009)

- Ground-motion model is:

$$\log y = a_1 + a_2(M - 6) + b \log r + cS$$

  where $y$ is in g, $a_1 = 1.330095 \pm 0.068$, $a_2 = 0.640047 \pm 0.066$, $b = -1.65663 \pm 0.055$, $c = 0.14963 \pm 0.098$, $\sigma_1 = 0.196$ (intra-event), $\sigma_2 = 0.191$ (inter-event) and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2} = 0.274$.

- Initially use four site classes:

  1. Rock. 6 stations, 20 records.
  2. Stiff soil. 11 stations, 57 records.
  3. Soil. 11 stations, 32 records.
  4. Deep soil. 9 stations, 59 records.

  Sites classified using horizontal/vertical spectral ratios of the S-wave window of records grouped by station (details not given). Only use data with S/N ratio $> 3$ and smooth spectra using a nine-point moving average. Since data insufficient to obtain coefficients for all classes, combine classes 1 and 2 and classes 3 and 4 to produce categories A ($S = 0$) and B ($S = 1$) based on 77 and 91 records, respectively. Display average H/V spectral ratios for each category.

- Focal depths between 4.3 and 31.8 km.
- Note that ideally would account for faulting mechanism but for many earthquakes this parameter is unknown and also dataset is not large enough to assess its impact.
- Use data from the Turkish National Strong Motion Network of the Earthquake Research Department of the General Directorate of Disaster Affairs and the temporary Western Anatolia Seismic Recording Experiment (WASRE).
- Use $r_{hypo}$ because fault geometries unknown for most earthquakes.
- Initially use 2123 records from all regions of Turkey. Discard records with unknown and poor estimates of magnitude, distance and/or site conditions and those outside western Anatolia. Select data with: $r_{hypo} < 200$ km, $M_w \geq 4.0$ and PGA $> 0.0015$ g.
- Check low- and high-frequency noise for all records. Find that much data from SMA-1s have significant long-period noise (especially records of small earthquakes at large distances). Do not filter data but eliminate suspect records. Apply correction for instrument response. Numerically differentiate data from velociometers of WASRE network. Baseline correct all data.
- Most data from $4.5 \leq M_w \leq 5.5$ and $25 \leq r_{hypo} \leq 125$ km.
- Note that due to lack of records from $< 10$ km cannot include fictitious depth in functional form.
- Initially include a quadratic magnitude term but this term does not improve match so drop this term.

- Test significance of site coefficients and find that they are generally significant at more than 90% confidence level.
- Plot residuals w.r.t. distance, magnitude and predicted $\log PGA$. Find systematic trends, especially for site B residuals versus $M_w$. Derive linear site coefficient correction terms to remove these trends (not clear how they are applied), which relate to nonlinear site response.
- Compare predictions and observations for selected earthquakes.
- Discuss reasons for differences in site effects in western Anatolia and in other regions.
- Based on results, suggest that number of stations on rock should be increase and site classifications should be re-evaluated.

## 2.309 Baruah et al. (2009)

- Ground-motion model is:

$$\log a_{PG} = aM + b \log R + c$$

where $a_{PG}$ is in unknown units (probably m/s$^2$), $a = 0.086$, $b = -0.547$, $c = 0.185$ and $\sigma = 0.18$.

- Data from 5 stations on hard rock, 1 on sandstone, 1 on granite gneiss and 1 on quartzite sandstone.
- Data from 8 broadband stations operated by NEIST-Jorhat and NGRI-Hyderabad: 5 with CMG-3T, 2 with CMG-3ESP and 1 with Trillium 240 sensors. Seismograms convert to acceleration using real-time simulation[24].
- Note lack of data from large events.

## 2.310 Bindi et al. (2009a)

- Ground-motion model is:

$$\begin{aligned}\log_{10} Y &= a + b_1(M_w - M_{ref}) + b_2(M_w - M_{ref})^2 \\ &\quad + [c_1 + c_2(M_w - M_{ref}] \log_{10} \sqrt{(R_{JB} + h^2)} + e_i S_i + f_j F_j\end{aligned}$$

where $Y$ is in cm/s$^2$ and $M_{ref} = 5.5$ (to reduce trade-offs between attenuation and source parameters), $a = 3.0761$, $b_1 = 0.1587$, $b_2 = 0.0845$, $c_1 = -1.0504$, $c_2 = -0.0148$, $h = 7.3469$, $e_1 = 0$, $e_2 = 0.2541$, $e_3 = 0.1367$, $f_1 = 0$, $f_2 = -0.0059$, $f_3 = 0.0168$, $\sigma_{event} = 0.1482$, $\sigma_{station} = 0.2083$, $\sigma_{record} = 0.1498$ and $\sigma = 0.2963$ for larger horizontal component; $a = 3.0191$, $b_1 = 0.1643$, $b_2 = 0.0674$, $c_1 = -1.0284$, $c_2 = -0.0041$, $h = 6.8963$, $e_1 = 0$, $e_2 = 0.2275$, $e_3 = 0.0774$, $f_1 = 0$, $f_2 = -0.0138$, $f_3 = 0.0005$, $\sigma_{event} = 0.1465$, $\sigma_{station} = 0.2184$, $\sigma_{record} = 0.1345$ and $\sigma = 0.2930$ for geometric mean of horizontal components; and $a = 3.0421$, $b_1 = 0.3762$, $b_2 = 0.0925$, $c_1 = -1.2350$, $c_2 = -0.0891$, $h = 9.3012$, $e_1 = 0$, $e_2 = 0.1787$, $e_3 = 0.1146$, $f_1 = 0$, $f_2 = -0.0073$, $f_3 = 0.0222$, $\sigma_{event} = 0.1266$, $\sigma_{station} = 0.2114$, $\sigma_{record} = 0.1394$ and $\sigma = 0.2831$ for vertical component.

- Use three site classes following Sabetta and Pugliese (1987, 1996):

Class 0 Rock: rock outcrops or deposits thinner than 5 m.. 98 records. $S_1 = 1$ and $S_2 = S_3 = 0$.

Class 1 Shallow alluvium: deposits thinner than or equal to 20 m and thicker than 5 m. $V_s$ of alluvium between 400 and 800 m/s. 62 records. $S_2 = 1$ and $S_1 = S_3 = 0$.

[24] Thought that this just means differentiation.

Class 2 Deep alluvium: deposits thicker than 20 m. 81 records. $S_3 = 1$ and $S_1 = S_2 = 0$.

Site classification performed using verified geological, geophysical and geotechnical information, which altered the previous categorization of some stations. Data from 146 different stations. Note that only 6% of 600 Italian stations are associated with a $V_s$ profile.

- Focal depths between 2 and 29 km.

- Use data from Italian Accelerometric Archive (ITACA) from between 1972 and 2004, which have been carefully revised during a project funded by the Italian Department of Civil Protection. Records individually processed using individually-selected filters. Analogue records corrected for linear trend and instrument response and then band-pass filtered, selecting high-pass frequency from visual inspection of Fourier spectra (generally between 0.3 and 0.5 Hz) and low-pass frequency chosen close to instrument frequency (generally between 20 and 25 Hz). Digital records corrected for linear trend using entire trace (because few records have usable pre-event portion) and then band-pass filtered in the same way as analogue data (but with generally lower cut-offs, 0.1–0.3 Hz and 25–30 Hz). Use raised cosine filter for analogue records, which often triggered on S-phase, and acausal fourth-order Butterworth for digital signals, which were padded with zeros at both ends.

- Use three faulting mechanisms:

Normal $F_1 = 1$ and $F_2 = F_3 = 0$.

Strike-slip $F_2 = 1$ and $F_1 = F_3 = 0$.

Reverse $F_3 = 1$ and $F_1 = F_2 = 0$.

Most earthquakes on normal faults in central and southern Apennines.

- Number of records per earthquake ranges from two (Ancona, 14/06/1972) to 25 (Umbria-Marche, 14/10/1997). Most earthquakes recorded by four stations or more.

- Near-source records are poorly represented: 11 records from 3 earthquakes have $r_{jb} < 5$ km (none with $M_w > 6.4$ for which shortest $r_{jb}$ is 7 km).

- Most data from $10 \leq r_{jb} \leq 100$ km and $5 \leq M_w \leq 6$.

- For Irpinia mainshock (23/11/1980), which is composed of three sub-events, used magnitude, location and time-histories of first sub-event because it can be clearly recognized.

- Assess the standard error of each coefficient using bootstrap technique based on randomly resampling, with replacement, the original dataset to obtain datasets of the same size as original (500 times). Note the coefficients using this technique are very similar.

- Note that some coefficients are not significantly different than zero (e.g. $c_2$ and $f_j$) because of the distribution of data w.r.t. $M_w$ and mechanism.

- Examine residual plots w.r.t. $M_w$ and $r_{jb}$ and find no significant bias or trends.

- Examine inter-event residuals and find them within range $\pm 0.2$ except for two earthquakes (2002 Molise second mainshock and 1990 eastern Sicily), which note could be due to inaccuracies in magnitudes and locations for these events. Find inter-event residuals for normal earthquakes show smallest dispersion, while largest variability affects strike-slip events.

- Examine inter-station residuals. Note that most are within range $\pm 0.3$ with few with absolute values larger than 0.4. Discuss the possible reasons for these large residuals in terms of local site profiles.

- Undertake other analyses to understand the source of observed variability in ground motions.
- Also derive model for larger horizontal component using hypocentral distance and no style-of-faulting terms: $\log_{10} Y = 3.4192+0.4672(M_w-5.5)+0.1231(M_w-5.5)^2+[-1.2221-0.1643(M_w-5.5)]\log_{10} r_{hypo}+0.2474S_2+0.1435S_3$.
- Note that unmodelled site effects are contributing a significant proportion of the observed variability and that a more sophisticated classification scheme using depth of soil deposit, average $V_s$ of soil deposit and resonance period could significantly reduce the inter-station variability component.

## 2.311 Bindi et al. (2009b)

- Ground-motion model is:

$$\log_{10} y = a + bM + c\log_{10}\sqrt{R^2+h^2} + e_i S_i$$

  where $y$ is in $\mathrm{cm/s^2}$; $a = 1.344$, $b = 0.328$, $c = -1.09$, $h = 5$, $e_0 = 0$, $e_1 = 0.262$, $e_2 = 0.096$ and $\sigma = 0.32$ using $r_{epi}$; and $a = 1.954$, $b = 0.193$, $c = -1.01$, $h = 5.88$, $e_0 = 0$, $e_1 = 0.264$, $e_2 = 0.144$ and $\sigma = 0.300$ using $r_{jb}$.

- Use three site classes following Sabetta and Pugliese (1987, 1996):

Class 0 Rock: rock outcrops or deposits thinner than 5 m. 95 records. $S_1 = 1$ and $S_2 = S_3 = 0$.

Class 1 Shallow alluvium: deposits thinner than or equal to 20 m and thicker than 5 m. $V_s$ of alluvium between 400 and 800 m/s. 61 records. $S_2 = 1$ and $S_1 = S_3 = 0$.

Class 2 Deep alluvium: deposits thicker than 20 m. 79 records. $S_3 = 1$ and $S_1 = S_2 = 0$.

  Site classification performed using verified geological, geophysical and geotechnical information, which altered the previous categorization of some stations. Data from 137 different stations.

- Focal depths from 2 to 29 km.
- Use data from Italian Accelerometric Archive (ITACA) from between 1972 and 2002, which have been carefully revised during a project funded by the Italian Department of Civil Protection, plus some data from the Northern Italy Strong Motion network (RAIS). Records individually processed. Analogue records corrected for linear trend and instrument response and then band-pass filtered, selecting high-pass frequency from visual inspection of Fourier spectra (generally between 0.3 and 0.5 Hz) and low-pass frequency chosen close to instrument frequency (generally between 20 and 25 Hz). Digital records corrected for linear trend using entire trace (because few records have usable pre-event portion) and then band-pass filtered in the same way as analogue data (but with generally lower cut-offs, 0.1–0.3 Hz and 25–30 Hz). Use raised cosine filter for analogue records, which often triggered on S-phase, and acausal fourth-order Butterworth for digital signals, which were padded with zeros at both ends. Find PGAs are consistent with those of Sabetta and Pugliese (1987, 1996) for common records.
- Very similar data to that used by Bindi et al. (2009a) (see Section 2.310).
- State that GMPEs are updates of those by Sabetta and Pugliese (1987, 1996).
- Examine goodness of fit of the GMPEs of Sabetta and Pugliese (1987, 1996) to the data and find that they do not adequately fit because of a too small $\sigma$ and non-zero bias. Therefore, derive new GMPEs.
- Use the data from the 17 earthquakes used by Sabetta and Pugliese (1987, 1996) plus data from ten events that occurred from 1990 to 2002 with $M_w > 5.3$ and one earlier shock (Ancona 1972) that was not used by Sabetta and Pugliese (1987, 1996).

- Most new earthquakes on normal faults in central and southern Apennines with a few on strike-slip faults.
- Best sampled areas are: eastern Alps (Friuli), central-southern Apennines from Marche to Pollino and north and east Sicily.
- Majority of earthquakes recorded by more than four stations (minimum two, maximum 24).
- For Irpinia mainshock (23/11/1980), which is composed of three sub-events, used magnitude, location and time-histories of first sub-event because it can be clearly recognized.
- Only seven records from $< 5$ km. Earthquakes with $M_w > 6$ recorded at distances $> 20$ km. Best-sampled interval is 10–100 km and $M_w$5–6.
- Compare observed and predicted PGAs for $M_w$5.5 and 6.9 and find good agreement.
- Calculate inter-event and inter-station residuals and relate observed large under- or over-estimation for particular events to deep focal depths or other source characteristics. Compute $\sigma_{eve} = 0.174$ and $\sigma_{sta} = 0.222$ as inter-event and inter-station standard deviations.
- Repeat regression using 17 earthquakes of Sabetta and Pugliese (1987, 1996) but including data from additional stations that were not used by Sabetta and Pugliese (1987, 1996) and using the updated site classes. Find significant differences for $M_w$6.5 at 20 km.

## 2.312 Bragato (2009)

- Ground-motion model is:

$$\log(\text{PGA}) = c_1 + c_2 M_L + c_3 \log(d_{epi}) + \sum_{k=1}^{N_s} S_k \delta_{kj}$$

  where PGA is in g, $c_1 = -0.45 \pm 0.44$, $c_2 = 0.85 \pm 0.09$, $c_3 = -2.39 \pm 0.20$ and $\sigma = 0.27$ for Italy with station correction and $c_1 = -0.49 \pm 0.38$, $c_2 = 0.86 \pm 0.08$, $c_3 = -2.41 \pm 0.16$ and $\sigma = 0.38$ for Italy without station correction. $S_k$ is correction term for $k$th station and $\delta_{kj}$ is Kroneker delta and $N_s$ is number of stations in a geographical cluster. Also provides coefficients for different zones but these are not reported here.
- Uses individual site terms for each station. Data from 137 different stations.
- Investigates theoretical improvement of GMPEs for ShakeMap purposes in Italy, obtainable by accounting for regional dependencies and site effects. Notes that presented GMPEs are explorative tools rather than proposals for ShakeMap implementation because of limited data and narrow magnitude range.
- Uses data from INGV stations from between December 2005 and July 2008. Stations give homogeneous coverage in central and southern Italy and eastern Sicily but more sparse elsewhere and not existent in NE Italy.
- To exclude possible outliers, performs preliminary regression on all data and removes those records with absolute normalised standard deviations greater than three. Also excludes data from stations that have recored only one earthquake.
- Data distribution roughly uniform w.r.t. magnitude and distance.
- Tries using $r_{hypo}$ but finds a slightly worse fit ($\sigma = 0.39$ rather than $\sigma = 0.38$), which relates to poor estimates of focal depths for some earthquakes (even though theoretically $r_{hypo}$ should be better since it includes more information).

- Considers various partitions of available stations into different geographical zones using Delaunay triangulation. Derive a GMPE for each zone with station correction terms. Applies a genetic algorithm to minimise the standard deviation, based on the Bayesian information criterion, over the set of possible partitions. Note that this approach cannot recognise regionalised site effects. Also this method uses some data from earthquakes occurring outside the zone where the station is located. Notes that considering these complexities is not possible with current data but that most earthquakes occur in the same zone as the station. Finds that the optimal zonation has four zones.
- Investigates source and focal depth characteristics of different zones to understand the possible causes of regional variations. Concludes that observed differences are attributable to crustal structure and anelastic attenuation.
- Computes GMPEs for the six regions used in ShakeMap implementation.
- Computes GMPEs for all of Italy after correction for site amplification modelled by $V_{s,30}$-based amplification factors of Borcherdt (1994), used by ShakeMap. Find $\sigma$ is unchanged. Also regress using site classes based on $V_{s,30}$s estimated from geology.
- Concludes that site effects contribute about 30% of overall standard deviation and that regional differences contribute only 4%.
- Find that station correction terms are weakly correlated to $V_{s,30}$-based amplification factors of Borcherdt (1994) used in ShakeMap to model site effects.

## 2.313 Cabalar and Cevik (2009)

- Ground-motion model is[25]:

$$\begin{aligned} \mathrm{PGA} &= \left(\frac{5.7}{A}\right)^2 + \frac{BM\log M}{\sqrt[3]{R}} \\ A &= \sqrt[4]{V_s} + (R - \sqrt[9]{V_s^4 + 238^5})^2 \\ B &= \sqrt[3]{\sqrt[4]{\frac{651}{V_s}} - \frac{\log R}{3}} \end{aligned}$$

  $\sigma$ not reported.

- Use average $V_s$ to characterise sites.
- Use data of Gülkan and Kalkan (2002) (see Section 2.196 for details) to derive model because it is most reliable (based on neural network prediction using training, 80% of records, and testing, remaining 20% of records, sets) of available datasets from Turkey.
- Use genetic programming (soft computing) approach (using software GeneXTools by Gepsoft) to derive model.
- Compare predicted and observed PGAs in the form of a scatter plot.
- Compare predicted and observed PGAs w.r.t. for 1999 Kocaeli ($M_w$7.4) earthquake.

[25]Model is given as reported in article because it is not known which coefficients were specified *a priori* and which found by derivation algorithm.

## 2.314 Garcìa Blanco (2009)

- Ground-motion model is:
$$\ln \mathrm{PGA} = a + bM + c \ln \Delta$$
where PGA is in cm/s$^2$, $a = 0.2368$, $b = 1.3285$, $c = 1.0749$ and $\sigma = 0.76$.
- Use same data as Mezcua et al. (2008).

## 2.315 Goda and Atkinson (2009)

- Ground-motion model is:
$$\begin{aligned}
\log Y &= c_1 + c_2 M + c_3 H + c_4 r_{rup} + c_5 \min[\log(r_{rup} + 15), \log(90)] \\
&\quad + c_6 \log(V_{s,30}/760) + G + A \\
G &= \begin{cases} -\log(r_{rup} + 0.00610^{0.5M}) & H \leq 30\,\mathrm{km} \\ -1.4\log(r_{rup} + 0.00610^{0.5M}) + 0.4\log(1.7H + 0.00610^{0.5M}) & H > 30\,\mathrm{km} \end{cases} \\
A &= \begin{cases} 0 & H \leq 30\,\mathrm{km} \\ (a_1 R_{tr} + a_2)(H - 30) & H > 30\,\mathrm{km} \end{cases}
\end{aligned}$$
where $Y$ is in cm/s$^2$, $c_1 = 0.447$, $c_2 = 0.597$, $c_3 = 0.00335$, $c_4 = -0.00330$, $c_5 = -0.334$, $c_6 = -0.373$, \$$a_1 = -6.73 \times 10^{-5}$ and $a_2 = 2.09 \times 10^{-2}$ [taken from Kanno et al. (2006)], $\sigma_\nu = 0.206$ (inter-event), $\sigma_\epsilon = 0.262$ (intra-event), $\sigma_T = 0.333$ (total) and $\sigma_c = 0.058$ (component). Take $G$ from Uchiyama and Midorikawa (2006).
- Use $V_{s,30}$, sometimes estimated using empirical relation between $V_{s,20}$ and $V_{s,30}$, to characterise sites. Distribution shows peak at about 300 m/s with few records > 800 m/s.
- Use data from KiK-Net (only surface instruments) and K-Net from before 08/2008. Use these networks because of their relatively high spatial densities, detailed site information and wide variety of source types (e.g. crustal and subduction) and sizes.
- Focal depth, roughly: $0 \leq H \leq 145$ km. No clear correlation between $M_w$ and $H$.
- To focus on motions for engineering applications, select data with: $M_w \geq 5.5$, $H < 200$ km, epicentres within 30°–46°N and 130°–148°E, $M$-$r_{rup}$ cut-off defined by Kanno et al. (2006) to ensure sufficient dynamic range and $100 \leq V_{s,30} \leq 1000$ m/s. Also generally eliminate events with < 5 records.
- Develop model for to study spatial correlation of ground-motion parameters. Similar to studies of Hong and Goda (2007) and Goda and Hong (2008) (see Section 2.283). Spatial-correlation models developed using inter- and intra-event residuals w.r.t. ground-motion model. This aspect of the model is not summarised here.
- Baseline correct records and apply 4th-order acausal Butterworth low-cut ($f_c = 0.05$ Hz) filter after padding with zeros.
- Use correction function $A$, where $R_{\mathrm{tr}}$ is shortest distance from site to Kuril and Izu-Bonin trenches, of Kanno et al. (2006) to model anomalous ground motions in NE Japan from intermediate and deep earthquakes occurring in the Pacific plate due to unique $Q$ structure beneath the island arc.
- Modify geometric decay term to model steeper decay for $r_{rup} < 75$ km and make additional adjustments to reduce biases seen in preliminary models and to achieve homoscedasticity in residuals, particularly for large $H$ and small $r_{rup}$.
- State that model should not be extrapolated to $M < 5.5$, $M > 8$ and $r_{rup} < 10$ km, where data scarce or non-existent.

## 2.316 Hong et al. (2009a)

- Ground-motion models are, for interface:

$$\log_{10} Y = c_1 + c_2 M_w + c_3 R - (1.82 - 0.16 M_w) \log_{10}(R + c_5 10^{c_6 M_w}) + c_7 H$$

where $Y$ is in $\mathrm{cm/s^2}$, $c_1 = 2.594$, $c_2 = 0.112$, $c_3 = -0.0037$, $c_5 = 0.0075$, $c_6 = 0.474$, $c_7 = -0.0033$, $\sigma_e = 0.20$ (inter-event), $\sigma_r = 0.27$ (intra-event) and $\sigma = 0.33$ (total) for maximum response; $c_1 = 2.545$, $c_2 = 0.108$, $c_3 = -0.0037$, $c_5 = 0.0075$, $c_6 = 0.474$, $c_7 = -0.0024$, $\sigma_e = 0.20$ (inter-event), $\sigma_r = 0.27$ (intra-event); $\sigma_c = 0.10$ (random-orientation variability) and $\sigma = 0.35$ (total) for geometric mean; and, for inslab:

$$\begin{aligned} \log_{10} Y &= c_1 + c_2 M_w + c_3 R - c_4 \log_{10} R + c_5 H \\ \text{where} \quad R &= \sqrt{R_{cld}^2 + (0.0075 \times 10^{0.507 M_w})^2} \end{aligned}$$

where $c_1 = -0.014$, $c_2 = 0.562$, $c_3 = -0.0039$, $c_5 = 0.0071$, $\sigma_e = 0.10$, $\sigma_r = 0.28$ and $\sigma = 0.30$ for maximum response; and $c_1 = -0.109$, $c_2 = 0.569$, $c_3 = -0.0039$, $c_5 = 0.0070$, $\sigma_e = 0.10$, $\sigma_r = 0.28$, $\sigma_c = 0.07$ and $\sigma = 0.30$ for geometric mean.

- All data from firm soil sites (NEHRP class B).
- Similar analysis to that of Hong and Goda (2007) (see Section 2.283) concerning orientation of major response axis but for data from Mexican subduction zone.
- Use data of García et al. (2005) (see Section 2.242) for inslab earthquakes.
- Focal depths, $H$, for interplate earthquakes are between 8 and 29 km and depths for inslab earthquakes are between 35 and 138 km.
- Examine correlation of ratio of response along an arbitrary direction to the maximum response in direction of major axis w.r.t. dependent and independent parameters and find that as an approximation there is no dependency.
- Provide statistical models to describe the ratio of response along an arbitrary direction to the maximum response in direction of major axis.
- Term expressing magnitude-dependency of decay (i.e. $1.82 - 0.16 M_w$) taken from previous study as is near-source saturation term (i.e. $0.0075 \times 10^{0.507 M_w}$).

## 2.317 Hong et al. (2009b)

- Ground-motion model is:

$$\ln Y = b_1 + b_2(\mathbf{M} - 7) + b_3(\mathbf{M} - 7)^2 + [b_4 + b_5(\mathbf{M} - 4.5)] \ln[(r_{jb}^2 + h^2)^{0.5}] + \mathrm{AF}_s$$

where $Y$ is in g, $b_1 = 1.143$, $b_2 = 0.398$, $b_3 = 0.0$, $b_4 = -1.125$, $b_5 = 0.064$, $h = 5.6$, $\sigma_\nu = 0.150$ (inter-event), $\sigma_\epsilon = 0.438$ (intra-event) and $\sigma_T = 0.463$ (total) for geometric mean and considering spatial correlation in regression analysis; $b_1 = 1.059(0.074)$, $b_2 = 0.383(0.095)$, $b_3 = -0.006(0.014)$, $b_4 = -1.083(0.068)$, $b_5 = 0.056(0.028)$, $h = 5.7(0.40)$, $\sigma_\nu = 0.187(0.014)$ (inter-event), $\sigma_\epsilon = 0.463(0.008)$ (intra-event) and $\sigma_T = 0.500(0.008)$ (total) for randomly-orientated component ignoring spatial correlation (based on 50 runs); and $b_1 = 1.087(00.072)$, $b_2 = 0.337(0.096)$, $b_3 = -0.011(0.018)$, $b_4 = -1.144(0.069)$, $b_5 = 0.077(0.027)$, $h = 5.6(0.38)$, $\sigma_\nu = 0.151(0.015)$ (inter-event), $\sigma_\epsilon = 0.467(0.008)$ (intra-event) and $\sigma_T = 0.491(0.008)$ (total) for randomly-orientated component considering spatial correlation (based on 50 runs). Numbers in brackets are standard deviations of coefficients.

- Use $V_{s,30}$ directly within amplification factor $\mathrm{AF}_s$ of Boore and Atkinson (2008) (see Section 2.276).

- Use same data and functional form as Hong and Goda (2007) (see Section 2.283).

- Modify the one- and two-stage maximum-likelihood regression methods of Joyner and Boore (1993) to consider spatial correlation of residuals from stations close together. The spatial correlation is incorporated into the covariance matrix of residuals, associated with both inter- and intra-event variability, via an empirical parametric spatial correlation model.

- Report results using two-stage approach but verify them using the one-stage method (not shown).

- Find that predictions of median ground motion not significantly affected by accounting for spatial correlation but $\sigma$s do change. When spatial correlation is considered, inter-event $\sigma$ decreases, intra-event $\sigma$ increases and total $\sigma$ decreases.

## 2.318 Kuehn et al. (2009)

- Ground-motion model is a nonphysical function (subsymbolic) (polynomial) of predictor variables ($M_w$, $r_{jb}$, $V_{s,30}$, fault mechanism and depth to top of rupture) with 48 coefficients (not reported) (14 for $M_w$, 5 for $r_{jb}$, 4 for $V_{s,30}$, 6 for rupture depth, 15 for combination of $M_w$ and $r_{jb}$, intercept parameter, pseudo-depth and 2 for mechanism). Use polynomials because simple, flexible and easy to understand.

- Characterize sites using $V_{s,30}$.

- Use three faulting mechanisms:

Reverse Rake angle between 30 and 150°. 19 earthquakes and 1870 records.

Normal Rake angle between −150 and −30°. 11 earthquakes and 49 records.

Strike slip Other rake angle. 30 earthquakes and 741 records.

- Use data from NGA project because best dataset currently available. Note that significant amount of metadata are missing. Discuss the problems of missing metadata. Assume that metadata are missing at random, which means that it is possible to perform unbiased statistical inference. To overcome missing metadata only select records where all metadata exist, which note is only strictly valid when metadata are missing completely at random.

- Select only records that are representative of free-field conditions based on Geomatrix classification C1.

- Exclude some data from Chi-Chi sequence due to poor quality or co-located instruments.

- Exclude data from $r_{jb} > 200$ km because of low engineering significance and to reduce correlation between magnitude and distance. Also note that this reduces possible bias due to different attenuation in different regions.

- In original selection one record with $M_w5.2$ and the next at $M_w5.61$. Record with $M_w5.2$ had a dominant role for small magnitudes so it was removed.

- Discuss the problem of over-fitting (modelling more spurious details of sample than are supported by data generating process) and propose the use of generalization error (estimated using cross validation), which directly estimates the average prediction error for data not used to develop model, to counteract it. Judge quality of model primarily in terms of predictive power. Conclude that approach is viable for large datasets.

- State that objective is not to develop a fully-fledged alternative NGA model but to present an extension to traditional modelling strategies, based on intelligent data analysis from the fields of machine learning and artificial intelligence.

- For $k$-fold cross validation, split data into $k$ roughly equal-sized subsets. Fit model to $k-1$ subsets and compute prediction error for unused subset. Repeat for all $k$ subsets. Combine $k$ prediction error estimates to obtain estimate of generalization error. Use $k = 10$, which is often used for this approach.

- Use $r_{jb}$ because some trials with simple functional form show that it gives a smaller generalization error than, e.g., $r_{rup}$.

- Start with simple functional form and add new terms and retain those that lead to a reduction in generalization error.

- Note that some coefficients not statistically significant at 5% level but note that 5% is an arbitrary level and they result in lower generalization error.

- Compare generalization error of final model to that from fitting the functional form of Akkar and Bommer (2007b) and an over-fit polynomial model with 58 coefficients and find they have considerably higher generalization errors.

- After having found the functional form, refit equation using random-effects regression.

- Note that little data for $r_{jb} < 5$ km.

- Note that weakness of model is that it is not physically interpretable and it cannot be extrapolated. Also note that could have problems if dataset is not representative of underlying data generating process.

- Note that problem with magnitude scaling of model since available data is not representative of underlying distribution.

## 2.319 Li et al. (2009)

- Ground-motion model is:

$$A_{max} = a10^{bM}(\Delta + 15)^c$$

  where $A_{max}$ is in cm/s$^2$, $a = 2.0$, $b = 0.8717$ and $c = -1.7631$ ($\sigma$ is not reported).

- Data from Yunnan between 1988 and 1998.

- Most data from $3.0 \leq M \leq 5.0$.

## 2.320 Mandal et al. (2009)

- Ground-motion model is:

$$\ln(Y) = a + bM_w - \ln(r_{jb}^2 + c^2)^{1/2} + dS$$

  where $Y$ is in g, $a = -7.9527$, $b = 1.4043$, $c = 19.82$, $d = -0.0682$ and $\sigma = 0.8243$.

- Use two site classes:

  $S = 0$ Rock/stiff. Relatively compact Jurassic formations. Believe that $V_{s,30} > 760$ m/s.

  $S = 1$ Soil. Alluvium or fragile Tertiary and Quaternary formations. Believe that $250 \leq V_{s,30} < 760$ m/s.

  Classify using geological information.

- Fault ruptures mainly less than 40 km depth.

- Use data from engineering seismoscopes (SRR) from 2001 $M_w$7.7 Bhuj earthquake and from strong-motion (20) and broadband (8) instruments of its aftershocks ($3.1 \leq M_w \leq 5.6$), which correct for instrument response. Earthquakes recorded at 3 to 15 stations.

- All data from aftershocks from $r_{epi} < 80$ km and all data from mainshock from $r_{jb} \leq 44$ km.

- Relocate earthquakes using local 1D velocity model. Report average error of 1 km in epicenter and 1.5 km in focal depth.

- Estimate seismic moments (from which compute $M_w$) and other source parameters, assuming Brune spectra, using spectral analysis of SH waves from transverse components. Report uncertainty of 0.05–0.1 units.

- Report that faults well mapped so believe $r_{jb}$s are quite reliable.

- Plot residuals w.r.t. $r_{jb}$. Find greater scatter in residuals for $0 \leq r_{jb} \leq 30$ km, which could be related to amplification/noise in data from stations in Kachchh sedimentary basin. Note lower scatter for range $100 \leq r_{jb} \leq 300$ km is unreliable due to lack of data.

- State equation less reliable for $100 \leq r_{jb} \leq 300$ km due to lack of data.

- Plot observations and predictions for $M_w$3.5, 4.1, 4.5, 5.6 and 7.7 and find fair match. Note that insufficient data to judge relation between $M_w$5.6 and 7.7. Find reasonable match to six records from 29 March 1999 Chamoli earthquake ($M_w$6.5) but poor match (predictions lower than observations) to single record from 10 December 1967 Koyna earthquake ($M_w$6.3).

## 2.321 Moss (2009) & Moss (2011)

- Ground-motion model is that of Chiou and Youngs (2008) (see Section 2.295). Also uses same data. This model selected since sufficiently complete and readily available at time of analysis.

- Notes that most GMPEs treat input variables as exact, neglecting uncertainties associated with measurements of $V_s$, $M_w$ and $r$. These uncertainties propagate through regression and result in model overestimating inherent variability in ground motion. Presents method to estimate uncertainty of input parameters and incorporate it into regression procedure using Bayesian framework.

- Follows on from Moss and Der Kiureghian (2006) (see Section 2.265).

- Presents the Bayesian framework used for regression. This procedure is iterative and leads to results that are slightly non-unique.

- Uses the functional form and data of Boore et al. (1997) for feasibility study. Repeat analysis of Boore et al. (1997) and confirm published results. Then assumes uncertainties on $V_{s,30}$ and $r_{jb}$ of coefficient of variation (COV) of 15% and find that intra-event $\sigma$ reduces by 15 and 17% respectively. Also introduces uncertainty of standard deviation of 0.1 on $M_w$ and finds inter-event $\sigma$ reduces by 20%. Overall finds reduction of 37%. Finds that coefficients obtained are similar to those found with standard regression.

- Discusses in detail the epistemic uncertainties associated with measurements of $V_s$ and the procedures and data used to quantify intra- and inter-method variabilities of measurement techniques. Conclusions are used to estimate standard deviations for each measurement of $V_{s,30}$ based on the measurement method, soil type and $V_{s,30}$ and possible bias in measurements are corrected using derived empirical formulae.

- Briefly discusses epistemic uncertainties associated with estimates of $M_w$. Plots standard deviations of $M_w$ estimates w.r.t. $M_w$ for NGA database. Finds negative correlation, which relates to a number of factors. Regression on data gives $\sigma_{M\_M} = -0.1820 \ln(M) + 0.4355$, which is combined with reported time component of standard deviation $\sigma_{M_t} = 0.081$ thus: $\sigma_M = \sqrt{\sigma^2_{M\_M} + \sigma_{M_t}}$ to give the overall uncertainty in $M_w$. Notes that more work is needed to quantify uncertainty in $M_w$. Does not include the uncertainty in $M_w$ in regression results.

- Discusses epistemic uncertainties in source-to-site distances and estimates different components of uncertainty. Notes that more work is needed to quantify uncertainties and, therefore, does not account for this uncertainty in regression.

- Replicates results reported by Chiou and Youngs (2008). Then assumes an average $V_{s,30}$ measurement uncertainty of COV$\approx$ 27% and reports the decrease in $\sigma$ (4%).

- Compare results to approximate solutions from first-order second-moment and Monte Carlo techniques, which are useful since they are quicker than the full Bayesian regression. Find reasonable match in results.

- Notes that the smaller $\sigma$s could have a large impact on PSHAs for long return periods.

## 2.322 Pétursson and Vogfjörd (2009)

- Ground-motion model is

$$\log_{10}(\mathrm{PGA}) = a \log_{10}(r + k10^{gM+eM^2}) + bM + c + dM^2$$

  where PGA is in g, $a = -2.26$, $b = 1.28$, $c = -2.85$, $d = -0.0437$, $e = -d/a = -0.0194$, $g = -b/a = 0.569$, $k = 0.0309$ and $\sigma = 0.302$.

- Detailed information on site conditions is not available hence do not include site terms in model.

- Focal depths between 0.04 and 9.49 km with most $\leq 6$ km.

- Use data from SIL national seismic network (3-component velocimeters) converted to acceleration. Most instruments are short-period Lennartz sensors (7 with corner frequency of 1 Hz and 35 with corner frequency of 0.2 Hz). 6 to 8 broadband sensors (CMG-3T, CMG-40T, CMG-ESP and STS2 with corner frequencies at 0.008 and 0.033 Hz). Full-scale amplitude of stations between 0.3 cm/s and 1.25 cm/s. Hence, at near-source distances records are often saturated and unusable. Most data have sampling rate of 100 Hz but some records are sampled at 20 Hz. First, remove instrument response. Next, high-pass filter (for short-period records use cut-off of 0.15 Hz and for broadband used 0.1 Hz). Finally, differentiate velocity to obtain acceleration. Do not use data sampled at 20 Hz nor data from distances $>$ 100 Hz from Lennartz 1 Hz sensors.

- Note that magnitudes of earthquaks with $M > 3$ are generally underestimated by SIL system, which is designed to monitor microseismicity. Therefore, use 5 of 6 largest earthquakes with teleseismic (Global CMT) $M_w$ estimates to calibrate the local moment magnitudes $M_{Lw}$ used for study.

- Develop model for use in ShakeMap and real-time aftershock hazard mapping applications.

- Most earthquakes from the Hengill region in 1997 and 1998. 7 are on Reykjanes Peninsula and 6 in the South Iceland Seismic Zone (mainly from sequence in 2000, which provides three largest earthquakes used).

- Note that model of Ágústsson et al. (2008) is significantly flawed. Use same data but remove data from Reykjanes Ridge and Myrdalsjokull because of uncertainties in magnitude estimates for these earthquakes.

- Data selected based on magnitude and number and quality of usable waveforms.

- Most data from $M_{Lw} \leq 5$ and $r_{epi} > 20$ km and distribution shows effect of saturation of records for larger ($M_{Lw} > 5$) earthquakes for $r_{epi} < 20$ km. Correlation coefficient between $M_{Lw}$ and $\log r_{epi}$ is 0.24. 39% of data is from 5 to 50 km.

- Also derive most using simpler functional form: $\log_{10}(\mathrm{PGA}) = -2.08 \log_{10}(r) - 0.0431M^2 + 1.21M - 2.96$ with $\sigma = 0.304$.

- In SW Iceland large earthquakes usually occur on NS faults. Hence, examine effect of radiation pattern. Add radiation pattern variable to model so that all earthquakes were assumed to take place on NS-striking vertical strike-slip faults. Find that, as predicted by theory, the coefficient multiplying this term was close to unity and standard deviation was significantly reduced. However, find that this term led to worse fit for some earthquakes and so it was dropped.

- Examine effect of instrument type using residual plots. Find that data from Lennartz 1 Hz sensors and Nanometrics RD3 0.5 Hz digitizers from > 100 km were lower than predicted, which led to them being excluded.

- Find that observations from hve station are consistently lower than predicted, which relate to strong attenuation in Western Volcanic Zone. Make similar observations for ada, bru and mok, which relate to propagation through crust and upper mantle of Eastern Volcanic Zone. Find data from snb station is consistently higher due to strong Moho relections from Hengill region earthquakes at about 130 km.

- Try form $\log_{10}(\mathrm{PGA}) = a \log_{10} \sqrt{r_{epi}^2 + k^2} + bM + c$ but find very small $k$. Also try form of Fukushima and Tanaka (1990) but find higher standard deviations.

- Discuss the theoretical basis of coefficient $g$ and its constraints w.r.t. $a$ and $b$. Initial regression with $g$ as free parameter led to coefficients very close to $g = -b/a$ (PGA independent of $M$ at source) and, therefore, impose this as constraint.

- Try weighted regression to correct for uneven magnitude and distance distribution but these are dropped since data follows magnitude distribution expected in SW Iceland and also run risk of putting too much emphasis on erroneous recordings.

- Find that residuals are approximately normally (in terms of $\log_{10}$) distributed, using normal $Q$-$Q$ plots.

- Compare predictions and observations for some magnitude ranges and for each earthquake grouped by geographical region.

- Fit $\log_{10}(\mathrm{PGA}) = a \log r_{epi} + \ldots$ using only data from < 150 km and $M_{Lw} > 4.7$ and find $a = -1.70$. Relate difference in distance scaling to lack of far-field data.

- Believe that model can be used between 0 and 380 km.

## 2.323 Rupakhety and Sigbjörnsson (2009)

- Ground-motion model is:

$$\log_{10}(S_a) = b_1 + b_2 M_w + b_3 \log_{10} \sqrt{d^2 + b_4^2} + b_5 S$$

where $S_a$ is in g, $b_1 = -1.038$, $b_2 = 0.387$, $b_3 = -1.159$, $b_4 = 2.600$, $b_5 = 0.123$ and $\sigma = 0.287$.

- Use two site classes:

Rock Eurocode 8 site class A, $V_{s30} > 800\,\mathrm{m/s}$. 64 records. $S = 0$.

Stiff soil Eurocode 8 site class B (21 records) or C (8 records), $180 < V_{s30} < 800\,\mathrm{m/s}$. $S = 1$.

- Most records from $M_w < 6.6$.
- Assume magnitude-independent decay rate, linear magnitude dependency and no anelastic term because insufficient data to do otherwise.
- Data primarily from south Iceland supplemented with records from Greece, Turkey and Slovenia.
- Exclude distant records because of low engineering significance and to minimise differences in anelastic decay between regions.
- Records from strike-slip earthquakes except for data from one oblique-faulting Icelandic earthquake. Select earthquakes from extensional regimes.
- Do not exclude data from buildings because of limited records. Exclude data from Thjorsarbru Bridge because they show clear structural effects and site dependent conditions not characteristic of study area as a whole.
- Records processed using individually-chosen filters.
- Show comparisons between predicted and observed normalized ground motions w.r.t. distance and conclude that selected functional form fits the data sufficiently well.
- Note that correlation matrix shows strong multi-collinearity between coefficients, which implies imprecise estimates of regression coefficients meaning that outside the range of the data predictions could be unreliable.

## 2.324 Akkar and Bommer (2010)

- Ground-motion model is:

$$\log y = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M) \log \sqrt{R_{\mathrm{jb}}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

  where $y$ is in $\mathrm{cm/s^2}$, $b_1 = 1.04159$, $b_2 = 0.91333$, $b_3 = -0.08140$, $b_4 = -2.92728$, $b_5 = 0.28120$, $b_6 = 7.86638$, $b_7 = 0.08753$, $b_8 = 0.01527$, $b_9 = -0.04189$, $b_{10} = 0.08015$, $\sigma_1 = 0.2610$ (intra-event) and $\sigma_2 = 0.0994$ (inter-event).

- Use three site categories:

Soft soil $S_S = 1$, $S_A = 0$.

Stiff soil $S_A = 1$, $S_S = 0$.

Rock $S_S = 0$, $S_A = 0$.

- Use three faulting mechanism categories:

Normal $F_N = 1$, $F_R = 0$.

Strike-slip $F_N = 0$, $F_R = 0$.

Reverse $F_R = 1$, $F_N = 0$.

- Use same data as Akkar and Bommer (2007b) (see Section 2.271) but repeat regression analysis for pseudo-spectral acceleration (rather than for spectral displacement), assuming homoscedastic variability, reporting the coefficients to five decimal places and not applying any smoothing. These changes made due to shortcomings revealed in GMPEs of Akkar and Bommer (2007b) after their use in various projects that required, for example, extrapolation outside their magnitude range of applicability and work reported in Bommer et al. (2007) (see Section 2.275) and other studies.

- Examine total, inter- and intra-event residuals w.r.t. $M_w$ and $r_{jb}$ and found no apparent trends (shown for a selection of periods). Note that some plots suggest magnitude-dependent variability but insufficient data to constrain it.

## 2.325 Akkar and Çağnan (2010) & Çağnan et al. (2011)

- Ground-motion model is [based on base model of Abrahamson and Silva (1997, 2008)]:

$$
\begin{aligned}
\ln(Y) &= a_1 + a_2(\mathbf{M} - c_1) + a_4(8.5 - \mathbf{M})^2 + [a_5 + a_6(\mathbf{M} - c_1)] \ln \sqrt{R_{jb}^2 + a_7^2} \\
&\quad + a_8 F_N + a_9 F_R + F_S \quad \text{for} \quad \mathbf{M} \le c_1 \\
\ln(Y) &= a_1 + a_3(\mathbf{M} - c_1) + a_4(8.5 - \mathbf{M})^2 + [a_5 + a_6(\mathbf{M} - c_1)] \ln \sqrt{R_{jb}^2 + a_7^2} \\
&\quad + a_8 F_N + a_9 F_R + F_S \quad \text{for} \quad \mathbf{M} > c_1 \\
\text{where} \quad F_S &= F_{LIN} + F_{NL} \\
F_{LIN} &= b_{lin} \ln\left(\frac{V_{S30}}{V_{ref}}\right) \\
F_{NL} &= b_{nl} \ln\left(\frac{\mathrm{pga_{low}}}{0.1}\right) \quad \text{for} \quad \mathrm{pga4nl} \le 0.03\,\mathrm{g} \\
F_{NL} &= b_{nl} \ln\left(\frac{\mathrm{pga_{low}}}{0.1}\right) + c\left[\ln\left(\frac{\mathrm{pga4nl}}{0.03}\right)\right]^2 + d\left[\ln\left(\frac{\mathrm{pga4nl}}{0.03}\right)\right]^3 \\
&\quad \text{for} \quad 0.03 < \mathrm{pga4nl} \le 0.09\,\mathrm{g} \\
F_{NL} &= b_{nl} \ln\left(\frac{\mathrm{pga4nl}}{0.1}\right) \quad \text{for} \quad \mathrm{pga4nl} > 0.09\,\mathrm{g}
\end{aligned}
$$

where $Y$ is in cm/s$^2$, $a_1 = 8.92418$, $a_2 = -0.513$, $a_3 = -0.695$, $a_4 = -0.18555$, $a_5 = -1.25594$, $a_6 = 0.18105$, $a_7 = 7.33617$, $a_8 = -0.02125$, $a_9 = 0.01851$, $\sigma = 0.6527$ (intra-event), $\tau = 0.5163$ (inter-event) and $\sigma_{Tot} = \sqrt{\sigma^2 + \tau^2} = 0.8322$ and $b_{lin} = -0.36$, $b_1 = -0.64$ and $b_2 = -0.14$ [taken from Boore and Atkinson (2008)]. Fix $c_1 = 6.5$. pga4nl is predicted PGA in g for $V_{s,30} = 760$ m/s. See Boore and Atkinson (2008) for $b_{nl}$, $c$ and $d$ [not repeated by Akkar and Çağnan (2010)].

- Characterise sites using $V_{s,30}$ and use the site response terms of Boore and Atkinson (2008) because of their simplicity and fairly good performance for data (demonstrated by intra-event residual plots and their distributions that do not show clear trends, except perhaps for $V_{s,30} > 720$ m/s). Majority of records from NEHRP C ($360 \le V_{s,30} \le 760$ m/s) and D ($180 \le V_{s,30} < 360$ m/s) sites with very few from sites with $V_{S30} \ge 760$ m/s. All sites have measured $V_{s,30}$ values.

- Use three faulting mechanisms:

Normal $F_N = 1$, $F_R = 0$. 28% of records.

Strike-slip $F_N = 0$, $F_R = 0$. 70% of records.

Reverse/thrust $F_N = 0$, $F_R = 1$. 2% of records.

- Focal depths between about 0 and 50 km with most between 5 and 20 km.

- Use data from the recently compiled Turkish strong-motion database (Akkar et al., 2010), for which the independent parameters were carefully reassessed.
- Note that there are many singly-recorded earthquakes.
- Vast majority of data from $M_w < 6$ and $r_{jb} > 10$ km.
- Explore several functional forms (not shown). Try to keep balance between rigorous model (for meaningful and reliable estimations) and a robust expression (for wider implementation in engineering applications).
- Data from 102 mainshocks (346 records) and 35 aftershocks (88 records).
- Bandpass filter records using method of Akkar and Bommer (2006).
- Compare PGAs from unfiltered and filter records and find negligible differences.
- Note that aim of study is not to promote the use of poorly-constrained local models.
- Use pure error analysis (Douglas and Smit, 2001) to investigate magnitude-dependence of $\sigma$. Find strong dependence of results on binning strategy (including some bins that suggest increase in $\sigma$ with magnitude) and, therefore, disregard magnitude dependency.
- Derive GMPEs using data with minimum thresholds of $M_w3.5$, $M_w4.0$, $M_w4.5$ and $M_w5.0$ to study influence of small-magnitude data on predictions. Find that equation using $M_w5.0$ threshold overestimates PGAs derived using lower thresholds; however, ranking of predictions from GMPEs using thresholds of $M_w3.5$, $M_w4.0$ and $M_w4.5$ is not systematic.
- Note that due to limited records from reverse-faulting earthquakes, the coefficient $a_9$ needs refining using additional data.
- Examine inter-event residuals for PGA, 0.2 s and 1 s w.r.t. $M_w$ and intra-event residuals w.r.t. $r_{jb}$ and $V_{s,30}$. Fit straight lines to residuals and also compute bias over ranges of independent variables. Test significance of trends at 5% level. Find no significant bias w.r.t. $M_w$ nor w.r.t. $r_{jb}$. For $V_{s,30}$ for 1 s find significant overestimation for $V_{s,30} > 450$ m/s, which relate to linear site term. Suggest linear site term needs adjustment using Turkish data.
- Compute inter-station residuals and identify 9 outlier stations, which are those with residuals mainly outside range generally observed.
- Examine bias of residuals for mainshock and aftershock records. Find weak evidence for overestimation of aftershock motions but this is not significant at the 5% level.
- Combine Turkish and Italian data from ITACA (1004 records) and derive GMPEs using same functional form, except using site classes rather than $V_{s,30}$ directly, to test observed differences between local and global GMPEs.
- Compare focal depth distributions, using histograms with intervals of 5 km, of the datasets for various GMPEs. Compute mean and standard deviations of $M_w$ for each depth bin. Find that records from Turkey and Italian are on average deeper than those for other GMPEs, which seems to explain lower observed motions. Conclude that focal depth can be important in explaining regional differences.

## 2.326 Arroyo et al. (2010)

- Ground-motion model is:

$$
\begin{aligned}
\ln \mathrm{SA}(T) &= \alpha_1(T) + \alpha_2(T) M_w + \alpha_3(T) \ln \left[ \frac{E_1(\alpha_4(T)R) - E_1(\alpha_4(T)\sqrt{R^2 + r_0^2})}{r_0^2} \right] \\
r_0^2 &= 1.4447 \times 10^{-5} \mathrm{e}^{2.3026 M_w}
\end{aligned}
$$

  where SA is in $\mathrm{cm/s^2}$, $E_1(x)$ is the exponential integral function, $\alpha_1 = 2.4862$, $\alpha_2 = 0.9392$, $\alpha_3 = 0.5061$, $\alpha_4 = 0.0150$, $b = -0.0181$, $\sigma = 0.7500$ (total), $\sigma_e = 0.4654$ (inter-event) and $\sigma_r = 0.5882$ (intra-event).

- All data from rock (NEHRP B) sites. Data from stations with known, significant site amplification and those located in volcanic belt are excluded. Use H/V ratios to verify that stations are all on generic rock. Data from 56 different stations.

- Focal depths between 10 and 29 km.

- Functional form is based on the analytical solution of a circular finite-source model and body waves, which also defines expression for $r_0$ (the radius of the circular fault based on Brune's model) using a stress drop of 100 bar in order to keep functional form as simple as possible. Note that functional form allows for oversaturation, whose existence is questionable.

- Select data of interplate, thrust-faulting events (interface) from permanent networks between 1985 and 2004 on the Pacific coast between Colima and Oaxaca (majority of data from Guerrero but some data from other regions, especially Oaxaca). Data from near-trench earthquakes whose high-frequency radiation is anomalously low are excluded. To focus on ground motions of engineering interest, exclude data from small ($M_w \leq 5.5$) with few records that are only from distant stations ($R > 100$ km). Exclude data from $> 400$ km (use a larger distance than usual because of previously observed slow decay). To reduce potential variability of data, select only one record from two stations recording the same earthquake at less than 5 km (based on visual inspection of data).

- Data from 12–19 bit digital accelerographs (66% of data), which have flat response down to less than 0.1 Hz, and 24 bit broadband seismographs (34% of data), which have flat response for velocities between 0.01 and 30 Hz. Broadband data mainly from $M_w < 6$ and distances $> 100$ km. Sampling rates between 80 and 250 Hz. Instrumental responses and sampling rates mean data reliable up to 30 Hz.

- Roughly 45% of records from 20–100 km. Only 16 records from $< 25$ km and only 5 from 3 earthquakes with $M_w > 7$ and, therefore, note that any anomalous records will strongly influence results in this distance range. State that more near-source data from large Mexican interplate earthquakes needed.

- Use Bayesian regression that accounts, for linear functions, for these correlations: 1) intra-event, 2) between coefficients and 3) between different periods. To linearize function perform regression as: for a given period and value of $\alpha_4$, compute coefficients $\alpha_1$, $\alpha_2$ and $\alpha_3$ through Bayesian analysis and iterate for different values of $\alpha_4$ to find the value that gives best fit to data. This is repeated for each period. Note that this means the regression is not fully Bayesian. To obtain prior information on coefficients $\alpha_1$, $\alpha_2$ and $\alpha_3$ use random vibration theory and theoretical expression for Fourier amplitude spectrum. Define other required prior parameters (covariances etc.) using previous studies. Smooth $\alpha_4$ w.r.t. period. Discuss differences between prior and posterior values and not that final results not over-constrained to mean prior values.

- Find that model systematically overestimates in whole period range but since less than 5% consider bias acceptable.

- Plot residuals w.r.t. $M_w$, distance and depth and find no significant trend. Note that even though focal depth is not included in model there is no significant dependence on it.

- Adjust observed near-source PGAs to a common distance of 16 km and include data from $M_w$2.5–4.9 from $r_{hypo}$ between 16 and 37 km. Compare to predictions. Note the large scatter (more than an order of magnitude) so note that statistical significance is low. Note that model matches observations reasonably well.

## 2.327 Bindi et al. (2010)

- Ground-motion model is:

$$\begin{aligned}\log_{10} Y &= a + b_1(M_w - M_{ref}) + b_2(M_w - M_{ref})^2 \\ &\quad +[c_1 + c_2(M_w - M_{ref})] \log_{10} \sqrt{(R^2 + h^2)} + e_i S_i + f_j F_j\end{aligned}$$

  where $Y$ is in $\mathrm{cm/s^2}$ and $M_{ref} = 4.5$; $a = 3.7691$, $b_1 = 0.0523$, $b_2 = -0.1389$, $c_1 = -1.9383$, $c_2 = 0.4661$, $h = 10.1057$, $C_0 = 0$, $C_1 = 0.2260$, $C_2 = 0.1043$, $\sigma_{eve} = 0.2084$, $\sigma_{sta} = 0.2634$ and $\sigma = 0.3523$ for horizontal PGA using $r_{jb}$; $a = 3.2191$, $b_1 = 0.1631$, $b_2 = -0.0765$, $c_1 = -1.7613$, $c_2 = 0.3144$, $h = 9.1688$, $C_0 = 0$, $C_1 = 0.1938$, $C_2 = 0.1242$, $\sigma_{eve} = 0.2080$, $\sigma_{sta} = 0.1859$ and $\sigma = 0.3384$ for vertical PGA using $r_{jb}$; $a = 3.750$, $b_1 = 0.1180$, $b_2 = -0.1147$, $c_1 = -1.9267$, $c_2 = 0.4285$, $h = 10.0497$, $C_0 = 0$, $C_1 = 0.2297$, $C_2 = 0.1022$, $\sigma_{eve} = 0.2103$, $\sigma_{sta} = 0.2666$ and $\sigma = 0.3555$ for horizontal PGA using $r_{epi}$; and $a = 3.2015$, $b_1 = 0.2482$, $b_2 = -0.0428$, $c_1 = -1.7514$, $c_2 = 0.2588$, $h = 9.1513$, $C_0 = 0$, $C_1 = 0.1983$, $C_2 = 0.1230$, $\sigma_{eve} = 0.1917$, $\sigma_{sta} = 0.1877$ and $\sigma = 0.3241$ for vertical PGA using $r_{epi}$[26].

- Use three site classes following Sabetta and Pugliese (1987, 1996):

  $C_0$ Rock. Corresponding to NEHRP A and B categories. 104 stations. $S_1 = 1$ and $S_2 = S_3 = 0$.

  $C_1$ Shallow sediment: deposits thinner than or equal to 20 m and thicker than 5 m. $V_s$ of sediment lower than 800 m/s. 47 stations. $S_2 = 1$ and $S_1 = S_3 = 0$.

  $C_2$ Deep sediment: deposits thicker than 20 m. 55 stations. $S_3 = 1$ and $S_1 = S_2 = 0$.

  Site classification performed using verified geological, geophysical and geotechnical information but of varying detail. Note that classification between $C_1$ and $C_2$ is a simple but efficient method to identify sites with amplifications at frequencies larger or smaller than 2–5 Hz. Data from 206 different stations.

- Use four faulting mechanism classes:

  Normal 50 earthquakes.

  Strike-slip 12 earthquakes.

  Reverse 17 earthquakes.

  Unknown 28 earthquakes.

  Find that mechanism coefficients are not significantly different than zero and, therefore, remove them.

- Focal depths between 0 and 29.21 km.

- Use data from Italian Accelerometric Archive (ITACA) from between 1972 and 2007, which have been carefully revised during a project funded by the Italian Department of Civil Protection, plus some data from the Northern Italy Strong Motion network (RAIS). Records individually processed using acausal fourth-order Butterworth filters with cut-offs selected by visual inspection of Fourier spectra.

- Select records with $r_{jb} < 100$ km from earthquakes with $M_w \geq 4$ recorded at two or more stations.

[26] There is an inconsistency between the names given to the site coefficients in the tables of this article ($C_0$, $C_1$ and $C_2$) and those used to describe the functional form ($e_0$, $e_1$ and $e_2$).

- $M_w \leq 6$ are well sampled for $r_{jb} > 5$ km, particularly for $4 \leq M_w \leq 4.6$. No data from $r_{jb} < 10$ km from earthquakes with $M_w > 6$.

- Compare PGAs and $r_{jb}$ for common records with Sabetta and Pugliese (1987). For PGA find similar values, indicating that the different processing applied results in consistent results. For $r_{jb}$ find significant differences for distances shorter than 20 km, which attribute to improvements in knowledge of source geometries.

- Examine inter-event and inter-station residuals. Find most inter-event errors are between $-0.2$ and 0.2 with a few events (e.g. 2002 Molise) with largely or over- or under-estimated.

- When comparing observations and predictions for Irpina ($M_w$6.9) 1980 earthquake state that comparisons unreliable for $r_{jb} < 10$ km due to lack of data.

- Compare predictions and observations for the 23/12/2008 ($M_w$5.4) northern Apennines earthquake mainshock to Parma and its $M_w$4.9 aftershock (both with focal depth $> 20$ km and reverse mechanism), which were not used to develop GMPEs. 33 records ($32 \leq r_{epi} \leq 217$ km) of mainshock and 26 ($9 \leq r_{epi} \leq 217$ km) records of aftershock. Find the most observations fall within $\pm 1\sigma$ but some for $30 \leq r_{epi} \leq 60$ km are over-estimated by up to one order of magnitude.

- Note importance of improving site categorization to reduce $\sigma_{sta}$.

## 2.328 Cua and Heaton (2010)

- Ground-motion model is:

$$
\begin{aligned}
\log Y &= aM + b[R_1 + C(M)] + d\log[R_1 + C(M)] + e \\
R_1 &= \sqrt{R^2 + 9} \\
C(M) &= c_1 \exp[c_2(M-5)][\tan^{-1}(M-5) + \pi/2]
\end{aligned}
$$

  where $Y$ is in cm/s$^2$, $a = 0.73$, $b = -7.2 \times 10^{-4}$, $c_1 = 1.16$, $c_2 = 0.96$, $d = -1.48$, $e = -0.42$ and $\sigma = 0.31$ for rock and $a = 0.71$, $b = -2.38 \times 10^{-3}$, $c_1 = 1.72$, $c_2 = 0.96$, $d = -1.44$, $e = -2.45 \times 10^{-2}$ and $\sigma = 0.33$ for soil.

- Use two site classes using southern California site classification map based on $V_{s,30}$ of Wills et al. (2000):

  Rock Class BC and above, $V_{s,30} > 464$ m/s. 35 SCSN stations with 958 records. 50 records from NGA.

  Soil Class C and below, $V_{s,30} \leq 464$ m/s. No data from very soft soils. 129 SCSN stations with 2630 records. 1557 records from NGA.

  and develop independent equations for each since sufficient data.

- Use data from the Southern California Seismic Network (SCSN) (150 stations) and COSMOS (6 events) supplemented by the Next Generation Attenuation (NGA) dataset. Mainly used broadband data from SCSN except when clipped, when accelerometric data is used instead.

- Correct records for gain and baseline and convert to acceleration using differentiation, if needed.

- For SCSN data use S-wave envelope amplitudes and not PGAs directly. Note that should be comparable to true PGAs.

- Constrain $c_2$ to be approximately unity within regression.

- Develop conversion factors for converting between different definitions of horizontal component and their $\sigma$s.
- Compare predicted and observed PGAs for ranges: $6.5 < M < 7.5$ (predictions for $M7.0$), $4.0 < M < 6.0$ (predictions for $M5.0$) and $M < 3.0$ (predictions for $M2.5$) and find good match.
- Examine residuals and find no significant trends w.r.t. distance or magnitude.
- Compute station-specific site corrections for SCSN stations that recorded more than 3 times. Applying these corrections for rock PGA produces a 20% reduction in $\sigma$ (to 0.24).

## 2.329 Douglas and Halldórsson (2010)

- Ground-motion model is the same as Ambraseys et al. (2005a) (see Section 2.237) with the addition of a term $b_{11}$AS, where AS $= 1$ for an aftershock record and 0 otherwise. Find predicted motions from aftershocks slightly smaller than from mainshocks.
- Examine total residual plots, biases and standard deviations of rederived GMPEs of Ambraseys et al. (2005a) with magnitude-independent $\sigma$ with earthquake classified as aftershock or other. Do not find significant differences in residuals between aftershocks and the rest of the data.
- Discuss the use of aftershock data when developing GMPEs.

## 2.330 Faccioli et al. (2010)

- Ground-motion model is:

$$\begin{aligned}\log_{10}\mathrm{DRS}(T) &= a_1 + a_2 M_w + a_3\log_{10}(R_{rup} + a_4 10^{a_5 M_w}) \\ &\quad + a_B S_B + a_C S_C + a_D S_D + a_N E_N + a_R E_R + a_S E_S\end{aligned}$$

  where DRS($T$) is in cm/s$^2$, $a_1 = -1.18$, $a_2 = 0.559$, $a_3 = -1.624$, $a_4 = 0.018$, $a_5 = 0.445$, $a_B = 0.25$, $a_C = 0.31$, $a_D = 0.33$, $a_N = -0.01$, $a_R = 0.09$, $a_S = -0.05$, $k_1 = 2.03$, $k_2 = -0.138$, $k_3 = -0.962$ and $\sigma = 0.36$[27].

- Use four Eurocode 8 classes:

  A Rock. $S_B = S_C = S_D = 0$.

  B Stiff soil. $S_B = 1$, $S_C = S_D = 0$.

  C Medium-dense soil deposits. $S_C = 1$, $S_B = S_D = 0$.

  D Soft soil deposits. $S_D = 1$, $S_B = S_C = 0$.

- Use three faulting mechanisms:

Normal $E_N = 1$, $E_R = E_S = 0$.

Reverse $E_R = 1$, $E_N = E_S = 0$.

Strike-slip $E_S = 1$, $E_N = E_R = 0$.

- Update of Cauzzi and Faccioli (2008) (see Section 2.293) using more data and $r_{rup}$ rather than $r_{hypo}$ because this is more appropriate close to large earthquakes.

[27] Typographical error in article ($E_I$ should be $E_S$).

- Find that differences between $r_{rup}$ and $r_{hypo}$ are not statistically significant for $M_w \leq 5.7$ so use $r_{hypo}$ below this threshold.
- Most data from Japan.
- Use a subset of data to decide on the best functional form, including forms with $M_w^2$ and/or distance-saturation terms and site classes or $V_{s,30}$ directly.
- Carefully examine (not show) fit between predicted and observed spectra in near-source region and find distance-saturation term provides best fit.
- Note that $M_w^2$ term has negligible impact on $\sigma$ but improves predictions for large $M_w$. Drops $M_w^2$ from final functional form.
- Find site terms significantly reduce $\sigma$.
- Effect of style of faulting terms on $\sigma$ is minimal but does improve predictions.
- Note that functional form means that one-step rather than two-step approach must be used that means that effects of magnitude and distance cannot be decoupled and $\sigma$s are larger.
- Compare predictions and observations for two records and find overprediction in one case and underprediction in other, which relate to the approximation of the model and not an error in determination of coefficients.
- Test model against data ($4.5 \leq M_w \leq 6.9$, $r_{rup} < 150$ km) from the Italian Accelerometric Archive (ITACA) using residual plots and method of Scherbaum et al. (2004). Find that good ranking is obtained using approach of Scherbaum et al. (2004). Find trends in residual plots, which correct using functions, with coefficients $k_1$, $k_2$ and $k_3$, fit to the residuals. $k_i$ can be added to $a_i$ to obtain corrected coefficients ($a_4$ and $a_5$ are unchanged).
- Note that improvements to Cauzzi and Faccioli (2008) are still ongoing.

## 2.331 Graizer et al. (2010) & Graizer et al. (2013)

- Ground-motion model is:

$$
\begin{aligned}
\ln(Y) &= \ln(A) - 0.5\ln\left[\left(1-\frac{R}{R_2}\right)^2 + 4D_2^2\frac{R}{R_2}\right] - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_3}}\right)^2 + 4D_3^2\sqrt{\frac{R}{R_3}}\right] + \\
&\quad b_v\ln\left(\frac{V_{s,30}}{V_A}\right) - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_5}}\right)^2 + 4D_5^2\sqrt{\frac{R}{R_5}}\right] \\
A &= [c_1\arctan(M+c_2)+c_3]F \\
R_2 &= c_4M + c_5 \\
D_2 &= c_6\cos[c_7(M+c_8)] + c_9 \\
R_5 &= c_{11}M^2 + c_{12}M + c_{13}
\end{aligned}
$$

where $Y$ is in g, $c_1 = 0.14$, $c_2 = -6.25$, $c_3 = 0.37$, $c_4 = 3.67$, $c_5 = -12.42$, $c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.15$, $c_9 = 0.525$, $c_{10} = -0.16$, $c_{11} = 18.04$, $c_{12} = -167.9$, $c_{13} = 476.3$, $D_5 = 0.7$, $b_v = -0.24$, $V_A = 484.5$, $R_3 = 100$ km, $\sigma = 0.83$ (given by (Graizer et al., 2010) and reported in text of Graizer et al. (2013)) and $\sigma = 0.55$ (Graizer et al., 2013, Figure 6). Coefficients $c_4$, $c_5$, $c_{10}$–$c_{13}$ and $D_5$ are newly derived as is $\sigma$ — the others are adopted from GMPE of Graizer and Kalkan (2007). $D_3 = 0.65$ for $Z < 1$ km and 0.35 for $Z \geq 1$ km.

- Use sediment depth $Z$ to model basin effects.
- Use two faulting mechanisms:
  1. Strike-slip and normal. $F = 1.00$
  2. Reverse. $F = 1.28$
- Update of GMPE of Graizer and Kalkan (2007) (see Section 2.281) to model faster attenuation for $R > 100$ km using more data (from the USGS-Atlas global database).
- Compare data binned into 9 magnitude ranges with interval 0.4 and find good match.
- Note that large $\sigma$ due to variability in Atlas database.
- Using data binned w.r.t. $M_w$ and into 25 distance bins (with spacing of 20 km) derive these models for $\sigma$: $\sigma = -0.043M + 1.10$ and $\sigma = -0.0004R + 0.89$.
- Examine residual plots w.r.t. distance, $M_w$ and $V_{s,30}$ and find no trends.

## 2.332 Hong and Goda (2010)

- Ground-motion models are the same as Hong et al. (2009a) (see Section 2.316) for interplate and inslab Mexican earthquakes and Hong and Goda (2007) and Goda and Hong (2008) (see Section 2.283) for intraplate Californian earthquakes. Coefficients are: $b_1 = 1.271$, $b_2 = 0.337$, $b_3 = 0.0$, $b_4 = -1.119$, $b_5 = 0.063$, $h = 5.9$, $\sigma_\eta = 0.190$, $\sigma_\epsilon = 0.463$, $\sigma_T = 0.501$ and $\text{PGA}_{ref} = \exp[1.0 + 0.446(M_w - 7) - 0.888 \ln(r_{jb}^2 + 6.3^2)^{0.5}]$ for major principal axis and $b_1 = 0.717$, $b_2 = 0.454$, $b_3 = -0.009$, $b_4 = -1.000$, $b_5 = 0.041$, $h = 5.0$, $\sigma_\eta = 0.182$ (inter-event), $\sigma_\epsilon = 0.441$ (intra-event), $\sigma_T = 0.477$ (total) and $\text{PGA}_{ref} = \exp[0.532 + 0.518(M_w - 7) - 0.846 \ln(r_{jb}^2 + 5.6^2)^{0.5}]$ for minor principal axis for intraplate California; $c_1 = -3.005$, $c_2 = 0.555$, $c_3 = -0.00392$, $c_4 = 0.0079$, $\sigma_\eta = 0.106$ (inter-event), $\sigma_\epsilon = 0.285$ (intra-event) and $\sigma_T = 0.304$ (total) for major principal axis and $c_1 = -3.253$, $c_2 = 0.575$, $c_3 = -0.00380$, $c_4 = 0.0079$, $\sigma_\eta = 0.121$, $\sigma_\epsilon = 0.270$ (intra-event) and $\sigma_T = 0.296$ (total) for minor principal axis for inslab Mexican earthquakes; and $d_1 = -0.396$, $d_2 = 0.113$, $d_3 = -0.00361$, $d_4 = 0.0075$, $d_5 = 0.474$, $d_6 = -0.0040$, $\sigma_\eta = 0.193$ (inter-event), $\sigma_\epsilon = 0.264$ (intra-event) and $\sigma_T = 0.327$ (total) for major principal axis and $d_1 = -0.653$, $d_2 = 0.125$, $d_3 = -0.00356$, $d_4 = 0.0075$, $d_5 = 0.474$, $d_6 = -0.00177$, $\sigma_\eta = 0.200$ (inter-event), $\sigma_\epsilon = 0.273$ and $\sigma_T = 0.339$ (total) for minor principal axis for interface Mexican earthquakes.
- Similar analysis to that of Hong and Goda (2007) (see Section 2.283) and Hong et al. (2009a) (see Section 2.316) concerning orientation of major response axis.
- Conduct analyses for intraplate Californian (Hong and Goda, 2007) and interface and inslab Mexican data (Hong et al., 2009a).
- Discuss impact of different definitions of horizontal component on predicted ground motions and $\sigma$s for the three types of earthquake.

## 2.333 Iervolino et al. (2010)

- Ground-motion model is:

$$\log_{10} Y = a + bM + c \log_{10}(R^2 + h^2)^{1/2} + dS_1 + eS_2$$

  where $Y$ is in cm/s$^2$, $a = 1.12$, $b = 0.34$, $c = -0.89$, $d = 0.16$, $e = -0.065$, $h = 5.0$ and $\sigma = 0.19$ (when using $r_{epi}$) and $a = 1.44$, $b = 0.27$, $c = -0.87$, $d = 0.16$, $e = -0.016$, $h = 5.8$ and $\sigma = 0.18$ (when using $r_{jb}$). $h$ values taken from Sabetta and Pugliese (1987).

- Use 3 site classes:

$$\begin{aligned} \text{Rock} \quad & S_1 = S_2 = 0 \\ \text{Shallow alluvium} \quad & S_1 = 1,\, S_2 = 0 \\ \text{Deep alluvium} \quad & S_2 = 1,\, S_1 = 0. \end{aligned}$$

- Use data of Sabetta and Pugliese (1987).
- Derive model to show concept of conditional hazard maps.
- Find that maximum-likelihood regression leads to similar coefficients.
- Test significance of $e$ using Student $t$-test and find that the null hypothesis that it equals zero cannot be rejected at 5%.
- Use Shapiro and Wilk test to check that residuals are normally distributed. Results (not shown) indicate that the null hypothesis of normality cannot be rejected at 5% significance level.

## 2.334 Jayaram and Baker (2010)

- Ground-motion model is that of Campbell and Bozorgnia (2008b) (see Section 2.277).
- Use same data as Campbell and Bozorgnia (2008b) (see Section 2.277).
- Modify the random-effects regression method of Abrahamson and Youngs (1992) to account for spatial correlation defined by a pre-defined empirical model dependent on separation distance or derived during the regression analysis. Prefer the use of a pre-defined empirical model for various reasons.
- To provide baseline model for comparison, refit model of Campbell and Bozorgnia (2008b) using random-effects regression ignoring spatial correlation. Find minor differences with reported coefficients of Campbell and Bozorgnia (2008b), which relate to manual coefficient smoothing.
- Find intra-event $\sigma$ increases and inter-event $\sigma$ decreases but total $\sigma$ remains roughly the same when spatial correlation is accounted for. Provide theoretical justification for difference in $\sigma$s if spatial correlation between records is considered or not.
- Do not report coefficients, only provide graphs of $\sigma$s.
- State that, because regression coefficients are not significant different if spatial correlation is accounted for, the regression procedure can be simplified.
- Discuss the implications of findings on risk assessments of spatially-distributed systems.

## 2.335 Montalva (2010) & Rodriguez-Marek et al. (2011)

- Ground-motion model is for combined model using both surface and borehole records[28] (same as Boore and Atkinson (2008)):

$$
\begin{aligned}
\mu^A_{med} &= F_m + F_d + F_{site}\mathrm{Surf}_{flag} + F_{100}\mathrm{S100}_{flag} + F_{200}\mathrm{S200}_{flag} \\
F_m &= e_1 + e_5(M_w - M_h) + e_6(M_w - M_h)^2 \quad \text{for} \quad M_w \le M_h \\
F_m &= e_1 + e_7(M_w - M_h) \quad \text{for} \quad M_w \ge M_h \\
F_d &= [c_1 + c_2(M_w - M_h)]\ln(R/R_{ref}) + c_3(R - R_{ref}) \\
R &= \sqrt{R^2_{RUP} + h^2} \\
F_{site} &= b_{lin}\ln(V_{s30}/V_{ref}) + \mathrm{bh800}\ln(\mathrm{h800}/h_{ref}) \\
F_{100} &= a_{100} + b_{100}\ln(V_{s30}/V_{ref}) + c_{100}\ln(\mathrm{Vshole}/\mathrm{Vshole}_{ref}) \\
F_{200} &= a_{200} + b_{200}\ln(V_{s30}/V_{ref}) + c_{200}\ln(\mathrm{Vshole}/\mathrm{Vshole}_{ref})
\end{aligned}
$$

  where $\mu^A_{med}$ is in g, $M_{ref} = 4.5$, $R_{ref} = 1$ km, $V_{ref} = 760$ m/s, $h_{ref} = 60$ m and $\mathrm{Vshole}_{ref} = 3000$ m/s (reference values); $c_1 = -1.2534$, $c_2 = 0.4271$, $c_3 = -0.0140$, $e_1 = -0.0663$, $e_5 = -0.5997$, $e_6 = -0.5012$, $e_7 = 0$, $b_{lin} = -0.4665$, $\mathrm{bh800} = -0.1801$, $a_{100} = -1.4372$, $a_{200} = -1.6518$, $b_{100} = -0.0269$, $b_{200} = -0.1884$, $c_{100} = -0.2666$, $c_{200} = -0.3793$, $\phi = 0.6293$ (intra-event) for $M_w < 5$, $\phi = 0.6202$ (intra-event) for $M_w > 6.5$, $\tau = 0.4929$ (inter-event) for $M_w < 5$, $\tau = 0.9164$ (inter-event) for $M_w > 6.5$ (linear interpolation of $\phi$ and $\tau$ between $M_w5$ and 6.5) and $\tau^* = 0.4981$ for $M_w > 6.5$ (computed using inter-event residuals corrected for the observed bias using a linear term) [29].

- Characterise sites by $V_{s,30}$, depth to reach $V_s$ of 800 m/s (h800) and $V_s$ at bedrock (Vshole).
- Uses an NGA functional form to reflect state of the art in ground-motion prediction and the form of Boore and Atkinson (2008) specifically because it can be constrained by the data.
- Extension of analysis by Rodriguez-Marek and Montalva (2010) (see Section 4.201).
- Analysis conducted to investigate single-site variability of ground motions.
- Data from KiK-net on surface and at depth as processed by Pousse et al. (2005) and Cotton et al. (2008) (see Sections 4.131 and 2.296 for details). Note that although Cotton et al. (2008) state that spectral accelerations up to 3 s can be used, in fact some spectral accelerations at long periods are less than the number of decimals used for storing the data. Hence limit analysis to periods $< 1.3$ s.
- Majority of data is for $M_w \le 6.1$, which will have an impact on the regression.
- Presents histogram of $V_{s,30}$ at surface stations: peak around 500 m/s with very few records for $V_{s,30} > 1000$ m/s.
- Presents histogram of borehole depths: almost all at 100 and 200 m. Use flag to indicate borehole instrument depth $\le 150$ m or $> 150$ m.
- Presents histogram of $V_{s,30}$ at borehole stations: roughly uniformly distributed between 1000 m/s and 2500 m/s with some higher and lower.
- Notes that geographical distribution of earthquakes shows clusters that could enable a further separation of source and path effects from site effects in future studies.

[28]Same functional form is used for separate models using only surface and only borehole records but without the flags indicating surface or borehole stations.

[29]$M_h$ not clearly stated in report but could be 5.6 (p. 150).

- Only uses data from earthquake that were recorded by $\geq 5$ stations to adequately constrain inter-event residuals.
- Uses multiple step regression method. First, uses only data from earthquakes recorded by $> 100$ stations to constrain $c_3$ and $h$ by maximum-likelihood regression (after fixing $c_1$ to a value between $-0.2$ and $-1.1$ and fixing $c_2$ to 0). Next finds $M_h$ and $e_7$. Originally find that $e_7$ is negative (oversaturation) but note that lack of data from large earthquakes so constrain it to be positive. $M_h$ is chosen by inspection. Rest of coefficients found by random-effects regression.
- Combined model assumes source and path terms are independent of near-surface layering, which note is desired from a phenomenological view.
- Plots inter-event residuals against $M_w$ and find overestimation for $M_w > 6.5$ due to constraint that ground motions do not oversaturate. Plots inter-event residuals against depth and find that motions from deeper events underestimated, which relate to less attenuation than shallower events and possibly different stress drops in shallow and deep earthquakes.
- Plots intra-event residuals against $M_w$ and $r_{rup}$ and site parameters and find no trends. However, finds trend in residuals from earthquakes recorded at $r_{rup} < 20$ km, which relate to lack of near-fault-effects and nonlinear soil terms. Also finds decreasing variation in the intra-event residuals for $r_{rup} > 200$ km.
- Examines correlation between normalised inter- and intra-event residuals and concludes that they are uncorrelated.
- Finds combined, surface and borehole inter-event residuals well correlated.
- Recommends use of combined model rather than the surface or borehole only models.
- Computes single-station residuals and $\sigma$s, by defining site terms for each station based on intra-event residuals, from 131 stations that recorded $> 10$ earthquakes. Finds slight magnitude dependence of residuals. Finds no correlation between intra-event residuals corrected by site terms and inter-event residuals. Examine in detail single-station residuals, associated $\sigma$s and their various components w.r.t. to their use in PSHA without the ergodic assumption. Report these single-station $\sigma$s: surface $\phi = 0.4967$, borehole $\phi = 0.5060$, surface $\sigma = 0.6725$ and borehole $\sigma = 0.6684$.
- Examine effect of selecting data from a station-to-event azimuthal bracket of 8° and finds that sigma is reduced.

## 2.336 Ornthammarath et al. (2010), Ornthammarath (2010) & Ornthammarath et al. (2011)

- Ground-motion model is:

$$\log y = b_1 + b_2 M_w + b_3 \log(\sqrt{r_{jb}^2 + b_4^2}) + b_5 S_S$$

  where $y$ is in m/s$^2$, $b_1 = -2.622$, $b_2 = 0.643$, $b_3 = -1.249$, $b_4 = 3.190$, $b_5 = 0.344$, $\sigma_{event} = 0.0723$, $\sigma_{station} = 0.1198$ and $\sigma_{record} = 0.1640$.

- Use two site classes:

  S Stiff soil, $360 \leq V_{s30} \leq 750$ m/s, 3 stations, 13 records, $S_S = 1$

  R Rock, $V_{s30} > 750$ m/s, 28 stations, 68 records, $S_S = 0$

  $V_{s30}$ at most stations unknown so use local site conditions to classify stations. Note that there are no deep alluvium soil deposits in Iceland so basin effects are limited.

- Focal depths between 10 and 15 km.
- All earthquakes have strike-slip mechanisms since the South Iceland Seismic Zone is transform zone.
- Develop model to investigate source of variability in ground motions in Iceland not for seismic hazard assessments.
- Data well distributed with respect to $M_w$, $r_{jb}$ and earthquakes (between 9 and 18 records per event).
- Only use high-quality data, following visual inspection.
- Dropped anelastic attenuation term since it was positive.
- Dropped quadratic magnitude term since insufficient data to constrain it, as were magnitude-dependent distance decay terms.
- Note that low $\sigma$ could be due to limited records from only six earthquake of similar sizes and mechanisms and from a small geographical area and few stations.
- Examines single-station residuals (site terms) and single-station $\sigma$s for a few stations.

## 2.337 Sokolov et al. (2010)

- Ground-motion model is:

  $$\ln G = a + bM + c\ln[R + d\exp(eM)] + pR$$

  where $G$ is in g, $a = -3.07$, $b = 0.83$, $c = -1.33$, $d = 0.15$, $e = 0.54$, $p = 0.0023$, $\nu = 0.37$ (inter-event), $\epsilon = 0.55$ (intra-event) and $\sigma = 0.66$ (total) (using 1-step regression) and $a = -2.59$, $b = 0.87$, $c = -1.53$, $d = 0.13$, $e = 0.53$, $p = 0.0029$, $\nu = 0.39$, $\epsilon = 0.55$ and $\sigma = 0.67$ (using 2-step regression).

- Use 4 site classes (Lee et al., 2001):

  B Rock

  C Very dense or stiff soil

  D Stiff soil

  E Soft soil

  Evaluate site terms based on residuals w.r.t. model derived without site terms.

- Derive model to study components of variability and spatial correlation of ground-motion residuals.
- Use data from Taiwan Strong-Motion Instrumentation Program (>650 16 bit or 24 bit stations within 7 arrays) from 1993 to 2004.
- Focal depths $< 30$ km.
- Select records with clear P- and S-wave onsets and signal-to-noise ratios (of Fourier amplitude spectra of S-wave and pre-event noise) $> 2$.
- Seek simplest reasonable functional form that can describe general features of ground motions.
- Examine residuals w.r.t. $r_{hypo}$.
- Believe that positive $p$ coefficient is due to: peculiarities of data, region and/or azimuth-specific propagation path effects or site-specific effects within Taipei basin and Ilan area.

- Check impact of grouping data from arrays (TAP, TCU, CHY and ILA) and within subgroups of site class. Compute average group-dependent correction factors: $D = a + bM_w + cR$ for each array and site class. Find significant (using F-test) trends. Use residuals from model including these correction factors to compute variability components. Find corrections reduce $\sigma$.

- Find magnitude-dependency in total residuals but inter-event residuals that are independent of magnitude, based on residuals binned in 0.5 magnitude-unit bins.

## 2.338 Ulutaş and Özer (2010)

- Ground-motion model is[30]:

$$\log A = C_1 + C_2 M_w - \log_{10}(r_{rup} + 0.0183 \times 10^{0.4537 M_w}) + \log C_3 r_{rup}$$

  where $A$ is in g, $C_1 = -2.7809$, $C_2 = 0.5344$, $C_3 = -0.0015$ and $\sigma = 0.392$ (stated to be in terms of natural logarithms although GMPE presented in terms of log).

- Purpose of develop GMPE is for rapid assessment of PGA following earthquake and, therefore, no distinction made between rock and soil sites.

- Focal depths between 2 and 22 km.

- All records from 1999 Kocaeli (Izmit) and Düzce earthquakes and their aftershocks from 132 permanent and temporary stations.

- Earthquakes are mainly strike-slip but some have normal mechanisms. Believe that model should only be used for these types of mechanisms.

- Baseline and instrument correct records. Examine Fourier amplitude spectra to select the high- and low-pass filters. Use the Basic strong-motion Accelerogram Processing (BAP) software: high-cut filtering with a cosine shape and then low-cut bi-directional second-order Butterworth filtering (after padding with zeros).

- Select data with $M_w \geq 4$.

- Distance saturation term ($0.0183 \times 10^{0.4537 M_w}$) within the $\log_{10}$ given by square root of rupture area estimated by regression analysis on areas for the two mainshocks and the equations of Wells and Coppersmith (1994) for other earthquakes.

- Compare observed and predicted PGAs for different $M_w$.

- State that GMPE can be used for $4 \leq M_w \leq 7.5$ and distances $\leq 200$ km.

- Note that site effects should be included within the model but currently lack of information.

## 2.339 Alavi et al. (2011)

- Ground-motion model is (it is not clear which coefficients were fixed and which obtained by the regression algorithm):

$$\begin{aligned}\ln(\text{PGA}) &= a_1 - \ln(R_{ClstD}) + a_2[\ln(R_{ClstD})]^2 + a_3 M_w \ln(R_{ClstD}) + a_4/V_{s,30} + [\ln(R_{ClstD})]^3/V_{s,30} \\ &+ \frac{a_5}{a_6 - V_{s,30} + a_7 V_{s,30}\sin(\lambda) + V_{s,30}/(M_w + a_8)}\end{aligned}$$

[30] Although $r_{rup}$ is used in Equation 4 of the paper it is probable that the distance metric is actually $r_{jb}$ since they default to $r_{epi}$ when the fault geometric is not known.

where $y$ is in $\text{cm/s}^2$, $a_1 = 6$, $a_2 = -1/6$, $a_3 = 1/6$, $a_4 = 6$, $a_5 = 64$, $a_6 = -8$, $a_7 = 5$, $a_8 = -7$ and $\sigma = 0.602$ (training set) and $\sigma = 0.624$ (testing set).

- Characterize sites using $V_{s,30}$. Most sites have $350 \leq V_{s,30} \leq 850\,\text{m/s}$.
- Characterize faulting mechanism using rake angle $\lambda$. Most records have $60 \leq \lambda \leq 180°$. Tried using classes for mechanism (strike-slip, normal and reverse) instead but did not find better results.
- Use variant of genetic programming (multi-expression programming, MEP) for derivation[31]. Technique seeks best functional form and coefficients.
- Use PEER-NGA database. Select 2815 records by excluding those with missing information and duplicates.
- Most data from $M_w > 5.5$ and $r_{rup} < 100\,\text{km}$.
- Note that the distribution of data w.r.t. parameter is not uniform and that MEP works best with uniform distributions.
- Randomly divide data into learning (1971 records), validation (281 records) and testing (563 records) subsets. Learning data used for the genetic evolution; validation data used to specify the generalization capability of the models on data not used for training; and testing data used to measure performance of the models on independent data.
- Examine correlations between independent variables ($M_w$, $r_{rup}$, $V_{s,30}$ and $\lambda$) because strong interdependency can exaggerate strength of relations between variables. Do not find strong correlations.
- Choose best models based on: a) simplicity (although not a predominant factor), which was controlled by parameter settings; b) best fitness value (objective function, which is a function of root-mean-square error, mean absolute error and coefficient of determination) on learning set; and c) best fitness value on validation set.
- Compare observed and predicted PGAs for training and testing data. Compute various statistics to check model. Conclude that derived models have predictive capability within the data range used for their calibration.

## 2.340 Anderson and Uchiyama (2011)

- Ground-motion model is:

$$\ln Y = a_1 M + a_2 Z + a_3 + a_4 R + a_5 - \ln[R + a_5 \exp(a_6 M)]$$

where $Y$ is in $\text{cm/s}^2$, $a_1 = 0.97412$, $a_2 = 0.0074138$, $a_3 = -0.0044524$ and $a_4 = 2.1041$ for mean horizontal; $a_1 = 0.95461$, $a_2 = 0.0073811$, $a_3 = -0.0045837$ and $a_4 = 2.4935$ for vectorially-resolved component including vertical; $a_1 = 0.96387$, $a_2 = 0.006973$, $a_3 = -0.00466$ and $a_4 = 2.3969$ for vectorially-resolved component using two horizontal components; and $a_1 = 0.98212$, $a_2 = 0.0073442$, $a_3 = -0.0044279$ and $a_4 = 1.7006$ for vertical; $a_5 = 0.0261$ and $a_6 = 0.9594$ for all. $\sigma = 0.70$.

- Data from 36 rock sites, which recorded between 1 and 23 events.
- All events recorded by $\geq 10$ stations so that number of events and stations are comparable.
- Only use earthquakes with Global CMT $M_w$ available.
- Focal depths, $Z$, between 5 and 69 km with most $\leq 25\,\text{km}$.

[31] This model is listed here, rather than in Chapter 6, because they provide an analytical expression for their model

- Try a different function for the distance decay ($-\ln\sqrt{R^2+[a_5\exp(a_6M)]^2}$) and find that fits the data almost equally well. Prefer the selected form because it has been used for Japanese models using more data.
- Correlation between parameters is: between $M$ and $R$ 0.49, between $M$ and $Z$ 0.21 and between $Z$ and $R$ 0.41.
- Fit distance decay term of form $-\ln(R+c)$ to each earthquake individually. Find $a_5$ and $a_6$ from plot of $c$ against $M$. Choose $a_5$ and $a_6$ that can be used for all across periods. Next find coefficients $a_1$ to $a_4$ based on data adjusted by distance decay term.
- Find no trends in residuals w.r.t. $M$, $Z$ or $R$.
- Plot observations against predictions for magnitude-unit wide intervals and find good fit.
- Note that model is not definitive because many other data available. Believe model is adequate for illustration of how a model can be improved by event, site and path terms.

## 2.341 Arroyo and Ordaz (2011)

- Ground-motion model is (same as Boore and Atkinson (2008) without site terms):

$$
\begin{aligned}
y &= F_M(M_w) + F_D(R_{rup}, M_w) \\
F_D &= c_1 \ln \frac{R}{R_{ref}} + c_2(M_w - M_{ref}) \ln \frac{R}{R_{ref}} + c_3(R - R_{ref}) \\
F_M &= e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_5(M_w - M_h) + e_6(M_w - M_h)^2 \quad \text{if} \quad M_w \le M_h \\
&= e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_7(M_w - M_h) \quad \text{otherwise} \\
R &= \sqrt{R_{rup}^2 + h^2}
\end{aligned}
$$

  where $y$ is in g, $c_1 = -9.748 \times 10^{-1}$, $c_2 = 1.859 \times 10^{-1}$, $e_2 = -3.387 \times 10^{-2}$, $e_3 = -2.159 \times 10^{-1}$, $e_4 = 1.074 \times 10^{-1}$, $e_5 = -2.528 \times 10^{-1}$, $e_6 = -8.017 \times 10^{-2}$, $M_{ref} = 4.5$, $R_{ref} = 1$, $M_h = 6.75$, ($c_3 = -0.01151$, $e_7 = 0$, $h = 1.35$, taken from Boore and Atkinson (2008)), $\sigma_e = 0.428$ (inter-event), $\sigma_r = 0.547$ (intra-event) and $\sigma = 0.695$ (total).

- Also consider functional forms of Abrahamson and Silva (2008) and Campbell and Bozorgnia (2008b).
- To facilitate analysis and comparisons only use data from rock sites. Use 874 from sites with $450 \le V_{s,30} \le 900$ m/s and 32 from sites with $900 \le V_{s,30} \le 1428$ m/s.
- Use records from free-field or ground floor of buildings with $\le 2$ storeys.
- Data selection similar to Idriss (2008) but exclude singly-recorded earthquakes.
- Use three types of earthquakes:

  SS Strike-slip: SS = 1, NS = 0, RS = 0.

  NS Normal-slip: NS = 1, SS = 0, RS = 0.

  RS Reverse-slip: RS = 1, SS = 0, NS = 0.

- Report covariance matrices from regression.
- Compute the extra epistemic uncertainty due to uncertainty in regression coefficients based on covariance matrices. Present contour plots of this additional uncertainty.

- Based on contour plots, discuss where the models can be extrapolated outside range of input parameters.
- Discuss how this extra uncertainty can be included within PSHA.

## 2.342 Beauducel et al. (2011)

- Ground-motion model is:

$$\log(\text{PGA}) = aM + bR - \log(R) + c$$

  where PGA is in g, $a = 0.61755$, $b = -0.0030746$, $c = -3.3968$ and $\sigma = 0.47$.
- Update of Beauducel et al. (2004) (see Section 2.219).
- Most data from Les Saintes (21/11/2004, $M_w$6.3) earthquake and aftershocks.
- Aim to develop model for use in predicting macroseismic intensities shortly after an earthquake. Hence model should be applicable for wide range of magnitudes and distances and, ideally, independent of tectonic context and depth. Hence use simple functional form.
- Many epicentres (95) offshore.
- Data from 14 stations on both rock and soil.
- Note that due to lack of quadratic magnitude term PGAs could be underestimated for large $r_{hyp}$.
- Because magnitudes follow power law and there are more records from short distances, apply weights that are proportion to magnitude and power of $r_{hyp}$ to give more weight to larger earthquakes and longer distances.
- Note that high $\sigma$ may be due to lack of site term, wide range of magnitudes and distances and too simple a functional form.
- Examine residuals w.r.t. magnitude and $r_{hyp}$. Find no trends for entire magnitude range but significant underestimation in PGA for $R < 15$ km.
- Compare observed and predicted PGAs for 6 earthquakes, including some not used to derive model, and compute average of the residuals. Find slight evidence for underestimation. Find PGA for one soil station underestimated by factor 10.

## 2.343 Bindi et al. (2011a)

- Ground-motion model is:

$$\begin{aligned}
\log_{10} Y &= e_1 + F_D + F_M + F_S + F_{sof} \\
F_D &= [c_1 + c_2(M - M_{ref})] \log_{10}\left(\sqrt{R_{JB}^2 + h^2}/R_{ref}\right) \\
&\quad - c_3\left(\sqrt{R_{JB}^2 + h^2} - R_{ref}\right) \\
F_M &= \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & \text{for} \quad M \leq M_h \\ b_3(M - M_h) & \text{otherwise} \end{cases} \\
F_S &= s_j C_j \\
F_{sof} &= f_j E_j
\end{aligned}$$

where $Y$ is in cm/s$^2$, $e_1 = 3.672$, $c_1 = -1.940$, $c_2 = 0.413$, $h = 10.322$, $c_3 = 1.34 \times 10^{-4}$, $b_1 = -0.262$, $b_2 = -0.0707$, $s_A = 0$, $s_B = 0.162$, $s_C = 0.240$, $s_D = 0.105$, $s_E = 0.570$, $f_1 = -5.03 \times 10^{-2}$, $f_2 = 0.105$, $f_3 = -5.44 \times 10^{-2}$, $f_4 = 0$, $\sigma_B = 0.172$ (inter-event), $\sigma_W = 0.290$ (intra-event) and $\sigma = 0.337$ for horizontal PGA and $e_1 = 3.511$, $c_1 = -1.741$, $c_2 = 0.324$, $h = 9.052$, $c_3 = 1.28 \times 10^{-3}$, $b_1 = 9.04 \times 10^{-3}$, $b_2 = -0.0270$, $s_A = 0$, $s_B = 0.167$, $s_C = 0.204$, $s_D = 0.190$, $s_E = 0.350$, $f_1 = -7.09 \times 10^{-2}$, $f_2 = 7.79 \times 10^{-2}$, $f_3 = -6.96 \times 10^{-3}$, $f_4 = 0$, $\sigma_B = 0.160$ (inter-event), $\sigma_W = 0.270$ (intra-event) and $\sigma = 0.314$ for vertical PGA (standard deviations of coefficients from bootstrap analysis also given but not reported here). After trial regressions and following Boore and Atkinson (2008) fix $R_{ref} = 1$, $M_{ref} = 5$, $M_h = 6.75$ and $b_3 = 0$.

- Use five site Eurocode 8 (EC8) classes (150 stations in total):

  A $V_{s,30} > 800$ m/s. 334 records. $C_A = 1$ and other $C_i$s are zero.

  B $360 < V_{s,30} \leq 800$ m/s. 99[32] records. $C_B = 1$ and other $C_i$s are zero.

  C $180 < V_{s,30} \leq 360$ m/s. 182 records. $C_C = 1$ and other $C_i$s are zero.

  D $V_{s,30} \leq 180$ m/s. 17 records. $C_D = 1$ and other $C_i$s are zero.

  E 5–20 m of C- or D-type alluvium underlain by stiffer material with $V_{s,30} > 800$ m/s. 37 records. $C_E = 1$ and other $C_i$s are zero.

  About 30% of classifications based on shear-wave velocity profiles and rest from geological and geophysical data.

- Use four faulting mechanism classes using classification of Zoback (1992):

Normal 593 records. $E_1 = 1$ and other $E_i$s are zero.

Reverse 87 records. $E_2 = 1$ and other $E_i$s are zero.

Strike-slip 61 records. $E_3 = 1$ and other $E_i$s are zero.

Unknown 28 records. $E_4 = 1$ and other $E_i$s are zero.

  Note that 'unknown' could be dominated by earthquakes of another class (e.g. normal).

- Use data from the Italian strong-motion database ITACA, which has been updated in various studies, including additional local site information, and all the records have been individually reprocessed.

- Note that the L'Aquila 2009 earthquake ($M_w$6.3) adds considerable data over a previously poorly-sampled magnitude-distance range.

- Firstly select data with $M > 4$, $r_{epi} < 200$ km and focal depths $h < 35$ km. This leaves 1213 records from 218 earthquakes and 353 stations. Note that for $M < 4.5$ only $M_L$ is available for most earthquakes. Also many stations recorded only one earthquake. Therefore, exclude earthquakes without $M_w$, those only recorded by one station and those stations with only one record. Finally data from 150 stations.

- Most earthquakes on normal faults in central and southern Appennines with $h < 20$ km. Some reverse-faulting earthquakes in north-eastern Italy and northern Apennines with $h > 15$ km. Strike-slip earthquakes generally in southern Italy with $h$ between 10 and 30 km.

- Only about 60 records from $M_w \geq 6$ (roughly evenly spread for smaller magnitudes). Most data from $10 < r_{jb} < 100$ km and most records with $r_{jb} < 5$ km are from $M_w \leq 6$.

[32] This value is given in the text (p. 1903) but they probably mean 199 records since otherwise the total is 669 (also see their Figure 4).

- Process records by: 1) baseline correction; 2) application of cosine taper, except for late-triggered records; 3) select bandpass filter cut-offs based on visual inspection of Fourier amplitude spectrum; 4) application of a second-order acausal time-domain Butterworth filter to zero-padded record; 5) double integration to displacement; 6) linear detrending of displacement; and 7) double differentiation to obtain final acceleration.

- Regress twice. Once to find inter-event and intra-event standard deviations and secondly to find inter-station and intra-station standard deviations, which are not explicitly given in the text but are shown on graphs.

- Analyze trade-off between coefficients by studying off-diagonal elements of unit covariance matrix (shown for 0.1 and 1.0 s). Find strong trade-offs for some coefficients.

- Note that care should be taken when considering site coefficients for classes D and E because they are based on limited records from only a handful of stations (i.e. for class E, 33 out of 27 records are from Nocera Umbra and for D, 12 records are from Colfiorito and 5 from Norcia). Because of this, remove data from these classes and re-regress. Find little difference in median predictions (less than 10%) (not shown). Hence conclude that data from D and E are not having a large impact on results.

- Constrain coefficient for unknown faulting class to zero and sum of coefficients for other classes to zero so that offset coefficient $e_1$ corresponds to average effect of faulting mechanism. Also tried various other constraints on faulting coefficients but find similar median predictions.

- Compare predicted and observed PGAs for Molise 2002, Friuli 1976, Irpinia 1980 and five $M_w$4.6 earthquakes. Find generally good agreement.

- For $T < 0.2$ s the inter-station component of variability is larger than the inter-event component while for $T > 0.4$ s the two are similar. By comparing variabilities to a previous model (Bindi et al., 2010) using a different site classification conclude that EC8 classification improves prediction of long-period motion for soft and very soft sites but may not be suitable for short-period site response of Italian sites.

- Find that inter- and intra-event residuals (shown for PGA, 0.1 s and 1.0 s) well behaved.

## 2.344 Emolo et al. (2011)

- Ground-motion model is:

$$\log Y = a + bM + c\log(R) + ds$$

  where $Y$ is in m/s$^2$, $a = -1.817$, $b = 0.460$, $c = -1.428$, $d = 0.271$ and $\sigma = 0.417$.

- Use 3 site classes in final model:

$s = -1$ Negative residuals from first regression

$s = 0$ Zero residuals from first regression

$s = 1$ Positive residuals from first regression

  Originally use 4 geological units from a macro-zoning for correction of observations to rock:

  Q Quaternary: very soft soils and alluvium gravel deposits ($V_{s,30} \leq 360$ m/s

  V Volcanic: quaternary-tertiary age ($360 \leq V_{s,30} \leq 1000$ m/s)

  T Tertiary: sediments, soft rocks and flysch deposit, $360 \leq V_{s,30} \leq 800$ m/s

  M Mesozoic: carbonate platform succession, $V_{s,30} > 800$ m/s

- Use data from 21 stations of Irpinia Seismic Network, a high dynamic-range, dense, seismographic network (co-located Geotech S-13J and CMG-5T instruments or a Trillium sensor), from 09/2005 onwards.
- Develop for use in ShakeMaps for small earthquakes.
- Exclude earthquakes from outside area of interest ($120 \times 120\,\mathrm{km}^2$) and events with $M_L < 1.5$.
- De-trend and band-pass filter (0.075–20 Hz, 4-pole Butterworth) records. Retain records with signal-to-noise ratio $> 5$ and where PGA occurs during 5–95% Arias-intensity interval.
- Reasonably uniform distribution w.r.t. $M$ and $R$, although only one event with $M_L > 2.9$.
- Use three-step approach. Firstly adjust PGAs to rock based on geological classification. Next derive model using these adjusted PGAs. Examine residuals for each station and perform a Z-test with 5% significant level to find sites with mean residuals significantly different from zero. Finally add site term to account for these average differences.
- Test inclusion of quadratic-magnitude term but find that not significantly different from zero.
- Test inclusion of anelastic attenuation term but find that not significantly different from zero.
- Find that the inclusion of the site term $d$ reduces $\sigma$ and that this reduction is significant by using the Akaike Information Criterion.
- Compare observed and predicted (grouped by magnitude ranges) PGAs by distance and via residual plots and find good match.

## 2.345 Gehl et al. (2011)

- Ground-motion model is:

$$\log y = \alpha + \beta(M-6) + \gamma(M-6)^2 + \log\sqrt{r_{rup}^2 + h^2} + \delta\sqrt{r_{rup}^2 + h^2} + \xi \log \frac{V_{s,30}}{760}$$

  Coefficients not reported.
- Use $V_{s,30}$ to characterise sites. Distribution w.r.t. NEHRP classes: A (6 records), B (399), C (2405), D (1022) and E (42).
- Study the influence of uncertainties in estimates of $V_{s,30}$ on model (coefficients and $\sigma$). Propose regression technique, based on generalized least-squares and maximum-likelihood approaches, to account for variable accuracy of $V_{s,30}$ estimates.
- Approach allows estimation of site-specific $\sigma$ for use when $V_{s,30}$ is known to different accuracies (e.g. specified only by class or specified by measured $V_s$ profile). Find that this approach leads to lower $\sigma$ for well-characterised site than one that is poorly known.
- Test procedure using the Joyner and Boore (1981) dataset, excluding the site term, since this allows comparison to previous results. Find very close match to results of Joyner and Boore (1993).
- Use data from KiK-Net provided by Cotton et al. (2008) and Rodriguez-Marek and Montalva (2010). Lack of data from large earthquakes.
- Data from 537 stations.
- State that objective is not to develop models for use in hazard assessments but to show impact of measurement uncertainty on model.

- Undertake various regressions assuming different uncertainties in $V_{s,30}$, including uniform for all sites and individual. When uniform uncertainties are assumed, coefficients unchanged but $\sigma_s$ (inter-site) decreases but the other components are unaltered. Find coefficients largely insensitive to assumption of non-uniform uncertainties but again $\sigma_s$ decreases.

- Discuss the use of the variance components in the context of seismic hazard assessment. Even if $\sigma_s$ has decreased have to consider the measurement error when computing total $\sigma$, which is unchanged in the case of uniform uncertainties in $V_{s,30}$ but decreases if know $V_{s,30}$ more accurately. Allows discrimination between aleatory variability and epistemic uncertainty.

## 2.346 Joshi et al. (2011) & Joshi et al. (2012)

- Ground-motion model is:

$$\ln(\text{PGA}) = a_1 + a_2 M_w + a_3 \ln r_{hypo} + a_4 \ln(r_{epi} + 15)$$

  where PGA in in gal, $a_1 = -5.8$, $a_2 = 2.62$, $a_3 = -0.16$, $a_4 = -1.33$ and $\sigma = 0.42$.

- Data from 8 stations in Pithoragarh region of Kumaon Himalaya (Uttarakhand,India) from 03/2006 to 03/2008. Stations cover area of 11812 km$^2$ (minimum inter-station distance is 11 km). Instrument trigger level is 0.1 gal so that almost continuous recording so as to record even smallest earthquakes. Sampling frequency is 100 Hz. Records baseline-corrected, corrected for instrument response and filtered.

- Locate earthquakes using HYPO71 for events recorded at $\geq 3$ stations and S-P intervals for other events.

- Compute $M_w$ from S-phase source spectrum at each station after correcting for geometrical and anelastic attenuation.

- Most data have $10 \leq r_{hypo} \leq 100$ km.

- Also derive model using anelastic attenuation term and geometrical decay term in terms of $r_{hypo}$ but find higher $\sigma$.

- Test fit and normality of model to data by plotting: observed v. predicted, cumulative probability plot and residuals w.r.t. PGA. Find good performance but note some weak tails.

## 2.347 Kayabali and Beyaz (2011)

- Ground-motion model is:

$$\log A = \beta_0 + \beta_1 M^2 + \beta_2 \log(R + 1)$$

  where $A$ is in cm/s$^2$, $\beta_0 = 2.08$, $\beta_1 = 0.0254$, $\beta = -1.001$ and $\sigma = 0.712$[33].

- Note that insufficient data from Turkey to develop model for rock sites hence use data from soil sites adjusted to rock to derive model.

- Drill $< 100$ m deep boreholes at 64 deep soil sites. Stop drilling when bedrock encountered (at depths between 25 and 100 m). Measure P- and S-wave velocities using downhole technique. Use these profiles to deconvolve, using Proshake, data from soil sites to obtain records from rock. Apply deconvolution to about 400 records.

[33] This $\sigma$ is very high. It could mean that natural logarithms were used to compute it.

- Use data from Earthquake Research Division (contributes almost all data), Kandilli Observatory and Research Centre and Istabul Technical University from 1976 to 2004. Select earthquakes with $M \geq 4$. Select records with PGA$\geq 10\,\text{cm/s}^2$. Exclude records with $r_{epi} > 200\,\text{km}$.

- Visually inspect all records. Process, including filtering, data.

- Derive models for 6 subsets of data (based on $M$, $R$, PGA threshold and combination of components) an 16 functional forms.

- Compare predictions and observations for some magnitude ranges and find good fit.

## 2.348 Lin et al. (2011b)

- Ground-motion model is:

$$\ln \text{PGA} = c_1 + c_2 M + c_3 \ln[R + c_4 \exp(c_5 M)]$$

where PGA is in g; $c_1 = -3.279$, $c_2 = 1.035$, $c_3 = -1.651$, $c_4 = 0.152$, $c_5 = 0.623$ and $\sigma = 0.651$ for hanging wall and rock sites; $c_1 = -3.232$, $c_2 = 1.047$, $c_3 = -1.662$, $c_4 = 0.192$, $c_5 = 0.630$ and $\sigma = 0.652$ for footwall and rock sites; $c_1 = -3.248$, $c_2 = 0.943$, $c_3 = -1.471$, $c_4 = 0.100$, $c_5 = 0.648$ and $\sigma = 0.628$ for hanging wall and soil sites; and $c_1 = -3.218$, $c_2 = 0.935$, $c_3 = -1.464$, $c_4 = 0.125$, $c_5 = 0.650$ and $\sigma = 0.630$ for footwall and soil sites.

- Use 2 site classes:

Rock Site classes B and C of Lee et al. (2001)

Soil Site classes D and E of Lee et al. (2001)

- Visually inspect baseline-corrected records and exclude poor-quality and questionable data and those where the instrument resolution is too low.

- Classify records into:

Hanging wall Defined as overlying side of a dip-slip fault, which assumed to extend to 30 km from and beyond the end of the fault line within 30° from normal to fault strike

Foot wall Defined as underlying side of dip-slip fault, which assumed to extend within 40 km from and beyond the end of the fault line within 30° from normal to fault strike

Other Other sites

Only Chi-Chi and some of the foreign events include records from hanging wall.

- Lack of Taiwanese data from $6.5 \leq M_w \leq 7.6$ and hence include near-source foreign data from similar geotectonic environments (Iran, USA and Canada).

- Most earthquakes are reverse or reverse-oblique faulting and hence do not consider mechanism.

- Assume 'total magnitude saturation' and hence assume that $c_5 = -c_2/c_3$.

- Compare observations and predictions for two earthquakes ($M_w$6.05 and $M_w$7.6) and find good fit.

- Examine residuals with respect to distance and as histograms and find no trends and find that residuals follow lognormal distribution.

## 2.349 Luzi et al. (2011)

- Ground-motion model is (for $r_{jb}$):

$$\begin{aligned}\log Y &= a + b_1(M-6) + [c_1 + c_2(M-5)]\log(\sqrt{r_{jb}^2 + h^2}) + k(\sqrt{r_{jb}^2 + h^2} - 1) \\ &\quad + e_2S_2 + e_3S_3 + e_4S_4 + e_5S_5 + f_2F_2 + f_3F_3\end{aligned}$$

  where $Y$ is in $\text{cm/s}^2$, $a = 3.847$, $b_1 = 0.131$, $c_1 = -1.831$, $c_2 = 0.263$, $h = 10.034$, $k = -0.0003$, $f_2 = 0.117$, $f_3 = 0.018$, $e_2 = 0.172$, $e_3 = 0.225$, $e_4 = 0.104$, $s_5 = 0.442$, $\sigma_{inter} = 0.193$, $\sigma_{intra} = 0.295$ and $\sigma_{tot} = 0.353$ for Italy and $a = 3.984$, $b_1 = 0.221$, $c_1 = -1.857$, $c_2 = 0.209$, $h = 9.528$, $k = -0.0007$, $e_2 = 0.118$, $e_3 = 0.245$, $e_4 = 0.070$, $s_5 = 0.539$, $\sigma_{inter} = 0.180$, $\sigma_{intra} = 0.275$ and $\sigma_{tot} = 0.329$ for Zone 2.
  Ground-motion model is (for $r_{hypo}$):

$$\begin{aligned}\log Y &= a + b_1(M-6) + [c_1 + c_2(M-5)]\log r_{hypo} + kr_{hypo} \\ &\quad + e_2S_2 + e_3S_3 + e_4S_4 + e_5S_5 + f_2F_2 + f_3F_3\end{aligned}$$

  where $a = 3.670$, $b_1 = 0.353$, $c_1 = -1.485$, $c_2 = 0.154$, $k = -0.0027$, $f_2 = 0.191$, $f_3 = 0.073$, $e_2 = 0.211$, $e_3 = 0.218$, $e_4 = 0.044$, $s_5 = 0.397$, $\sigma_{inter} = 0.220$, $\sigma_{intra} = 0.300$ and $\sigma_{tot} = 0.371$ for Italy and $a = 3.850$, $b_1 = 0.524$, $c_1 = -1.501$, $c_2 = 0.050$, $k = -0.0026$, $e_2 = 0.175$, $e_3 = 0.232$, $e_4 = 0.017$, $s_5 = 0.512$, $\sigma_{inter} = 0.188$, $\sigma_{intra} = 0.287$ and $\sigma_{tot} = 0.343$ for Zone 2.

- Use 5 site classes following Eurocode 8:

  A $S_2 = S_3 = S_4 = S_5 = 0$.

  B $S_2 = 1$, $S_3 = S_4 = S_5 = 0$.

  C $S_3 = 1$, $S_2 = S_4 = S_5 = 0$.

  D $S_4 = 1$, $S_2 = S_3 = S_5 = 0$.

  E $S_5 = 1$, $S_2 = S_3 = S_4 = 0$.

- Use 3 mechanisms:

Normal $F_2 = F_3 = 0$.

Strike-slip $F_2 = 1$, $F_3 = 0$.

Reverse $F_3 = 1$, $F_2 = 0$.

- Select data from ITACA database with $4 \leq M_w \leq 6.9$ and distance $< 300$ km to explore regional dependency of ground motions and effect of mechanism.

- Find that all coefficients are significantly different than zero.

- Divide Italy into three zones characterised by homogeneous tectonic regimes and focal depths. Derive model using only data in zone 2 (central-southern Apennines, characterised by extensional regime and focal depths $< 10$ km). Because all focal mechanisms are normal, remove the mechanism terms in model. Then use this Zone 2 model to predict observations in zone 1 (NE Italy and northern Apennines, characterised by compressional regime and focal depths between 15 and 25 km) and zone 3 (Apulian foreland, characterised by strike-slip regime and focal depths between 20 and 30 km. Find model predicts observations well if the effect of mechanism is removed.

## 2.350 Yilmaz (2011)

- Ground-motion model is[34]:

$$\begin{aligned}
\text{PGA} &= a_1 + a_2 \sin[\exp(a_3 m^{a_4})] + a_5 S_3 + a_6 \exp(m^{a_7}) + a_8 \log(m^{a_9}) \log(r^{a_10}) \\
&\quad + a_{11} \sin[\exp(a_{12} m^{a_{13}})] \exp(z^{a_{14}}) + a_{15} m^{a_{16}} \log[\exp(r^{a_{17}}) + a_{18} \exp(a_{19} h)] \\
m &= 4(M_d - 2.5)/(6.5 - 2.5) + 1 \\
r &= 4(R - 0)/(150 - 0) + 1 \\
z &= 4(Z - 0)/(150 - 0) + 1 \\
h &= 4(H - 0)/(250 - 0) + 1
\end{aligned}$$

  where PGA is in gal, $a_1 = 4.47$, $a_2 = -8.96$, $a_3 = 0.51$, $a_4 = 0.97$, $a_5 = 10.2$, $a_6 = -8.8$, $a_7 = 0.63$, $a_8 = -9.35$, $a_9 = 4.44$, $a_{10} = 4.72$, $a_{11} = -8$, $a_{12} = 0.3$, $a_{13} = 1.74$, $a_{14} = 0.37$, $a_{15} = 7.6$, $a_{16} = 2.41$, $a_{17} = -4.8$, $a_{18} = 0.017$ and $a_{19} = 2$ ($\sigma$ not given).

- Use 2 site classes:

$S_3 = 1$ Soft soil

$S_3 = 0$ Other sites.

  Classification based on $V_S$ (range 200–700 m/s) but not stated how. Notes that few records from medium and hard sites.

- Also uses 'slope height' ($H$) [35] to characterise sites.
- Focal depths between 1.2 and 34 km.
- Uses $M_d$ since available for most earthquakes and to avoid converting from one scale to another.
- To limit effect of small PGAs exclude those with PGA$<$ 20 gal.
- To reduce number of near-source records from small events applies a $r_{epi}$ limit of 2 km, which increases with magnitude. Notes that model valid for $r_{epi} < 30$ km for $M_d < 4$ and $r_{epi} < 65$ km for larger $M_d$.
- Uses genetic algorithm to derive model. Defines an initial general functional form that is modified by the genetic algorithm. To avoid problems with different ranges of input parameters linearly normalises all parameters to a standard range. Fitness function used within algorithm accounts for absolute error and ratio of observed PGAs smaller and lower that predictions and it is multiplied by observed PGA to increase the importance of larger PGAs since these are most important for engineering purposes.
- Split available data into training and testing (26 records from 21 earthquakes) subsets.
- Compares predicted and observed PGAs and find good correlation.
- Notes that due to limitations in the data the equation may not yield reliable results for higher slopes.
- Notes that due to lack of data equation may not be valid for higher magnitudes.

[34]There appears to be a problem with this model since it seems to always give infinity.

[35]It is not clear what this is but it appears to be altitude of the site.

## 2.351 Yuen and Mu (2011)

- Ground-motion model is:

$$\ln \mathrm{PGA} = b_1 + b_2(M - M_0) + b_3(M - M_0)^2 + b_4 r + b_5 \ln r + b_6 G_B + b_7 G_C + \text{nonlinear terms}$$

  where PGA is in $\mathrm{cm/s^2}$, $M_0 = 3.5$, $b_1 = 2.8$, $b_2 = 0.72$, $b_3 = -0.038$, $b_4 = -0.0060$, $b_5 = -0.0095$, $b_6 = 0.72$, $b_7 = 0.035$ and $\sigma = 0.77$. nonlinear terms are not given but stated to be almost negligible.

- Use 3 site classes:

Class A Granite, sandstone, bedrock, siltstone and conglomerate. 14 stations, 72 records. Both stations in Guangdong on granite. $G_B = G_C = 0$.

Class B Alluvium, diluvium, weathered conglomerate. 12 stations (none in Guangdong), 146 records. $G_B = 1$ and $G_C = 0$.

Class C Soft soil, clay and subclay. 8 stations (none in Guangdong), 48 records. $G_C = 1$ and $G_B = 0$.

  Cannot use $V_{s,30}$ as information not available.

- Use data from China Earthquake Data Center for three regions: Tangshan (94 records, 18 earthquakes, 19 stations), Xinjiang (155 records, 125 earthquakes, 13 stations) and Guangdong (17 records, 4 earthquakes, 2 stations).

- Use Bayesian model class selection approach to find the model that balances data-fitting capability and sensitivity to noise. Believe that this approach reduces the chance of overfitting. Compute the plausibility of each model conditional on the database. For the linear models use an analytical solution for this and for the nonlinear models (in this case including a term $b_8 \ln[r + b_9 \exp(b_{10} M)]$) use a Monte Carlo approach to evaluate the plausibility.

- Derive 48 models (by including different combinations of terms) for Tangshan and Xinjiang separately as well as for all data. Find $\sigma$ smaller for regional models. Recommend using the regional models but note that the model for all regions is best for prediction in another region without sufficient data.

- Derive many models assuming different functional forms. Choose model that is the most plausible using the Bayesian model class selection approach as final one.

- Plot predictions versus observations and find strong correlation.

## 2.352 Chang et al. (2012)

- Ground-motion model is:

$$\ln Y = c_1 + C_2 M - C_3 \ln[R + C_4 \exp(C_5 M)]$$

  where $Y$ is in g, $c_1 = -5.36874$, $C_2 = 1.72882$, $C_3 = 2.06573$, $C_4 = 0.11318$, $C_5 = 0.80312$ and $\sigma = 0.6619$.

- Only use data from rock sites ($V_{s,30} > 760$ m/s).

- Use data from networks of Central Weather Bureau betwen 1991 and 2008.

- Use data from earthquakes with $M_L > 5.5$ and depth $< 35$ km. Includes data from 1999 Chi-Chi mainshock and 5 aftershocks. Select all data from Real-Time Digital (RTD) network and all data with $r_{hypo} < 50$ km from stations of Taiwan Strong-Motion Instrumental Program because of lack of near-source data from RTD network and distribution w.r.t. $r_{hypo}$.

- Compare predictions and observations for 1999 Chi-Chi earthquake and find good match. Also compute the standard deviation of the residuals from this event.

## 2.353 Contreras and Boroschek (2012)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10}(Y) &= C_1 + C_2 M_w + C_3 H + C_4 R - g \log_{10}(R) + C_5 Z \\
R &= \sqrt{R_{rup}^2 + (C_6 10^{C_7 M_w})^2} \\
g &= C_8 + C_9 M_w
\end{aligned}
$$

  where $Y$ is in g, $C_1 = -1.8559$, $C_2 = 0.2549$, $C_3 = 0.0111$, $C_4 = -0.0013$, $C_5 = 0.3061$, $C_6 = 0.0734$, $C_7 = 0.3552$, $C_8 = 1.5149$, $C_9 = -0.103$ and $\sigma = 0.2137$.

- Use two site classes because of limited number of records:

- enumerate

Rock $V_{s,30} \geq 900$ m/s, Rock Quality Designation $\geq 50\%$ or compressive strength $q_u \geq 10$ MPa. 25 records. $Z = 0$

Soil Otherwise. 92 records. $Z = 1$ following the Chilean seismic code.

- Focal depths ($H$) from 18 to 53 km.

- Use data from 1985 to 2010 obtained from public databases and records from National Accelerograph Network.

- Most records from SMA-1s or similar analogue instruments.

- Most instruments on ground floor of 1-storey buildings (79 different stations).

- Only use data from large interface earthquakes (9 mainshocks and 4 aftershocks). 8 events in north (including two in Peru) and 5 in central area of Chile.

- Locations from Chilean Seismological Service and magnitudes from Global CMT.

- Data well-distributed w.r.t. $M_w$ and $r_{rup}$.

- Two events: 3/3/1985 and 27/2/2010 contribute 27 and 31 records, respectively; about half the data.

- Estimate $r_{rup}$ using CMT solutions and aftershock distributions assuming that rupture area generally smaller than aftershock area.

- Filter (using acausal 4th-order Butterworth) based on visual inspection of Fourier amplitude spectra in log-log space. Generally use $f_{max}$ of 90 Hz for Nyquist of 100 Hz and 40 Hz for Nyquist of 50 Hz. Use iterative process to find $f_{min}$ based on examination of displacements and displacement response spectra. Seek lowest $f_{min}$ that preserves natural appearance in time domain and without obvious drift.

- Coefficients $C_6$, $C_7$, $C_8$ and $C_9$ derived using algorithm to minimize mean residual for PGA from $r_{rup} \leq$ 80 km (47 records). Fix these coefficients for other periods.

- Compare predictions and observations for $8.3 \leq M_w \leq 9.3$ and find good fit.

- Plot total residuals w.r.t. distance and find no trends.

## 2.354 Convertito et al. (2012)

- Ground-motion model is:

$$\log \mathrm{PGA} = a + bM + c \log \sqrt{R^2 + h^2} + dR + eS$$

  where PGA is in $\mathrm{m/s^2}$, $a = -2.268 \pm 0.356$, $b = 1.276 \pm 0.026$, $c = -3.528 \pm 0.624$, $d = 0.053 \pm 0.029$, $h = 3.5$, $e = 0.218 \pm 0.014$ and $\sigma = 0.324$.

- Use 2 site classes, corresponding to $S = 0$ and $S = 1$, but classes not defined in article.

- Use data from The Geysers vapour-dominated geothermal field recorded from 01/09/2007 to 15/11/2010 by 29 stations of the network of Lawrence Berkeley National Laboratory Geysers/Calpine seismic network. Select earthquakes with focal depths $\leq 6$ km[36] to limit data to induced seismicity only. Do not use PGAs from COBB, ADSP and GCVB from 2009, which retain for comparison to results of time-dependent hazard assessment. Based on pre-processing select best quality data, i.e. those earthquakes with $\geq 20$ P picks and those records with a signal-to-noise ratio $> 10$.

- Apply instrument-correction within frequency band 1–25 Hz.

- Derive model to compute time-dependent seismic hazard.

## 2.355 Cui et al. (2012)

- Ground-motion model is:

$$\log Y = c_1 + c_2 M + c_3 \log(R + R_0) + c_4 S$$

  where $Y$ is in $\mathrm{cm/s^2}$, $C_1 = 1.8207$, $C_2 = 0.3506$, $C_3 = -1.2775$, $C_4 = -0.1370$, $R_0 = 10$ and $\sigma = 0.3445$ (for unweighted regression); $C_1 = 2.4911$, $C_2 = 0.3647$, $C_3 = -1.7654$, $C_4 = -0.0575$, $R_0 = 8$ and $\sigma = 0.3902$ (for weighted regression); and $C_1 = 2.7831$, $C_2 = 0.4956$, $C_3 = -2.6029$, $C_4 = 0.4220$, $R_0 = 15$ and $\sigma = 0.3546$ (for unweighted regression excluding Wenchuan aftershocks).

- Use 2 site classes:

  Rock $S = 0$

  Soil $S = 1$

- Use data from National Strong-Motion Observation Network System of China.

- Select data using these criteria: $r_{epi} < 110$ km, $M \geq 4.5$, both horizontal components available and PGA $\geq 0.01$ g on at least one horizontal component. Data from 6 mainshocks ($5 \leq M \leq 6.4$), their aftershocks and aftershocks of the 2008 Wenchuan ($M_s 8$) mainshock. Most data (837 records) from aftershocks of Wenchuan earthquake. Most data from $M < 4.8$ and $r_{epi} < 110$ km.

- Use 3 regression approaches: 1) without weighting, 2) with weighting except for Wenchuan aftershocks and 3) without weighting and excluding Wenchuan aftershocks, to study influence of these data. Results vary. Prefer weighted regression since predictions match observations from Ninger $M_s 6.4$ earthquake the best.

- Compare observations (grouped by magnitude ranges) and predictions.

- Plot absolute (not using logarithms) residuals w.r.t. $r_{epi}$.

[36] Or 4 km — both values are cited.

## 2.356 Di Alessandro et al. (2012)

- Ground-motion model is:

$$\log \mathrm{Sa}(T) = a + bM + cM^2 + dR - \log(R + e10^{0.42M}) + S_j\delta_j$$

  Sa is in $\mathrm{cm/s^2}$, $a = -1.1682$, $b = 1.0821$, $c = -0.04182$, $d = -0.0052$, $e = 0.00236$, $S_1 = 0$, $S_2 = -0.18257$, $S_3 = -0.08882$, $S_4 = -0.19547$, $S_5 = -0.32286$, $S_6 = -0.15611$, $S_7 = -0.16570$ and $\sigma = 0.38438$.

- Use 7 site classes defined based on predominant period ($T_g$) of horizontal-to-vertical response spectral ratios (5% damping) following Zhao et al. (2006) and Fukushima et al. (2007c) with the addition of 3 classes:

  CL-I $T_g < 0.2$ s. E.g. NCR. 22 stations, 155 records.

  CL-II $0.2 \leq T_g < 0.4$ s. E.g. ASSI. 21 stations, 113 records.

  CL-III $0.4 \leq T_g < 0.6$ s. E.g. CHT. 18 stations, 79 records.

  CL-IV $T_g \geq 0.6$ s. E.g. RTI. 20 stations, 91 records.

  CL-V $T_g$ not identifiable (flat H/V and amplitude $< 2$). E.g GSG. 11 stations, 73 records.

  CL-VI Broad amplification/multiple peaks for $T_g > 0.2$ s. E.g. MTL. 5 stations, 36 records.

  CL-VII Unclassifiable. $T_g$ not identifiable (multiple peaks over entire period range). E.g. MAJ. 14 stations, 65 records.

  $\delta_j = 1$ for site class $j$ and 0 otherwise.

- Data from 214 stations of Italian accelerometric network of Department of Civil Protection plus 4% of records from broadband velocity sensors converted to acceleration, which helps constrain model for $r > 100$ km.

- Remove data with suspected soil-structure interaction. Examine time-histories and Fourier amplitude spectra to confirm strongest part of shaking well recorded and that signal-to-noise ratio $> 3$ for $0.5 \leq f \leq 20$ Hz.

- Focal depths for largest events from 5 km to 32 km with one event at 46 km (included since consistent with shallower events). Some small events have shallower depths.

- About half of data from Friuli, Irpinia, Umbria-Marche and Molise sequences.

- Remove pre-event mean from record and then filter using 4th-order acausal high-pass Butterworth filter after cosine tapering and zero-padding. Do not low-pass filter since sites do not have low $\kappa$ and hence short-period spectra not controlled by high frequencies.

- Most data have $M_w < 5.5$. Data distribution reasonable uniform w.r.t. site class.

- Find that applying $M$-$R$ filter to remove distant data from small events has limited impact so do not apply it.

- Also consider subset of 111 stations that recorded $> 1$ event.

- Note that purpose of model is to check the impact of new site classification not to propose a model for hazard assessment.

- Find decrease in $\sigma$ w.r.t. rock (Eurocode 8 classes A, B and E, 91 stations, 492 records)/soil (Eurocode 8 classes C and D, 20 stations, 110 records) classification is small. Prefer proposed classification because it recognises well-distinguished behaviour of the proposed classes.

- Examine match between predictions and observations for 2009 L'Aquila ($M_w$6.3) earthquake and find reasonable match.

## 2.357 Gómez-Bernal et al. (2012)

- Ground-motion model is:

$$\log A = aM_w + dH + e_1S_1 + e_2S_2 + e_3S_3 + f - \log(R + 0.0055\,10^{0.525M_w}) - 0.0015R$$

  where $A$ is in cm/s$^2$; $a = 0.6066$, $d = 0.0021$, $e_1 = -0.4083$, $e_2 = -0.2019$, $e_3 = -0.9771$ and $F = 0.1270$ for horizontal; and $a = 0.6042$, $d = 0.0019$, $e_1 = -0.5420$, $e_2 = -0.2891$, $e_3 = -1.0899$ and $F = 0.0154$ for vertical. $\sigma$ is not reported.

- Only use data from rock and firm soil. Exclude data from lakebed zone of Mexico City and those from very compressible soil, e.g. Chilpancingo City.

- Focal depths, $H$ between 5.0 and 163.8 km.

- Use 3 event types:

Intraslab $S_1 = 1$, $S_2 = S_3 = 0$. 254 records, 5 events.

Interface $S_2 = 1$, $S_1 = S_3 = 0$. 299 records, 10 events.

Crustal $S_3 = 1$ and $S_1 = S_2 = 0$. 54 records, 2 events.

- Data from earthquakes between 14/04/1979 and 30/09/1999 taken from Base Mexicana de Datos de Sismos Fuertes.

- Baseline correct and bandpass filter records.

- Compare predictions and observations for 19/09/1985 ($M_w$8.1) earthquake.

## 2.358 Hamzehloo and Mahood (2012)

- Ground-motion model is[37].:

$$\log Y = a + b(M - 6) + c(M - 6)^2 + d\sqrt{r_{jb}^2 + 7^2} - \log\sqrt{r_{jb}^2 + 7^2}$$

  where $Y$ is in g, $a = 2.610$, $b = 0.2689$, $c = -0.03275$, $d = -0.01264$ and $\sigma = 0.37$.

- Use only data from hard rock sites.

- Use data from network [SMA-1 and SSA-2 (trigger threshold of 10 gal) instruments] of Building and Housing Research Center from 1978 to 2008.

- Originally collect 497 records from 137 earthquakes but remove data with unknown source parameters, site conditions and low signal-to-noise ratios.

- Most data from $M_w < 7$, with gap between 5.6 and 6.3, and $r_{jb} > 10$ km.

- Also derive model using stochastic finite-fault approach.

- Compare observations and predictions w.r.t. $r_{jb}$.

[37] It seems that the equation given in the article is missing a $-\log\sqrt{r_{jb}^2 + h^2}$ term since other the predictions do not match those reported and stated that the form of Joyner and Boore (1993) is used.

## 2.359 Hung and Kiyomiya (2012)

- Ground-motion model is:

$$\log A = aM + bX - \log(X + d10^{eM}) + c + p\log(V_{s,30}/V_{ref})$$

  where $A$ is in $\text{cm/s}^2$, $a = 0.59$, $c = -0.003$, $d = 0.005$, $e = 0.5$, $c = 0.01$, $p = -0.209$, $V_{ref} = 472.8$ and $\sigma = 0.26$[38].

- Use $V_{s,30}$, estimated from shallower depths if required, to characterise sites. Derive site term based on residuals of model without this term. Distribution by NEHRP classes: A (8 records), B (114), C (253), D (83) and E (9).

- Note that 24 broadband instruments are deployed in Vietnam by Institute of Geophysics (Vietnam) and Institute of Earth Sciences (Academia Sinica, Taiwan) since 2005 and some records from 2001 (Dien Bien $M5.3$ and aftershocks) and 5 other events 4.0–4.9. Note that limited data from Vietnam, particularly from moderate and large earthquakes, (1 mainshock and 16 aftershocks, 17 records, $2.7 \leq M_w \leq 5.1$) and hence supplement it with data from Yunnan (China, 1 earthquake, 4 records, $M_w6.4$), which is adjacent and has similar tectonics, and particularly Japan (K-Net, 5 events, $3.9 \leq M_w \leq 6.9$).

- Select records following these criteria: strike-slip event, inland-type earthquake, $3.5 \leq M_w \leq 7.0$ (the largest event thought to be possible in northern Vietnam), ground-surface records and from source distance less than previously-defined $M$-dependent cut-off.

- Only use data from strike-slip earthquakes because dominant mechanism in northern Vietnam.

- Vast majority of data is from $M_w \geq 5.8$.

- Also derive models based on only data from Japan and only data from Vietnam and Yunnan. Find similar coefficients and $\sigma$s.

- Compare predicted and observed PGAs and find good fit and no apparent trends w.r.t. region, for example.

- Also compare predictions and observations for 2007 Ninger (Yunnan, China, $M_w6.4$) earthquake and find fairly good match.

## 2.360 Laouami and Slimani (2012)

- Ground-motion model is:

$$\log_{10} \text{PSA}(f) = a(f)M + b(f)d - \log_{10} d + c_{1,2}(f)$$

  $\sigma = 0.314$ for regional model and 0.331 for local model. No coefficients are reported.

- Use 2 site classes:

  Rock Use coefficient $c_1$

  Alluvium Use coefficient $c_2$

  Use $V_s$ when available and otherwise geological and geophysical (e.g. H/V ratios) information. Because most Algerian stations on firm soils/rock model applies to these sites.

[38]It is possible that the coefficients $d$, $e$ and $c$ were assumed *a priori* and not found by regression since they are the same for the three record subsets.

- Derive two models: regional (using data from Algeria up to 06/06/2008, Europe and USA) and local (only data from Algeria).
- Find local model overestimates observations for large earthquakes.
- Examine residuals w.r.t. $r_{hypo}$ and find no bias. Relate large residuals to local site effects.
- Data from: SMA-1 (analogue), SSA-1 and Etna (digital) instruments.
- Instrument-correct data, fit baseline and band-pass Ormsby filter with cut-offs 0.12–0.2 Hz with roll-off width of 0.06 Hz for digital instruments and 0.2–0.3 Hz with roll-off width of 0.1 Hz for analogue instruments and 25 Hz (with 3 Hz roll-off width for all instruments). Cut-offs based on signal-to-noise ratio of each component.
- Algerian data mainly covers $3 \leq M_s \leq 6$ and $7 \leq r_{hypo} \leq 100$ km. Include foreign data to supplement Algerian data outside these ranges.

## 2.361 Mohammadnejad et al. (2012)

- Ground-motion model is (it is not clear which coefficients were fixed and which obtained by the regression algorithm):

$$\ln(\mathrm{PGA}) = a_1 M_w - \ln(R_{ClstD}) + \frac{[\ln(R_{ClstD}) + a_2(a_3 F + a_4 M + a_5 \ln(R_{ClstD}) + a_6)^2 + a_7][F - \ln(R_{ClstD}) + a_8]}{V_{s,30}} + a_9$$

  where PGA is in cm/s$^2$, $a_1 = 0.5$, $a_2 = -1/9$, $a_3 = 2$, $a_4 = -6$, $a_5 = 4$, $a_6 = 23$, $a_7 = 1$, $a_8 = 21$ and $a_9 = 4.5$ ($\sigma$ not given).
- Characterise sites by $V_{s,30}$, which ranges from 116.35 to 2016.13 m/s.
- Use 3 faulting mechanisms, using rake angle to define them:

$F = 1$ Reverse
$F = 2$ Normal
$F = 3$ Strike-slip

- Use PEER NGA (v 7.3) database (Chiou et al., 2008). Exclude records missing required information and duplicates to obtain 2815 in total. Probably same data as Alavi et al. (2011) (see Section 2.339) because studies similar but final equations different.
- Use hybrid method coupling genetic programming and simulated annealing to derive model[39]. Technique seeks best functional form and coefficients.
- Best models chosen based on: models with simplest structure (although not a predominant factor) and models that provided best predictions for training set.
- Use correlation coefficient, root mean square error and mean absolute percent error to judge performance of models.
- Randomly divide data into training (2252 records), used in learning process, and testing (563 records), used to measure performance of model, subsets. Consider several training and testing sets, selected such that maximum, minimum, mean and standard deviation of parameters were the same in training and testing.
- Compare observed and predicted motions for training and testing subsets. Find good fit.
- Also derive model using traditional genetic programming. Compare to model from hybrid technique.

[39] This model is listed here, rather than in Chapter 6, because they provide an analytical expression for their model

## 2.362 Nabilah and Balendra (2012)

- Ground-motion model is:

$$\ln(\mathrm{PGA}) = a_1 M - \ln(R) - a_2 R + a_3$$

where PGA is in gal, $a_1 = 1.3858$, $a_2 = 0.002478$, $a_3 = -3.6589$ and $\sigma = 0.3917$.

- Focal depths $< 35$ km.
- Data from 6 stations (broadband or short-period) on granite in Peninsular Malaysia and one stations in Singapore. Records corrected and filtered.
- Develop model because previous models overpredict PGAs in Malaysia.
- Compare observed and predicted PGAs w.r.t. distance and grouped by magnitude and find good fit.

## 2.363 Nguyen et al. (2012)

- Ground-motion model is:

$$\log A = a + bM - \log R + cR$$

where $A$ is in cm/s$^2$, $a = -0.987$, $b = 0.7521$, $c = -0.00475$, $\sigma = 0.914$ (without site correction) and $\sigma = 0.716$ (with site correction)[40]

- Compute site corrections (absolute factors between 0.34 and 5.72) based on mean residuals w.r.t. each station. Relate site terms to variations in soil conditions.
- Records from portable broadband network of 14 different stations (3 STS-2 and 11 Trillium 40 instruments) operated by Institute of Geophysics (Vietnamese Academy of Science and Technology, Vietnam) and Institute of Earth Sciences (Academia Sinica, Taiwan). Data from 01/2006 to 12/2009
- Focal depths between 0.5 and 28 km.
- Only use good-quality records, records with $r_{epi} < 500$ km and events recored by $\geq 3$ stations.
- Check signal-to-noise ratios for the weakest records and find ratios $> 1.5$ for frequencies $< 15$ Hz and hence conclude that data are suitable.
- Try using quadratic $M$ term and using $r_{hypo}$ rather than $r_{epi}$ and find similar coefficients but higher $\sigma$, which relate to poor focal depths or PGAs being associated with surface waves.
- Do not consider faulting mechanism because no estimates for selected events and major faults in Vietnam are strike-slip.
- Compare predicted and observed (grouped by magnitude) PGAs w.r.t. $r_{epi}$ for used data and independent data (SSA-1 instruments) from period 04/1997 to 08/1999 ($3.2 \leq M_w \leq 4.3$) and 19/02/2001 to 05/03/2001 [Dien Bien, $M_w$5.3 and aftershocks ($3 \leq M_w \leq 4.8$) recorded at Dien Bien and Tuan Giao]. Find good match for both sets.

[40] These $\sigma$s are very large. They are probably given in terms of natural logarithms rather than common logarithms, which are used for the model of the median.

### 2.364 Saffari et al. (2012)

- Ground-motion model is:

$$\log A = aM_w - bX - \log(X + d10^{0.5M_w}) + c_1\delta_1 + c_2\delta_2 + c_3\delta_3 + fF + gZ$$

where $A$ is in gal, $a = 0.38$, $b = 0.0045$, $d = 0.005$, $c_1 = 1.30$, $c_2 = 1.35$, $c_3 = 1.53$, $f = 0.03$, $g = 0.02$, $\sigma_{intra} = 0.23$, $\sigma_{inter} = 0.16$ and $\sigma_{total} = 0.28$.

- Use 3 site classes (same as Iranian Code of Practice for the Seismic Resistant Design of Buildings):

  I $V_{s,30} > 750$ m/s. Average $V_{s,30} = 994$ m/s. 135 records. $c_1 = 1$ and $c_2 = c_3 = 0$.

  II $375 \leq V_{s,30} \leq 750$ m/s. Average $V_{s,30} = 558$ m/s. 160 records. $c_2 = 1$ and $c_1 = c_3 = 0$.

  III $175 \leq V_{s,30} \leq 375$ m/s. Average $V_{s,30} = 306$ m/s. 56 records. $c_3 = 1$ and $c_1 = c_2 = 0$.

  There is a fourth class in the Iranian code ($V_{s,30} < 175$ m/s) but no records from this class so not considered in model.

- Consider two faulting mechanisms:

  Reverse-thrust $F = 0$

  Strike-slip $F = 1$

  Exclude data from normal-faulting events, which occur rarely in Iran.

- Use data from free-field or ground floors from stations of the Iran Strong Motion Network of the Building and Housing Research Centre from 07/03/1975 to 07/12/2008. Data from SSA-2 (digital) and SMA-1 (analogue) instruments.

- Select data using these criteria: $M_w \geq 5.0$, records from ground surface and both horizontal components available. Apply $M_w$-dependent truncation of distant records because instrument acceleration trigger is 10 gal.

- Consider difference in motions between Central Iran (42 events, $Z = 0$) and Zagros (36 events, $Z = 1$) zones, where tectonics are different.

- Focal depths between 5 and 34 km. Exclude deeper events because insufficient data.

- Filter records with bandpass cosine filter with cut-offs 0.2 and 20 Hz, which were chosen based on characteristics of instruments.

- Exclude data from events with specific geological or other effects.

- 83% of data have PGA$<$ 100 gal hence do not consider nonlinear site response.

- Majority of data from $M_w \leq 6.5$.

- Examine residuals w.r.t. $M_w$, $r$, focal depth, zone and faulting mechanism and find no significant trends. Based on these plots believe model reliable for $5.0 \leq M_w \leq 7.3$ in Central Iran and $5.0 \leq M_w \leq 6.5$ in Zagros, $15 \leq r_{rup} \leq 135$ km and focal depths 7–27 km.

- Believe higher motions in Zagros zone due to ductile bed, which means ruptures do not reach surface.

## 2.365 Shah et al. (2012)

- Ground-motion model is:

$$\ln y = a + bM + c \ln R$$

  where $y$ is in g, $a = -6.0985 \pm 0.7364$, $b = 1.4004 \pm 0.1189$ and $c = -1.5357 \pm 0.1010$ ($\sigma$ is not reported).

- Use data from about 10 stations of network of Micro Seismic Studies Programme[41] from 08/10/2005 (Muzaffarabad, $M_w$7.6 earthquake) to 10/10/2010.

- Select data from shallow crustal earthquakes.

- Only two earthquakes with $M_w > 5.8$ (7 records from $M_w$6.4 event and 6 for $M_w$7.6 earthquake); majority of data from $4.7 \leq M \leq 5.8$. Most data from $r_{epi} < 175$ km.

- Use simple functional form because independent parameters other than $M$ and $R$ lacking and since first model for studied region.

- Note that data is not abundant and it is mainly low-amplitude.

- Compare observed and predicted PGAs for 3 largest events. Find match, although model overestimates near-source observations for $M$7.6 earthquake.

[41] And possibly from the Pakistan Meteorological Department — it is not clear if these data were used.

## 2.366 Abrahamson et al. (2013, 2014)

- Ground-motion model is (for median):

$$
\begin{aligned}
\ln \mathrm{Sa} &= f_1 + F_{RV} f_7 + F_N f_8 + F_{AS} f_{11} + f_5 + F_{HW} f_4 + f_6 + f_{10} + \text{Regional} \\
f_1 &= \begin{cases} a_1 + a_5(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)] \ln R + a_{17} r_{rup} & M > M_1 \\ a_1 + a_4(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)] \ln R + a_{17} r_{rup} & M_2 \leq M < M_1 \\ a_1 + a_4(M_2 - M_1) + a_8(8.5 - M)^2 + a_6(M - M_2) + a_7(M - M_2)^2 & \\ +[a_2 + a_3(M_2 - M_1)] \ln R + a_{17} r_{rup} & M < M_2 \end{cases} \\
R &= \sqrt{r_{rup}^2 + c_{4M}^2} \\
c_{4M} &= \begin{cases} c_4 & M > 5 \\ c_4 - (c_4 - 1)(5 - M) & 4 < M \leq 5 \\ 1 & M \leq 4 \end{cases} \\
f_7 &= \begin{cases} a_{11} & M > 5 \\ a_{11}(M - 4) & 4 \leq M \leq 5 \\ 0 & M < 4 \end{cases} \\
f_8 &= \begin{cases} a_{12} & M > 5 \\ a_{12}(M - 4) & 4 \leq M \leq 5 \\ 0 & M < 4 \end{cases} \\
f_5 &= \begin{cases} (a_{10} + bn) \ln\left(\frac{V_{s,30}^*}{V_{Lin}}\right) & V_{s,30} \geq V_{Lin} \\ a_{10} \ln\left(\frac{V_{s,30}^*}{V_{Lin}}\right) - b \ln(\hat{\mathrm{Sa}} + c) + b \ln\left[\hat{\mathrm{Sa}} + c\left(\frac{V_{s,30}^*}{V_{Lin}}\right)^n\right] & V_{s,30} < V_{Lin} \end{cases} \\
V_{s,30}^* &= \begin{cases} V_{s,30} & V_{s,30} < V_1 \\ V_1 & V_{s,30} \geq V_1 \end{cases} \\
V_1 &= \begin{cases} 1500 & T \leq 0.5\,\mathrm{s} \\ \exp\left[-0.35 \ln\left(\frac{T}{0.5}\right) + \ln(1500)\right] & 0.5 < T < 3\,\mathrm{s} \\ 800 & T \geq 3\,\mathrm{s} \end{cases} \\
f_4 &= a_{13} T_1 T_2 T_3 T_4 T_5 \\
T_1 &= \begin{cases} (90 - \mathrm{dip})/45 & \mathrm{dip} > 30^\circ \\ 60/45 & \mathrm{dip} < 30^\circ \end{cases} \\
T_2 &= \begin{cases} 1 + a_{2HW}(M - 6.5) & M \geq 6.5 \\ 1 + a_{2HW}(M - 6.5) - (1 - a_{2HW})(M - 6.5)^2 & 5.5 < M < 6.5 \\ 0 & M \leq 5.5 \end{cases} \\
T_3 &= \begin{cases} h_1 + h_2(R_x/R_1) + h_3(R_x/R_1)^2 & R_x < R_1 \\ 1 - \left(\frac{R_x - R_1}{R_2 - R_1}\right) & R_1 \leq R_x \leq R_2 \\ 0 & R_x > R_1 \end{cases} \\
T_4 &= \begin{cases} 1 - \frac{Z_{TOR}^2}{100} & Z_{TOR} \leq 10\,\mathrm{km} \\ 0 & Z_{TOR} > 10\,\mathrm{km} \end{cases} \\
T_5 &= \begin{cases} 1 & R_{y0} - R_{y1} \leq 0 \\ 1 - \frac{R_{y0} - R_{y1}}{5} & 0 < R_{y0} - R_{y1} < 5 \\ 0 & R_{y0} - R_{y1} \geq 5 \end{cases} \\
R_1 &= W \cos(\mathrm{dip}) \\
R_2 &= 3R_1 \\
R_{y1} &= R_x \tan(20) \\
h_1 &= 0.25 \\
h_2 &= 1.5 \\
h_3 &= -0.75
\end{aligned}
$$

$$\text{If } R_{y0} \text{ not available:} \quad T_5 = \begin{cases} 1 & r_{jb} = 0 \\ 1 - \frac{r_{jb}}{30} & r_{jb} < 30 \\ 0 & r_{jb} \geq 30 \end{cases}$$

$$f_6 = \begin{cases} a_{15}\frac{Z_{TOR}}{20} & Z_{TOR} < 20\,\mathrm{km} \\ a_{15} & Z_{TOR} \geq 20\,\mathrm{km} \end{cases}$$

$$f_{10} = \begin{cases} a_{43}\ln\left(\frac{Z_1+0.01}{Z_{1,ref}+0.01}\right) & V_{s,30} \leq 200\,\mathrm{m/s} \\ a_{44}\ln\left(\frac{Z_1+0.01}{Z_{1,ref}+0.01}\right) & 200 < V_{s,30} \leq 300\,\mathrm{m/s} \\ a_{45}\ln\left(\frac{Z_1+0.01}{Z_{1,ref}+0.01}\right) & 300 < V_{s,30} \leq 500\,\mathrm{m/s} \\ a_{46}\ln\left(\frac{Z_1+0.01}{Z_{1,ref}+0.01}\right) & V_{s,30} > 500\,\mathrm{m/s} \end{cases}$$

$$Z_{1,ref} = \begin{cases} \frac{1}{1000}\exp\left[\frac{-7.15}{4}\ln\left(\frac{V_{s,30}^4+570.94^4}{1360^4+570.94^4}\right)\right] & \text{for California} \\ \frac{1}{1000}\exp\left[\frac{-5.23}{2}\ln\left(\frac{V_{s,30}^2+412.39^2}{1360^2+412.39^4}\right)\right] & \text{for Japan} \end{cases}$$

$$f_{11} = \begin{cases} a_{14} & CR_{jb} \leq 5\,\mathrm{km} \\ a_{14}\left[1 - \frac{CR_{jb}-5}{10}\right] & 5 < CR_{jb} < 15\,\mathrm{km} \\ 0 & CR_{jb} \geq 15\,\mathrm{km} \end{cases}$$

$$\text{Regional} = F_{TW}(f_{12} + a_{25}r_{rup}) + F_{CN}a_{28}r_rup + F_{JP}(f_{13} + a_{29}r_{rup})$$

$$f_{12} = a_{31}\ln\left(\frac{V_{s,30}^*}{V_{Lin}}\right)$$

$$f_{13} = \begin{cases} a_{36} & V_{s,30} < 200\,\mathrm{m/s} \\ a_{37} & 200 \leq V_{s,30} < 300\,\mathrm{m/s} \\ a_{38} & 300 \leq V_{s,30} < 400\,\mathrm{m/s} \\ a_{39} & 400 \leq V_{s,30} < 500\,\mathrm{m/s} \\ a_{40} & 500 \leq V_{s,30} < 700\,\mathrm{m/s} \\ a_{41} & 700 \leq V_{s,30} < 1000\,\mathrm{m/s} \\ a_{42} & V_{s,30} \geq 1000\,\mathrm{m/s} \end{cases}$$

where: Sa is in g, $\hat{\mathrm{Sa}}$ is median spectral acceleration in g for reference $V_{s,30} = 1180\,\mathrm{m/s}$, Dip is fault dip in degrees, $W$ is down-dip rupture width, $c_4 = 4.5$, $M_1 = 6.75$, $M_2 = 5$, $a_1 = 0.587$, $a_2 = -0.790$, $a_3 = 0.275$, $a_4 = -0.1$, $a_5 = -0.41$, $a_6 = 2.154$, $a_8 = -0.015$, $a_{10} = 1.735$, $a_{11} = 0$, $a_{12} = -0.1$, $a_{13} = 0.6$, $a_{14} = -0.3$, $a_{15} = 1.1$, $a_{17} = -0.0072$, $V_{Lin} = 660$, $b = -1.47$, $n = 1.5$, $c = 2.4$, $a_{43} = 0.1$, $a_{44} = 0.05$, $a_{45} = 0$, $a_{46} = -0.05$, $a_{25} = -0.0015$, $a_{28} = 0.0025$, $a_{29} = -0.0034$, $a_{31} = -0.1503$, $a_{36} = 0.265$, $a_{37} = 0.337$, $a_{38} = 0.188$, $a_{39} = 0$, $a_{40} = 0.088$, $a_{41} = -0.196$ and $a_{42} = 0.044$.

- Ground-motion model is (for aleatory variability):

$$\sigma = \sqrt{\phi^2 + \tau^2}$$

$$\phi_{A,L} = \begin{cases} s_1 & M < 4 \\ s_1 + \frac{s_2 - s_1}{2}(M-4) & 4 \leq M < 6 \\ s_2 & M > 6 \end{cases}$$

Or for Japanese sites: $$\phi_{A,L-JP} = \begin{cases} s_5 & r_{rup} < 30\,\mathrm{km} \\ s_5 + \frac{s_6 - s_5}{50}(r_{rup} - 30) & 30 \leq r_{rup} \leq 80\,\mathrm{km} \\ s_6 & r_{rup} > 80\,\mathrm{km} \end{cases}$$

$$\phi_B = \sqrt{\phi_{A,L}^2 - \phi_{Amp}^2}$$

$$\phi_{Amp} = 0.4$$

$$\tau_{A,L} = \begin{cases} s_3 & M < 5 \\ s_3 + \frac{s_4 - s_3}{2}(M-5) & 5 \leq M < 7 \\ s_4 & M > 7 \end{cases}$$

$$\tau_B = \tau_{A,L}$$

$$\phi = \sqrt{\phi_B^2 \left(1 + \frac{\partial \ln \mathrm{Amp}}{\partial \ln \mathrm{Sa}_{1180}}\right)^2 + \phi_{Amp}^2}$$

$$\tau = \tau_B \left(1 + \frac{\partial \ln \mathrm{Amp}}{\partial \ln \mathrm{Sa}_{1180}}\right)$$

$$\frac{\partial \ln \mathrm{Amp}}{\partial \ln \mathrm{Sa}_{1180}} = \begin{cases} 0 & V_{s,30} \geq V_{Lin} \\ \frac{-b\hat{\mathrm{Sa}}_{1180}}{\hat{\mathrm{Sa}}_{1180} + c} + \frac{b\hat{\mathrm{Sa}}_{1180}}{\hat{\mathrm{Sa}}_{1180} + c\left(\frac{V_{s,30}}{V_{Lin}}\right)^n} & V_{s,30} < V_{Lin} \end{cases}$$

  where: $s_1 = 0.754$ and $s_2 = 0.520$ for estimated $V_{s,30}$, $s_1 = 0.741$ and $s_2 = 0.501$ for measured $V_{s,30}$, $s_3 = 0.47$, $s_4 = 0.36$, $s_5 = 0.54$ and $s_6 = 0.63$.

- Coefficients in Abrahamson et al. (2013) and Abrahamson et al. (2014) are not exactly the same. Coefficients of Abrahamson et al. (2014) are final values.

- Use $V_{s,30}$ and $Z_1$ (depth to 1 km/s shear-wave velocity horizon) to characterise sites. 9668 records have $Z_1$ estimates (for remaining 6082 records set $Z_1$ to $Z_{1,ref}$, the average $Z_1$ for given $V_{s,30}$). Because correlation between $V_{s,30}$ and deeper structure may be regional dependent, allow model-scaling with $V_{s,30}$ to depend on region. Note that $Z_{2.5}$ may be more directly related to long-period site response but choose $Z_1$ because closer to traditional geotechnical deep-to-bedrock parameter and easier to measure for specific projects. Note that model applicable for $V_{s,30} \geq 180$ m/s.

- Use 3 faulting mechanisms:

Strike-slip Other rake angles. 221 events. $F_{RV} = F_N = 0$.

Reverse Rake angles between 30 and 150°. 79 events. $F_{RV} = 1$, $F_N = 0$.

Normal Rake angles between −30 and −150°. 26 events, mostly $4.6 \leq M_w \leq 6$. $F_N = 1$, $F_{RV} = 0$.

  Use two earthquake types:

Class 1 Mainshocks. $F_{AS} = 0$.

Class 2 Aftershocks. Events with centroid $r_{jb} < 15$ km ($CR_{jb}$). $F_{AS} = 1$.

  Use two locations w.r.t. vertical projection of the top of rupture:

Hanging wall $F_{HW} = 1$.

Foot wall $F_{HW} = 0$.

Use three regional terms to adjust model w.r.t. base model (all other regions, dominated by California):

Taiwan $F_{TW} = 1$

China $F_{CN} = 1$

Japan $F_{JP} = 1$

- Model derived within NGA West 2 project, using the project database (Ancheta et al., 2014).
- Update of Abrahamson and Silva (2008) to: extend down to $M_w 3$, better constrain hanging-wall effects and model regional differences in attenuation and $V_{s,30}$.
- Try to use all data from active crustal regions under assumption that median motions at distances $< 80$ km are similar worldwide, which implies similar median stress drops in California (12044 records, 274 events), Alaska (7 records, 2 events), Taiwan (1535 records, 6 events), Japan (1700 records, 5 events), Middle East (43 records, 5 events), Italy (175 records, 25 events), Greece (3 records, 1 event), New Zealand (72 records, 2 events), other European countries (6 record, 1 event) and other region (5 records, 1 event). Account for differences can longer distances, due to crustal structure or $Q$, through additional terms.
- Exclude earthquakes not representative of active crustal regions. Remove events with questionable hypocentral depths. Remove events with fewer than 3 records for $M_w > 5$ and fewer than 10 records with good distance coverage for $M_w < 5$ (because of abundance of small-magnitude data). Remove 2008 Wenchuan aftershocks because of residuals and spectral shapes that were very different than other data, which may be due to unreliable metadata. Remove records not representative of free-field motions. Remove records missing key metadata. Remove questionable data due to apparent incorrect gain or spectral shape. Remove records from distances greater than magnitude-distance censoring distances, which depend on instrument type.
- Use 1D finite-fault kinematic simulations to constrain hanging-wall (Donahue and Abrahamson, 2014) and magnitude scaling and equivalent-linear modelling of Peninsula Range soil to constrain site response terms (Kamai et al., 2014).
- Almost all data from $M_w < 5$ are from western USA.
- Use different number of records in Step 1 (less than 4000 from about 130 events) and Step 2 (about 7000 from about 130 events) because of data selection criteria applied. Within these general three stages (Step 1, 2 and, the final step) various regression analysis undertaken to constrain different sets of coefficients.
- Find 2008 Wenchuan ($M_w 7.9$) earthquake has very weak long-period motions, hich are inconsistent with scaling from finite-fault simulations. Therefore, remove this event from Steps 1 and 2 and only include it once magnitude scaling is fixed.
- Use four distance measures to model hanging-wall effects: $r_{jb}$, $R_x$ (horizontal distance from top edge of rupture, measured perpendicular to fault strike), $R_1$ (value of $R_x$ at bottom edge of rupture) and $R_{y0}$ (horizontal distance off the end of the rupture measured parallel to strike).
- Use site-response model of Kamai et al. (2014) based on PSA on reference rock rather than PGA because simplifies aleatory variability model.
- Note correlation between $Z_{TOR}$ and mechanism: reverse earthquakes tend to be deeper than strike-slip events.
- Constrain $V_1$ based on non-parametric models of $V_{s,30}$ scaling.

- Note that nonlinear site term not intended to replace site-specific response analysis for nonlinear soils but rather to allow use of data from such sites to help constrain model.
- For hanging-wall terms only $a_{13}$ is found from regression of empirical data. Other terms found from simulations of Donahue and Abrahamson (2014).
- Some evidence for reduction of depth dependency at shallow depths but use linear scaling for simplicity. Avoid having the small-magnitude data controlling $Z_{TOR}$ scaling by constraining the scaling when using all data.
- Smooth coefficients in a series of steps.
- Examine inter- and intra-event residuals w.r.t. $M_w$, $r_{rup}$, $V_{s,30}$, $\mathrm{Sa}_{1180}$ and $Z_1$ (raw and binned) and find no trends.

## 2.367 Boore et al. (2013, 2014)

- Ground-motion model is (for median):

$$
\begin{aligned}
\ln Y &= F_E + F_P + F_S \\
F_E &= \begin{cases} e_0\mathrm{U} + e_1\mathrm{SS} + e_2\mathrm{NS} + e_3\mathrm{RS} + e_4(M_w - M_h) + e_5(M - M_h)^2 & M \leq M_h \\ e_0\mathrm{U} + e_1\mathrm{SS} + e_2\mathrm{NS} + e_3\mathrm{RS} + e_6(M_w - M_h) & M > M_h \end{cases} \\
F_P &= [c_1 + c_2(M_w - M_{ref})]\ln(R/R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref}) \\
R &= \sqrt{r_{jb}^2 + h^2} \\
F_S &= \ln(F_{lin}) + \ln(F_{nl}) + F_{\delta z_1}(\delta z_1) \\
\ln(F_{lin}) &= \begin{cases} c\ln\left(\frac{V_{s,30}}{V_{ref}}\right) & V_{s,30} \leq V_c \\ c\ln\left(\frac{V_c}{V_{ref}}\right) & V_{s,30} > V_c \end{cases} \\
\ln(F_{nl}) &= f_1 + f_2 \ln\left(\frac{\mathrm{PGA}_r + f_3}{f_3}\right) \\
f_2 &= f_4[\exp\{f_5(\min(V_{s,30}, 760) - 360)\} - \exp f_5(760 - 360)] \\
F_{\delta z_1} &= \begin{cases} 0 & T < 0.65 \\ f_6\delta z_1 & T \geq 0.65 \& \delta z_1 \leq f_7/f_6 \\ f_7 & T \leq 0.65 \& \delta z_1 > f_7/f_6 \end{cases} \\
\delta z_1 &= z_1 - \mu_{z1} \\
\ln(\mu_{z1}) &= \begin{cases} \frac{-7.15}{4}\ln\left(\frac{V_{s,30}^4 + 570.94^4}{1360^4 + 570.94^4}\right) & \text{for California} \\ \frac{-5.23}{2}\ln\left(\frac{V_{s,30}^2 + 412.39^2}{1360^2 + 412.39^4}\right) & \text{for Japan} \end{cases}
\end{aligned}
$$

where: $Y$ is in g, $M_{ref} = 4.5$, $R_{ref} = 1$ km, $V_{ref} = 760$ m/s, $\mathrm{PGA}_r$ is median PGA for reference rock (i.e. $V_{s,30} = V_{ref}$), $e_0 = 0.4473$, $e_1 = 0.4856$, $e_2 = 0.2459$, $e_3 = 0.4539$, $e_4 = 1.4310$, $e_5 = 0.05053$, $e_6 = -0.1662$, $M_h = 5.5$, $c_1 = -1.134$, $c_2 = 0.1917$, $c_3 = -0.008088$, $h = 4.5$, $\Delta c_{3,China,Turkey} = 0.0028576$, $\Delta c_{3,Italy,Japan} = -0.0025500$, $c = -0.6$, $V_c = 1500$ m/s, $f_1 = 0$, $f_3 = 0.1$, $f_4 = -0.15$, $f_5 = -0.00701$, $f_6 = -9.9$ and $f_7 = -9.9$.

- Ground-motion model is (for aleatory variability):

$$
\begin{aligned}
\sigma &= \sqrt{\phi^2+\tau^2} \\
\tau &= \begin{cases} \tau_1 & M_w \leq 4.5 \\ \tau_1+(\tau_2+\tau_1)(M_w-4.5) & 4.5 < M_w < 5.5 \\ \tau_2 & M_w \geq 5.5 \end{cases} \\
\phi &= \begin{cases} \phi(M_w,r_{jb}) & V_{s,30} \geq V_2 \\ \phi(M_w,r_{jb}) - \Delta\phi_V \left[\frac{\ln(V_2/V_{s,30})}{\ln(V_2/V_1)}\right] & V_1 \leq V_{s,30} \leq V_2 \\ \phi(M_w,r_{jb}) - \Delta\phi_V & V_{s,30} \leq V_1 \end{cases} \\
\phi(M_w,r_{jb}) &= \begin{cases} \phi(M_w) & r_{jb} \leq R_1 \\ \phi(M_w) + \Delta\phi_R \left[\frac{\ln(r_{jb}/R_1)}{\ln(R_2/R_1)}\right] & R_1 < r_{jb} \leq R_2 \\ \phi(M_w) + \Delta\phi_R & \end{cases} \\
\phi(M_w) &= \begin{cases} \phi_1 & M_w \leq 4.5 \\ \phi_1+(\phi_2-\phi_1)(M_w-4.5) & 4.5 < M_w < 5.5 \\ \phi_2 & M_w \geq 5.5 \end{cases}
\end{aligned}
$$

  where: $\phi$ is intra-event, $\tau$ is inter-event variability, $R_1 = 110$, $R_2 = 270$, $\Delta\phi_R = 0.10$, $\Delta\phi_V = 0.07$, $V_1 = 225$, $V_2 = 300$, $\phi_1 = 0.695$, $\phi_2 = 0.495$, $\tau_1 = 0.398$ and $\tau_2 = 0.348$.

- Use $V_{s30}$ (both measured and inferred) to characterise sites. $V_{s,30}$ between about 100 and 2016 m/s but state model applicable from 150–1500 m/s. Most data from soil and soft rock sites (NEHRP C and D) (peak in distribution about 400 m/s).

- Use basin depth (from surface to 1.0 km/s shear-wave velocity horizon) $z_1$ to characterise sites. State model applicable from 0–3 km. Recommend that when $z_1$ is unknown to set $\delta z_1$ to zero to turn off basin-depth adjustment factor.

- Use 4 faulting mechanisms:

  SS Strike-slip, P-axis plunge $\leq 40°$ and T-axis plunge $\leq 40°$. About 8500 records from about 210 events. SS = 1. Other mechanism variables are zero.

  NS Normal, P-axis plunge $> 40°$ and T-axis plunge $\leq 40°$. About 1000 records from about 40 events. NS = 1. Other mechanism variables are zero.

  RS Reverse, P-axis plunge $\leq 40°$ and T-axis plunge $> 40°$. About 5500 records from about 100 events. RS = 1. Other mechanism variables are zero.

  U Unspecified. No records are from unknown mechanism in input data. U = 1. Other mechanism variables are zero.

  Classify based on plunges of P- and T-axes but almost the same classification using rake angle within 30° of horizontal for SS and normal and reverse for negative and positive rake angles not within 30°.

- Model derived within NGA West 2 project, using the project database (Ancheta et al., 2014). Data principally from: California, Taiwan, Japan, China, Italy, Greece, Turkey and Alaska.

- Use three-step approach to balance prediction accuracy and simplicity of form and application. After constraining site response and some additional effects based on initial analysis (Phase 1), perform regression (Phase 2) to constrain effects of $M_w$, $r_{jb}$ and mechanism (base-case model). In Phase 3 examine inter- and intra-event residuals against secondary variables: region, event type (roughly mainshock or aftershock), source depth and basin depth. Assess whether secondary variables are statistically significant and practically meaningful. If so include variables as optional adjustments.

- Note lack of constraint for $M_w > 7$ normal-faulting events.

- Develop model to overcome limitations with Boore and Atkinson (2008) in terms of predictions for small magnitudes and regional dependency in anelastic attenuation.

- Exclude data without $M_w$, $r_{jb}$ and site metadata. Use only one record from co-located stations (e.g. in a differential array) of same earthquake. Exclude records without both horizontal components. Exclude earthquakes from oceanic crust or stable continental regions. Exclude records thought not to reasonably reflect free-field conditions due to site-structure interaction. Only use publicly-available data. Exclude records (based on visual inspection) with: S-wave triggers, second triggers, noisy traces or time-step problems. Apply magnitude-distance cut-offs based on instrument type to minimise potential sampling bias because of triggering of instruments by unusually strong shaking. Only consider earthquakes with $\geq 4$ records with $r_{jb} \leq 80$ km after applying other criteria.

- Secondary variables are: depth to top of rupture $Z_{tor}$ and hypocentral depth $Z_{hypo}$; basin depth (from surface to 1.0 km/s shear-wave velocity horizon) $z_1$; event type: class 1 (mainshocks) or class 2 (aftershocks) using minimum centroid $r_{jb}$ separation of 10 km. Do not consider hanging-wall effects because $r_{jb}$ already accounts for this.

- Magnitude range widest for SS and narrowest for NS so magnitude-scaling better determined for SS earthquakes. Hence assume common magnitude-scaling for all mechanisms.

- Note lack of data at close distances from small events and hence model not constrained here.

- Select functional form based on subjective inspection and study of nonparametric data plots. Note magnitude-dependent geometric spreading, anelastic attenuation and strongly nonlinear (and period dependent) magnitude-dependency of amplitude-scaling at fixed distance.

- Use site-response model of Seyhan and Stewart (2014), which was developed in iterative manner alongside overall ground-motion model.

- Note that, due to trade-offs between geometric and anelastic attenuation, regression cannot simultaneously determine both. Hence use data from California from $M_w \leq 5$ (to minimise finite-fault and nonlinear site effects) to constrain $c_3$ in Phase 1. Correct data for linear site effects. Group data into 0.5 magnitude unit bins and regress using form $\nu' + c_1' \ln(R/R_{ref}) + c_3(R - R_{ref})$ to find $c_3$. Find $c_3$ is relatively independent of $M_w$.

- In Phase 2 exclude Class 2 events (aftershocks) and data from $r_{jb} > 80$ km and adjust data to $V_{ref}$.

- Find evidence for apparent oversaturation in source term but this is compensated by the other terms in the model.

- Coefficient $e_0$ is a weighted average of coefficients for other faulting mechanisms.

- Recompute coefficients excluding 2008 Wenchuan earthquake ($M_w$7.9) for which some debate over suitability for model development. Removal has no effect at short periods but long-period motions increase for large $M_w$. See no justification for removal of these data hence retain it for final model.

- In Phase 3 (based on mixed-effects residual analyses) find need to include $\Delta c_3$ (for regional anelastic attenuation effects) and $F_{\delta z_1}$ but not source type or depth adjustments.

- Plot inter-event residuals against $M_w$ and rake angle and intra-event residuals against $r_{jb}$ and $V_{s,30}$. Find no trends w.r.t. $M_w$ after excluding Class 2 events from China. Find no trends w.r.t rake angle except for positive residuals for NS for $M_w < 5$ and positive bias for $T > 1$ s for RS when $M_w > 5$. Do not consider trends sufficient to warrant adjustments. Find no trends w.r.t. $r_{jb}$ nor w.r.t. $V_{s,30}$.

- Examine influence of non-Californian earthquakes on model by considering Class 1 event terms by region and fault type. No magnitude overlap for NS events so cannot conclude. For SS event terms similar. For RS find evidence for higher motions in California for $T > 1$ s but because model for global use do not adjust model.
- Plot intra-event residuals w.r.t. $r_{jb}$ split into different regions: California, New Zealand and Taiwan, for which find no trends (average $Q$); Japan and Italy, for which downward trends (low $Q$); and China and Turkey, for which upward trends (high $Q$). For low and high $Q$ cases fit model to residuals for $r_{jb} > 25$ km to find $\Delta c_3$.
- Use $z_1$ because of its greater practicality and lack of evidence that deeper metrics are more useful for basin effects. Find stronger residuals when using $\delta z_1$ than $z_1$ directly. Find no clear trends in intra-event residuals w.r.t $\delta z_1$ at short periods but non-zero residuals for longer periods so add additional term using all data. Find regional variations minor and do not include them.
- Find correlation in event terms between parent Class 1 and children Class 2 events hence examine difference between Class 1 event terms and mean of their children Class 2 event terms w.r.t. $M_w$. Find no systematic departure from zero meaning average Class 2 events do not have any more bias than parent Class 1 events. Conclude that model equally applicable to both types of events.
- Examine inter-event residuals w.r.t. $Z_{tor}$ and $Z_{hypo}$. Find no trends for $M_w \geq 5$. Find trend for smaller events but since most hazard is governed by $M_w \geq 5$ did not include extra term.
- Derive aleatory variability model based on binned Phase 3 inter- and intra-event residuals.
- Note that aleatory variability model may be too high for a more controlled set of region and site conditions.
- Check extrapolation to $M_w 8.5$ (beyond observations) using simple stochastic simulations (not shown) and model appears reasonable.

## 2.368 Campbell and Bozorgnia (2013, 2014)

- Ground-motion model is (for median):

$$\ln Y = \begin{cases} \ln \mathrm{PGA} & \mathrm{PSA} < \mathrm{PGA} \quad \& \quad T < 0.25\,\mathrm{s} \\ f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} + f_{hyp} + f_{dip} + f_{atn} & \text{otherwise} \end{cases}$$

$$f_{mag} = \begin{cases} c_0 + c_1 M & M \leq 4.5 \\ c_0 + c_1 M + c_2(M - 4.5) & 4.5 < M \leq 5.5 \\ c_0 + c_1 M + c_2(M - 4.5) + c_3(M - 5.5) & 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M - 4.5) + c_3(M - 5.5) + c_4(M - 6.5) & M > 6.5 \end{cases}$$

$$f_{dis} = (c_5 + c_6 M) \ln \sqrt{r_{rup}^2 + c_7^2}$$

$$f_{flt} = f_{flt,F} f_{flt,M}$$

$$f_{flt,F} = c_8 F_{RV} + c_9 F_{NM}$$

$$f_{flt,M} = \begin{cases} 0 & M \leq 4.5 \\ M - 4.5 & 4.5 < M \leq 5.5 \\ 1 & M > 5.5 \end{cases}$$

$$f_{hng} = c_{10} f_{hng,R_x} f_{hng,R_{rup}} f_{hng,M} f_{hng,Z} f_{hng,\delta}$$

$$f_{hng,R_x} = \begin{cases} 0 & R_x < 0 \\ f_1(R_x) & 0 \leq R_x < R_1 \\ \max[f_2(R_x), 0] & R_x \geq R_1 \end{cases}$$

$$f_1(R_x) = h_1 + h_2(R_x/R_1) + h_3(R_x/R_1)^2$$

$$f_2(R_x) = h_4 + h_5\left(\frac{R_x - R_1}{R_2 - R_1}\right) + h_6\left(\frac{R_x - R_1}{R_2 - R_1}\right)^2$$

$$R_1 = W \cos\delta$$

$$R_2 = 62M - 350$$

$$f_{hng,R_{rup}} = \begin{cases} 1 & r_{rup} = 0\,\mathrm{km} \\ (r_{rup} - r_{jb})/r_{rup} & r_{rup} > 0\,\mathrm{km} \end{cases}$$

$$f_{hng,M} = \begin{cases} 0 & M \leq 5.5 \\ (M - 5.5)[1 + a_2(M - 6.5)] & 5.5 < M \leq 6.5 \\ 1 + a_2(M - 6.5) & M > 6.5 \end{cases}$$

$$f_{hng,Z} = \begin{cases} 1 - 0.06 Z_{TOR} & Z_{TOR} \leq 16.66\,\mathrm{km} \\ 0 & Z_{TOR} > 16.66\,\mathrm{km} \end{cases}$$

$$f_{hng,\delta} = (90 - \delta)/45$$

$$f_{site} = f_{site,G} + S_f f_{site,J}$$

$$f_{site,G} = \begin{cases} c_{11} \ln\left(\frac{V_{s,30}}{k_1}\right) + k_2 \left\{\ln\left[A_{1100} + c\left(\frac{V_{s,30}}{k_1}\right)^n\right] - \ln[A_{1100} + c]\right\} & V_{s,30} \leq k_1 \\ (c_{11} + k_2 n) \ln\left(\frac{V_{s,30}}{k_1}\right) & V_{s,30} > k_1 \end{cases}$$

$$f_{site,J} = \begin{cases} (c_{12} + k_2 n)\left[\ln\left(\frac{V_{s,30}}{k_1}\right) - \ln\left(\frac{200}{k_1}\right)\right] & V_{s,30} \leq 200\,\mathrm{m/s} \\ (c_{13} + k_2 n) \ln\left(\frac{V_{s,30}}{k_1}\right) & \text{All } V_{s,30} \end{cases}$$

$$f_{sed} = \begin{cases} (c_{14} + c_{15} S_J)(Z_{2.5} - 1) & Z_{2.5} \leq 1\,\mathrm{km} \\ 0 & 1 < Z_{2.5} \leq 3\,\mathrm{km} \\ c_{16} k_3 \mathrm{e}^{-0.75}\{1 - \exp[-0.25(Z_{2.5} - 3)]\} & Z_{2.5} > 3\,\mathrm{km} \end{cases}$$

$$f_{hyp} = f_{hyp,H} f_{hyp,M}$$

$$f_{hyp,H} = \begin{cases} 0 & Z_{HYP} \leq 7\,\mathrm{km} \\ Z_{HYP} - 7 & 7 < Z_{HYP} \leq 20\,\mathrm{km} \\ 13 & Z_{HYP} > 20\,\mathrm{km} \end{cases}$$

$$f_{hyp,M} = \begin{cases} c_{17} & M \leq 5.5 \\ c_{17} + (c_{18} - c_{17})(M - 5.5) & 5.5 < M \leq 6.5 \\ c_{18} & M > 6.5 \end{cases}$$

$$
\begin{aligned}
f_{dip} &= \begin{cases} c_{19}\delta & M \leq 4.5 \\ c_{19}(5.5-M)\delta & 4.5 < M \leq 5.5 \\ 0 & M > 5.5 \end{cases} \\
f_{atn} &= \begin{cases} (c_{20}+\Delta c_{20})(r_{rup}-80) & r_{rup} > 80\,\mathrm{km} \\ 0 & r_{rup} \leq 80\,\mathrm{km} \end{cases}
\end{aligned}
$$

where $Y$ is in g, $R_x$ is closest distance to surface projection of top edge of rupture measured perpendicular to its average strike, $W$ is down-dip width of rupture, $A_{1100}$ is median estimated PGA for $V_{s,30} = 1100\,\mathrm{m/s}$, $c = 1.88$, $n = 1.18$, $h_4 = 1$, $c_0 = -4.416$, $c_1 = 0.984$, $c_2 = 0.537$, $c_3 = -1.499$, $c_4 = -0.496$, $c_5 = -2.773$, $c_6 = 0.248$, $c_7 = 6.768$, $c_8 = 0$, $c_9 = -0.212$, $c_{10} = 0.720$, $c_{11} = 1.090$, $c_{12} = 2.186$, $c_{13} = 1.420$, $c_{14} = -0.0064$, $c_{15} = -0.202$, $c_{16} = 0.393$, $c_{17} = 0.0977$, $c_{18} = 0.0333$, $c_{19} = 0.00757$, $c_{20} = -0.0055$, $\Delta c_{20,JI} = -0.0035$, $\Delta c_{20,CH} = 0.0036$, $k_1 = 865$, $k_2 = -1.186$, $k_3 = 1.839$, $a_2 = 0.167$, $h_1 = 0.241$, $h_2 = 1.474$, $h_3 = -0.715$, $h_5 = -0.337$ and $h_6 = -0.270$.

- Ground-motion model is (for aleatory variability):

$$
\begin{aligned}
\tau_{\ln Y} &= \begin{cases} \tau_1 & M \leq 4.5 \\ \tau_2 + (\tau_1 - \tau_2)(5.5-M) & 4.5 < M < 5.5 \\ \tau_2 & M \geq 5.5 \end{cases} \\
\phi_{\ln Y} &= \begin{cases} \phi_1 & M \leq 4.5 \\ \phi_2 + (\phi_1 + \phi_2)(5.5-M) & 4.5 < M < 5.5 \\ \phi_2 & M \geq 5.5 \end{cases} \\
\tau &= \sqrt{\tau^2_{\ln Y_B} + \alpha^2 \tau^2_{\ln PGA_B} + 2\alpha\rho_{\ln PGA,\ln Y}\tau_{\ln Y_B}\tau_{\ln PGA_B}} \\
\phi &= \sqrt{\phi^2_{\ln Y_B} + \phi^2_{\ln AF} + \alpha^2\phi^2_{\ln PGA_B} + 2\alpha\rho_{\ln PGA,\ln Y}\phi_{\ln Y_B}\phi_{\ln PGA_B}} \\
\tau_{\ln Y_B} &= \tau_{\ln Y} \\
\tau_{\ln PGA_B} &= \tau_{\ln PGA} \\
\phi_{\ln Y_B} &= \sqrt{\phi^2_{\ln Y} + \phi^2_{\ln AF}} \\
\phi_{\ln PGA_B} &= \sqrt{\phi^2_{\ln PGA} - \phi^2_{\ln AF}} \\
\alpha = \frac{\partial f_{site}}{\partial \ln A_{1100}} &= \begin{cases} k_2 A_{1100}\{[A_{1100} + c(V_{s,30}/k_1)^n]^{-1} - (A_{1100}+c)^{-1}\} & V_{s,30} < k_1 \\ 0 & V_{s,30} \geq k_1 \end{cases} \\
\sigma &= \sqrt{\tau^2 + \phi^2}
\end{aligned}
$$

where $\rho_{\ln PGA,\ln Y}$ is correlation coefficient between the intra-event residuals of intensity measure of interest and PGA, $\tau_1 = 0.409$, $\tau_2 = 0.322$, $\phi_1 = 0.734$, $\phi_2 = 0.492$, $\phi_{\ln AF} = 0.300$, $\sigma = 0.840$ (for $M_w \leq 4.5$), $\sigma = 0.588$ (for $M_w \geq 5.5$) and $\rho_{\ln PGA,\ln Y} = 1$.

- Use $V_{s,30}$ and depth to 2.5 km/s shear-wave velocity horizon ($Z_{2.5}$) to characterise sites. State model applicable for $150 \leq V_{s,30} \leq 1500\,\mathrm{m/s}$ and $0 \leq Z_{2.5} \leq 10\,\mathrm{km}$.

- Use 3 mechanisms:

  1. Reverse/reverse-oblique. Rake angle $30 < \lambda < 150°$. $F_{RV} = 1$, $F_{NM} = 0$.
  2. Normal/Normal-oblique. Rake angle $-150 < \lambda < -30°$. $F_{NM} = 1$, $F_{RV} = 0$.
  3. Strike-slip. Other rake angles. $F_{RV} = F_{NM} = 0$.

  Use 2 regions:

Japan $S_J = 1$

Elsewhere $S_J = 0$

- Model derived within NGA West 2 project, using the project database (Ancheta et al., 2014).

- Update model of Campbell and Bozorgnia (2008b) to include more-detailed hanging-wall model, scaling with focal depth ($Z_{HYP}$) and fault dip ($\delta$), regionally-dependent anelastic attenuation and site effects and magnitude-dependent $\sigma$.

- Note that NGA West 2 database provides better constraints on scaling of small earthquakes and at further distances.

- Fewer records for $5 \leq M_w \leq 6$.

- Apply similar selection criteria as Campbell and Bozorgnia (2008b). Exclude: 1) records with only one horizontal component, 2) stations with no measured or estimated $V_{s,30}$, 3) earthquakes with no rake angle or focal mechanism, 4) earthquakes with focal depths > 20 km and those in oceanic plate or stable continental region, 5) unreliable records because of unrealistic spectral shape, late trigger, incorrect but unknown instrument gain, low quality or non-free-field location, 6) aftershocks (Class 2) located in immediate vicinity (centroid $r_{jb} < 10$ km) of mainshock rupture plane and 7) poorly-recorded earthquakes: for $M_w < 5.5 < 5$ records and for $5.5 \leq M_w < 6.5 < 3$ records with $r_{rup} \leq 80$ km (no criterion on minimum number of records were applied for $M_w \geq 6.5$ because of limited data). Near-source dataset: 7208 records from 282 events. Use same criteria (except for 7) to select records in range $80 < r_{rup} \leq 500$ km to derive anelastic attenuation term. Far-source dataset: 8313 records from 276 events.

- 11125 records from 245 earthquakes, primarily from California, with $3 \leq M_w < 5.5$ and 4396 records from 77 earthquakes with $5.5 \leq M_w < 7.9$.

- Develop or confirm functional form using standard data exploration techniques such as analysis of residuals. Undertake numerous iterations to capture trends in observations. Start with form of Campbell and Bozorgnia (2008b) and add or modify terms as required. Use hanging-wall simulations of Donahue and Abrahamson (2014) to update hanging-wall term. If variables missing either estimated using proxies or perform regression using only records were information available.

- Develop model in 2 phases. Firstly, use near-source database to develop model capturing near-source effects, including geometric attenuation. Use $r_{rup} \leq 80$ km because the importance of these distances for seismic hazard. Using only this range of distances avoids trade-off between geometric and anelastic terms. Residuals from this phase confirm near-source recordings do not exhibit significant anelastic attenuation. Secondly, use far-source database and residual analysis to develop regionally-dependent anelastic attenuation term. Finally, apply limited smoothing to remove roughness in estimated spectra.

- Compute $\rho_{\ln PGA, \ln Y}$ from intra-event residuals of near-source regression. Find $\rho_{\ln PGA, \ln Y}$ is magnitude-dependent. Use values for $M_w \geq 5$ because: these earthquakes are most concern for seismic hazard analysis, 2) correlation coefficient similar for both inter- and intra-event residuals (so can use one set for both types of variability) and 3) only large earthquakes produce significant nonlinear site response, one of the principal uses for $\rho_{\ln PGA, \ln Y}$.

- Find anelastic attenuation is regional dependent and derive $\Delta c_{20}$ to model difference between base region (California, Taiwan and Middle East; $\Delta c_{20} = 0$), Japan and Italy (JI, higher attenuation) and eastern China (CH, lower attenuation).

- Plot inter- and intra-event residuals w.r.t. independent variables. Find no strong systematic trends or biases.

- Suggest default values for various independent variables ($Z_{HYP}$, $Z_{TOR}$, $W$, $Z_{BOT}$ (depth to bottom of seismogenic crust) and $V_{s,30}$ and $Z_{2.5}$ for each NEHRP site class. For California find: $\ln Z_{2.5} = 7.089 - 1.144 \ln V_{s,30}$ ($\sigma = 1.026$) and for Japan: $\ln Z_{2.5} = 5.359 - 1.102 \ln V_{s,30}$ ($\sigma = 1.403$), but recommend caution when using them because of large standard deviations. Also present relations between $Z_{1.0}$ and $Z_{2.5}$.

- Suggest that $\tau$ might be regionally-dependent.

- State model applicable for $0 \leq Z_{TOR} \leq 20$ km, $0 \leq Z_{HYP} \leq 20$ km and $15 \leq \delta \leq 90°$.

- Even those database includes some data from $V_{s,30} < 180$ m/s, caution against using model for NEHRP E and F sites because of potentially unusual site conditions that make site effects more complicated than the model suggests and because equivalent-linear simulations used to derive nonlinear site terms are less reliable for high strains. Note that if soil properties deviate significantly from those used in simulations for nonlinear site term then site response under strong shaking may be different than predicted by the model.

- Did not include directivity because of large differences between candidate models for reverse and faults with complicated rupture geometry.

- Find shallow site response similar in all regions except California.

## 2.369 Chiou and Youngs (2013, 2014)

- Ground-motion model is (for median):

$$
\begin{aligned}
\ln y_{ref} &= c_1 + \left\{c_{1a} + \frac{c_{1c}}{\cosh[2\max(M-4.5,0)]}\right\} F_{RV} + \left\{c_{1b} + \frac{c_{1d}}{\cosh[2\max(M-4.5,0)]}\right\} F_{NM} \\
&+ \left\{c_7 + \frac{c_{7b}}{\cosh[2\max(M-4.5,0)]}\right\} \Delta Z_{TOR} + \left\{c_{11} + \frac{c_{11b}}{\cosh[2\max(M-4.5,0)]}\right\} (\cos\delta)^2 \\
&+ c_2(M-6) + \frac{c_2-c_3}{c_n} \ln\left[1+\mathrm{e}^{c_n(c_M-M)}\right] + c_4 \ln\{r_{rup} + c_5 \cosh[c_6 \max(M-c_{HM},0)]\} \\
&+ (c_{4a}-c_4)\ln\sqrt{r_{rup}^2 + c_{RB}^2} + \left\{c_{\gamma 1} + \frac{c_{\gamma 2}}{\cosh[\max(M-c_{\gamma 3},0)]}\right\} r_{rup} \\
&+ c_8 \max\left[1 - \frac{\max(r_{rup}-40,0)}{30}, 0\right] \min\left[\frac{\max(M-5.5,0)}{0.8}, 1\right] \mathrm{e}^{-c_{8a}(M-c_{8b})^2} \Delta\mathrm{DPP} \\
&+ c_9 F_{HW} \cos\delta \left[c_{9a} + (1-c_{9a})\tanh\left(\frac{R_x}{c_{9b}}\right)\right] \left[1 - \frac{\sqrt{r_{jb}^2 + Z_{TOR}^2}}{r_{rup}+1}\right] \\
\ln y &= \ln y_{ref} + \phi_1 \min\left[\ln\left(\frac{V_{s,30}}{1130}\right), 0\right] \\
& \phi_2 \left\{\mathrm{e}^{\phi_3[\min(V_{s,30},1130)-360]} - \mathrm{e}^{\phi_3(1130-360)}\right\} \ln\left(\frac{y_{ref}+\phi_4}{\phi_4}\right) \\
& \phi_5 \left(1 - \mathrm{e}^{-\Delta Z_{1.0}/\phi_6}\right) \\
\Delta Z_{TOR} &= Z_{TOR} - E[Z_{TOR}] \\
E[Z_{TOR}] &= \max[2.704 - 1.226\max(M-5.849,0),0]^2 \quad \text{for reverse} \\
E[Z_{TOR}] &= \max[2.673 - 1.136\max(M-4.970,0),0]^2 \quad \text{For strike-slip/normal}
\end{aligned}
$$

where $y$ is in g, $c_1 = -1.5065$, $c_{1a} = 0.1650$, $c_{1b} = -0.2550$, $c_{1c} = -0.1650$, $c_{1d} = 0.2550$, $c_2 = 1.06$, $c_3 = 1.9636$, $c_4 = -2.1$, $c_{4a} = -0.5$, $c_5 = 6.4551$, $c_6 = 0.4908$, $c_7 = 0.0352$, $c_{7b} = 0.0462$, $c_8 = 0.0000$, $c_{8a} = 0.2695$, $c_{8b} = 0.4833$, $c_9 = 0.9228$, $c_{9a} = 0.1202$, $c_{9b} = 6.8607$, $c_{11} = 0$, $c_{11b} = -0.4536$, $c_{RB} = 50$, $c_n = 16.0875$, $c_M = 4.9993$, $c_{HM} = 3.0956$, $c_{\gamma 1} = -0.007146$, $c_{\gamma 2} = -0.006758$, $c_{\gamma 3} = 4.2542$, $\phi_1 = -0.5210$, $\phi_2 = -0.1417$, $\phi_3 = -0.007010$, $\phi_4 = 0.102151$, $\phi_5 = 0.0000$, $\phi_6 = 300$, $\gamma_{Jp-It} = 1.5817$ (use for Japan and Italy), $\gamma_{Wn} = 0.7594$ (use for 2008 Wenchuan earthquake), $\phi_{1Jp} = -0.6846$ (use for Japan), $\phi_{5Jp} = 0.4590$ (use for Japan) and $\phi_{6Jp} = 800$ (use for Japan).

- Ground-motion model is (for aleatory variability):

$$
\begin{aligned}
\sigma_T^2 &= (1+\mathrm{NL}_0)^2\tau^2 + \sigma_{NL_0}^2 \\
\tau &= \tau_1 + \frac{\tau_2-\tau_1}{1.5}\{\min[\max(M,5),6.5]-5\} \\
\sigma_{NL_0} &= \left\{\sigma_1 + \frac{\sigma_2-\sigma_1}{1.5}[\min(\max(M,5),6.5)-5]\right\}\sqrt{\sigma_3 F_{inferred} + 0.7F_{measured} + (1+\mathrm{NL}_0}^2 \\
\mathrm{NL}_0 &= \phi_2\left\{\mathrm{e}^{\phi_3[\min(V_{s,30},1130)-360]} - \mathrm{e}^{\phi_3(1130-360)}\right\}\left(\frac{y_{ref}}{y_{ref}+\phi_4}\right)
\end{aligned}
$$

where $\tau_1 = 0.4000$, $\tau_2 = 0.2600$, $\sigma_1 = 0.4912$, $\sigma_2 = 0.3762$, $\sigma_3 = 0.8000$ and $\sigma_{2Jp} = 0.4528$ (for Japan).

- Use $V_{s,30}$ ($F_{inferred}$=1 for inferred values and $F_{measured} = 1$ for measured values) and depth to 1 km/s shear-wave velocity horizon ($Z_{1.0}$) to characterise sites. State model applicable for $180 \leq V_{s,30} \leq 1500$ m/s. Estimate $Z_{1.0}$ for those sites lacking measured value by empirical relations linking $Z_{1.0}$ and $V_{s,30}$.

- Use 3 mechanisms:

Normal: Rake angle $-120 \leq \lambda \leq -60°$. 8 $M_w < 5.9$ Californian events and 3 $M_w \geq 6$ Italian events. $F_{NM} = 1$.

Reverse: Rake angle $30 \leq \lambda \leq 150°$. $F_{RV} = 1$.

Strike-slip: Other rake angles. $F_{NM} = F_{RV} = 0$.

Use two locations w.r.t. vertical projection of the top of rupture:

Hanging wall: $R_x \geq 0$ km. $F_{HW} = 1$.

Foot wall: $R_x < 0$ km. $F_{HW} = 0$.

- Model derived within NGA West 2 project, using the project database (Ancheta et al., 2014).

- Update model of Chiou and Youngs (2008) w.r.t. faulting mechanism, hanging-wall effects, scaling with the depth to top of rupture ($Z_{TOR}$), scaling with sediment thickness ($Z_{1.0}$), fault dip ($\delta$) and rupture directivity. Also account for regional differences in distance attenuation and site effects.

- Use observations and simulations (Donahue and Abrahamson, 2014) to develop model.

- Since database consists mainly of Californian data initially focus on developing moel for California using primarily Californian data. Then supplement these data with records from large earthquakes elsewhere to refine magnitude-scaling and to derive more robust $\sigma$ for larger events. Examine regional differences.

- Use same selection criteria as Chiou and Youngs (2008) except for these changes. Include only free-field data from 18 well-recorded $M_w \geq 6$ earthquakes (2587 records) from outside California. Assess maximum usable distance ($R_{max}$) for each earthquake using truncated regression with truncation level equal to second lowest PGA for each earthquake. Set $R_{max}$ equal to distance where truncation level equals $-2.5$ standard deviations below fitted median from a event-specific model. This allows final model to be derived using non-truncated regression. Older earthquakes with high truncation levels have $R_{max} < 70$ km but $R_{max}$ for recent events is relatively large. Exclude Class 2 earthquakes (including 1999 Duzce event) located within 20 km of Class 1 earthquake.

- Functional form based on stochastic simulations, seismological arguments (e.g. change from body-wave spreading to surface/Lg-wave spreading) and examination of data for various periods. Mainly unchanged from Chiou and Youngs (2008).

- Assess variation of $\gamma$ (anelastic attenuation) with $T$ for 3 magnitude intervals. For each $T$ and interval compute variance-weighted average of fitted values of $\gamma$ for individual events. Find variation in $\gamma$ with $T$ is magnitude dependent. Examine regional differences in $\gamma$ for non-Californian earthquakes, including aftershocks not selected for final model. Find $\gamma$ for New Zealand, Taiwan and Turkey are similar to those for California, whereas those for Italy and Japan (only use data in range $6 \leq M_w \leq 6.9$) indicate more rapid far-source attenuation and data for Wenchuan slower attenuation. Include regional differences in $\gamma$ in final model.

- Exploratory analysis of data indicates mechanism effect weaker for $M_w < 5$ than for $M_w > 6$. Find similar effects for $Z_{TOR}$. Hence include these effects in final model using term that prevents undue influence on large-magnitude scaling by small earthquakes whose estimates of $M_w$, $Z_{TOR}$ and mechanism are more uncertain than those for larger events.

- Develop $M$-$Z_{TOR}$ relation to centre the $Z_{TOR}$ adjustment.

- Preliminary analysis indicates dependence of event terms for $M_w < 5$ increase with $\delta$ but that there is no effect for $M_w > 6$.

- Note very few observations for region inside surface projection of rupture ($r_{jb} = 0$). Hence use simulations of (Donahue and Abrahamson, 2014) to develop hanging-wall model here using $R_x$, the horizontal distance from top of rupture measured perpendicular to strike. Foot-wall data for each simulation fit using simple functional form. Compute residuals at $r_{jb} = 0$ and plot w.r.t $R_x$ for specific dip angle. Derive model using $R_x$ trend excluding data for $M_w6$, which showed different behaviour. Find model matches simulations and empirical data for $r_{jb} > 0$.

- Include directivity effects using direct point parameter (DPP), centred on its mean, as variable. Use narrow-band formulation of directivity effects, excluding linear-magnitude dependence which is unstable w.r.t $T$ and statistically insignificant for many $T$. Assume directivity for $M_w < 5.5$ is negligible because of absence of finite-fault information for $M_w < 5.7$ but note that this assumption may not be true.

- Use centred $Z_{1.0}$ to investigate de-amplification for shallow sediment sites. Find evidence for differences in $\Delta Z_{1.0}$ scaling between Japan and California. State model applicable for $Z_{TOR} \leq 20$ km and do not recommend using large depth for $M_w > 7$ because of lack of data.

- Find nonlinear $V_{s,30}$ component does not need updating w.r.t. Chiou and Youngs (2008) but linear scaling does. Find evidence for difference in linear $V_{s,30}$ between Japan and California, which include in model.

- Normal-faulting term not well constrained because of limited data hence do not update coefficients of Chiou and Youngs (2008).

- Model developed through iterative process of regression for all $T$s with some parts of model fixed, smoothing a few coefficients w.r.t. $T$, then repeating regression using smoothed coefficients. Correct for sample bias at long-periods smooth $c_1$ by imposing smooth variation in the slope of $c_1$ w.r.t. $T$.

- 2 earthquakes (2000 Tottori ($M_w6.61$) and 1999 Chi-Chi ($M_w7.6$)) have large absolute event terms. Analysis of event-term distribution using robust regression suggest Tottori may be a outlier so remove it when assessing $\tau$. Do not remove Chi-Chi event term because may lead to underestimate of $\tau$.

- Bin $\tau$ and $\sigma$ in 0.5-magnitude-unit bins. Find magnitude dependency for most $T$. Use trilinear form. Allow for discontinuity in $\sigma$ at $M_w5$ but not for $\tau$. Find inclusion of data from events with $< 5$ records inflates $\tau$, at least for small events, and hence derive aleatory variability model using only events with $\geq 5$ records. Between-event residuals suggest dependence on $r_{rup}$ but this largely explained for small $T$ by nonlinear site amplification and increased intra-event variability for Japanese data. Observed dependence for large $T$ may be due to unmodelled basin effects because of lack of $Z_{1.0}$ for areas outside California and Japan.

- Note that useful to include $\kappa$ in future models because of potential influence on aleatory variability model.
- Examine inter-event residuals w.r.t. $M_w$ and do not find significant trends. Some outliers ($> 2\tau$) for large non-California earthquakes (1999 Chi-Chi, 2000 Tottori and 2008 Wenchuan). Add loess fits to plot and find 95% confidence limits emcompass zero hence outliers not significant. Also using only California earthquakes results in similar event terms.
- Examine intra-event residuals w.r.t. $M_w$, $r_{rup}$, $V_{s,30}$ and $\Delta Z_{1.0}$. Find no significant trends except at edges of data. Using loess fits conclude that trends are not significant.
- Plot intra-event residuals without $V_{s,30}$ term grouped by $y_{ref}$ w.r.t. $V_{s,30}$. Compare to predicted site amplification. Find good agreement. For $V_{s,30}$ model overestimates amplification for Japanese data suggesting deviation from linear $\ln V_{s,30}$ scaling for stronger nonlinearity at Japanese sites.
- Note that, because all $M_w < 6$ earthquakes are from California, model may not be applicable for small events in other regions.
- Note that for application to regions with different anelastic attenuation may adjust $\gamma$ model using estimates of $Q$ for regions derived using geometric spreading models consistent with model.
- Note that amplification for $V_{s,30} > 1130\,\text{m/s}$ constrained to unity. Little data in database to examine amplification for higher $V_{s,30}$, where $\kappa$ may decrease.
- Recommend setting $\Delta Z_{1.0} = 0$ when $Z_{1.0}$ unknown.
- When $Z_{1.0}$ is much lower than $E(Z_{1.0})$ recommend checking predictions not lower than predictions for reference condition of $V_{s,30} = 1130\,\text{m/s}$.

## 2.370 Douglas et al. (2013)

- Ground-motion model is:

$$\ln Y = a + bM + c \ln \sqrt{r_{hypo}^2 + h^2} + dr_{hyp}$$

  where $Y$ is in $\text{m/s}^2$, $a = -5.984 \pm 0.427$, $b = 2.146 \pm 0.069$, $c = -1.772 \pm 0.208$, $h = 2.511 \pm 0.595$, $d = -0.023 \pm 0.011$, $\phi = 0.792$, $\tau = 0.829$ and $\sigma = 1.147$ for data uncorrected for site response and $a = -6.514 \pm 0.423$, $b = 1.995 \pm 0.085$, $c = -1.468 \pm 0.200$, $h = 2.490 \pm 0.688$, $d = -0.029 \pm 0.010$, $\phi = 0.730$, $\tau = 1.079$ and $\sigma = 1.303$ for data corrected for site response.
- Correct all data in frequency domain to uniform reference site condition (generic rock profile for Switzerland and $\kappa = 0.016\,\text{s}$). Derive models from data with and without site correction.
- Data from: geothermal-related [Basel, Switzerland (963 records); Geysers, USA (2328 records); Soultz-sous-Forêts, France (223 records)]; gas-extraction-induced [Roswinkel, Netherlands (61 records)] and natural [Hengill, Iceland (231 records); Voerendaal, Netherlands (162 records)] seismicity. Data from 119 stations used.
- Focal mechanisms of majority of events not known.
- Select earthquakes down to about $M_w1$ because this is about the magnitude threshold for felt events at Soultz.
- Data from mixture of short-period, broadband and, in a few cases, accelerometric instruments.

- Instrument correct records and assess quality based on visual inspection and analysis of signal-to-noise ratios to retain those with ratios above 3. Note that sharp drop off in data from 0.2 s upwards so restrict analysis to 0.5 s. Exclude records requiring high cut-off frequency of $< 10$ Hz because could be affecting PGA. Compute residuals w.r.t. to model of Bommer et al. (2007) and find some records, predominantly from Geysers, had very low PGAs (more than 100 times smaller) relative to predictions. Because they would hamper analysis they were removed.

- Data from different regions shows poor overlap for some magnitude-distance ranges. Overall range from $5 \leq r_{hypo} \leq 20$ km and $1 \leq M_w \leq 4$ well covered.

- Recompute $M_w$ based on far-field source spectra to obtain mutually-consistent magnitudes. Check recomputed magnitudes against published $M_w$ estimates and find that similar. Derive $M_w$-$M_L$ or $M_D$ conversion formulae for each region and apply them to convert $M_L$ or $M_D$ to $M_w$ for those events that $M_w$ could not be recomputed. Note that this conversion introduces uncertainty into the analysis but increases available data.

- Using analysis of variance on data binned into magnitude-distance intervals conclude ground motions from induced and natural earthquakes cannot be statistically distinguished so combine.

- Compare predictions to 55 records (22 events, 13 stations) from a geothermally-active zone at Campi Flegrei (Italy) and find reasonable match, although note the large large scatter in the observations.

- Examine residuals w.r.t. $M_w$ and $r_{hypo}$ and as histograms and find no clear trends.

- Examine impact of focal depth on results by deriving models without $h$ and with $r_{epi}$ rather than $r_{hypo}$. Find $\tau$ slightly reduced when using $r_{epi}$, which relate to poorly-defined focal depths. Find that focal depth has a strong impact on predictions and hence recommend model using $r_{hypo}$.

- Study residuals w.r.t. region and find data from some regions significantly over or under-estimated by the model.

- Do not recommend model for use for $M_w > 3$ due to limited magnitude-distance spread of data.

- Argue that high values of $\sigma$ associated with model are not due to inaccuracies in locations or magnitudes because all records come from well-monitored regions where event locations are well-constrained and $M_w$ have been carefully recomputed.

- Derive zone-specific estimates of $\tau$ for Basel and Soultz, where sufficient data available.

- Derive single-station $\phi$ ($\phi_{SS,S}$) for all 62 stations recording $\geq 10$ events. Find that $\phi_{SS,S}$ varies considerably from one station to next. Compute mean $\phi_{SS}$.

## 2.371 Edwards and Douglas (2013)

- Ground-motion model is:

$$\ln \mathrm{PSA}(0.01\,\mathrm{s}) = a + bM_w + c \ln r_{hypo}$$

  where PSA(0.01 s) is in m/s$^2$, $a = -6.899$, $b = 2.569$, $c = -2.589$, $\tau = 0.099$ (inter-event), $\phi = 0.627$ (intra-event) and $\sigma = 0.635$ (total).

- Use data from seismic network installed to monitor hot-fractured-rock project at Cooper Basin (Habanero granite reservoir) with induced seismicity. Use records from 2005 stimulation experiment from 8 stations, all of which are located below surface (depths $\leq 357$ m except 1 station at 1.8 km).

- Convert data from velocity to acceleration by time-domain differentiation. Assume PGA(0.01 s) equals PGA. Instrument bandwidths do not allow PSAs to be reliably computed for $< 15$ Hz. High-cut filter records with cut-offs based on signal-to-noise ratio. About a third of cut-offs are $> 20$ Hz, which could affect PGA. However, find results are insensitive to exclusion of these records so use all data.

- Consistently compute $M_w$.

- Focal depths between 3.9 and 4.5 km following rough normal distribution with peak at 4.2 km.

- Develop model for comparison with GMPE logic tree developed using models of Douglas et al. (2013), to compare with stochastic model and to assess $\sigma$ and single-station $\sigma$.

- Original use $c\sqrt{r_{hypo}^2 + h^2}$ (rather than $c \ln r_{hypo}$) and $dr_{hypo}$ terms but data not sufficient to constrain them so they are removed.

- Attribute small $\tau$ to small variability in stress drops.

- Compute single-station $\phi$ ($\phi_{SS,S}$) for 8 stations and mean $\phi_{SS}$.

## 2.372 Idriss (2013, 2014)

- Ground-motion model is:

$$\ln \mathrm{PSA} = \alpha_1 + \alpha_2 M + \alpha_3(8.5 - M)^2 - [\beta_1 + \beta_2 M] \ln(r_{rup} + 10) + \xi \ln V_{s,30} + \gamma r_{rup} + \phi F$$

  where PSA is in g, $\alpha_1 = 7.0887$, $\alpha_2 = 0.2058$, $\alpha_3 = 0.0589$, $\beta_1 = 2.9935$, $\beta_2 = -0.2287$, $\xi = -0.854$, $\gamma = -0.0027$ and $\phi = 0.08$ (for $M_w \leq 6.75$) and $\alpha_1 = 9.0138$, $\alpha_2 = -0.0794$, $\alpha_3 = 0.0589$, $\beta_1 = 2.9935$, $\beta_2 = -0.2287$, $\xi = -0.854$, $\gamma = -0.0027$ and $\phi = 0.08$ (for $M_w > 6.75$). $\sigma = 1.18 + 0.035 \ln(T) - 0.06M$, where for $M_w < 5$ use $\sigma$ for $M_w 5$, for $M_w > 7.5$ use $\sigma$ for $M_w 7.5$, for $T < 0.05$ s use $\sigma$ for $T = 0.05$ s and for $T > 3$ s use $\sigma$ for $T = 3$ s.

- Uses $V_{s,30}$ to characterise sites. Notes that $V_{s,30}$ is not being used to account for nonlinearity but only to better fit the observations. Presents coefficients for $450 \leq V_{s,30} \leq 2000$ m/s. Only 34 records from $V_{s,30} > 1200$ m/s hence for $V_{s,30} > 1200$ m/s recommends using $V_{s,30} = 1200$ m/s.

- Uses 2 mechanisms:

Strike-slip Mechanisms 0 (strike-slip) and 1 (normal, only 39 records of all data from $M_w \geq 4.5$) of Flatfile. $F = 0$.

Reverse Mechanisms 2 (reverse), 3 and 4 (reverse-oblique) of Flatfile. $F = 1$.

- Model update of Idriss (2008) (see Section 2.299).

- Model derived within NGA West 2 project, using the project database (Ancheta et al., 2014). Data principally from: California (74 events) with some data from Idaho (1) and Nevada (1), Taiwan (5), China (55), Japan (5), New Zealand (2) and other countries (Canada, Mexico, Italy, Turkey and Iran) (15).

- Uses PSA(0.01 s) to approximate PGA rather than true PGA.

- Selects records with $M_w \geq 4.5$, all the required independent and dependent parameters and at free-field location. Because finds a significant change in decay of PGA (and spectral values) beyond $r_{rup} = 150$–175 km, excludes more distant records. Next excludes events with $< 3$ records and multiple records from same earthquake at arrays (e.g. Taiwan SMART).

- Examines data binned into: soft soil sites (100–211 m/s), nonlinear soil sites (211–450 m/s) and quasi-linear sites ($\geq$ 450 m/s). Assesses rough shear strain using PGV/$V_{s,30}$ for all records and plots against PGA. Finds that for quasi-linear sites the behaviour of sites in 1999 Chi-Chi mainshock is significantly different than remaining records and, hence, excludes these data. Estimates thresholds for nonlinear ranges based on modulus reduction curves for each bin. Finds that $\leq$ 4% of records in quasi-linear bin could be in mildly nonlinear range. Henceforth uses only data from this bin.
- Examine total residuals w.r.t. $M_w$, $r_{rup}$ and $V_{s,30}$. Finds that model fits well in range 5.2–7.9 for PGA, 5.3–7.3 for $T = 0.2$ s and 5.2–7.5 for $T = 1$ s.
- Does not include depth to top of rupture ($Z_{TOR}$) in model because finds, based on residuals, that this parameter does not bias results for $Z_{TOR} < 13$ km.
- Does not include dip angle ($\delta$) in model because finds, based on residuals, that this parameter does not bias results for $24 < \delta \leq 90°$.
- Does not include distance to surface projection of top of rupture $R_x$ or $r_{jb}$ because not independent distance measures.
- Examines residual plots w.r.t. depth to 1.0 km/s and 2.5 km/s shear-wave horizons. Finds little dependence and hence does not include these parameters.
- Insufficient data (95 records) on hanging wall to examine the effect of this parameter.

## 2.373 Joshi et al. (2013a)

- Ground-motion model is:
$$\ln \mathrm{PGA} = a + bM + cR + d\ln(R + 15)$$
where PGA is in gal, $a = -0.336$, $b = 2.58$, $c = 0.018$ and $d = -2.96$ for Kumaon subregion and $a = 2.29$, $b = 2.07$, $c = 1.95$ and $d = -4.03$ for Garhwal Himalaya subregion ($\sigma$ is not reported).
- Compare observed and predicted PGAs w.r.t. $r_{hypo}$ and $M_w$.
- Derive models for use within semi-empirical ground-motion simulations.

## 2.374 Laurendeau et al. (2013)

- Ground-motion model is:
$$\begin{aligned}
\ln \mathrm{SA} &= F_M + F_D + F_S \\
F_M &= \begin{cases} a_1 + a_2(M - M_h) + a_3(M - M_h)^2 & M \leq M_h \\ a_1 + a_4(M - M_h) & M > M_h \end{cases} \\
F_D &= [b_1 + b_2(M - 4.5)]\ln R + b_3(R - 1) \\
R &= \sqrt{R_{rup}^2 + h^2} \\
F_S &= c_1 \ln(V_{s,30}/800)
\end{aligned}$$
where SA is in g, $a_1 = -0.033598$, $a_2 = 0.49784$, $a_3 = -0.14873$, $a_4 = 0.22496$, $M_h = 5.6$, $b_1 = -0.96495$, $b_2 = 0.20938$, $b_3 = -0.014$, $h = 1.36$, $c_1 = -0.34393$, $\phi = 0.65621$ (intra-event), $\tau = 0.53412$ (inter-event) and $\sigma = 0.84611$ (total) [take $M_h$, $h$ and $b_3$ from Rodriguez-Marek et al. (2011)].
- Use $V_{s,30}$ to characterise sites. $V_{s,30}$ from 500 to 2000 m/s but only 94 records with $V_{s,30} > 1000$ m/s and majority of data from $V_{s,30} < 700$ m/s.

- Use data from surface stations of KiK-Net (240 sites, mainly on weathered rock or thin sediments) and K-Net (165 sites, mainly on sediments) up to 2009. Use only earthquakes in the F-net catalogue to have consistent metadata. Data similar to that used by Rodriguez-Marek et al. (2011).
- Only use data from events with focal depth $< 25$ km to consider only crustal earthquakes.
- Exclude offshore earthquakes except those in Sea of Japan with $M_w \geq 5.5$.
- Apply magnitude-distance cut-off using threshold of $2.5\,\mathrm{cm/s^2}$ and predicted median from model of Kanno et al. (2006) to exclude higher than average distant records.
- Correct records for linear baseline trends. Visually inspect records and remove faulty records (e.g. S-wave triggers) and shorten those with multi-events. Note that this does not cause significant loss of data. Add Tukey-windowing taper to last 2 s and add zeros to obtain homogeneous durations. Re-sample records to 100 Hz to remove difference between KiK-Net and K-Net records.
- Only limited near-source data ($< 10$ km). Magnitude-distance coverage roughly uniform.
- Derive model to investigate site amplification at stiff-soil and rock sites and effect of $\kappa$ not to present a new model for use in hazard assessments.
- Constrain some coefficients based on previous study because of interdependence between coefficients.
- Compare predictions and observations and inter- and intra-event residuals w.r.t. $M_w$, $r_{rup}$ and $V_{s,30}$. Find residuals well distributed except for possible slight underestimation for $V_{s,30} \geq 1300$ m/s but this is based on very limited data.
- Believe higher $\sigma$ due to consider variability in sites.
- Plot intra-event residuals w.r.t. $\kappa$ computed using technique of Anderson and Hough (1984) for short periods. Find no trends. Note that this may be due to response of KiK-Net and K-Net instruments, which could lead to overestimated $\kappa$.
- Also consider various definitions of $\kappa$ computed from response spectral shape based on stochastic simulations. Compute $\kappa$ based on one of these definitions for 53 sites with three or more records (701 records and 123 events). Find that intra-event residuals w.r.t. $\kappa$ computed using this approach show clear trend. Derive new site function incorporating $\kappa$ for $T \leq 0.2$ s based on residuals: $F_S = a_1 \ln(V_{s,30}/800) + c_2\kappa_{0,RESP1}$, where $a_1 = 0.42164$ and $c_2 = -18.3175$ ($\phi = 0.6194$, $\tau = 0.54418$ and $\sigma = 0.82449$) for PGA. Find that this new site term removes trend in residuals and reduces $\phi$.

## 2.375 Morikawa and Fujiwara (2013)

- Ground-motion model is (Model 1):

$$\log \mathrm{pre} = a_1[\min(M_w, M_{w,01}) - M_{w,1}]^2 + b_{1,k}X + c_{1,k} - \log[X + d_1 10^{0.5\min(M_w,M_{w,01})}]$$

where pre is in $\mathrm{cm/s^2}$, $M_{w,01} = 8.2$, $M_{w,1} = 16.0$, $a_1 = -0.0321$, $b_{1,I} = -0.005315$, $b_{1,II} = -0.005042$, $b_{1,III} = -0.005605$, $c_{1,I} = 7.0830$, $c_{1,II} = 7.1181$, $c_{1,III} = 7.5035$, $d_1 = 0.011641$ and $\sigma = 0.3761$.

Ground-motion model is (Model 2):

$$\log \mathrm{pre} = a_2 \min(M_w, M_{w,02}) + b_{2,k}X + c_{2,k} - \log[X + d_2 10^{0.5\min(M_w,M_{w,02})}]$$

where pre is in $\mathrm{cm/s^2}$, $M_{w,02} = 8.1$, $a_2 = 0.5507$, $b_{2,I} = -0.004531$, $b_{2,II} = -0.004716$, $b_{2,III} = -0.005273$, $c_{2,I} = 0.4631$, $c_{2,II} = 0.5418$, $c_{2,III} = 0.9338$, $d_2 = 0.006875$ and $\sigma = 0.377556$.

Both models include these adjustment factors (add to log pre):

$$
\begin{aligned}
G_d &= p_d \log[\max(D_{l,min}, D_l)/D_0] \\
G_s &= p_s \log[\min(V_{s,max}, V_{s,30})/V_0] \\
\mathrm{AI} &= \gamma X_{v,f} \max(H - 30, 0)
\end{aligned}
$$

where $p_d = 0.0663$, $D_{l,min} = 100.00$, $D_0 = 250$, $p_s = -0.3709$, $V_{s,max} = 1950.00$, $V_0 = 350$, $\gamma_{NEJapan} = 0.00007602$ and $\gamma = 0.00006327$.

- Use $V_{s,30}$ and $D_l$ (the depth to the layer whose $V_s$ is $l$ in m/s) to characterise sites.
- Use 3 types of earthquake:
  1. Crustal. Use coefficients $b_{,I}$ and $c_{,I}$.
  2. Interface. Use coefficients $b_{,II}$ and $c_{,II}$.
  3. Intra-slab. Use coefficients $b_{,III}$ and $c_{,III}$.
- Focal depths, $H$, from 5 to 108 km[42].
- Use data of Kanno et al. (2006) extended with data from K-Net, KiK-Net, JMA and Port and Airport Research Institute to the end of 2011.
- Data selection criteria are: $M_w \geq 5.5$, record from ground surface, two orthogonal horizontal components available, $\geq 5$ stations triggered by earthquake and $r_{rup} < 200$ km. Truncate data at $r_{rup}$ where PGA predicted by model of Kanno et al. (2006) $< 10\,\mathrm{cm/s^2}$.
- Few earthquakes for $M_w > 8$. Lack of data for $r_{rup} < 50$ km and $M_w > 7$.
- Apply distance-dependent weight in regression to increase statistical power of near-source data (note that no physical meaning of weights). Weights are: 8 for $r_{rup} \leq 10$ km, 4 for $10 \leq r_{rup} \leq 20$ km, 2 for $20 \leq r_{rup} \leq 40$ km and 1 for $r_{rup} > 40$ km.
- Based on the first step of a two-step analysis, find evidence for saturation beyond $M_w 8$. This analysis is basis of functional forms adopted.
- Find $\sigma$ of model 1 is slightly lower than that of model 2 but that this difference is not statistically significant. Hence cannot conclude which model is better.
- Adjustment factors based on analysis of residuals from model 1, which are assumed to apply also for model 2.
- To find $G_d$ use data with $H < 30$ km (to avoid anomalous results from deeper events) and PGA$< 100\,\mathrm{cm/s^2}$ (to avoid nonlinear site response). Use model of deep sedimentary layers in Japan to define $D_l$. Choose $D_{1400}$ as $D_l$ based on residual analyses and trial-and-error fitting of $p_d$ for different $D_{l,min}$ and $D_0$. Next fix $D_0 = 250$ m as average value for $D_{1400}$ from first step and obtain $D_{l,min}$ and $p_d$.
- To find $G_s$ use same data as for $G_d$ but with the additional criterion that the $V_s$ profile down to 20 m or more is known. $V_{s,30}$ is estimated from $V_{s,20}$ using previously-published conversion formula. Use residuals after correcting for $G_d$. Find $V_0$ and $p_s$ by trial-and-error analysis of residuals. Fix $V_0 = 350$ m/s and find $V_{s,max}$ and $p_s$. Note that this correection cannot account for differences in predominant periods between sites.

[42] It is not clear if this is the entire depth range.

- Use $X_{v,f}$, the distance from a volcanic front to an observation site, to model anomalous motions for deep earthquakes. Use residuals after correction for shallow and deep site response ($G_s$ and $G_d$) from data with $H > 30$ km and PGA$< 100\,\mathrm{cm/s^2}$. Use data from earthquakes in NE Japan from Pacific Plate (excluding those from stations south of 36N) and in SW Japan occuring in Philippine Sea Plate (setting absolute value of $X_{v,f}$ to 75 km or less) separately to find $\gamma$ via weighted regression in three steps.

## 2.376 Pacific Earthquake Engineering Research Center (2013)

- Provide models for the prediction of the vertical component of 4 NGA West 2 models (Abrahamson et al., 2013, 2014; Boore et al., 2013, 2014; Chiou and Youngs, 2013, 2014; Campbell and Bozorgnia, 2013, 2014) (see Sections 2.366, 2.367, 2.369 and 2.368).
- Details not given here. See published versions of these models that are summarised below.

## 2.377 Segou and Voulgaris (2013)

- Ground-motion model is:

$$\log Y = a + bM + cM^2 + (d + eM)\log\sqrt{R_{epi}^2 + (H-h)^2} + f_1\mathrm{RS} + f_2\mathrm{SS} + e_1\mathrm{ST_s} + e_2\mathrm{SF_s}$$

  where $Y$ is in $\mathrm{cm/s^2}$, $a = 1.92909$, $b = 0.21829$, $c = 0.00328$, $d = -1.06750$, $e = 0.01016$, $h = 0.01005$, $f_1 = 0.09664$, $f_2 = 0.08438$, $e_1 = 0.12297$, $e_2 = 0.09175$ and $\sigma = 0.35530$.

- Use 3 site classes using the NEHRP classification:

Rock Classes A and B ($V_s > 760$ m/s). $\mathrm{ST_s} = \mathrm{SF_s} = 0$.

Stiff soil Class C ($360 < V_s \leq 760$ m/s). $\mathrm{ST_s} = 1$, $\mathrm{SF_s} = 0$.

Soft soil Classes D and E ($V_{s,30} \leq 360$ m/s. $\mathrm{SF_s} = 1$, $\mathrm{ST_s} = 0$.

  Combine classes A and B and D and E together because of lack of records in classes A and E.

- Use 3 faulting mechanisms:

Normal SS = RS = 0.

Strike-slip SS = 1, RS = 0.

Reverse RS = 1, SS = 0.

- Include focal depth $H$ (1–30 km) because it reduces $\sigma$.
- Model developed to demonstrate advantage of regression technique based on genetic algorithm with initial population development, using Latin Hypercube sampling over standard nonlinear least-square regression techniques. Compare results for PGA and simplified model using various regression techniques and adopted method.
- Unprocessed records taken from the Internet Site for European Strong-motion Data (Ambraseys et al., 2004), Geodynamic Institute of the National Observatory of Athens and ITSAK. Data from Greece, Italy, Turkey and Iran. Use metadata from ISC to reduce epistemic uncertainty.
- Use only data from free-field and basement-level (of buildings up to 2-storeys) stations.

- Records resampled to 200 Hz and rejected poor-quality time-histories. Instrument-correct records from analogue instruments. Baseline-correct records (using pre-event mean for digital records and entire record for analogue records). Bandpass filter using zero-phase fourth-order Butterworth with optimal cut-off frequencies (depending of individual components).

- Use $r_{epi}$ because information on location of fault rupture not available for majority of events.

- Note that alternative site classification should be investigated because current scheme does not account for depth of sediment.

- Find that using standard one-step random-effects technique that difficult to find physically-reasonable coefficients and the site and mechanism coefficients are poorly determined because of poor data distribution. Do not use a two-step approach because of the large number of singly-recorded events.

- Most data from $r_{epi} > 10$ km.

- Plot residuals w.r.t. magnitude and fit trends. Find overestimation up to $M_w 5$, which relate to poor metadata.

- Compute $\sigma$s for sites with measured and estimated $V_{s,30}$ and for the three site classes. Find $\sigma$ 10% lower for sites with measurements compared to those with only estimates. Find $\sigma$ for rock sites 20% lower than for other classes.

- Plot residuals w.r.t. distance and find no correlation.

## 2.378 Sharma et al. (2013)

- Ground-motion model is (MOD1 and MOD3):

$$\log_{10} Y = a + bM_w + c \log_{10} \sqrt{R_{hypo}^2 + h^2}(+es)$$

where: $Y$ is in m/s$^2$, $a = -2.666 \pm 0.072$, $b = 1.158 \pm 0.020$, $c = -2.312 \pm 0.055$, $h = 1.734 \pm 0.197$, $\sigma_{inter-event} = 0.142$, $\sigma_{intra-event} = 0.358$ and $\sigma = 0.385$ for MOD1 without site term and $a = -2.710 \pm 0.064$, $b = 1.165 \pm 0.021$, $c = -2.244 \pm 0.044$, $h = 1.779 \pm 0.158$, $e = 0.225 \pm 0.004$, $\sigma_{inter-event} = 0.151$, $\sigma_{intra-event} = 0.276$ and $\sigma = 0.315$ for MOD3 with site term.

- Use 3 site classes using approach of Emolo et al. (2011) (see Section 2.344):

$s = 1$ Site with significant positive mean residual.

$s = 0$ Site with mean residual not significantly different from zero.

$s = -1$ Site with significant negative mean residual.

Derive site terms for all stations in second step, based on residuals w.r.t. to overall model derived without considering site effects. Only statistically-significant terms (using Z-test and 5% level) are retained. Assign site corrections of either $-1$, 0 or 1 based on residuals. Find reduction in $\phi$ but not in $\tau$ when applying site correction.

- Use data from 29 stations (with 104 to 211 records each) of dense ($20 \times 10\,\mathrm{km}^2$) Lawrence Berkeley National Laboratory/Calpine-Geysers network (01/09/2007–15/11/2010) of induced (by water injection and steam extraction) seismicity at The Geysers vapour-dominated geothermal field (N. California, USA). Instruments I/O Sensor SM-6 geophones ($f_0 = 14$ Hz) then Oyo GS-11D 4.5 Hz sensors.

- Select earthquakes with focal depths $\leq 5$ km since deep events assumed to be natural earthquakes.

- Select only waveforms with signal-to-noise ratio greater than 10 in frequency range 0.5–35 Hz.

- Instrument correct data. Remove mean and trend baselines. Filter using zero-phase 4-pole Butterworth filter with passband 0.7–35 Hz. Extract parameters in time window starting at origin time and ending at time corresponding to 98% of total energy in waveform, which were tapered with 0.1 taper width with a cosine window. Finally differentiated and filtered again to obtain accelerations.

- Test another functional form including term for anelastic attenuation, for which report coefficients. Choose final model due to: its simplicity, $\sigma$ and $R^2$.

- Examine inter-event and intra-event residuals (as scatter plots and histograms) w.r.t. $M_w$, $r_{hypo}$ and for each station separately. Find no significant trends based on fitting lines to residuals.

- Examine standard deviations at each station before and after site correction (single-station $\sigma$, $\phi_{SS}$, analysis). Compute average value weighted by number of records per station, $\phi_{SS}$. Compare to overall total $\sigma$ and find single-station $\sigma$ is lower (0.2410 compared to 0.3849) and that the different between them is smaller when using MOD3 (0.2377 compared to 0.3152). For one station (CLV) find $\phi_{SS,S}$ is higher than $\sigma$, which relate to local geological conditions.

- Find slight positive trend in inter-event residuals w.r.t. focal depth, which relate to possible decrease in stress with depth or variation in rigidity modulus due to heterogeneities in highly-fractured medium.

## 2.379 Skarlatoudis et al. (2013)

- Ground-motion model is (for in-slab):

$$
\begin{aligned}
\log Y &= c_1 + c_2(M-5.5) + c_{31}\log R + c_{32}(R-R_{ref}) + c_{41}(1-\mathrm{ARC})H(h-h_0) \\
&\quad + c_{42}(1-\mathrm{ARC})H(h_0-h)f(h,R) + c_{51}\mathrm{ARC}H(h-h_0) \\
&\quad + c_{52}\mathrm{ARC}H(h_0-h)f(h,R) + c_{61}S + c_{62}SS \\
\text{where} f(h,R) &= \begin{cases} & \text{if} \quad 60 \le h < 80\,\mathrm{km} \\ 0 & \text{if} \quad R < 205\,\mathrm{km} \\ (205-R)/150 & \text{if} \quad 205 \le R < 355\,\mathrm{km} \\ 1 & \text{if} \quad R > 355\,\mathrm{km} \\ \text{or} & \text{if} \\ & \text{if} \quad \text{if } 80 \le h < 100\,\mathrm{km} \\ 0 & \text{if} \quad \text{if } R < 140\,\mathrm{km} \\ (140-R)/100 & \text{if} \quad 140 < R \le 240\,\mathrm{km} \\ 1 & \text{if} \quad \text{if } R > 240\,\mathrm{km} \end{cases}
\end{aligned}
$$

where $Y$ is in cm/s$^2$, $H$ is the Heaviside function, $h_0 = 100\,\mathrm{km}$, $c_{31} = -1.7$ (fixed, see below), $R_{ref} = 1\,\mathrm{km}$, $c_1 = 4.229$, $c_2 = 0.877$, $c_{32} = -0.00206$, $c_{41} = -0.481$, $c_{42} = -0.152$, $c_{51} = 0.425$, $c_{61} = 0.267$, $c_{62} = 0.491$, $\sigma = 0.351$ (intra-event), $\tau = 0.112$ (inter-event) and $\epsilon = 0.369$ (total).

- Ground-motion model is (for interface):

$$\log Y = c_1 + c_2(M-5.5) + c_3\log R + c_{41}(1-\mathrm{ARC})(R-R_{ref}) + c_{42}\mathrm{ARC}(R-R_{ref}) + c_{51}S + c_{52}SS$$

where $Y$ is in cm/s$^2$, $c_{31} = -1.7$ (fixed, see below), $R_{ref} = 1\,\mathrm{km}$, $c_1 = 3.945$, $c_2 = 0.974$, $c_{41} = -0.00172$, $c_{42} = -0.00099$, $c_{51} = 0.189$, $c_{52} = 0.707$, $\sigma = 0.330$ (intra-event), $\tau = 0.257$ (inter-event) and $\epsilon = 0.418$ (total).

- Use 3 site classes:

$S = 1$, $SS = 0$ NEHRP class C site (stiff soil)

$SS = 0$, $S = 1$ NEHRP class D site (soft soil)

$S = 0$, $SS = 0$ NEHRP class B site (rock)

- Use 2 earthquake classes:

In-slab Often oblique-thrust mechanism with down-dip extension and arc-parallel compression. Focal depths ($h$) between 67 and 163 km. $4.4 \leq M_w \leq 6.7$. Generally on inner Hellenic arc. 14 earthquakes.

Interface Often thrust mechanism. $47 \leq h \leq 66$ km. $4.6 \leq M_w \leq 6.4$. Generally on outer Hellenic arc. 7 earthquakes.

Separation made based on Atkinson and Boore (2003) and source location relative to subducting slab.

- Consider 2 locations w.r.t. arc:

ARC = 0 Back-arc

ARC = 1 Along-arc

For $h < 100$ km, define record as back-arc or along-arc based on whether the travel path from source to site predominantly passes through back-arc or along-arc area (complex classification). For $h \geq 100$ km classification is based on location of station, independently of $r_{hyp}$.

- Locations and magnitudes selected by comparing values from several national and international institutes.

- Use data from accelerometers and broadband instruments (both permanent and temporary) from various networks from 1994 to 2008.

- Check converted $M_w$ to measured $M_w$ for those earthquakes with both and find good fit (mean difference of 0.04) with low scatter (standard deviation of 0.16).

- Kythera earthquake (8/1/2006, $M_w$6.7, $h = 67$ km) contributes large portion of data.

- Note lack of data for $h > 100$ km and $M_w > 5.5$.

- Study effects of back-arc low-velocity/low-$Q$ mantle wedge. Note challenge in expressing in functional forms the conceptual geotectonic and wave-propagation model.

- To determine final form of model firstly fit a simple functional form: $\log Y = c_1 + c_2(M - 5.5) + c_3 \log R + c_4 R + c_{51} S + c_5 2SS$. Classify data by focal depth: $60 \leq g < 80$ km, $80 \leq h < 100$ km and $h \geq 100$ km. Also classify records into back-arc and along-arc. Use $c_2$, $c_{51}$ and $c_{52}$ to adjust motions to $M_w$5.5 and rock and compute running averages for the different classes. Find large difference in back-arc along-arc motions for $h \geq 100$ km for short periods but not for long periods. For shallower depths the difference between back-arc and along-arc motions is noticeable at long $r_{hyp}$. These observations motivate the final functional form. Provide a schematic presentation of the different wave propagation paths depending on depth and location w.r.t. arc.

- For in-slab events, the limited range of $r_{hyp}$ does not allow reliable estimation of geometrical spreading due to trade-off with anelastic-attenuation coefficient. Hence regress to find geometric coefficient after fixing anelastic attenuation and using data from two magnitude bins (to examine magnitude dependency). Use average value of $-1.7$ as a fixed coefficient in all regressions. Try similar technique for interface events but did not find reasonable value so use the same coefficient as for in-slab events.

- Examine event terms as function of $M_w$ and $h$ and intra-event residuals w.r.t. $r_{hyp}$ and find no trends.

- Compare observed (adjusted to $M_w5.5$ and rock) and predicted motions for earthquakes with $60 \leq h < 100$ km. Find sufficient fit.
- Note that the large difference between back-arc and along-arc motions may not be usual for other subduction zones.

## 2.380 Villalobos-Escobar and Castro (2013)

- Ground-motion model is:

$$\log \mathrm{PGA} = a_1 M + a_2 \log R + a_3 H + C_{st}$$

where PGA is in cm/s$^2$, $a_1 = 0.5586$, $a_2 = -1.0902$, $a_3 = -0.0035$ and $\sigma_A = 0.2030$ (intra-event) and $\sigma_E = 0.2006$ (inter-event). Derive individual $C_{st}$ values for each of the 35 stations (not reported here).

- Focal depths $0.1 \leq H \leq 226.3$ km. 10 events in Bucaramanga nest.
- Also derive models using functional forms of García et al. (2005) and Joyner and Boore (1981) (using 2-stage method).
- Use data from networks in Medellìn (1997–2010) and Aburrà Valley (2008–2010). Medellìn array has had 27 stations of which 22 (3 on rock, 1 at 40 m depth) are still operating. 13 stations with Etna Episensors, 1 with K2, 1 FBA-23DH (in borehole) and 8 CUSP-3C. Aburrà Valley array has 11 surface stations (9 with CUSP-3C and 2 Etna Episensors). Do not use data from 1 station because it did not record any selected events.
- Select events that were recorded at $\geq 40\%$ (15 of 36) of stations.
- Baseline correct records. Examine signal-to-noise ratios (3 s around peak to 3 s before P-wave) and conclude high enough to estimate PGA.
- Strong positive correlation between $M_L$ and $r_{epi}$.
- Compute residuals w.r.t. model, plot residuals w.r.t $r_{epi}$ and also use approach of Scherbaum et al. (2004) to examine fit of candidate models to observations. Find that model reported above performs best.

## 2.381 Akkar et al. (2014b,c)

- Ground-motion model is:

$$\begin{aligned}
\ln Y &= \ln Y_{REF} + \ln S \\
\ln Y_{REF} &= \begin{cases} a_1 + a_2(M-6.75) + a_3(8.5-M)^2 + [a_4 + a_5(M-6.75)]\ln\sqrt{R^2+a_6^2} + a_8F_N + a_9F_R & M_w \leq 6.75 \\ a_1 + a_7(M-6.75) + a_3(8.5-M)^2 + [a_4 + a_5(M-6.75)]\ln\sqrt{R^2+a_6^2} + a_8F_N + a_9F_R & M_w > 6.75 \end{cases} \\
\ln S &= \begin{cases} b_1 \ln(V_{s,30}/V_{REF}) + b_2 \ln\left[\frac{\mathrm{PGA}_{REF}+c(V_{s,30}/V_{REF})^n}{(\mathrm{PGA}_{REF}+c)(V_{s,30}/V_{REF})^n}\right] & V_{s,30} \leq V_{REF} \\ b_1 \ln\left[\frac{\min(V_{s,30},V_{CON})}{V_{REF}}\right] & V_{s,30} > V_{REF} \end{cases}
\end{aligned}$$

where $Y$ is in g; $a_8 = -0.1091$, $a_9 = 0.0937$, $a_2 = 0.0029$, $a_5 = 0.2529$, $a_6 = 7.5$ and $a_7 = -0.5096$ for all distance metrics; $a_1 = 1.85329$, $a_3 = -0.02807$, $a_4 = -1.23452$, $\phi = 0.6201$ (intra-event), $\tau = 0.3501$ (inter-event) and $\sigma = 0.7121$ (total) for $r_{jb}$; $a_1 = 2.52977$, $a_3 = -0.05496$, $a_4 = -1.31001$, $\phi = 0.6375$ (intra-event), $\tau = 0.3581$ (inter-event) and $\sigma = 0.7312$ (total) for $r_{epi}$; $a_1 = 3.26685$, $a_3 = -0.04846$, $a_4 = -1.47905$, $\phi = 0.6475$ (intra-event), $\tau = 0.3472$ (inter-event) and $\sigma = 0.7347$ (total) for $r_{hypo}$; $V_{REF} = 750$ m/s, $V_{CON} = 1000$ m/s, $b_1 = -0.41997$, $b_2 = -0.28846$, $c = 2.5$ and $n = 3.2$ are from Sandikkaya et al. (2013).

- Use $V_{s,30}$ to characterise sites. Most sites classified in Eurocode 8 classes B and C, i.e. $180 \leq V_{s,30} \leq 800$ m/s. Note limited data from $V_s > 800$ m/s. Use nonlinear site amplification model of Sandikkaya et al. (2013) for model. Recommend model for $150 \leq V_{s,30} \leq 1200$ m/s.

- Focal depths between roughly 0 and 29 km. No dependency on mechanism. Vast majority of earthquakes with $M_w > 6$ have depths $< 20$ km and distribution for smaller events roughly uniform.

- Data from 322 stations.

- Use 3 mechanisms:

Strike-slip $F_N = F_R = 0$.

Normal $F_N = 1$, $F_R = 0$. Most data from this mechanism.

Reverse $F_R = 1$, $F_N = 0$. Relatively few records.

- Derive using RESORCE (Akkar et al., 2014d) as part of special issue (Douglas, 2014) including 4 other ground-motion models (Douglas et al., 2014).

- Most data from Italy, Turkey and Greece but believe models can be used for seismically-active areas in S. Europe and Middle East.

- Derive models using $r_{jb}$, $r_{epi}$ and $r_{hypo}$ so as to avoid requirement for distance conversion or virtual faults when using the models in probabilistic seismic hazard assessments.

- Include records from aftershocks because: difficult to classify European events into mainshocks and aftershocks, about half records come from aftershocks, and there is limited evidence for differences in motions for European data (Douglas and Halldórsson, 2010). Note that this inclusion could increase $\sigma$.

- Note that possible bias in data at great distances because of trigger thresholds but conclude, based on predictions from previous model and various instrument resolutions, that data roughly unbiased for $M_w > 4$ and $r_{jb} < 200$ km.

- Exclude data from 163 singly-recorded events so as not to inflate $\tau$ (inter-event variability).

- Only include data from 3-component accelerograms so that a consistent model for vertical-to-horizontal spectral ratio can be derived.

- Remove events with $M_w < 5$ with $< 3$ records to make the distribution w.r.t. mechanism more uniform and to prevent small events dominating derivation of mechanism terms.

- Note that data covers $M_w \leq 7$ well, particularly for normal and strike-slip mechanisms. For $M_w > 7$ almost no records from normal and reverse events and most data from 3 strike-slip earthquakes: 1990 Manjil, 1999 Kocaeli and 1999 Düzce.

- Undertake trial regressions adjusting motions to $V_{s,30} = 750$ m/s using nonlinear site amplification model of Sandikkaya et al. (2013) to choose functional form. Also regress using simple site classes to check Sandikkaya et al. (2013) and find similar results. Consider quadratic, cubic and hinged magnitude scaling and visually compare observations and predictions and study reduction in $\tau$ (inter-event). Impact on $\tau$ was limited so mainly use visual comparisons. Plot predicted and observed ground motions scaled to $r_{jb} = 10$ km and $V_{s,30} = 750$ m/s against $M_w$. Find similar results for $M_w < 6$ and significant differences for $M_w > 7$. Find oversaturation predicted by cubic model that is not seen in data. Find hinged magnitude scaling best matches observations but note that this is somewhat unconservative and higher epistemic uncertainty at these magnitudes because of lack of data.

- Try including anelastic attenuation term but find non-physical positive coefficients so remove it.

- Try including magnitude-dependent distance saturation but find similar predictions and no significant impact on $\sigma$. Hence remove it to reduce number of coefficients.

- Do not consider effect of depth to top of rupture because of limited information.

- Find that $a_2$, $a_5$, $a_6$ and $a_7$ show little variation with $T$ and hence make them period-independent coefficients, which leads to smooth spectra.

- Find mechanism coefficients $a_8$ and $a_9$ are very similar for three distance metrics so use same coefficients for $r_{jb}$, $r_{epi}$ and $r_{hypo}$.

- Plot residuals, grouped into bins, w.r.t. $M_w$, $R$ and $V_{s,30}$. Intra-event residuals do not show trends. Find model overestimates observations for $V_{s,30} < 180$ m/s and underestimates short-period motions for $V_{s,30} > 800$ m/s. But note that data in these bins are sparse and poorly distributed. Inter-event residuals suggest some bias for large magnitudes. Narrowing in residuals for large magnitudes could suggest magnitude-dependent $\sigma$ but note sparse data for $M_w > 7$. Decide not to model magnitude-dependent $\sigma$ since apparent dependency in residuals could be due to uncertain metadata (particularly $M_w$) for smaller events and data from only handful of events for $M_w > 6.5$ leading to underestimation of true $\sigma$ here.

- Note that $\sigma$s for $r_{epi}$ may underestimate true variability because of lack of data from $M_w > 6$ and $r_{jb} < 15$ km for which the impact of using $r_{epi}$ rather than $r_{jb}$ is largest.

- Note possible overprediction of motions for $M_w < 5$ based on comparisons to previous models.

- Note uncertainty in model beyond the data ($M_w > 7.6$) but believe that can be used up to $M_w 8$ based on comparisons to other models.

- Note that extrapolation to $r_{jb} > 200$ km can be done with some caution.

## 2.382 Ansary (2014)

- Ground-motion models are:
$$\log Y = b_1 + b_2 r + b_3 M + b_4 \log r$$
where $Y$ is in cm/s$^2$; $b_1 = 0.57259$, $b_2 = -5.77618 \times 10^{-4}$, $b_3 = 0.16954$, $b_4 = -0.20404$ and $\sigma = 0.36013$ for rock sites using all data; $b_1 = 0.58663$, $b_2 = -4.85358 \times 10^{-4}$, $b_3 = 0.17325$, $b_4 = -0.22588$ and $\sigma = 0.36984$ for rock sites using only data with $h < 70$ km (201 records); $b_1 = 0.43375$, $b_2 = -5.97479 \times 10^{-4}$, $b_3 = 0.2742$, $b_4 = -0.40632$ and $\sigma = 0.35759$ for rock sites using only data with $M > 4$ and $h < 70$ km (160 records); $b_1 = 0.80932$, $b_2 = -5.09526 \times 10^{-4}$, $b_3 = 0.2297$, $b_4 = -0.46683$ and $\sigma = 0.3755$ for soil sites using all data; $b_1 = 1.11211$, $b_2 = -2.89605 \times 10^{-4}$, $b_3 = 0.27169$, $b_4 = -0.74158$ and $\sigma = 0.38073$ for soil sites using only data with $h < 70$ km (163 records); $b_1 = 1.53895$, $b_2 = -1.19581 \times 10^{-4}$, $b_3 = 0.21482$, $b_4 = -0.80811$ and $\sigma = 0.38551$ for soil sites using only data with $M > 4$ and $h < 70$ km (147 records); and:
$$\log Y = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M) \log r$$
where $Y$ is in cm/s$^2$; $b_1 = -1.29562$, $b_2 = 0.33231$, $b_3 = 0.05844$, $b_4 = 1.38054$, $b_5 = -0.36172$ and $\sigma = 0.34269$ for rock sites using all data; $b_1 = -1.32206$, $b_2 = 0.30076$, $b_3 = 0.06902$, $b_4 = 1.5027$, $b_5 = -0.3951$ and $\sigma = 0.35074$ for rock sites using only data with $h < 70$ km (201 records); $b_1 = -2.71702$, $b_2 = 1.14476$, $b_3 = -0.03585$, $b_4 = 0.52328$, $b_5 = -0.22012$ and $\sigma = 0.3476$ for rock sites using only data with $M > 4$ and $h < 70$ km (160 records); $b_1 = 0.53083$, $b_2 = 1.0689$, $b_3 = -0.13013$, $b_4 = -2.0099$, $b_5 = 0.24215$ and $\sigma = 0.35542$ for soil sites using all data.

- Uses 2 site classes:

Rock 229 records

Soil 187 records

and derives independent models for each class

- Split data by focal depth, $h$.
- Data from stations of Indian Institute of Technology, Roorkee (298 stations in total) from 2005 to 2013.
- Compares predictions and observations for 3 earthquakes with $M \sim 6$.

## 2.383 Bindi et al. (2014a,b)

- Ground-motion model using $V_{s,30}$ is:

$$\begin{aligned}
\log Y &= e_1 + F_D + F_M + F_S + F_{sof} \\
F_D &= [c_1 + c_2(M-5.5)]\log\sqrt{R^2+h^2} - c_3(\sqrt{R^2+h^2}-1) \\
F_M &= \begin{cases} b_1(M-6.75) + b_2(M-6.75)^2 & M_w \leq 6.75 \\ b_3(M-6.75) & M_w > 6.75 \end{cases} \\
F_S &= \gamma\log(V_{s,30}/800) \\
F_{sof} &= f_1E_1 + f_2E_2 + f_3E_3
\end{aligned}$$

where $Y$ is in cm/s$^2$, $e_1 = 3.32819$, $c_1 = -1.2398$, $c_2 = 0.21732$, $h = 5.26486$, $c_3 = 0.001186$, $b_1 = -0.0855$, $b_2 = -0.09256$, $b_3 = 0$, $\gamma = -0.3019$, $f_1 = -0.03977$, $f_2 = 0.077525$, $f_3 = -0.03776$, $\tau = 0.149977$ (inter-event), $\phi = 0.282398$ (intra-event), $\phi_{S2S} = 0.165611$ (site-to-site) and $\sigma = 0.319753$ (total) for $r_{jb}$ and $e_1 = 4.27391$, $c_1 = -1.57821$, $c_2 = 0.108218$, $h = 4.82743$, $c_3 = 9.64\times10^{-5}$, $b_1 = 0.217109$, $b_2 = -0.06826$, $b_3 = 0.352976$, $\gamma = -0.293242$, $f_1 = -0.04721$, $f_2 = 0.110979$, $f_3 = -0.06376$, $\tau = 0.145783$ (inter-event), $\phi = 0.291566$ (intra-event), $\phi_{S2S} = 0.186662$ (site-to-site) and $\sigma = 0.325981$ (total) for $r_{hypo}$. Also provide 95% confidence limits for each coefficient based on bootstrapping (30 replications of original dataset) but these are not reported here.

Ground-motion model using site classes is the same as for $V_{s,30}$ but with $F_S$ given by:

$$F_S = s_jC_j$$

where $e_1 = 3.45078$, $c_1 = -1.36061$, $c_2 = 0.215873$, $h = 6.14717$, $c_3 = 0.000733$, $b_1 = -0.02087$, $b_2 = -0.07224$, $b_3 = 0$, $s_1 = 0$, $s_2 = 0.137715$, $s_3 = 0.233048$, $s_4 = 0.214227$, $f_1 = -0.03228$, $f_2 = 0.073678$, $f_3 = -0.01943$, $\tau = 0.180904$ (inter-event), $\phi = 0.276335$ (intra-event), $\phi_{S2S} = 0.206288$ (site-to-site) and $\sigma = 0.330284$ (total) for $r_{jb}$ and $e_1 = 4.36693$, $c_1 = -1.75212$, $c_2 = 0.150507$, $h = 7.32192$, $c_3 = 0.0$, $b_1 = 0.144291$, $b_2 = -0.06608$, $b_3 = 0.284211$, $s_1 = 0$, $s_2 = 0.143778$, $s_3 = 0.231064$, $s_4 = 0.187402$, $f_1 = -0.07175$, $f_2 = 0.084958$, $f_3 = -0.0571$, $\tau = 0.195249$ (inter-event), $\phi = 0.284622$ (intra-event), $\phi_{S2S} = 0.213455$ (site-to-site) and $\sigma = 0.345155$ (total) for $r_{hypo}$. Also provide 95% confidence limits for each coefficient based on bootstrapping (30 replications of original dataset) but these are not reported here.

- Derive one model using $V_{s,30}$ (mainly in range 100–1000 m/s) and another model using 4 Eurocode 8 site classes:

  A $V_{s,30} > 800$ m/s. About 5% of records. $C_1 = 1$ and other $C_i$s zero.

  B $360 < V_{s,30} \leq 800$ m/s. About 60% of records. $C_2 = 1$ and other $C_i$s zero.

  C $180 < V_{s,30} \leq 360$ m/s. About 30% of records. $C_3 = 1$ and other $C_i$s zero.

D $V_{s,30} \leq 180$ m/s. About 5% of records. 31 stations but only 5 have $\geq 5$ records (Bevagna, Colfiorito, Norcia, Rieti and Ambarli), which strongly control coefficient for this class. $C_4 = 1$ and other $C_i$s zero.

Eurocode 8 class E is excluded since only 5 records available.

- Use 4 mechanisms:

Normal $E_1 = 1$ and other $E_i$s zero. About 40% of records.

Reverse $E_2 = 1$ and other $E_i$s zero. About 15% of reords.

Strike-slip $E_3 = 1$ and other $E_i$s zero. About 40% of records.

Unspecified All $E_i$s zero. About 5% of records.

Unspecified class is not included in model using $V_{s,30}$ since events with unknown mechanisms excluded.

- Data from 345 stations.
- Focal depths $\leq 35$ km.
- Derive using RESORCE (Akkar et al., 2014d) as part of special issue (Douglas, 2014) including 4 other ground-motion models (Douglas et al., 2014).
- Also derive model using Eurocode 8 site classes (697 stations).
- Derive models using $r_{jb}$, $r_{epi}$ and $r_{hypo}$ so as to avoid requirement for distance conversion or virtual faults when using the models in probabilistic seismic hazard assessments.
- Exclude: unprocessed records, data lacking all 3-components and earthquakes without $M_w$ or with unreliable $M_w$. Next, exclude data: with $M_w < 4$, focal depth $> 35$ km, $r_{epi}$ or $r_{jb} < 300$ km, records without $r_{jb}$ if $M_w > 5$ or $r_{epi} < 10$ km, records with low-pass $f_c \geq 20$ Hz and singly-recorded earthquakes.
- Most data from Ialy and Turkey, particularly for model using $V_{s,30}$. Other principal countries supplying data: Greece, Iceland and Iran. Most data from 4–6.5 and 10–200 km. 16 events with $M_w > 6.5$ and 7 with $M_w > 7$.
- Choose functional form based on preliminary analysis.
- Do not consider other parameters (e.g. hanging wall effect and depth to top of rupture) or other distance metrics because of lack of information in RESORCE.
- Constrain $c_3$ and $b_3$ to be non-negative.
- Find predictions from two sets of models are similar.
- Because of increase in $\phi_{S2S}$ at long periods conclude that $V_{s,30}$ is not a good site proxy.
- Compute unit covariance matrix to understand propagation of data errors to results. Find that $e_1$, $h$ and $b_3$ are most affected by data errors. Also consider trade-offs between coefficients.
- Plot total, inter-event, site-to-site and record-to-record residuals grouped by site classes and country.
- Find no significant trends in residuals w.r.t. mainshock or aftershock (classified using Gardner and Knopoff (1974) approach).

- Find increase in inter-event residuals for small magnitudes and long $T$ but note that this could be due to poor sampling for large events and poor filtering for small events. Residuals suggest heteroscedastic $\sigma$ but this would require more data for large events. Also suggest that higher $\tau$ for small events could be due to conversion from other magnitude scales to $M_w$. Use White test to compute significance of magnitude-dependency. Find that the null hypothesis of homoscedasticity can be rejected for all periods at the 5% level.

- Find evidence for site-class dependency for $\phi_{S2S}$.

- Find evidence for record-to-record variability depending on country (e.g. data from Greece most variable and data from Iceland the least).

- Find no evidence for nonlinear site effects. Few records on which nonlinear effects are expected are present in RESORCE.

## 2.384 Derras et al. (2014)

- Ground-motion model is not given here since it requires evaluation of a matrix equation that cannot be summarised. Derive model using feed-forward artifical neural network (1 5-neuron hidden layer; 1 neuron for each independent parameter considered: $M_w$, $\log(r_{jb})$, $\log(V_{s,30})$, focal depth and mechanism class) with a procedure similar to random-effects approach to compute inter- and intra-event $\sigma$. Because provide the matrices and functional form to evaluate model it is included in this section rather than simply being listed. Authors provide spreadsheet to evaluate model. Standard deviations (in terms of common logarithms): $\tau = 0.155$ (inter-event), $\phi = 0.267$ (intra-event) and $\sigma = 0.309$.

- Use $V_{s,30}$ to characterise sites. Only 6.9% of sites have $V_{s,30} > 800$ m/s. Italian sites have higher average $V_{s,30}$ (496 m/s) than Turkish sites (389 m/s).

- Use 3 mechanisms (classified using plunge and rake angles):

Normal 540 records.

Reverse 93 records.

Strike-slip 455 records.

Most (76%) Italian events are normal and most (57%) Turkish events are strike-slip.

- Select records from events with focal depth $\leq 25$ km and measured values of $V_{s,30}$.

- Derive using RESORCE (Akkar et al., 2014d) as part of special issue (Douglas, 2014) including 4 other ground-motion models (Douglas et al., 2014).

- Most data from Turkey and Italy. Most Turkish data from $r_{jb} > 30$ km and larger magnitude range than Italian data.

- Data roughly uniformly distributed w.r.t. $M_w$ and $r_{jb}$ for $M_w \leq 6$. Few larger events.

- Find increasing the number of hidden layers would risk the problem of over-determination without a significant decrease in $\sigma$. Find that including depth and mechanism leads to marginal decrease in $\sigma$ but are included to aid comparisons with other models. Undertake various tests to find most appropriate model.

- Note that despite not imposing a functional form the model is physically sound and suggests nonlinear magnitude, distance and $V_{s,30}$ scaling.

- Examine inter-event residuals w.r.t. $M_w$ and intra-event residuals w.r.t. $r_{jb}$ and $V_{s,30}$ grouped by principal country of origin (Italy, Turkey or other). Compute mean residuals by bins and generally find no evidence for bias by country or significant trends. Find bias for Italian intra-event residuals in range $400 \leq V_{s,30} \leq 600$ m/s, which may indicate that $V_{s,30}$ is not a universal proxy for site amplification (the sites might include those with shallow soft soil overlying hard bedrock).

- Recommend that model is never used outside these ranges of applicability: $4 \leq M_w \leq 7$, $5 \leq r_{jb} \leq 200$ km, $200 \leq V_{s,30} \leq 800$ m/s and $0.01 \leq \text{PGA} \leq 10$ m/s. Also recommend model is not used for reverse-faulting events because lack of data.

## 2.385 Ghofrani and Atkinson (2014)

- Ground-motion model is:

$$\begin{aligned} \log Y &= c_0 - \log\sqrt{R_{cd} + h^2} + c_1 F R_{cd} + c_2 B R_{cd} + c_3 \log(V_{s,30}/760) \\ c_0 &= a + bM \end{aligned}$$

  where $c_1 = -0.00219$, $c_2 = -0.00298$, $c_3 = -0.219$, $h = 60$, $a = 2.8193 \pm 1.006$, $b = 0.1908 \pm 0.130$, $\phi = 0.284$ (intra-event), $\tau = 0.196$ (inter-event) and $\sigma = 0.345$ (total).

- Characterise sites using $V_{s,30}$ (all based on measured profiles, most down to $10 - -20$ m. Extend site velocity profiles to 30 m using approach of Boore et al. (2011). Note that data are affected by highly-significant shallow soil response that is specific to Japan. Median $V_{s,30}$ is 266 m/s for forearc stations and 313 m/s for backarc stations.

- Classify station locations into location relative to volcanic front:

  1. Forearc. $F = 1$ and $B = 0$.
  2. Backarc. $B = 1$ and $F = 0$.

- Use data from Japanese K-Net. Zero pad records, cosine taper and apply acausal band-pass 4th-order Butterworth filters with cut-offs of 0.04 and 15 Hz.

- Only use data from Japan to reduce ambiguity from combining data from different regions.

- Derive event-specific model using only data (> 600 records) from the 2011 Tohoku (Japan) $M_w$9.0 earthquake.

- $h$ is chosen as the value that minimizes the standard deviation and average absolute residual.

- Assume linear site term because previous studies have shown nonlinear effects relatively small for Tohoku earthquake at most stations and because nonlinear part of response trades off against near-source saturation term.

- For Tohoku model, estimate $c_0$ using only forearc records within 200 km and then fix $c_0$ and compute other coefficients using all data.

- Note that the shallow site response affects estimates of $\phi$.

- Provide multiplicative factor to adjust predictions for Cascadia (for PGA it is 0.50) because of differences in average site profiles.

- Show residuals from Tohoku model w.r.t. distance.

- Adjust the source term ($c_0$) by using data from 5 other $7 \leq M_w \leq 8.1$ events from Japan. Do this by computing mean residuals of ground motions w.r.t. Tohoku GMPE using only forearc stations (which are the nearest) and exclude records beyond a cut-off where PGA v $R_{rup}$ plot starts to flatten (due to instrument noise and/or non-triggered stations). Find that for some earthquakes the attenuation is less rapid. Hence only use data from $\leq 200$ km to compute residuals for all events to reduce residuals at shorter distances at the expense of greater over-prediction for $> 200$ km. Plot $c_0$ against $M_w$. Then fit these mean residuals with linear function to obtain equation for $c_0$. Consider making $h$ a function of magnitude but do not find strong evidence in data for this.

- Find slope of function for $c_0$ is of marginal significance at higher frequencies based on P-value of Student's t test.

- Plot observed and predicted ground motions and residuals w.r.t. distance for all data.

- Compute mean residuals for 60 sites that have all events. Find that some sites show large residuals, particularly at high frequencies, which relate to shallow site response that is not captured by $V_{s,30}$. Conclude that the value of $\phi$ estimated may not be representative for other regions with more homogeneous conditions nor representative of expected variability at a single site. Hence believe reported variabilities are upper bounds on actual aleatory variability as it includes some epistemic components.

- Provide estimates of epistemic uncertainty range (low and high branches) of model based on arguments from recent studies.

## 2.386 Gianniotis et al. (2014)

- Ground-motion model is[43]:

$$\ln y = c_1 + c_2 M_w + c_3 M_w^2 + (c_4 + c_5 M_w) \log(\sqrt{r_{hypo}^2 + c_6^2}) + c_7 \ln V_{s,30} + c_8 \phi$$

  Coefficients are not reported.

- Use $V_{s,30}$ to characterise sites.

- Use data from RESORCE (Akkar et al., 2014d), a pan-European database.

- Select data with $M_w > 4$, $r_{hypo} < 230$ km, focal depth $\leq 30$ km and a value of $V_{s,30}$.

- Use regression approach to investigate regional dependency.

- Modelled derived using 1261 records from 437 earthquakes, separated thus: north Turkey (324), Appenines (303), south Turkey (250), east Turkey (122), east Alps (91), south Greece (87), north Greece (58), Iran (19) and Sicily (7 records). Coefficients can be regionally-dependent but they are constrained to fall on a common low-dimension manifold.

- Compare results with manifold-aligned approach to grouping all data together (global) or keeping data from each region separate (regional). Manifold-aligned approach generally works better than global or regional approaches for regions with limited (about 50–250 records); when fewer records recommend global approach and when more records prefer regional approach.

- Find coefficients using neural networks.

- Use two faulting mechanisms:

[43] Mixture of ln and log present in original formulation.

$\phi = 0$ Strike-slip/normal.

$\phi = 1$ Reverse.

- Note only a few records for $M_w > 7$ and limited data from $M_w > 6$ and hence magnitude scaling would be poorly constrained if using regional datasets individually.

## 2.387 Kurzon et al. (2014)

- Ground-motion model is:

$$\begin{aligned}\ln Y_1 &= e_1 + e_2(M-2.5) + e_3(M-2.5)^2 + [c_1 + c_2(M-3] \ln \sqrt{r_{epi}^2 + h_A^2} + c_3[\sqrt{r_{epi}^2 + h_A^2} - 1] \\ \ln Y_2 &= b_1 + b_2 \ln I_{Dir} + b_3 \ln Y_1 \quad \text{Using directivity terms} \\ \ln Y_2 &= a_1 + a_2 \ln D + a_3 \ln Y_1 \quad \text{Using fault zone terms}\end{aligned}$$

  where $Y_1$ is in cm/s$^2$, $e_1 = 0.210$, $e_2 = 3.220$, $e_3 = 0.036$, $c_1 = -2.840$, $c_2 = -0.361$, $c_3 = 0.021$, $h_A = 13.452$ and $\sigma_t = 0.968$ (total)for basic Phase 1 model; $b_1 = -2.558$, $b_2 = 0.912$, $b_3 = 0.952$ and $\sigma_t = 0.896$ for directivity model; $a_1 = -0.538$, $a_2 = 0.130$, $a_3 = 0.957$ and $\sigma = 0.852$ for borehole damping and fault zone amplification model; $e_1 = -6.822$, $e_2 = 2.549$, $e_3 = -0.121$, $c_1 = -0.953$, $c_2 = -0.138$, $c_3 = -0.013$, $d_1 = 0.892$, $h_A = 3.547$ and $\sigma_t = 0.924$ for Phase 2 model; $e_1 = -7.532$, $e_2 = 2.557$, $e_3 = -0.105$, $c_1 = -1.121$, $c_2 = -0.142$, $c_3 = -0.008$, $d_1 = 1.308$, $h_A = 3.749$ and $\sigma_t = 0.985$ for Phase 2 model using only stations in direction of rupture. In Phase 2 models model for $Y_1$ has additional term $d_1 \ln I_{Dir}$.

- Select data from events in $45 \times 125\,\text{km}^2$ rectangular area around the San Jacinto fault zone, a strike-slip fault system, from 02/2010 to 05/2012 plus data from 3 moderate events: 03/2013 ($M_L$5.1), 07/2010 ($M_L$5.9) and 06/2005 ($M_L$5.6), and their aftershocks.

- Data from 140 stations, including broadband instruments, from various networks within $90 \times 275$ km rectangle around fault zone. Broadband data converted to acceleration. Bandpass filter data using 1–30 Hz 4th-order Butterworth filter. Prefer accelerometric data for $M > 3$ (to avoid saturation) and velocimetric data for $M < 3$ (because of higher sensivity). Pick ground-motion parameters automatically using signal-to-noise ratio algorithm.

- Derive two sets of models: Phase 1 (using data up to 05/2012, about 20000 records) and Phase 2 (including 03/2013 earthquake sequence).

- Focal depths between about 0 and 25 km with peak between 5 and 20 km.

- Vast majority of data from $M_L < 3.5$ (only a handful of events have higher magnitudes).

- Find using $r_{epi}$ and $h_A$ rather than $r_{hypo}$ results in slightly smaller $\sigma$.

- Derive series of models starting from one including only $M$ and $r$ and then adding site, directivity and fault-zone amplification terms. Examine reduction in $\sigma$ and residuals as additional terms added.

- Because of lack of $V_{s,30}$ measurements for stations use various geological and topographical methods to estimate $V_{s,30}$. Find none of these approaches leads to significant reduction in $\sigma$. Hence neglect this factor.

- Find strong indication in residuals and reduction in $\sigma$ of fault zone amplification (characterised by distance normal to fault, $D$).

- Find strong impact of directivity (characterised by index, $I_{Dir}$) in residuals and reduction in $\sigma$.

- Derive final model by adding directivity and then fault zone amplification to basic model.

- Classify stations into: amplifiers, dampers, and good-fit, based on their average residuals within magnitude bins. Examine residuals geographically and find amplifiers are often close to fault and dampers are often in boreholes or posthole sites buried $\geq 10$ m below surface.
- Initial regression of Phase 2 dataset did not converge. Attempt various regressions of subsets and obtain large $\sigma$s. Conclude that additional directivity factor needs to be included in basic model.
- In Phase 2 exclude data from $r_{epi} > 80$ km for $M < 3$, $r_{epi} > 100$ km for $3 \leq M < 5$ and $r_{epi} > 150$ km for $M \geq 5$ to decrease weight of small events at large distances.
- Examine $\sigma$ for various subsets of Phase 1 and 2 data (e.g. only mainshocks or specific sequences).
- Examine geographical distribution of variance of total residuals per event binned into various magnitude ranges. Find very high variances for 03/2013 dataset, which relate to combination of source characteristics and new fault-zone stations.

## 2.388 Luzi et al. (2014)

- Ground-motion model is (same functional form as Bindi et al. (2011a) to which study is similar):

$$
\begin{aligned}
\log_{10} Y &= e_1 + F_D + F_M + F_S + F_{sof} \\
F_D &= [c_1 + c_2(M-5)] \log_{10}\left(\sqrt{R_{JB}^2 + h^2}\right) - c_3\left(\sqrt{R_{JB}^2 + h^2} - 1\right) \\
F_M &= \begin{cases} b_1(M-6.75) + b_2(M-6.75)^2 & \text{for} \quad M \leq 6.75 \\ b_3(M-6.75) & \text{otherwise} \end{cases} \\
F_S &= s_j C_j \\
F_{sof} &= f_j E_j
\end{aligned}
$$

  where $Y$ is in cm/s$^2$, $e_1 = 3.72318$, $b_1 = -0.06573$, $b_2 = -0.05886$, $b_3 = 0$, $c_1 = -1.81275$, $c_2 = 0.31914$, $h = 8.61357$, $c_3 = -0.00008$, $f_1 = -0.02604$, $f_2 = 0.13674$, $f_3 = 0.02803$, $f_4 = 0$, $s_1 = 0$, $s_2 = 0.16032$, $s_3 = 0.18900$, $s_4 = 0.17194$, $s_5 = 0.59823$, $\tau = 0.21738$ (inter-event), $\phi = 0.28063$ (intra-event) and $\sigma = 0.35498$ (total) for BIea dataset; $e_1 = 3.80924$, $b_1 = 0.19680$, $b_2 = -0.11244$, $b_3 = 0.00001$, $c_1 = -1.50507$, $c_2 = 0.02642$, $h = 5.52095$, $c_3 = 0.00004$, $f_1 = 0.09705$, $f_2 = 0.15338$, $f_3 = 0.14478$, $f_4 = 0$, $s_1 = 0$, $s_2 = 0.12467$, $s_3 = 0.21216$, $s_4 = -0.00558$, $s_5 = 0.55732$, $\tau = 0.27238$ (inter-event), $\phi = 0.28635$ (intra-event) and $\sigma = 0.39520$ (total) for BIea2 dataset; $e_1 = 3.49977$, $b_1 = -0.00084$, $b_2 = -0.11122$, $b_3 = 0$, $c_1 = -1.59946$, $c_2 = 0.21243$, $h = 5.63087$, $c_3 = -0.00097$, $s_1 = 0$, $s_2 = 0.16701$, $s_3 = 0.09431$, $s_4 = 0.04135$, $s_5 = 0$, $\tau = 0.13690$ (inter-event), $\phi = 0.25777$ (intra-event) and $\sigma = 0.29187$ (total) for ABR dataset (mechanism terms removed).

- Use 5 site Eurocode 8 (EC8) classes (150 stations in total):

  A $V_{s,30} > 800$ m/s. $C_A = 1$ and other $C_i$s are zero.

  B $360 < V_{s,30} \leq 800$ m/s. $C_B = 1$ and other $C_i$s are zero.

  C $180 < V_{s,30} \leq 360$ m/s. $C_C = 1$ and other $C_i$s are zero.

  D $V_{s,30} \leq 180$ m/s. $C_D = 1$ and other $C_i$s are zero.

  E 5–20 m of C- or D-type alluvium underlain by stiffer material with $V_{s,30} > 800$ m/s. $C_E = 1$ and other $C_i$s are zero.

  About 130 stations are classified based on shear-wave velocity profiles and rest from geological and geophysical data.

- Use 4 faulting mechanism classes using classification of Zoback (1992):

Normal $E_1 = 1$ and other $E_i$s are zero.

Reverse $E_2 = 1$ and other $E_i$s are zero.

Strike-slip $E_3 = 1$ and other $E_i$s are zero.

Unknown $E_4 = 1$ and other $E_i$s are zero.

- Derive models using 3 datasets:

BIea Dataset of Bindi et al. (2011a) but retaining singly-recorded events to increase number of stations with $> 2$ records. Only 25 stations recorded $> 9$ events. 117 stations.

BIea2 Extend BIea to include all records from $4.0 \leq M_w 6.9$ including those for which magnitude conversion required. 254 stations.

ABR Data from 2009 L'Aquila sequence (42.4-42.8N, 13.2-13.6E). 38 stations. All events are normal-faulting (hence mechanism terms removed) and have focal depths $< 10$ km.

- Records baseline corrected and filtered using 2-order acausal Butterworth filter after cosine tapering. Select cut-offs based on Fourier amplitude spectra. Double integrate to get displacements. Linearly detrend displacements. Double differentiate to get correct accelerations.
- Develop model to examine single-station $\sigma$ (computed using approach of Rodriguez-Marek et al. (2011)) and influence of datasets on its value.
- Examine inter-event residuals w.r.t. $M_w$ and find no trends.
- Examine intra-event residuals w.r.t. station number.
- Examine intra-event residuals w.r.t. $r$ and find large variability in range 80–100 km, which relate to Moho bounce.
- Examine histograms of $\phi_{SS,S}$, distribution of $\phi_{SS,S}$ w.r.t. site class, and $\phi_{SS,S}$ w.r.t. station number. Identify stations with large $\phi_{SS,S}$ and discuss reasons for large values.
- Examine single-station $\sigma$ w.r.t. magnitude-distance bins. Find that it is generally higher for 0–40 km.
- Examine influence of number of records per station on mean $\phi_{SS}$ and find results are quite stable.
- Find $\sigma$ is higher for BIea2 compared to BIea, which relate to use of converted $M_w$.
- Find $\sigma$ for ABR is lower compared to other datasets, which relate to restriction of events from small geographical area.

## 2.389 Rodríguez-Pérez (2014)

- Ground-motion model is:

$$\begin{aligned}
\log Y &= c_1 + c_2 M + c_3 H + c_4 R - c_5 \log R \\
R &= \sqrt{r_{rup}^2 + \Delta^2} \\
\Delta &= 0.0075010^{0.507M}
\end{aligned}$$

where $Y$ is in cm/s$^2$, $c_1 = -1.2324$, $c_2 = 0.5016$, $c_3 = 0.0141$, $c_4 = -0.0006$, $c_5 = 0.9432$, $\sigma_e = 0.12$ (inter-event), $\sigma_r = 0.35$ (intra-event) and $\sigma = 0.37$ (total) for near-trench events and $c_1 = -1.1321$, $c_2 = 0.8038$, $c_3 = 0.0033$, $c_4 = -0.0014$, $c_5 = 1.3219$, $\sigma_e = 0.12$ (inter-event), $\sigma_r = 0.37$ (intra-event) and $\sigma = 0.39$ (total) for intraslab events.

- Only use data from rock sites (limestone, basalt, diorite and quartz monzonite).
- Focal depths: $6 \leq H \leq 20$ km for interface, $55 \leq H \leq 198$ km for intraslab.
- Uses data from high-frequency-depleted thrust near-trench events (interface) in central Mexico and normal-faulting intraslab earthquakes in southern Mexico. Earthquakes in subduction zone between Cocos and North American plate. Select near-trench events that have low ratios of energy to moment and large disparity between $M_s$ and $M_w$.
- Uses data from about 25 stations in central Mexico and about 15 in southern Mexico.
- Most data from $r > 150$ km.
- Baseline correct and low-cut filter (0.05 Hz for $M_w > 6.5$ and 0.1 Hz otherwise) records.
- Tries various functional forms (e.g. quadratic magnitude term and magnitude-dependent saturation) and choose form that leads to lowest $\sigma$.
- Examines residuals in four magnitude ranges w.r.t. distance. Fits lines and finds no significant trends.
- Notes that slightly higher $\sigma$ may due to uncertainties in earthquake characteristics and simple functional form.
- Compares observations and predictions for $M_w8$ and $M_w6.7$ events w.r.t. distances. Finds good match with most observations within $\pm 1\sigma$ limits.

## 2.390 Vacareanu et al. (2014)

- Ground-motion model is:

$$\begin{aligned} \ln y &= c_1 + c_2(M-6) + c_3(M-6)^2 - \ln R + c_5 R + c_6 h \\ M &= 7.6 \quad \text{for } M_w > 7.6 \text{ and } T \leq 1\,\text{s} \\ M &= 8.0 \quad \text{for } M_w > 8.0 \text{ and } T > 1\,\text{s} \end{aligned}$$

  where $y$ is in cm/s$^2$, $c_1 = 8.5851$, $c_2 = 1.4863$, $c_3 = -0.4758$, $c_5 = -0.00138$, $c_6 = 0.00484$, $\sigma = 0.491$ (intra-event), $\tau = 0.550$ (inter-event) and $\sigma_T = 0.738$ (total).

- Data from 4 site classes based on Eurocode 8:

  A $V_{s,30} > 800$ m/s

  B $360 < V_{s,30} \leq 800$ m/s.

  C $180 < V_{s,30} \leq 360$ m/s.

  D $V_{s,30} \leq 180$ m/s.

  Vast majority of data from B, C and D except some class-A records from epicentral zone of Vrancea events. Do not consider effect of site in model. Believe that model predicts motions on soil sites.

- Use records of intermediate-depth earthquakes in Vrancea (recorded in Romania, Moldova, Bulgaria and Serbia) and elsewhere (Japan, New Zealand, Mexico, Chile, India and Myanmar).
- Focal depths $69 \leq h \leq 173$ km. Believe can be used for $60 \leq h \leq 200$ km
- Data mainly from $100 \leq r_{epi} \leq 200$ km.

- Similar data distributions w.r.t. $r_{epi}$, $M_w$, $h$ and site class for Vrancea and foreign events.

- Compare predictions and observations from 3 most-well-recorded Vrancea events (1986, $M_w$7.1; 1990, $M_w$6.9; 2004, $M_w$6.0). Find good match with most data within $\pm 1\sigma$.

- Examine normalised residuals w.r.t. $M_w$, $r_{epi}$ and $h$ (binned into $M_w$ ranges). Find no significant trends. In particular find no evidence for magnitude dependency of $\tau$.

- Plot histograms of normalised total, inter-event and intra-event residuals and likelihoods and find that fit normal distribution closely.

- Mean, median and standard deviations of normalised residuals considering only Vrancea data are $-0.06$, $-0.03$ and 0.82 and hence conclude that model can be used for Vrancea events.

- Examine azimuthal dependency for Vrancea data by plotting normalised residuals on map. Find no evidence for azimuthal variations nor w.r.t. site class but find slight underestimation in area in front of Carpathians (fore-arc) and overestimation behind mountains (back-arc).

- Cap magnitudes for $M_w > 7.6$ ($T \leq 1$ s) or $M_w > 8$ ($T > 1$ s) to avoid decrease in predictions due to quadratic $M$ term. Note that this capping could be avoided by assuming linear $M$ dependency but find quadratic dependency fits observations better.

## 2.391 Atkinson (2015)

- Ground-motion model is:

$$
\begin{aligned}
\log Y &= c_0 + c_1 M + c_2 M^2 + c_3 \log R \\
R &= \sqrt{R_{hypo}^2 + h_{eff}^2} \\
h_{eff} &= \max(1, 10^{-1.72+0.43M})
\end{aligned}
$$

  where $Y$ in in cm/s$^2$, $c_0 = -2.376$, $c_1 = 1.818$, $c_2 = -0.1153$, $c_3 = -1.752$, $\sigma_{intra} = 0.28$, $\sigma_{inter} = 0.24$ and $\sigma_{total} = 0.37$.

- Adjusts data to NEHRP B/C boundary ($V_{s,30} = 760$ m/s) using site amplification term of Boore et al. (2013). Suggests that this site amplification term can be used to evaluate model for other site conditions.

- Uses data from Next Generation Attenuation-West 2 with $3 \leq M_w \leq 6$ and $r_{hypo} \leq 40$ km that pass selection criteria of Boore et al. (2013).

- Aim is a model for use in evaluating hazard from induced seismicity but use natural seismicity data because induced seismicity data lacking. Assumes that ground motions of the two types are similar.

- Little data from $r_{hypo} < 10$ km, which means that control on distance saturation is uncertain. Hence use $h_{eff}$ from Yenier and Atkinson (2014) from stochastic modelling of global earthquakes with $M_w \geq 6$. Suggests that $h_{eff} = 1$ km (corresponding to $M_w$4) is the lower limit that should be used. Tries alternative functions for $h_{eff}$ and note that they fit the data almost as well but lead to different very near source predictions. This implies an epistemic uncertainty of up to a factor of two in the near-source area.

- Chooses functional form as simplest likely to be applicable.

- Finds that standard least-squares regression gives similar results.

- Plots predictions against observations grouped into $0.5M_w$ width bins. Finds good fit.

- Plots residuals w.r.t. $r_{hypo}$ and finds no trends, which means that a more complex functional form is not required.

- Note that model is strictly applicable only to about 40 km because of lack of anelastic attenuation term. Proposes adding a additional term $c_4 R$ with $c_4$ calibrated using the behaviour of the Boore et al. (2013) model beyond 40 km. For PGA $c_4 = -0.002$ is proposed.

## 2.392 Breska et al. (2015)

- Refit 44 published ground-motion models using the database of Perus and Fajfar (2009, 2010). Coefficients and $\sigma$s are reported but they are not given here due to lack of space.

- Use sets of independent parameters and functional forms of original models.

## 2.393 Cauzzi et al. (2015b) & Cauzzi and Faccioli (2018a,b)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10} y &= f_M + f_R + f_S + f_{SOF} \\
f_M &= c_1 + m_1 M_w + m_2 M_w^2 \\
f_R &= (r_1 + r_2 M_w) \log_{10}(r_{rup} + r_3) \\
f_S &= \begin{cases} s_B S_B + s_C S_C + s_D S_D & \text{or alternatively} \\ b_V \log_{10}\left(\frac{V_{s,30}}{V_A}\right) & \text{or alternatively} \\ b_{V800} \log_{10}\left(\frac{V_{s,30}}{800}\right) & \end{cases} \\
f_{SOF} &= f_N F_N + f_R F_R + f_{SS} F_{SS}
\end{aligned}
$$

where $y$ is in cm (to obtain PGA in cm/s$^2$ it is necessary to multiply $y$ by $(2\pi/0.01)^2$), $c_1 = -2.19617$, $m_1 = 0.52375$, $m_2 = -0.06094$, $r_1 = -3.80190$, $r_2 = 0.35508$, $r_3 = 11.64156$, $s_B = 0.21070$, $s_C = 0.28251$, $s_D = 0.28288$, $b_V = -0.31007$, $b_{V800} = -0.70244$, $V_A = 2319.18598$, $f_N = -0.02411$, $f_R = 0.07246$, $f_{SS} = -0.05632$, $\phi = 0.25892$ (intra-event), $\tau = 0.22145$ (inter-event) and $\sigma = 0.34071$ (total).

- Use three alternative site terms. Mean $V_{s,30}$ equals 365 m/s. Either use $V_{s,30}$ to characterise sites or four Eurocode 8 site classes:

  A Rocklike, $V_{s,30} \geq 800$ m/s. 7% of data. $S_B = S_C = S_D = 0$.

  B Stiff, $360 \leq V_{s,30} < 800$ m/s. 43% of data. $S_B = 1$, $S_C = S_D = 0$.

  C Soft, $180 \leq V_{s,30} < 360$ m/s. 40% of data. $S_C = 1$, $S_B = S_D = 0$.

  D Very soft, $V_{s,30} < 180$ m/s. 10% of data. $S_D = 1$, $S_B = S_C = 0$.

- Use three faulting mechanisms using classification of Boore and Atkinson (2008):

Normal 20 earthquakes. $F_N = 1$, $F_R = F_{SS} = 0$.

Strike-slip 43 earthquakes. $F_{SS} = 1$, $F_N = F_R = 0$.

Reverse 26 earthquakes. $F_R = 1$, $F_N = F_{SS} = 0$.

- Focal depths $\leq 20$ km..

- Update of previous models by Cauzzi and Faccioli (2008), Cauzzi (2008), Cauzzi et al. (2008), Faccioli et al. (2010) and Cauzzi et al. (2011).

- All data from digital accelerometers.
- Most data from Japan (K-Net) (1448 records, 49 earthquakes) with some data from Europe and Middle East (Italy, Iceland, Iran, Turkey, Switzerland, Greece) (195 records, 35 earthquakes), western USA (California and Alaska) (79 records, 7 earthquakes), New Zealand (61 records, 5 earthquakes) and China and Taiwan (95 records, 2 earthquakes).
- Only use data from earthquakes with known fault geometries (from which $r_{rup}$ can be estimated) except for $M_w \leq 5.7$, where comparison of $r_{rup}$ and $r_{hypo}$ shows that statistically indistinguishable.
- Use procedure of Paolucci et al. (2008) to avoid filtering records with a probability $> 0.9$ of long-period disturbance levels being $< 15\%$. High-pass filter remaining records with 20 s cut-off.
- Did not check for regional dependency since now largely accepted to merge data from various regions.
- Aim for simple though physically-sound functional form. Prefer a simple magnitude-independent $r_3$ over one that is magnitude-dependent because of stability in regression results and lack of trade-off with other coefficients. Also this choice allows use of two-stage regression thereby yielding a smaller $\sigma$. Do not include anelastic term because of negligible impact on predictions for $r_{rup} < 150$ km.
- Derive model in four stages. First, undertake regressions to investigate overall variation of coefficients and to identify trade-offs. Constrain $r_2$ and $r_3$ from this step in subsequent steps. Second, undertake two-step maximum-likelihood regression to find $r_1$, $s_B$, $s_C$, $s_D$, $c_1$, $m_1$ and $m_2$. Smooth $m_2(T)$ for $T < 1$ s by fitting a high-order polynomial to the raw coefficients. Next repeat regression holding $m_2$ fixed. This had a positive effect on stability of $c_1$ and $m_1$. Third, find $b_V$, $b_{V800}$ and $V_A$ by two-stage weighted maximum-likelihood regression. Fourth, find $f_N$, $f_R$ and $f_{SS}$ by two-step maximum-likelihood regression.
- Examine predicted magnitude-scaling and observations from $r_{rup} < 10$ km adjusted to rock-like conditions. Find evidence for over-saturation at large magnitudes but note that there is large uncertainty because of limited data for $M_w > 7.2$. Model predicts oversaturation for short-periods and large magnitudes, which is retained. Provide equations to remove oversaturation from model.
- Examine residuals w.r.t. predicted PGA on rock and grouped by EC8 site class to seek nonlinear site amplification. Fit lines to residuals and find trends, which could interpret as nonlinearity but given scatter in results believe evidence for soil nonlinearity is weak.
- Find inclusion of faulting mechanism terms slightly reduces $\sigma$ for $T < 0.3$ s.
- Believe that because model developed independently of other recent models and using an independent dataset that it can contribute to capturing epistemic uncertainty in ground-motion prediction.
- Note that one limitation of model is the use of $V_{s,30}$ but cannot add terms to account for 2D or 3D basin-type effects because of lack of require information for most records.
- Note that there is still a lack of data from rock-like sites.

## 2.394 Emolo et al. (2015)

- Ground-motion model is:

$$\log Y = a + bM + c \log \sqrt{R_{epi}^2 + h^2} + dR_{epi} + es$$

where $Y$ is in m/s$^2$, $a = -3.07 \pm 0.14$, $b = 0.73 \pm 0.03$, $c = -0.76 \pm 0.06$, $h = 1.7 \pm 2.3$, $d = -0.0029 \pm 0.0002$, $e = 0.326 \pm 0.006$, $\tau = 0.17$ (inter-event), $\sigma = 0.34$ (intra-event) and $\sigma = 0.38$ (total).

- Derive station terms for each site because insufficient geological information to use, e.g., $V_{s,30}$. Firstly derive reference model not including site effects. Then compute first-order station corrections from residuals w.r.t. reference. Use $Z$-test at 95% confidence level to check null hypothesis of a zero mean. Stations where null hypothesis was rejected are assumed to have a site effect. Derive site correction for each station by assigning $s = 0$ to all sites with zero-mean residual, $s = 1$ to stations with positive deviation and $s = -1$ to stations with a negative deviation. Prefer adjusted model based on the total $\sigma$ and $R^2$ statistics.
- Data from 132 stations of Korean Seismic Network from March 2007 to March 2012. Data from both accelerometers and weak-motion (broadband and short-period) sensors. Also data from 24-bit digital recorders. Analyse about 30 000 records in terms of signal-to-noise ratios and by visual inspection. Use only records with signal-to-noise ratios $> 5$. Data from over almost all over South Korea, both inland and offshore. Remove mean and trend from records and bandpass filter using a zero-phase 4-pole Butterworth filter with cut-offs of 0.1 and 20 Hz. Select motions by taking portion from 2 s before P-wave arrival up to time corresponding to 98% of total energy. Signals tapered by cosine function.
- Only two earthquakes with $M_L > 4$.
- Compare predictions and observations for the 1/4/2014 $M5.1$ earthquake that was not used to derive the model. Find quite a good match.
- Compare reference model to data in magnitude bins around 2.5, 3.5 and 4.5.
- Examine residuals w.r.t. $M$ and $r_{epi}$ and find no trends.

## 2.395 Graizer and Kalkan (2015) & Graizer and Kalkan (2016)

- Ground-motion model is:

$$\begin{aligned}
\ln(Y) &= \ln G_1 + \ln G_2 + \ln G_3 + \ln G_4 + \ln G_5 \\
\ln G_1 &= \ln\{[c_1 \arctan(M + c_2) + c_3]F\} \\
\ln G_2 &= -0.5 \ln\left[\left(1 - \frac{R}{R_0}\right)^2 + 4D_0^2 \frac{R}{R_0}\right] \\
R_0 &= c_4 M + c_5 \\
D_0 &= c_6 \cos[c_7(M + c_8)] + c_9 \\
\ln G_3 &= -c_{10} R / Q_0 \\
\ln G_4 &= b_v \ln\left(\frac{V_{s,30}}{V_A}\right) \\
\ln G_5 &= \ln[1 + A_{B_{dist}} A_{B_{depth}}] \\
A_{B_{depth}} &= \frac{1.077}{\sqrt{\{1 - [1.5/(B_{depth} + 0.1)]^2\}^2 + 4 \times 0.7^2 [1.5/(B_{depth} + 0.1)]^2}} \\
A_{B_{dist}} &= \frac{1}{\sqrt{\{1 - [40/(R + 0.1)]^2\}^2 + 4 \times 0.7^2 [40/(R + 0.1)]^2}}
\end{aligned}$$

where $Y$ is in g, $c_1 = 0.14$, $c_2 = -6.25$, $c_3 = 0.37$, $c_4 = 2.237$, $c_5 = -7.542$, $c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.15$, $c_9 = 0.6$, $c_{10} = 0.345$, $b_v = -0.24$, $V_A = 484.5$; $\tau = 0.435$ (inter-event), $\phi = 0.508$ (intra-event) and $\sigma = 0.669$ (total) for homoscedastic variability; and $\tau(M) = s_1$ for $M \leq 7.1$, $\tau(M) = s_1 + (s_2 - s_1)(M_w - 7.1)$ for $7.1 < M_w < 7.5$ and $\tau(M) = s_2$ for $M_w \geq 7.5$ where $s_1 = 0.28$ and $s_2 = 0.04$, $\tau(M, R) = \tau(M) + r_1$ for $R \leq 100$ km, $\tau(M, R) = \tau(M) + (r_1 - r_2)(R - 100)$ for $100 < R < 130$ km and $\tau(M, R) = \tau(M) + r_2$ for $R \geq 130$ km where $r_1 = 0.30$ and $r_2 = 0.52$ for heteroscastic inter-event variability.

- Characterise sites using $V_{s,30}$. State that valid between 200 and 1300 m/s.
- Use $B_{depth}$ (depth to 1.5 km/s shear-wave velocity isosurface), which ranges from about 100 m to about 2400 m. Only 353 records have estimates of $B_{depth}$. Believe model applicable for $B_{depth}$ between 0 and 10 km.
- Use 3 styles of faulting:
  1. Strike-slip (1120 records) and normal (13 records). $F = 1.0$.
  2. Reverse (1450 records). $F = 1.28$.
  3. Reverse/strike-slip oblique. $F = 1.14$.
- Update of model of Graizer and Kalkan (2007, 2008) (see Section 2.281) to include anelastic attenuation term based on $Q_0$, the regional quality factor, and a frequency-dependent sedimentary-basin scaling term based on $B_{depth}$. Use same database as Graizer and Kalkan (2007, 2008).
- Choose $c_{10} = 0.345$ based on average $Q_0 = 150$ for California. Recommend using model with $Q_0$ determined from Lg or coda waves for region of interest. Believe model applicable for $Q_0 \leq 250$.
- Constrain coefficients of basin-effect terms using data from 1999 $M_w$7.1 Hector Mine, 1992 $M_w$7.3 Landers and 1989 $M_w$6.9 Loma Prieta earthquakes.
- Analyse inter- and intra-event residuals using best-fit lines against various independent parameters and find no trends or large offsets.
- Provide model for pseudo-spectral accelerations. This is not summarised hear because it is not in the style of coefficients for many periods but as a closed-form function.
- Define heteroscastic variability models by dividing standard deviations into 8 magnitude and 10 distance bins.
- Compare observations and predictions for 13 Californian earthquakes and find a good match.

## 2.396 Haendel et al. (2015)

- Ground-motion model is:

$$\ln Z = aM_w + br_{rup} - (c + M_w)\ln r_{rup} + e\min(h, 125) + \begin{cases} + q_i(M_w - 6.3)^2 + s_i & \text{if interface} \\ + q_s(M_w - 6.5)^2 + s_s + s_{sl}\ln r_{rup} & \text{if intraslab} \\ + x & \text{if not NEHRP B site} \end{cases}$$

  where $Z$ is in cm/s$^2$, $a = 0.7401$, $b = -0.0098$, $c = 1.0273$, $d = -0.1099$, $e = 0.0071$, $s_i = 0.2841$, $s_s = 4.1648$, $s_{sl} = -0.6199$, $x = 0.4998$, $q_i = -0.0662$, $q_s = -0.1807$, $\phi = 0.3745$, $\tau = 0.1568$ and $\sigma_{tot} = 0.7289$[44].

- Use NEHRP site classes. Most are NEHRP B (rock).
- Classify events into two types:

Interface 374 records from 48 earthquakes

Intraslab 720 records from 90 earthquakes

[44] There appears to be something wrong with $\phi$ and $\tau$ since $\sigma_{tot}$ does not equal $\sqrt{\phi^2 + \tau^2}$

based on geometry and stress regime in subduction zone. Finally classify events manually based on depth, distance to trench, style-of-faulting and dip angle. Plot vertical cross sections to visualize downgoing Nazca plate and to display positions of studied events w.r.t. slab. Hence remove crustal and spurious events. Remove those that cannot be clearly classified.

- Functional form based on Zhao et al. (2006) but simplified because of characteristics of available database and difficulty in obtaining stable coefficients.
- Data mainly from 20 stations in a dense network deployed as part of Integrated Plate Boundary Observatory Chile (IPOC) supplemented with data from 8 triggered stations in area and 47 records (11 earthquakes) from 40 stations in other networks to extend model to higher magnitudes.
- For data from IPOC use a semi-automatic tool to extract records from continuous data streams for earthquakes with $M_w \geq 5$.
- IPOC data from 2006 to May 2012 and other data from 1966 to 2007.
- Generally prefer locations from local agency (Chilean Seismological Service) over those from teleseismic records.
- Only use those earthquakes with focal mechanisms from Global CMT so that all required information available. Only use those earthquakes with $M_w > 5$ since because majority of models calibrated for large events.
- Use empirical relations between rupture length, width and $M_w$ to estimate location of rupture plane and hence compute $r_{rup}$. For those events where fault plane is ambiguous use distance-conversion equations.
- Do not correct for instrument response because not required up to 100 Hz. Apply zeroth-order baseline correction. Subtract mean of pre-event portion of record. Integrate some of the records to check for long-period drifts that would indicate changes in reference baseline. Generally baseline offsets small so band/high-pass filter using acausal 4th-order Butterworth after zero padding. Choose cut-off frequencies based on smoothed Fourier amplitude spectra and signal-to-noise ratios of 2, with a default of 0.05 Hz if signal-to-noise is always higher than 2. Reject those records with signal-to-noise ratio barely larger than 3 over whole frequency range. Randomly check velocity and displacement traces. Use same filter cut-offs for all components with cut-offs chosen based on horizontal components.
- Most data from $M_w < 6.5$. Data well-distributed w.r.t. $r_{rup}$.
- Plot residuals w.r.t. $M_w$ and $r_{rup}$ and find no trends.

## 2.397 Jaimes et al. (2015)

- Ground-motion model is:

$$\ln Y = \alpha_1 + \alpha_2 M_w + \alpha_3 \ln R + \alpha_4 R$$

  where $Y$ is in cm/s$^2$; $\alpha_1 = -1.7918$, $\alpha_2 = 1.61$, $\alpha_3 = -1.00$, $\alpha_4 = -0.0058$ and $\sigma = 0.60$ for CU; $\alpha_1 = 0.4089$, $\alpha_2 = 1.23$, $\alpha_3 = -1.00$, $\alpha_4 = -0.0016$ and $\sigma = 0.55$ for SCT; $\alpha_1 = 0.4656$, $\alpha_2 = 1.22$, $\alpha_3 = -1.00$, $\alpha_4 = -0.0012$ and $\sigma = 0.58$ for CDAO.
- Use data from 3 stations in hill (Ciudad Universitaria, CU, 22 records) and lake-bed (Secretaría de Comunicaciones y Transportes, SCT, 15 records, and Central de Abastos, CDAO, 13 records) zones of Mexico City.
- Focal depths $40.0 \leq H \leq 128.4$ km.

- Data quite well distributed w.r.t. $M_w$.
- Most data from $r_{rup} < 300$ km.
- Use Bayesian linear regression (Ordaz et al., 1994) because of limited data. Prior probability distributions of coefficients are obtained from empirical model of source spectrum with 2 corner frequencies, frequency-dependent attenuation parameters for the region, duration estimates and random vibration theory. For the lake-bed stations use this information plus the 1D analytical transfer function using soil profiles.
- Compare final coefficients to prior estimates.
- Examine residuals w.r.t. $M_w$ and $r_{rup}$ and find no clear trends.
- Try including $H$ in model but insufficient data to constrain coefficient.
- Compare predicted and observed spectra for all data. Find good match except for a few poorly-recorded events.

## 2.398 Kale et al. (2015)

- Ground-motion model is (based on Akkar and Çağnan (2010) and the site terms are from Sandikkaya et al. (2013) with smoothed coefficients):

$$
\begin{aligned}
\ln \bar{Y} &= f_{mag} + f_{dis} + f_{sof} + f_{aat} + f_{site} \\
f_{mag} &= \begin{cases} (b_1 + \Delta b_1) + (b_2 + \Delta b_2)[M_w - (c_1 + \Delta c_1)] + (b_3 + \Delta b_3)(8.5 - M_w)^2 & M_w \leq c_1 + \Delta c_1 \\ (b_1 + \Delta b_1) + (b_7 + \Delta b_7)[M_w - (c_1 + \Delta c_1)] + (b_3 + \Delta b_3)(8.5 - M_w)^2 & M_w > c_1 + \Delta c_1 \end{cases} \\
f_{dis} &= \{[b_4 + \Delta b_4] + [b_5 + \Delta b_5][M_w - (c_1 + \Delta c_1)]\} \ln \sqrt{R_{JB}^2 + (b_6 + \Delta b_6)^2} \\
f_{sof} &= (b_8 + \Delta b_8) F_{NM} + (b_9 + \Delta b_9) F_{RV} \\
f_{aat} &= \begin{cases} 0 & R_{JB} \leq 80\,\text{km} \\ (b_{10} + \Delta b_{10})(R_{JB} - 80) & R_{JB} > 80\,\text{km} \end{cases} \\
f_{site} &= \begin{cases} sb_1 \ln\left(\frac{V_{s,30}}{V_{REF}}\right) + sb_2 \ln\left[\frac{\text{PGA}_{REF} + c(V_{s,30}/V_{REF})^n}{(\text{PGA}_{REF} + c)(V_{s,30}/V_{REF})^n}\right] & V_{s,30} < V_{REF} \\ sb_1 \ln\left[\frac{\min(V_{s,30}, V_{CON})}{V_{REF}}\right] & V_{s,30} \geq V_{REF} \end{cases}
\end{aligned}
$$

where $\bar{Y}$ in in g, $c_1 = 6.75$, $\Delta c_1 = 0.25$, $b_1 = 1.74221$, $\Delta b_1 = -0.21234$, $b_2 = 0.193$, $\Delta b_2 = -0.146$, $b_3 = -0.07049$, $\Delta b_3 = -0.03826$, $b_4 = -1.18164$, $\Delta b_4 = 0.17210$, $b_5 = 0.170$, $\Delta b_5 = -0.120$, $b_6 = 8.00$, $\Delta b_6 = 0.00$, $b_7 = -0.354$, $\Delta b_7 = 0.396$, $b_8 = -0.01329$, $\Delta b_8 = -0.11697$, $b_9 = -0.09158$, $\Delta b_9 = 0.0$, $b_{10} = -0.00156$, $\Delta b_{10} = 0.00156$, $V_{REF} = 750$ m/s, $c = 2.5$, $n = 3.2$, $V_{CON} = 1000$ m/s, $sb_1 = -0.41997$ and $sb_2 = -0.28846$.

Model for $\sigma$ is:

$$
\begin{aligned}
\sigma &= \sqrt{\tau^2 + \phi^2} \\
\phi &= w \times sd_1 \\
\tau &= w \times sd_2 \\
w &= \begin{cases} (a_1 + \Delta a_1) & M_w < 6.0 \\ (a_1 + \Delta a_1) + [(a_2 + \Delta a_2) - (a_1 + \Delta a_1)]\left(\frac{M_w - 6}{0.5}\right) & 6.0 \leq M_w < 6.5 \\ (a_2 + \Delta a_2) & M_w \geq 6.5 \end{cases}
\end{aligned}
$$

where $a_1 = 0.570$, $\Delta a_1 = 0.120$, $a_2 = 0.450$, $\Delta a_2 = 0.050$, $sd_1 = 1.0521$, $\Delta sd_1 = -0.0808$, $sd_2 = 0.7203$ and $\Delta sd_2 = -0.3250$.

- Use $V_{s,30}$ to characterise sites. Only used data with $150 \leq V_{s,30} \leq 1200$ m/s to be consistent with site terms of Sandikkaya et al. (2013). Turkish sites are mainly NEHRP class C and D (180–760 m/s) and Iranian sites are mainly NEHRP class B and C (360–1500 m).
- Use 3 styles of faulting:

  RV Reverse. $F_{RV} = 1$ and $F_{NM} = 0$.

  SS Strike-slip. Best represented for both countries. $F_{RV} = F_{NM} = 0$.

  NM Normal. Few records from Iran. $F_{NM} = 1$ and $F_{RV} = 0$.
- Focal depths $\leq 33$ m to exclude subcrustal events. Iranian events slightly deeper on average.
- Use data from the database compiled for the Earthquake Model of the Middle East Region (EMME). Select data with highest waveform and metadata quality. 670 records, 175 earthquakes and 163 stations from Turkey and 528 records, 138 earthquakes and 254 stations from Iran.
- Use approach of Akkar and Bommer (2006) to process data and choose maximum spectral period.
- Estimate $r_{jb}$ either from reported fault geometries or by using fault extent estimates from equations of Wells and Coppersmith (1994).
- Exclude earthquakes without true $M_w$ estimates.
- Vast majority of data from $M_w \leq 6.5$ and from $r_{jb} > 30$ km. Distribution of data from Turkey is more uniform than data from Iran, which has few records from $M_w < 5$ and $r_{jb} > 80$ km.
- Retain singly-recorded earthquakes (62 from Turkey and 50 from Iran).
- Before regression plot PGA scaled to reference rock and binned into distance bins for data from $5 \leq M_w \leq 6$ and $6 \leq M_w \leq 7$ against $r_{jb}$ for the two countries. Find evidence for differences.
- Use relatively simple functional form because of available metadata.
- Terms with $\Delta$ are to evaluate model for Iran.
- Use pure-error analysis (Draper and Smith, 1981; Douglas and Smit, 2001; Ambraseys et al., 2005a) to derive weighting function ($w$) for regression by dividing data into $0.5M_w$ bins and fitting model within each bin to find standard deviations. From these standard deviations $w$ was found. Some bins give large standard deviations, which are ignored when finding $w$.
- Coefficients $b_2$, $b_3$, $b_5$, $b_6$, $b_7$, $b_8$ and $b_9$ are obtained from data with $r_{jb} \leq 80$ km. $b_4$ is obtained from all data. $b_{10}$ is obtained using only data with $r_{jb} \geq 80$ km. $b_1$ is found in final step of regression considering all data. Smooth coefficients after each step to remove jagged variation in estimated response spectra.
- Use inter- and intra-event residual plots to explore potential differences between Turkish and Iranian ground motions.
- Find that inter-event residuals from Turkey show more dispersion than those from Iran, which does not disappear if only the best-recorded events are considered. Suggest that this is related to the complex nature of some Turkish events.
- Find differences in ground motions between Turkey and Iran, which relate to differences in $Q$, $\kappa$, near-surface $V_s$ profiles and focal depth.
- Re-run regressions using only data from $M_w > 5$ to check if differences in data distribution between Turkey and Iran are affecting the results. Find that the new model predicts similar motions. Conclude that findings are not being strongly affected by the differences in data distribution.

## 2.399 Kuehn and Scherbaum (2015)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= a_0 + a_1 M_w + a_2 M_w^2 + (a_3 + a_4 M_w) \ln \sqrt{R_{JB}^2 + a_5^2} \\ &+ a_6 \ln \frac{V_{s,30}}{760} + a_7 S_N + a_8 S_R\end{aligned}$$

  where $Y$ is in $\mathrm{m/s^2}$, $a_0 = -2.154894158$, $a_1 = 2.015257331$, $a_2 = -0.160029327$, $a_3 = -2.819451336$, $a_4 = 0.227083419$, $a_5 = 12.11797779$, $a_6 = -0.448080444$, $a_7 = -0.141680182$, $a_8 = 0.128978526$, $\tau = 0.37718$ (inter-event), $\phi_{S2S} = 0.40838$ (inter-station) and $\phi = 0.49836$ (within-event). Here the mean of the posterior distributions are reported.

- Use $V_{s,30}$ to characterise sites.

- Use 3 mechanisms:

Normal $S_N = 1$ and $S_R = 0$.

Reverse $S_R = 1$ and $S_N = 0$.

Strike-slip $S_N = S_R = 0$.

- Use same subset of RESORCE (Akkar et al., 2014d) as Hermkes et al. (2014).

- Use Bayesian inference via Markov Chain Monte Carlo sampling that jointly estimates coefficients and correlations between periods and also outputs various components of $\sigma$. Use broad normal distributions as priors for the coefficients so that they are fairly unconstrained. For covariance matrices use inverse-Wishart distributions as priors to ensure they are positive definite. Check convergence of chains using the potential scale reduction factor.

- Data from 251 stations.

- Formulate model as a multi-level model with levels for earthquake, station and record, which allows simultaneous estimation of coefficients and correlations for all parameters.

- Choose functional form because relatively simple but it is still able to capture general characteristics of ground-motion scaling.

- Provide full covariance matrices.

- Examine residuals w.r.t. $M_w$, $r_{jb}$ and $V_{s,30}$ and find no clear trends.

- Present predictions from model by sampling from the posterior distributions of the coefficients, demonstrating the epistemic uncertainty in the median predictions.

## 2.400 Pacific Earthquake Engineering Research Center (2015) — Al Noman and Cramer

- Ground-motion model is:

$$\begin{aligned}\log Y &= f(R) + f(M) \\ f(R) &= (c_1 + c_2 M) \log R + c_3(R-1) + d_1 \log(V_{s,30}/760) \\ f(M) &= a_1 \mathrm{U} + a_2 \mathrm{RR} + a_3 \mathrm{SS} + b_1 M + b_2 M^2 \\ R^2 &= R_{RUP}^2 + h^2\end{aligned}$$

where $Y$ is in g, $a_1 = -0.3299$, $a_2 = -0.3114$, $a_3 = -0.3320$, $b_1 = 0.3498$, $b_2 = -0.0294$, $c_1 = -2.7994$, $c_2 = 0.2734$, $c_3 = -0.0005$, $d_1 = -0.3827$, $\phi = 0.37$ (intra-event), $\tau_u = 0.21$ (inter-event unspecified mechanism), $\tau_S = 0.21$ (inter-event specified mechanism), $\sigma_u = 0.43$ (total unspecified mechanism) and $\sigma_S = 0.43$ (total specified mechanism). Fix $h = 10$ km because insufficient data.

- Use $V_{s,30}$ to characterise sites. Most sites have only estimated $V_{s,30}$.
- Class earthquakes into 3 mechanisms:

Reverse RR = 1, U = SS = 0.

Strike-slip Includes 1 normal earthquake. SS = 1, U = RR = 0.

Unspecified Earthquakes that did not have a reported mechanism. U = 1, RR = SS = 0.

- Use data from: NGA-East flatfile, 1976 $M_w$6.8 Gazli, 1985 $M_w$6.9 Nahanni, 2001 $M_w$7.6 Bhuj and macroseismic intensities converted into ground motions from 1811-1812 $M_w$7.5, 7.3 and 7.7 New Madrid, 1886 $M_w$7.0 Charleston, 1925 $M_w$6.2 Charlevoix and 1929 $M_w$7.2 Grand Banks earthquakes ($M_w > 6$). Exclude data from higher attenuating areas of the Gulf Coast and western North America, i.e. west of 100W or south of 35N.
- Use only a single term for geometric spreading due to limited data at $< 50$ km.
- 13 records from Bhuj event only for PGA and 0.4, 0.75, 1.0 and 1.25 s.
- Vast majority of data from $M_w < 6$ and $r_{epi} > 50$ km.
- Compare predictions at $M_w$5.9 and observations for three events with magnitudes close to $M_w$5.9. Also compare predictinos and observations at $M_w$7.6. Repeat regressions without the intensity-derived data. Find small effect for $M_w$5.9 because large number of records for smaller magnitudes but a large impact at $M_w$7.6.

## 2.401 Pacific Earthquake Engineering Research Center (2015) — Graizer & Graizer (2016)

- Ground-motion model, based on Graizer and Kalkan (2015) (see Section 2.395), is:

$$\begin{aligned}
\ln(Y) &= \ln G_1 + \ln G_2 + \ln G_3 + \ln G_4 + \ln G_5 \\
\ln G_1 &= \ln\{[c_1 \arctan(M + c_2) + c_3]F\} \\
\ln G_2 &= -0.5 \ln[(1 - r_2)^2 + 4D_2^2 r_2] \\
r_2 &= R/R_2 \\
R_2 &= c_4 M + c_5 \\
D_2 &= 0.7 \\
\ln G_3 &= -\frac{c_{11} + c_{12} M}{Q_0} R \\
\ln G_4 &= 0 \\
\ln G_5 &= 0
\end{aligned}$$

where $c_1 = 0.40$, $c_2 = -6.25$, $c_3 = 0.55$, $c_4 = 2.237$, $c_5 = -7.542$, $c_{11} = 3.9$, $c_{12} = -0.3445$, $F = 2.232$ and $\sigma = 0.53$.

- Uses $V_{s,30}$ to characterise sites. States that model applies for $450 \leq V_{s,30} \leq 2800$ m/s.

- Uses data from NGA-East database (both mid-continent and Gulf Coast regions). Also includes 6 records from 12/11/2014 $M_w$4.8 Kansas earthquake.

- Notes that insufficient data, especially for $M_w > 6$ and close source-to-site distances, in NGA-East database to derive purely empirical model.

- Includes the regional quality factor for 1 Hz, $Q_0$, to model anelastic attenuation (notes that $Q_0$ for central and eastern USA is between 650 and 1000).

- Adjusts coefficients from the western USA model (Graizer and Kalkan, 2015) by: a) ratios between observations in NGA-East and NGA-West databases for $3.75 < M_w < 6$, b) average stress-drop ratio between western and central and eastern USA and c) by checking predictions w.r.t. recent ground-motion simulations for central and eastern USA for $M_w > 5$.

- Presents equations (Equation 9.6) for adjusting model to other $V_{s,30}$ through the terms $G_4$ but it is not clear how they are used as in the presentation of the model (Figure 9.2) $\ln G_4$ is set to zero. Similarly 4 additional coefficients ($c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.13$ and $c_9 = 0.60$) are listed in Figure 9.2 but they are not included within the presented model.

- Compares predictions and observations binned into magnitude ranges against $r_{rup}$.

- Presents functions to correct for trends w.r.t. $r_{rup}$ in residuals. For PGA correction is: $\text{PGA}_{cor} = \text{PGA}/\text{Residual}$ where $\text{Residual} = \exp(-0.000257 r_{rup} + 0.270)$.

## 2.402 Vacareanu et al. (2015b)

- Ground-motion model is:

$$\begin{aligned}\ln y &= c_1 + c_2(M_w - 6) + c_3(M_w - 6)^2 + c_4 \ln R + c_5(1 - \text{ARC})R + c_6\text{ARC}R \\ &\quad + c_7 h + c_8 S_b + c_9 S_c + c_{10} S_s\end{aligned}$$

  where $y$ is in cm/s$^2$, $c_1 = 9.6231$, $c_2 = 1.4232$, $c_3 = -0.1555$, $c_4 = -1.1316$, $c_5 = -0.0114$, $c_6 = -0.0024$, $c_7 = -0.0007$, $c_8 = -0.0835$, $c_9 = 0.1589$, $c_{10} = 0.0488$, $\tau = 0.406$ (inter-event), $\sigma = 0.568$ (intra-event) and $\sigma_T = 0.698$ (total).

- Use 3 site classes (2 are based on Eurocode 8):

  B $360 < V_{s,30} \leq 800$ m/s. Includes a few class A ($V_{s,30} > 800$ m/s) sites, which are included here because of scarcity of data. $S_b = 1$ and $S_c = S_s = 0$.

  C $180 < V_{s,30} \leq 360$ m/s. $S_c = 1$ and $S_b = S_s = 0$.

  Soil Sites that could not be assigned into B or C. Generally stations in Mexico, India and Martinique. $S_s = 1$ and $S_b = S_c = 0$. B, C and soil sites are grouped within regression to find $c_{10}$.

- Classify records into 2 classes on location w.r.t. arc:

Fore-arc ARC = 1.

Back-arc ARC = 0.

  For Romania this is based on location w.r.t. Carpathian Mountains.

- Focal depths, $h$, between 87 and 151 km for Vrancea events and 60 and 173 km for others.

- Investigate the impact of the fore-arc and back-arc regions on ground motions, in particular w.r.t. the Vrancea intermediate-depth source. Aim to improve model of Vacareanu et al. (2014) (see Section 2.390).

- Use data from NIEP, INCERC, CNRRS and GEOTEC analogue and digital networks. Use some already-processed records so processing procedures are not uniform. Filter raw analogue records using Ormsby bandpass filter with cut-offs 0.15–0.25 and 25–28 Hz. Filter raw digital records using 4th-order Butterworth bandpass with cut-offs 0.05 and 50 Hz.

- Include data from foreign intermediate-depth in-slab earthquakes in Japan (fore-arc data with $r_{epi} \leq 80$ km to limit number of records), New Zealand, Mexico, Chile, India, Martinique (France) and Peru to fill in gap in magnitude-depth-distance distribution.

- Fore-arc data from 8 countries. Back-arc data from only Romania and Japan.

- Limited Romanian data for $r_{epi} \leq 80$ km and larger number for $100 \leq r_{epi} \leq 200$ km.

- Try fixing $c_4$ to $-1$ but find that this is not valid at all periods.

- Find average misfits (offset) (using total residuals) for entire set is around 5%, with peaks of 10%, and for Vrancea records only it is around 10%, with peaks of 18%.

- Derive model without site terms but based on analysis of variance and the $F$ test on intra-event residuals w.r.t. site classes find that site effects are significant at the 5% level for all periods except 0.1 s.

- Examine inter- and intra-event residuals and the average misfits. Find that ground motions from Vrancea and foreign events are similar and justifies inclusion of foreign data.

- Find that by examining inter-event residuals w.r.t. $M_w$ that obtained magnitude scaling is appropriate and that there is no difference between Vrancea and foreign data.

- Examine inter-event residuals w.r.t. number of records per event. Find weak correlations (correlation coefficient in range 0.1 to 0.2) and hence conclude that no undue influence from well-recorded events.

- Examine intra-event residuals classified by site category w.r.t. $r_{epi}$. Find no trends in residuals and hence conclude that distance scaling is appropriate, at least for B, C and average soil classes (there are insufficient records from Eurocode 8 A and D classes to conclude).

- Examine intra-event residuals grouped into back-arc and fore-arc classes w.r.t. $r_{epi}$. Find no clear trends.

- Compare observed (corrected to soil class) and predicted motions for the $M_w$6 27/10/2004 Vrancea earthquake. Find good match for both fore-arc and back-arc.

- Do not advise using model for soil classes A or D because of lack of data from these categories and hence model is not calibrated for these classes.

## 2.403 Vuorinen et al. (2015)

- Ground-motion model is unknown.

- Data from 88 stations.

- Find residuals show no clear trends w.r.t. $M$ or $R$.

- Check predictions against data that was not used for derivation.

## 2.404 Wan Ahmad et al. (2015)

- Ground-motion model is[45]:

$$\ln Y = a_1 + a_2 M_w + a_3 M_w^{a_4} + a_5 \ln[R + a_6 \mathrm{e}^{a_7}(a_8 M_w)] + a_9 H$$

  where $Y$ is in gal, $a_1 = -115.88$, $a_2 = -5.07$, $a_3 = 101.42$, $a_4 = 0.20$, $a_5 = -1.42$, $a_6 = 17.77$, $a_7 = -1$, $a_8 = -20.09$ and $a_9 = -0.12$ ($\sigma$ is not given).

- Use data from stations operated by Malaysian Meteorological Department from between 2004 and 2012.

- More than 200 records available. Exclude poor quality records, those from distances outside targeted range and those from earthquakes with non-strike-slip mechanisms.

- Focal depths, $H$, between 0 and 22 km.

- Earthquakes occurred along Sumatran, Peninsular Malaysia, Sabah and Sarawak faults.

- Records are all from great distances, although no information is given.

[45] Article is poorly written and hence it is not clear if this is the correct functional form.

## 2.405 Zhao et al. (2015)

- Ground-motion model is:

$$
\begin{aligned}
\log_e y &= f_{cr} + f_{um} + f_{int} + f_{SL} - \log_e r + g_{cr} + g_{um} r + g_{intS} + g_{intD} + g_{SL} \\
&\quad + g_L \log(x + 200.0) + e_{cr} x + e_{um} x + e_{intS} x + e_{intD} x + e_{SL} x + q_{SLh} x \\
&\quad + e^v_{cr} + x^v + e^v_{int} x^v + e^v_{SL} x + S_k + S_{kNL} \\
q_{SLh} &= e_{SLh} \begin{cases} 0 & h < 50\,\text{km} \\ 0.02h - 1.0 & h \geq 50\,\text{km} \end{cases} \\
r &= x + \exp(c_1 + c_2 C_m) \\
C_m &= \begin{cases} m & m \leq C_{max} \\ C_{max} & m > C_{max} \end{cases} \\
g_{intS} &= \frac{h_m - h}{h_m - hcrc} \begin{cases} a_5 \ln r & x \leq x_1 \\ a_5 \ln r_1 + a_6(\ln r - \ln r_1) & x_1 \leq x < x_2 \\ a_5 \ln r_1 + a_6(\ln r - \ln r_1) + a_7(\ln r - \ln r_2) & x_2 \leq x < x_3 \\ a_5 \ln r_1 + a_6(\ln r_2 - \ln r_1) + a_7(\ln r_3 - \ln r_2) + a_8(\ln r - \ln r_3) & x \geq x_3 \end{cases} \\
f_{cr} &= b_{cr} h + F_R + F_N + \begin{cases} c_{cr} m + c_{cr2} m^2 & m \leq m_c \\ c_{cr} m_c + c_{cr2} m_c^2 + d_{cr}(m - m_c) & m > m_c \end{cases} \\
g_{intD} &= \frac{h - h_1}{h_{intD} - h_1} \delta(h - h_1) \begin{cases} a_9 \ln r & x \leq x_9 \\ a_9 \ln r_9 + a_{10}(\ln r - \ln r_9) & x_9 \leq x < x_{10} \\ a_9 \ln r_9 + a_{10}(\ln r_{10} - \ln r_9) + a_{11}(\ln r - \ln r_{10}) & x \geq x_{10} \end{cases} \\
g_{cr} &= \frac{h_m - h}{h_m - hcrc} \begin{cases} a_1 \ln r & x \leq x_1 \\ a_1 \ln r_1 + a_2(\ln r - \ln r_1) & x_1 \leq x < x_2 \\ a_1 \ln r_1 + a_2(\ln r - \ln r_1) + a_3(\ln r - \ln r_2) & x_2 \leq x < x_3 \\ a_1 \ln r_1 + a_2(\ln r_2 - \ln r_1) + a_3(\ln r_3 - \ln r_2) + a_4(\ln r - \ln r_3) & x \geq x_3 \end{cases} \\
g_{SL} &= \frac{h - h_2}{h_{Slbc} - h_2} \delta(h - h_2) \begin{cases} a_{12} \ln r & x \leq x_{12} \\ a_{12} \ln r_{12} + a_{13}(\ln r - \ln r_{12}) & x_{12} \leq x < x_{13} \\ a_{12} \ln r_{12} + a_{13}(\ln r_{13} - \ln r_{12}) + a_{14}(\ln r - \ln r_{14}) & x \geq x_{13} \end{cases} \\
r_n &= x_n + \exp(c_1 + c_2 C_m) \\
\delta(h - h_2) &= \begin{cases} 1 & h \geq h_2 \\ 0 & h < h_2 \end{cases}
\end{aligned}
$$

All other $f$s are the same as $f_{cr}$ but without $F_R$ and $F_N$. $h$ is depth to top of rupture for events with rupture geometry model and focal depth otherwise. $x^v$ is horizontal distance of path through volcanic zones (straight line). $S_{kNL}$ is previously-published nonlinear site response term. $g_{um}$ is geometric attenuation rate for upper-mantle events. $g_L$ is geometric attenuation rate for distances $>$ 40 km. $cr$ is for crustal events, $um$ is for upper-mantle events, $intS$ is for shallow subduction interface events, $intD$ is for deep suduction events with depth $h > 25$ km and $SL$ is for subuction slab events. $C_{max} = 7.1$ as determined by goodness-of-fit parameter. $h_1 = 25$ km and $h_{intD} = 50$ km.

- Use site classes of Zhao et al. (2006).

- Use three faulting mechanisms using definitions of Boore and Atkinson (2008):

    1. Reverse. Plunge of T axis $> 40°$. Use $F_R$.
    2. Normal. Plunge of P axis $> 40°$. Use $F_N$.
    3. Strike-slip. Other plunge angles.

- Develop functional form because of previous observations on effect of mantle wedge etc. on attenuation rate.

- Purpose of model is to classify earthquakes into types rather than for ground-motion prediction. Hence coefficients not reported.

- Use Slab1.0 subduction interface geometry model (Hayes et al., 2012) for classification schemes.

- Use some data from Alaska, California, Turkey and Iran, Taiwan and Wenchuan (China) to supplement Japanese data for large crustal earthquakes and near-source distances.

- 31 Japanese earthquakes from before 1996 have $M_w \geq 6.5$.

- Use maximum log-likelihood as goodness-of-fit measure because $\sigma$ not very sensitive to the selection of model parameters when they are close to the best solutions using a random effects model and maximum log-likelihood sensitive to biased residual distribution and it is important to eliminate any bias in residuals because models often extrapolated. Use Akaike information criterion to check if model parameter should be retained.

- Try 4 classification schemes and various combinations of earthquake catalogues. Find using locations from the International Seismological Centre (ISC)/Engdahl et al. (1998) (EHB) for events before 2005 then using locations of 1) Japan Meteological Agency (only those with high precision level), 2) ISC/EHB and 3) National Earthquake Information Center (excluding events with a fixed depth) for more recent events produced best models in terms of maximum log-likelihoods. The best event classification is the following. Classify reverse events, depth within 5 km of interface, depth < 50 km and dip angle for one of nodal planes within 15° from interface dip angle as interface earthquakes. Classify events above the interface that are not classified as interface and have depth ≤ 25 km as shallow crustal earthquakes. Classify events above subduction interface but are not shallow crustal earthquakes are upper-mantle events. Classify all other earthquakes as subduction slab earthquakes. Note that this leads to highest maximum log-likelihood but little reduction in $\sigma$. Also note that this classification does not guarantee correct classification and that misclassification of a small number of events would not affect the goodness-of-fit parameters.

## 2.406 Abrahamson et al. (2016) & BC Hydro (2012)

- Ground-motion model is:

$$
\begin{aligned}
\text{For interface} \quad \ln \mathrm{Sa} &= \theta_1 + \theta_4 \Delta C_1 + [\theta_2 + \theta_3 (M - 7.8)] \ln\{R_{rup} + C_4 \exp[\theta_9 (M-6)]\} \\
&\quad + \theta_6 R_{rup} + f_{mag} + f_{FABA} + f_{site} \\
\text{For intraslab} \quad \ln \mathrm{Sa} &= \theta_1 + \theta_4 \Delta C_1 + [\theta_2 + \theta_{14} F_{event} + \theta_3 (M - 7.8)] \ln\{R_{hypo} + C_4 \exp[\theta_9 (M-6)]\} \\
&\quad + \theta_6 R_{hypo} + \theta_{10} F_{event} + f_{mag} + f_{depth} + f_{FABA} + f_{site} \\
f_{mag} &= \begin{cases} \theta_4 [M - (C_1 + \Delta C_1)] + \theta_{13} (10 - M)^2 & \text{For } M \leq C_1 + \Delta C_1 \\ \theta_5 [M - (C_1 + \Delta C_1)] + \theta_{13} (10 - M)^2 & \text{For } M > C_1 + \Delta C_1 \end{cases} \\
f_{depth} &= \theta_{11} [\min(Z_h, 120) - 60] F_{event} \\
f_{FABA} &= \begin{cases} \left\{\theta_7 + \theta_8 \ln\left[\frac{\max(R_{hypo}, 85)}{40}\right]\right\} F_{FABA} & \text{For intraslab} \\ \left\{\theta_{15} + \theta_{16} \ln\left[\frac{\max(R_{rup}, 100)}{40}\right]\right\} F_{FABA} & \text{For interface} \end{cases} \\
f_{site} &= \begin{cases} \theta_{12} \ln\left(\frac{V_s^*}{V_{lin}}\right) - b \ln(\mathrm{PGA}_{1000} + c) + b \ln\left[\mathrm{PGA}_{1000} + c \left(\frac{V_s^*}{V_{lin}}\right)^n\right] & \text{For } V_{S30} < V_{lin} \\ \theta_{12} \ln\left(\frac{V_s^*}{V_{lin}}\right) + bn \ln\left(\frac{V_s^*}{V_{lin}}\right) & \text{For } V_{S30} \geq V_{lin} \end{cases} \\
V_s^* &= \begin{cases} 1000 & \text{For } V_{S30} > 1000 \\ V_{S30} & \text{For } V_{S30} \leq 1000 \end{cases}
\end{aligned}
$$

where Sa is in g, $C_1 = 7.8$, $n = 1.18$, $c = 1.88$, $C_4 = 10$, $V_{lin} = 865.1$, $b = -1.186$, $\theta_1 = 4.2203$, $\theta_2 = -1.350$, $\theta_3 = 0.1$, $\theta_4 = 0.9$, $\theta_5 = 0.0$, $\theta_6 = -0.0012$, $\theta_7 = 1.0988$, $\theta_8 = -1.42$, $\theta_9 = 0.4$, $\theta_{10} = 3.12$, $\theta_{11} = 0.0130$, $\theta_{12} = 0.980$, $\theta_{13} = -0.0135$, $\theta_{14} = -0.40$, $\theta_{15} = 0.9996$, $\theta_{16} = -1.00$; for interface events: $\Delta C_1$(central value) $= 0.2$, $\Delta C_1$(lower value) $= 0.$, $\Delta C_1$(upper value) $= 0.4$; for intraslab events: $\Delta C_1$(central value) $= -0.3$, $\Delta C_1$(lower value) $= -0.5.$, $\Delta C_1$(upper value) $= -0.1$; $\mathrm{PGA}_{1000}$ is median PGA for $V_{s,30} = 1000\,\mathrm{m/s}$, $\phi = 0.60$ (intra-event), $\tau = 0.43$ (inter-event) and $\sigma = 0.74$ (total).

- Characterise sites by $V_{s,30}$. Most $V_{s,30}$ from correlations between site class and $V_{s,30}$ and not measured. Because of insufficient data and because believe should be similar to crustal site amplification adopt slightly modified Walling et al. (2008) site model.

- Classify events into 2 categories:

$F_{event} = 0$ Interface

$F_{event} = 1$ Intraslab

- Classify sites into 2 locations:

$F_{FABA} = 0$ Forearc or unknown sites

$F_{FABA} = 1$ Backarc sites

- Use data from Atkinson and Boore (2003) combined with additional data from Japan, Taiwan, South and Central America, including Mexico. Collect 3557 horizontal pairs of components from 163 interface events and 6389 horizontal pairs from 129 intraslab events. Some older records are not available so only PGA and PSA at 0.1, 0.2, 0.4, 1.0, 2.0 and 3.0 s are used. Use record for frequencies above 1.2 times the high-pass corner frequency. Some recent Taiwanese data available in terms of GMRotI50, which assume equivalent to geometric mean.

- Check available classification of earthquakes into interface/intraslab and find some problems. Correct problematic classifications using available information (often from International Seismological Centre). Use Global CMT for $M_w$ unless not available when use regional CMT. Prefer pP depths if available. Changed classification of 9 intraslab events to interface.

- Classify stations in Japan, Cascadia and Taiwan into forearc (between subduction trench axis and axis of volcanic fronts) and backarc location. Almost all backarc data from Japan and so differences in backarc attenuation may be regional rather than global backarc differences.

- Note that definition of distances for some records (particularly older ones) is not clear. Adopt distances without re-evaluation. Note that mixture of $r_{rup}$ and $r_{hypo}$ is used, which could be significant for shallow large interface events.

- Remove questionable data (e.g. clear outliers by a factor of 100 or more and 1992 $M_w$7 Cape Mendocino event that could be crustal). To focus on large interface and moderate to large intraslab events: exclude data from interface events with $M_w < 6$ and intraslab with $M_w < 5$.

- To avoid upward bias in data at large distances due to triggering apply magnitude-dependent distance limits based on PGA.

- Find that $M$-scaling for 5–7 for intraslab is similar to scaling for 6–8 for interface with constant offset. Hence use common scaling. Use numerical simulations for Cascadia to constrain scaling for $M_w > 8$, where little data. Bin PGAs in 0.5-unit bins and correct to rock site and 100 km and compare to scaling from simulations. Find break in scaling at $M_w$7.8. Find cannot simultaneously find geometric spreading and saturation from data and hence fix depth term to 10 km. Note that another value could be chosen and the other coefficients would adjust.

- Initially did not use focal depth $Z_h$ in model. Inter-event residuals showed strong trend with $Z_h$ for intraslab but not for interface. Include $Z_h$ term in intraslab model with maximum depth limit of 120 km.
- Initially did not account for forearc/back arc but intra-event residuals showed trend with distance for backarc sites. Hence include additional attenuation term.
- Find coefficients in steps, smoothing coefficients 1 or 2 at a time and re-computing the others. Only use events with $\leq 5$ records before final regression to avoid poorly-recorded earthquakes strongly impacting results. First find coefficients $\theta_3$, $\theta_4$ and $\theta_5$ for PGA and constrain them to these values for other periods. Run test using different minimum number of records per event. Find results insensitive to inclusion of poorly-recorded earthquakes.
- Examine inter- and intra-event residuals. Find limited evidence for regional dependency in inter-event residuals except for poorly-sampled regions and Cascadia (5 intraslab events). Find no trends in intra-event residuals w.r.t. $r$. Find no trends w.r.t. $V_{s,30}$.
- Use data from 2010 $M_w$8.8 Maule, Chile, and 2011 $M_w$9.0 Tohoku, Japan, earthquakes, which occurred after data collection, to check model using residual analysis. For PGA find Tohoku data shows much stronger forearc attenuation than model predicts. Believe that this is a regional effect for Japan and hence do not modify model. Find evidence for bias in the model for large interface events and hence introduce $\Delta C_1$ term that includes epistemic uncertainty. Note that break in intraslab $M$-scaling is not well constrained but propose $\Delta C_1$ term and its uncertainty based on available data and previous models.
- Provide estimates of epistemic uncertainty from region-specific event terms that can be used to define logic tree branches.

## 2.407 Bozorgnia and Campbell (2016b)

- Ground-motion model is the same as for the associated horizontal model Campbell and Bozorgnia (2014) (see Section 2.368) with the following coefficients: $h_4 = 1$, $c_0 = -4.729$, $c_1 = 0.984$, $c_2 = 0.537$, $c_3 = -1.499$, $c_4 = -0.443$, $c_5 = -2.666$, $c_6 = 0.214$, $c_7 = 7.166$, $c_8 = 0$, $c_9 = -0.230$, $c_{10} = 0.759$, $c_{11} = -0.356$, $c_{12} = 1.019$, $c_{13} = 0.373$, $c_{14} = -0.117$, $c_{15} = -0.097$, $c_{17} = 0.1020$, $c_{18} = 0.0442$, $c_{19} = 0.00784$, $c_{20} = -0.0053$, $\Delta c_{20,JI} = -0.0018$, $\Delta c_{20,CH} = 0.0039$, $k_1 = 865$, $a_2 = 0.167$, $h_1 = 0.241$, $h_2 = 1.474$, $h_3 = -0.715$, $h_5 = -0.337$ and $h_6 = -0.270$, $c_{16} = 0.0$ (no deep basin effects), $k_2 = 0.0$ (no soil nonlinearity), $k_3 = 0.0$ (no deep basin effects) and $c$ and $n$ are not need because $k_2 = 0$.
- Ground-motion model is (for aleatory variability):

$$
\begin{aligned}
\tau_V &= \begin{cases} \tau_{1V} & M \leq 4.5 \\ \tau_{2V} + (\tau_{1V} - \tau_{2V})(5.5 - M) & 4.5 < M < 5.5 \\ \tau_{2V} & M \geq 5.5 \end{cases} \\
\phi_V &= \begin{cases} \phi_{1V} & M \leq 4.5 \\ \phi_{2V} + (\phi_{1V} + \phi_{2V})(5.5 - M) & 4.5 < M < 5.5 \\ \phi_{2V} & M \geq 5.5 \end{cases} \\
\sigma &= \sqrt{\tau_V^2 + \phi_V^2}
\end{aligned}
$$

  where $\tau_{1V} = 0.461$, $\tau_{2V} = 0.347$, $\phi_{1V} = 0.694$, $\phi_{2V} = 0.493$, $\sigma_V = 0.833$ for $M_w \leq 4.5$ and $\sigma_V = 0.603$ for $M_w \geq 5.5$.
- Characterise sites using $V_{s,30}$. Because vertical site response behaves linearly in most cases (even when horizontal response may be strongly nonlinear) do not model soil nonlinearity. Do not think that this affects the applicability of the model. Recommend model for $V_{s,30}$ between 150 and 1500 m/s (for higher $V_{s,30}$ recommend setting $V_{s,30}$ to 1500 m/s).

- Use 3 mechanisms:

  1. Reverse/reverse-oblique. Rake angle $30 < \lambda < 150°$. $F_{RV} = 1$, $F_{NM} = 0$.
  2. Normal/Normal-oblique. Rake angle $-150 < \lambda < -30°$. $F_{NM} = 1$, $F_{RV} = 0$.
  3. Strike-slip. Other rake angles. $F_{RV} = F_{NM} = 0$.

  Use 2 regions:

$$\begin{aligned} \text{Japan} \quad & S_J = 1 \\ \text{Elsewhere} \quad & S_J = 0 \end{aligned}$$

- Do not include deep basin terms in model because modelling is inconclusive and little evidence from data that basin effects are important for vertical motions.

- Recommend model for depth to top of rupture $Z_{TOR}$ between 0 and 20 km, hypocentral depths between 0 and 20 km and fault dips $\delta$ between 15 and 90°.

- Vertical-component NGA-West 2 model corresponding to horizontal model of Campbell and Bozorgnia (2014) (see Section 2.368 for details of data and approach used to develop model). Use similar database and functional form but aspects are different. Use same data selection criteria as Campbell and Bozorgnia (2014) but exclude: records without vertical components, those that triggered on horizontal motion or are of questionable quality. Exclude aftershocks (class 2 events) within immediate vicinity of inferred mainshock fault rupture plane.

- 6989 near-source ($r_{rup} \leq 80$ km) records from 282 events. Use these with 2-stage maximum-likelihood regression to derive near-source model. Use far-source database (80–500 km) to develop regionally-dependent anelastic attenuation terms. Apply limited smoothing to coefficients.

- From regression $f_{mag}$ predicted oversaturation for PGA and short-period PSA at large $M_w$ and short $r_{rup}$. Decide to constrain $f_{mag}$ to be constant at $M_w > 6.5$ and $r_{rup} = 0$ when regression indicates oversaturation. Find $c_1$, $c_2$ and $c_3$ were not significantly different to those from horizontal model and hence fix them to the horizontal coefficients in final regression.

- Plot inter- and intra-event residuals (individual and binned into small intervals) w.r.t. different variables. Find no significant biases or trends.

## 2.408 Kaveh et al. (2016)

- Ground-motion model is[46]:

$$\ln \mathrm{PGA} = \begin{cases} 0.014M_w - 0.5901 \ln R_{ClstD} + 6.6386 & R_{ClstD} \leq 39.5\,\mathrm{km} \\ 0.0138M_w - 1.1622 \ln R_{ClstD} - 0.001V_{s,30} + 8.4983 & R_{ClstD} > 39.5\,\mathrm{km}, M_w < 6.66 \\ 0.0222M_w - 1.0163 \ln R_{ClstD} + 8.3106 & R_{ClstD} > 39.5\,\mathrm{km}, M_w > 6.66 \end{cases}$$

  where PGA is in cm/s$^2$ and $\sigma = 0.6219$.

- Use $V_{s,30}$ to characterise sites. $V_{s,30}$ ranges from 100 to 2000 m/s. Most sites with $V_{s,30} \leq 500$ m/s.

- Consider 3 styles of faulting based on rake angle:

  1. Reverse. About 1700 records.

[46] Because the functional form and classes are decided by an automatic algorithm the coefficients have been included in the equations directly.

2. Normal. About 100 records.
3. Strike-slip. About 600 records.

But this effect is not included in final model.

- Use the Pacific Earthquake Engineering Research Center database.
- Use the M5' model tree approach, which is a soft computing method. M5' searches for best model using tree building, tree pruning and smoothing steps. Choose best model based on: simplest structure and minimum rules; models providing best predictions for training set; and minimum number of instances in each class or leaf should be larger than 100 (to avoid over-fitting). M5' only proposes linear equations, which note is a limitation.
- Randomly split 2815 records into part for training (2252 records) and part for testing (563 records).
- Most data from $M_w \leq 6.6$.
- Use mean absolute error, root mean square error, correlation coefficient and discrepancy ratio to evaluate model both using training and testing sets. Find good fits.
- Undertake sensitivity analysis by developing models leaving out each of the input parameters in turn. Find $r_{rup}$ is the most important parameter and then $M_w$.

## 2.409 Kotha et al. (2016a,b)

- Ground-motion model is [following Bindi et al. (2014a)]:

$$
\begin{aligned}
\ln Y &= e_1 + F_D + F_M + \delta B_s \\
F_D &= [c_1 + c_2(M - M_{ref})] \ln \frac{\sqrt{R^2 + h^2}}{R_{ref}} + (c_3 + \Delta c_{3,r})(\sqrt{R^2 + h^2} - R_{ref}) \\
F_M &= \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & M < M_h \\ b_3(M - M_h) & M \geq M_h \end{cases} \\
\delta B_s &= (g_1 + \Delta g_{1,r}) + (g_2 + \Delta g_{2,r}) \ln V_{s,30}
\end{aligned}
$$

  where $Y$ is in $\mathrm{m/s^2}$. $M_h = 6.75$, $M_{ref} = 5.5$ and $R_{ref} = 1$ km. $e_1 = 2.982$, $b_1 = -0.363$, $b_2 = -0.195$, $b_3 = -0.406$, $c_1 = -1.231$, $c_2 = 0.272$, $c_3 = -0.00395$, $h = 6.390$, $\Delta c_{3,Italy} = -0.00326 \pm 0.00079$, $\Delta c_{3,Others} = 0.00326 \pm 0.00076$, $\Delta_{3,Turkey} = 0.00000 \pm 0.00034$, $g_1 = 1.407$, $g_2 = -0.234$, $\Delta g_{1,Italy} = -0.360 \pm 0.258$, $\Delta g_{1,Others} = -0.678 \pm 0.212$, $\Delta g_{1,Turkey} = 1.038 \pm 0.314$, $\Delta g_{2,Italy} = 0.063 \pm 0.045$, $\Delta g_{2,Others} = 0.119 \pm 0.037$, $\Delta g_{2,Turkey} = -0.182 \pm 0.055$, $\tau = 0.350$ (inter-event), $\phi_0 = 0.451$ (intra-event), $\phi_{S2S} = 0.330$ (site-to-site) and $\sigma = 0.657$ (total).

- Use $V_{s,30}$ to characterise sites. Range is from 90 to 2000 m/s but bulk is from 200 to 600 m/s. Recommend model for $180 \leq V_{s,30} leq 1000$ m/s.
- Use data from RESORCE (Akkar et al., 2014d) (2013 version).
- Exclude poor quality, unprocessed records and those without 3 components. Also exclude singly-recorded earthquakes and those with $M_w$ from empirical conversion formulae. Select data with: $M_w \geq 4$, focal depth $< 35$ km, $R < 300$ km (exclude records with $M_w > 5$ and/or $R_{epi} < 10$ km without $r_{jb}$), and known or inferred $V_{s,30}$.

- Consider regional effects in Italy (378 records), Turkey (659 records) and rest of Europe and the Middle East [all those countries with fewer than 200 records, mainly: Greece (137), Montenegro (35), Iran (20) and France] (214 records) to partially mitigate the ergodic assumption. Note that could prefer a regionalisation based on tectonics but not possible given unbalanced composition of RESORCE.

- Display $M_w$-$R$ distribution w.r.t. region and Eurocode 8 site class. Very few records from Turkey in class A ($V_{s,30} > 800$ m/s), which means model for this range of $V_{s,30}$ controlled by data from elsewhere. Note model for $R > 100$ km and site classes B and C ($360 \leq V_{s,30} \leq 800$ m/s) could be mainly controlled by Turkish data.

- Median magnitude is $M_w 5.5$.

- Bulk of data within 150 km.

- Conduct preliminary non-parametric analysis (not shown) and find evidence for regional dependency of attenuation.

- Use mixed-effect regression.

- Try to separate Greece from Others category but find that adjustments are not significant at 5% level so keep it inside this category.

- Constrain $c_3$ to be $\leq 0$ for all periods to avoid unphysical behaviour (this constraint is required for $T > 1$ s).

- Try including style-of-faulting terms but find them poorly-constrained and associated with large standard errors. Because of this, the unbalanced nature of the database (e.g. most events in Italy are normal), the lack of reverse-faulting events in database and preliminary analysis showing limited impact of style-of-faulting these terms were dropped.

- Examine residuals w.r.t. $V_{s,30}$ and find evidence for regional effects but large scatter, which suggests need for other parameters to characterise sites.

- Note that attenuation of high-frequency motions could be result of both anelastic attenuation and site effects. Check for correlation and trade-off between $c_3$ and $g_2$ as well as between regional variation of these coefficients. Do not find significant correlation (not shown).

- Find regional adjustments are statistically significant at short periods.

- Test model including correlated regional variation on coefficients controlling distance scaling ($c_1$, $c_2$ and $c_3$) or combinations of them. Do not find appreciable improvements based on Akaike information criterion, significance tests or residuals.

- Note that regionally dependency in site terms could be related to differences in the average velocity profiles in different regions.

- Find $\sigma$ reduces by about 10% and $\phi_{S2S}$ by about 20% when using regional terms.

- Find $\tau$ reduces by up to 30% when events with converted $M_w$ estimates are removed.

- Do not recommend model for use outside Europe and the Middle without a compatibility check.

- Provide estimates of epistemic uncertainty in regional adjustments based on bootstrap method.

## 2.410 Kuehn and Scherbaum (2016)

- Ground-motion model is:

$$\ln \mathrm{PGA} = c_0 + c_1 M + c_2 M^2 + c_3 F_R + c_4 F_N + (c_5 + c_6 M_w) \ln \sqrt{R^2 + c_7^2} + c_8 R + c_9 \ln \frac{V_{s,30}}{760}$$

- Use $V_{s,30}$ to characterise sites.
- Use 3 faulting mechanisms:
  1. Reverse. $F_R = 1$ and $F_N = 0$.
  2. Normal. $F_N = 1$ and $F_R = 0$.
  3. Strike-slip. $F_R = F_N = 0$.
- Coefficients not reported.
- Use same data as Gianniotis et al. (2014).
- Data from 359 different stations.
- Develop a hierarchical/multi-level model, which is slightly adjusted from Kuehn and Scherbaum (2015), to account for regional differences, which are at a higher level than event and station effects.
- Scaling of PGA is assumed to be similar but not identical in 9 different regions: Alps (29 earthquakes, 91 records), Apennines (78 earthquakes, 303 records), south Greece (41 earthquakes, 87 records), north Greece (18 earthquakes, 58 records), north Turkey (53 earthquakes, 324 records), south Turkey (70 earthquakes, 250 records), east Turkey/Caucasus/Israel (62 earthquakes, 122 records), Iran/Central Asia (6 earthquakes, 19 records) and Sicily (5 earthquakes, 7 records). Coefficients are treated as random variables which are sampled from an underlying global distribution.
- Coefficients estimated by Bayesian inference using the program Stan, which performs Hamiltonian Monte Carlo sampling. Regions with only few records borrow strength from regions with more data.
- Prior distributions of the global coefficients are normal distributions based on the model of Abrahamson et al. (2014), which is chosen as works well for large magnitudes and short distances and it is based on a global database and hence has only partial overlap with data used to derive model. Prior distributions of the standard deviations are half-Cauchy distributions.
- Evaluate Abrahamson et al. (2014) for many $M_w$, $R$, $V_{s,30}$ and mechanism. Fit model to these predictions to find means and their standard errors as the parameters of the prior normal distributions of the coefficients. Constrain coefficients (except $c_0$) to be either positive or negative to avoid unphysical behaviour.
- Run 4 chains of samples from different starting values. Discard first 1000 samples. Each chain run for another 1000 samples. Keep every fifth sample, leading to 800 draws from posterior distribution. Assess convergence using Gelman-Rubin statistics.
- Use the Widely-Applicable Information Criterion (WAIC) to estimate the generalisation error. Use this to compare: a global model using all the data, a individual model were all coefficients are regionalised and models where various sets of coefficients are regionalised. Assume $\sigma$ is the same for all regions to avoid trade-offs. Find that all regionalised models are better in terms of WAIC and components of $\sigma$ than the global model. Select model where all coefficients except $c_3$, $c_4$ and $c_7$ vary by region.
- Use Sammon's map (Scherbaum et al., 2010) to examine similarity between regional models.

## 2.411 Landwehr et al. (2016)

- Ground-motion is:

$$\begin{aligned} y &= \beta_{-1} + \beta_0 + \beta_1 M + \beta_2 M^2 + (\beta_3 + \beta_4 M)\ln\sqrt{R_{JB}^2 + 6^2} + \beta_5 R_{JB} \\ &\quad + \beta_6 \ln V_{S30} + \beta_7 F_R + \beta_8 F_{NM} \end{aligned}$$

  where $y$ is in g, $\beta_1 = 2.4228$, $\beta_2 = -0.17267$, $\beta_4 = 0.1983$, $\beta_7 = 0.074761$, $\beta_8 = -0.1$ (fixed a priori as few normal events), $\sigma_0 = 0.5219$ and $\sigma_T = 0.8127$. Values are not given for all coefficients as some are spatially varying and only shown on maps.

- Characterise sites using $V_{s,30}$.
- Classify events into 3 mechanisms:

  S Strike-slip. $F_N M = F_R = 0$.

  N Normal. $F_N M = 1$ and $F_R = 0$.

  R Reverse. $F_R = 1$ and $F_N M = 0$.

- Assume spectral acceleration at 0.01 s is PGA.
- Use subset of data from California and Nevada from Abrahamson et al. (2014) as data from other regions will be spatially uncorrelated.
- Data well distributed from about 5 km to 200 km and for $M_w < 7$, although a slight lack of data between $M_w 5$ and 6.
- Data from most of coastal California, although limited data north of 38°N. Data from 1425 different stations.
- Develop a varying-coefficient model to relax the ergodic assumption. Coefficients $\beta_{-1}$, $\beta_3$ and $\beta_5$ depend on earthquake location (horizontal projection of the geographical centre of the rupture) and coefficients $\beta_0$ and $\beta_6$ depend on station location. Constrain coefficients to be similar for nearby locations by imposing a Gaussian process prior because insufficient data to estimate independent models for every location. Choose certain coefficients to spatially vary to capture expected physics as well as avoiding problems of extrapolating the predictions to large magnitudes and due to a lack of data from different mechanisms.
- Also derive a model with spatially-fixed coefficients. Find that this model leads to higher generalisation error (estimated using a 10-fold cross validation approach to compute the root mean squared prediction error) as well as total $\sigma$ compared with the nonergodic $\sigma_0$ of the model with spatially-varying coefficients.

## 2.412 Lanzano et al. (2016)

- Ground-motion model is (similar to Bindi et al. (2011a)):

$$\begin{aligned} \log_{10} Y &= a + F_D + F_M + F_S + F_{sof} + F_{bas} \\ F_D &= [c_{1j} + c_{2j}(M - M_r)] \log_{10}\sqrt{R_{JB}^2 + h^2}/R_h \quad \text{for} \quad j = 1, \dots 4 \\ F_M &= b_1(M - M_r) + b_2(M - M_r)^2 \\ F_S &= s_j C_j \\ F_{sof} &= f_j E_j \\ F_{bas} &= \delta_{bas}\Delta_{bas} \end{aligned}$$

where $Y$ is in $\mathrm{cm/s^2}$, $M_r = 5.0$, $a = 0.071$, $b_1 = 0.603$, $b_2 = -0.019$, $c_{11} = -1.895$, $c_{21} = 0.286$, $c_{12} = -0.926$, $c_{22} = 0.035$, $c_{13} = -1.838$, $c_{23} = 0.511$, $c_{14} = -2.256$, $c_{24} = 0.455$, $h = 6.701$, $f_{NF} = 0.035$, $f_{TF} = 0.181$, $s_B = 0.050$, $s_C = 0.203$, $\delta_{bas} = -0.060$, $\tau_0.106$ (inter-event), $\phi = 0.318$ (intra-event) and $\sigma = 0.336$ (total) when using $r_{jb}$; and $a = 0.053$, $b_1 = 0.619$, $b_2 = 0.023$, $c_{11} = -2.036$, $c_{21} = 0.150$, $c_{12} = -0.949$, $c_{22} = -0.006$, $c_{13} = -2.129$, $c_{23} = 0.383$, $c_{14} = -2.257$, $c_{24} = 0.455$, $f_{NF} = 0.011$, $f_{TF} = 0.192$, $s_B = 0.059$, $s_C = 0.212$, $\delta_{bas} = -0.059$, $\tau_0.109$ (inter-event), $\phi = 0.327$ (intra-event) and $\sigma = 0.344$ (total) when using $r_{hypo}$ ($h$ is then the focal depth).

- Use 3 site Eurocode 8 (EC8) classes:

  A $V_{s,30} > 800\,\mathrm{m/s}$. $C_A = 1$ and other $C_i$s are zero. About 300 records.

  B $360 < V_{s,30} \leq 800\,\mathrm{m/s}$. $C_B = 1$ and other $C_i$s are zero. About 800 records.

  C $180 < V_{s,30} \leq 360\,\mathrm{m/s}$. $C_C = 1$ and other $C_i$s are zero. Most near-source records. About 1600 records.

  Data from 300 different stations. Most stations classified based on geological information.

- Use 2 classes based on location w.r.t. basins (either Po Plain or in smaller basins in Apennines):

  1. Middle of a basin (C1). $\Delta_{bas} = 1$. About 950 records (all site class C stations). Most near-source records.
  2. Otherwise. $\Delta_{bas} = 0$. About 1500 records.

- Use 3 faulting mechanism classes using classification of Zoback (1992):

Normal $E_{NF} = 1$ and $E_{TF} = 0$. 11.8% of records.

Reverse $E_{TF} = 1$ and $E_{NF} = 0$. 47.8% of records.

Unspecified $E_{NF} = E_{TF} = 0$. All have $M_w < 5.0$. 35.9% of records.

  Discard the 4.5% of strike-slip records as not representative of area.

- Use 4 locations w.r.t. Po Plain and eastern Alps (PEA) and distance (corresponds to index $j$ of $c_1$ and $c_2$):

  1. Sites within PEA and $R \leq R_h$.
  2. Sites within PEA and $R < R_h$.
  3. Sites within northern Apennines (NA) and $R \leq R_h$.
  4. Sites within NA and $R < R_h$.

  $R_h = 70\,\mathrm{km}$. Use relation $\mathrm{LAT}_{ref} = -0.33\mathrm{LON}_s + 48.3$, where $\mathrm{LON}_s$ is station longitude and $\mathrm{LAT}_{ref}$ is reference latitude. Positive differences between station latitude and $\mathrm{LAT}_{ref}$ imply PEA and negative differences imply NA.

- Data from 44.0–46.3°N and 8.0–13.5°E. Most ( 60% of records) data from 20/5/2012 ($M_w$6.1) and 29/5/2012 ($M_w$6.0) Emilia earthquakes and aftershocks plus the Friuli 1976–1977 sequence. Data from permanent and temporary stations of national Italy network (Rete Accelerometrica Nazionale), INGV network plus 3% from other Italian, French and Swiss networks. Data extracted from ITACA 2.0 database.

- Select data with: $M_w$ or $M_L > 4.0$, $r_{jb}$ or $r_{epi} < 200\,\mathrm{km}$ and focal depth $< 30\,\mathrm{km}$.

- Most data from $M_W < 5.5$, $r_{jb} \leq 120\,\mathrm{km}$ and focal depths 5–10 km.

- Station distribution is uniform in northern Apennines, eastern Alps and central Po Plain whereas few stations in western Alps and western Po Plain.
- About 10% of records with $r_{jb} < 10$ km.
- Zero-pad acceleration time-series. Apply 2nd-order acausal time-domain Butterworth filter. Remove zero-pads to make acceleration and displacement consistent. Typical band-pass frequency range is 0.1 to 40 Hz for digital records and 0.3 to 25 Hz for analogue records.
- Plot PGAs v $r_{jb}$ for 29/5/2012 Emilia earthquake and find that PGAs at stations to north of Po Plain are 3–5 times larger than that to the south for $r_{jb} > 50$ km, which relate to reflections off the Moho (SmS phase).
- Do not include magnitude saturation in functional form because no evidence from data.
- Compare predictions and observations for data around $M_w6$ and $M_w4.5$ and find good match.
- Plot residuals as histograms and w.r.t. $r_{jb}$ and find no trends.

## 2.413 Mu and Yuen (2016)

- Ground-motion model is:

$$\log_{10} \text{PGA} = b_1 + b_2(M - 4) + b_5 \log_{10} R + b_9 R$$

where PGA is in cm/s$^2$, $b_1 = 2.479 \pm 0.308$, $b_2 = 0.513 \pm 0.062$, $b_5 = -0.800 \pm 0.242$, $b_9 = -0.003 \pm 0.001$ and $\sigma = \sqrt{0.495\text{PGA}^{-0.446}}$.

- Categorise 29 stations into 3 classes:

  A Rock: Granite, sandstone, bedrock, siltstone and conglomerate. 17 stations, 54 records.

  B Soil: alluvium, diluvium and weathered conglomerate. 5 stations, 61 records.

  C Soft soil: clay and subclay. 7 stations, 17 records.

  but site terms are not included in the preferred model.

- Use Heterogeneous Bayesian Learning (HERBAL) with an Automatic Relevance Determination (ARD) prior to find simultaneously: the optimum functional form and the model of the ground-motion variability. Approach explores many possible functional forms with different magnitude and distance scaling as well as different homo- and hetero-scedastic $\sigma$ models.
- Report coefficients for top eight models. Coefficients for only the top model are reported here.
- Plot residuals w.r.t. PGA. and compute variances of data binned into PGA intervals. Find that variance from binned residuals match those from $\sigma$ model derived using HERBAL closely.

## 2.414 Noor et al. (2016) & Nazir et al. (2016)

- Ground-motion model is:

$$\ln Y = a_1 + a_2 M_w + a_3 M_w^{a_4} + a_5 \ln[R + a_6 \mathrm{e}^{a_7}(a_8 M_w)] + a_9 H$$

where $Y$ is in gal, $a_1 = 3.24857$, $a_2 = -2.27216$, $a_3 = 2.7529$, $a_4 = 1.12783$, $a_5 = -2.21827$, $a_6 = 360.46122$, $a_7 = -1$, $a_8 = -0.05307$ and $a_9 = -0.0484$ ($\sigma$ is not given).

- Very similar to study of Wan Ahmad et al. (2015) but coefficients are different[47].
- Use data from stations operated by Malaysian Meteorological Department from between 2004 and 2012.
- More than 200 records available. Exclude poor quality records, those from distances outside targeted range and those from earthquakes with non-strike-slip mechanisms.
- Focal depths, $H$, between 10 and 40.63 km.
- Earthquakes occurred along Sumatran, Peninsular Malaysia, Sabah and Sarawak faults.
- All earthquakes with $M_w \geq 6.6$ except two events with $M_w 3.53$ and 3.78.

## 2.415 Sedaghati and Pezeshk (2016)

- Ground-motion model is (following Ambraseys et al. (2005a)):

$$\log y = a_1 + a_2 M + (a_3 + a_4 M) \log \sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

  where (using the preferred 1-stage maximum-likelihood technique): $y$ is in m/s$^2$, $a_1 = 1.42397$, $a_2 = 0.00761$, $a_3 = -2.52433$, $a_4 = 0.22046$, $a_5 = 7.43578$, $a_6 = 0.10268$, $a_7 = 0.01468$, $a_8 = -0.05073$, $a_9 = 0.06443$, $a_{10} = -0.05634$, $\tau = 0.27410$ (inter-event)[48], $\phi = 0.11514$ (intra-event)[49] and $\sigma = 0.29760$ (total)[50]

- Use three site categories:

$S_S = 1$, $S_A = 0$ Soft soil (S), $180 < V_{s,30} \leq 360$ m/s. 67 records.

$S_S = 0$, $S_A = 1$ Stiff soil (A), $360 < V_{s,30} \leq 750$ m/s. 140 records.

$S_S = 0$, $S_A = 0$ Rock (R), $V_{s,30} > 750$ m/s. 136 records.

  Originally include a fourth category, very soft soil ($V_{s,30} \leq 180$ m/s), but only included 7 records so combined with soft soil records.

- Classify earthquakes using method of Frohlich and Apperson (1992):

Thrust Plunge of T axis $> 50°$. 59 records, $F_T = 1$, $F_N = 0$, $F_O = 0$.

Normal Plunge of P axis $> 60°$. 138 records, $F_T = 0$, $F_N = 1$, $F_O = 0$.

Strike-slip Plunge of B axis $> 60°$. 89 records, $F_T = 0$, $F_N = 0$, $F_O = 0$.

Odd All other earthquakes. 34 earthquakes, 64 records, $F_T = 0$, $F_N = 0$, $F_O = 1$.

- Study the effect of different regression techniques: unweighted (method 1) and weighted (method 2) least-squares, 1-stage maximum-likelihood (method 3), 3 types of 2-stage methods (unweighted, method 4; Joyner and Boore (1993), method 5; Fukushima and Tanaka (1990), method 6) and using a genetic algorithm (method 7).
- Use a reduced version of the dataset of Ambraseys et al. (2005a) (see Section 2.237).

[47] The 2 articles are poorly written and neither cites the other, although they appear to present the same model. It is not easy to understand what data has been used, e.g. it could be that only data from a single location (Terengganu) has been used.

[48] This is probably the intra-event standard deviation.

[49] This is probably the inter-event standard deviation.

[50] They report coefficients for the other methods but they are not given here due to lack of space.

- Conduct pure-error analysis (Douglas and Smit, 2001) with bins of size $10\,\mathrm{km} \times 0.2 M_w$. Find a significant (at the 5% level) dependency of the standard deviation from each bin w.r.t. $M_w$, which model using a linear equation. Use this equation for the weights in the method 2.
- Compare the fit of the 7 models to the data using histograms of the residuals, quantile-quantile plots and various statistical measures as well as comparing predictions and observations for different sets of data.
- Find that the predictions of the 7 models are very similar.
- Conclude that the 1-stage maximum-likelihood technique with pure-error analysis being used to obtain the true variance is the best method.

## 2.416 Shoushtari et al. (2016)

- Ground-motion model is:
$$\log Y = aM + bR - \log(R + c10^{aM}) + d + S_k$$
where $Y$ is in $\mathrm{cm/s^2}$, $a = 0.6241$, $b = -0.001623$, $c = 0.01134646$, $d = 0.1694$, $S_B = -0.5930$, $S_C = -0.1206$, $S_D = 0.0830$, $S_E = 0.1597$ and $\sigma = 0.489$.
- Use 4 NEHRP site classes:

  B $760 < V_{s,30} \leq 1500\,\mathrm{m/s}$. 11 Malaysian stations. Use $S_B$.

  C $360 < V_{s,30} \leq 760\,\mathrm{m/s}$. Use $S_C$.

  D $180 < V_{s,30} \leq 360\,\mathrm{m/s}$. Use $S_D$.

  E $V_{s,30} < 180\,\mathrm{m/s}$. Use $S_E$.

  For Japanese stations based on measurements, for Malaysian stations based on geological descriptions and for Iranian stations, because of lack of information, based on topographic slope using approach of Wald and Allen (2007) (note uncertainty in these classifications).
- Focal depths between 51 and 305 km with 11 out of 13 earthquakes $\leq$ 105 km (contributing all but 5 records).
- Purpose of model is to assess seismic hazard in Peninsular Malaysia from distant intraslab subduction events.
- Use data from Peninsular Malaysia (34 records), Java (1 record), Japan (474 records) and Saravan-Iran (22 records) because limited data from Malaysia and since no detectable differences between ground motions in different subduction zones. Based on previous studies believe that attenuation rate in Malaysia and Japan is similar.
- Classify earthquakes as intraslab based on their locations and mechanisms using approach of Atkinson and Boore (2003): if depth $< 50$ km and extensional then intraslab; reverse-faulting earthquakes are classified as intraslab if depth $> 50$ km or if on steeply-dipping planes.
- Use locations, $M_w$ and mechanisms from Global Centroid Moment Tensor.
- Data reasonably well distributed w.r.t. $M_w$, $r_{hypo}$ and site class.
- Data from Malaysian Meteorological Department (note that some doubts about accuracy of these records), K-Net, KiK-Net and Building and Housing Research Center.
- Records baseline adjusted and acausal filtered using 4th-order Butterworth filters after zero padding at both ends. For late-triggered records taper using a raised cosine to first and last 5% of record.

- Decide on functional form using trial and error.
- Plot residuals w.r.t. $r_{hypo}$ grouped into classes of $0.5M_w$ wide. Find no apparent trends.
- Plot histograms of residuals and find good match with normal distribution.
- Compare predictions and observations (including additional PGAs from Singapore) for various magnitude ranges and focal depths w.r.t. $r_{hypo}$. Find good match.
- Note that more data from Peninsular Malaysia would make the model more reliable.
- Note that the maximum-likelihood or two-step approaches should be used to resolve related to data distribution and to evaluate the different components of variability.

## 2.417 Stewart et al. (2016)

- Ground-motion model for median motions is:

$$\begin{aligned}
\ln Y &= F_E + F_P + F_S \\
F_E &= \begin{cases} e_0\mathrm{U} + e_1\mathrm{SS} + e_2\mathrm{NS} + e_3\mathrm{RS} + e_4(M_w - M_h) + e_5(M - M_h)^2 & M_w \leq M_h \\ e_0\mathrm{U} + e_1\mathrm{SS} + e_2\mathrm{NS} + e_3\mathrm{RS} + e_6(M_w - M_h) & M_w > M_h \end{cases} \\
F_P &= [c_1 + c_2(M - M_{ref})]\ln(R/R_{ref}) + (c_3 + \Delta c_3)(R - R_{ref}) \\
R &= \sqrt{R_{JB}^2 + h^2} \\
F_S &= \ln F_{lin} + \ln F_{nl} \\
\ln F_{lin} &= \begin{cases} c\ln\left(\frac{V_{s,30}}{V_{ref}}\right) & V_{s,30} \leq V_c \\ c\ln\left(\frac{V_c}{V_{ref}}\right) & V_{s,30} > V_c \end{cases} \\
\ln F_{nl} &= f_1 + f_2 \ln\left(\frac{\mathrm{PGA}_r + f_3}{f_3}\right) \\
f_2 &= f_4\{\exp[f_5(\min(V_{s,30}, 760) - 360)] - \exp[f_5(760 - 360)]\}
\end{aligned}$$

where $Y$ is in g, $R_{ref} = 1$ km, $M_{ref} = 4.5$, $e_0 = 0.1836$, $e_1 = 0.2337$, $e_2 = 0.01562$, $e_3 = 0.1538$, $e_4 = 1.247$, $e_5 = 0$, $e_6 = 0.02257$, $M_h = 5.5$, $c_1 = -1.1750$, $c_2 = 0.1577$, $c_3 = -0.00922$, $\Delta c_{3,China} = 0.00475$, $\Delta c_{3,Japan} = 0$, $h = 5.1$, $c = -0.329$, $V_{ref} = 760$, $V_c = 1500$, $f_1 = 0$, $f_3 = 0.1$, $f_4 = -0.05$, $f_5 = -0.00701$ and $\mathrm{PGA}_r$ is the PGA obtained by evaluating model for $V_{s,30} = 760$ m/s. Model for aleatory variability is:

$$\begin{aligned}
\sigma &= \sqrt{\phi^2 + \tau^2} \\
\tau &= \begin{cases} \tau_1 & M_w \leq 4.5 \\ \tau_1 + (\tau_2 - \tau_1)(M_w - 4.5) & 4.5 < M_w < 5.5 \\ \tau_2 & M_w \geq 5.5 \end{cases} \\
\phi &= \begin{cases} \phi_1 & M_w \leq 4.5 \\ \phi_1 + (\phi_2 - \phi_1)(M_w - 4.5) & 4.5 < M_w < 5.5 \\ \phi_2 & M_w \geq 5.5 \end{cases}
\end{aligned}$$

where $\tau_1 = 0.47631$, $\tau_2 = 0.37634$, $\phi_1 = 0.71175$ and $\phi_2 = 0.53387$.

- Characterise sites using $V_{s,30}$. Recommend model is used for $200 \leq V_{s,30} \leq 1500$ m/s. Note modest over-prediction for $V_{s,30} > 600$ m/s for periods $< 0.7$ s.
- Classify events into 4 mechanisms using same criteria as Boore et al. (2013):

SS Strike-slip. SS = 1, RS = NS = U = 0.

NS Normal. NS = 1, RS = SS = U = 0.

RS Reverse. RS = 1, SS = NS = U = 0.

U Unspecified. U = 1. SS = NS = RS = 0.

- Vertical-component NGA-West 2 model corresponding to horizontal model of Boore et al. (2013) (see Section 2.367 for details of data and approach used to develop model). Use similar database and functional form but aspects are different.

- Select data having required source, path and site metadata and from active crustal regions. Exclude data from large structures. Apply screening of data at large distances as a function of $M_w$ and instrument type. Use data from Class 1 (mainshocks) and class 2 (aftershocks) using the minimum centroid $r_{jb}$ separation of 10 km based on subjective interpretation of results from exploratory analysis. Include data only for periods within usable frequency band for the vertical component and to exclude any records that are questionable by manual inspection. These two criteria lead to some differences between horizontal and vertical data.

- Did not consider hanging-wall effects because using $r_{jb}$ implicit accounts for larger motions over hanging wall for dips between 25 and 70°, which are well represented in database.

- Find no dependence on sediment depth.

- Find that $\sigma$ is only a function of $M_w$ and not $r_{jb}$ or $V_{s,30}$, which were required for the horizontal model.

- Develop model in 3 phases. In phase 1 set coefficients in site amplification model and the anelastic attenuation coefficient $c_3$, which could not be well-constrained by regression. In phase 2 undertake main regression for event and path terms. In phase 3 undertake mixed-effects regression to check model and derive $\sigma$ model (adjust some of the coefficients from phase 1).

- Set site coefficients through mixed-effects residual analysis of 8075 records with $r_{jb} < 80$ km of vertical data relative to horizontal model of Boore et al. (2013).

- Estimate $c_3$ through mixed-effects regression by using Californian data with $M_w < 5.5$ binned into $0.5M_w$ intervals corrected to $V_{s,30} = 760$ m/s. Find $c_3$ is not dependent on $M_w$.

- For phase 2 adjust data to reference $V_{s,30} = 760$ m/s using the site amplification model. Find $F_E$ and $F_P$ coefficients (except $c_3$ and $\Delta c_3$) using mainshock data from events with $\geq 4$ records with $r_{jb} \leq 80$ km (7001 records). For some periods found slight upward curvature in quadratic function for $M_w < M_h$. For these repeated regression using a linear function. Use $M_h$ from horizontal model of Boore et al. (2013), which check are appropriate. Compute $e_0$ as weighted average of coefficients for other fault types. Smooth $h$, re-regress model using smoothed $h$ and then compute 11-point running means of coefficients (and 9-, 7-, 5- and 3-point operators near ends of period range). Also perform some manual smoothing.

- For phase 3 undertake mixed-effects residual analyses to: check model from phase 1 and 2 and remove any trends; check for possible regional trends for $r_{jb}$ and $V_{s,30}$; check for trends for source terms not included (rupture depth, fault dip and rake angle). For this phase use all data. Plot inter-event residuals against $M_w$ (and binned into small magnitude intervals) and find no trends, although do find some local fluctuations. Plot intra-event residuals against $r_{jb}$ and find some trends at long distances so adjust $c_3$. Find positive bias for $r_{jb} > 300$ m and hence conclude model is not applicable at those distances. Plot intra-event residuals against $V_{s,30}$ and find need to slightly adjust $c$. After these changes still find some minor trends in residuals.

- Plot intra-event residuals against $r_{jb}$ for different countries and find need for non-zero $\Delta c_3$ for some regions (Japan and China), which find by regression. Do not find need for regional variations in $V_{s,30}$ scaling.

- Investigate need to include depth to top of rupture, hypocentral depth and fault dip in model but find no trends in residuals w.r.t. these parameters.
- Check overall model bias after all phases and find that it is small, although it increases when data from 80–300 km is included.
- Bin event terms and intra-event residuals into magnitude bins to evaluate magnitude dependency. Find evidence for $M_w$ dependency. Also check distance dependency of $\phi$ for $M_w > 5.5$ but, although evident for some periods and distances, no strong trends overall. Believe high $\tau$ near 0.1 s is site effect.
- Recommend model for mainshocks. Note that model may be applicable for Class 2 events but this is not checked.

## 2.418 Sung and Lee (2016)

- Ground-motion model is:

$$\ln y = C_1 + C_2 M + C_3 M^2 + C_4 \ln(R + C_5 e^{C_6 M}) + C_7 \ln(V_{S30}/V_{ref}) + C_8 F_N + C_9 F_R$$

  where $y$ is in g, $V_{ref} = 1130$ m/s, $C_1 = -4.407$, $C_2 = 1.142$, $C_3 = -0.012$, $C_4 = -1.450$, $C_5 = 0.140$, $C_6 = 0.623$, $C_7 = -0.389$, $C_8 = -0.057$, $C_9 = 0.188$, $\tau = 0.322$ (inter-event), $\sigma = 0.530$ (intra-event), $\tau_S = 0.230$(site-to-site), $\sigma_R = 0.477$ (record-to-record sigma), $\tau_P = 0.337$ (path-to-path), $\sigma_0 = 0.338$ (remaining unexplained variability) and $\sigma_T = 0.621$ (total).
- Use $V_{s,30}$ to characterise sites. $110 \leq V_{s,30} \leq 1056.71$ m/s. Good distribution of data between about 200 and 800 m/s.
- Classify events into 3 mechanisms:

  S Strike-slip. $F_N = F_R = 0$.

  N Normal. $F_N = 1$ and $F_R = 0$.

  R Reverse. $F_R = 1$ and $F_N = 0$.
- Focal depths between about 1 and about 32 km with most between 5 and 20 km.
- Use data from the Taiwan Strong Motion Instrumentation Program from crustal earthquakes between 1995 and 2009. All selected events have at least 50 records.
- Baseline correct and filter data using procedure of Pacific Earthquake Engineering Research Center.
- Most data from $M_w < 6.5$ and $R > 20$ km.
- Develop maximum-likelihood method (the path diagram) based on mixed-effect model to quantify path effects for each station. Divide record-to-record residuals into small brackets in a rose diagram for 6 source-to-site distance bins (< 50, 50–100, 100–150, 150–200, 200–250 and 250–300 km) and 8 azimuth bins (every 45°). Then estimate mean residual for each path bin. Obtain $8 \times 6 = 48$ path bins (path-to-path residuals) at a site and hence compute repeatable path term for all path-to-path residuals for all stations.
- Examine path diagrams for 8 stations in the Ilan Plain as an example. Find similar results.
- Examine path-to-path residuals w.r.t. azimuth and distance. Find no recognizable trends for azimuth. Path-to-path residuals become smaller as distance increases but note could be due to having fewer data at long distances.
- Estimate $\tau_P$ and $\sigma_0$ for each station. Find geographical patterns in these values.
- Also apply Closeness Index (CI) approach (Lin et al., 2011a). Find similarities and differences (e.g. CI approach leads to slightly higher $\sigma_0$ estimates) between results from the two methods.

## 2.419 Tusa and Langer (2016)

- Ground-motion model for shallow events is:

$$\log Y = a + b_1 M + c_1 \log \sqrt{R^2 + h^2} + e_B S_B + e_D S_D$$

  where $a = -1.186 \pm 0.169$, $b_1 = 0.726 \pm 0.033$, $c_1 = -1.719 \pm 0.060$, $h = 1.551 \pm 1.003$, $e_B = 0.357 \pm 0.055$, $e_D = 0.376 \pm 0.062$, $\sigma_{eve} = 0.223$ (inter-event), $\sigma_{sta} = 0.229$ (inter-station) and $\sigma_T = 0.393$ (total) for horizontal; and $a = -1.110 \pm 0.168$, $b_1 = 0.691 \pm 0.034$, $c_1 = -1.749 \pm 0.061$, $h = 1.245 \pm 0.151$, $e_B = 0.338 \pm 0.055$, $e_D = 0.430 \pm 0.064$, $\sigma_{eve} = 0.230$ (inter-event), $\sigma_{sta} = 0.218$ (inter-station) and $\sigma_T = 0.393$ (total) for vertical.

- Ground-motion model for deep events is:

$$\log Y = a + b_1 M + b_2 M^2 + [c_1 + c_2(M - M_{ref})] \log \sqrt{R^2 + h^2} + c_3(\sqrt{R^2 + h^2} - 1) + e_B S_B + e_D S_D$$

  where $M_{ref} = 3.0$, $R_{ref} = 1$; $a = 2.527 \pm 2.437$, $b_1 = -0.397 \pm 0.308$, $b_2 = 0.094 \pm 0.039$, $c_1 = -1.998 \pm 1.450$, $c_2 = 0.315 \pm 0.070$, $h = 9.608 \pm 5.229$, $c_3 = 0 \pm 0.008$, $e_B = -0.200 \pm 0.075$, $e_D = 0.002 \pm 0.086$, $\sigma_{eve} = 0.161$ (inter-event), $\sigma_{sta} = 0.276$ (inter-station) and $\sigma_T = 0.399$ (total) for horizontal; and $a = 2.459 \pm 0.888$, $b_1 = -0.407 \pm 0.293$, $b_2 = 0.100 \pm 0.038$, $c_1 = -1.956 \pm 0.428$, $c_2 = 0.273 \pm 0.061$, $h = 9.315 \pm 2.632$, $c_3 = -0.001 \pm 0.003$, $e_B = 0.229 \pm 0.058$, $e_D = -0.013 \pm 0.066$, $\sigma_{eve} = 0.157$ (inter-event), $\sigma_{sta} = 0.249$ (inter-station) and $\sigma_T = 0.387$ (total) for vertical.

- Use 3 Eurocode 8 site classes:

  A $V_{s,30} > 800$ m/s. About 40% of data. $S_B = S_D = 0$.

  B $360 < V_{s,30} \leq 800$ m/s. About 50% of data. $S_B = 1$, $S_D = 0$.

  D $V_{s,30} < 180$ m/s. 5.4% of data. $S_D = 1$. $S_B = 0$.

  Originally included data from site class C ($180 \leq V_{s,30} \leq 360$ m/s) sites but only 42 (SE) and 77 (DE) records so coefficients poorly constrained. Removed data from this category. Classification based on GIS maps based on seismic logs in Catania province and geo-lithographical maps of Sicily and other classifications outside this province.

- Divide data into two classes based on focal depth $h$:

  SE Shallow. $h < 5$ km. Events related to dynamics of volcanic edifice rather than regional stress field. Events within sedimentary substratum. 95% of events have $h < 2$ km. Deepest event has $h = 4.5$ km.

  DE Deep. $5 < h \leq 30$ km.

  Find clear difference in records from these two classes with data from shallow events having more low frequencies.

- Data from 72 24-bit Nanometrics Trillium broadband velocity instruments (sample rate 100 Hz) in the Rete Sismica Permanente della Sicilia Orientale of INGV, from 04/2006 to 11/2012. Stations located between Aeolian Islands and Hyblean Plateau. Magnitudes and locations from INGV.

- Exclude data from $M_L < 3$ based on quality and homogeneity.

- Visually inspect all data to exclude traces with electronic glitches or that are amplitude saturated. Baseline correct (offset and linear trend removal) records. Correct for instrument response. Bandpass filter data with cut-offs of 0.1 and 25 Hz. Differentiate records to obtain acceleration.

- Data reasonably well distributed up to 100 km and because motions from further distances of limited engineering interest exclude data beyond this distance. No correlation between magnitude and distance. Vast majority ( 90%) of data from $M_L < 4$.

- Try various functional forms and report coefficients. Compare results based on $\sigma$, F-tests to check reduction in variance and Akaike and Bayesian Information Criteria. Prefer the models reported above, despite the coefficients of the deep model not conforming to expectations. Use bootstrap (sampling with replacement) to assess standard deviations of coefficients.

- Study residuals w.r.t. $M$ and $R$. Find no significant trends. Histograms suggest that residuals follow a normal distribution, although the Lilliefors test does not confirm this for low significance levels.

- Compute inter-event and inter-station $\sigma$ using analysis of variance.

- Examine inter-station errors w.r.t. each station. Examine inter-event errors w.r.t. earthquake ID.

- Compute confidence intervals of predictions. Find that confidence intervals of complex models broaden greatly at edges of data. Warn against extrapolation of models.

- Use data not used within the boot-strapping to find the confidence limits of the coefficients within cross-validation exercise to check the root-mean-squared errors. Conclusions on best models match those obtained through other techniques.

- Compare observations and predictions w.r.t. $R$ for various magnitude ranges. Find good fits.

## 2.420 Wang et al. (2016)

- Ground-motion model is:

$$\ln y = C_1 + C_2 M + C_3 \ln[R + C_4 \exp(C_5 M)] + C_6 H + C_7 (V_{s,30}/1130)$$

  where $y$ is in g, $C_1 = -5.60$, $C_2 = 1.63$, $C_3 = -1.70$, $C_4 = 0.51552$, $C_5 = 0.63255$, $C_6 = 0.0075$, $C_7 = -0.27$ and $\sigma = 0.61$.

- Use $V_{s,30}$ to characterise sites. $V_{s,30}$ are from PS logging at or near the station.

- Focal depths $11 \leq H \leq 45$ km, with only one earthquake with $H > 27$ km.

- Use data from Taiwan Strong Motion Instrumentation Program from 1995–2013.

- Only use data from normal-faulting events, which are defined as those with rake between −60 and −90°.

- Only include earthquakes with $M_w \geq$ because focus is on events that can cause damage. Only one earthquake has $M_w > 5.1$.

- Only retained earthquakes recorded by $\geq 20$ stations.

- Baseline correct records after removing instrument response. High-pass filter (Butterworth) data using cut-offs determined by the signal-to-noise ratio in respective displacement waveform. Signal amplitude determined by averaging the absolute displacement within a 10 s time window starting from P arrival. Noise amplitude estimated using 10 s time window before P arrival. Use automatic procedure to determine filtering band to obtain signal-to-noise ratio of $\geq 14$ by incrementally trying high-pass filters with cut-offs increasing by 0.01 Hz. Finally visually check data.

- Find that $C_4$, $C_5$ and $C_6$ are fairly consistent across periods so fix them to avoid trade-offs between coefficients.

- Plot residuals as histogram, w.r.t. $M_w$, $V_{s,30}$, $H$ and $R$ and find no trends and good match to lognormal distribution.

- Compare predictions and observations for 201102010816 earthquake ($M_w4.9$, $H = 23\,\mathrm{km}$), for a $M_w4.1$ event not used because fewer than 20 records, and two earthquakes in the USA (Borah Peak, $M_w5.1$, and SW Nevada, $M_w5.7$). Find most observations within one standard deviation of prediction even when data not used in regression.

## 2.421 Zhao et al. (2016a)

- Ground-motion model is:

$$
\begin{aligned}
\log_e y &= f_{mSL} + g_{SL}\log_e r + g_{SLL}\log_e(x+200.0) + e_{SL}x + q_{SLH}x + e^v_{SL}x^v + \gamma_{SL} + \log_e A \\
f_{mSL} &= b_{SL}h + \begin{cases} c_{SL1}m + c_{SL2}(m-m_{sc})^2 & m \le m_c \\ c_{SL1}m_c + c_{SL2}(m_c-m_{sc})^2 + d_{SL}(m-m_c) & m > m_c \end{cases} \\
r &= x + \exp(c_1 + c_2 C_m) \\
C_m &= \begin{cases} m & m \le C_{max} \\ C_{max} & m > C_{max} \end{cases} \\
q_{SLH} &= e_{SLH}\begin{cases} 0 & h < 50\,\mathrm{km} \\ 0.02h - 1.0 & h \ge 50\,\mathrm{km} \end{cases}
\end{aligned}
$$

where $y$ is in g, $m_{sc} = 6.3$, $m_c = 7.1$ (from previous studies), $C_{max} = m_c$, $c_2 = 1.151$ (from magnitude-fault length relations), $c_1 = -5.30119$, $c_{SL1} = 1.44758$, $c_{SL2} = 0.37625$, $d_{SL} = 0.42646$, $b_{SL} = 0.01826$, $g_{SL} = -1.98471$, $g_{SLL} = 1.12071$, $e^v_{SL} = -0.01499$, $e_{SL} = -0.00340$, $e_{SLH} = -0.00050$, $\gamma = -9.880$, $S_2 = 0.2320$, $S_3 = 0.1437$, $S_4 = 0.1470$, $\sigma = 0.587$ (intra-event), $\tau = 0.457$ (inter-event) and $\sigma_T = 0.744$ (total).

- Use 4 site classes ($T$ is natural period of site):

  SC I Rock, NEHRP site classes A+B+C, $V_{s,30} > 600\,\mathrm{m/s}$, $T < 0.2\,\mathrm{s}$. Note that these sites are neither rock or engineering bedrock sites as many have a layer of stiff soil of thickness $\le 24\,\mathrm{m}$ and $V_s > 200\,\mathrm{m/s}$ at the surface. Many sites have strong impedance ratios. Note that nonlinear effects at these sites is limited. 2002 records (2031 in complete dataset).

  SC II Hard soil, NEHRP site class C, $300 < V_{s,30} \le 600\,\mathrm{m/s}$, $0.2 \le T < 0.4\,\mathrm{s}$. 1292 records (1354 in complete dataset).

  SC III Medium soil, NEHRP site class D, $200 < V_{s,30} \le 300\,\mathrm{m/s}$, $0.4 \le T < 0.6\,\mathrm{s}$. 414 records (443 in complete dataset).

  SC IV Soft soil, NEHRP site classes E+F, $V_{s,30} \le 200\,\mathrm{m/s}$, $T \ge 0.6\,\mathrm{s}$. 847 records (882 in complete dataset).

  Prefer site classes because useful for design codes and for application of model for sites with no accurate site period or $V_{s,30}$. Classify stations for early data and for some K-Net stations from H/V response spectral ratios. Use site terms derived in previous studies that account for nonlinear response (see article for details) — $S_2$, $S_3$ and $S_4$ are the linear site terms.

- Partner model to those of Zhao et al. (2016b) (see Section 2.422) for interface earthquakes and Zhao et al. (2016c) (see Section 2.423) for crustal earthquakes. Derive separate models for three different types of earthquakes because it allows $\sigma$ (and its components) and site amplification to vary with event type. Sufficient data available for separate models.

- Focal depths between 10 and 170 km, which most between 30 and 70 km.

- Focal mechanisms: reverse: 98 (95 in dataset 2); strike-slip: 13 (10 in dataset 2); and normal: 25 (20 in dataset 2).
- Data reasonably well distributed w.r.t. $M_w$ and $x$. 7 earthquakes (539 records) with $M_w > 7.0$ in dataset 1 but fewer large events in dataset 2.
- Use maximum log likelihood (MLL), rather than model standard deviation, as the indicator of goodness of fit. Find MLL is useful for identifying biased distribution of residuals when this is strongly influenced by an outlier because if an additional term is included to correct bias the MLL does not change and hence the correction is not necessary.
- Use data up from 1968 to 2012.
- Use dataset 1 (all data) to find magnitude-scaling for events with $M_w \geq 7.1$ and then dataset 2 (excluding sites with inferred site class) for rest of derivation with magnitude-scaling taken from first dataset. Find removing records from sites with inferred site class improves goodness of fit.
- Account for volcanic zone by using an anelastic attenuation term based on horizontal distance within possible volcanic zones ($x^v$). $x^v$ is capped at 12 km for shorter lengths and at 80 km for longer lengths.
- Use fault-top depth $h$.
- Plot intra-event residuals w.r.t. site period, $T$, for SC I sites. Find clear trend, which use to estimate deamplification ratios for a site with $T = 0$ s.
- Smooth the coefficients w.r.t. the logarithm of the period. Note that smooth spectra are not obtained at all $M_w$ and $x$.
- Plot inter- and intra-event residuals and fit trend lines. Find slopes of trend lines are small.
- Compute intra- and intra-site standard deviations for each site class.
- Check if $\sigma$ depends on $M_w$ by splitting residuals into $0.5M_w$ unit bins and compute standard deviations in each magnitude bin. Do not find evidence for magnitude-dependent $\sigma$s.

## 2.422 Zhao et al. (2016b)

- Ground-motion model for shallow events is:

$$\begin{aligned}
\log_e y &= f_{mintS} + g_{int} \log_e r + g_{intSL} \log_e(x + 200.0) + e_{intS}x + e^v_{int}x^v + \gamma_{int} + \log_e A \\
f_{mintS} &= b_{int}h + \gamma_{intS} + \begin{cases} c_{intS}m & m \leq m_c \\ c_{intS}m_c + d_{int}(m - m_c) & m > m_c \end{cases}
\end{aligned}$$

and for deep events:

$$\begin{aligned}
\log_e y &= f_{mintD} + g_{int} \log_e r + g_{intDL} \log_e(x + 200.0) + e^v_{int}x^v + \gamma_{int} + \log_e A \\
f_{mintD} &= b_{int}h + \gamma_{intS} + \begin{cases} c_{intD}m & m \leq m_c \\ c_{intD}m_c + d_{int}(m - m_c) & m > m_c \end{cases}
\end{aligned}$$

where

$$\begin{aligned}
r &= x_{into} + x + \exp(c_1 + c_2 C_m) \\
C_m &= \begin{cases} m & m \leq C_{max} \\ C_{max} & m > C_{max} \end{cases}
\end{aligned}$$

and $y$ is in g, $m_c = 7.1$ (from previous studies), $C_{max} = m_c$, $c_2 = 1.151$ (from magnitude-fault length relations), $x_{into} = 10.0$ km, $c_1 = -5.301$, $c_2 = 1.151$, $c_{intD} = 1.0997$, $c_{intS} = 1.3148$, $d_{int} = 0.553$, $\gamma_{intS} = -3.8953$, $b_{int} = 0.0200$, $g_{int} = -2.0559$, $g_{intLD} = 0.5454$, $g_{intLS} = 1.1336$, $e^v_{int} = -0.011223$, $e_{intS} = -0.00628$, $\gamma_{int} = -4.4986$, $S_2 = 0.3129$, $S_3 = -0.0043$, $S_4 = 0.2284$, $S_5 = 0.3129$, $S_6 = -0.0043$, $S_7 = 0.2284$, $\sigma = 0.553$ (intra-event), $\tau = 0.378$ (inter-event) and $\sigma_T = 0.670$ (total).

- Use 4 site classes ($T$ is natural period of site):

  SC I Rock, NEHRP site classes A+B+C, $V_{s,30} > 600$ m/s, $T < 0.2$ s. 1494 records (1563 in complete dataset).

  SC II Hard soil, NEHRP site class C, $300 < V_{s,30} \leq 600$ m/s, $0.2 \leq T < 0.4$ s. 995 records (786 in complete dataset).

  SC III Medium soil, NEHRP site class D, $200 < V_{s,30} \leq 300$ m/s, $0.4 \leq T < 0.6$ s. 360 records (284 in complete dataset).

  SC IV Soft soil, NEHRP site classes E+F, $V_{s,30} \leq 200$ m/s, $T \geq 0.6$ s. 656 records (547 in complete dataset).

  Classify stations for early data and for some K-Net stations from H/V response spectral ratios. Use site terms derived in previous studies that account for nonlinear response (see article for details).

- Partner model to those of Zhao et al. (2016a) and Zhao et al. (2016c). See Section 2.421 for details of the data used and the approach.

- Select earthquakes that occurred at the interface between crust and the subducting slab or between mantle wedge ad subducting slab at a depth of $\leq 50$ km. Also require: focal depth within 5 km of subduction interface defined by Slab1.0, reverse or thrust focal mechanism and dip angle for one of the nodal planes is within 15° of dip of subduction interface.

- Focal depths between about 5 and 49 km with only 11 shallow events (798 records) with $< 25$ km. Deep events have focal depth $\geq 25$ km.

- Dataset 1 includes 1222 records from 13 earthquakes with $M_w \geq 7.1$.

- Plots intra-event residuals for Tohoku 2011 ($M_w$9.0) earthquake w.r.t. distance. Find that observed PGAs are underestimated within 130 km. Fit trend line ($\log_e y = g \log_e r + ex + c$) to residuals, which corrects bias in residuals. Relate this observation to Moho reflections.

- Note that predictions will be different for an event at the 25 km boundary depending on whether model for shallow or deep earthquakes is used. Try to derive model using continuous variables to avoid this problem but could not obtain smooth predictions. Recommend that the average ground motions predicted from both the shallow and deep models are used for earthquakes at the boundary.

## 2.423 Zhao et al. (2016c)

- Ground-motion model for shallow crustal is:

$$\begin{aligned}
\log_e y &= f_{mcr} + g_{cr} \log_e r + g_{crL} \log_e(x + 200.0) + g_N + e_{cr}x + e^v_{cr}x^v + \gamma_{cr} + \log_e A^{cr} \\
f_{mcr} &= b_{cr}h + F_{crN} + \begin{cases} c_{cr}m & m \leq m_c \\ c_{cr}m_c + d_{cr}(m - m_c) & m > m_c \end{cases}
\end{aligned}$$

and for upper mantle:

$$
\begin{aligned}
\log_e y &= f_{mum} + g_{um}\log_e r + g_{crL}\log_e(x+200.0) + g_N + e_{um}x + e^v_{cr}x^v + \gamma_{cr} + \log_e A^{um} \\
f_{mum} &= \begin{cases} F_{umRV} & \text{reverse} \\ F_{umNS} & \text{normal/strike-slip} \end{cases} \\
&\quad + \begin{cases} c_{cr}m & m \le m_c \\ c_{cr}m_c + d_{cr}(m - m_c) & m > m_c \end{cases}
\end{aligned}
$$

where

$$
\begin{aligned}
r &= x_{cro} + x + \exp(c_1 + c_2 C_m) \\
C_m &= \begin{cases} m & m \le C_{max} \\ C_{max} & m > C_{max} \end{cases} \\
g_N &= g_{crN} \begin{cases} \log_e[x + \exp(c_1 + 6.5c_2)] & x \le 30\,\text{km} \\ \log_e[30.0 + \exp(c_1 + 6.5c_2)] & x > 30\,\text{km} \end{cases}
\end{aligned}
$$

and $y$ is in g, $m_c = 7.1$ (from previous studies), $C_{max} = m_c$, $c_2 = 1.151$ (from magnitude-fault length relations), $c_1 = -3.224$, $c_2 = 0.900$, $c_{cr} = 1.0731$, $d_{cr} = 0.200$, $F_{CRN} = 0.3128$, $F_{umRV} = -0.2024$, $F_{umNS} = 0.2519$, $b_{cr} = 0.00907$, $g_{cr} = -1.2603$, $g_{UM} = -1.0999$, $g_{crN} = -0.4992$, $g_{crL} = 1.2656$, $e_{cr} = -0.00794$, $e_{um} = -0.01083$, $e^v_{cr} = -0.00628$, $\gamma_{cr} = -9.0872$, $S_2 = 0.2888$, $S_3 = 0.1221$, $S_4 = 0.2081$, $\sigma = 0.556$ (intra-event), $\tau = 0.391$ (inter-event) and $\sigma_T = 0.680$ (total).

- Use 4 site classes ($T$ is natural period of site):

  SC I Rock, NEHRP site classes A+B+C, $V_{s,30} > 600$ m/s, $T < 0.2$ s. 1968 records from crustal, 979 records from upper mantle.

  SC II Hard soil, NEHRP site class C, $300 < V_{s,30} \le 600$ m/s, $0.2 \le T < 0.4$ s. 1064 records from crustal, 562 from upper mantle.

  SC III Medium soil, NEHRP site class D, $200 < V_{s,30} \le 300$ m/s, $0.4 \le T < 0.6$ s. 371 records from crustal, 137 from upper mantle.

  SC IV Soft soil, NEHRP site classes E+F, $V_{s,30} \le 200$ m/s, $T \ge 0.6$ s. 612 records from crustal, 264 from upper mantle.

  Originally included some data from sites with inferred site classes but after initial testing excluded these data as less reliable. Use site terms derived in previous studies that account for nonlinear response (see article for details).

- Use 3 styles of faulting:

  Reverse 35 (2096 records) crustal and 26 (1021 records) upper-mantle earthquakes. Use $F_{umRV}$.

  Strike slip 17 (973 records) crustal and 5 (209 records) upper-mantle earthquakes. Use $F_{umNS}$.

  Normal 18 (946 records) crustal and 16 (712 records) upper-mantle earthquakes. Use $F_{crN}$ for shallow crustal and $F_{umNS}$ for upper mantle. Note that all crustal normal events occurred following Tohoku earthquake in a small region and hence the applicability to other regions is not clear.

  Find reverse and strike-slip events are statistically similar for shallow crustal events and strike-slip and normal similar for upper mantle events (at 5% level).

- Partner model to those of Zhao et al. (2016a) and Zhao et al. (2016b). See Section 2.421 for details of the data used and the approach.

- Choose functional form based on physics of earthquakes and previous studies. Remove term if not significant at 5% level.

- Use data from shallow crustal (fault-top depth $< 25$ km, 70 events) and upper-mantle (fault-top depth $25 \leq h \leq 64$ km, 47 events) earthquakes.

- Use some near-source data from outside Japan to derive magnitude-scaling for $M_w > 7.1$ and terms controlling near-source spectrum.

- Exclude records below a straight line in magnitude-distance plot ($M_w$5.0-$x = 124$ km to $M_w$7.3-$x = 300$ km) to avoid effects from untriggered stations. Data well distributed w.r.t. magnitude and distance. No upper-mantle earthquakes with $M_w > 7$.

- Introduce $x_{cro}$ to avoid magnitude-distance oversaturation.

- Use term $g_{crL} \log_e(x + 200)$ to avoid a positive anelastic attenuation rate. Choice of 200 km as constant significantly improves fit but note that it does not have a physical justification.

- Introduce term $g_N$ to eliminate near-source bias for Japan, which is related to use of foreign data to constrain large-magnitude/near-source terms in model.

- Note that difficult to split variability into intra-site and inter-site as well as inter-event for many records. Use approximate technique to compute these components.

- Find that predicted spectra from shallow-crustal and upper-mantle models differs by a factor up to 1.47 when evaluated for a depth of 25 km. Propose depth-scaling functions: $S_{cr} = 1.0$ for $h \leq h_1$, $S_{cr} = (h_2 - h)/(h_2 - h_1)$ for $h_1 < h \leq h_2$ and $S_{cr} = 0.0$ for $h > h_2$; and $S_{um} = 0.0$ for $h \leq h_1$, $S_{um} = (h - h_1)/(h_2 - h_1)$ for $h_1 < h \leq h_2$ and $S_{um} = 1.0$ for $h > h_2$; with $h_1 = 20$ km and $h_2 = 30$ km to obtain continuously varying spectra as a function of depth, if required.

- Attempt to model hanging wall effect but insufficient data from Japan to obtain reliable results. Recommend using models from California and then calibrated with Japanese data, if required.

- Believe model more suitable for soil sites with low impedance ratios (i.e. $< 3$) than for sites with high impedance ratios.

## 2.424 Ameri et al. (2017)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10} Y &= a + F_D + F_M + F_S + F_{sof} \\
F_D &= [c_1 + c_2(M - M_{ref})] \log_{10}\left(\sqrt{R^2 + h^2}/R_{ref}\right) \\
F_M &= \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & M \leq M_h \\ b_3(M - M_h) & \text{otherwise} \end{cases} \\
F_{sof} &= f_1 E_N + f_2 E_R + f_3 E_S \\
F_S &= e_1 F_A + e_2 F_B + e_3 F_C + e_4 F_D \\
\tau &= \begin{cases} \tau_1 & M \leq 4 \\ \tau_1 + (\tau_2 - \tau_1)(M - 4) & 4 < M < 5 \\ \tau_2 & M \geq 5 \end{cases}
\end{aligned}
$$

where $Y$ is in cm/s$^2$, $\tau$ is inter-event variability, $a = 3.90119$, $c_1 = -1.5472$, $c_2 = 0.203801$, $h = 6.78654$, $b_1 = 0.157748$, $b_2 = -0.0375241$, $b_3 = 0$, $e_1 = 0$, $e_2 = 0.183962$, $e_3 = 0.265793$, $e_4 = 0.223751$, $f_1 =$

$-0.0467904$, $f_2 = 0.0184746$, $f_3 = 0$, $M_{ref} = 5.5$, $M_h = 6.75$, $R_{ref} = 1$[51]; $\tau_1 = 0.311636$, $\tau_2 = 0.180874$, $\tau = 0.171510$ (homoscedastic) and $\phi = 0.305205$ for $r_{epi}$; and $\tau_1 = 0.299730$, $\tau_2 = 0.177908$, $\tau = 0.170688$ (homoscedastic) and $\phi = 0.303741$ for $r_{jb}$.

- Use 4 Eurocode 8 site classes (to be able to use most about of French data):

  A $F_A = 1$, $F_B = F_C = F_D = 0$.

  B $F_B = 1$, $F_A = F_C = F_D = 0$.

  C $F_C = 1$, $F_A = F_B = F_D = 0$.

  D Poorly represented compared to other classes. $F_D = 1$, $F_A = F_B = F_C = 0$.

  Note that many French and other stations lack measured $V_{s,30}$. 40% of records have $V_{s,30}$. Try regressing using a continuous $V_{s,30}$-based site term and find negligible differences in terms of $\sigma$.

- Use 3 styles of faulting:

Normal Most data. $E_N = 1$, $E_R = E_S = 0$.

Strike-slip Second most data. $E_S = 1$, $E_N = E_R = 0$.

Reverse About half of normal events. $E_R = 1$, $E_N = E_S = 0$.

- Use data from RESORCE-2013 database. Focus of study is French (432 records from 65 events) and Swiss data.

- Note that metadata from small events generally less accurate in terms of $M_w$ and fault mechanism. Swiss data are reliable because of time-domain moment-tensor inversion. Seek to obtain consistent $M_w$ for French data from previous studies but some uncertainty and potential slight overestimation. Mechanisms from literature or from dominant stress regime and seismotectonic zonation. Note that this is a rough approach.

- Exclude data from: events with depth $> 30$ km, $r_{epi} > 200$ km, $M_w < 3$, stations that are known not to be in free-field (e.g. from galleries or dams), bad-quality records or those lacking a horizontal component, stations without $V_{s,30}$ or site class, events with only converted $M_w$, singly-recorded events and records filtered with low-pass corner frequency $\leq 20$ Hz and for each period records with high-pass corner frequency $\geq 1/(1.25T)$.

- Most data with $M > 4$ from Italy and Turkey, with smaller amount from Greece. Most smaller events are from France and Switzerland.

- Do not include anelastic attenuation term because not statistically different from zero.

- Choose $M_{ref} = 5.5$ because it is close to 50th percentile of cumulative number of records v. $M_w$.

- Use $M_h = 6.75$ based on previous studies and by inspection of plots of magnitude scaling. Note that lack of data from $M_w > 6.5$ so magnitude scaling poorly constrained. Find that when $b_3$ is constrained to be non-negative it is found not to be statistically significant so constrain it to zero in final regression. Note that no magnitude oversaturation is found.

- Do not consider other terms (e.g. hanging/foot wall, depth to top of rupture) due to lack of information.

- Do not find any bias or trends in inter-event residuals w.r.t. $M_w$ nor in intra-event residuals w.r.t. $R$. Do not find evidence for regional dependency between French intra-event residuals and other regions, which note may be due to lack of data. Do not find evidence for trend in intra-event residuals w.r.t. $\kappa_0$ estimated in previous studies.

[51] There is a second set of coefficients for this model. It is not clear which should be used. $a = 3.57937$, $c_1 = -1.4864$, $c_2 = 0.231465$, $h = 6.65758$, $b_1 = -0.0240888$, $b_2 = -0.0631411$, $b_3 = 0$, $e_1 = 0$, $e_2 = 0.167762$, $e_3 = 0.249286$, $e_4 = 0.223014$, $f_1 = -0.0382253$, $f_2 = 0.013243$, $f_3 = 0$, $M_{ref} = 5.5$, $M_h = 6.75$ and $R_{ref} = 1$.

- Find large variability in residuals from French and Swiss data at small magnitudes. Find inter-event residuals correlated with stress parameter and different groups of residuals for different parts of France and Switzerland: Swiss Alps and Foreland; French Alps and Rhine Graben; and Pyrenees. Derive an empirical correction for the base-case model that is a function of the stress parameter based on the model of Yenier and Atkinson (2015b), which find to match observations at small magnitudes. Find reductions in inter-event variability for French and Swiss small-magnitude events because of this correction. Find reduced magnitude-dependency of $\tau$ because of this correction.

- Compute $\phi_{SS}$ for all stations and only considering French stations when each stations has $\geq 5$ records.

## 2.425 Baltay et al. (2017)

- Ground-motion model is:

$$\ln \mathrm{PGA} = a_1 + a_2 M - \ln R_{hyp} + a_3 \ln(V_{s,30}/V_{ref})$$

where PGA is in g, $V_{ref} = 760\,\mathrm{m/s}$, $a_1 = -16.16$, $a_2 = 1.5 \ln 10$, $a_3 = -0.6$, $\tau = 0.45$ (inter-event), $\phi = 0.86$ (intra-event) and $\sigma = 0.97$ (total)[52].

- Characterise sites by $V_{s,30}$. 5 are measured values and 5 are from topographic slope.

- Data from 10 central stations of Anza network (BZN, CRY, FRD, KNW, LVA2, PFO, RDM, SND, TRO and WMC) from 1997 to 2010. Instruments are STS-2 100 samples per second broadband velocimeters with corner frequency of 0.0083 Hz. Instrument correct. Use only A-quality data. Only use earthquakes recorded by $\geq 5$ stations with $r_{hypo} \leq 20$ km.

- All coefficients except $a_1$ are fixed *a priori* based on physical considerations.

- Do not consider anelastic attenuation because data from short distances.

- Find no trends in residuals (total, event and within-event) w.r.t. magnitude.

- Split residuals into various components: event residuals (split further into average location residual and the remainder) and within-event residual (split further into average site residual, average path residual and remainder).

## 2.426 Bindi et al. (2017)

- Ground-motion model is:

$$\begin{aligned}
\ln Y &= e_1 + F_D + F_M + F_S \\
F_D &= [c_1 + c_2(M - M_{ref})] \ln(\sqrt{R_{JB}^2 + h^2}/R_{ref}) \\
&\quad + c_3(\sqrt{R_{JB}^2 + h^2} - R_{ref}) \quad \text{using } r_{jb} \\
F_D &= [c_1 + c_2(M - M_{ref})] \ln(R_{hypo}/R_{ref}) \\
&\quad + c_3(R_{hypo} - R_{ref}) \quad \text{using } r_{hypo} \\
F_M &= \begin{cases} b_1(M - M_{ref}) + b_2(M - M_{ref})^2 & M < M_h \\ b_3(M - M_h) + b_1(M_h - M_{ref}) + b_2(M_h - M_{ref})^2 & \text{otherwise} \end{cases} \\
F_S &= s_A \ln(V_{s,30}/800)
\end{aligned}$$

[52]Various other components of aleatory variability are reported in the article, which should be consulted for details.

where $Y$ is in m/s$^2$, $R_{ref} = 1$, $M_{ref} = 4.5$ and $M_h = 6.5$ (slightly higher than value suggested by data, 6–6.2 to move change of magnitude-scaling to above controlling earthquake scenario in hazard calculations); $e_1 = 0.635138$, $b_1 = 1.241105$, $b_2 = -0.13181$, $b_3 = -0.32192$, $c_1 = -0.93085$, $c_2 = 0.143762$, $c_3 = -0.01088$, $h = 3.875582$, $s_A = -0.60915$, $\tau = 0.495337$ (inter-event) and $\phi = 0.631336$ (intra-event) for model using $r_{jb}$; $e_1 = 1.494544$, $b_1 = 1.514441$, $b_2 = -0.09357$, $b_3 = 0.332407$, $c_1 = -1.15213$, $c_2 = 0.091751$, $c_3 = -0.00930$, $s_A = -0.61492$, $\tau = 0.501564$ (inter-event) and $\phi = 0.637574$ (intra-event) for model using $r_{hypo}$.

- Use $V_{s,30}$ to characterise sites (16th, 50th and 84th percentiles of data are 393 m/s, 511 and 786 m/s). Only use data from sites with $V_{s,30} \geq 360$ m/s since focus is on prediction for stiff site conditions and to exclude sites behaving nonlinearly.
- Use few input parameters because of lack of information on, e.g., hanging/foot wall in Germany (the focus for the application of the model), and because hazard in application computed for $V_{s,30} = 800$ m/s so basin effects and soil nonlinearity can be neglected.
- Develop models using $r_{jb}$ and $r_{hypo}$ so that they can be used both for fault and area sources.
- As model will be applied in Germany, particularly focus on predictions in $5.5 \leq M_w \leq 6$.
- Do not recommend model for $M_w > 7.4$ or for long return periods (because of relatively high $\sigma$).
- Data from 1025 different stations.
- Do not include style-of-faulting terms because not justified using AIC analysis.
- Most data from $M_w \leq 5.5$ and $r_{hypo} \geq 20$ km.
- Report the variance-covariance matrix of the model, which use to assess epistemic uncertainty in the median.
- Compare predictions and observations for bins $M_w 4 \pm 0.25$ and $M_w 6.7 \pm 0.25$ and find good fit.
- Examine residuals w.r.t. $r_{hypo}$ (intra-event) and $M_w$ (inter-event) and find no trends. Compute average bias w.r.t. 3 style-of-faulting classes (normal, strike-slip and reverse) and find slight (but not significant) evidence that model overpredicts motions from normal-faulting events.

## 2.427 Çağnan et al. (2017a,b)

- Ground-motion model is:

$$\begin{aligned}
\ln Y_v &= \ln Y_{v,REF} + \ln S \\
\ln Y_{v,REF} &= \begin{cases} a_1 + a_2(M - 6.75) + a_3(8.5 - M)^2 + [a_4 + a_5(M - 6.75)] \ln \sqrt{R^2 + a_6^2} & \\ \quad + a_8 F_N + a_9 F_R & M_w \leq 6.75 \\ a_1 + a_7(M - 6.75) + a_3(8.5 - M)^2 + [a_4 + a_5(M - 6.75)] \ln \sqrt{R^2 + a_6^2} & \\ \quad + a_8 F_N + a_9 F_R & M_w > 6.75 \end{cases} \\
\ln S &= a_{10} \ln \left[ \frac{\min(V_{s,30}, 1000)}{V_{REF}} \right]
\end{aligned}$$

where $Y_v$ is in g, $V_{REF} = 750$ m/s, $a_1 = 1.299$, $a_2 = 0.3329$, $a_3 = 0.00317$, $a_4 = -1.24624$, $a_5 = 0.2129$, $a_6 = 7.5192$, $a_7 = 0.3196$, $a_8 = -0.06736$, $a_9 = 0.09853$, $a_{10} = -0.20467$, $\phi_v = 0.5753$ (intra-event), $\tau_v = 0.3311$ (inter-event) and $\sigma_v = 0.6638$.

- Corresponding vertical model of Akkar et al. (2014b,c) (see Section 2.381). Derive by combining the models for the horizontal component and vertical-to-horizontal ratio rather than direct regression on data.

- Validate model by computing inter- and intra-event residuals using the vertical data and the proposed model. Find model is unbiased w.r.t. $M_w$, $r_{jb}$ and $V_{s,30}$.

## 2.428 Derras et al. (2017)

- Ground-motion model is not given here since it requires evaluation of a matrix equation that cannot be summarised. Study similar to Derras et al. (2014) (see Section 2.384). Model derived using an artificial neural network.

- Investigate the effect of using different site-condition proxies (SCPs) on predictions and particularly on $\sigma$ (separated into $\tau$ and $\phi$). Consider 4 SCPs, which use in models in terms of their logarithms as find they are lognormally distributed:

  1. $V_{s,30}$: with values 152.94–1432.8 m/s.
  2. Topographic slope: with values 0.0025–0.3748 m/ m.
  3. Fundamental resonance frequency, $f_0$: with values 0.22–22.72 Hz.
  4. Depth at which $V_s > 800$ m, $H_{800}$: with values 1–550 m.

- Derive models using no SCPs, each SCP individually, the 6 unique pairs of SCPs, the four unique triples of SCPs and, finally, a model using all 4 SCPs. Find some correlation between SCP pairs but sufficient scatter to consider them as almost independent.

- Find choice of SCP has little impact on predictions of the median but it does affect $\sigma$.

- Use data from KiK-net database of Dawood et al. (2016) because all considered SCPs are available for many sites. Use data from 199 different sites.

- Focal depths from 0 to 30 km.

- Few records for $< 10$ km and when only considering stiff-to-rock sites few records for $< 30$ km.

- Provide ranges of applicability of models w.r.t. independent parameters by considering 5th and 95th fractiles of observed distributions.

- Find evidence of nonlinearity in site amplification.

## 2.429 García-Soto and Jaimes (2017)

- Ground-motion model is:

$$\ln Y = \alpha_1 + \alpha_2 M_w - 0.5 \ln R + \alpha_4 R$$

  where $Y$ is in cm/s$^2$; $\alpha_1 = 0.4648$, $\alpha_2 = 0.9125$, $\alpha_4 = -0.0118$ and $\sigma = 0.77$ for horizontal PGA; and $\alpha_1 = -0.1276$, $\alpha_2 = 0.9384$, $\alpha_4 = -0.0111$ and $\sigma = 0.75$ for vertical PGA.

- Data from 56 NEHRP class B (rock) sites.

- Focal depths between 10 and 29 km. Do not include this in model based on previous study.

- Use data from 1985 to 2004 from free-field stations. Dataset quite well balance w.r.t. number of records for each event.

- Data reasonably well distributed but data predominantly from $M_w \leq 6$.
- Baseline correct and high-pass filter data (0.05 Hz cut-off for $M_w > 6.5$ and 0.1 Hz otherwise).
- Use quadratic mean to combine horizontal components because likely to be slightly more conservative than geometric mean.
- Constrain geometric decay coefficient to $-0.5$ to avoid unrealistic values.
- Examine residuals w.r.t. $M_w$ and $R$ and find no trends.

## 2.430 Gülerce et al. (2017)

- Ground-motion model is [based on Abrahamson et al. (2013, 2014)] (for median):

$$
\begin{aligned}
\ln \mathrm{Sa} &= f_1 + F_{RV} f_7 + F_N f_8 + F_{AS} f_{11} + f_5 + F_{HW} f_4 + f_6 + \text{Regional} \\
f_1 &= \begin{cases} a_1 + a_5(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)] \ln R + a_{17} r_{rup} & M > M_1 \\ a_1 + a_4(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)] \ln R + a_{17} r_{rup} & M_2 \leq M < M_1 \\ a_1 + a_4(M_2 - M_1) + a_8(8.5 - M)^2 + a_6(M - M_2) + [a_2 + a_3(M_2 - M_1)] \ln R & \\ \quad + a_{17} r_{rup} & M < M_2 \end{cases} \\
R &= \sqrt{r_{rup}^2 + c_{4M}^2} \\
c_{4M} &= \begin{cases} c_4 & M > 6 \\ c_4 - (c_4 - 1)(6 - M) & 4 < M \leq 6 \\ 1 & M \leq 4 \end{cases} \\
f_7 &= \begin{cases} a_{11} & M > 5 \\ a_{11}(M - 4) & 4 \leq M \leq 5 \\ 0 & M < 4 \end{cases} \\
f_8 &= \begin{cases} a_{12} & M > 5 \\ a_{12}(M - 4) & 4 \leq M \leq 5 \\ 0 & M < 4 \end{cases} \\
f_5 &= a_{10} \ln \left( \frac{V_{s,30}^*}{V_{Lin}} \right) \\
V_{s,30}^* &= \begin{cases} V_{s,30} & V_{s,30} < V_1 \\ V_1 & V_{s,30} \geq V_1 \end{cases} \\
V_1 &= \begin{cases} 1500 & T \leq 0.5\,\mathrm{s} \\ \exp\left[-0.35 \ln\left(\frac{T}{0.5}\right) + \ln(1500)\right] & 0.5 < T < 3\,\mathrm{s} \\ 800 & T \geq 3\,\mathrm{s} \end{cases} \\
f_4 &= a_{13} T_1 T_2 T_3 T_4 T_5 \\
T_1 &= \begin{cases} (90 - \mathrm{dip})/45 & \mathrm{dip} > 30^\circ \\ 60/45 & \mathrm{dip} < 30^\circ \end{cases} \\
T_2 &= \begin{cases} 1 + 0.2(M - 6.5) & M \geq 6.5 \\ 1 + 0.2(M - 6.5) - (1 - 0.2)(M - 6.5)^2 & 5.5 < M < 6.5 \\ 0 & M \leq 5.5 \end{cases} \\
T_3 &= \begin{cases} h_1 + h_2(R_x/R_1) + h_3(R_x/R_1)^2 & R_x < R_1 \\ 1 - \left(\frac{R_x - R_1}{R_2 - R_1}\right) & R_1 \leq R_x \leq R_2 \\ 0 & R_x > R_1 \end{cases} \\
T_4 &= \begin{cases} 1 - \frac{Z_{TOR}^2}{100} & Z_{TOR} \leq 10\,\mathrm{km} \\ 0 & Z_{TOR} > 10\,\mathrm{km} \end{cases} \\
T_5 &= \begin{cases} 1 & R_{y0} - R_{y1} \leq 0 \\ 1 - \frac{R_{y0} - R_{y1}}{5} & 0 < R_{y0} - R_{y1} < 5 \\ 0 & R_{y0} - R_{y1} \geq 5 \end{cases} \\
R_1 &= W \cos(\mathrm{dip}) \\
R_2 &= 4 R_1 \\
R_{y1} &= R_x \tan(20) \\
h_1 &= 0.25 \\
h_2 &= 1.5 \\
h_3 &= -0.75
\end{aligned}
$$

$$
\text{If } R_{y0} \text{ not available:} \quad T_5 = \begin{cases} 1 & r_{jb} = 0 \\ 1 - \frac{r_{jb}}{30} & r_{jb} < 30 \\ 0 & r_{jb} \geq 30 \end{cases}
$$

$$
f_6 = \begin{cases} a_{15} \frac{Z_{TOR}}{20} & Z_{TOR} < 20\,\text{km} \\ a_{15} & Z_{TOR} \geq 20\,\text{km} \end{cases}
$$

$$
f_{11} = \begin{cases} a_{14} & CR_{jb} \leq 5\,\text{km} \\ a_{14}\left[1 - \frac{CR_{jb}-5}{10}\right] & 5 < CR_{jb} < 15\,\text{km} \\ 0 & CR_{jb} \geq 15\,\text{km} \end{cases}
$$

$$
\begin{aligned}
\text{Regional} &= F_{TW}\left[a_{31}\ln\left(\frac{V^*_{s,30}}{V_{Lin}}\right) + a_{25}r_{rup}\right] + F_{IT}\left[a_{32}\ln\left(\frac{V^*_{s,30}}{V_{Lin}}\right) + a_{26}r_{rup}\right] \\
&\quad + F_{ME}a_{27}r_{rup} + F_{CN}a_{28}r_{rup} + F_{JP}\left[a_{35}\ln\left(\frac{V^*_{s,30}}{V_{Lin}}\right) + a_{29}r_{rup}\right]
\end{aligned}
$$

where: Sa is in g, Dip is fault dip in degrees, $W$ is down-dip rupture width, $V_{Lin} = 660$, $c_4 = 8.6$, $a_1 = 1.350$, $a_2 = -1.087$, $a_3 = 0.275$, $a_4 = 0.121$, $a_5 = -0.592$, $a_6 = 1.780$, $a_8 = 0.0$, $a_{10} = -0.397$, $a_{11} = -0.200$, $a_{12} = -0.120$, $a_{13} = 0.670$, $a_{14} = -0.168$, $a_{15} = 1.100$, $a_{17} = -0.0062$, $a_{25} = 0.0015$, $a_{26} = -0.0007$, $a_{27} = 0.0031$, $a_{28} = 0.0035$, $a_{29} = -0.0010$, $a_{31} = 0.252$ and $a_{35} = 0.380$.

- Ground-motion model is (for aleatory variability):

$$
\sigma = \sqrt{\phi^2 + \tau^2}
$$

$$
\phi = \begin{cases} s_1 & M < 4 \\ s_1 + \frac{s_2 - s_1}{2}(M-4) & 4 \leq M < 6 \\ s_2 & M > 6 \end{cases}
$$

$$
\tau = \begin{cases} s_3 & M < 5 \\ s_3 + \frac{s_4 - s_3}{2}(M-5) & 5 \leq M < 7 \\ s_4 & M > 7 \end{cases}
$$

where: $s_1 = 0.734$ and $s_{2,all} = 0.520$, $s_3 = 0.440$, $s_4 = 0.350$, $s_{2,NoJP} = 0.450$ and $s_{4,NoJP} = 0.322$.

- Use 3 faulting mechanisms:

Strike-slip Other rake angles. 221 events. $F_{RV} = F_N = 0$.

Reverse Rake angles between 30 and 150°. 79 events. $F_{RV} = 1$, $F_N = 0$.

Normal Rake angles between $-30$ and $-150$°. 26 events, mostly $4.6 \leq M_w \leq 6$. $F_N = 1$, $F_{RV} = 0$.

Use two earthquake types:

Class 1 Mainshocks. $F_{AS} = 0$.

Class 2 Aftershocks. Events with centroid $r_{jb} < 15$ km ($CR_{jb}$). $F_{AS} = 1$.

Use two locations w.r.t. vertical projection of the top of rupture:

Hanging wall $F_{HW} = 1$.

Foot wall $F_{HW} = 0$.

Use five regional terms to adjust model w.r.t. base model (all other regions, dominated by California):

Taiwan $F_{TW} = 1$

China $F_{CN} = 1$

Japan $F_{JP} = 1$

Middle East $F_{ME} = 1$

Italy $F_{IT} = 1$

- Vertical-component NGA-West 2 model corresponding to horizontal model of Abrahamson et al. (2013, 2014) (see Section 2.366 for details of data and approach used to develop model). Use similar database and functional form but aspects are different.

- Functional form does not include terms for nonlinear site amplification or soil depth used by Abrahamson et al. (2013, 2014). Simulations of nonlinear site amplification not consistent with data. Notes that reduced confidence in using the model away from an average site with $V_{s,30} = 450$ m/s because of lack of nonlinear terms.

- Use same database as Abrahamson et al. (2013, 2014) but remove records without vertical component (55 records) and those for which vertical component is questionable (98 records).

- Regress in a number of steps following approach of Abrahamson et al. (2013, 2014).

- Smooth coefficients to assure smooth spectra and to make model extrapolate in reasonable manner.

- Find $\phi$ from Japanese data much higher than from Californian or Taiwanese data, which relate to shallower soils in Japan. Recommend $s_{2,NoJP}$ and $s_{4,NoJP}$ for use outside Japan.

- Note that $V_{s,30}$ scaling for Japanese sites is distance dependent but $V_{s,30}$ slope in model is distance independent. Use $V_{s,30}$ slope from $r_{rup} \leq 50$ km for model because most relevant for applications. Note that at larger distance may be a misfit between predictions of regional model and observations from Japan.

- Examine inter-event residuals w.r.t. $M_w$ and separated by region. Find no trends.

- Examine intra-event residuals w.r.t. $V_{s,30}$, $\mathrm{Sa}_{1180}$ (predicted spectral acceleration for $V_{s,30} = 1180$ m/s) and $Z_1$ (depth to $V_{s,30} = 1$ km/s horizon). Find no trends.

## 2.431 Idini et al. (2017)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10} Y &= F_F + F_D + F_S \\
F_F &= c_1 + c_2 M_w + c_8 (H - h_0) F_{eve} + \Delta f_M \\
\Delta f_M &= \begin{cases} c_9 M_w^2 & F_{eve} = 0 \\ \Delta c_1 + \Delta c_2 M_w & F_{eve} = 1 \end{cases} \\
F_D &= g \log_{10}(R + R_0) + c_5 R \\
R_0 &= (1 - F_{eve}) c_6 10^{c_7 (M_w - M_r)} \\
g &= c_3 + c_4 (M_w - M_r) + \Delta c_3 F_{eve} \\
F_S &= S_{T^*} \log_{10}\left(\frac{V_{S30}}{V_{ref}}\right)
\end{aligned}
$$

$h_0 = 50$ km, $M_r = 5$, $S_I = 0$, $S_{II} = -0.584$, $S_{III} = -0.322$, $S_{IV} = -0.109$, $S_V = -0.095$, $S_{VI} = -0.212$, $c_1 = -2.8548$, $\Delta c_1 = 2.5699$, $c_2 = 0.7741$, $\Delta c_2 = -0.4761$, $c_3 = -0.97558$, $\Delta c_3 = -0.52745$, $c_4 = 0.1$ (fixed to avoid trade-offs in regression), $c_5 = -0.00174$, $c_6 = 5$ (fixed), $c_7 = 0.35$ (fixed), $c_8 = 0.00586$, $c_9 = -0.03958$, $\sigma_e = 0.172$ (inter-event), $\sigma_r = 0.232$ (intra-event) and $\sigma_t = 0.289$ (total).

- Use $V_{s,30}$ to characterise sites as well as 6 site classes based on predominant period of the soil ($T^*$) from horizontal-to-vertical response spectral ratios (HVRSR):

I Not identifiable: HVRSR $\leq 2$

II $T^* \leq 0.2$ s

III $0.2 < T^* \leq 0.4$ s

IV $0.4 < T^* \leq 0.8$ s

V $T^* > 0.8$ s

VI Not identifiable: broadband amplification or two or more peaks

- Classify events into 2 classes using hypocentral depth and dip and strike criteria:

Interface Focal depth, $H$, between 10 and 50 km and dip of $20° \pm 5°$ and strike of $0° \pm 20°$ and they occur close to subduction contact zone $F_{eve} = 0$.

Intraslab Intraslab events have greater depths (exclude events with $H > 150$ km). $F_{eve} = 1$.

- Use data from National Seismological Center and National Accelerometer Network of the Department of Civil Engineering (RENADIC), University of Chile. Collect 1207 records from 184 events. Apply magnitude-dependent limits to avoid bias from trigger thresholds. Also exclude records based on signal-processing criteria.
- Data from 154 different stations, most in northern and central Chile (near Santiago).
- Data quite well distributed w.r.t. $M_w$ and $r_{hypo}$ but few intraslab records between $M_w$6.5 and 7.5.
- 22% of records from analogue (SMA-1 and QDR) instruments. Recent records generally digital (CMG-5 and FBA ES-T).
- Baseline correct to remove trend. Apply cosine taper over 5% of total length of detrended signal. Zero pad (30 s length) beginning and end of signal. Bandpass filter using 4th order Butterworth acausal filter. Highpass corner frequencies chosen based on instrument (0.2, 0.1 and 0.06 Hz for SMA-1, QDR and digital sensors, respectively). Lowpass corner frequency for analog and QDR instruments is 25 Hz. For digital instruments lowpass filtering was applied when the Fourier amplitude spectra showed an unusual high frequency amplitude (e.g. for sensors with natural frequencies lower than the Nyquist). For only 3% of digital records was such filtering required. Remove 91 records (mainly from rock sites at short source-to-site distances) because believe they are significantly affected by high-frequency noise.
- Chose functional form based on iterative approach. Start with a simple model and add terms by examining plots of data w.r.t. $R$ and $M_w$. Only include terms that are identified by the data (e.g. no quadratic magnitude-scaling seen in intraslab data), which note could mean certain dependencies are not included because of lack of data.
- Use a 2-stage approach fixing certain coefficients and using simplified functional forms to avoid trade-offs.
- Smooth coefficients with a linear fit using 20% of the total coefficient vector length.
- Examine first-stage residuals w.r.t. distance (grouped by $M_w$ and site class) and find no trends.
- Show event terms w.r.t. predictions from second stage and find good fit.
- Compare observations grouped by $M_w$ against predictions w.r.t. $R$ and when good match.

## 2.432 Institute of Seismology at the University of Helsinki (2017) cited by Ader et al. (2019)

- Ground-motion model is unknown.

## 2.433 Kumar et al. (2017)

- Ground-motion model is:

$$\log A = c_1 + c_2 M - b \log(X + \mathrm{e}^{c_3})$$

  where $A$ is in g, $c_1 = -1.497 \pm 0.3494$, $c_2 = 0.3882 \pm 0.1203$, $c_3 = 0.2876$[53], $b = 1.19$ and $\sigma = 0.1451$.

- Data from National Strong Motion Network (111 analogue SMA-1 records, 7 earthquakes, $5.2 \leq M \leq 6.8$) and strong-motion arrays (105 digital GSR-18 records, 17 earthquakes, $4.0 \leq M \leq 6.8$) from Garhwal and Kumaon Himalaya from 1986 to 2011. Analogue data bandpass filtered using Ormsby filter with cut-offs 0.17–0.20 Hz and 25–27 Hz.

- Focal depths from 5 to 122 km.

- Most data from $r_{hypo} > 100$ km.

- Regress data from each earthquake individually using function: $\log A = -b \log X + c$ and find average $b = 1.20$. Using all data together gives $b = 0.55 \pm 0.11$, which note shows that a 2-stage method is required.

## 2.434 Liew et al. (2017)

- Ground-motion model is (for interface and crustal/back arc):

$$\ln \mathrm{PGA} = C_1 + C_2 M_w + C_3 M_w^2 + C_4 D_e + C_5 D_e^2 + C_6 \ln[D_e + \exp(C_7 m_b)] + C_8 h + C_9 h^3$$

  where PGA is in g; $C_1 = -28.778$, $C_2 = 3.180$, $C_3 = -0.147$, $C_4 = -0.002$, $C_5 = 0.8314 \times 10^{-10}$, $C_6 = 0.295$, $C_7 = 1.026$, $C_8 = 0.198$, $C_9 = -0.4771 \times 10^{-4}$ and $\sigma = 0.594$ for interface; and $C_1 = 105.969$, $C_2 = -19.923$, $C_3 = 1.746$, $C_4 = 0.013$, $C_5 = -0.1094 \times 10^{-8}$, $C_6 = -10.495$, $C_7 = -0.048$, $C_8 = 0.016$, $C_9 = 0.986 \times 10^{-6}$ and $\sigma = 0.656$ for crustal/back arc.

  Ground-motion model is (for intraslab):

$$\ln \mathrm{PGA} = C_1 + C_2 M_w^2 + C_3 \ln[D_f + \exp(C_4 m_b)] + C_5 D_f + C_6 D_f^3 + C_7 D_e^2 + C_8 h + C_9 h^2$$

  where PGA is in g; $C_1 = -68.566$, $C_2 = 0.091$, $C_3 = 12.858$, $C_4 = -3.806$, $C_5 = -0.060$, $C_6 = -0.6577 \times 10^{-8}$, $C_7 = 0.325 \times 10^{-4}$, $C_8 = -0.009$, $C_9 = -0.4548 \times 10^{-4}$ and $\sigma = 0.5$.

- Data from stations of the Malaysian Meteorological Department since 2004.

- Classify earthquakes into 3 types:

Interface: Exclude data from $M_w < 7$. 10 earthquakes, 111 records.

Intraslab: Generally have focal depths $h > 70$ km. Exclude data from $M_w > 6$. 5 earthquakes, 65 records.

Crustal/back arc: 7 earthquakes, 82 records.

  Do not use data from 2 deep events in Java and Celebes, 3 shallow events in Sabah and 2 earthquakes in Indian oceanic plate as insufficient data to investigate these types.

- Functional form found by trial and error and independent variables chosen through correlation analysis.

[53] They also give $c_3 = 0.8579 \pm 0.2341$.

## 2.435 Montalva et al. (2017a,c,b)

- Ground-motion model is (following Abrahamson et al. (2016)):

$$
\begin{aligned}
\ln \mathrm{SA} &= \theta_1 + f_{source} + f_{path} + f_{event/depth} + f_{site} + f_{FABA} \\
f_{source} &= \theta_4 \Delta C_1 + f_{mag} \\
f_{mag} &= \begin{cases} \theta_4[M_w - (C_1 + \Delta C_1)] & M_w \leq C_1 + \Delta C_1 \\ \theta_5[M_w - (C_1 + \Delta C_1)] & M_w > C_1 + \Delta C_1 \end{cases} \\
f_{path} &= [\theta_2 + \theta_{14} F_{event} + \theta_3(M_w - 7.2)] \ln\{R + C_4 \exp[\theta_9(M_w - 6)]\} + \theta_6 R \\
f_{event/depth} &= \{\theta_{10} + \theta_{11}[\min(Z_h, 120) - 60]\} F_{event} \\
f_{site} &= \begin{cases} \theta_{12} \ln(V_S^*/V_{lin}) - b \ln(\mathrm{PGA}_{1000} + c) & \\ \quad + b \ln[\mathrm{PGA}_{1000} + c(V_S^*/V_{lin})^n] & V_{s,30} < V_{lin} \\ \theta_{12} \ln(V_S^*/V_{lin}) + bn \ln(V_S^*/V_{lin}) & V_{s,30} \geq V_{lin} \end{cases} \\
V_S^* &= \begin{cases} 1000 & V_{s,30} > 1000 \\ V_{s,30} & V_{s,30} \leq 1000 \end{cases} \\
f_{FABA} &= \begin{cases} \{\theta_7 + \theta_8 \ln[\max(R, 85)/40]\} F_{FABA} & F_{event} = 1 \\ \{\theta_{15} + \theta_{16} \ln[\max(R, 100)/40]\} F_{FABA} & F_{event} = 0 \end{cases}
\end{aligned}
$$

  where SA is in g, $\theta_1 = 5.87504$, $\theta_4 = 0.80277$, $\theta_5 = -0.33487$, $\theta_2 = -1.75360$, $\theta_3 = 0.13125$, $\theta_6 = -0.00039$, $\theta_{14} = -0.73080$, $\theta_{10} = 4.53143$, $\theta_{11} = 0.00567$, $\theta_{12} = 1.01495$, $\theta_7 = 1.0988$, $\theta_8 = -1.420$, $\theta_{15} = 0.9969$, $\theta_{16} = -1.000$, $\theta_9 = 0.4$, $\Delta C_{1,interface} = 0.200$, $\Delta_{1,in-slab} = -0.300$, $V_{lin} = 865.1$, $b = -1.186$, $n = 1.18$, $C_4 = 10$, $C_1 = 7.2$; $\tau = 0.47462$ (inter-event), $\phi_{S2S} = 0.56436$ (site-to-site), $\phi = SS = 0.39903$ (single station intra-event) and $\sigma = 0.83845$ (total) for the standard model; and $\tau = 0.48274$ (inter-event), $\phi_{S2S} = 0.35438$ (site-to-site), $\phi = SS = 0.29315$ (single station intra-event) for the high-quality model. $\mathrm{PGA}_{1000}$ is median PGA for $V_{s,30} = 1000\,\mathrm{m/s}$.

- Characterise sites using $V_{s,30}$, some measured for study. Only 57 stations (with 744 records) have measured $V_{s,30}$. For others (178 stations) use topographic slope and site's predominant period as proxy for $V_{s,30}$ (using a weighted average). $V_{s,30}$ between 108 and 1951 m/s but believe model only valid from 100–1000 m. Insufficient data to constrain nonlinear model so adopt coefficients from Abrahamson et al. (2016) for this part of model.

- Use data from networks of Integrated Plate boundary Observatory Chile and Red Nacional de Acelerografos and Seismometer Network of Centro Sismológico Nacional from 1985 to 2015.

- Classify earthquakes into 2 types using its location w.r.t. trench axis and focal mechanism, when available:

Interface Generally associated with reverse faulting, occur between the Peru-Chile trench and Chile's coast and at depths $\leq 50$ km. Shallow reserve-faulting events were interface earthquakes whereas other shallow events were crustal (and excluded). $F_{event} = 0$.

Intraslab Generally normal faulting and have depths $> 50$ km. For events without focal mechanism, classify using a slab subduction model. $F_{event} = 1$.

- Classify records into 2 classes:

Back-arc $f_{FABA} = 1$

Fore-arc $f_{FABA} = 0$

  No data from back-arc sites so adopt coefficients from Abrahamson et al. (2016).

- Use finite-fault rupture models to compute distances, when available, and empirical relationships to estimate fault location, otherwise.

- Individually bandpass filter each record using a smoothed signal-to-noise ratio of three to choose low cut-off frequency and Nyquist and frequency at which Fourier amplitude spectrum becomes flat for high cut-off. Use data down to 1.25 times the low cut-off frequency.

- Focal depths, $Z_h$, of interface events between about 5 and about 50 km and for intraslab between about 40 and about 280 km.

- About 70% of events have $\geq 3$ records. Nearly 60% of stations have $\geq 3$ records.

- Regress using all data. Remove outliers (defined using the Rosner algorithm) and then regress again. Force coefficient $\theta_6$ to be negative to avoid unrealistic distance attenuation. Do not smooth coefficients as believe this can be done by hazard analyst if necessary.

- Derive second model using only high-quality data (measured $V_{s,30}$ and $M_w$ from Global CMT catalogue, 411 records from 151 interface events and 109 records from 57 intraslab events). Find much lower intra-event variabilities but higher uncertainties in coefficients due to fewer records. This model only valid for interface events because of limited intraslab data.

- Define 95% confidence intervals for coefficients using 1000 bootstrap replications using datasets with same number of records as original database but accepting duplicate data.

- Create 100 random data subsets with various sizes from 500 to 3500 records and regress. Assess the convergence of statistical tests to evaluate models.

- Examine inter-event residuals w.r.t. $M_w$, single-station residuals w.r.t. $R$ and site-to-site residual w.r.t. $V_{s,30}$. Find no trends so conclude regression is robust and reliable.

- Note that model shows reasonable behaviour up to 1000 km but may only be valid for $\leq 300$ km considering data distribution. Also note that model strictly valid from $5 \leq M_w \leq 8$ but could be extended to $M_w 9$ because of presence of $M_w 8.8$ Maule event, which is well represented.

## 2.436 Oth et al. (2017)

- Ground-motion model is:

$$\begin{aligned}
\log_{10}(\mathrm{PGA}) &= e_0 + F_D + F_M \\
F_D &= [c_1 + c_2(M_w - M_{ref})] \log\left(\frac{\sqrt{R_{rup}^2 + h^2}}{R_{ref}}\right) + c_3\left(\sqrt{R_{rup}^2 + h^2} - R_{ref}\right) \\
F_M &= \begin{cases} b_1(M_w - M_h) + b_2(M_w - M_h)^2 & M_w < M_h \\ b_3(M_w - M_h) & M_w \geq M_h \end{cases}
\end{aligned}$$

  where $M_h = 6.5$; $h = 5$ km and $c_2 = 0$ (fixed due to instabilities in regression due to lack of near-source data); $c_3 = 0$ (fixed because either statistically insignificant or positive). Do not report coefficients only show graphs of predictions.

- Data from K-Net and KiK-Net from May 1996 to October 2011. 38 226 are borehole records from KiK-Net (581 stations) and 79 876 are surface records (1411 stations).

- Select data from events recorded by $\geq 3$ stations and sites that have recorded $\geq 3$ events.

- Focal depths from about 0.4 to about 30 km with most between 5 and 20 km.

- Data well distributed w.r.t. $M_w$ and for $R > 10$ km.

- Separate variability into components describing between sequence, between event, between site-class and between station using a mixed-effects regression technique.
- Do not aim to develop a model to calculate hazard but to understand between-event variability in terms of stress (drop) parameter. Hence aim for a simple model that does not include effects that affect only a small subset of data (e.g. nonlinear site response and directivity).
- Examine residuals and find no substantial bias. Some slight overprediction at $R \geq 180$ km, underprediction for 5–15 km and overprediction for very short distances.

## 2.437 Peruzza et al. (2017)

- Ground-motion model is:

$$\log Y = a + b_1 M + b_2 M^2 + [c_1 - c_2(M - M_{ref})]\log(\sqrt{R^2+h^2}/R_{ref}) + c_3(\sqrt{R^2+h^2} - R_{ref}) + e_i S_i$$

  where $Y$ is in gal, $M_{ref} = 3.6$ (mode magnitude for dataset), $R_{ref} = 1$, $a = 0.329$, $b_1 = 0.105$, $b_2 = 0.076$, $c_1 = -2.111$, $c_2 = 0.039$, $h = 1.553$, $c_3 = 0.006$, $e_B = 0.450$, $e_D = 0.457$, $\sigma_{eve} = 0.228$ (inter-event), $\sigma_{sta} = 0.222$ (inter-station) and $\sigma_T = 0.394$ (total).
- Use 3 Eurocode 8 site classes:

  A $V_{s,30} > 800$ m/s. About 40% of data. $S_B = S_D = 0$.

  B $360 < V_{s,30} \leq 800$ m/s. About 50% of data. $S_B = 1$, $S_D = 0$.

  D $V_{s,30} < 180$ m/s. 5.4% of data. $S_D = 1$. $S_B = 0$.
- Use shallow dataset of Tusa and Langer (2016) (see Section 2.419).
- 95% of focal depths $< 2.5$ km and 85% of focal depths are $\leq 0.5$ km.
- Try different starting values for the regression and chose the values to which several inversions converged.
- Also compute 95% confidence intervals for coefficients and uncertainties through bootstrap technique, which believe has advantages over use of the Jacobian matrix.
- Compare predictions and observations for $3.9 \leq M_L \leq 4.1$ and find good fit.

## 2.438 Sedaghati and Pezeshk (2017)

- Ground-motion model is:

$$\begin{aligned}
\ln Y &= f_{source} + f_{path} + f_{site} \\
f_{source} &= \begin{cases} a_1 + a_2(M - M_h) + a_3(M - M_h)^2 & M \leq M_h \\ a_1 + a_4(M - M_h) & M > M_h \end{cases} \\
f_{path} &= (b_1 + b_2 M)\ln\sqrt{r_{jb}^2 + h^2} + (b_3 + \Delta b_{3,region})\sqrt{r_{jb}^2 + h^2} \\
f_{site} &= c_1 + c_2 \ln V_{s,30}
\end{aligned}$$

  where $Y$ is in g, $M_h = 7.0$; $a_1 = 0.44780$, $a_2 = 0.24582$, $a_3 = -0.14444$, $a_4 = 0.49645$, $b_1 = -1.17792$, $b_2 = 0.04959$, $b_3 = 0.00000$, $h = 4.52478$, $c_1 = 0.68185$, $c_2 = -0.10727$, $\Delta b_{3,Alborz} = 0.00000$, $\Delta b_{3,Zagros} = 0.00000$, $\Delta_{3,Others} = 0.00000$, $\tau = 0.20592$ (inter-event), $\phi_{S2S} = 0.20338$ (site-to-site), $\phi_0 = 0.45542$ and $\sigma = 0.53961$ (total) for horizontal PGA; and $a_1 = -0.32176$, $a_2 = 0.00795$, $a_3 = -0.14011$, $a_4 = 0.32612$, $b_1 = -1.60377$, $b_2 = 0.12555$, $b_3 = -0.00223$, $h = 4.90710$, $c_1 = -0.01229$, $c_2 = 0.00132$, $\Delta b_{3,Alborz} = 0.00000$, $\Delta b_{3,Zagros} = 0.00000$, $\Delta_{3,Others} = 0.00000$, $\tau = 0.21104$ (inter-event), $\phi_{S2S} = 0.16597$ (site-to-site), $\phi_0 = 0.50317$ and $\sigma = 0.57032$ (total) for vertical PGA.

- Characterise sites using $V_{s,30}$. Data from 321 different stations. Data has $155 \leq V_{s,30} \leq 1564$ m/s but only recommend use for $300 \leq V_{s,30} \leq 1000$ m/s.
- Use data from Iranian Strong Motion Network from 1979 to 2013. Data from SMA-1 and SSA-2 instruments. Visually inspect data and remove poor-quality records. Baseline correct records. Remove instrument response. Individually bandpass filter zero-padded records using phaseless 8-pole filter using cut-off frequencies determined for when signal-to-noise ratio is $< 3$.
- Exclude data that:
  1. Lack all 3 components;
  2. Have a focal depth $\geq 35$ km;
  3. Have a $r_{jb} \geq 250$ km;
  4. Do not have known $V_{s,30}$ (30% of original data have no $V_{s,30}$);
- 46 earthquakes have only a single record. Note that this may mean $\tau$ and $\phi_{S2S}$ are slightly underestimated.
- Note that few data from $r_{jb} < 10$ km so model not well constrained for short distances.
- Include terms to account for potential differences in anelastic attenuation between: Alborz (132 records), Zagros (262 records) and other (e.g. central and eastern Iran) regions (294 records).
- Use nonparametric plots of data against, e.g., $r_{jb}$, Akaike and Bayesian information criteria and try various trial functional forms to choose final functional form.
- Allow for oversaturation of ground motions for large magnitudes within functional form.
- Constrain $b_3$ to be zero or negative to avoid unrealistic distance scaling and because of trade-off between geometric and anelastic terms.
- Do not account for nonlinear site effects because dataset is deficient in records with high $M_w$, short $r_{jb}$ and low $V_{s,30}$.
- Originally try to model regionality in $c_1$ and $c_2$ but effect is not significant.
- Do not include fault mechanism in model because total $\sigma$ reduced by 10% by removing this term and effect of inclusion of these terms is statistically insignificant.
- Regress to obtain source and path coefficients and then regress again to find site coefficients.
- Examine residuals (unbinned and binned: using $0.25M_w$, 100 m/s and 25 km intervals, computing mean and 95% confidence intervals when $\geq 3$ records). Find no trends.

## 2.439 Shahidzadeh and Yazdani (2017)

- Ground-motion model is:

$$\begin{aligned}\log y &= \theta_1 + \theta_2 M_w + (\theta_3 + \theta_4 M_w) \log \sqrt{d^2 + \theta_5^2} + \theta_6 S_S + \theta_7 S_A \\ &\quad + \theta_8 F_N + \theta_9 F_T + \theta_{10} F_O + \theta_{11} M_w^2\end{aligned}$$

  where $y$ is in m/s$^2$, $\theta_1 = 2.4393$, $\theta_2 = -0.1375$, $\theta_3 = -2.7372$, $\theta_4 = 0.3348$, $\theta_5 = 7.6$, $\theta_6 = 0.0145$, $\theta_7 = 0.0663$, $\theta_8 = -0.0780$, $\theta_9 = 0.0517$, $\theta_{10} = -0.0405$, $\theta_{11} = -0.0141$ and $\sigma = 0.2552$ for AAK; $\theta_1 = 1.6123$, $\theta_2 = -0.1329$, $\theta_3 = -1.8494$, $\theta_4 = 0.2043$, $\theta_5 = 7.6$, $\theta_6 = 0.1427$, $\theta_7 = 0.0489$, $\theta_8 = -0.0864$, $\theta_9 = 0.0466$, $\theta_{10} = -0.0358$, $\theta_{11} = 0$ and $\sigma = 0.2891$ for CEI; and $\theta_1 = 2.0872$, $\theta_2 = -0.1335$, $\theta_3 = -2.5370$, $\theta_4 = 0.3173$, $\theta_5 = 7.6$, $\theta_6 = 0.0770$, $\theta_7 = 0.0578$, $\theta_8 = -0.0884$, $\theta_9 = 0.0329$, $\theta_{10} = -0.0283$, $\theta_{11} = -0.0082$ and $\sigma = 0.2836$ for ZM.

- Use 3 site classes:

Rock $S_S = S_A = 0$.

Stiff soil $S_A = 1$ and $S_S = 0$.

Soft soil $S_S = 1$ and $S_A = 0$.

- Use 3 faulting mechanisms:

Normal AAK: 5 records, CEI: 4 records, ZM: 3 records. $F_N = 1$ and $F_T = F_O = 0$.

Thrust AAK: 48 records, CEI: 31 records, ZM: 76 records. $F_T = 1$ and $F_N = F_O = 0$.

Strike-slip AAK: 20 records, CEI: 60 records, ZM: 42 records. $F_O = 1$ and $F_N = F_T = 0$.

- Focal depths from 3 to 59 km.
- Use data from Iranian Strong-Motion Network (195 different stations) of the Building and Housing Research Center from 1976 to 2012.
- Select data from earthquakes with $M_w > 5$ and $R < 100$ km[54]. Also only select data from stations with known site classification and $M_w$s from Global CMT.
- Data from earthquakes with fault rupture mainly at depths < 15 km.
- High-cut filter with roll-offs of 23 (analogue instruments) and 50 Hz (digital) and cut-offs of 25 (analogue) and 100 Hz (digital). Baseline correct and low-cut filter to exclude data where signal-to-noise ratio < 2. Note that predictions for PGA and PSA< 0.1 s may be affected by filters.
- Update model of Ambraseys et al. (2005a) using the Bayesian approach of Wang and Takada (2009). This model was chosen as prior because: previous work ranked this model highly for use in Iran and the data for evaluation of this model are available (e.g. site classes rather than $V_{s,30}$). Find Ambraseys et al. (2005a) overestimates motions in different areas.
- Split Iran into 3 regions: Azarbayejan-Alborz-Kopeh Dagh (AAK, 73 records), Zagros-Makran (ZM, 121 records) and central-east Iran (CEI, 95 records) and derive models for each.
- Note that little data for most important $M$-$R$ ranges.
- Include $M_w^2$ term to correct for bias outside $M_w$ range of database.
- Do not update $\theta_5$ from Ambraseys et al. (2005a) because approach works for linear coefficients.
- Plot normalised residuals w.r.t. $M_w$ and find no trends and almost zero bias.
- Compare predictions and observations for records from earthquakes with $5.5 \leq M_w \leq 6.5$. Find better match than for original model.
- Apply approach of Scherbaum et al. (2004) to check fit of model to observations. Find a rank of 'B'.

[54]The scatter plots of the data show records from distances > 100 km.

## 2.440 Soghrat and Ziyaeifar (2017)

- Ground-motion model is:

$$\log_{10} Y = b_1 + b_2 M_w + b_3 M_w^2 + (b_4 + b_5 M_w) \log_{10} \sqrt{R^2 + b_6^2} + S_i + f_s F_s + f_{rv} F_{RV} + f_{uu} F_U$$

  where $Y$ is in $\text{cm/s}^2$, $b_1 = -2.237$, $b_2 = 1.695$, $b_3 = -0.131$, $b_4 = -1.407$, $b_5 = 0.063$, $b_6 = 7.5$, $S_1 = 0.250$, $S_2 = 0.221$, $S_3 = 0.281$, $S_{4b} = -0.021$, $f_s = -0.137$, $f_{rv} = -0.124$, $f_{uu} = -0.008$, $\phi = 0.028$ (intra-event) and $\tau = 0.259$ (inter-event) for horizontal PGA; and $b_1 = -0.357$, $b_2 = 0.639$, $b_3 = -0.045$, $b_4 = -1.733$, $b_5 = 0.105$, $b_6 = 7.5$, $S_1 = 0.771$, $S_2 = 0.744$, $S_3 = 0.746$, $S_{4b} = 0.382$, $f_s = 0.527$, $f_{rv} = 0.523$, $f_{uu} = 0.594$, $\phi = 0.052$ (intra-event) and $\tau = 0.271$ for vertical PGA. Also derive model with $S_i$ replaced by $\gamma \log_{10}(V_{s,30}/V_{ref})$, where $b_1 = -2.093$, $b_2 = 1.702$, $b_3 = -0.132$, $b_4 = -1.389$, $b_5 = 0.064$, $b_6 = 7.5$, $\gamma = 0.013$, $f_s = -0.074$, $f_{rv} = -0.061$, $f_{uu} = 0.043$, $\phi = 0.028$ (intra-event) and $\tau = 0.263$ (inter-event) for horizontal PGA; and $b_1 = 0.320$, $b_2 = 0.572$, $b_3 = -0.038$, $b_4 = -1.684$, $b_5 = 0.098$, $b_6 = 7.5$, $\gamma = 0.148$, $f_s = 0.755$, $f_{rv} = 0.751$, $f_{uu} = 0.815$, $\phi = 0.082$ (intra-event) and $\tau = 0.275$ (inter-event) for vertical PGA.

- Use 4 site classes based on Iranian Code of Practice for Seismic Resistant Design:

  I $V_{s,30} > 750$ m/s. Use $S_1$.

  II $375 < V_{s,30} < 750$ m/s. Use $S_2$.

  III $175 < V_{s,30} < 375$ m/s. Use $S_3$.

  IV $V_{s,30} < 175$ m/s. $< 2\%$ of records. Use $S_4$.

  Classification for 318 records is the same as if Eurocode 8 classes had been used. Also derive model using $V_{s,30}$ to characterise sites.

- Use 3 style-of-faulting classes:

  1. Reverse. 14 earthquakes, 158 records. $F_{RV} = 1$ and $F_S = F_U = 0$.
  2. Strike-slip. 11 earthquakes, 65 records. $F_S = 1$ and $F_{RV} = F_U = 0$.
  3. Unknown. 30 earthquakes, 102 records. $F_U = 1$ and $F_{RV} = F_S = 0$.

- Focal depths from 4 to 57.8 km with vast majority $< 20$ km.

- Use data from Azerbaijan-Alborz and Kopeh-Dagh regions recorded by Iranian Strong Motion Network (Building and Housing Research Center).

- Only use data from stations with measured $V_{s,30}$. Also exclude S-wave-triggered records, poor-quality records, records with a single horizontal component and events recorded by only one station.

- $M_w$ for 10 earthquakes with 26 records converted from unknown magnitude scales. Repeat analysis with these removed and find almost no change.

- Most data from $M_w \leq 6.5$ and $R \leq 200$ km. 35% of records from 50–100 km and 38% from $M_w$6.0–6.5.

- Process data using multi-resolution wavelet analysis to remove noise.

- After trial and error fix $b_6 = 7.5$ to stabilise the results.

- Examine inter-event residuals w.r.t. $M_w$ and intra-event residuals w.r.t. $M_w$ and $R$ and find no bias or trend (after binning).

- Note that model for site class IV may not be accurate due to lack of data.

- Compare predictions and observations for earthquakes with $5.7 \leq M_w \leq 6.3$ and find good match.

## 2.441 Zuccolo et al. (2017)

- Ground-motion model is:

$$\log Y = a + bM + c \log R$$

where $Y$ is in $\mathrm{m/s^2}$, $a = -2.1575$, $b = 0.8359$, $c = -1.9690$ and $\sigma = 0.3542$.

- Data from 61 stations on Eurocode 8 class B ($360 \le V_{s,30} < 800\,\mathrm{m/s}$) sites mainly from 33 stations in the Irpinia Seismic Network (ISNet, located in Campania and Basilicata regions) with the addition of data ($M_L > 3$) from other networks. Originally collect data from sites of other classes but as 93% of these accelerograms from class B develop model only using those records.

- Exclude data with focal depth $h > 30\,\mathrm{km}$. $1 \le h \le 28\,\mathrm{km}$ with most 12–20 km.

- Model for use in earthquake early warning system.

- Linearly detrend records. Then bandpass filter (4-pole Butterworth with cut-offs of 0.075 and 20 Hz) and 2% cosine taper. Exclude records with signal-to-noise ratio $< 10$ on either component using the pre-event portion as the noise estimate. Exclude some records from before 2002 due to late triggering.

- Did not include term to account for focal mechanism (normal v strike-slip) because of difficulty in estimating mechanism for small earthquakes immediately after occurrence.

- Regression method gives higher weight (0.7) to data recorded at stations with geotechnical and geophysical measurements compared with sites with only estimated B class (0.3).

- Compare predictions to an independent dataset (data from ISNet from 2015, 262 records from 41 earthquakes, $1.5 \le M_L \le 3.2$, $3 \le r_{hyp} \le 60\,\mathrm{km}$) using the LLH method of Scherbaum et al. (2009). Find LLH of derived model is the lowest of all those GMPEs test using these data.

- Compare predictions and observations for 2 well-recorded earthquakes ($M_L 3.2$ and $M_L 2.1$) and find good fit.

## 2.442 Ameur et al. (2018)

- Ground-motion model is not given here since it requires evaluation of a complex equation that cannot be summarised. Derive model using an adaptive network-based fuzzy inference system and the random-effects algorithm to split the variability into inter- and intra-event components. Provide details but these are not given here.

- Characterise sites by $V_{s,30}$: values 110–1540 m/s.

- Use data from the NGA-West2 database. Exclude earthquakes with focal depth $> 25\,\mathrm{km}$ and aftershocks. Exclude non-free-field stations. Also exclude sites without measured $V_{s,30}$. Most remaining data from Japan, Taiwan and California.

- Provide cumulative distribution functions of dataset. 80% of data from $4.0 \le M_w \le 7.0$, $10 \le r_{jb} \le 200\,\mathrm{km}$ and $210 \le V_{s,30} \le 650\,\mathrm{m/s}$.

- Data from 580 different sites.

- Examine residuals on normal probability plots and find that they conform to the lognormal distribution.

- Test robustness of result by re-deriving model using only half of records. Find predictions are almost unchanged when using only half the records.

- Find limited evidence for nonlinear site amplification.

## 2.443 Bajaj and Anbazhagan (2018)

- Ground-motion model is[55]:

$$
\begin{aligned}
\ln \mathrm{PGA} &= f + F \\
f &= \begin{cases} a_1 + a_2(M - M_h)^2 & M < M_h \\ a_1 + a_2(M - M_h)^2 + a_3(M_{max} - M) & M \geq M_h \end{cases} \\
F &= \begin{cases} a_4 + a_5(M - M_h)\ln R + a_6 R & R < R_h \\ a_4 + a_5(M - M_h)\ln R + a_6 R + a_7 \ln(R + R_h) & R \geq R_h \end{cases}
\end{aligned}
$$

  where PGA is in g, $a_1 = 5.391 \pm 0.28$, $a_2 = 0.121 \pm 0.01$, $a_3 = 0.356 \pm 0.025$, $a_4 = -0.465 \pm 0.008$, $a_5 = 0.056 \pm 0.01$, $a_6 = -0.007 \pm 0.0$, $a_7 = -0.013 \pm 0.0$, $M_h = 6.5$, $R_h = 300$, $M_max = 8$, $\tau = 0.52 \pm 0.063$ (inter-event) and $\sigma = 0.81 \pm 0.036$ (total).

- Data from rock and soil sites but do not include site terms in model because of lack of data.

- Data from Indian Himalaya taken from PESMOS, Virtual Data Centre (VDC) and Indian and GNSS network (ISGN).

- Data from VDC baseline corrected and bandpass filtered between 0.75–0.9 and 25–27 Hz. Data from PESMOS and ISGN bandpass filtered with cut-offs of 0.1 and 25 Hz using 4th order Butterworth filter.

- Reject data from $M_w < 5$ and $> 200$ km because of low signal-to-noise ratios.

- Use $r_{hypo}$ because insufficient information on rupture planes.

- Use Monte Carlo method to estimate standard errors in coefficients.

- Choose functional form through residual analysis of previously-published models.

## 2.444 Chousianitis et al. (2018)

- Ground-motion model is:

$$\log Y = a + bM + c \log \sqrt{R^2 + h^2} + d\sqrt{R^2 + h^2} + (es) + (fm)$$

  where $Y$ is in cm/s$^2$; $a = 0.787$, $b = 0.478$, $c = -1.092$, $d = -0.0044$, $e = 0.096$, $f = 0.146$, $h = 10.688$ and $\sigma = 0.285$ including site and mechanism terms; $a = 0.829$, $b = 0.474$, $c = -1.062$, $d = -0.004$, $e = 0.082$, $h = 10.772$ and $\sigma = 0.291$ including only site term; $a = 0.881$, $b = 0.479$, $c = -1.107$, $d = -0.0043$, $f = 0.142$, $h = 10.802$ and $\sigma = 0.289$ including only mechanism term; and $a = 0.907$, $b = 0.474$, $c = -1.074$, $d = -0.004$, $h = 10.763$ and $\sigma = 0.296$ including neither term.

- Use 2 site classes:

  $s = 0$ NEHRP class B (rock).

  $s = 1$ NEHRP class C and D (stiff and soft soil).

  Also consider separate terms for classes C and D.

- Use 2 faulting mechanisms:

  $m = 0$ Normal.

[55] In the article there is an extra opening bracket in the equations for $F$ but not a closing bracket so it could be that the term $a_4 + a_5(M - M_h)$ could be all in brackets.

$m = 1$ Strike-slip and thrust.

- Use data from 1973 to 2014. Filter records not already processed using a bidirectional 2nd-order Butterworth filter with cut-offs of 0.2–0.3 Hz and 25–30 Hz after zero-padding.

- Use $r_{epi}$ because lack of information on rupture planes for most moderate and small events. Note that this is a limitation of the model but because vast majority of earthquakes have $M_w < 6.4$ it is not a major limitation.

- Do not use $r_{hypo}$ because of poorly-resolved focal depths.

- Split data into training and validation datasets. Regression performed on training datasets, which includes only earthquakes recorded by $> 1$ station. Training dataset includes records from 124 different stations. Validation dataset includes singly-recorded earthquakes plus a few records from training dataset so that training and validation datasets have same distance range. Validation dataset has 254 records from 123 earthquakes and 45 different stations. No data in validation dataset with $r_{epi} < 5$ km.

- Note potential limitation of dataset when using 2-stage regression is number of events with only 2 records, which provide weak constraints on separation into inter- and intra-event variabilities.

- Note few records from $M_w > 6$ and $r_{epi} < 20$ km so lack of constraint in model for these magnitudes and distances.

- Check significance of coefficients using Student's t-test and goodness of fit using efficiency coefficient.

- In total consider 24 alternative functional forms. In addition to 4 reported above also consider using $h$ or not, using $d$ or not and using 3 site classes. Coefficients reported in electronic supplement but not reported here due to lack of space. Coefficients reported above have the lowest $\sigma$ and highest efficiency coefficient.

- Consider residuals w.r.t. $M_w$ and $r_{epi}$ and the 'studentized' residuals w.r.t. predicted PGA, which use to detect outliers. Find no trends nor outliers. Plot probability density function graphs and normal quantile-quantile plots. Find that the normality assumption is justified.

## 2.445 D'Amico et al. (2018a)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10} Y &= a + F_D + F_M + F_S + F_{sof} \\
F_D &= [c_1 + c_2(M - M_{ref})] \log_{10}\left(\frac{\sqrt{R^2 + h^2}}{R_{ref}}\right) \\
F_M &= \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & M < M_h \\ 0 & M \geq M_h \end{cases} \\
F_S &= s_i S_i \\
F_{sof} &= f_j E_j
\end{aligned}
$$

where $Y$ is in cm/s$^2$, $M_{ref} = 5.0$, $R_{ref} = 1.0$, $M_h = 6.75$, $a = 3.863$, $b_1 = 0.004$, $b_2 = -0.070$, $c_1 = -2.039$, $c_2 = 0.222$, $H = 11.91$ km, $f_{NF} = 0.036$, $f_{SS} = -0.036$, $s_{GR} = 0.479$, $s_{ST} = 0.475$, $s_{SO} = 0.617$, $\phi = 0.107$ (intra-event), $\tau = 0.322$ (inter-event) and $\sigma = 0.339$ (total).

- Distribution w.r.t. Eurocode 8 site classes shows vast majority of records from classes A or B based on surface geological information (few measurements of $V_{s,30}$.

Identify 22 reference rock (RR) sites based on the lowest misfit between recorded response spectra and predicted response spectra from Bindi et al. (2011a) GMPE for Italy. Find a lower amplification for these stations than those used to derive the Bindi et al. (2011a) model. Find a number of Eurocode A sites in Sicily are not classed as RR sites and a number of Eurocode B and C sites in Calabria are.

Use 4 site classes:

RR Reference rock. About 160 records.

GR Eurocode 8 class A sites but not RR. Use $S_{GR}$. About 300 records.

ST Stiff soil: Eurocode 8 class B and E sites. Use $S_{ST}$. About 290 records.

SO Soft soil: Eurocode 8 class C and D sites. Use $S_{SO}$. About 90 records.

- Use 3 mechanisms (exclude data from reverse events because poorly represented in dataset):

  NF Normal. Use $F_{NF}$

  SS Strike-slip. Use $F_{SS}$

  UN Unknown.

  Distribution of complete database w.r.t. mechanism is: normal (43 events), strike-slip (22 events), thrust (13 events) and unknown (98 events).

- Data from southern Calabria and Sicily (Italy) from 1978 to 2016 from about 230 different stations of 4 networks: Rete Accelerometrica Nazionale, Italian National Seismic Network, Mediterranean Very Broadband Seismographic Network and Calabria-Appennine-Tyrrhenian/Subduction-Collision-Accretion Network (2003–2006). About 1200 records from accelerometric stations and about 2000 from velocimetric stations.

- Selection criteria are: 35.6-40.2° N and 12-18° E; $r_{epi} \leq 200$ km and $M > 3.5$.

- Uniformly process all records using the tool of the Engineering Strong Motion database.

- More than 90% of records from $M \leq 5$.

- Roughly uniform distribution w.r.t. distance.

- Select a calibration subset by excluding records from $M \leq 4.0$, focal depth $\geq 25$ km and volcanic events of Mount Etna and the Aeolian Islands with depth $< 5$ km.

- Data from 194 different stations in calibration subset.

- Examine residuals w.r.t. magnitude and distance and find no trends.

- Model poorly constrained for $< 10$ km because of lack of data.

- Compare predictions and observations for $M4.0$ and $M5.0$ and find good fit.

## 2.446 Erken et al. (2018)

- Ground-motion model is:

$$\begin{aligned} \ln \mathrm{PGA} &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_v \ln \frac{V_{s,30}}{V_{ref}} + F_{NL} \\ r &= \sqrt{R_{jb}^2 + h^2} \end{aligned}$$

where PGA is in g, $V_{ref} = 760\,\mathrm{m/s}$, $F_{NL}$ is the nonlinear site term from Boore and Atkinson (2008); $b_1 = 1.835$, $b_2 = 1.034$, $b_3 = -0.252$, $b_5 = -1.397$, $b_v = -0.069$, $h = 9.718$ and $\sigma = 0.730$ for rock; and $b_1 = 2.135$, $b_2 = 1.008$, $b_3 = -0.163$, $b_5 = -1.380$, $b_v = -0.133$, $h = 10.510$ and $\sigma = 0.630$ for soii.

- Use 2 site classes:

  Rock NEHRP site classes B and C. $362 \leq V_{s,30} \leq 1602\,\mathrm{m/s}$. 220 records. 68 stations.

  Soil NEHRP site class D. $175 \leq V_{s,30} \leq 359\,\mathrm{m/s}$. 173 records. 42 stations.

  Combined classes B and C and did not use data from classes A and E due to lack of data.

- Data from earthquakes occuring in NW Anatolia (39.39–41.03N and 26.04–31.73E) between 1999 and 2006 plus 33 records from mainshocks worldwide,
- Data from 76 different stations in Turkey and 34 different stations elsewhere.
- Select data with PGA $> 0.8$ gal and $M_w > 4.0$.
- Except for Kocaeli ($M_w 7.4$) and Duzce ($M_w 7.1$) earthquakes all Turkish earthquakes have $M_w \leq 5.7$ hence include data from elsewhere (USA, Japan and Taiwan).
- Focal depths of Turkish earthquakes between 4.9 and 18.5 km and of foreign earthquakes between 5.5 and 17.9 km.
- Baseline correct and bandpass filter data with cut-offs of 0.1 and 25 Hz.
- Most data from 10–200 km.
- Present residuals w.r.t. $M_w$, $r_{jb}$ and $V_{s,30}$ and find no trends.

## 2.447 Felicetta et al. (2018)

- Ground-motion model is the same as Bindi et al. (2011a) (see Section 2.343) but with different coefficients. Using 5 site classes (MOD1): $a = 3.478$, $c_1 = -1.734$, $c_2 = 0.378$, $h = 8.119$, $c_3 = -1.08 \times 10^{-3}$, $b_1 = -0.166$, $b_2 = -0.062$, $b_3 = 0$, $s_A = 0$, $s_B = 0.085$, $s_C = 0.248$, $s_D = 0.240$, $s_E = 0.477$, $f_{NF} = -0.037$, $f_{SS} = 0.099$, $f_{TF} = -0.062$, $f_{UN} = 0$, $\tau = 0.172$ (inter-event), $\phi = 0.298$ (intra-event) and $\sigma = 0.344$ (total); and using 6 site classes (MOD2): $a = 3.415$, $c_1 = -1.876$, $c_2 = 0.438$, $h = 10.095$, $c_3 = -9.75 \times 10^{-4}$, $b_1 = -0.266$, $b_2 = -0.065$, $b_3 = 0$, $s_{AA} = 0$, $s_A = 0.211$, $s_B = 0.227$, $s_C = 0.386$, $s_D = 0.401$, $s_E = 0.614$, $f_{NF} = -0.041$, $f_{SS} = 0.104$, $f_{TF} = -0.063$, $f_{UN} = 0$, $\tau = 0.161$ (inter-event), $\phi = 0.299$ (intra-event) and $\sigma = 0.340$ (total).
- Reassess the 47 sites currently classified as Eurocode A in Italian strong-motion database (many of sites originally classified by Bindi et al. (2011a) as Eurocode A had subsequently been reclassified). Use 6 proxies based on geological, topographical and geophysical indicators: 1) $V_{s,30} \geq 800\,\mathrm{m/s}$, 2) rock conditions according to surface geology, 3) flat topographic surface, 4) absence of interaction with structures, 5) flat H/V spectral ratio of noise measurements without directional effects and 6) flat or moderately broadband H/V response spectral ratio of earthquake waveforms. Require 4 out of 6 criteria to be satisfied for a site to be classed as reference rock. Class 23 stations as reference rock.
- Derive two models: MOD1) use 5 site classes with coefficient for class A constrained to zero; and MOD2) use 6 site class, where generic rock sites (A) and reference rock sites (Aref) are separated and coefficient for Aref is constrained to zero.
- Also derive $\sigma$ for the rock site classes separately.
- Find significant reduction in predicted ground motions and standard deviations for reference rock sites.

## 2.448 Javan-Emrooz et al. (2018)

- Ground-motion model for horizontal PGA:

$$\begin{aligned}\log \mathrm{PGA}_H &= \log\left[\log\left(\mathrm{e}^{-\sqrt{S}/8}\sqrt{\mathrm{e}^{M/4}-\mathrm{e}^{\sqrt{S}/4}}\right)\right] - \log[-\ln\left(R-\sqrt[3]{M+1+\sqrt{1.122M+1}}\right)\\ &\quad + R + F] + \log(M) + \log(\sqrt{M}) + 3\end{aligned}$$

  where $\mathrm{PGA}_H$ is in cm/s$^2$ and $\sigma = 0.295$ for training set and $\sigma = 0.300$ for testing set. Ground-motion model for vertical PGA:

$$\log \mathrm{PGA}_V = \log\left(\frac{\sqrt[6]{S}}{R}\right) + \log\left(S + \frac{1}{\sqrt[3]{\mathrm{e}^{\log[\ln(M)^2]}}}\right) + \frac{\ln[(\ln(M)^3 - S)^2]}{2} + \frac{1}{\sqrt[3]{R} + F} + 1$$

  where $\mathrm{PGA}_V$ is in cm/s$^2$ and $\sigma = 0.295$ for training set and $\sigma = 0.315$ for testing set.

- Use 2 site classes because of limited number of records:

  1. Rock/stiff soil, $V_{s,30} \geq 375$ m/s. $S = 1$.
  2. Soil, $V_{s,30} < 375$ m/s. $S = 2$.

  Use method based on topographic slope to classify stations without measurements.

- Use 2 faulting mechanisms because only 9 records from normal-faulting events:

  1. Reverse, rake angles between 30 and 150°. $F = 1$.
  2. Strike-slip, rake angles within 30° of horizontal. $F = 0.25$.

- Data from 1976 to 2016. Mainly from the Building and Housing Research Center (Iran) (419 records) and the Disaster and Emergency Management Presidency of Turkey (41 records) with 2 records from Armenia and 1 from Georgia. Records mainly from SSA-2 instruments (385 records) with some from SMA-1 (34), CMG-5TD (32), GSR-16 (6), SMACH (5) and SM-2 (1).

- Use an analysis of variance technique (Douglas, 2004b) to confirm that there is no significance difference in ground motions in Alborz-Azarbayejan and Kopeh Dagh regions. Find some significant differences between ground motions in Iran and Turkey/Armenia/Georgia so derive additional models using only Iranian data (not reported here due to lack of space).

- Only use data from $M_w \geq 4.5$ to concrete on data with engineering interest and because most reliable.

- Use $r_{epi}$ because of lack of information on source geometries for many events.

- Only use data from $r_{epi} \geq 2$ km because of minimum error of 2 km in $r_{epi}$. Exclude data from $r_{epi} > 100$ km following arguments of Ambraseys et al. (2005a) (see Section 2.237).

- Mean $M_w$ of the data is 5.39 and mean $r_{epi}$ of the data is 45.41 km.

- Use vector sum of both horizontal components because geometric or arithmetic means underestimate peak motion.

- Linear baseline correct records. Bandpass filter using acausal 4th-order Butterworth filter with cut-offs chosen based on visual inspection of Fourier amplitude spectra. Low cut-off frequencies between 0.1 and 1 Hz, which may be different for the 3 components. Use a uniform high cut-off frequency of 25 Hz.

- Use Prefix Gene Expression Programming (using software HSGEP), a form of genetic algorithm, to find the most appropriate functional form based on the independent variables and various mathematical operators. Find models that give highest fitness (lower error, using various measures).
- Use a random 80% in training phase and the remaining 20% in the testing phase.
- Because of a lack of near-source data magnitude-distance saturation not apparent.
- Examine residuals w.r.t. $r_{epi}$ and $M_w$ for both training and testing sets and find no trends.

## 2.449 Ktenidou et al. (2018)

- Ground-motion model is:

$$\ln \mathrm{PGA} = b_1 + b_2 M^2 + [b_3 + b_4(M-4)] \ln(R_{rup} + 10) + b_5 R_{rup} + b_6 S + b_7$$

  Do not report coefficients as aim of study is to examine the residuals and the various components of variability.
- Characterise sites by $V_{s,30}$. 2 sites classed as Eurocode A, 6 as Eurocode B and the rest as Eurocode C.
- Data from 3D strong-motion array of 16 surface and 6 downhole stations in Mygdonia valley. Number of records per station is between 9 and 90 with an average of about 33.
- Records filtered using acausal 4th-order bandpass Butterworth filter with a threshold signal-to-noise ratio of 3. Lowest usable frequencies from 0.1 to 3 Hz (decreasing with magnitude) and highest usable frequencies from 10 to 50 Hz.
- Exclude data from before 2003 as most data from low-resolution instruments and not all array operational. Exclude data from $> 220$ km. Exclude records without both horizontal components. Exclude data from events with focal depths $> 25$ km to reject subduction events. Finally exclude records from earthquakes not recorded by $\geq 3$ stations because this could increase $\tau$.
- Examine influence of various steps on $\tau$, $\phi$, $\sigma$ and $\phi_{SS}$.
- Find improving seismological data (going from routine locations and magnitudes to reassessed values) reduces $\tau$ by 30–50%. Most of this reduction is due to better magnitude estimates.
- Find improving site information (i.e. changing the site term from $S = 0$ to more complex forms: binary soil/rock, $V_{s,30}$ and finally individual site terms) reduces system site-to-site variability $\phi_{S2S}$ by 20–30%.
- Find through sensitivity checks (increasing the minimum number of records to 5, 8, 10, 12 and 14) that 3 records per event is sufficient for robust results.
- Examine $\phi_{SS,S}$ and $\delta S2S$, the correlations between them and with geology for the various stations.

## 2.450 Laouami et al. (2018a,b)

- Ground-motion model is:

$$\log_{10} \mathrm{PSA} = aM + bd - \log_{10} d + c_1 + c_2 + c_3$$

  where PSA is in g, $a = 0.3872$, $b = -0.0009$, $c_1 = 1.0240$, $c_2 = 1.0870$, $c_3 = 1.1390$ and $\sigma = 0.2847$.
- Use 3 site classes following approach of Zhao et al. (2006) (see Section 2.248) that uses horizontal-to-vertical response spectral ratios:

Rock SC-I. 844 in larger dataset.

Stiff soil SC-II. 390 in larger dataset.

Soft soil SC-III and SC-IV. 414 in larger dataset.

Originally had very soft soil category but insufficient data. Use this approach because $V_{s,30}$ lacking and because it accounts for predominant period of the site. Find clear differences in average H/V ratios among the different classes.

- Focal depths 0–29 km with most around 10 km, which agrees with seismotectonics of Algeria.
- Combine data from Algeria, Europe (Ambraseys et al., 2000) and western USA (USGS and CDMG) because insufficient data from larger events to develop model solely using Algerian data. Based on a residual analysis, find using only Algerian data leads to over-prediction of ground motions from larger earthquakes.
- Algerian data from SMA-1, SSA-1 and Etna instrumentsv from 1980 to 2014. Instrument and baseline correct records. Then bandpass Ormsby filter records using cut-off of 25 Hz (roll-off width of 3 Hz), and 0.12–0.2 Hz (with roll-off width of 0.06 Hz) for digital and 0.2–0.3 Hz (with roll-off width of 0.1 Hz) for analogue records.
- Remove data from distances likely beyond distance at which instrument triggering is likely using: 1) distances suggested Boore et al. (2014) and 2) distances estimated by predicted PGAs$< 10\,\mathrm{cm/s^2}$ using model of Fukushima et al. (2003).
- Find no trends in residuals, including w.r.t. region (Algeria, Europe or W. USA).

## 2.451 Mahani and Kao (2018)

- Ground-motion model is:

$$\log Y = c_0 + c_1 M + b \log R$$

where $Y$ is in $\mathrm{cm/s^2}$, $c_0 = -0.13$, $c_1 = 0.77$, $b = -2.63$, $\sigma_{intra} = 0.22$ (intra-event), $\sigma_{inter} = 0.19$ (inter-event) and $\sigma_{total} = 0.29$ (total) for the Graham area; $c_0 = -1.14$, $c_1 = 0.94$, $b = -1.78$, $\sigma_{intra} = 0.39$ (intra-event), $\sigma_{inter} = 0.13$ (inter-event) and $\sigma_{total} = 0.41$ (total) for the Septimus area; and $c_0 = -0.78$, $c_1 = 0.88$, $b = -2.12$, $\sigma_{intra} = 0.31$ (intra-event), $\sigma_{inter} = 0.27$ (inter-event) and $\sigma_{total} = 0.41$ (total) for the combined dataset.

- Correct data to $V_{s,30} = 760\,\mathrm{m/s}$ using linear site factors of Boore et al. (2014). Estimate $V_{s,30}$ using the horizontal-to-vertical ratio of the Fourier amplitude spectra. All sites classified as either NEHRP categories C or D.
- Data of potentially-induced earthquakes from wastewater disposal and hydraulic fracturing recorded by networks operated by energy companies and stations of the Canadian National Seismic Network in Montney Play (British Columbia, Canada) area.
- Correct data for instrument response and then high-pass Butterworth filter the data with corner frequency of 0.1 Hz. Corner frequency chosen from qualitative analysis to remove long-period trends from records.
- Most data from $M < 2$ and focal depths between 3 and 4 km. No events with depth $> 8$ km.
- Do not include anelastic attenuation term in model because data from relatively short distances. Do not include effective depth parameter to model saturation because earthquakes are small and effect not observed in data.

- Examine residuals w.r.t. $M$ and $R$. For the Graham area find no trends but for the Septimus area find evidence for significant under- and over-prediction at some distances.

- Find that in general ground motions in both areas are similar for $M \geq 2.5$. Therefore, derive model for combined data but only using data from $M \geq 2.5$. No trends seen in residuals for this combined model even for the Septimus data.

## 2.452 Rahpeyma et al. (2018)

- Ground-motion model is:

$$\log \mathrm{PGA} = \beta_1 + \beta_2 M + \beta_3 \log_{10} R + \beta_4 D$$

PGA is in cm/s$^2$, $\beta_1 = 0.8807$, $\beta_2 = 0.7056$, $\beta_3 = -2.8645$, $\beta_4 = 0.0923$, $\tau = 0.1977 \pm 0.0067$ (inter-event), $\phi_{S2S} = 0.0915 \pm 0.0240$ (site-to-site), $\phi_{SS} = 0.1164 \pm 0.0032$ (single-station intra-event) and $\phi_R = 0.0577 \pm 0.0017$ (remaining intra-event). Also report station effects but not reported here due to space constraints.

- Focal depths, $D$, between about 0 and 9 km.

- Data from 10 different stations of ICEARRAY I, which are all located on a lava layer.

- Remove poor quality records.

- All data from aftershocks of 2008 Ölfus earthquake ($M_w$6.3).

- Use a Bayesian hierarchical model to determine the various components of ground-motion variability: event, station, event-station and unexplained effects. Use a Matérn covariance function (with 3 parameters: decay, smoothness and amplitude parameters) to model a mean-zero Gaussian spatial fields. Use a Markov chain Monte Carlo to determine the coefficients.

- Verify that the determined coefficients and variabilities are stable.

- Examine inter- and intra-event residuals w.r.t. $M_L$, $R$, $D$ and back-azimuthal angle and find no trends.

- Examine correlations between station effects. Find effects are highly correlated for close-by stations.

## 2.453 Sahakian et al. (2018)

- Ground-motion model is:

$$\begin{aligned}
\ln \mathrm{PGA} &= a_1 + a_2 M + a_3 (8.5 - M)^2 + a_4 \ln R + a_5 R_{rup} + a_6 \ln(V_{s,30}/V_{ref}) \\
R &= \sqrt{R_{rup}^2 + 4.5^2}
\end{aligned}$$

where PGA is in g. Derive models with and without $a_6$ constrained to zero. Model A6 (least-squares): $a_1 = 2.45$, $a_2 = 0.42$, $a_3 = -0.17$, $a_4 = -1.73$, $a_5 = -0.0056$, $a_6 = 0.56$, $\sigma = 0.9$ (total), $\tau = 0.48$ (inter-event), $\phi_S = 0.65$ (intra-event) and $\phi_{SS} = 0.46$ (single-station intra-event). Model F5 (the authors' preferred model): $a_1 = -4.23$, $a_2 = 1.31$, $a_3 = -0.09$, $a_4 = -1.2$ (fixed *a priori*), $a_5 = -0.02$, $a_6 = 0$, $\sigma = 0.87$, $\tau = 0.34$, $\phi_S = 0.67$ and $\phi_{SS} = 0.44$. Provide coefficients for 11 other models but these are not given here due to space limitations.

- Characterise sites by $V_{s,30}$ (measured at 32 stations and estimated using terrain-based proxies at rest). $V_{s,30}$ between about 200 and about 1100 m/s with most 300–700 m/s.

- Data from Anza, San Jacinto Fault Zone, Caltech, UC Santa Barbara and Plate Boundary Observatory seismic networks from 2013. Most instruments are STS-2s with Quanterra digitizers.

- Vast majority of data from $1 \leq M_w \leq 2$ and from $r_{rup} < 30$ km. Very few events have $M_w > 3$.

- Focal depths between about 0 and about 25 km with vast majority between 5 and 20 km.

- Data from 78 different stations. All events recorded by $\geq 5$ stations.

- High-pass filter records with cut-off of 0.5 Hz to remove noise but preserve PGAs. Automatically find PGAs using measured or estimated P- and S-wave arrivals at each station. Compute signal-to-noise ratios between PGA and maximum-amplitude in noise window before P-wave arrival.

- Because all events are small, consider only linear $V_{s,30}$ term and assume $r_{rup} = r_{hypo}$.

- Derive models to investigate the path component of ground-motion variability for building a non-ergodic model.

- Compare coefficients, residuals and variabilities computed using pooled ordinary least-squares and mixed-effects maximum-likelihood regression.

- Often find that using mixed-effects regression $a_4$ and $a_5$ are unrealistic because these terms are highly correlated so fix *a priori* certain coefficients.

- Find very weak correlation between residuals and $V_{s,30}$, which relate to homogeneity of site response in region and perhaps site amplification for this region may be better correlated with deeper structure than modelled by $V_{s,30}$. Provide individual average site terms and standard errors from the residuals for considered stations as believe more useful than $V_{s,30}$-based term.

## 2.454 Sharma and Convertito (2018)

- Ground-motion model is:
$$\log Y = a + bM + c \log \sqrt{R^2 + h^2} + es_j$$
where $Y$ is in m/s$^2$, $a = -4.976 \pm 0.013$, $b = 1.281 \pm 0.006$, $c = -1.660 \pm 0.008$, $h = 1.485 \pm 0.036$, $e = 0.161 \pm 0.001$, $\tau = 0.237$ (inter-event), $\phi = 0.283$ (intra-event) and $\sigma = 0.370$.

- Focal roughly uniformly distributed between 0 and 5 km.

- Update of Sharma et al. (2013) (see Section 2.378) with much larger set of records, retrieved from the period 24/07/2007 to 18/11/2010.

- Data from 29 different stations.

- Data roughly uniformly distributed for all $M_w$ and $R_{hypo}$ up to about 20 km. Only a small proportion of data for larger distances.

- Only use data with signal-to-noise ratio > 10 in frequency range 0.5–35 Hz. Instrument correct and remove mean and trend from records. Bandpass filer with zero-phase shift and 4-pole Butterworth filter with cut-offs of 0.7 and 35 Hz. Retain waveforms within the interval: origin time and time corresponding to 98% of the total energy (to remove coda). Taper signal with a 0.1% cosine-taper function. Then differentiate the records and filter again to remove noise introduced due to differentiation.

- Do not include $M^2$ term because of theoretical and observational reasons.

- Site terms ($s_j$) derived from residuals using same approach as Sharma et al. (2013). Find that addition of these terms improve fit to data. Do not report $s_j$ here due to lack of space.

- Find no significant trends in residuals w.r.t. $M_w$ and $r_{hypo}$.

- Find positive trend in residuals w.r.t. focal depth.

## 2.455 Shoushtari et al. (2018)

- Ground-motion model is (chosen after testing various functional forms):

$$\log Y = aM + bR - \log(R + c10^{aM}) + d + S_k$$

where $Y$ is in cm/s$^2$, $a = 0.4683$, $b = -0.002159$, $c = 0$, $d = 0.6524$, $S_B = -0.2571$, $S_C = 0.1464$, $S_D = 0.3654$, $S_E = 0.3428$ and $\sigma = 0.387$.

- Use 4 NEHRP site classes:

  B Rock, $760 < V_{s,30} \leq 1500$ m/s. 11 records from Malaysia. Use $S_B$ term.

  C Hard soil/soft rock, $360 < V_{s,30} \leq 760$ m/s. Use $S_C$ term.

  D Medium soil, $180 < V_{s,30} \leq 360$ m/s. Use $S_D$ term.

  E Soft soil, $V_{s,30} < 180$ m/s. 5 records from Malaysia. Use $S_E$ term.

  Classification for Malaysian stations done using geological description.

- Develop model for use in assessing hazard from distant Sumatran earthquakes. Because available data from this region is sparse also use data from Japan, which believe is tectonically similar. Data from 16 stations in Malaysia.

- Partner model to Shoushtari et al. (2016) (see Section 2.416) for intraslab events.

- Consider events with thrust mechanisms on shallow dipping planes with focal depths $\leq 50$ km as interface.

- Focal depths between 12 and 50 km.

- Process records using acausal 4th-order bandpass Butterworth filter after zero-padding and cosine tapering.

- Data roughly uniformly distributed w.r.t. distance and magnitude.

- Examine residuals w.r.t. magnitude and distance and find no trends.

- Compare predictions and observations (including one from Singapore, which is not used to derive model) binned by magnitude interval. Find good match.

- State that in future would recommend using two-stage or maximum-likelihood regression techniques.

## 2.456 Wen et al. (2018)

- Ground-motion model is:

$$\ln Y = a_1 + a_2 M_s + a_3 \ln(R_{JB} + a_4 M_s) + a_5 R_{JB} + a_6 \ln(V_{S30})$$

$Y$ is in unknown units, $a_1 = 0.5258$, $a_2 = -1.7383$ (sic), $a_3 = -1.0153$, $a_4 = 0.4079$, $a_5 = -0.0006$, $a_6 = -0.179$, $\tau = 0.350$ (inter-event), $\phi = 0.0.567$ (intra-event), $\sigma = 0.666$ (total), $\sigma_{SS} = 0.586$ (single-station) and bracketed $\sigma_{SS} = 0.508$ (see below).

- Use $V_{s,30}$ to characterise sites. $V_{s,30}$ estimates often from extrapolated profiles shallower than 30 m or proxies. $227 \leq V_{s,30} \leq 649$ m/s with vast majority in range $240 \leq V_{s,30} \leq 480$ m/s.
- Focal depths $\leq 30$ km.
- Derive model to examine single-station $\sigma$. Note that model is not expected to be used for engineering purposes.
- Data from National Strong-Motion Observation Network System from end of 2007 to end of 2015. 125 events are Wenchuan aftershocks, 39 are Lushan aftershocks and 22 are other events in Sichuan region.
- Exclude data with: $r_{jb} > 200$ km, $M_s > 7.0$, $M_s < 4.0$, zero focal depths and stations with unknown $V_{s,30}$. Only use a single record from the same site and same event. Only use 3-component records. Exclude poor-quality records (e.g. multiple events, spikes, noise or very high/low amplitudes) after visual inspection. Exclude events with $< 4$ records.
- Data from 103 different stations.
- Believe higher $\phi_{SS}$ found may be due to heterogeneous propagation medium in region (boundary of Sichuan basin/eastern margin of Tibet plateau) and/or use of aftershock records.
- Reasonably uniform distribution of data w.r.t. $M_s$ and $r_{jb}$ except all records with $r_{jb} < 10$ km are from $M_s < 5.5$.
- $r_{jb}$ estimated from hypocentral locations and focal mechanisms or locations of seismogenic faults.
- Bandpass filter using acausal Butterworth filter with low cut-offs of 0.06 to 0.35 Hz (depending on magnitude) and uniform high cut-off of 30 Hz. Visually inspect Fourier amplitude spectra and integrated displacements to check selected cut-offs.
- Examine unit covariance between pairs of coefficients to check if necessary and resolvable.
- Compute inter- and intra-event residuals. Find no clear trends. Examine average site residuals w.r.t. $V_{s,30}$ and find no trends.
- Consider the 47 stations (contributing 1463 records) that have recorded $\geq 10$ records. 91 records from one station. Compute $\delta S2S$ and $\phi_{ss,s}$. Find considerable variation, which relate to various sources and paths. Compute $\phi_{SS}$ for four distance ranges: $< 50$ (403 records), 50–100 (504), $100 - 150$ (396) and $> 150$ km (160). Find higher values for shortest bin. Compute bracketed $\phi_{ss}$ values using records obtained at stations within a 10° bracket of event-to-station azimuths, thereby excluding sparse ray paths. Use data from 327 records at 21 of 47 stations to compute these bracketed $\phi_{ss}$ values. Find considerable reduction in values w.r.t. unbracketed estimates.
- Compute event-corrected single-path single-station standard deviations $\phi ss - sp$ using clusters of Lushan aftershocks recorded by several stations. Find considerable reduction in $\phi$ over total and single-station values.

## 2.457 Zafarani et al. (2018)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10} Y &= e_1 + F_D + F_M + F_S + F_{sof} \\
F_D &= [c_1 + c_2(M - M_{ref})] \log_{10}\left(\sqrt{R_{JB}^2 + h^2}/R_{ref}\right) \\
F_M &= \begin{cases} b_1(M - M_h) + b_2(M - M_h)^2 & \text{for} \quad M \leq M_h \\ b_3(M - M_h) & \text{otherwise} \end{cases} \\
F_S &= s_j C_j \\
F_{sof} &= f_j E_j
\end{aligned}
$$

  where $Y$ is in cm/s$^2$, $R_{ref} = 1.0$, $M_{ref} = 5.0$, $M_h = 5.0$, $e_1 = 2.880$, $b_1 = 0.554$, $b_2 = 0.103$, $b_3 = 0.103$, $c_1 = -0.960$, $c_2 = 0.0$, $h = 7.283$, $f_{SS} = -0.030$, $f_{TF} = -0.039$, $f_{UN} = 0$, $s_A = 0$, $s_B = 0.027$, $s_C = 0.010$, $s_D = -0.017$, $\tau = 0.094$ (inter-event), $\phi = 0.283$ (intra-event) and $\sigma = 0.298$ (total).

- Use 4 site classes:

  A About 400 records. $C_A = 1$, $C_B = C_C = C_D = 0$.

  B About 700 records. $C_B = 1$, $C_A = C_C = C_D = 0$.

  C About 400 records. $C_C = 1$, $C_A = C_B = C_D = 0$.

  D About 100 records. $C_D = 1$, $C_A = C_B = C_C = 0$.

  About half the classifications based on H/V spectral ratios and geology.

- Use 3 faulting mechanisms:

  Thrust About 60 earthquakes and about 700 records. $E_{TF} = 1$, $E_{SS} = E_{UN} = 0$.

  Strike-slip About 40 earthquakes and about 400 records. $E_{SS} = 1$, $E_{TF} = E_{UN} = 0$.

  Undefined About 100 earthquakes and about 500 records. $E_{UN} = 1$, $E_{SS} = E_{TF} = 0$.

- Exclude data from $M_w < 4$, normal faulting earthquakes, earthquakes with focal depths $> 30$ km and records from $r_{jb} > 200$ km because of their scarcity and minor significance for hazard analysis for Iran.

- Include only records from earthquakes with $\geq 2$ high-quality records and known site conditions.

- Instrument and baseline correct. Apply multi-resolution wavelet analysis to remove noise.

- Scarce data for $M < 5.5$ and $r_{jb} > 100$ km so model insufficiently constrained for those magnitudes and distances.

- 6 events with $6.5 < M_w \leq 7$ and 7 events with $M_w > 7$ but often with a lack of near-source records.

- Preliminary regressions gave non-physical negative $c_2$ values. Believe due to lack of data from $M < 5$ and $r_{jb} > 80$ km. Therefore, constrain $c_2$ to zero and re-run regression.

- Examine inter- and intra-event residuals w.r.t. $M_w$ and $r_{jb}$ respectively. Find no trends, although some evidence for larger variability for smaller events.

- Do not model nonlinear soil behaviour because of believe its influence is minimal in the dataset.

## 2.458 Ashadi and Kaka (2019)

- Ground-motion model is:

$$\log_{10} Y = C_1 + C_2 M + C_3 H + C_4 R - 10^{(C_5 + C_6 M)} \log_{10} R + C_7 S_t$$

  where $Y$ is in cm/s$^2$, $C_1 = -0.7957$, $C_2 = 0.3418$, $C_3 = 0.0016$, $C_4 = -0.0019$, $C_5 = 0.4669$, $C_6 = -0.2020$, $C_7 = 0.1789$ and $\sigma = 0.4293$ for interface; and $C_1 = -1.5737$, $C_2 = 0.5367$, $C_3 = 0.0047$, $C_4 = -0.0037$, $C_5 = 1.7869$, $C_6 = -0.6094$[56], $C_7 = 0.2290$ and $\sigma = 0.5275$ for intraslab.

- Data from between March 2008 and February 2013 recorded by 175 stations of Indonesian Meteorological Climatological and Geophysical Agency. 112 mainly moderate events in Java subduction zone and 42 larger events that are mainly from Sumatra subduction zone.

- Use two site classes:

  Rock NEHRP B and C class (350 m/s [sic] $\leq V_{s,30} \leq$ 1500 m/s). $S_t = 0$.

  Soil NEHRP D and E class ($V_{s,30} <$ 350 m/s). $S_t = 1$.

  Some site classes estimated using topographic slope.

- Consider two earthquake types:

  Interface 95 events. Focal depth, $H$, between 9.00 and 45.40 km.

  Intraslab 57 events. Focal depth, $H$, between 45.80 and 104.00 km.

- Only a handful of events with $M_w > 6.5$.

- Determine coefficients $C_5$ and $C_6$ using preliminary regression for SA(1 s) for $50 \leq r_{hypo} \leq 500$ km split into 1-unit magnitude increments.

- Considered quadratic magnitude scaling and found a better fit but sign of quadratic term is positive rather than negative (as expected) so select linear magnitude scaling in final model.

- Plot predictions and observations for various magnitude ranges and find good fit.

- Plot residuals w.r.t. distance. Conclude that model fits better for $200 < r_{hypo} < 800$ km because of a lack of data at closer distances.

- Note that the model is preliminary due to lack of data from larger events, uncertain site amplification and use of standard least-squares rather than maximum-likelihood.

## 2.459 Darzi et al. (2019)

- Ground-motion model is:

$$\begin{aligned}
\log_{10} y &= f_M + f_R + f_{site} + f_{SoF} \\
f_M &= c_1 + m_1 M + m_2 M^2 \\
f_R &= r_1 \log_{10} \sqrt{R^2 + h^2} \\
f_{site} &= s_{II}\mathrm{II} + s_{III}\mathrm{III} \\
f_{SoF} &= f_{RV}\mathrm{RV} + f_{SS}\mathrm{SS}
\end{aligned}$$

[56] Elsewhere this is reported as −0.4605.

where $y$ is in $\mathrm{cm/s^2}$; $c_1 = 0.191$, $m_1 = 0.728$, $m_2 = -0.031$, $h = 9.094$, $r_1 = -1.142$, $s_{II} = 0.000$, $s_{III} = 0.054$, $f_{RV} = -0.001$, $f_{SS} = 0.002$, $\phi = 0.226$ (intra-event), $\tau_1 = 0.181$ (inter-event without considering faulting mechanism), $\tau_2 = 0.127$ (inter-event considering faulting mechanism) and $\sigma = 0.259$ (total) for $r_{jb}$; $c_1 = 0.254$, $m_1 = 0.769$, $m_2 = -0.035$, $h = 4.993$, $r_1 = -1.222$, $s_{II} = -0.008$, $s_{III} = 0.057$, $f_{RV} = -0.006$, $f_{SS} = -0.007$, $\phi = 0.225$ (intra-event), $\tau_1 = 0.201$ (inter-event without considering faulting mechanism), $\tau_2 = 0.136$ (inter-event considering faulting mechanism) and $\sigma = 0.264$ (total) for $r_{rup}$; $c_1 = 0.724$, $m_1 = 0.552$, $m_2 = -0.010$, $h = 10.444$, $r_1 = -1.240$, $s_{II} = 0.002$, $s_{III} = 0.056$, $f_{RV} = -0.002$, $f_{SS} = -0.011$, $\phi = 0.227$ (intra-event), $\tau_1 = 0.183$ (inter-event without considering faulting mechanism), $\tau_2 = 0.129$ (inter-event considering faulting mechanism) and $\sigma = 0.261$ (total) for $r_{epi}$; and $c_1 = 0.549$, $m_1 = 0.702$, $m_2 = -0.023$, $h = 6.629$, $r_1 = -1.356$, $s_{II} = -0.007$, $s_{III} = 0.054$, $f_{RV} = -0.023$, $f_{SS} = -0.032$, $\phi = 0.226$ (intra-event), $\tau_1 = 0.207$ (inter-event without considering faulting mechanism), $\tau_2 = 0.143$ (inter-event considering faulting mechanism) and $\sigma = 0.267$ (total) for $r_{hypo}$.

- Use 3 site classes based on Iranian seismic design code:

  I $V_{s,30} > 750\,\mathrm{m/s}$. II = III = 0. About 500 records and 140 stations.

  II $375 < V_{s,30} < 750\,\mathrm{m/s}$. II = 1, III = 0. About 690 records and 220 stations.

  III $V_{s,30} < 375\,\mathrm{m/s}$. III = 1, II = 0. About 230 records and 80 stations.

  Originally considered 4 site classes but class IV for $V_{s,30} < 175\,\mathrm{m/s}$ included few records so combined with class III. Exclude data from stations with unknown $V_{s,30}$ (most from classes I and II). Data from 431 different stations. Similar $M$-$R$ distributions for all site classes. Do not consider nonlinear site terms because of lack of near-source records from (very) soft sites.

- Use 3 faulting mechanisms:

  Reverse Rake angles between 45 and 135°. 219 events, 999 records. RV = 1, SS = 0.

  Strike-slip Other rake angles not covered by reverse and normal categories. 189 events, 834 records. SS = 1, RV = 0.

  Unspecified 6 events, 13 records. RV = SS = 0.

  Do not consider normal events (rakes between −135 and 45°) because of lack of data (11 events, 64 records). Use tectonic arguments, types of faults and mechanisms of previous events to assess mechanism for earthquakes without publish focal mechanism. Similar $M$-$R$ distributions for reverse and strike-slip data.

- Focal depths between about 1 and 39 km with most $\leq 20$ km. Reject events with depth $> 40$ km.

- Use data from the Iranian Strong Motion Network from 1975 to 2014. Only include good-quality records with $M_w \geq 4.5$ and $R < 200$ km. Visually inspect all data. Reject 560 records through various criteria).

- Process records using adaptive wavelet denoising to extend period range of model after baseline correction.

- Lack of data for $6.7 < M_w < 7.1$ and $R < 20$ km for $M_w > 6.5$.

- Investigate regional dependency between Alborz-Azerbaijan-Kopeh Dagh, Zagros and central Iran-Makran using analysis of variance but find little evidence for differences so use a combined database.

- Explore a magnitude-dependent geometric decay term but drop this term because of lack of constraint. Also drop anelastic attenuation term because of lack of data.

- Constrain $h$ *a priori* to improve stability of multi-stage regression. Also smooth $h$ w.r.t. $T$ using 5-point moving-average. Determine $f_{RV}$ and $f_{SS}$ after main regression (conducted ignoring singly-recorded earthquakes) using all data. This allows reduction in $\tau$ by inclusion of those terms to be determined. Find similar results only using best-recorded events.

- Find $\phi$ is similar when using different distance metrics but that $\tau$ changes.
- Examine inter-event and intra-event residuals and find no trends or bias.
- Compare predictions and observations for 2 earthquakes within the dataset and find good match. Also make comparison for 12/11/2017 $M_w$7.3 earthquakes and its aftershocks, which were not used within the regression. Find good match.

## 2.460 Farajpour et al. (2019)

- Ground-motion model is[57]:

$$\begin{aligned}
\ln Y &= f_{source} + f_{path} + f_{site} \\
f_{source} &= f_{magnitude} + f_{SOF} + f_{dip} + f_{hyp} \\
f_{magnitude} &= \begin{cases} z_1 + z_2(M - M_h) + z_3(M - M_h)^2 & M \leq M_h \\ z_1 + z_4(M - M_h) + z_3(M - M_h)^2 & M > M_h \end{cases} \\
f_{SOF} &= c_8 f_{RV} + c_9 f_{NM} \\
f_{dip} &= \begin{cases} z_{12}\delta & M \leq M_{h1} \\ z_{12}(5.5 - M)\delta & M_{h1} < M \leq M_{h2} \\ 0 & M > M_{h2} \end{cases} \\
f_{hyp} &= f_{hyp,H} f_{hyp,M} \\
f_{hyp,H} &= \begin{cases} 0 & Z_{HYP} \leq 7 \\ Z_{HYP} - 7 & 7 < Z_{HYP} \leq 20 \\ 13 & Z_{HYP} > 20 \end{cases} \\
f_{hyp,M} &= \begin{cases} z_{10} + (z_{11} - z_{10})(M - 6.5) & M \leq 6.5 \\ z_{11} & M > 6.5 \end{cases} \\
f_{path} &= f_{geometric} + f_{atn} \\
f_{geometric} &= (z_5 + z_6 M) \ln \sqrt{R_{RUP}^2 + z_7^2} \\
f_{atn} &= \begin{cases} (z_{13} + \Delta z_{13})(R_{RUP} - 80) & R_{RUP} > 80 \\ 0 & R_{RUP} \leq 80 \end{cases} \\
f_{site} &= \begin{cases} z_{14} \ln\left(\frac{V_{S30}}{k_1}\right) + k_2 \left\{\ln\left[\mathrm{PGA}_{\mathrm{Rock}} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln(\mathrm{PGA}_{\mathrm{Rock}} + c)\right\} & V_{S30} \leq k_1 \\ (z_{14} + k_2 n) \ln\left(\frac{V_{S30}}{k_1}\right) & V_{S30} > k_1 \end{cases}
\end{aligned}$$

$Y$ is in g, $M_h = 6.5$, $M_{h1} = 4.5$, $M_{h2} = 8.5$, $c = 1.88$, $n = 1.18$; $z_1 = 0.6755$, $z_2 = 0.362$, $z_3 = -0.1889$, $z_4 = 1.0966$, $z_5 = -0.8165$, $z_6 = -0.0189$, $z_7 = 6.1175$, $z_8 = 0.0829$, $z_9 = 0.0008$, $z_{10} = -0.0291$, $z_{11} = -0.061$, $z_{12} = -0.0025$, $z_{13} = 0$, $z_{14} = 1.4323$, $k_1 = 865$, $k_2 = -1.186$, $\Delta z_{13}$, $\tau = 0.3510$ (inter-event), $\phi_{S2S} = 0.3482$ (site-to-site), $\phi_{SS} = 0.5680$ (single-station intra-event) and $\sigma_{total} = 0.7530$ (total); and $z_1 = 1.3532$, $z_2 = 0.5437$, $z_3 = -0.1489$, $z_4 = 1.147$, $z_5 = -0.739$, $z_6 = -0.0582$, $z_7 = 11.8246$, $z_8 = 0.0965$, $z_9 = 0.0136$ to predict $\mathrm{PGA}_{\mathrm{Rock}}$ (derived using data from stations with $V_{s,30} \geq 760$ m/s).

- Use $V_{s,30}$ to characterise sites. Estimate $V_{s,30}$ for stations without information using technique of Wald and Allen (2007). Most data from NEHRP classes B and C, i.e. $360 \leq V_{s,30} \leq 1500$ m/s.
- Use 3 faulting mechanism categories:

Reverse $30 < \lambda < 150°$, where $\lambda$ is rake. $f_{RV} = 1$ and $f_{NM} = 0$.

[57] Equation for $f_{path}$ not explictly given in the article.

Normal $-150 < \lambda < -30°$. $f_{NM} = 1$ and $f_{RV} = 0$.

Strike-slip Other $\lambda$. $f_{RV} = 0$ and $f_{NM} = 0$.

- Consider effect of average dip of rupture plane, $\delta$, and hypocentral depth, $Z_{HYP}$.
- Use data from 1976 to 2013 from the Iranian Strong-Motion Network. 4 earthquakes occurred in Turkey or Greece and the rest in Iran. Exclude records from aftershocks. Exclude records with $r_{rup} > 400$ km.
- Data well distributed for all distances and $M_w < 6.6$ and $M_w > 7.0$ but lack of data for intermediate $M_w$.
- Process data (no details given) and check quality.
- Find fault geometry of earthquakes using estimated fault lengths and focal mechanism.
- Consider various published functional forms. Use Akaike and Bayesian information criteria to choose final form.
- Constrain $z_{13}$ to be negative or zero due to trade-off between $f_{atn}$ and $f_{geometric}$.
- Include $\Delta z_{13}$ to model differences among Zagros, Alborz-Azarbaijan, Kope Dagh and central east Iran. Find these are not significant so set $\Delta z_{13} = 0$.
- Conclude that nonlinear site term improves fit to the data by examining residuals and components of $\sigma$ with and without this term.
- Find no significant trends in inter-event, site-to-site and event-station residuals.
- Compare observations binned into magnitude bins to predictions w.r.t. $r_{rup}$ and find good match.

## 2.461 Huang and Galasso (2019)

- Ground-motion model is:

$$
\begin{aligned}
f &= b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M) \log \sqrt{R_{JB}^2 + b_6^2} \\
&\quad + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R
\end{aligned}
$$

  where $f$ is in cm/s$^2$, $b_1 = 3.524$, $b_2 = 0.247$, $b_3 = -0.020$, $b_4 = -3.936$, $b_5 = 0.351$, $b_6 = 12.417$, $b_7 = 0.228$, $b_8 = 0.160$, $b_9 = -0.060$, $b_{10} = 0.080$, $\tau = 0.247$ (inter-event), $\sigma = 0.370$ (intra-event) and $h = 8.476$ (range of exponential spatial correlation model).

- Use 3 site classes:

  1. Soft soil. $S_S = 1$, $S_A = 0$.
  2. Stiff soil. Most data. $S_A = 1$, $S_S = 0$.
  3. Rock. $S_S = S_A = 0$.

  Median $V_{s,30}$ of data is 637 m/s.

- Use 3 faulting mechanisms:

  1. Normal. 66% of data. $F_N = 1$, $F_R = 0$.
  2. Reverse. 23% of data. $F_R = 1$, $F_N = 0$.
  3. Strike-slip. 11% of data. $F_N = F_R = 0$.

- Focus of study is on correlation amongst intensity measures so use a simple functional form as correlation is relatively insensitive to functional form.

- Use flatfile of Engineering Strong-Motion (ESM) database. Only use data from earthquakes with $M_w \geq 4$ recorded at $\geq 2$ stations; data with $r_{jb} \leq 250$ km; data from free-field stations, and; records with $M_w$, faulting mechanism and $V_{s,30}$. Exclude data from co-located stations. Data from 1976 to 2016.

- Use scoring estimation approach of Ming et al. (2019) to derive model accounting for spatial correlation between stations recording same event. Assume exponential model for spatial correlation with the coefficient of this model (the range, $h$) found as part of the regression.

- Compare predictions for a stiff soil site and a $M_w5.5$ normal earthquake and observations for $M_w5.5 \pm 0.3$, normal earthquakes at stiff soil sites. Find close match. Residual analysis confirms there are no trends.

- Find that considering spatial correlation in regression does not strongly affect coefficients but it does reduce inter-event variance and increases intra-event variance by comparing results obtained with and without considering spatial correlation. Find Akaike and Bayesian information criteria (AIC and BIC) are about 10% lower when considering spatial correlation than when it is ignored so conclude model considering spatial correlation is a better representation of the data.

- Assess significance of the coefficients for a 5% threshold. Find magnitude scaling and style of faulting coefficients not significantly different than zero but retain them.

## 2.462 Konovalov et al. (2019)

- Ground-motion model is:
$$\log \mathrm{PGA} = aM_w - \log(R_{rup} + c) - kR_{rup} + e$$
where PGA is in cm/s$^2$, $a = 0.87 \pm 0.07$, $k = 0.0038 \pm 0.0003$, $e = -1.726 \pm 0.336$, $c = 0.006 \times 10^{0.5M_w}$ from Si and Midorikawa (1999, 2000) and $\sigma = 0.34$.

- Use data from both accelerometers and seismometers (instrument corrected and converted to acceleration).

- Use data from 20 stations.

- Data from 2006 to 2016.

- Focal depths from 4.0 to 16.6 km.

- Focal mechanisms mainly reverse.

- Only 8% of records have $r_{epi} < 20$ km.

- Believe site conditions of model are roughly $V_{s,30} = 350$ m/s. Believe high $\sigma$ due to lack of site term in model.

- Take term $c$ from previous study because of lack of near-source data to constrain it.

- Compare observations grouped by magnitude and predictions.

## 2.463 Lanzano et al. (2019a,b)

- Ground-motion model is (chosen based on plots of data w.r.t. magnitude and distance):

$$
\begin{aligned}
\log_{10} Y &= a + F_M + F_D + F_S \\
F_M &= f_j + \begin{cases} b_1(M - M_h) & \text{for} \quad M \leq M_h \\ b_2(M - M_h) & \text{otherwise} \end{cases} \\
F_D &= [c_1(M - M_{ref}) + c_2] \log_{10} R + c_3 R \\
R &= \sqrt{R_i^2 + h^2} \\
F_S &= k \log_{10}\left(\frac{V_0}{800}\right) \\
V_0 &= \min(V_{s,30}, 1500) \\
\phi_0 &= \begin{cases} \phi_{0,1} & \text{for} \quad M \leq M_1 \\ \phi_{0,1} + (\phi_{0,2} - \phi_{0,1})(M - M_1) & \text{for} \quad M_1 < M < M_2 \\ \phi_{0,2} & \text{otherwise} \end{cases} \\
\phi_{S2S} &= \begin{cases} \phi_{S2S,1} & \text{for} \quad V_{s,30} \leq V_1 \\ \phi_{S2S,1} + (\phi_{S2S,2} - \phi_{S2S,1})[\log_{10}(V_2/V_{s,30})/\log_{10}(V_2/V1)] & \text{for} \quad V_1 < V_{s,30} < V_2 \\ \phi_{S2S,2} & \text{otherwise} \end{cases}
\end{aligned}
$$

where $Y$ is in cm/s$^2$; $a = 3.421046$, $b_1 = 0.193954$, $b_2 = -0.02198$, $c_1 = 0.287149$, $c_2 = -1.40564$, $c_3 = -0.00291$, $k = -0.39458$, $f_1 = 0.085984$, $f_2 = 0.0105$, $f_3 = 0$, $\tau = 0.155988$ (inter-event), $\phi_{S2S} = 0.220582$ (site-to-site), $\phi_0 = 0.20099$ (residual variability), $M_h = 5.5$, $M_{ref} = 5.323973$, $h = 6.923743$, $phi_{0,1} = 0.249907$, $\phi_{0,2} = 0.115486$, $M_1 = 4.5$, $M_2 = 6$, $\phi_{S2S,1} = 0.148648$ and $\phi_{S2S,2} = 0.237926$ for $R_i = R_{jb}$; $a = 3.847601$, $b_1 = 0.077442$, $b_2 = -0.142$, $c_1 = 0.347865$, $c_2 = -1.55332$, $c_3 = -0.00188$, $k = -0.38048$, $f_1 = 0.098186$, $f_2 = 0.031284$, $f_3 = 0$, $\tau = 0.161485$ (inter-event), $\phi_{S2S} = 0.221469$ (site-to-site), $\phi_0 = 0.200986$ (residual variability), $M_h = 5.5$, $M_{ref} = 5.716123$, $h = 6.641217$, $phi_{0,1} = 0.247419$, $\phi_{0,2} = 0.10965$, $M_1 = 4.5$, $M_2 = 6$, $\phi_{S2S,1} = 0.151112$ and $\phi_{S2S,2} = 0.237948$ for $R_i = R_{rup}$.

- Use $Vs, 30$ to characterise sites as it is more flexible than site classes. Data from 1657 different stations. About 500 stations (30% of total) have measured $V_{s,30}$. Other values are obtained from the topographic slope. Few sites with $V_{s,30} > 1500$ m/s so apply cap to site term.

- Use 3 faulting mechanism classes using the criteria of Boore and Atkinson (2008) based on rake angles:

Strike-slip 1283 records, 38 events. Use $f_1$.
Reverse 1688 records, 44 events. Use $f_2$.
Normal 2807 records, 74 events. Use $f_3$.

- Aim to revise the model of Bindi et al. (2011a) (see Section 2.343) to remove its limitations.

- Use Italian data from the Engineering Strong Motion flatfile. To increase the magnitude range and number of records from reverse and strike-slip earthquakes include data from 12 events from elsewhere (3 from Turkey, 2 from Japan, 2 from New Zealand, 2 from California, 1 from Iceland, 1 from Iran and 1 from Greece). Did not include more foreign data to avoid the model not being representative of Italian regional attenuation and stress drop.

- Use following selection criteria: earthquakes from active shallow (focal depth$<$ 30 km) crustal regions (excluding volcanic and subduction events), magnitude range 3.5 to 8.0, exclude several aftershocks of major sequences to present oversampling of small magnitudes or regions, exclude events with $<$ 10 records, only distances $<$ 200 km, only records with all 3 components, only include surface instruments with little or no soil-structure interaction. Many records from digital instruments.

- About 300 records with $R < 10$ km. Data is well distributed from 3.5 to 6.5.
- Individually process all records using uniform procedure.
- In first step, find $M_h$, $M_{ref}$ and $h$ using nonlinear ordinary regression. In second step, use linear mixed-effects regression to find other terms. $c_3$ is positive for some periods so constrain it to zero to avoid unphysical behaviour.
- Report correlation matrices of coefficients. Find some large trade-offs.
- Test significance of coefficients and find some coefficients are of limited usefulness, e.g. style-of-faulting terms, but keep them.
- Try including a quadratic magnitude term but find it is of low statistical significance.
- Find some evidence for oversaturation at short-periods and large magnitudes, which retain.
- Find variability is greatest for sites with estimated $V_{s,30}$ and hence $\sigma$ is much reduced if these are excluded but do not so as this would significantly reduce the number of data used.
- Compare observations corrected by source and site terms w.r.t. distance and observations corrected by attenuation and site terms w.r.t. magnitude to model and find good match.
- Plot residuals w.r.t. $M$, $V_{s,30}$ and $R$ and find no trends, although some foreign events have large absolute event terms.
- Find weak evidence for nonlinear behaviour for sites with $V_{s,30} \leq 360$ m/s based on the limited data at high ground motion levels. Use this to justify not including a nonlinear site term in the model.
- Plot predictions for $M_w$4.0 and 6.8 and $V_{s,30} = 300$ and 600 m/s against data for these magnitudes $\pm 0.3$ and find close match.
- Develop both homoscedastic and hetroscedastic models of the intra-event components of variability.
- Compute the epistemic uncertainty using the covariance matrix. Find lower uncertainties for magnitudes 4.5 and 6.5. Uncertainties w.r.t. $R$ and $V_{s,30}$ are roughly constant.

## 2.464 Laouami (2019)

- Ground-motion model is:
$$\log_{10} \mathrm{PSA} = aM + bd - \log_{10} d + c_1 + c_2 + c_3$$
where PSA is in g, $a = 0.4256$, $b = -0.0021$, $c_1 = 0.6493$, $c_2 = 0.6893$, $c_3 = 0.6487$ and $\sigma = 0.2809$.
- Vertical version of horizontal model by Laouami et al. (2018a) (see Section 2.450).
- Use 3 site classes following approach of Zhao et al. (2006) (see Section 2.248) that uses horizontal-to-vertical response spectral ratios:

Rock SC-I. 324 records. Use $c_1$.

Stiff soil SC-II. 177 records. Use $c_2$.

Soft soil SC-III and SC-IV. 173 records. Use $c_3$.

- Examines total residuals w.r.t. magnitude and distance and find no significant trends.

## 2.465 Podili and Raghukanth (2019)

- Ground-motion model is:

$$
\begin{aligned}
\ln(\text{GMP}) &= d_0 + f(M_w) + d_6 h + S_c + S_s + d_f F_M + d_7 R + d_8 \ln[R + d_9 \exp(d_{10} M_w)] + d_{S_s} R \\
&\quad + d_{11} \ln V_{s30} + d_{12} L_{arc} R \\
f(M_w) &= \begin{cases} d_1 M_w + d_2 \ln M_w & M_w < 6.5 \\ d_1 M_w + d_2 \ln M_w + d_3(M_w - 6.5) & 6.5 \leq M_w < 7.5 \\ d_1 M_w + d_2 \ln M_w + d_3(M_w - 6.5) + d_4(M_w - 7.5)^2 & 7.5 \leq M_w < 8.5 \\ d_1 M_w + d_2 \ln M_w + d_3(M_w - 6.5) + d_4(M_w - 7.5)^2 + d_5(M_w - 8.5)^2 & M_w \geq 8.5 \end{cases} \\
L_{arc} &= \begin{cases} 0 & \text{Fore-arc} \\ 1 & \text{Back-arc} \end{cases}
\end{aligned}
$$

  where GMP is in cm/s$^2$, $d_0 = 18.693$, $d_1 = 1.881$, $d_2 = -5.384$, $d_3 = 0.763$, $d_4 = -3.591$, $d_5 = 2.79108$, $d_6 = 0.001$, $S_c = -8.738$, $S_s = -8.338$, $d_f = 0.034$, $d_7 = -0.003$, $d_8 = -1.491$, $d_9 = 0.0055$, $d_{10} = 1.08$, $d_{S_s} = -0.015$, $d_{11} = -0.297$, $\sigma_{intra} = 0.605$ (intra-event), $\sigma_{inter} = 0.612$ (inter-event) and $\sigma = 0.861$ (total). Derive, using trial and error, modified coefficients for large magnitudes to avoid oversaturation in the near-source area: $d_9 = 0.0035$ and $d_{10} = 1.06$ for $7.5 < M_w < 8.5$ and $d_9 = 0.0025$ and $d_{10} = 1.02$ for $8.5 < M_w < 9.0$.

- Characterise sites by $V_{s30}$. Apply constant-velocity extrapolation to extend shorter profiles. Most sites in NEHRP D class. Exclude sites with no measured $V_{s30}$.

- Use 4 faulting mechanisms based on rake angle:

Strike-slip Rake within 30° of horizontal. 332 events. $F_M = 1$

Normal Rake within 60° of $-90°$. 279 events. $F_M = 2$

Reverse Rake within 60° of 90°. 716 events. $F_M = 3$

Unspecified Rake unknown. 13 events. $F_M = 0$

- Use 3 tectonic types:

Slab $M_w > 7.7$ and $h < 50$ km or $M_w < 7.7$ and $22 < h < 50$ km. $h$ is focal depth. $S_s = 1$, $S_c = 0$, $S_I = 0$. Also include $d_{S_s}$ in model. 988 events.

Crustal $M_w < 7.7$ and $h < 22$ km. $S_c = 1$, $S_s = 0$, $S_I = 0$. 350 events.

Interface $M_w > 7.7$ and $h < 50$ km [sic][58]. $S_I = 1$, $S_s = 0$, $S_c = 0$. 2 events. This term is removed from final model as negligible.

- Use data from K-Net from 1996 to 2016. There are 3 events with $M_w > 8$, 29 between $M_w7$ and 8, 228 between $M_w6$ and 7 and 1080 events with $M_w < 6$.

- Exclude data with distance > 350 km because inclusion of distant records increases $\sigma$.

- Baseline correct data by subtracting non-zero mean.

- Account for location of site and earthquake w.r.t. volcanic arc through $L_{arc}$ variable.

- Decide on functional form through trial-and-error and observations of behaviour of data.

- Compare observations and predictions for two Kumamoto earthquakes ($M_w6.5$, $M_w7.3$) and find good match.

- Find no trends in inter-event and intra-event residual plots.

[58] This is the same definition as the subduction slab so there is likely a typographic error somewhere.

## 2.466 Stafford (2019)

- Ground-motion model is (simplified version of Abrahamson et al. (2013, 2014)):

$$
\begin{aligned}
\ln \mathrm{Sa} &= f_1 + F_N f_7 + F_R f_8 + f_5 \\
f_1 &= \begin{cases} a_1 + a_5(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)] \ln R + a_{17} R_{rup} & M > M_1 \\ a_1 + a_4(M - M_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - M_1)] \ln R + a_{17} R_{rup} & M_2 \leq M \leq M_1 \\ a_1 + a_4(M_2 - M_1) + a_8(8.5 - M_2)^2 + a_6(M - M_2) + [a_2 + a_3(M_2 - M_1)] \ln R + a_{17} R_{rup} & M < M_2 \end{cases} \\
R &= \sqrt{R_{rup}^2 + c_{4M}^2} \\
c_{4M} &= \begin{cases} c_4 & M > 5 \\ c_4 + (c_4 - 1)(M - 5) & 4 < M \leq 5 \\ 1 & M \leq 4 \end{cases} \\
f_7 &= \begin{cases} a_{11} & M > 5 \\ a_{11}(M - 4) & 4 < M \leq 5 \\ 0 & M \leq 4 \end{cases} \\
f_8 &= \begin{cases} a_{12} & M > 5 \\ a_{12}(M - 4) & 4 < M \leq 5 \\ 0 & M \leq 4 \end{cases} \\
f_5 &= \begin{cases} (a_{10} + bn) \ln \frac{V_{s,30}^*}{V_{lin}} & V_{s,30} \geq V_{lin} \\ a_{10} \ln \frac{V_{s,30}^*}{V_{lin}} - b \ln(\hat{\mathrm{Sa}}_{\mathrm{r}} + c) + b \ln \left[\hat{\mathrm{Sa}}_{\mathrm{r}} + c \left(\frac{V_{s,30}^*}{V_{lin}}\right)^n\right] & \end{cases} \\
V_{s,30}^* &= \min(V_{s,30}, V_1)
\end{aligned}
$$

  Only graphs of coefficients given — no exact values. $M_1 = 6.75$, $M_2 = 5.0$, $c_4 = 4.5$. $V_1 = 1500\,\mathrm{m/s}$, $V_{lin} = 660\,\mathrm{m/s}$, $c = 2.4$ and $n = 1.5$ taken from Abrahamson et al. (2013, 2014) as these are from external numerical constraints. $\hat{\mathrm{Sa}}_{\mathrm{r}}$ is reference expected spectral acceleration for $V_{s,30} = 1180\,\mathrm{m/s}$.

- Characterises sites using $V_{s,30}$.

- Uses 3 faulting mechanism categories:

Strike-slip $F_N = F_R = 0$.

Normal Includes normal-oblique. $F_N = 1$, $F_R = 0$.

Reverse Includes reverse-oblique. $F_R = 1$, $F_N = 0$.

- Uses the NGA-West2 database. Only uses data from Class 1 mainshocks with $R \leq 200\,\mathrm{km}$, PGA $\geq 10^{-4}\,\mathrm{g}$ and significant durations $\leq 2.75$ standard deviations above average based on a recent ground-motion model for this intensity measure.

- Data from 3097 stations.

- Derives original model using data available in 1995 (924 records, 103 events and 629 stations). Uses Bayesian updating with crossed-mixed effects to modify the coefficients of the original model as the set of records from each of the 281 subsequent events becomes available through time. Also conducts 282 separate regression analyses where the set of records from each event are included within the original dataset. Finds differences in coefficients from two methods, particularly those related to magnitude scaling of moderate and large events. Results converge as more data are used. Also finds differences in components of aleatory variability due to varying number of records per event included at each step within the regression. Finds consistent results in random effects for individual stations but that the error estimates in the Bayesian case are far greater than from traditional regression analysis.

- Omits secondary terms related to hanging-wall effects, sediment depth and depth of rupture because aims to demonstrate the method and inclusion of these terms would increase the number of free coefficients.

## 2.467 Sung and Lee (2019)

- Ground-motion model is:

$$\ln y = C_1 + C_2 M + C_3 M^2 + C_4 \ln(R + C_5 e^{C_6 M}) + C_7 \ln(V_{S30}/V_{ref}) + C_8 F_N + C_9 F_R + C_{10} R$$

  where $y$ is in cm/s$^2$, $V_{ref} = 1130$ m/s; $C_1 = -5.310$, $C_2 = 1.323$, $C_3 = -0.021$, $C_4 = -1.450$, $C_5 = 0.140$, $C_6 = 0.632$, $C_7 = -0.308$, $C_8 = -0.086$, $C_9 = 0.078$, $C_{10} = -0.0006$, $\sigma_T = 0.613$ (total), $\tau = 0.317$ (inter-event), $\sigma = 0.511$ (intra-event), $\tau_S = 0.231$ (site-to-site), $\sigma_R = 0.455$ (record-to-record) and $\sigma_{SS} = 0.576$ (single-station) for regional model; $C_1 = -5.494$, $C_2 = 1.565$, $C_3 = -0.021$, $C_4 = -1.450$, $C_5 = 0.140$, $C_6 = 0.632$, $C_8 = -0.4403$, $C_9 = 0.1193$, $C_{10} = -0.0084$ and $\sigma_{SS,S} = 0.463$ (single-station) for HWA033 model (term using $C_7$ is removed as $V_{s,30}$ is constant).

- Characterise sites using $V_{s,30}$. $V_{s,30}$ between 110 and 1538 m/s with almost all between 150 and 800 m/s.

- Use 3 faulting mechanism categories:

Strike-slip $F_N = F_R = 0$.
Normal $F_N = 1$, $F_R = 0$.
Reverse $F_R = 1$, $F_N = 0$.

- Focal depths between 0.5 and 34.9 km with most between 10 and 20 km.

- Include data from the 1999 Chi-Chi event to constrain models in near-source region despite it increasing the variability of the models.

- Records baseline corrected and filtered using standard procedures.

- Inclusion of anelastic attenuation term slightly reduces $\sigma$.

- Develop two models: a regional model using all data from 570 stations (each with $\geq$ 10 records, 151 stations (mostly in W and E Taiwan) with $>$ 50 records each) of the Taiwan Strong Motion Instrumentation Program (1995 to 06/2016) and one using the 117 stations from a single-station (HWA033, $V_{s,30} = 393$ m/s) (constrain $C_3$, $C_4$, $C_5$ and $C_6$ to those from regional model).

- Find site-specific model fits observations from HWA033 better than regional model.

- Compare total sigma of regional model, the single-station sigma of the regional model estimated using variance decomposition and the sigma of the single-station model.

- Draw map of $\sigma_{SS,S}$ and find regions with higher and lower values, which relate to geology.

- Use the epistemic-residual diagram, which is a rose diagram with distance and azimuth bins, []similar to path diagram proposed by Sung and Lee (2016) (see Section 2.418)] to estimate the epistemic uncertainty per station that could be reduced and the remaining unexplained variability per station. These values show spatial variation so use kriging to estimate maps of these values.

- Draw interpolated maps of $C_1$, $C_2$ and $C_10$ and find considerable spatial variation, which relate to geology.

- Investigate effect of different distance-azimuth bin sizes on results.

## 2.468 Zolfaghari and Darzi (2019a)

- Ground-motion model is:

$$\begin{aligned}
\log_{10} y &= f_M + f_R + f_{site} + f_{SoF} \\
f_M &= c_1 + m_1 M + m_2 M^2 \\
f_R &= r_1 \log_{10} \sqrt{R^2 + h^2} \\
f_{site} &= s_{II}\mathrm{II} + s_{III}\mathrm{III} \\
f_{SoF} &= f_{RV}\mathrm{RV} + f_{SS}\mathrm{SS}
\end{aligned}$$

  where $y$ is in $\mathrm{cm/s^2}$; $c_1 = 0.667$, $m_1 = 0.559$, $m_2 = -0.012$, $h = 11.158$, $r_1 = -1.351$, $s_{II} = -0.025$, $s_{III} = -0.009$, $f_{RV} = -0.002$, $f_{SS} = 0.027$, $\phi = 0.229$ (intra-event), $\tau = 0.144$ (inter-event) and $\sigma = 0.270$ (total) for $r_{jb}$; $c_1 = 0.741$, $m_1 = 0.611$, $m_2 = -0.017$, $h = 8.505$, $r_1 = -1.446$, $s_{II} = -0.033$, $s_{III} = -0.007$, $f_{RV} = -0.017$, $f_{SS} = 0.011$, $\phi = 0.229$ (intra-event), $\tau = 0.155$ (inter-event) and $\sigma = 0.277$ (total) for $r_{rup}$; $c_1 = 1.007$, $m_1 = 0.477$, $m_2 = 0.000$, $h = 13.246$, $r_1 = -1.479$, $s_{II} = -0.024$, $s_{III} = -0.008$, $f_{RV} = -0.002$, $f_{SS} = 0.016$, $\phi = 0.230$ (intra-event), $\tau = 0.147$ (inter-event) and $\sigma = 0.273$ (total) for $r_{epi}$; and $c_1 = 1.324$, $m_1 = 0.482$, $m_2 = -0.001$, $h = 12.044$, $r_1 = -1.631$, $s_{II} = -0.033$, $s_{III} = -0.010$, $f_{RV} = -0.023$, $f_{SS} = -0.004$, $\phi = 0.231$ (intra-event), $\tau = 0.162$ (inter-event) and $\sigma = 0.282$ (total) for $r_{hypo}$.

- Vertical version of Darzi et al. (2019) (see Section 2.459).

## 2.469 Chao et al. (2020)

- Ground-motion model for median is:

$$
\begin{aligned}
\ln S_a &= \ln S_a^{ref} + S_{source} + S_{path} + S_{site,lin} + S_{site,non} \\
\ln S_a^{ref} &= E_{ref} + S_{ref} \\
E_{ref} &= c_1 F_{cr,ro} + c_2 F_{cr,ss} + c_3 F_{cr,no} + c_4 F_{sb,inter} + c_5 F_{sb,intra} + c_6 F_{as} + c_7 F_{manila} \\
S_{ref} &= c_{26} F_{measured} + c_{27} F_{geology} + c_{28} F_{seismic} \\
Z_{1.0}^{ref} &= \exp\left[\frac{-4.08}{2}\ln\left(\frac{V_{S30}^2 + 355.4^2}{1750^2 + 355.4^2}\right)\right] \\
S_{source} &= S_{mag} + S_{Z_{tor}} \\
S_{mag} &= S_{mag,cr} F_{cr} + S_{mag,sb} F_{sb} \\
S_{mag,cr} &= c_8(M - M_{ref}) + c_{10}(M - M_{ref})^2 - c_{10}(M - 7.6)^2 u(M - 7.6) + c_{11}(5 - M)u(5 - M) \\
S_{mag,sb} &= c_9(M - M_{ref}) + c_{12}(5 - M)u(5 - M) + c_{13}(6 - M)u(6 - M) \\
&\quad + c_{29} F_{inter}(M - M_c)u(M - M_c) + c_{30} F_{intra}(M - M_c)u(M - M_c) \\
S_{Z_tor} &= c_{14} F_{cr}(Z_{tor} - Z_{tor,cr}^{ref}) + c_{15} F_{sb,inter}(Z_{tor} - Z_{tor,sb,inter}^{ref}) + c_{16} F_{sb,intra}(Z_{tor} - Z_{tor,sb,intra}^{ref}) \\
S_{path} &= S_{geom} + S_{anel} \\
S_{geom} &= S_{geom,cr} F_{cr} + S_{geom,sb} F_{sb} \\
S_{geom,cr} &= [c_{17} + c_{19}(M - M_{ref})]\ln\left(\frac{\sqrt{R_{rup}^2 + H^2}}{\sqrt{(R_{rup}^{ref})^2 + H^2}}\right) \\
S_{geom,sb} &= \{c_{18} + c_{20}[\min(M, M_c) - M_{ref}]\}\ln\left(\frac{\sqrt{R_{rup}^2 + H^2}}{\sqrt{(R_{rup}^{ref})^2 + H^2}}\right) \\
S_{anel} &= c_{21} F_{cr}(R_{rup} - R_{rup}^{ref}) + c_{22} F_{sb}(R_{rup} - R_{rup}^{ref}) \\
H &= hF_{cr} + hF_{sb,inter}\exp[C_{4inter}(M - M_c)u(M - M_c)] + hF_{sb,intra}\exp[C_{4intra}(M - M_c)u(M - M_c)] \\
S_{site,lin} &= c_{24}\ln\left(\frac{V_{S30}}{V_{S30}^{ref}}\right) + c_{25}\ln\left(\frac{Z_{1.0}}{Z_{1.0}^{ref}}\right) \\
S_{site,non} &= c_{23} u(760 - V_{S30})\left\{-1.5\ln\left(\frac{V_{S30}}{V_{S30}^{ref}}\right) - \ln(\hat{S}_{a1180} + 2.4) + \ln\left[\hat{S}_{a1180} + 2.4\left(\frac{V_{S30}}{V_{S30}^{ref}}\right)^{1.5}\right]\right\}
\end{aligned}
$$

Model for aleatory variability is:

$$
\begin{aligned}
\tau &= \tau_{cr} F_{cr} + \tau_{sb} F_{sb} \\
\tau_{cr} &= \tau_{1,cr} + (\tau_{2,cr} - \tau_{1,cr}) f(M) \\
\tau_{sb} &= \tau_{1,sb} + (\tau_{2,sb} - \tau_{1,sb}) f(M) \\
\phi_{ss} &= \phi_{ss,cr} F_{cr} + \phi_{ss,sb} F_{sb} \\
\phi_{ss,cr} &= \phi_{ss1,cr} + (\phi_{ss2,cr} - \phi_{ss1,cr}) f(M) \\
\phi_{ss,sb} &= \phi_{ss1,sb} + (\phi_{ss2,sb} - \phi_{ss1,sb}) f(M) \\
f(M) &= 0.5\{\min[6.5, \max(4.5, M)] - 4.5\}
\end{aligned}
$$

where $S_a$ is in g, $c_1 = -0.5193$, $c_2 = -0.6150$, $c_3 = -0.6488$, $c_4 = -0.5860$, $c_5 = 0.2995$, $c_6 = -0.1253$, $c_7 = 0.1860$, $c_8 = 0.4129$, $c_9 = 0.6654$, $c_{10} = -0.1376$, $c_{11} = 0.0000$, $c_{12} = 0.0000$, $c_{13} = 0.0000$, $c_{14} = 0.0325$, $c_{15} = 0.0188$, $c_{16} = 0.0066$, $c_{17} = -1.3033$, $c_{18} = -1.4222$, $c_{19} = 0.3874$, $c_{20} = 0.1816$,

$c_{21} = -0.0034$, $c_{22} = -0.0034$, $c_{23} = -2.5526$, $c_{24} = -0.4821$, $c_{25} = 0.0636$, $c_{26} = -0.5681$, $c_{27} = -0.6442$, $c_{28} = -0.6148$, $c_{29} = -0.4945$, $c_{30} = -0.4948$, $\tau_{1,cr} = 0.3675$, $\tau_{2,cr} = 0.3157$, $\tau_{1,sb} = 0.2747$, $\tau_{2,sb} = 0.5404$, $\phi_{ss1,cr} = 0.5284$, $\phi_{ss2,cr} = 0.4400$, $\phi_{ss1,sb} = 0.4359$, $\phi_{ss2,sb} = 0.4983$, $\phi_{s2s} = 0.3436$ (site-to-site), $h = 10$, $M_c = 7.1$, $M_{ref} = 6.5$, $M_{max} = 8$, $R_{rup}^{ref} = 0$, $V_{S30}^{ref} = 760$, $Z_{tor,cr}^{ref} = 0$, $Z_{tor,inter}^{ref} = 0$, $Z_{tor,intra}^{ref} = 35$, $C_{4inter} = 0.3$, $C_{4intra} = 0.2$. $u(\dot{})$ is Heaviside step function. $\hat{S}_{a1180}$ is median PSA for $V_{s,30} = 1180$ m/s.

- Use $V_{s,30}$ and depth to $V_s = 1.0$ km/s horizon, $Z_{1.0}$ to characterise sites. $V_{s,30}$ and $Z_{1.0}$ obtained from direct measurements ($F_{measured} = 1$), inferred from geology ($F_{geology} = 1$) or inferred from receiver function analysis using seismic data ($F_{seismic} = 1$). Data from 681 stations. 2 peaks in $V_{s,30}$ distribution: one $\sim 220$ m/s and one $\sim 500$ m. Very limited data with $V_{s,30} > 800$ m. $121.45 \leq V_{s,30} \leq 1538.03$ m/s. $0.5 \leq Z_{1.0} \leq 1154$ m.

- Classify events by event type:

  1. Crustal/strike-slip, 8586 records, 77 events. $F_{cr,ss} = 1$ and $F_{cr} = 1$ and all others 0.
  2. Crustal/reverse/reverse-oblique, 15154 records, 87 events. $F_{cr,ro} = 1$ and $F_{cr} = 1$ and all others 0.
  3. Crustal/normal/normal-oblique, 2833 records, 34 events. $F_{cr,no} = 1$ and $F_{cr} = 1$ and all others 0.
  4. Subduction/interface, 3953 records, 34 events. $F_{sb,inter} = 1$ and $F_{sb} = 1$ and all others 0.
  5. Subduction/intraslab, 10366 records, 84 events. $F_{sb,intra} = 1$ and $F_{sb} = 1$ and all others 0

  using hypocentral location and focal mechanism.

- Group all earthquakes within 3 days and within 5 km hypocentral distance as same series. Largest event classified as mainshock and the others as aftershocks, $F_{as} = 1$.

- Model difference between earthquakes from Manila ($F_{manila} = 1$) and Ryukyu ($F_{manila} = 0$) subduction zones.

- Consider depth to top of rupture, $Z_{tor}$. $0 \leq Z_{tor} \leq 68.39$ km for crustal events, $0.79 \leq Z_{tor} \leq 29.88$ km for interface, $24.13 \leq Z_{tor} \leq 262.88$ km for intraslab.

- Use 2-step maximum-likelihood regression accounting for correlation among records from same event and those from same site, in addition to accounting for bias in the observations due to the database not including records from non-triggered instruments [randomly-truncated regression, (Chao and Chen, 2019)]. Demonstrate, by selecting another dataset using the maximum usable distance $R_{max}$, that the use of randomly-truncated regression allows more than twice the number of records to be used than would be the case if records beyond $R_{max}$ were excluded. First step of regression finds $S_{path}$ and $S_{site,non}$ and second step finds $S_{source}$ and $S_{site,lin}$ using event and site terms of first step respectively. $S_a^{ref}$ computed in subsequent step. Nonlinear site term derived via iteration.

- Use data from both subduction and crustal events so that station terms more reliable than they would be if the data was split into 2 datasets. Functional form accounts for different source and path effects in the different event types.

- Only use records from strong-motion instruments of TSMIP network. Exclude data from real-time instruments in Taiwan because they are co-located with strong-motion instruments and sampling and resolution lower than strong-motion stations. Only records with all 3 components selected so that same dataset can be used in future to develop vertical and V/H models. Exclude records with PGA on any component $< 4$ gal because of regression method used. Exclude data showing unreasonable event-specific or record-specific residuals in preliminary analysis to avoid biased results. Only select events with $> 10$ records to obtain accurate event terms. Only select stations with $> 10$ records to obtain accurate station terms.

- Note that insufficient data from $M > 6.5$ (only a handful of events) from crustal earthquakes and no data from $M > 7.1$ from subduction earthquakes to constrain model for large magnitudes. Therefore, apply constraints when deriving model coefficients for crustal earthquakes and use coefficients from previously-published models for subduction earthquakes.

- Prevent over-saturation of magnitude scaling for crustal earthquakes by applying a constraint during regression.

- Derive large magnitude scaling coefficients $c_{29}$ and $c_{30}$ using Japanese data (20 events, 1761 records).

- Some coefficients based on judgement or previous studies but most based on regression analyses.

- Smooth coefficients using low-pass filter on interpolated values for densely-spaced periods.

- Examine event-specific, station-specific and record-specific residuals w.r.t. various independent parameters. Fit non-parametric curves to residuals. Find no trends. Examine residuals beyond $R_{max}$ and find expected behaviour, i.e. generally positive residuals, because weaker motions did not trigger instruments.

## 2.470 Cremen et al. (2020)

- Ground-motion model is (based on Douglas et al. (2013), which they find most appropriate using a model testing approach):

$$\ln Y = a + bM + c\ln\sqrt{r_{hypo}^2 + h^2} + dr_{hypo}$$

  where $Y$ is in unknown units (probably mm/s$^2$, $a = -5.096$, $b = 2.146$, $c = -2.611$, $h = 0$ (constrained), $d = -0.023$ (from Douglas et al. (2013) because of short $r_{hypo}$), $\phi = 0.563$ (intra-event), $\tau = 0.437$ (inter-event) and $\sigma = 0.712$ (total).

- Use data from Preston New Road shale gas site (Lancashire) from 2018 and 2019 and New Ollerton coal mining site (N. Nottinghamshire), which include as from similar distances and magnitudes, ground motions are similar and the events occured in same geological formation. Only use data with $r_{hypo} < 10$ km and $M_L > 0$ to restrict to ground motions that were potentially felt.

- Focal depths < 3 km.

- Data from 9 Guralp 3-ESP broadband instruments, 2 Kinemetrics Shallow Borehole Episensor 2 accelerometers and 6 Geospace Technologies SNG 3C GS-ONE LF geophones for Preston New Road and 4 Guralp 3-ESP broadband instruments for New Ollerton. Convert raw data to velocities or accelerations using a causal 3rd-order high-pass Butterworth filter with cut-off of 3 Hz, a causal 5th-order low-pass Butterworth filter with cut-off of 20 Hz and an oversampling rate of 5 and either differentiation or integration depending on intensity measure. Use time-window from P-wave arrival to 5 s after occurence of maximum displacement amplitude. Exclude data with signal-to-noise ratio $\leq 3$. Most earthquakes are associated with 4 to 6 records.

- All sites are alluvium so assume $V_{s,30} = 280$ m/s.

- Derive model by adjusting coefficients of Douglas et al. (2013) to better fit data using a maximum-likelihood approach based on the residuals with respect to the Douglas et al. (2013) model. Because almost all the coefficients change it is included here rather than in the referenced-empirical section of this report.

## 2.471 Hu et al. (2020)

- Ground-motion model is:

$$\log y = b_1 M_w + b_2 x - \log(x + b_3) + b_4[\min(h, 130) - h_c]\delta_h + b_5 F_I + b_6 F_S + S_k + SC_p$$

  where $y$ is in gal, $b_3 = 5$ (fixed as no near-source data to constrain it), $\delta_h = 1$ for $h \geq h_c$ and 0 otherwise, $h_c = 15$ km; $b_1 = 1.073$, $b_2 = -0.00509$, $b_4 = 0.00609$, $b_5 = 0.164$, $b_6 = 0.344$, $S_1 = 2.86$, $S_2 = 2.72$, $S_3 = 2.70$, $S_4 = 2.26$, $S_5 = 2.72$, $S_6 = 2.79$, $SC_1 = 1.18$, $SC_2 = 1.70$, $SC_3 = 1.82$, $SC_4 = 1.59$, $\tau = 0.342$ (inter-event) and $\phi = 0.545$ (intra-event) for horizontal; and $b_1 = 1.055$, $b_2 = -0.00514$, $b_4 = 0.00652$, $b_5 = 0.117$, $b_6 = 0.281$, $S_1 = 0.22$, $S_2 = 1.58$, $S_3 = 0.30$, $S_4 = 0.75$, $S_5 = 0.52$, $S_6 = 0.78$, $SC_1 = 0.12$, $SC_2 = 0.73$, $SC_3 = 0.92$, $SC_4 = 0.81$, $\tau = 0.339$ (inter-event) and $\phi = 0.548$ (intra-event) for vertical.[59]

- Use 4 site classes for onshore stations:

  SC I Rock/stiff soil. $V_{s,30} > 600$ m/s. 2 stations, 171 records. Use $SC_1$.

  SC II Hard soil. $300 < V_{s,30} \leq 600$ m/s. 17 stations, 1583 records. Use $SC_2$.

  SC III Medium soil. $200 < V_{s,30} \leq 300$ m/s. 5 stations, 651 records. Use $SC_3$.

  SC IV Soft soil. $V_{s,30} \leq 200$ m/s. 13 stations, 1399 records. Use $SC_4$.

- Classify offshore stations using horizontal-to-vertical response (H/V) spectral ratios because of a lack of site information. Use individual terms for each station ($S_1$ to $S_6$) due to variability in site responses and difficulties of using H/V ratios for offshore locations.

- Use 3 event types:

  1. Crustal. Focal depths $h \leq 50$ km. $F_I = F_S = 0$.
  2. Interface. Focal depths, $h$, between 20 and 50 km. $F_I = 1$, $F_S = 0$.
  3. Slab. Focal depths, $h$, between 50 and 180 km. $F_S = 1$, $F_I = 1$.

  Classify based on location w.r.t. trench axis and focal mechanism.

- Derive model using data between 2000 and 2018 from offshore (6 ocean-based K-NET instruments at depths between 900 and 2300 m) and onshore (37 adjacent K-NET instruments) sites so that can compare predicted motions at offshore and onshore sites. Select data with P-wave and S-wave onsets included, $r_{hypo} < 300$ km, focal depth $< 180$ km and $M_w > 4.0$. Exclude records with signal-to-pre-event-noise ratios $< 3$ in band 0.2–20 Hz.

- Most data from $r_{hypo} > 50$ km and $M_w < 5$ with few records with $r_{hypo} < 20$ km, especially offshore.

- Process records by subtracting the mean of the pre-event portion from whole record, integrate to find velocity and then fit quadratic curve, subtract derivate of quadratic curve from acceleration and then bandpass (acausal, 4th-order Butterworth) filter zero-padded record with cut-off frequencies of 0.1 and 20 Hz[60].

- Examine residuals w.r.t. $M_w$, $h$ and $r_{hypo}$ and find no trends. Also plot observations and predictions for binned magnitude ranges w.r.t. $r_{hypo}$ and find good match.

[59]It is likely that the $\tau$ and $\phi$ values reported in Tables 5 and 6 of the article are reversed as they do not correspond to Figure 7 of article. Reported the reversed values here.

[60]It may be 25 Hz as both are stated.

## 2.472 Jaimes and García-Soto (2020)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y_H &= \alpha_1 + \alpha_2 M_w + \alpha_3 \ln R^* + \alpha_4 R^* + \alpha_5 H^* \\
R^* &= \sqrt{R^2 + \Delta^2} \\
\Delta &= 0.0075 \times 10^{0.507 M_w} \\
H^* &= \min(H_D, 75) - 50
\end{aligned}
$$

  where $Y_H$ is in cm/s$^2$; $\alpha_1 = 0.1571$, $\alpha_2 = 1.3581$, $\alpha_3 = -1.0$ (fixed to avoid unrealistic values), $\alpha_4 = -0.0084$, $\alpha_5 = 0.0268$, $\tau = 0.35$ (inter-event), $\phi = 0.60$ (intra-event) and $\sigma = 0.70$ (total) for horizontal; and $\alpha_1 = -0.0082$, $\alpha_2 = 1.3218$, $\alpha_3 = -1.0$ (fixed to avoid unrealistic values), $\alpha_4 = -0.0079$, $\alpha_5 = 0.0215$, $\tau = 0.30$ (inter-event), $\phi = 0.56$ (intra-event) and $\sigma = 0.63$ (total) for vertical. $\Delta$ is taken from Atkinson and Boore (2003).

- All data from rock (NEHRP class B) sites.

- Extends database used by García et al. (2005) (see Section 2.242) with 80 records from 7 earthquakes between 2005 and 2017. Data from 69 different stations on Mexican Pacific coast and in central Mexico.

- Focal depths, $H_D$, between 35 and 138 km. Gap in focal depths between 75 and 110 km, which led to functional form adopted as it centres the predictions at $H_D = 50$ km. Note uncertainty in predictions for events with $H_D > 110$ km due to lack of data.

- No records between $M_w 7.4$ and $M_w 8.2$ but lower magnitude range well sampled. Records well-distributed w.r.t. distance.

- Baseline correct records and apply high-pass filter with cut-offs of 0.05 Hz for events with $M_w > 6.5$ and 0.1 Hz for smaller earthquakes.

- Also derive a model without a focal-depth term and find no significant differences in predictions except for events with $H_D > 110$ km.

- Plot total residuals w.r.t. $M_w$, $R$ and $H_D$. Find no clear trends.

- Note that some records (e.g. those from Laguna Verde) may be affected by travel through the mantle wedge or active volcanoes (with higher attenuation). Excluding these 3 records had an insignificant impact on the results.

- Consider inclusion of a quadratic magnitude term for large earthquakes but find this is not justified based on residuals and comparisons to other models. Note that finite-fault models could provide insight into this question.

- Compare predictions and observations for the 2017 Tehuantepec ($M_w 8.2$) and Puebla-Morelos ($M_w 7.1$) events and find good agreement.

### 2.473 Kotha et al. (2020)

- Ground-motion model is:

$$
\begin{aligned}
\ln \mu &= e_1 + f_{R,g} + f_{R,a} + f_M \\
f_{R,g} &= [c_1 + c_2(M_w - M_{ref}] \ln \sqrt{(R_{JB}^2 + h_D^2)/(R_{ref}^2 + h_D^2)} \\
f_{R,a} &= \frac{c_3}{100}\left(\sqrt{R_{JB}^2 + h_D^2} - \sqrt{R_{ref}^2 + h_D^2}\right) \\
f_M &= \begin{cases} b_1(M_w - M_h) + b_2(M_w - M_h)^2 & M_w \leq M_h \\ b_3(M_w - M_h) & M_h < M_w \end{cases}
\end{aligned}
$$

  $R_{ref} = 30$ km, $M_{ref} = 4.5$, $M_h = 6.2$. Other coefficients not reported in article. Components of variability split into: between-region, between-locality, event-to-event (inter-event), site-to-site and unexplained variability.

- Do not exclude data from stations lacking measured $V_{s,30}$ because derive site-specific terms. Data from 1829 stations. 1077 stations have $\geq 3$ records. Do not include site-response terms in model because only 419 out of 1829 sites have measured $V_{s,30}$ and since individual site terms can be correlated in a subsequent step to $V_{s,30}$, topographic slope or geology.

- Use data from the Engineering Strong-Motion (ESM) database to update model of Kotha et al. (2016a) (see Section 2.409).

- Select data only from shallow crustal earthquakes. Focal depths $D \leq 39$ km. Moho depth in region covered by model between 14 and 49 km. Only use earthquakes with $\geq 3$ records.

- Split earthquakes into 3 focal depth bins: $D < 10$ km, $10\,\text{km} \leq D < 20$ km and $D \geq 20$ km based on preliminary analysis of non-parametric fits to the data. Set $h_D = 12$ km for deep bin, $h_D = 8$ km for intermediate-depth bin and $h_D = 4$ km for shallow bin to match observations. Do not find $h_D$ during regression so as to keep regression linear.

- Much data from $r_{jb} > 50$ km and $4 < M_w < 5$.

- Derive regionalised model with adjustments for 46 attenuating regions, 56 earthquake locations and 1829 sites. Assess robustness of these adjustments through a 10-fold cross-validation exercise.

- Use robust linear mixed-effects regression to down weight the influence of outliers.

- Use geological-geophysical regionalisation of Europe from previous study (TSUMAPS-NEAM project) to derive anelastic attenuation coefficients for each region based on which region the site is in (earthquake location is not used because regions are surficial and cannot account for different focal depths). Some regions have $> 1000$ records but some $< 100$ records so uncertainty of regional attenuation coefficients varies.

- Use seismotectonic zones from previous study (ESHM2020 project) to derive earthquake locality coefficients based on which zone an earthquake is in, to capture effect of local tectonics (e.g. fault maturity) on ground motions. Some regions have $> 1000$ records but some $< 100$ records so uncertainty of earthquake locality coefficients varies.

- Plot predictions and observations binned into magnitude bins w.r.t. $r_{jb}$ and distance bins w.r.t. $M_w$ for the 3 depth intervals. Find good matches. Find that the model predicts over-saturation at large magnitudes and note that whether this is realistic needs further investigation.

- Examine via plots and maps the various random-effects of the model and propose physical reasons for the observations. Examine site random-effects w.r.t. $V_{s,30}$ and topographic slope binned into intervals and find strong trends. Derive quadratic functions for the site response as a functional of $V_{s,30}$ and topographic slope based on these plots. Examine the decrease in variability after accounting for site response using these functions. Plot the remaining residuals after removing all the random-effects w.r.t. $r_{jb}$ and find evidence for anisotropic shear-wave radiation pattern for $r_{jb} \leq 80$ km and Moho reflections for $60 \leq r_{jb} \leq 200$ km.

- Present 3 applications of the model to show how it can be applied, including computation of the variability, for different situations: ergodic application (ignoring repeatable effects, i.e. region, locality, and site-specific adjustments), region-specific application (ignoring site-specific adjustment) and region- and site-specific application, for central Italy.

## 2.474 Kowsari et al. (2020)

- Ground-motion model is:

$$\begin{aligned}\log Y &= C_1 + C_2 M_w + C_3 \log\sqrt{R^2 + z^2} + C_7 S \\ z &= C_4 + C_5 (M - C_6)^2 H(M - C_6)\end{aligned}$$

where $Y$ is in m/s$^2$, $H$ is the Heaviside function, $C_1 = -1.21686$, $C_2 = 0.49537$, $C_3 = -1.61034$, $C_4 = 4.51333$, $C_5 = 0.50199$, $C_6 = 5.24258$, $C_7 = 0.36653$, $\tau = 0.03691$ (inter-event) and $\phi = 0.17496$ (intra-event).

- Use 2 site classes:

$S = 0$ Rock. Eurocode 8 site class A. 62 records.

$S = 1$ Soil. Eurocode 8 site class B. 21 records.

- Focal depths between 5.0 and 11.3 km.

- Derive model using regression method based on Bayesian inference and Markov Chain Monte Carlo.

- Regression method provides the probability distribution of all coefficient and components of variability. Therefore, provides information on which coefficients are poorly determined, cross-correlated and/or superfluous.

- Residual plots w.r.t. magnitude and distance show no trends or bias. Test for linear trends using hypotheses tests and find no significant results.

- Note that the posterior distribution of $\tau$ is not normal and is associated with a large uncertainty so low $\tau$ found may not be real reflection of event variability.

## 2.475 Kuehn et al. (2020a)

## 2.476 Kuehn et al. (2020b)

- Ground-motion model for Taiwan is:

$$\begin{aligned}f &= \beta_1 + \beta_2(M-5) + \beta_4 \ln\min(V_{s,30}/400, 1100/400) + (\beta_5 + \beta_6 M)\ln\sqrt{R_{JB}^2 + \beta_7^2} + \beta_8 R_{JB} \quad \text{for} M \leq 5 \\ f &= \beta_1 + \beta_3(M-5) + \beta_4 \ln\min(V_{s,30}/400, 1100/400) + (\beta_5 + \beta_6 M)\ln\sqrt{R_{JB}^2 + \beta_7^2} + \beta_8 R_{JB} \quad \text{for} M > 5\end{aligned}$$

Ground-motion model for Iran is:

$$
\begin{aligned}
f &= \beta_0 + g_M + [\beta_4 + \beta_5(M-5)] \ln \sqrt{R_{HYP}^2 + \beta_6^2} + \beta_7 R_{HYP} \\
g_M &= -\beta_1 + \beta_2(M-5.5) \quad \text{for} M < 5.5 \\
g_M &= \beta_1(M-6.5) \quad \text{for} 5.5 \leq M \leq 6.5 \\
g_M &= \beta_3(M-6.5) \quad \text{for} M > 6.5
\end{aligned}
$$

Coefficients not reported as only purpose is testing regression algorithm.

- Develop a multi-level Bayesian regression method to develop ground-motion models using truncated data, which occurs due to the triggering of instruments (not continuous recording). Model considers truncation on one variable (e.g. PGA) and models joint occurrence of PGA and other intensity measures (e.g. spectral accelerations) conditional on truncation for PGA. Method can account for prior information on the coefficients. Method also keeps track of uncertainties in all parts of the model.

- Test method using simulated data based on the NGA-West2 dataset and find not accounting for truncation leads to biased models. Using the developed regression method leads to unbiased models.

- Test method using Taiwanese (moderate trigger level of 2–4 gal) and Iranian (high trigger level of 10 gal as most data from SSA-2 instruments) crustal earthquake datasets. Taiwanese data from 652 different stations

- Apply both developed method and normal mixed-effects regression (removing data from distances > $R_{MAX}$, the maximum distance at which the data should not be affected by truncation, and considering all data) to both datasets and compare the resulting models.

- For the large Taiwanese dataset use simple non-informative prior distributions for all coefficients and apply some constraints on the coefficients. Find limited differences among the models, with larger differences at large distances. Find lower components of aleatory variability when not accounting for truncation.

- Iran dataset quality-checked and processed using the NGA procedures. Due to uncertain $V_{s,30}$ values did not include site term. Use only records from earthquakes with focal depth < 30 km and only with ≥ 3 records per event. Find large differences using truncated and non-truncated regression because of the high trigger level. Not considering truncation of the data leads to predicting flatter attenuation. Observe that the within-event residuals from the truncated model show a clear bias and trend with distance but not that this is does not indicate model misfit but is due to the truncation of the data (the data below the trigger level are missing). Also find much higher components of aleatory variability when accounting for the truncation of the data.

- Note that method is computationally expensive and has a much longer run time than a maximum-likelihood approach.

## 2.477 Lanzano and Luzi (2020)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10} Y &= a + bM + F_D + F_S \\
F_D &= \begin{cases} c_1 \log_{10} \sqrt{R_{hyp}^2 + h_1^2} & h \leq 5\,\text{km} \\ c_2 \log_{10} \sqrt{R_{hyp}^2 + h_2^2} + c_3 \sqrt{R_{hyp}^2 + h_2^2} & h > 5\,\text{km} \end{cases} \\
F_S &= s_i
\end{aligned}
$$

where $Y$ is in cm/s$^2$, $a = -0.4185$, $b = 0.8146$, $c_1 = -2.0926$, $c_2 = -1.5694$, $c_3 = -0.0062$, $s_1 = 0$, $s_2 = 0.0880$, $s_3 = 0.3382$, $h_1 = 2$, $h_2 = 5$, $\tau = 0.1892$ (inter-event), $\phi_{S2S} = 0.2624$ (site-to-site) and $\sigma_0 = 0.2215$ (residual variability). $h_1$ and $h_2$ are from preliminary regressions, averaged over period and then fixed in final regression.

- Use 3 site classes to be consistent with European and Italian building codes even though other approaches (using H/V curves) were more effective:

  $i = 1$ Eurocode 8 class A. About 350 records.

  $i = 2$ Eurocode 8 class B. About 200 records.

  $i = 3$ Eurocode 8 class C, D and E. About 50 records.

  Only have $V_{s,30}$ for 13% of stations so use topographic slope to estimate it for other stations.

- Focal depths, $h$, . Observe different behaviour for earthquakes shallower and deeper than 5 km so include this in the functional form.

- Data taken from ITACA from DPC-RAN, IHGV-INSN and INGV-MEDNET accelerometers and broadband instruments (155 different stations) on Mount Etna and the Aeolian Islands plus one earthquake from Ischia from 2001–2019. For co-located instruments only retain data from broadband instruments. Uniformly process data.

- Data distribution is good between $M_w$3.5 and 4.9 and $20 \leq r_{hypo} \leq 120$ km. About 40 records at short distances (only 3 records with $r_{epi} < 5$ km).

- Note that high $\sigma$ may be partially due to poor classification of sites and variability in site response.

- Compare observations and predictions for $M_w$4.5, for 2017 Ischia $M_w$3.9 and 2018 Viagrande $M_4$.9 events and find good match and clear differences between shallow and deep events.

- Examine residual plots w.r.t. $M_w$ and $r_{hypo}$ and find no clear trends.

- Compute the epistemic uncertainty using the covariance matrix. Find lower uncertainties for shallower events and between 3.5 and 4.5 and 10 to 100 km.

## 2.478 Li et al. (2020)

- Ground-motion model is:

$$
\begin{aligned}
\ln y &= f_B + f_{mech} + f_{site} + F_{HW} f_{HW}(M) f_{HW}(R) \\
f_B &= b_1 M^2 + b_2 M + b_3 M \ln R + b_4 \ln R \\
R &= \sqrt{R_{rup}^2 + h^2} \\
f_{mech} &= d_1 \mathrm{SS} + d_2 \mathrm{NS} + d_3 \mathrm{RS} \\
f_{site} &= \begin{cases} s \ln\left(\frac{2V_2 - V_{S30}}{V_{ref}}\right) & V_{S30} \leq V_2 \\ s \ln\left(\frac{V_{S30}}{V_{ref}}\right) & V_2 < V_{S30} \leq V_1 \\ s \ln\left(\frac{V_1}{V_{ref}}\right) & V_{S30} > V_1 \end{cases} \\
V_1 &= \begin{cases} 1500 & T \leq 0.5\,\mathrm{s} \\ \exp\left[7.31322 - 0.42536 \ln\left(\frac{T}{0.5}\right)\right] & 0.5 < T \leq 3\,\mathrm{s} \\ 700 & T > 3\,\mathrm{s} \end{cases} \\
V_2 &= \begin{cases} 300 & T \leq 0.5\,\mathrm{s} \\ \exp\left[5.70378 - 0.38685 \ln\left(\frac{T}{0.5}\right)\right] & 0.5 < T \leq 3\,\mathrm{s} \\ 150 & T > 3\,\mathrm{s} \end{cases} \\
f_{HW}(M) &= \begin{cases} M - 6 & 6 \leq M < 7 \\ 1 & M \geq 7 \end{cases} \\
f_{HW}(R) &= \begin{cases} 0 & R_{rup} < r_1 \\ \beta(R_{rup} - r_1)(R_{rup} - r_2) & r_1 \leq R_{rup} \leq r_2 \\ 0 & R_{rup} > r_2 \end{cases} \\
r_2 &= \begin{cases} 29 \exp(-0.2T^0.6) & T \leq 3\,\mathrm{s} \\ 29 \exp(-0.23^0.6) & T > 3\,\mathrm{s} \end{cases}
\end{aligned}
$$

where $Y$ is in g, $b_1 = -0.081$, $b_2 = 0.541$, $b_3 = 0.310$, $b_4 = -3.195$, $h = 9.533$, $d_1 = 1.396$, $d_2 = 1.109$, $d_3 = 1.455$, $s = -0.322$, $\beta = -0.014$, $\sigma = 0.578$ (intra-event) and $\tau = 0.333$ (inter-event).

- Use $V_{s,30}$ to characterise sites because it is more objective than site classes.

- Use 3 faulting mechanism categories:

Strike-slip SS = 1, NS = 0 and RS = 0.

Normal NS = 1, SS = 0 and RS = 0. Includes normal-oblique.

Reverse RS = 1, SS = 0 and NS = 0. Includes reverse-oblique.

- Consider differences in ground motions between sites on hanging wall ($F_{HW} = 1$) and foot wall ($F_{HW} = 0$).

- Select data based on these critiera: $M_w \geq 6.0$, both horizontal components available and $r_{rup} \leq 200$ km.

- Bandpass filter Sichuan-Yunnan records with cut-offs 0.05 and 30 Hz. Choose low-cut frequency based on visual examination of Fourier amplitude spectra and displacements from double integration of records.

- Include 276 records from global shallow crustal earthquakes in active tectonic regions (from NGA-West2 database) to increase database and fill in gap between 6.6 and 7.9 (largest 2 earthquakes in Sichuan-Yunnan database). Select only free-field records and try to select similar numbers of records from different faulting mechanisms and on footwall and hanging wall.

- Combined database roughly uniformly distributed w.r.t. magnitude and distance.
- Determine functional form based on plots of observations w.r.t. magnitude and distance and residual plots w.r.t. base model ($f_b$).
- Find including style-of-faulting and hanging-wall terms decreases $\tau$ and including site terms decreases $\sigma$.
- Do not consider nonlinear site effects as not expected for ground-motion amplitudes in database.
- Examine residuals w.r.t. distance and find no trends. Hence conclude anelastic attenuation term is not needed.
- Examine residuals w.r.t. final model and find no significant trends.
- Compare predictions and observations for Wenchuan, Lushan, Ludian and Jinggu earthquakes and find good match.
- Examine residuals and find good match to range expected for the normal distribution. Find observations from Lushan earthquake are higher than expected.

## 2.479 Parker et al. (2020, 2022)

## 2.480 Phung et al. (2020a)

- Ground-motion model is (based on Abrahamson et al. (2016) with minor modifications/simplifications):

$$
\begin{aligned}
\ln \mathrm{PSA} &= a_1 + F_{MAG} + F_{DIST} + a_7 F_{eve} + F_{DEP} + F_{SITE} + F_{Basin} \\
F_{MAG} &= \begin{cases} a_4(M - M_{ref}) + a_{13}(10 - M)^2 & M \leq M_{ref} \\ a_5(M - M_{ref}) + a_{13}(10 - M)^2 & M > M_{ref} \end{cases} \\
F_{DEP} &= \begin{cases} a_{10}[\min(Z_{tor}, 40) - 20] & \text{interface} \\ a_{11}[\min(Z_{tor}, 80) - 40] & \text{intraslab} \end{cases} \\
F_{DIST} &= [a_2 + a_{14} F_{eve} + a_3(M - 7.8)] \ln\{R_{rup} + C_4 \exp[a_9(M - 6)]\} + a_6 R_{rup} \\
F_{SITE} &= \begin{cases} a_{12} \ln\left(\frac{V_S^*}{V_{Lin}}\right) - b\ln(\mathrm{PGA}_{1000} + c) + b\ln\left[\mathrm{PGA}_{1000} + c\left(\frac{V_S^*}{V_{Lin}}\right)^n\right] & V_{s,30} < V_{Lin} \\ a_{12} \ln\left(\frac{V_S^*}{V_{Lin}}\right) + bn\ln\left(\frac{V_S^*}{V_{Lin}}\right) & V_{s,30} \geq V_{Lin} \end{cases} \\
F_{Basin} &= a_8 \min\left[\ln\left(\frac{Z_{1.0}}{Z_{1.0ref}}\right), 1\right] \\
\ln Z_{1.0ref} &= \frac{-3.96}{2} \ln\left(\frac{V_{s,30}^2 + 352.7^2}{1750^2 + 352.7^2}\right)
\end{aligned}
$$

where PSA is in g, $\mathrm{PGA}_{1000}$ is median PGA at $V_{s,30} = 1000\,\mathrm{m/s}$, $V_S^* = \min(V_{s,30}, 1000)$; $a_3 = 0.1$, $C_4 = 10$, $a_9 = 0.25$ are fixed and taken from Abrahamson et al. (2016); $a_1 = 4.4642$, $a_4 = 0.4420$, $a_5 = 0.0385$, $a_{13} = -0.0257$, $M_{ref} = 7.68$, $a_2 = -1.5528$, $a_{14} = -0.0119$, $a_7 = 0.6819$, $a_{10} = 0.0160$, $a_{11} = 0.0150$, $a_6 = -0.0006$, $a_{12} = 0.9903$, $a_8 = -0.0628$, $n = 1.18$, $c = 1.88$, $b = -1.186$, $V_{Lin} = 865.1$, $\tau = 0.3523$ (inter-event), $\phi_{S2S} = 0.3443$ (site-to-site) and $\phi_{SS} = 0.4130$ (single-station). Derive separate $a_6$ and $a_{12}$ coefficients for Japan and Taiwan.

- Use $V_{s,30}$ and depth-to-$V_s = 1000\,\mathrm{m/s}$-horizon, $Z_{1.0}$, to characterise sites. Adopt the nonlinear site amplification function from Abrahamson et al. (2016) due to the lack of data from sites with low $V_{s,30}$ with large amplitude ground motions. Use only local data from sites with $V_{s,30} > 330\,\mathrm{m/s}$ to develop model as these are likely to display very weak nonlinearity. 3354 (Japan) + 2943 (Taiwan) records from

$V_{s,30} \leq 760$ m/s and 392 (Japan) + 284 (Taiwan) from $V_{s,30} > 760$ m/s. Do not recommend model for sites with $V_{s,30} < 250$ m/s as data from that range not used in

- Classify earthquakes into 2 types:

Intraslab Generally deeper. 30 events from Taiwan, 10 from Japan. $F_{eve} = 1$.

Interface Generally shallower. 21 events from Taiwan, 15 from Japan. $F_{eve} = 0$.

- Use depth-to-top-of-rupture $Z_{tor}$, which is 0 to 35 km for Taiwanese interface, > 35 km for Taiwanese intraslab and 0 to 60 km for Japanese events.

- Only use data with focal depths < 100 km.

- Supplement data from Taiwan with records from large Japanese earthquakes to constrain the large-magnitude scaling. Most data from Taiwan off north-east coast with some to south of island. Taiwanese data mainly from TSMIP with 36 records from Broadband Array in Taiwan for Seismology. Data from roughly 700 different stations. Assess maximum usable distance, $R_{max}$, for each event considering triggering level (4 gal for TSMIP data). Exclude data beyond $R_{max}$ to avoid biasing the predictions upwards at long distances. Application of $R_{max}$ excludes about 75% of available records from Taiwan. Apply similar approach to Japanese data from the NGA-Sub database. Only use earthquakes if recorded by 5 or more stations.

- Compare data to predictions from Abrahamson et al. (2016) (see Section 2.406) to examine which coefficients need adjustment to better fit observations.

- Discuss and illustrate strong trade-offs between geometric decay and anelastic attenuation coefficients.

- Derive coefficients of model in 4 main stages: 1) constrain path term, 2) constrain source term, 3) repeat stages 1 and 2 after constraining $Z_{tor}$ term, and 4) constrain site amplification and basin term using region-specific data. Within each stage use multiple regression analyses and examine fits and trade-offs. Use random-effects regression and repeat stages until convergence. Use only Taiwanese data to compute components of variability. Compute magnitude-independent $\tau$ only using events with $\geq 5$ records. Assess single-station $\phi$ as well as site-to-site $\phi$ using only stations with $\geq 10$ records. Smoothing of coefficients performed in multiple stages and also by manually adjusting some coefficients.

- Examine residuals w.r.t. various parameters. Find some evidence for bias against $Z_{tor}$ but no trends for other parameters.

- Note that the model lacks terms to model differences between fore-arc and back-arc motions.

## 2.481 Phung et al. (2020b)

- Ground-motion model is (based on Chiou and Youngs (2014)):

$$
\begin{aligned}
\ln y &= c_1 + \left\{ c_{1a} + \frac{c_{1c}}{\cosh[2\max(M-4.5,0)]} \right\} F_{RV} \\
&+ \left\{ c_{1b} + \frac{c_{1d}}{\cosh[2\max(M-4.5,0)]} \right\} F_{NM} \\
&+ \left\{ c_7 + \frac{c_{7b}}{\cosh[2\max(M-4.5,0)]} \right\} Z_{tor} \\
&+ \left\{ c_{11} + \frac{c_{11b}}{\cosh[2\max(M-4.5,0)]} \right\} \cos\delta \\
&+ c_2(M-6) + \frac{c_2-c_3}{c_n} \ln[1+\mathrm{e}^{c_n(c_M-M)}]^2 \\
&+ c_8 \max\left[1-\frac{\max(R_{rup}-40,0)}{30},0\right] \min\left[\frac{\max(M-5.5,0)}{0.8},1\right] \mathrm{e}^{-c_{8a}(M-c_{8b})}\Delta_{DPP} \\
&+ c_9 F_{HW} \cos\delta \left[c_{9a} + (1-c_{9a})\tanh\left(\frac{R_x}{c_9 b}\right)\right] \left[1-\frac{\sqrt{R_{jb}^2+Z_{tor}^2}}{R_{rup}+1}\right] \\
&+ c_4 \ln\{R_{rup} + [c_5 + d_p \max\left(\frac{Z_{tor}-20}{50},0\right)] \cosh[c_6 \max(M-c_{HM},0)]\} + (c_{4a}-c_4)\ln\sqrt{R_{rup}^2+c_{RB}^2} \\
&+ \left\{ c_{g1} + \frac{c_{g2}}{\cosh[\max(M-c_{g3},0)]} \right\} R_{rup} + \phi_1 \min[\ln\left(\frac{V_{S30}}{1130}\right),0] \\
&+ \phi_2 \left\{ \mathrm{e}^{\phi_3[\min(V_{S30},1130)-360]} - \mathrm{e}^{\phi_3(1130-360)} \right\} \ln\left(\frac{y_{1130}\mathrm{e}^{\eta}+\phi_4}{\phi_4}\right) \\
&+ \phi_5\left(1-\mathrm{e}^{-\Delta Z_{1.0}/\phi_6}\right)
\end{aligned}
$$

where $y$ is in g, $y_{1130}$ is median PGA (or PSA) when $V_{s,30} = 1130$ m/s, $c_2 = 1.06$ (fixed based on simulations for large earthquakes), $c_4 = -2.1$, $c_{4a} = -0.5$ and $c_{RB} = 50$ from NGA analyses; $c_1 = -1.4526$, $c_3 = 1.4379$, $c_n = 12.1487$, $c_m = 5.50455$, $c_{1a} = 0.1379$, $c_{1c} = 0.04273$, $c_{1b} = 0$, $c_{1d} = -0.1653$, $c_7 = 0.0080$, $c_{7b} = 0.0210$, $c_8 = 0$, $c_{8a} = 0.2695$, $c_{8b} = 0.4833$, $c_9 = 0.9228$, $c_{9a} = 0.1202$, $c_{9b} = 6.8607$, $c_{11} = -0.108$, $c_{11b} = 0.196$, $d_p = -6.7852$, $c_5 = 6.4551$, $c_{HM} = 3.0956$, $c_6 = 0.4908$, $c_{g1} = -0.0088$, $c_{g2} = -0.0071$, $c_{g3} = 4.2256$, $\phi_1 = -0.5107$, $\phi_2 = -0.1417$, $\phi_3 = -0.007$, $\phi_4 = 0.1022$, $\phi_5 = 0.0744$, $\phi_6 = 300$, $\tau = 0.3730$ (inter-event), $\phi_{SS} = 0.4397$ (single-station) and $\phi_{S2S} = 0.3149$ (station-to-station). Also provide coefficients for other regions in appendix. These are not included here for space reasons.

- Use $V_{s,30}$ and depth-to-$V_s = 1000$ m/s-horizon, $Z_{1.0}$, to characterise sites. 463 stations have measured $V_{s,30}$. $V_{s,30}$ estimated for others using proxies and receiver functions. 746 stations had known $Z_{1.0}$ and rest estimated using correlation with $V_{s,30}$. No data with $V_{s,30} > 1500$ m/s and few with $V_{s,30} > 760$ m/s. Many records with $V_{s,30} < 360$ m/s from basins and valleys. $\Delta Z_{1.0}$ is difference between $Z_{1.0}$ and reference value given by relationship between $Z_{1.0}$ and $V_{s,30}$: $EZ_{1.0} = \frac{-3.73}{2}\ln\left(\frac{V_{S30}^2+290.53^2}{1750^2+290.53^2}\right)$.

- Use 3 faulting mechanisms:

Normal Rake angle between −120 and −60°. 22 events, 991 records. $F_{NM} = 1$, $F_{RV} = 0$.

Strike-slip Other rake angles. 65 events, 3670 records. $F_{RV} = 0$, $F_{NM} = 0$.

Reverse Rake angle between 30 and 150°. 100 events, 9896 records. $F_{RV} = 1$, $F_{NM} = 0$.

- Model hanging-wall effect using $r_{jb}$, $R_x$ (site coordinate in km measured perpendicular to fault strike from fault line with a positive down-dip direction) and $F_{HW}$ (0 for $R_x < 0$ and 1 otherwise).

- Model directivity effect using DPP, the direct point parameter. $\Delta$DPP is DPP on the site at the centre of the earthquake minus the specific average DPP.

- Data mainly from the dense TSMIP network. Data from 827 stations. Process data as in NGA-West1 project.

- Supplement Taiwanese data with data from worldwide data from NGA-West2 database (in addition to Fukushima, Japan, earthquake) for $M \geq 6.46$ because of a lack of normal-faulting and large earthquakes from Taiwan (use data from California, New Zealand, Japan, Italy, China, Iran, Turkey and other countries). Select data from $M_w > 3.5$ from Taiwan (although only one event with $M_w < 4$ selected) and data from distances $< R_{max}$ (determined based on triggering) for Taiwanese data and $< 150$ km for worldwide data. Select earthquakes with $\geq 10$ records from Taiwan (or $\geq 5$ for worldwide events).

- Use distance-to-top-of-rupture, $Z_{tor}$, and dip, $\delta$, (in radians) to characterise events. $Z_{tor}$ between 0 and about 45 km with all worldwide data with $Z_{tor} < 10$ km. $\Delta Z_{tor}$ is difference between observed $Z_{tor}$ and $Z_{tor}$ from relationships between $Z_{tor}$ and $M_w$: $EZ_{tor}) = \max[3.5384 - 2.600 \max(M - 5.8530, 0), 0]^2$ for reverse and $EZ_{tor}) = \max[2.7482 - 1.7639 \max(M - 5.5210, 0), 0]^2$ for strike-slip or normal earthquakes.

- Modify the near-source term of Chiou and Youngs (2014) to account for behaviour of deepest ($Z_{tor} > 20$ km) earthquakes in Taiwan.

- 39 events (24% of total records) are aftershocks. Find ground motions decay faster in these events to introduce $\Delta c_{gas}$ term.

- Derive coefficients of model in 4 main stages: 1) constrain path term, 2) constrain source term, 3) repeat stages 1 and 2 after constraining $Z_{tor}$, style-of-faulting and $\delta$ terms, and 4) constrain site amplification and basin term using region-specific data. Within each stage use multiple regression analyses and examine fits and trade-offs. Use random-effects regression and repeat stages until convergence. Use only Taiwanese data to compute components of variability. Assess single-station $\phi$ as well as site-to-site $\phi$ using only stations that recorded $\geq 10$ earthquakes. Smoothing of coefficients performed in multiple stages and also by manually adjusting some coefficients.

- Assess impact of including additional source parameters in the model on the inter-event variability, which reduces as the additional parameters are included. $Z_{tor}$ and then style-of-faulting most significant.

- Under detailed mixed-effects residual analysis to check for bias and trends w.r.t. many independent parameters. Fit linear trends to residuals and test the significance of the slope. Generally no bias or trends found, although some local trends present in plots w.r.t. $Z_{tor}$.

## 2.482 Ramkrishnan et al. (2022)

- Ground-motion model is:
$$\log Y = c_1 + c_2 M + b \log[X + \exp(c_3 M)]$$
where $Y$ is in g, $c_1 = -2.607$, $c_2 = 0.580$, $b = -1.004$, $c_3 = -1.332$ and $\sigma = 0.477$.

- Use data from Shillong array from a mixture of analogue (SMA-1) (earthquakes from 1986 to 1997) and digital instruments (earthquakes from 2009 to 2013.

- Focal depths from 5 to 119 km with most less than 50 km.

- Data from largest earthquakes only from $r_{hypo} > 180$ km.

- Do not consider effect of faulting mechanism because information is not available for all events.

- Perform regression of data from each individual earthquake separately to find decay rates for each earthquake and compare with the decay rate from regression of complete dataset. Find large differences. Therefore, adopt a two-step regression technique to determine $b$ for final model to avoid trade-offs in coefficients.

- Plot observations against predictions for all data as well as residuals. State good match between predictions and observations[61].

- Plot predictions and observations for 4 events in database w.r.t. distance and note good match.

## 2.483 Si et al. (2020, 2022)

## 2.484 Tusa et al. (2020)

- Ground-motion models are (based on Boore and Atkinson (2008)):

$$
\begin{aligned}
\log_{10} Y &= f_{source} + f_{path} + f_{site} \\
f_{source} &= a + b_1 M + b_2 M^2 \\
f_{path} &= [c_1 + c_2(M - M_{ref})] \log_{10}(\sqrt{R_{hyp}^2 + g^2}/R_{ref}) + c_3(\sqrt{R_{hyp}^2 + g^2} - R_{ref}) \\
f_{site} &= e_i S_i \\
g &= h \quad \text{Model a} \\
g &= 10^{\frac{M_L - 3.391}{2.076}} \quad \text{Model b}
\end{aligned}
$$

where $Y$ is in gal, $M_{ref} = 3.6$, $R_{ref} = 1$; $a = 4.8901$, $b_1 = -2.1144$, $b_2 = 0.4148$, $c_1 = -2.6173$, $c_2 = 0.0255$, $h = 2.9538$, $c_3 = 0.0065$, $S_B = 0.0510$, $S_{C/D} = 0.0317$, $\tau = 0.2246$ (inter-event) and $\phi = 0.3009$ (intra-event) for model a, horizontal PGA and using data from $r_{hypo} < 100$ km; $a = 4.5949$, $b_1 = -2.0603$, $b_2 = 0.4109$, $c_1 = -2.5669$, $c_2 = -0.0070$, $h = 2.4017$, $c_3 = 0.0058$, $S_B = 0.0535$, $S_{C/D} = 0.0716$, $\tau = 0.2255$ (inter-event) and $\phi = 0.3003$ (intra-event) for model a, vertical PGA and using data from $r_{hypo} < 100$ km; $a = 4.3726$, $b_1 = -2.2482$, $b_2 = 0.4431$, $c_1 = -1.8893$, $c_2 = -0.0104$, $c_3 = -0.0089$, $S_B = 0.0645$, $S_{C/D} = 0.0482$, $\tau = 0.2184$ (inter-event) and $\phi = 0.2987$ (intra-event) for model b, horizontal PGA and using data from $r_{hypo} < 60$ km; $a = 4.2632$, $b_1 = -2.1960$, $b_2 = 0.4369$, $c_1 = -2.0417$, $c_2 = -0.0199$, $c_3 = -0.0055$, $S_B = 0.1009$, $S_{C/D} = 0.1469$, $\tau = 0.2355$ (inter-event) and $\phi = 0.2873$ (intra-event) for model b, vertical PGA and using data from $r_{hypo} < 60$ km. Coefficients for other models not given here due to lack of space.

- Use 3 site classes based on Eurocode 8:

  A $V_{s,30} \geq 800$ m/s. About 680 records. $e_B = e_{C/D} = 0$.

  B $360 \leq V_{s,30} < 800$ m/s. About 820 records. $e_B = 1$, $e_{C/D} = 0$.

  C and D $V_{s,30} < 360$ m/s. 157 records. $e_{C/D} = 1$, $e_B = 0$.

  Classification based on borehole logs and local geology. Note model poorly constrained for C and D due to limited records.

- Focal depths $\leq 6$ km.

[61] The residuals in their Figure 5 are almost all positive, meaning systematic under-prediction.

- Update of Tusa and Langer (2016) (see Section 2.419) using data from April 2006 to January 2019 and different functional form to improve fit of model to observations close to epicentre and for $M_L > 4.3$.

- Use data from INGV and RAN/DPC strong-motion and INGV broadband stations (discard some broadband records as saturated). Broadband data visually inspected, linear baseline corrected, bandpass filtered (cut-offs of 0.1 and 25 Hz) and differentiated to obtain acceleration. Obtain processed strong-motion data from ITACA.

- Data mainly from $r_{epi} < 30$ km with a second lower peak around 70 km, and from $M_L < 4$.

- Derive separate models using data with $r_{hypo} < 100$ km and with $r_{hypo} < 60$ km. Assess models using Akaike information criterion, Bayesian information criterion, Nash-Sutcliffe model efficiency coefficient, residuals and plots of observed and predicted motions w.r.t. $r_{hypo}$. Also report coefficients using simpler functional form with a fixed pseudo-depth $h$ rather than a magnitude-dependent $g$, which is proposed based on previously-published relation between magnitude and fault length. Find predictions using $g$ are better for very short distances and larger magnitudes for some intensity measures. Find some minor differences between the models for $r_{hypo} < 100$ km and $r_{hypo} < 60$ km. Overall, prefer Model b using data from $r_{hypo} < 60$ km.

- Find residual plots w.r.t. distance and magnitude do not show any clear trends.

- Use bootstrap and cross-validation tests to assess the confidence intervals of predictions from the various models.

## 2.485 Abdelfattah et al. (2021)

- Ground-motion model is:

$$\log_{10} A = a + bM_L - c\log_{10} r - dr$$

  where $A$ is in cm/s$^2$, $a = -1.36$, $b = 0.85$, $c = 0.85$ and $d = 0.005$ ($\sigma$ not reported).

- Assess terms for each site based on average residuals.

- Earthquakes have normal and strike-slip mechanisms. Most events have focal depths $< 10$ km.

- Use $M_L$ as only magnitude available for most events.

- Use signal-to-noise ratio to select records.

- Data from broadband instruments (STS-2 and Trillium 120) of the Saudi Geological Survey (17 stations). Records instrument corrected and converted to acceleration.

- Data quite well-distributed in terms of magnitude and distance, although most data from $> 100$ km.

- Compare predictions to observations from a 2014 ($M_L$4.9) earthquake and find good match.

## 2.486 Boore et al. (2021)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= F_E + F_P + F_S \\
F_E &= \begin{cases} e_0 U + e_1 \mathrm{SS} + e_2 \mathrm{NS} + e_3 \mathrm{RS} + e_4(M - M_h) + e_5(M - M_h)^2 & M \leq M_h \\ e_0 U + e_1 \mathrm{SS} + e_2 \mathrm{NS} + e_3 \mathrm{RS} + e_6(M - M_h) & M > M_h \end{cases} \\
F_P &= [c_1 + c_2(M - M_{ref})] \ln(R/R_{ref}) \\
R &= \sqrt{R_{jb}^2 + h^2} \\
F_S &= F_{lin} + F_{nl} \\
F_{lin} &= \begin{cases} c_{lin} \ln(V_1/V_{ref}) & V_{s,30} \leq V_1 \\ c_{lin} \ln(V_{s,30}/V_{ref}) & V_1 < V_{s,30} \leq V_c \\ c_{lin} \ln(V_c/V_{ref}) & V_{s,30} > V_c \end{cases} \\
F_{nl} &= f_1 + f_2 \ln(1 + \mathrm{PGA}_r/f_3) \\
f_2 &= f_4[\exp\{f_5(\min(V_{s,30}, 760) - 360)\} - \exp\{f_5(760 - 360)\}] \\
\sigma &= \sqrt{\phi^2 + \tau^2} \\
\tau &= \begin{cases} \tau_1 & M \leq M_{\tau 1} \\ \tau_1 + (\tau_2 - \tau_1)\frac{M - M_{\tau 1}}{M_{tau2} - M_{tau1}} & M_{\tau 1} < M < M_{\tau 2} \\ \tau_2 & M \geq M_{tau2} \end{cases}
\end{aligned}
$$

where $Y$ is in $\mathrm{cm/s^2}$, $B = -1.49920E-01$, $e_0 = 7.28273E+00$, $e_1 = 7.35054E+00$, $e_2 = 7.13618E+00$, $e_3 = 7.37659E+00$, $e_4 = 8.33636E-01$, $e_5 = 5.05300E-02$, $e_6 = -1.66200E-01$, $M_h = 6.2$, $c_1 = -1.13400E+00$, $c_2 = 1.91700E-01$, $c_3 = -1.15138E-02$, $M_{ref} = 4.5$, $R_{ref} = 1.0$, $h = 4.5$, $c_{lin} = -6.00000E-01$, $V_1 = 200$, $V_c = 1500$, $V_{ref} = 760$, $f_1 = 0.0$, $f_3 = 981$, $f_4 = -1.50000E-01$, $f_5 = -7.01000E-03$, $\phi = 5.97441E-01$, $\tau_1 = 5.00000E-01$. $M_{\tau 1} = 5.50000E+00$, $M_{\tau 2} = 6.00000E+00$, $\tau_2 = 3.50000E-01$ and $\sigma(M \geq 6.0) = 6.92413E-01$. $\mathrm{PGA}_r$ is PGA for $V_{s,30} = 760$ m/s.

- Use $V_{s,30}$ to characterise sites. Recommend model for use for $150 \leq V_{s,30} \leq 1200$ m/s.
- Use 3 faulting mechanisms:

  NS Normal-slip. About 35% of data. NS = 1, RS = 0, SS = 0.

  RS Reverse-slip. About 15% of data. NS = 0, RS = 1, SS = 0.

  SS Strike-slip. About 50% of data. NS = 0, RS = 0, SS = 1.

- Use data from a recent database of uniformly-processed data from Greece. Select data with focal depth $\leq 30$ km to avoid including intermediate depth in-slab subduction events. Only select data with $r_{jb} \leq 300$ km. Only use events with $\geq 2$ records with $r_{jb} \leq 80$ km. Find similar results using other selection criteria.
- Examine intra- and inter-event residuals. Identify 44 records (37 from a single $M_w$5.8 reverse earthquake) as outliers. Reason for this is unknown so remove these 44 records, which has little impact on the results.
- Apply magnitude-distance-instrument type screening to account for the effect of instrument triggering from small earthquakes. This prevents residuals from small events increasing for $r_{jb} > 200$ km.
- Use simulation technique based on focal mechanism to assess $r_{jb}$ for some small events with no published fault geometries.
- Do not include basin depth term, because of lack of data, or regional adjustments, because assume Greece is a single region.

- Use total residuals w.r.t. Boore et al. (2014) and perform mixed-effects analysis of residuals, to separate them into inter- and intra-event residuals, to derive model using adjustment factors based on trends fitted to residuals. Iterate process and smooth coefficients to find final model. Adjustments of Boore et al. (2014) are prefered as it produces model that is effective for hazard-controlling scenarios ($M_w$6.5–7.0 and $r_{jb} < 20$ km), even though believe sufficient data to derive model in standard way.

- First, adjust path component by altering $c_3$. Next adjust source component by changing $e_4$ and $M_h$. Then modify coefficients $e_0$ to $e_3$ for faulting mechanism. Next revise linear site amplification component for $V_{s,30} < 200$ m/s. Finally, derive intra- and inter-event variability terms.

- Observe that inter-event variability computed using mixed-effects analysis is higher than that obtained from the standard deviation of the event terms. Believe due to mixed-effects analysis accounting for errors in event terms, which are quite high because only an average of 11 records per event. Discuss which values of $\tau$ should be used in different cases.

- Smooth model by averaging the coefficients for 11 periods centred on a given period as well as applying some subjective smoothing to remove variations over small ranges of periods. Repeat residual analysis to check no trends introduced by smoothing.

- Briefly investigate single-station and site-to-site $\phi$ but note that most stations have $< 5$ records so results not robust.

- Because of the use of Boore et al. (2014) believe model applicable to $M_w$8.0, although with additional uncertainty.

- Find overall negative bias w.r.t. model of Boore et al. (2014), which is robust for different choices of minimum magnitude. Note that soil-structure interaction may be causing bias, although believe more likely a regional feature.

## 2.487 Gao et al. (2021)

- Ground-motion model is:

$$\ln y = c_1 + c_2 M + c_3 \ln(R + c_4 \mathrm{e}^{c_5 M})$$

  where $y$ is in g, $c_1 = -2.822$, $c_2 = 1.076$, $c_3 = -1.777$, $c_4 = 0.3828$, $c_5 = 0.583$ and $\sigma = 0.549$.

- Focal depths between 2.6 and 33.9 km. Depths quite uniformly distributed.

- Select data from about 25 TSMIP stations with similar site conditions (class C, $360 \leq V_{s,30} \leq 760$ m/s) within 70 km of the Mudan dam site ($V_{s,30} = 529$ m/s to minimize uncertainties in assessed hazard.

- Only use earthquakes with data from $> 10$ selected stations.

- Base-line correct and filter records.

- Majority of data from $R > 50$ km and $M_w < 6.5$.

- Because data from $R \leq 300$ km do not include anelastic attenuation term and because earthquakes with $M_w > 8.0$ are not possible in region do not include quadratic magnitude term.

- Examine residuals w.r.t. $R$, $M_w$ and $V_{s,30}$ and not find systematic trends. Residuals closely follow lognormal distribution.

- Test different functional forms and found the selected model fits data with smallest residuals. Also included some Taiwanese data from outside the 70 km radius from $M_w > 6.5$ and $r_{rup} < 40$ km within the regression and based on residual analysis conclude that the model is robust. Finally, compare predictions and observations for the 1999 Chi-Chi ($M_w$7.6) event and obtain good match.

## 2.488 Klimasewski et al. (2021)

## 2.489 Kumar et al. (2021)

- Ground-motion model is:
$$\log A = c_1 + c_2 M - b \log(X + \mathrm{e}^{c_3})$$
where $A$ is in g, $c_1 = -1.091 \pm 0.013117$, $c_2 = 0.3245 \pm 0.07506$, $c_3 = 0.4561 \pm 0.16994$, $b = 1.0632 \pm 0.01413$ and $\sigma = 0.281$.

- Data from U.P. array (24 analogue records from 2 earthquakes with $M_w$6.6 and 6.8), Indian National Strong Motion Instrumentation Network (GSR-18 instruments, 5 earthquakes with $5.0 \leq M_w$5.7) and accelerometers of the Earthquake Early Warning System for northern India (2 earthquakes with $M_w$5.2 and 5.5).

- Focal depths from 10 to 33 km.

- Regress data from each earthquake individually using function: $\log A = -b \log X + c$ and find average $b = 1.0632$. Using all data together gives $b = 1.2309 \pm 0.1613$, which note shows that a 2-stage method is required. Use the weighted regression technique of Campbell (1981) for the 2nd stage to find other coefficients.

- Compare predictions for example magnitudes and data w.r.t. $r_{hypo}$.

- Believe model valid for $15 \leq r_{hypo} \leq 250$ km and $5 \leq M_w \leq 7$.

- Compute root-mean-square error between predictions and observations.

## 2.490 Lanzano et al. (2021) and Caramenti et al. (2022)

- Ground-motion model is:
$$\begin{aligned} \log_{10} \mathrm{PGA} &= a + \begin{cases} b_1(M - M_h) & \text{for} \quad M \leq M_h \\ b_2(M - M_h) & \text{otherwise} \end{cases} \\ &= + [c_1(M - M_{ref}) + c_2(u_e, v_e)] \log_{10} \sqrt{R_{JB}^2 + h^2} + c_3(u_e, v_e)\sqrt{R_{JB}^2 + h^2} \\ &= + k(u_s, v_s) \log_{10} \left( \frac{\min(V_{s,30}, 1500)}{800} \right) + f_1 \mathrm{SoF}_1 + f_2 \mathrm{SoF}_2 \end{aligned}$$
where $u_e$ and $v_e$ denote the epicentre and $u_s$ and $v_s$ denote the site location. Coefficients not reported here due to lack of space. Total $\sigma = 0.30$.

- Characterise sites using $V_{s,30}$, which mainly ranges from 360 to 1000 m/s.

- Classify events into 3 faulting mechanisms: normal, strike-slip and reverse.

- Use multi-source geographically-weighted regression (MS-GWR) to derive a spatially-varying model where some coefficients are constant in space and some vary with location (earthquake and station).

- Use dataset of Lanzano et al. (2019a) but remove data from Turkey, Japan, New Zealand, California, Iceland, Iran and Greece, although retain data from Slovenia, France and Croatia as neighbouring countries. Data from 925 stations.

- Most data from $M_w < 5.5$ and $r_{jb} > 10$ km. Most of Italy well covered by data except for Puglia, Sicily and north of Po Valley.

- Provide details of developed estimation algorithm (not repeated here due to lack of space). Algorithm allows uncertainties in the coefficients and the aleatory variability and epistemic uncertainty in the predictions to be estimated.
- Use a 10 km grid spacing for analysis. Present maps of the non-stationary coefficients.
- Test significance of the non-stationarity and find strong evidence.
- Compare stationary coefficients with those fromLanzano et al. (2019a) and find a close match. Find that introducing non-stationarity moderately reduces $\sigma$ from the stationary value in Lanzano et al. (2019a). Find this reduction is due to about a large reduction in inter-event variability and a smaller reduction in site-related variability.
- Find epistemic uncertainty varies over Italy and it is lowest for highest density (central Italy) and highest where data is sparse (W Sicily, S Puglia).
- Validate the model using a 10-fold cross-validation.
- Examine residuals and do not find strong trends.
- Examine maps of the residuals for the 2018 Muccia $M_w4.6$ event that was not included in the original dataset. Find that residuals do not show spatial patterns.

## 2.491 Ramkrishnan et al. (2021)

- Ground-motion model is:
$$\log Y = c_1 + c_2 M - b \log(X + \mathrm{e}^{c_3 M})$$
where $Y$ is in g, $c_1 = -2.135$, $c_2 = 0.437$, $b = 1.099$, $c_3 = -0.080$ and $\sigma = 0.549$[62]
- Data taken from Kangra and Uttar Pradesh arrays as well as more recent data from IIT Roorkee's strong-motion network and some from Nepalese network. Most data from PESMOS database. Data covers 1986 to 2016.
- Note that lack of data for $> 600$ km, which could lead to prediction errors.
- Strong correlation between magnitude and distance in data. Vast majority of data is from $M_w < 5.5$.
- Use 3 regression approaches: the two-step approach of Fukushima and Tanaka (1990), a one-step approach and the two-step approach of Joyner and Boore (1981). Found similar values of $b$ using one-step approach and two-step approach of Joyner and Boore (1981) so fix $b$ to the value obtained using the approach of Joyner and Boore (1981) and find other coefficients using one-step approach.
- Plot residuals against observation number[63].
- Show predictions against observations for 4 earthquakes not used to derive the model: Hindukush (17/09/2010, $M_w6.1$), Tibet (26/02/2010, $M_w5.2$), Sonipat (07/09/2011, $M_w4.2$) and Nepal-India (04/04/2011, $M_w5.4$) events. Find a good match between predictions and observations.
- Suggest that models for response spectral acceleration for 5% damping were derived but the coefficients of these are not reported nor are there any predictions shown.

[62] This is stated to be the 'standard error'. 0.176 is reported as the 'residual sum of squares', which could correspond to $\sigma$.
[63] This plot, their Figure 6, suggests that there is a strong bias in the model as the vast majority of residuals are positive.

## 2.492 Yao et al. (2021)

- Ground-motion model is:

$$\log y_{af} = a + b \log M_{af} + c \log(R_{af} + h)$$

  where $y_{af}$ is in cm/s$^2$, $M_{af}$ is seismic moment in dyne.cm, $a = -3.0050$, $b = 0.2855$, $c = -1.4929$, $h = 3$ and $\sigma = 0.276$.

- Only use data from 12 stations whose $V_{s,20}$ and $V_{s,30}$ are similar and correspond to soft soil (around 300 m/s).

- Develop model as part of an approach to predict near-source ground motions from large earthquakes accounting for complexity in rupture process.

- Weights in 2-stage regression based on number of records in distance-magnitude bins.

- Choose EW component for regression because largest component for most records of 2008 Wenchuan mainshock.

- Focal depths from 10 to 21 km.

## 2.493 Akhani and Pezeshk (2022)

- Ground-motion model is:

$$\log_{10} Y = \theta_1 + \theta_2 M + \theta_3 M^2 + \theta_4 R + \theta_5 \log_{10}(R + \theta_6 10^{\theta_7 M})$$

  where $Y$ is in cm/s$^2$, $\theta_1 = -3.7439$, $\theta_2 = 2.0711$, $\theta_3 = -0.1420$, $\theta_4 = 0.0018$, $\theta_5 = -1.2624$, $\theta_6 = 0.0413$, $\theta_7 = 0.3037$, $\phi = 0.2550$ (intra-event), $\tau = 0.1551$ (inter-event) and $\sigma = 0.2985$ using TLBO; and $\theta_1 = -4.4035$, $\theta_2 = 2.3011$, $\theta_3 = -0.1633$, $\theta_4 = 0.0019$, $\theta_5 = -1.2808$, $\theta_6 = 0.0073$, $\theta_7 = 0.3194$, $\phi = 0.2287$ (intra-event), $\tau = 0.1533$ (inter-event) and $\sigma = 0.2764$.

- Use 2 metaheuristic (particle swarm and teaching-learning-based) optimization algorithms (PSO and TLBO) to derive mixed-effects models. Compare results to standard regression algorithms by Brillinger and Preisler (1985), Joyner and Boore (1993), Chen and Tsai (2002) and Tavakoli and Pezeshk (2007) using the data of Chen and Tsai (2002).

- Provide details of how the 2 algorithms are applied (not repeated here due to lack of space).

- Evaluate 4 statistical measures to understand accuracy of algorithms: a) root mean square error (RMSE), b) mean absolute error (MAE), c) mean absolute percentage error (MAPE) and d) correlation coefficient (R).

- Find PSO converges more quickly than TLBO.

- Find coefficients obtained using PSO and TLBO are similar to those obtained using other methods but that the components of $\sigma$ are smaller.

- Find that the log-likelihood values using PSO and TLBO are much higher than using other approaches so conclude that the algorithms do an excellent job of estimating coefficients. This is also see by comparing the statistical measures.

- Find total residuals show no trends with distance or magnitude.

- Plot scatter plot of observations (x-axis) against predictions (y-axis) and find some ranges of magnitudes are overpredicted by the algorithms.

## 2.494 Allen (2022)

- Ground-motion model is:

$$
\begin{aligned}
\ln Y &= F_R + F_M + F_D + F_N + F_S \\
F_R &= \begin{cases} c_3 \log_{10} R_{hyp} & R_{hyp} \leq R_x \\ c_3 \log_{10} R_x + c_4(\log_{10} R_{hyp} - \log_{10} R_x) & R_{hyp} > R_x \end{cases} \\
F_M &= c_0 + c_1(M_w - 6)^2 + c_2(M_w - 6) \\
F_H &= d_0 + d_1(\log_{10} h_z)^3 + d_2(\log_{10} h_z)^2 + d_3 \log_{10} h_z \\
F_N &= \begin{cases} n_0(\log_{10} R_{hyp} - \log_{10} R_x) & R_{hyp} \leq R_x \\ 0 & R_{hyp} > R_x \end{cases} \\
F_S &= s_0 + s_1/(\log_{10} V_{S30} - \log_{10} 150)
\end{aligned}
$$

  where $Y$ is in g, $R_x = 600$ km, $h_z = h$ for $10 \leq h \leq 500$ km ($h_z = 10$ km for $h < 10$ km and $h_z = 500$ km for $h > 500$ km), $c_0 = -4.5508$, $c_1 = 0.0000$, $c_2 = 1.6129$, $c_3 = -0.4923$, $c_4 = -10.167$, $d_0 = 4.8787$, $d_1 = -2.5207$, $d_2 = 12.070$, $d_3 = -16.388$, $n_0 = -1.3651$, $s_0 = -1.0254$, $s_1 = 0.4008$, $\tau = 0.7066$ (inter-event), $\phi = 0.5094$ (intra-event) and $\sigma = 0.9118$ (total). $\sigma$ includes the additional aleatory variability (of 0.270) from the PGA correction due to low sample rates.

- Characterises sites using $V_{s,30}$. Data with $V_{s,30}$ between about 200 m/s and 950 m/s with a roughly uniform distribution. Uses topographic slope to estimate $V_{s,30}$ as it yields more systematic scaling of residuals than other weighted combinations of proxy-based estimates.

- Develops model for subduction earthquakes in Sunda-Banda Arc. Earthquakes in this area are often felt (and can cause damage) in N. Australia because of low-attenuation in craton.

- Selects earthquakes within Banda Sea-Timor Trough region with $M_w \geq 6.0$ from 1990 to 2009 and with $M_w \geq 5.25$ from 2010 to mid-2021. Use data mainly from weak-motion broadband and early digital short-period instruments with some strong-motion instruments in N. Australia. Uses data from various networks (including from a rolling array). Most data have sampling rates of $\leq 40$ Hz so short-period motions not fully captured. Applys a correction factor of 1.11 to PGAs to account for this artifact for low sample-rate data. Derives this correction factor by using a limited set of high-sample records that were downsampled to 40 Hz and then a ratio with the original record computed. Also uses data from GEOFON sites in Indonesia to constrain model in near source.

- Uses $r_{hypo}$ rather than $r_{rup}$ as distances large and sources roughly perpendicular to travel path so differences minor. Uses data to 1750 km so model well constrained to 1500 km. Very little data between 400 and 600 km.

- Excludes data outside a source-receiver azimuth of 135–225° to avoid atypical data.

- Focal depths, $h$, from 10 to 650 km, with most $< 200$ km.

- Visually inspects data to check for data gaps or amplitude saturation. Also manually selects time windows to capture P-wave arrival and 1000 s of coda. Only use data with signal-to-noise ratios $\geq 4$.

- Uses a multi-stage approach: a) defines period-dependent far-field attenuation rate for $R > R_{ref} = 650$ km, b) anchor near-source attenuation rate to this far-field rate, c) normalises data using these attenuation terms to estimate period-dependent magnitude scaling, d) applies a depth correction factor and e) adjusts the near-source terms. Provides details of the various steps.

- Considers anelastic attenuation terms but finds a hinged bilinear functional form matches observations better.

- Originally included data from large Sumatran earthquakes but found observations much lower than those from Australia so does not include these when determining $F_M$.
- For PGA and $T < 0.3$ s finds concave-up $F_M$ so set $c_1 = 0$ and re-regress.
- Notes that there is uncertainty in extrapolating model to $M_w 8.3$ (the largest earthquake considered for this zone) and that more work may be necessary.
- Examines inter- and intra-event residuals w.r.t. magnitude and distance and find no clear trends.
- Only uses data from ANSN sites to compute aleatory variability components as these sites are less prone to resonance or poor coupling due to shallow burial depths of the sensor.
- Notes that high $\tau$ may be due to earthquakes from a wide diversity of tectonic settings and travel paths.
- Cautions against use of model to predict motions at NE Australian sites from earthquakes in New Guinea Highlands. Also does not recommend model for E Indonesia or Timor.

## 2.495 Bai and Zhao (2022)

## 2.496 Kang and Zhao (2022)

## 2.497 Manea et al. (2022)

## 2.498 Miyazawa et al. (2022)

- Ground-motion model is (based on Si et al. (2020)):

$$\begin{aligned}\log_{10} Y &= (a_1 \min(M_w, 8.3) + a_2 + a_3 D) - n \log_{10}(R + C) - kR \\ C &= 0.0055 \times 10^{0.5 M_w}\end{aligned}$$

  where $Y$ is in cm/s$^2$, $D$ is focal depth, $a_1 = 1.1384$, $a_2 = -3.8864$, $a_3 = 0.0010$, $n = 1.000$, $k = 0.00297$, $\phi = 0.2324$ (intra-event), $\tau = 0.0520$ (inter-event) and $\sigma = 0.2382$ for SMGA magnitude model; and $a_1 = 1.8482$, $a_2 = -10.4386$, $a_3 = 0.0$ (fixed), $n = 1.000$, $k = 0.00294$, $\phi = 0.2472$ (intra-event), $\tau = 0.000$ (inter-event) and $\sigma = 0.2472$ for SMGA distance model. Do not report coefficients for conventional model.

- Use records from 2003 Tokachi-Oki and 2011 Tohoku earthquakes. Bandpass K-Net records between $1/T$ and 30 Hz, where $T$ is the source duration in s, which means 2003 records filtered from 0.015 Hz and 2011 records from 0.007 Hz.
- Examine use of considering strong-motion generation areas (SMGAs) rather than entire rupture plane to improve model for large subduction events.
- 2011 Tohoku earthquake had 4 or 5 SMGAs and 2003 Tokachi-Oki earthquake had 3 SMGAs. Only use 2 SMGAs ($M_w 7.55$ and $M_w 7.81$) for the 2011 event and 1 SMGA ($M_w 7.51$) for the 2003 event within analysis as these are the most significant and distinguishable in the data.
- Develop a SMGA distance model using distance to the nearest SMGA. Also develop a SMGA magnitude model where each SMGA is considered as a separate earthquakes with its own magnitude. Finally develop conventional model considering the two events and not the SMGAs.
- Adjust data to $V_{s,30} = 760$ m/s.

- Use only data within 300 km, because more distant records feature prominent surface waves, and from the fore-arc, because back-arc records do not feature clear peaks from SMGAs.
- Believe that may not be able to robustly determine magnitude scaling because of limited magnitude range of data.
- Examine residuals w.r.t. distance. Compute 95% confidence intervals using bootstrapping. Find no trends and zero is contained within 95% confidence intervals. Do find data at certain distance ranges is under- or over-predicted.
- Find $\sigma$ for SMGA models much lower than for the conventional model.
- Vary the locations of the SMGAs and repeat analysis and find significant changes in results.
- State that model is only a proposal and that there still are uncertainties due to the approach and the lack of data.

## 2.499 Montalva et al. (2022)

## 2.500 Phung et al. (2022)

## 2.501 Zeiß et al. (2022)

- Ground-motion models are the following. Basic GMPE:

$$\log_{10} \mathrm{PGA} = a \log(r) + br + c + dM + s$$

where PGA is in m/s$^2$, $a = -1.61$, $b = -0.0009$ (fixed), $c = -2.87$, $d = 0.98$.

Also derive model including a term to account for potential Moho reflections:

$$f_{Moho} = \log_{10}\left[1 + g \sin^2\left(\frac{r - r_{min}}{r_{max} - r_{min}}\right)\right] \quad \text{for} \quad r_{min} \leq r \leq r_{max}$$

where $r_{min} = 50$ km, $r_{max} = 160$ km, $a = -1.59$, $b = -0.0009$ (fixed), $c = -3.47$, $d = 1.12$, $g = 0.61$.

Finally derive model include a therm to account for steep PGA decay at short distances:

$$\log_{10} \mathrm{PGA} = a \log(r) + \log_{10}(1 + z 10^{mM} r^p) + br + c + dM + s$$

where PGA is in m/s$^2$, $a = -1$ (fixed), $b = -0.0009$ (fixed), $c = -2.87$, $d = 0.98$, $p = -1$ (fixed), $m = 0.5$ (fixed), $z = \beta/2\pi 10^{c'}$, where $\beta$ is S-wave velocity in km/s, $c'$ is a constant between $-1.2$ and $-2.6$, and $\sigma = 0.36$.

- Use data from 2010 to 2017 with $2 \leq M_L \leq 4.0$ and from $0.9 \leq M_L \leq 4.0$ for 2018 and 2019. Data from about 110 stations (both strong-motion and high-gain). Process records by: removing linear trends, bandpass filtering from 1 to 35 Hz, differentiating velocity trace and then computing the vector sum of the two horizontal components. Exclude records affected by noise but estimating the pre-event noise level. Only use stations with at least 14 records.
- Compute and report (not given here due to lack of space) average site deviations at the various stations. Find that surface lithology can explain regional trends of these deviations to first order. Classification stations by lithology and provide average deviations within each group.
- Consider 31 small seismogeographical regions with number of earthquakes in each zone varying from 5 to 5922, with most less than 100.

- Most records (300 to 700 per 5 km bin) are from 25 to 125 km with only around 50 records per 5 km bin for shorter and around 80 per bin for longer distances. Most data (1000 records per 0.1-unit bin) from $1.6 \leq M_w \leq 2.3$. Only 100 values per 0.1-unit bin for $M_w > 3.2$ and about 200 per bin for $1.4 \leq M_w \leq 1.6$.
- Note that considering $r_{min}$ and $r_{max}$ as a function of crustal thickness and source depth may be better.
- Observe increasing residuals with decreasing distance for $r < 30$ km and hence introduce term to model steep decay in this range. Term based on intermediate and far S-wavefield of a general moment-tensor source simplified by: a) considering only wavefield at predominant period $T_0$, b) neglecting azimuthal dependency of source radiation, c) neglecting periodicities with number of wavelengths, d) assuming PGA decay behaves like the full wavefield and e) using empirical relation between $M$ and $T_0$.
- Use a three-phase iterative regression procedure using various subsets of the data to determine different coefficients, starting with initial estimates based on theoretical arguments. Some coefficients need to be fixed *a priori* as insufficient data to determine them empirically.Apply weights dependent on number of records in magnitude-distance-region bins. Assess the misfit reduction, measured using a weighted cost function, and find that no significant changes occur to the coefficients in interations 5 to 8.
- Conduct bootstrapping with 250 replications to assess statistical uncertainties of coefficients.
- Find that the addition of the Moho term have a small but significance difference to the weighted cost function. The short-distance term has a insufficient impact and hence this model is not recommended. Try various tests to improve the model including the short-distance term but find insignificant or unstable results.
- Find strong regional dependency of $g$ (Moho coefficient).
- Examine residuals w.r.t. distance and find that the Moho model corrects for underprediction of the basic model for distances between 75 and 130 km.
- Compute uncertainties of model w.r.t. distance and magnitude using bootstrapping. Find considerable variation, which is related to available data.
- Due to linear magnitude scaling, warn against extrapolation to higher magnitudes.

## 2.502 Zhang et al. (2022)

- Ground-motion model is (following Campbell and Bozorgnia (2008b)):

$$
\begin{aligned}
\ln \hat{Y} &= f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{atn} \\
f_{mag} &= \begin{cases} c_0 + c_1 M & \text{for} \quad M \leq 5.5 \\ c_0 + c_1 M + c_2(M-5.5) & \text{for} \quad 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M-5.5) + c_3(M-6.5) & \text{for} \quad M > 6.5 \end{cases} \\
f_{dis} &= (c_4 + c_5 M) \ln(\sqrt{R_{RUP}^2 + c_6^2}) \\
f_{flt} &= c_7 F_{RV} f_{flt,Z} + c_8 F_{NM} \\
f_{flt,Z} &= \begin{cases} Z_{TOR} & \text{for} \quad Z_{TOR} < 1 \\ 1 & \text{for} \quad Z_{TOR} \geq 1 \end{cases} \\
f_{hng} &= c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta} \\
f_{hng,R} &= \begin{cases} 1 & \text{for} \quad R_{JB} = 0 \\ \{\max(R_{RUP}, \sqrt{R_{JB}^2+1}) - R_{JB}\}/ & \\ \quad \max(R_{RUP}, \sqrt{R_{JB}^2+1}) & \text{for} \quad R_{JB} > 0, Z_{TOR} < 1 \\ (R_{RUP} - R_{JB})/R_{RUP} & \text{for} \quad R_{JB} > 0, Z_{TOR} \geq 1 \end{cases} \\
f_{hng,M} &= \begin{cases} 0 & \text{for} \quad M \leq 6.0 \\ 2(M-6.0) & \text{for} \quad 6.0 < M < 6.5 \\ 1 & \text{for} \quad M \geq 6.5 \end{cases} \\
f_{hng,Z} &= \begin{cases} 0 & \text{for} \quad Z_{TOR} \geq 20 \\ (20 - Z_{TOR})/20 & \text{for} \quad 0 \leq Z_{TOR} < 20 \end{cases} \\
f_{hng,\delta} &= \begin{cases} 1 & \text{for} \quad \delta \leq 70 \\ (90-\delta)/20 & \text{for} \quad \delta > 70 \end{cases} \\
f_{site} &= \begin{cases} c_{10} \ln\left(\frac{V_{S30}}{k_1}\right) + k_2 \left\{\ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n\right] - \ln(A_{1100}+c)\right\} & \text{for} \quad V_{S30} < k_1 \\ (c_{10} + k_2 n) \ln\left(\frac{V_{S30}}{k_1}\right) & \text{for} \quad k_1 \leq V_{S30} < 1100 \\ (c_{10} + k_2 n) \ln\left(\frac{1100}{k_1}\right) & \text{for} \quad V_{S30} \geq 1100 \end{cases} \\
f_{atn} &= \begin{cases} 0 & \text{for} \quad R_{rup} \leq 80\,\text{km} \\ c_{11}(R_{rup} - 80) & \text{for} \quad R_{rup} > 80\,\text{km} \end{cases} \\
\sigma &= \sqrt{\sigma_{\ln Y}^2 + \sigma_{\ln AF}^2 + \alpha^2 \sigma_{\ln A_B}^2 + 2\alpha\rho\sigma_{\ln Y_B}\sigma_{\ln A_B}} \\
\alpha &= \begin{cases} k_2 A_{1100}\{[A_{1100} + c(V_{S30}/k_1)^n]^{-1} - (A_{1100}+c)^{-1}\} & \text{for} \quad V_{S30} < k_1 \\ 0 & \text{for} \quad V_{S30} \geq k_1 \end{cases}
\end{aligned}
$$

where PGA is in g, $c_0 = 0.766$, $c_1 = 0.143$, $c_2 = 0.885$, $c_3 = -0.877$, $c_4 = -2.129$, $c_5 = 0.100$, $c_6 = 7.400$, $c_7 = 0.404$, $c_8 = -0.260$, $c_9 = 1.021$, $c_{10} = 1.071$, $c_{11} = 0.0003$, $V_{LIN} = 865.095$, $k_2 = -1.186$, $n = 1.18$, $c = 1.88$, $V_1 = 1100\,\text{m/s}$, $\sigma = 0.577$ (intra-event), $\tau = 0.519$ (inter-event) and $\sigma_T = 0.776$ (total). $A_{1100}$ is the median estimated PGA on the reference site ($V_{s,30} = 1100\,\text{m/s}$.

- Characterise sites using $V_{s,30}$. 453 stations in total. Data from sites with $140 \leq V_{s,30} \leq 1130\,\text{m/s}$. $V_{s,30}$ measured for 75% of stations and estimated for the rest (mostly from topographic slope).

- Consider 3 faulting mechanisms (classified using rake angles):

Normal 7 earthquakes. $-150° < \lambda < -30°$. $F_{NM} = 1$, $F_{RV} = 0$.

Strike-slip 44 earthquakes. Other $\lambda$ values. $F_{NM} = 0$, $F_{RV} = 0$.

Reverse 19 earthquakes. $30° < \lambda < 150°$. $F_{NM} = 0$, $F_{RV} = 1$.

- Use data from between 03/06/2007 and 08/09/2018 from the National Strong Motion Observation Network System in SW China (Yunnan and Sichuan provinces).
- Exclude data from aftershocks because believe ground motions on average lower in these events compared with mainshocks. Also apply following criteria: 1) focal depth $\leq 30$ km, 2) finite fault model or focal mechanism known, 3) exclude data from stable regions (e.g. Sichuan Basin), 4) exclude poorly-recorded events with $< 5$ records for $M_w < 5.0$, $< 3$ records for $5.0 \leq M_w < 6.0$, $< 2$ records for $6.0 \leq M_w < 7.0$, 5) exclude low-quality records, 6) exclude non-free-field records, 7) only use records with both horizontal components, 8) measured or estimated $V_{s,30}$ must be available and 9) $r_{rup} \leq 300$ km.
- Vast majority of data (1008 records from $M_w \leq 6.0$. Only Wenchuan (12/05/2008) earthquake with $M_w > 6.7$.
- Process data using NGA-West2 workflow: bandpass using 4th-order Butterworth filter with cut-offs of 30 Hz and a record-specific frequency determined based on Fourier amplitude signal and noise spectra and processed velocities and displacements. High-pass cut-offs between 0.07 and 0.25 Hz.
- Determine $r_{rup}$ and $Z_{TOR}$ from published finite-fault models (6 events), and from focal mechanisms (choosing the nodal plane that best matches the seismogenic fault and using global relationships between magnitude, fault dimensions and hypocentral location).
- Introduce $f_{atn}$ because use data from $r_{rup} > 80$ km, where anelastic attenuation becomes important and since prediction of ground motions at larger distances is potentially useful in low seismicity regions.
- Plot inter-event residuals w.r.t. $M_w$, $Z_{TOR}$, dip angle ($\delta$) and rake angle ($\lambda$) and find no trends. Plot intra-event residuals w.r.t. $r_{rup}$, $V_{s,30}$ and $A_{1110}$ and find no trends.
- Compare predictions with observations from Ludian earthquake and find a reasonable fit. Also compare predictions with observations from 2021 Yangbi County/Dali Prefecture earthquake (not included in the dataset used to develop model) and find that most observations within $\pm 1$ standard deviation.
- Note that there are very few records with $r_{rup} < 10$ km so do not recommend model at such distances.

## 2.503 Gogoi et al. (2023)

- Ground-motion model is:

$$\log Y = b_0 - b_1 \log X + b_2 M$$

  $Y$ is in g; $b_0 = -1.733$, $b_1 = 0.691$, $b_2 = 0.236$ and $\sigma = 0.266$ for EW; $b_0 = -1.728$, $b_1 = 0.877$, $b_2 = 0.304$ and $\sigma = 0.302$ for NS; $b_0 = -1.674$, $b_1 = 0.777$, $b_2 = 0.227$ and $\sigma = 0.289$ for vertical; and $b_0 = -1.610$, $b_1 = 0.836$, $b_2 = 0.253$ and $\sigma = 0.395$ for all components.
- Classify stations by geological age but do not consider within model as $V_{s30}$ is unknown for most sites.
- Do not consider focal mechanism as believe effect is nonlinear. Also do not consider earthquake type.
- Focal depths between 5 km and 100 km with most $< 40$ km.
- Data from 31 stations (mainly AC-63/GSR-18 GeoSIG instruments) in NE India from 2009 to 2016. Only use data from events with $\geq 3$ records (one event recorded by 12 stations and rest by $\leq 8$.
- Most data from $r_{epi} < 300$ km.
- Baseline correct and apply low- and high-pass filters.

- Use data from 24 events to derive model and reserve data from 2 events (both with $M_w 5.5$) that were not used in derivation to compare against predictions from the model. Find good match.

- Compare predictions with data from the 2016 Tamenglong ($M_w 6.7$) event (focal depth 55 km). Find good match.

## 2.504 İçen and Sandikkaya (2023)

## 2.505 Khansefid et al. (2023)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M_w + C_3 \ln R + C_4 \ln V_{s,30}$$

where $Y$ is in m/s$^2$, $C_1 = -2.918$, 1.235, $C_3 = -1.512$, $C_4 = -0.091$, $\phi = 0.41$ (intra-event), $\tau = 0.25$ (inter-event) and $\sigma = 0.49$ (total).

- Use $V_{s,30}$ to characterise sites. Stations have $200 \leq V_{s,30} \leq 900$ m/s, with most $< 500$ m/s. Recommend model for $V_{s,30} \leq 800$ m/s.

- Use data from geothermal sites in USA (Geysers, Casa Diablo, Coso, Salton Sea and Brawley), Costa Rica (Miravalles and Las Pailas), Italy (Piancastagnaio), Turkey (Kizildere) and South Korea (Pohang), with well depths between 1210 and 4000 m.

- Focal depths, $D$, between 0 and about 12 km. Most between 2 and 8 km (70% are from $< 5$ km).

- Only use records with a signal-to-noise ratio of $> 3$. Process data using wavelet denoising, baseline correction and high-pass filtering. Processing slightly reduces the ground-motion amplitudes.

- 60% of earthquakes from $3 \leq M_w \leq 4$.

- Vast majority of records from $r_{hypo} < 50$ km.

- Find intra- and inter-event residuals show limited trends with distance and magnitude, respectively, and follow a lognormal distribution.

- Plot observations and predictions for various distance bins w.r.t. $M_w$ and for various magnitude bins w.r.t. $r_{epi}$ and find close fits. Find no dependency on $D$.

# Chapter 3

# General characteristics of GMPEs for PGA

Table 3.1 gives the general characteristics of published attenuation relations for peak ground acceleration. The columns are:

H Number of horizontal records (if both horizontal components are used then multiply by two to get total number)

V Number of vertical components

E Number of earthquakes

$M_{\min}$ Magnitude of smallest earthquake

$M_{\max}$ Magnitude of largest earthquake

$M$ scale Magnitude scale (scales in brackets refer to those scales which the main $M$ values were sometimes converted from, or used without conversion, when no data existed), where:

- $m_1$ Intermediate spectral magnitude (Chen and Atkinson, 2002)
- $m_b$ Body-wave magnitude
- $M_C$ Chinese surface wave magnitude
- $M_{CL}$ Coda length magnitude
- $M_D$ Duration magnitude
- $M_{\mathrm{JMA}}$ Japanese Meteorological Agency magnitude
- $M_L$ Local magnitude
- $M_{Lw}$ Local moment magnitude reported by the Icelandic Meterological Office
- $M_{bLg}$ Magnitude calculated using Lg amplitudes on short-period vertical seismographs
- $M_s$ Surface-wave magnitude
- $M_w$ Moment magnitude

$r_{\min}$ Shortest source-to-site distance

$r_{\max}$ Longest source-to-site distance

$r$ scale Distance metric, where (when available the *de facto* standard abbreviations of Abrahamson and Shedlock (1997) are used):

- $r_c$ Distance to rupture centroid

$r_{epi}$ Epicentral distance

$r_E$ Distance to energy centre

$r_{jb}$ Distance to projection of rupture plane on surface (Joyner and Boore, 1981)

$r_{hypo}$ Hypocentral (or focal) distance

$r_q$ Equivalent hypocentral distance (EHD) (Ohno et al., 1993)

$r_{rup}$ Distance to rupture plane

$r_{seis}$ Distance to seismogenic rupture plane (assumes near-surface rupture in sediments is non-seismogenic) (Campbell, 1997)

$r_{SMGA}$ Distance to the nearest strong-motion generation area

S Number of different site conditions modelled, where:

C Continuous classification

I Individual classification for each site

C Use of the two horizontal components of each accelerogram [see Beyer and Bommer (2006)], where:

1 Principal 1

2 Principal 2

A Arithmetic mean

All All 3 components

B Both components

C Randomly chosen component

D50 GMrotD50 (Boore et al., 2006).

EW East-west direction.

G Geometric mean

I50 GMrotI50 (Boore et al., 2006).

L Larger component

L3 Largest of all 3 components (including vertical)

M Mean (not stated what type)

N Fault normal

NS North-south direction

O Randomly oriented component

P Fault parallel

Q Quadratic mean, $\sqrt{(a_1^2 + a_2^2)/2}$, where $a_1$ and $a_2$ are the two components (Hong and Goda, 2007)

R Resolved component

S $\sqrt{(a_1 + a_2)/2}$, where $a_1$ and $a_2$ are the two components (Reyes, 1998)

U Unknown

V Vectorially-resolved component, i.e. square root of sum of squares of the two components

V3 Vectorially-resolved component including vertical, i.e. square root of sum of squares of the three components

R Regression method used, where:

- 1 Ordinary one-stage
- 1B Bayesian one-stage (Ordaz et al., 1994)
- 1M Maximum likelihood one-stage or random-effects (Abrahamson and Youngs, 1992; Joyner and Boore, 1993)
- 1W Weighted one-stage
- 1WM Weighted maximum-likelihood one-stage
- 2 Two-stage (Joyner and Boore, 1981)
- 2M Maximum likelihood two-stage (Joyner and Boore, 1993)
- 2W Two-stage with second staged weighted as described in Joyner and Boore (1988)
- O Other (see section referring to study)
- U Unknown (often probably ordinary one-stage regression)

M Source mechanisms (and tectonic type) of earthquakes (letters in brackets refer to those mechanism that are separately modelled), where:

- A All (this is assumed if no information is given in the reference)
- AS Aftershock
- B Interslab
- C Shallow crustal
- E Gas extraction
- F Interface
- G Geothermal-related
- HW Hanging wall
- I Intraplate
- M Mining-induced
- N Normal
- O Oblique or odd (Frohlich and Apperson, 1992)
- P Potentially-induced
- R Reverse
- S Strike-slip
- T Thrust
- U Unspecified
- UM Upper mantle
- V Volcanic
- W Wastewater disposal
- Z Subduction zone

'+' refers to extra records from outside region used to supplement data. (...) refer either to magnitudes of supplementing records or to those used for part of analysis. * means information is approximate because either read from graph or found in another way.

Table 3.1: Characteristics of published peak ground acceleration relations

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Esteva and Rosenblueth (1964) | W. USA | 46* | - | U | U | U | U | 15* | 450* | $r_{hypo}$ | 1 | U | U | A |
| Kanai (1966) | California & Japan | U | - | U | U | U | U | U | U | $r_{rup}$ | C | U | U | A |
| Milne and Davenport (1969) | W. USA | U | - | U | U | U | U | U | U | $r_{epi}$ | 1 | U | U | A |
| Esteva (1970) | W. USA | U | - | U | U | U | U | 15* | 500* | $r_{hypo}$ | 1 | U | U | A |
| Denham and Small (1971) | Yonki, New Guinea | 8 | - | 8 | U | U | $M_L$[1] | U | U | $r_{hypo}$ | 1 | U | U | A |
| Davenport (1972) | Unknown | U | - | U | U | U | U | U | U | $r_{hypo}$ | 1 | U | U | A |
| Denham et al. (1973) | Papua New Guinea | 25 | - | 25 | 5.2 | 8.0 | $M_L$ | 80* | 300 | U | 1 | U | 1 | A |
| Donovan (1973) | Mostly W. USA but 100+ foreign | 678 | - | U | <5 | >8 | U | 3* | 450* | $r_{hypo}$ | 1 | U | U | A |
| Esteva and Villaverde (1973) & Esteva (1974) | W. USA | U | - | U | U | U | U | 15* | 150* | $r_{hypo}$ | 1 | B | U | A |
| Katayama (1974) | Japan | 330 | - | 46 | 5.1 | 7.8 | U[2] | U | U | $r_{hypo}$ | 1 | A | 1 | A |
| McGuire (1974) & McGuire (1977) | W. USA | 34 | - | 22 | 5.3 | 7.6 | $M_L$ | 14 | 125 | $r_{hypo}$ | 1 | B | U | A |
| Orphal and Lahoud (1974) | California | 140 | - | 31 | 4.1 | 7.0 | $M_L$ | 15 | 350 | $r_{hypo}$ | 1 | U | O | A |
| Ahorner and Rosenhauer (1975) | Worldwide | U | - | U | U | U | U | U | U | U | U | U | U | A |
| Ambraseys (1975b), Ambraseys (1975a) & Ambraseys (1978a) | Europe | 58 | - | U[3] | 3.5 | 5.0 | $M_L$ | 5 | 35 | $r_{hypo}$ | 1 | U[4] | U | A |
| Shah and Movassate (1975) | Worldwide | U | - | U | U | U | U | U | U | U | U | U | U | A |
| Trifunac and Brady (1975a), Trifunac (1976a) & Trifunac and Brady (1976) | W. USA | 181 | 181 | 57 | 3.8 | 7.7 | Mostly $M_L$ | 6[5]* | 400[6]* | $r_{epi}$ | 3 | B | O | A |

*continued on next page*

[1]State that it is Richter magnitude which assume to be $M_L$
[2]Probably $M_{JMA}$
[3]Ambraseys and Bommer (1995) state that uses 38 earthquakes.
[4]Ambraseys and Bommer (1995) state that uses larger component.
[5]Note only valid for $R \geq 20\,\mathrm{km}$
[6]Note only valid for $R \leq 200\,\mathrm{km}$

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Blume (1977) | California & W. Nevada | 795[7] | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 2 (1) | B | U | A |
| Gürpinar (1977) | California | 64, 34, 13 | - | U | U | U | $M_L$ | 28* | 70* | $r_{hypo}$ | 3 | B | 1 | A |
| Milne (1977) | W. USA | 200* | - | U | 3.5 | 7.7 | U | 1 | 380 | $r_{hypo}$ | 1 | U | U | A |
| Saeki et al. (1977) | Japan | 298 | - | U | U | U | U[8] | U | U | $r_{epi}$ | 4 | U | 1 | A |
| Ambraseys (1978b) | Europe & Middle East | 162 | - | U | 3.0* | 6.6 | $m_b$ | 0* | 30* | $r_{hypo}$ | 1 | L | O | A |
| Donovan and Bornstein (1978) | W. USA | 59 | - | 10 | 5.0 | 7.7 | U[9] | 0.1 | 321 | $r_E$, $r_{rup}$ and $r_{hypo}$ | 1 | B | O | A |
| Faccioli (1978) | Mostly W. USA & Japan, some foreign | 47[10] | - | 23 | 4.9 | 7.8 | U[11] | 15 | 342 | $r_{hypo}$ | 1 | B | U | A |
| Goto et al. (1978) | Japan | 45 | - | U | U | U | U[12] | U | U | $r_{epi}$ | 1 | U | 1 | A |
| McGuire (1978a) | W. USA | 70 | - | 17+* | 4.5* | 7.7 | U[13] | 11* | 210* | $r_{hypo}$ | 2 | B | U | A |
| A. Patwardhan *et al.* (1978)[14] | Worldwide | 63 (32) | - | 25 (23) | 4 (5.3) | 7.7 (7.8) | $M_s$ | U | U | $r_{rup}$ | 2 | B | U | A |
| Cornell et al. (1979) | W. USA | 70 | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | C | U | A |
| Faccioli (1979) | Friuli, Italy | 19[15] | - | 5* | 3.7 | 6.3 | $M_L$ | 10* | 30* | $r_{hypo}$ | 1 | B | 1 | A |
| Faccioli and Agalbato (1979) | Friuli, Italy | 66 | 52 | 14 | 3.7 | 6.3 | $M_L$ | 5 ($r_{epi}$) | 190 ($r_{epi}$) | $r_{hypo}$ | 2 | B | 1 | A |
| Aptikaev and Kopnichev (1980) | Worldwide | Many 100s | - (70*) | U (59) | U | U | U | U | U | $r_{hypo}$ | 1 | U | U | A (T, TS, S, SN, N)[16] |
| Blume (1980) | W. USA | 816 | - | U | 2.1 | 7.6 | U | 0 | 449 | $r_{hypo}$ | 1 | B | 1, O | A |
| Iwasaki et al. (1980) | Japan | 301 | - | 51 | >5.0 | <7.9 | $M_L$[17] | <20 | >200 | $r_{epi}$ | 4 | U | 1 | A |
| Matuschka (1980) | New Zealand | 61 | - | U | 4.5* | U | U | U | 120 | $d_{hypo}$ | U | U | 1 | A |
| Ohsaki et al. (1980b) | Japan | 75 | 75 | U | 4 | 7.4 | U | 6 | 500 | $r_{hypo}$ | 1 | U | 1 | A |
| TERA Corporation (1980) | W. USA+7 foreign | 96 | - | 22 | 4.0 | 7.7 | $M_s$ ($M_L$) | 0.08 | 47.00 | $r_{rup}$ | 1 | B | O | A |

*continued on next page*

[7] Total earthquake components (does not need to be multiplied by two) for magnitude and distance dependence. Uses 2713 underground nuclear explosion records for site dependence.

[8] Probably $M_{JMA}$

[9] Idriss (1978) finds magnitudes to be mixture of $M_L$ and $M_s$.

[10] Total earthquake components (does not need to be multiplied by two)

[11] Idriss (1978) believes majority are $M_s$.

[12] Probably $M_{JMA}$

[13] Idriss (1978) finds magnitudes to be mixture of $M_L$, $m_b$ and $M_s$.

[14] Reported in Idriss (1978).

[15] Does not need to be multiplied by two.

[16] Assume dip-slip means normal mechanism.

[17] State that it is Richter magnitude which assume to be $M_L$

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Campbell (1981) | W. USA+8 foreign | 116 | - | 27 | 5.0 | 7.7 | $M_L$ for $M < 6.0$ and $M_s$ otherwise | 0.08 | 47.7 | $r_{rup}$ | 1 | M | O | A |
| Chiaruttini and Siro (1981) | Europe & Mid. East | 224 | - | 117 | 2.7 | 7.8 | $M_L$ ($m_b$) | 3 | 480 | $r_{hypo}$ | 1 | L | 1 | A |
| Goto et al. (1981) | Japan | 84 | - | 28 | 4.3* | 7.8* | U[18] | 11* | 300* | $r_{epi}$ | 1, C | L | 1 | A |
| Joyner and Boore (1981) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | 2 | A |
| Bolt and Abrahamson (1982) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 1 | L | O | A |
| Joyner and Boore (1982b) & Joyner and Boore (1988) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | 2 | A |
| PML (1982) | Europe + USA + others | 113 | - | 32 | 4.3 | 8 | $M_s$ | 0.1 | 330 | $r_{hypo}$ or $r_{rup}$ | 1 | U | U | A |
| Schenk (1982) | Unknown | 3500 | - | U | 2.5 | 6.5 | $M_s$ | 2 | 600 | $r_{hypo}$ | 1 | U | O | A |
| Brillinger and Preisler (1984) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | 1M | A |
| Campbell (1984) & K.W. Campbell (1988)[19] | Worldwide | U | - | U | $\geq 5$ | U | $M_L$ for $M < 6.0$ and $M_s$ otherwise | U | <50 | $r_{seis}$ | 2 | M | U | A (S, R) |
| Joyner and Fumal (1984) and Joyner and Fumal (1985) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | C | L | 2 | A |
| Kawashima et al. (1984) & Kawashima et al. (1986) | Japan | 197 | - | 90 | 5.0 | 7.9 | $M_{\mathrm{JMA}}$ | 5* | 550* | $r_{epi}$ | 3 | R | 1 | A |
| McCann Jr. and Echezwia (1984) | N. America + foreign | 83 | - | 18 | 5.0+ | U | $M_w$ | U | U | $r_{rup}$ | 1 | U | O | A |
| Schenk (1984) | Unknown | 3500 | - | U | 2.5 | 6.5 | U | 2 | 600 | $r_{hypo}$ | 1 | U | O | A |
| Xu et al. (1984) | N. China | 19 | - | 10 | 4.5 | 7.8 | $M_w$ ($M_L$ for $M < 6.0$, $M_s$ for $M \geq 6.0$) | 10.1 | 157 | $r_{epi}$ | 1 | L | 1 | A |
| Brillinger and Preisler (1985) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | 1M | A |

*continued on next page*

[18] Probably $M_{JMA}$

[19] Reported in Joyner and Boore (1988).

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kawashima et al. (1985) | Japan | - | 119 | 90* | 5.0* | 7.5* | $M_{\mathrm{JMA}}$ | 5* | 500* | $r_{epi}$ | 3 | - | 1 | A |
| Makropoulos and Burton (1985) & Makropoulos (1978) | Worldwide | U | - | U | U | U | U | U | U | U | U | U | U | A |
| Peng et al. (1985b) | N.E. China | 73 | - | 20 | 3.7 | 7.8 | $M_C$ | 2 | 442.5 | $r_{epi}$ | 1 | U | 1 | A |
| Peng et al. (1985a) | Tangshan region, China | 93 | 87 | 19 | 2.9 | 5.3 | $M_L$ | 2* | 50* | $r_{epi}$ | 1 | L | 2 | A |
| PML (1985) | USA + Europe + others | 203 | - | 46 | 3.1 | 6.9 | $M_s$ | 0.1 | 40 | $r_{rup}$ | 1 | U | U | A (S, T) |
| McCue (1986) | E. Australia | U | - | U | 1.7 | 5.4 | $M_L$ | 2.5 | 134 | $r_{hypo}$ | 1 | U | U | A |
| C.B. Crouse (1987)[20] | S. California | U | - | U | U | U | $M_s$ | U | U | $r_{rup}$ | 1 | B | U | A |
| Krinitzsky et al. (1987) & Krinitzsky et al. (1988) | Plate boundaries[21] | 389[22] | - | U | 5.0* | 7.4*[23] | $M$[24] | 7*[25] | 200*[26] | $r_{hypo}$[27] | 2 | B | O | A |
| Sabetta and Pugliese (1987) | Italy | 95 | - | 17 | 4.6 | 6.8 | $M_s$ for $M \geq 5.5$, $M_L$ otherwise | 1.5, 1.5 | 179, 180 | Both $r_{jb}$ & $r_{epi}$ | 2 | L | 1 | A |
| K. Sadigh (1987)[28] | W. USA + others | U | - | U | U | U | $M_w$ | U | U | $r_{rup}$ | 2 | B | U | A (S, R) |
| Singh et al. (1987) | Mexico | 16 | - | 16 | 5.6 | 8.1 | $M_s$ | 282 | 466 | $r_{rup}$ | 1 | U | 1 | A |
| Algermissen et al. (1988) | Vicinity of San Salvador | 82 | - | U | U | U | $M_s$ | U | U | $r_{hypo}$ | 1 | M | U | A |
| Annaka and Nozawa (1988) | Japan | U | - | 45 | U | U | U | U | U | U | 1 | U | 1 | A |
| Fukushima et al. (1988) & Fukushima and Tanaka (1990) | Japan+200 W. USA | 486+200 | - | 28+15 | 4.6(5.0) | 8.2(7.7) | $M_s$ ($M_{\mathrm{JMA}}$) | 16 (0.1) | 303 (48) | $r_{hypo}$, $r_{rup}$ for 2 Japanese & all US | 4 | G | 2 | A |
| Gaull (1988) | S.W. W. Australia | 25+ | - | 12+ | 2.6 | 6.9 | $M_L$ | 2.5 | 175 | $r_{hypo}$ | 1 | U | O | A |
| Joyner and Boore (1988) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L, O | 2W | A |
| McCue et al. (1988) | S.E. Australia | 62 | - | U | 0.5* | 6* | $M_L$ | 5* | 833 | $r_{epi}$ | 1 | U | O | A |

*continued on next page*

[20] Reported in Joyner and Boore (1988).
[21] Also derive equations for Japan subduction zones.
[22] 195 for subduction zone equations.
[23] >7.5 for subduction zone equations.
[24] Call magnitude scale Richter magnitude, which note is equivalent to $M_w$ for $M \leq 8.3$, $M_L$ for $M < 5.9$ and $M_s$ for $5.9 \leq M \leq 8.0$.
[25] About 15km for subduction zone equations.
[26] About 400km for subduction zone equations.
[27] $r_{epi}$ for subduction zone equations.
[28] Reported in Joyner and Boore (1988).

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Petrovski and Marcellini (1988) | Europe | 120 | 120 | 46 | 3 | 7 | U | 8 | 200 | $r_{hypo}$ | 1 | L | 1 | A |
| PML (1988)[29] | USA + Europe + others | 162 | 124 | 30* | 3.0* | $\geq 7.0$ | $M_s$ | 10* | $\geq 150$ | $r_{hypo}$ | 3 | L, V | 1 | A |
| Tong and Katayama (1988) | Kanto (Japan) | <227 | - | <27 | 4.5* | 7.9* | U | 10* | 750* | $r_{epi}$ | C | L | O | A |
| Yamabe and Kanai (1988) | Japan | U | - | 22 | 5.3 | 7.9 | U | U | U | $r_{hypo}$ | 1 | U | O | A |
| Youngs et al. (1988) | Worldwide subduction zones | 197+389 | - | 60 | 5 | 8.1 (8.2)[30] | $M_w$ ($M_s$, $m_b$) | 15* (20*) | 450* (450*) | $r_{rup}$, $r_{hypo}$ for $M_w \lesssim 7.5$ | 1 | G | 1W | A (B,F) |
| Abrahamson and Litehiser (1989) | 75%+ California, rest foreign | 585 | 585 | 76 | 5.0 | 8.1 | $M_s$ for $M_s \geq 6.0$, $M_L$ ($m_b$) otherwise | 0.08 | 400 | $r_{rup}$ | 1 | L | O | A (R & RO, I) |
| Campbell (1989) | W. N. America + 3 from Managua | 190 | - | 91 | 2.9 | 5.0 | $M_L$ | 0.6 | 18.3 | $r_{epi}$ | 1 | M | O | A |
| Huo (1989) | W. USA & S. China | U | - | U | U | U | U | U | U | U | 1 | G | 1 | A |
| Ordaz et al. (1989) | Guerrero, Mexico | U | - | U | U | U | U | U | U | U | U | U | U | A |
| Alfaro et al. (1990) | Guatemala, Nicaragua & El Salvador | 20 | - | 12 | 4.1 | 7.5 | $M_s$ | 1 | 27 | $r_{epi}$ | 1 | L | U | A |
| Ambraseys (1990) | W. N. America | 182 | - | 23 | 5.03 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | 2 | A |
| Campbell (1990) | Unknown | U | - | U | U | U | $M_L$ for $M < 6$, $M_s$ for $M \geq 6$ | U | U | $r_{seis}$ | 1 | U | U | A |
| Dahle et al. (1990b) & Dahle et al. (1990a) | Worldwide intraplate regions | 87 | - | 56 | 2.9 | 7.8 | $M_s$ ($M_L$, $m_b$, $M_{CL}$) | 6 | 1300 | $r_{hypo}$ | 1 | L | 2 | A |
| Jacob et al. (1990) | E. N. America | U | - | 8 | 1.8 | 6.4 | $m_b$ | $\leq 20$ | 820 | U[31] | 1 | U | O | A |
| Sen (1990) | Whittier Narrows area | 72* | - | 11 | 2.2 | 3.5 | $M_L$ | 12* | 21* | $r_{hypo}$ | 1 | U | 1M | A (T) |
| Sigbjörnsson (1990) | Iceland | U | - | U | U | 5.8[32] | U | U | U | $r_{jb}$ | 1 | U | U | A |
| Tsai et al. (1990) | Worldwide | <217 | - | <51 | 4.9* | 7.4 | $M_w$ | 3* | 150* | $r_{rup}$ | 1 | M | U | T (S,O) |

*continued on next page*

[29]Details of dataset are given in tables but quality of scan too poor to clearly see digits.
[30]Consider equations valid for $M_w \leq 8$
[31]Free (1996) believes it is $r_{hypo}$.
[32]This is $M_s$.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ambraseys and Bommer (1991) & Ambraseys and Bommer (1992) | Europe & Mid. East | 529 | 459 | H:219, V:191 | 4 | 7.34 | $M_s$ | 1 | H:313, V:214 | $r_{jb}$ for $M_s \gtrsim 6.0$, $r_{epi}$ otherwise | 1 | L | 1, 2 | A |
| Crouse (1991) | Worldwide subduction zones | 697[33] | - | U | 4.8 | 8.2 | $M_w$ ($M_s$, $M_{\mathrm{JMA}}$) | >8 | >866 | $r_E$, $r_{hypo}$ for $M < 7.5$ | 1 | B | 1 | A |
| Garcìa-Fernàndez and Canas (1991) & Garcia-Fernandez and Canas (1995) | Iberia[34] | 57 | 367 | U | 3.1 | 5.0 | $m_{bLg}$ | U | U | $r_{epi}$ | 1 | - | 1 | A |
| Geomatrix Consultants (1991), Sadigh et al. (1993) & Sadigh et al. (1997) | California with 4 foreign | 960+4 | U | 119+2 | 3.8 (6.8) | 7.4 (7.4) | $M_w$ | 0.1 (3) | 305 (172)[35] | $r_{rup}$ for some, $r_{hypo}$ for small ones | 2 | G | U | A(R,S) |
| Huo and Hu (1991) | W. USA with 25 foreign | 383+25 | - | 14+2 | 5.0 | 7.4 (7.3) | $M_L$ or $m_b$ for $M < 6.0$ and $M_s$ otherwise | 0.1 | 227 (265) | $r_{jb}$ | 2 | B | O | A |
| I.M. Idriss (1991) reported in Idriss (1993) | Unknown | 572 | - | 30* | 4.6 | 7.4 | $M_L$ for $M < 6$, $M_s$ for $M \geq 6$ | 1 | 100 | $r_{rup}, r_{hypo}$ for $M < 6$ | 1 | U | U | A |
| Loh et al. (1991) | Taiwan | 112 | - | 63 | 4.0 | 7.1 | $M_L$ | 5.0 | 178.3 | $r_{hypo}$ | 1 | L | U | A |
| Matuschka and Davis (1991) | New Zealand | 80 | 80 | 30 | U | U | U | U | U | U | 3 | B | U | A |
| Niazi and Bozorgnia (1991) | SMART-1 array, Taiwan | 236 | 234 | 12 | 3.6 | 7.8 | $M_L$ ($M_D$) for $M_L < 6.6$, else $M_s$ | 3.1[36] | 119.7[36] | $r_{hypo}$ | 1 | M | 2W | A |
| Rogers et al. (1991) | Worldwide | 1241 | - | 180* | 5.3* | 8.1* | $M_L$ for $M \leq 6$, $M_s$ for $6 < M < 8$ and $M_w$ for $M \geq 8$ | 4* | 400* | $r_{rup}$ if have, $r_{hypo}$ otherwise | 6 | L | 1 | A |

*continued on next page*

[33] Total number of components, does not need to be multiplied by two.
[34] Also present equations for SSE (using 140 records) and NE Iberia (using 107 records).
[35] Equations stated to be for distances up to 100 km
[36] Distance to centre of array

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Stamatovska and Petrovski (1991) | Mainly Italy and former Yugoslavia | 489[37] | - | 78 | 3* | 8* | $M_L$ | 10* | 500* | $r_{hypo}$ | 1 | B | 1 | A |
| Abrahamson and Youngs (1992) | Unknown | U | - | U | U | U | U | U | U | U | 1 | U | 1M | A (U, U) |
| Ambraseys et al. (1992) | USA + Europe + others | 504 | - | 45 | 3.1 | 6.87 | $M_s$ | 0.5 | 39 | $r_{jb}$, $r_{epi}$ for some | 1 | L | 1 | A |
| Huo and Hu (1992) | China & W. USA | U | - | U | U | U | $M_s$ | U | U | $r_{jb}$ | 1 | U | 1 | A |
| Kamiyama et al. (1992) & Kamiyama (1995) | Japan | 357 | - | 82 | 4.1 | 7.9 | $M_{\mathrm{JMA}}$ | 3.4 | 413.3 | $r_{hypo}$ | I | B | O | A |
| Sigbjörnsson and Baldvinsson (1992) | Iceland | 262 | - | 39 | 2.0 | 6.0 | U | 2 | 80 | $r_{jb}$ | 2 | B,L | 2 | A |
| Silva and Abrahamson (1992) | W. USA with 4 foreign | 136 | - | 12 | 6.1 | 7.4 | $M_w$ | 3* | 100* | $r_{seis}$ | 2 | G | 1M | A (S,R) |
| Taylor Castillo et al. (1992) | Nicaragua, El Salvador & Costa Rica | 89 | - | 27 | 3.0 | 7.6 | $M_s$ | 6 | 210 | $r_{hypo}$ | 1 | L | U | A |
| Tento et al. (1992) | Italy | 137 | - | 40 | 4 | 6.6 | $M_L$ | 3.2 | 170 | $r_{jb}$ for $M_L \geq 5.7$, $r_{epi}$ otherwise | 1 | L | 2 | A |
| Theodulidis and Papazachos (1992) | Greece+16 foreign | 105+16[38] | - | 36+4 | 4.5 (7.2) | 7.0 (7.5) | $M_s$, $M_w$, $M_{\mathrm{JMA}}$ | 1 (48) | 128 (236) | $r_{epi}$ | 2 | B | O | A |
| Abrahamson and Silva (1993) | W. USA with 4 foreign | 201 | - | 18 | 6.0 | 7.4 | $M_w$ | 0.6* | 100* | $r_{rup}$ | 2 | G | 1M | A (S, R) |
| Boore et al. (1993), Boore et al. (1997) & Boore (2005) | W. N. America | 271 | - | 20 | 5.1[39] | 7.7 | $M_w$ | 0 | 118.2 | $r_{jb}$ | 3 | L, G | 2M | A |
| Campbell (1993) | Worldwide | U | - | U | U[40] | U | $M_L$ for $M < 6.0$ and $M_s$ otherwise | U | U[41] | $r_{seis}$ | 2 | M | O | A (T,S) |
| Dowrick and Sritharan (1993) | New Zealand | U | - | 8 | U | U | U | U | U | $r_{jb}$ | U | U | 1 | A |
| Gitterman et al. (1993) | Israel | U | - | U | 3.9 | 5.1 | $M_L$ | U | U | $r_{epi}$ | 1 | U | U | A |

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[37] Does not need to be multiplied by two.
[38] Total number of components does not need to be multiplied by two
[39] Boore et al. (1997) revise this magnitude to 5.87. New minimum magnitude is 5.2.
[40] Considers equation valid for $M \geq 4.7$.
[41] Considers equation valid for $d \leq 300$ km.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| McVerry et al. (1993) & McVerry et al. (1995) | New Zealand | 256 | - | 31* | 5.1 | 7.3 | $M_w$ | 13 | 312 | $r_c$ or $r_{hypo}$ | 1 | L | 1 | A, R |
| Midorikawa (1993a) | Japan | U | - | U | 6.5 | 7.8 | $M_w$ | U | U | $r_{rup}$ | 1 | G | 1 | A |
| Quijada et al. (1993) | S. America | U | - | U | U | U | U | U | U | U | U | U | U | A |
| Singh et al. (1993) | Nicaragua, El Salvador & Costa Rica | 89 | - | 27 | 3.0 | 7.6 | $M_s$ | 6 | 210 | $r_{hypo}$ | 1 | V | O | A |
| Steinberg et al. (1993) | Worldwide | U | - | U | U | 5* | U | U | U | $r_{epi}$ | 1 | U | 1 | A |
| Sun and Peng (1993) | W. USA with 1 foreign | 150+1 | - | 42+1 | 4.1 | 7.7 | $M_L$ for $M < 6$, else $M_s$ | 2* | 150* | $r_{epi}$ | C | R | 1 | A |
| Ambraseys and Srbulov (1994) | Worldwide | 947 | - | 76 | 5.0 | 7.7 | $M_s$ | 1 | 375 | $r_{jb}$, $r_{epi}$ | 1 | L | 2W | A |
| Boore et al. (1994a) & Boore et al. (1997) | W. N. America | 271 (70) | - | 20 (9) | 5.1[42] (5.3) | 7.7 (7.4) | $M_w$ | 0 | 118.2 (109) | $r_{jb}$ | C | L, G | 1M, 2M | A (R,S)[43] |
| El Hassan (1994) | Unknown | U | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | U | 1 | A |
| Fat-Helbary and Ohta (1994) | Aswan, Egypt | 50 | - | 50 | U | U | $m_b$ | U | U | $r_{hypo}$ | 1 | U | 1 | A |
| Fukushima et al. (1994) & Fukushima et al. (1995) | 3 vertical arrays in Japan | 285 | 284 | 42 | 5.0 | 7.7 | $M_{\mathrm{JMA}}$ | 60* | 400* | $r_{hypo}$ | I | B | 1,2 | A |
| Lawson and Krawinkler (1994) | W. USA | 250+ | - | 11 | 5.8 | 7.4 | $M_w$ | U | 100 | $r_{jb}$ | 3 | U | 1M | A |
| Lungu et al. (1994) | Romania | $\approx 300$ | 125 | 4 | 6.3 | 7.4 | $M_w$ | U | U | $r_{hypo}$ | 1 | U | 1 | A |
| Musson et al. (1994) | UK + 30* foreign | 15 + 30* | - | 4+16 | 3 (3.7) | 3.5 (6.4) | $M_L$ | 70* (>1.3) | >477.4 (200*) | $r_{hypo}$ | 1 | U[44] | O | A |
| Radu et al. (1994), Lungu et al. (1995a) & Lungu et al. (1996) | Romania | 106 | - | 3 | 6.7($M_L$) or 7.0($M_w$) | 7.2($M_L$) or 7.5($M_w$) | U[45] | 90* | 320* | $r_{hypo}$ | 1 | L | 1 | A |
| Ramazi and Schenk (1994) | Iran | 83 | 83 | 20 | 5.1 | 7.7 | $M_s$[46] | $\leq 8$ | $\geq$ 180 | $r_{hypo}$ for most, $r_{rup}$ for 19[47] | 2 | U | U | A |
| Xiang and Gao (1994) | Yunnan, China + 114 W. N. America | 131+114 | - | U | 2.5* | 7.6* | $M_s$ ($M_L$) | 2* | 120* | $r_{epi}$ | 1 | L | U | A |

*continued on next page*

[42] Boore et al. (1997) revise this magnitude to 5.87. New minimum magnitude is 5.2.
[43] Coefficients given in Boore et al. (1994b)
[44] Free (1996) believes it is largest horizontal component.
[45] It is not clear whether use Richter magnitude ($M_L$) or $M_w$.
[46] Some may be $m_b$ because in their Table 1 some earthquakes to not have $M_s$ given but do have $m_b$. If so new minimum is 5.0.
[47] They state it is 'closest distance from the exposure of ruptured part of the fault, instead of focal distances' so may not be rupture distance.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aman et al. (1995) | Himalayan region | 84* | - | 5 | 5.7 | 7.2 | $M_B$ | 3* | 350* | $r_{epi}$ | 1 | U | U | A |
| Ambraseys (1995) | Europe and Mid. East | 830 | 620 | 334 | 4.0 | 7.3 | $M_s$ | 0* | 260* | $r_{jb}$ for $M_s > 6.0$, $r_{epi}$ otherwise | 1 | L | 2W | A |
| Dahle et al. (1995) | Cen. America | 280 | - | 72 | 3* | 8* | $M_w$ ($M_s$, $m_b$,$M_D$) | 6* | 490* | $r_{hypo}$ | 2 | L | 1B | A |
| Lee et al. (1995) | W. N. America | 1926 | 1926 | 297 | 1.7 | 7.7 | Usually $M_L$ for $M \leq 6.5$ and $M_s$ for $M > 6.5$ | 2 | 200+ | $r_{hypo}$ | 9, 3 $\times$ C | U | 1 | A |
| Lungu et al. (1995b) | Romania | 106 | - | 3 | 6.7($M_L$) or 7.0($M_w$) | 7.2($M_L$) or 7.5($M_w$) | U[48] | U | U | $r_{hypo}$ | 1 | L | 1 | A |
| Molas and Yamazaki (1995) | Japan | 2166 | - | 387 | 4.1* | 7.8* | $M_{\mathrm{JMA}}$ | 8* | 1000* | $r_{rup}$ for 2 earthquakes, $r_{hypo}$ otherwise | I | L | O | A |
| Sarma and Free (1995) | E. N. America[49] | 77 | - | 33 | 2.8 | 5.9 | $M_w$ ($m_b$, $M_L$, $M_s$) | 0 | 820 | $r_{jb}$ or $r_{epi}$ | 2 | U | 1 | A |
| Ambraseys et al. (1996) & Simpson (1996) | Europe & Mid. East | 422 | - | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M_s > 6.0$, $r_{epi}$ otherwise | 3 | L | 2W[50] | A |
| Ambraseys and Simpson (1996) & Simpson (1996) | Europe & Mid. East | - | 417 | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M > 6.0$, $r_{epi}$ otherwise | 3 | - | 2W[51] | A |
| Aydan et al. (1996) & Aydan (2001) | Turkey | 27* | 23* | 19* | 3.5* | 7.6* | $M_s$ | 10* | 350* | $r_{hypo}$ | 1 | U | 1 | A |
| Bommer et al. (1996) | El Salvador & Nicaragua | 36 | - | 20 | 3.7 | 7.0 | $M_s$ | 62 | 260 | $r_{hypo}$ | 1 | L | U | A |
| Crouse and McGuire (1996) | Cen. & S. California | 238 | - | 16 | 6.0 | 7.7 | $M_s$ | 0.1 | 211 | $r_{rup}$ | 4 | G | 1W | R,S (R,S) |

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[48] It is not clear whether use Richter magnitude ($M_L$) or $M_w$.
[49] Also derive equations for Australia and N. E. China
[50] Ambraseys et al. (1996) state it is two-stage of Joyner and Boore (1981) but in fact it is two-stage method of Joyner and Boore (1988).
[51] Ambraseys et al. (1996) state it is two-stage of Joyner and Boore (1981) but in fact it is two-stage method of Joyner and Boore (1988).

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Free (1996) & Free et al. (1998) | Stable continental regions | 558 | 478 | H: 222, V: 189 | 1.5 | 6.8 | $M_w$ | 0 | 820 | $r_{jb}$ for some, $r_{epi}$ for most | 2 | L | 1 | A |
| Inan et al. (1996) | Turkey | U | - | U | U | U | U | U | U | $r_{epi}$ | 1 | U | U | A |
| Ohno et al. (1996) | California | 248 | - | 17 | 5.0 | 7.5 | $M_w$ ($M_L$) | 7.2 | 99.6 | $r_q$ for $M > 5.3$, $r_{hypo}$ otherwise | 2 | B | 2M | A |
| Romeo et al. (1996) | Italy | 95 | - | 17 | 4.6* | 6.8* | $M_w$ | 1.5, 1.5 | 179, 180 | Both $r_{jb}$ & $r_{epi}$ | 2 | L | 1 | A |
| Sarma and Srbulov (1996) | Worldwide | 350 | - | 114 | 3.9 | 7.7 | $M_s$ | 1 | 213 | $r_{jb}$ & $r_{epi}$ | 1 | B, L | U | A |
| Singh et al. (1996) | Himalayas | 86 | - | 5 | 5.7 | 7.2 | $m_b$ | 33.15 | 340.97 | $r_{hypo}$ | 1 | U | 1 | A |
| Spudich et al. (1996) & Spudich et al. (1997) | Worldwide extensional regimes | 128 | - | 30 | 5.10 | 6.90 | $M_w$ | 0 | 102.1 | $r_{jb}$ | 2 | G, O | 2M | NS |
| Stamatovska and Petrovski (1996) | Romania, Bulgaria & former Yugoslavia | 190[52] | - | 4 | 6.1 | 7.2 | $M_L$[53] | 10* | 310* | $r_{epi}$ | 1 | B | 1 | A |
| Ansal (1997) | Turkey | U | - | U | U | U | $M_w$ | U | U | $r_{hypo}$ | 1 | U | U | A |
| Campbell (1997), Campbell (2000), Campbell (2001) & Campbell and Bozorgnia (1994) | Worldwide | 645 | 225 | H:47, V:26 | 4.7 | H:8.0, V:8.1 | $M_w$ | 3 | 60 | $r_{seis}$ | 3 | G | 1 | A(S,R,N) |
| Munson and Thurber (1997) | Hawaii | 51 | - | 22 | 4.0 | 7.2 | $M_s$ for $M_s \geq 6.1$, $M_L$ otherwise | 0 | 88 | $r_{jb}$ | 2 | L | 2M | A |
| Pancha and Taber (1997) | New Zealand | U | - | U | U | U | U | U | U | U | 1 | U | 2 | A |
| Rhoades (1997) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 1 | L | O | A |
| Schmidt et al. (1997) | Costa Rica | 200 | - | 57 | 3.3 | 7.6 | $M_w$ ($M_s$, $m_b$, $M_D$) | 6.1 | 182.1 | $r_{hypo}$ | 3 | L, B | O | A |
| Youngs et al. (1997) | Worldwide subduction zones | 476 | - | 164 | 5.0 | 8.2 | $M_w$ ($M_s$,$m_b$) | 8.5 | 550.9 | $r_{rup}$, $r_{hypo}$ for some | 2 | G | 1M | NT |
| Zhao et al. (1997) | NZ with 66 foreign | 461[54]+66 | - | 49+17 | 5.08 | 7.23(7.41) | $M_w$ | 11 (0.1) | 573 (10) | $r_{rup}$ for some, $r_c$ for most | 2 | U | 1 | A(R) |
| Baag et al. (1998) | Korea | U | - | U | U | U | U | U | U | $r_{epi}$ | 1 | U | U | A |

*continued on next page*

[52]Total number of components. Does not need to be multiplied by two.
[53]Called Richter magnitude.
[54]Includes some not used for regression

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bouhadad et al. (1998) | Algeria | U | - | 2 | 5.6 | 6.1 | $M_s$ | 20 | 70 | $r_{hypo}$ | 1 | L, M | 1 | A |
| Costa et al. (1998) | Friuli | 80* | 80* | 20* | 1.3* | 4.3* | $M_D$ | 3* | 66* | $r_{hypo}$ | 1 | U | 1 | A |
| Manic (1998) | N.W. Balkans | 276[55] | - | 56 | 4 | 7 | $M_s$ | U | U | $r_{hypo}$ | 2 | B | 1 | A |
| Reyes (1998) | University City, Mexico City | 20+ | - | 20+ | U | U | $M_w$ | U | U | $r_{rup}$ | I | S | U | A |
| Rinaldis et al. (1998) | Italy & Greece | 137* | - | 24* | 4.5 | 7 | $M_s$ or $M_w$ | 7 | 138 | $r_{epi}$ | 2 | U | O | A (N,ST) |
| Sadigh and Egan (1998) | California with 4 foreign | 960+4 | - | 119+2 | 3.8 | 7.4 | $M_w$ | 0.1 | 305[56] | $r_{rup}$ for some, $r_{hypo}$ for small ones | 2 | G | U | A(R,SN) |
| Sarma and Srbulov (1998) | Worldwide | 690[57] | - | 113 | 3.9 | 7.7 | $M_s$ (U) | 0 | 197 | $r_{jb}$, $r_{epi}$ | 2 | B | 1 | A |
| Sharma (1998) | Indian Himalayas | 66 | - | 5 | 5.5 | 6.6 | U | 8 | 248 | $r_{hypo}$ | 1 | L | 1W | A |
| Smit (1998) | Switzerland + some from S. Germany | $\ll$ 1546 | <1546 | H: <120, V: 120 | 2.0 | 5.1 | $M_L$ | 1 | 290 | $r_{hypo}$ | 1 | U | 2 | A |
| Theodulidis (1998) | EuroSeisTest (N. Greece) | 225 | - | 51 | 1.7 | 5.1 | $M_w$ | 8 | 88 | $r_{hypo}$, $r_{epi}$ | 1 | B | 1 | A |
| Theodulidis et al. (1998) | Kozani-Grevena (Greece) | 232[58] | - | >23 | 3.1 | 6.6 | $M_w$ | 1 | 140* | $r_{epi}$ | 1 | B | O | A |
| Cabañas et al. (1999), Cabañas et al. (2000), Benito et al. (2000) & Benito and Gaspar-Escribano (2007) | Mediterranean region[59] | U | U | U | 2.5 | 7.0 | $M_s$[60] | 0 | 250 | $r_{epi}$[61] | 4 | L | 1 | A |
| Chapman (1999) | W. N. America | 304 | - | 23 | 5.0 | 7.7 | $M_w$ | 0.1 | 189.4 | $r_{jb}$ | 3 | G | 2M | A |
| Cousins et al. (1999) | NZ with 66 foreign | 610+66 | - | 25+17 | 5.17 | 7.09(7.41) | $M_w$ | 0.1 | 400 | $r_{rup}$ for some, $r_c$ for most | 3 | U | U | A(R) |
| Gallego and Ordaz (1999) & Gallego (2000) | Colombia | U | - | U | U | U | U | U | U | U | U | U | U | A |

*continued on next page*

[55] Total number of components do not need to be multiplied by two.
[56] Equations stated to be for distances up to 100 km
[57] Total number of components do not need to be multiplied by two.
[58] Total number of components do not need to be multiplied by two.
[59] Also derive equations for Spain.
[60] Also derive equations using $M_L$.
[61] Also derive equations using $r_{hypo}$.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ólafsson and Sigbjörnsson (1999) | Iceland | 88[62] | - | 17 | 3.4 | 5.9 | $M_w$[63] | 2 | 112 | $r_{epi}$ | 1 | B | 1 | A |
| Spudich et al. (1999) | Worldwide extensional regimes | 142 | - | 39 | 5.1 | 7.2 | $M_w$ | 0 | 99.4 | $r_{jb}$ | 2 | G, O | 1M | NS |
| Wang et al. (1999) | Tangshan, N. China | 44 | - | 6 | 3.7 | 4.9 | $M_s$ ($M_L$) | 2.1 | 41.3 | $r_{epi}$ | 1 | L | 1 | A |
| Zaré et al. (1999) | Iran | 468 | 468 | 47* | 2.7 | 7.4 | $M_w$ ($M_s$, $m_b$, $M_L$) | 4 | 224 | $r_{hypo}$ ($r_{rup}$ for 2) | 4 | B | 2M | R, RS & S |
| Ambraseys and Douglas (2000), Douglas (2001a) & Ambraseys and Douglas (2003) | Worldwide | 186 | 183 | 44 | 5.83 | 7.8 | $M_s$ | 0 | 15 | $r_{jb}$ | 3 | L | 1 | A |
| Bozorgnia et al. (2000) | Worldwide | 2823 | 2823 | 48 | 4.7 | 7.7 | $M_w$ | U | $\leq$ 60 | $r_{seis}$ | 4 | G | U | A (R,S,T) |
| Campbell and Bozorgnia (2000) | Worldwide | 960[64] | 941[65] | 49[66] | 4.7 | 7.7 | $M_w$ | 1* | 60* | $r_{seis}$ | 4 | G | 1 | A (S,R,T) |
| Field (2000) | S California | 447 | - | 28 | 5.1 | 7.5 | $M_w$ | 0 | 148.9 | $r_{jb}$ | C (6) | G | 1M | A (R, S, O) |
| Jain et al. (2000) | Central Himalayas | 32 (117) | - | 3 | 5.5 | 7.0 | U | 2 (4) | 152 (322) | $r_{epi}$ | 1 | U | 1 | T |
| Kobayashi et al. (2000) | Japan | U | - | U | 5.0 | 7.8 | $M_w$ | 0.9* | 400* | U | 4 | B | 1M | A |
| Monguilner et al. (2000a) | W. Argentina | 54[67] | - | 10[67] | 4.3[67] | 7.4 | $M_s$ if $M_L$ & $M_s > 6$, $M_L$ otherwise | 11[67] | 350[67] | $r_{hypo}$ | 2 | U | 1W | A |
| Paciello et al. (2000) | Greece & Italy | 115 | - | 18 | 4.5* | U | $M_w$ or $M_s$ | U | U | $r_{epi}$ | 3 | B | 1 | A (N) |
| Sharma (2000) | Indian Himalayas | - | 66 | 5 | 5.5 | 6.6 | U | 8 | 248 | $r_{hypo}$ | 1 | - | 1W | A |
| Si and Midorikawa (1999, 2000) | Japan | 856 | - | 21 | 5.8 | 8.3 | $M_w$ | 0* | 280* | Both $r_q$ & $r_{rup}$ | 2 | L | O | A |
| Smit et al. (2000) | Caucasus | 84 | - | 26 | 4.0 | 7.1 | $M_s$ | 4 | 230 | $r_{epi}$[68] | 1 | L | 2 | A |
| Takahashi et al. (2000) | Japan+166 foreign | 1332 | - | U+7* | 5* (5.8*) | 8.3* (8*) | $M_w$ | 1* (0.1*) | 300* (100*) | $r_{rup}$, $r_{hypo}$ for some | 4 | G | O | A |
| Wang and Tao (2000) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | O | A |

*continued on next page*

[62]Total number of components. Does not need to be multiplied by two.
[63]Equation given in terms of $\log M_0$.
[64]Equation for corrected PGA uses 443 records.
[65]Equation for corrected PGA uses 439 records.
[66]Equation for corrected PGA uses data from 36 earthquakes.
[67]Assuming they use same data as Monguilner et al. (2000b).
[68]Smit et al. (2000) give $r_{hypo}$ but this is typographical error (Smit, 2000).

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wang et al. (2000) | China | U | - | U | U | U | U | U | U | $r_{hypo}$ | 1 | U | 1 | A |
| Chang et al. (2001) | Taiwan | 4720[69], 2528[70] | - | 45[69], 19[70] | 4.1[69], 4.6[70] | 7.0[69], 6.3[70] | $M_w$ ($M_L$ for $M_L < 6.5$) | 0[69], 40.2[70] | 264.4[69], 272.4[70] | $r_{epi}$[69], $r_{hypo}$[70] | 1 | G | 2 | A |
| Herak et al. (2001) | Dinarides | 145 | 145 | 46 | 4.5 | 6.8 | $M_L$ | 3* | 200* | $r_{epi}$ | 1 | L | 2 | A |
| Lussou et al. (2001) | Japan | 3011 | 3011 | 102 | 3.7 | 6.3 | $M_{\mathrm{JMA}}$ | 4* | 600* | $r_{hypo}$ | 4 | B | 2 | A |
| Sanchez and Jara (2001) | Pacific coast of Mexico | U | - | U | U | U | $M_s$ | U | U | $r_{epi}$ | 1 | U | U | BF |
| Wu et al. (2001) | Taiwan | 1941 | - | 60 | 4.8 | 7.6 | $M_w$ ($M_L$) | 0.05* | 400* | $r_{rup}$ ($r_{epi}$ for some) | 1 & I | U | U | A |
| Chen and Tsai (2002) | Taiwan | 424 | - | 48 | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | U | O | A |
| Gregor et al. (2002a) | Shallow crustal worldwide (mainly California) | 993 | 993 | 68 | 4.4 | 7.4 | $M_w$ | 0.1 | 267.3 | $r_{rup}$ | 2 | U | 1M | A (S, R/O, T) |
| Gülkan and Kalkan (2002) | Turkey | 93[71] | - | 19 | 4.5 | 7.4 | $M_w$ | 1.20 | 150 | $r_{jb}$, $r_{epi}$ | 3 | L, R | 1 | A |
| Iglesias et al. (2002) | Mexico | U | - | 10 | 5.4 | 7.4 | $M_w$ | U | 400* | $r_{hypo}$ | 1 | V | 1 | B |
| Khademi (2002) | Iran | 160 | 160 | 28* | 3.4* | 7.4 | $M_w$ ($m_b$ for $M_s < 5$ and $M_s$ otherwise) | 0.1* | 180* | $r_{jb}$, $r_{epi}$ for $M < 5.9$ | 2 | L | O | A |
| Margaris et al. (2002b) & Margaris et al. (2002a) | Greece | 744 | - | 142 | 4.5 | 7.0 | $M_w$ | 1 | 150 | $r_{epi}$ | 3 | B | O | A |
| Saini et al. (2002) | Indian Himalayas | U | U | U | U | U | U | U | U | U | U | U | U | A |
| Schwarz et al. (2002) | N.W. Turkey | 683 | 683 | U | 0.9* | 7.2 | $M_L$ | 0* | 250* | $r_{epi}$ | 3 | U | 1 | A |
| Stamatovska (2002) | Romania | 190[72] | - | 4 | 6.1 | 7.2 | U | 10* | 310* | $r_{epi}$ | 1 | B | 1 | A |
| Tromans and Bommer (2002) | Europe | 249 | - | 51 | 5.5 | 7.9 | $M_s$ | 1 | 359 | $r_{jb}$ | 3 | L | 2 | A |
| Zonno and Montaldo (2002) | Umbria-Marche | 161 | - | 15 | 4.5 | 5.9 | $M_L$ | 2* | 100* | $r_{epi}$ | 2 | L | 2 | N, O |
| Alarcón (2003) | Colombia | 47 | - | U | 4.0 | 6.7 | $M_s$ | 49.7 | 322.4 | $r_{hypo}$ | 1 | U | U | A |
| Alchalbi et al. (2003) | Syria | 49 | 49 | 10 | 3.5 | 5.8 | $M_{CL}$ | 21 | 400 | $r_{hypo}$ | 2 | U | 1 | A |
| Atkinson and Boore (2003) | Subduction zones | 1200+ | - | 43* | 5.5 | 8.3 | $M_w$ | 11* | 550* | $r_{rup}$ | 4 | C | 1M | F, B |

*continued on next page*

[69] Shallow crustal records.
[70] Subduction records.
[71] This is total number of horizontal components used. They come from 47 triaxial records.
[72] This is total number of components. Does not need to be multiplied by two.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boatwright et al. (2003) | N. California | 4028 | - | 104 | 3.3 | 7.1 | Mainly $M_w$, $M_L$ for some | 1* | 370* | $r_{hypo}$ | 4 | U | O | A |
| Bommer et al. (2003) | Europe & Mid. East | 422 | - | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M_s > 6.0$, $r_{epi}$ otherwise | 3 | L | 1M | A (S, R, N) |
| Campbell and Bozorgnia (2003d), Campbell and Bozorgnia (2003a) & Bozorgnia and Campbell (2004b) | Worldwide | 443[73] | 439[74] | 36[75] | 4.7 | 7.7 | $M_w$ | 2* | 60* | $r_{seis}$ | 4 | G | 1 | A (S & N, R, T) |
| Halldórsson and Sveinsson (2003) | Iceland | 131 | - | 12 | 4.1 | 6.6 | $M_{Lw}$ | 5* | 300* | U | 1 | U | 1 | A |
| Li et al. (2003) | Yunnan, China | U | - | U | U | 7.6 | U | U | U | $r_{epi}$ | 1 | EW | 1 | A |
| Nishimura and Horike (2003) | Japan | U | U | U | U | U | $M_{JMA}$ | U | U | $r_{hypo}$ | U | U | 1 | A |
| Shi and Shen (2003) | Shanghai region | U | - | U | U | U | $M_s$ | U | U | $r_{hypo}$ | 1 | U | U | A |
| Sigbjörnsson and Ambraseys (2003) | Europe & Middle East | 465 | - | U | 5* | 7* | $M_w$ or $M_s$ | 1* | 500* | $r_{jb}$ if available, $r_{epi}$ otherwise | 1 | L | 1 | S |
| Skarlatoudis et al. (2003) | Greece | 1000 | - | 225 | 4.5 | 7.0 | $M_w$ ($M_L$) | 1.5* | 150* | $r_{epi}$ | 2 | U | O | A (N, ST) |
| Ulutaş and Özer (2003) | Turkey | 221 | - | U | 5 | 7.4 | $M_w$ | U | U | $r_{epi}$ | 1 | U | U | A |
| Zhao et al. (2003) | Yunnan, China | U | - | U | U | 7.6 | U | U | U | $r_{epi}$ | 1 | U | 1 | A |
| Beauducel et al. (2004) | Guadeloupe | 1430 | - | 398 | 1.1 | 6.3 | $M_D$ ($m_b$, $M_w$) | 1.7 | 450 | $r_{hypo}$ | 1 | R | 1 | A |
| Beyaz (2004) | Unknown (Turkey?) | U | - | U | U | U | $M_w$ | U | U | $r_{epi}$ | 1 | U | 1 | A |
| Bragato (2004) | NE Italy (45–46.5°N & 12–14°E) | 814 | - | 192 | 2.5 | 4.5 | $M_L$ | U | U | $r_{epi}$ | 1 | U | O | A |
| Cantavella et al. (2004) | Iberia | U | - | U | 2.5 | 5.1 | $M_{bLg}$ | 4 | 284 | $r_{epi}$ | 1 | U | 1 | A |
| Gupta and Gupta (2004) | Koyna region, India | 31 | 31 | U | U | 6.5 | $M_L$ | 3* | 25* | $r_{hypo}$ | 1 | L | O | A |
| Iyengar and Ghosh (2004) | N India | 61 | - | >5 | 5.5* | 6.6* | U | 8* | 248* | $r_{hypo}$ | 1 | L | 1 | A |

*continued on next page*

[73] There are 960 components for uncorrected PGA.
[74] There are 941 components for uncorrected PGA.
[75] For horizontal corrected records. There are 49 for horizontal uncorrected PGA. There are 34 for vertical corrected records and 46 for vertical uncorrected PGA.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kalkan and Gülkan (2004a) | Turkey | - | 100 | 47 | 4.2 | 7.4 | $M_w$ (unspecified scales) | 1.2 | 250 | $r_{jb}$, $r_{epi}$ for small events | 3 | - | 1 | A |
| Kalkan and Gülkan (2004b) and Kalkan and Gülkan (2005) | Turkey | 112 | - | 57 | 4.0 | 7.4 | $M_w$ (unspecified scales) | 1.2 | 250 | $r_{jb}$, $r_{epi}$ for small events | 3 | L[76] | 1 | A |
| Lubkowski et al. (2004) | Stable continental regions | 163 | - | U | 3.0 | 6.8 | $M_w$ ($M_L$) | 0 | 854 | $r_{epi}$ ($r_{jb}$ for 1 event) | 1 | U | 1, 1M, 2, 2M | A |
| Marin et al. (2004) | France | 63 | - | 14 | 2.6 | 5.6 | $M_L$ | 5 | 700 | $r_{hypo}$ | 1 | L | 1 | A |
| Midorikawa and Ohtake (2004) | Japan | 3335 | - | 33 | 5.5 | 8.3 | $M_w$ | 0* | 300* | $r_{rup}$ | 2 | L | 1 | A (C, B, F) |
| Özbey et al. (2004) | NW Turkey | 195 | - | 17 | 5.0 | 7.4 | $M_w$ ($M_L$) | 5* | 300* | $r_{jb}$ | 3 | G | 1M | NS |
| Pankow and Pechmann (2004) and Pankow and Pechmann (2006) | Worldwide extensional regimes | 142 | - | 39 | 5.1 | 7.2 | $M_w$ | 0 | 99.4 | $r_{jb}$ | 2 | G, O | 1M | NS |
| Skarlatoudis et al. (2004) | Greece | 819 | - | 423 | 1.7 | 5.1 | $M_w$ | 3 | 40 | $r_{epi}$ | 1 | U | O | A |
| Sunuwar et al. (2004) | Okhotsk-Amur plate boundary | 667 | 667 | 42 | 4.0 | 5.6 | $M_{\mathrm{JMA}}$ | >3 | >264 | $r_{hypo}$ | 1 | L | 2M | A |
| Ulusay et al. (2004) | Turkey | 221 | - | 122 | 4.1 | 7.5 | $M_w$ ($M_s$, $m_b$, $M_d$, $M_L$) | 5.1 | 99.7 | $r_{epi}$ | 3 | L | 1 | A |
| Yu and Wang (2004) | W USA | 187 | - | >17 | 5.0* | 7.8* | U | 2* | 200* | $r_{epi}$ | 1 | B | O | A |
| Adnan et al. (2005) | Worldwide subduction | 1100 | - | U | 5.3 | 8.5 | $M_w$ | U | U | $r_{hypo}$ | 1 | A | 1 | BF |
| Ambraseys et al. (2005a) | Europe & Middle East | 595 | - | 135 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | L | 1WM | A (N, T, S, O) |
| Ambraseys et al. (2005b) | Europe & Middle East | - | 595 | 135 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | - | 1WM | A (N, T, S, O) |
| Bragato (2005) | Worldwide | 243 | - | 60* | 5.0 | 7.8 | $M_s$ | 0 | 15 | $r_{jb}$ | 1 | L | O | A |
| Bragato and Slejko (2005) | E Alps (45.6–46.8°N & 12–14°E) | 1402 | 3168 | 240 | 2.5 | 6.3 | $M_L$ | 0 | 130 | $r_{jb}$ & $r_{epi}$ | 1 | R | O | A |
| Frisenda et al. (2005) | NW Italy | 6899[77] | - | >1152 | 0.0* | 5.1[78] | $M_L$ | 0 | 300[79] | $r_{hypo}$ | 2 | B | 1 | A |

*continued on next page*

[76]The caption of their Table 2 states that reported coefficients are for mean.
[77]Authors state in text that 'more than 14 000' values were used but their Table 1 gives $2 \times 6899$.
[78]State equations valid to 4.5.
[79]State equations valid up to 200 km.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| García et al. (2005) | Central Mexico | 277 | 277 | 16 | 5.2 | 7.4 | $M_w$ | 4* | 400* | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | G[80] | 1M | B |
| Liu and Tsai (2005) | Taiwan | 7907 | 7907 | 51 | 4.05 | 7.10 | $M_w$ ($M_L$) | 5* | 300* | $r_{hypo}$ | 1 | M | 2M | A |
| McGarr and Fletcher (2005) | Central Utah coal-mining areas | 72 | - | 12 | 0.98 | 4.2 | $M_w$ ($M_{CL}$) | 0.5* | 10* | $r_{hypo}$ | 2 | L | 2M | M |
| Nath et al. (2005a) | Sikkim (Himalaya) | 240* | - | 80 | 3 | 5.6 | $M_L$ | 10* | 100* | $r_{hypo}$ | 1 | U | 1 | A |
| Nowroozi (2005) | Iran | 279 | 279 | 45 | 3.0* | 7.4 | $M_w$ ($M_s$, $m_b$, $M_L$) | 2 | 245 | $r_{epi}$ | 4 | V | 1 | A |
| Ruiz and Saragoni (2005) & Saragoni et al. (2004)[81] | Chile | 41 | 41 | 8 | 6.4 | 7.8 | $M_s$ | 35.72 | 315.01 | $r_{hypo}$ | 1 | B | 1 | F |
| Takahashi et al. (2005), Zhao et al. (2006) and Fukushima et al. (2006) | Japan+208 overseas | 4518+208 | - | 249+20 | 5.0 | 8.3 | $M_w$ | 0* | 300* | $r_{rup}$ | 5 | G | 1M | C (R, S/N) & F, B |
| Wald et al. (2005) | California | U | - | U | U | 5.3* | $M_w$ | U | U | $r_{jb}$ | 1 | L | U | A |
| Atkinson (2006) | Los Angeles region | 4179 | - | 485+ | 3.1* | 7.1* | $M_w$ | 5* | 300* | $r_{epi}$ ($r_{jb}$ for some) | I, C | B | 1 | A |
| Beyer and Bommer (2006) | Shallow crustal (USA, Taiwan, Turkey and others) | 949 | - | 103 | 4.3* | 7.9* | $M_w$ | 6* | 200* | $r_{hypo}$ | U | 1, 2, A, B, C, D50, G, I50, L, N, P, R | 1M | A (U) |
| Bindi et al. (2006) | Umbria-Marche | 239 | - | 45 | 4.0 | 5.9 | $M_L$ | 1* | 100* | $r_{epi}$ & $r_{hypo}$ | 4 | L | 1M | NS |
| Campbell and Bozorgnia (2006a) and Campbell and Bozorgnia (2006b) | Worldwide | 1500+ | - | 60+ | 4.2 | 7.9 | $M_w$ | 0 | 200 | $r_{rup}$ | C | G | 2M | A (R, S, N) |

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[80] Call it 'quadratic mean', which is assumed to be geometric mean.
[81] Also develop equations for hard rock sites and intraslab events.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Costa et al. (2006) | NE Italy & Slovenia | 900* | 900* | 123 | 3.0* | 6.5* | U | 1* | 100* | $r_{epi}$ | 2 | L, V | 1 | A |
| Gómez-Soberón et al. (2006) | Mexico | 1983 | - | 109 | 4.5* | 8.1* | $M_w$ ($M_s$ if $M > 6$, $m_b$ if $M < 6$) | 5* | 800* | $r_{hypo}$ ($r_{rup}$ for some) | 1 | U | 2 | F |
| Hernandez et al. (2006) | Haulien LSTT (Taiwan) | 456 | 456 | 51 | 5 | 7.3 | $M_L$ | 13.7 | 134.8 | $r_{hypo}$ | 5 | B | 1 | A |
| Jaimes et al. (2006) | Ciudad Universitaria station, Mexico City | 21 | - | 21 | 6.0 | 8.1 | $M_w$ | 285 | 530 | $r_{rup}$ | 1 | U | 1B | F |
| Jean et al. (2006) | Taiwan | U (>3000) | - | 59 (>242) | 5.0* | 7.5* | $M_L$ | 0.1* | 300* | $r_{hypo}$ ($r_{rup}$ for 1 event) | 1, I | G | 1 | A |
| Kanno et al. (2006) | Japan+some foreign | 3392+377 (shallow) & 8150 (deep) | - | 73+10 & 111 | 5.0* (6.1) & 5.5* | 8.2* (7.4) & 8.0* | $M_w$ ($M_{\mathrm{JMA}}$) | 1* (1.5*) & 30* | 450* (350*) & 450* | $r_{rup}$ ($r_{hypo}$ for some) | C | R | 2M | A |
| Kataoka et al. (2006) | Japan | 5160 | - | 47 | 4.8* | 6.9* | $M_w$ | 1* | 200* | U | 1 | U | U | C |
| Laouami et al. (2006) | Algeria | 28 | - | 4 | 5.6 | 6.0 | $M_s$ | 13 | 70 | $r_{epi}$ & $r_{hypo}$ | 1 | U | 1 | A |
| Luzi et al. (2006) | Molise (Italy) | 886 | - | U | 2.6* | 5.7 | $M_L$ | 5* | 55* | $r_{hypo}$ | 2 | L | 1M | A |
| Mahdavian (2006) | Central Iran[82] | 150 | 150 | U | 3.1 | 7.4 | $M_s$ ($m_b$) | 4 | 98 | $r_{hypo}$ | 2 | A | 1 | A |
| McVerry et al. (2006) | New Zealand+66 overseas | 535+66 | - | 49+17 | 5.08 (5.2) | 7.23 (7.4) | $M_w$ | 6 (0.1) | 400 (10) | $r_c$ ($r_{rup}$) | 3 | L, G | 1M | C (R, OR, S & N) & F, B |
| Moss and Der Kiureghian (2006) | W. N. America | 271 | - | 20 | 5.2 | 7.7 | $M_w$ | 0 | 118.2 | $r_{jb}$ | C | G | O | A |
| Pousse et al. (2006) | Japan | 9390[83] | - | U | 4.1 | 7.3 | ($M_w$) | 5* | 250* | $r_{hypo}$ ($r_{rup}$ for some) | 5 | B | 2M | A |
| Souriau (2006) | France | 175 | - | 20 | 3.0 | 5.4 | $M_L$ (Re-Nass & LDG) | 10* | 800* | $r_{hypo}$ | 1 | L | 1 | A |
| Tapia (2006) & Tapia et al. (2007) | Western Mediterranean | 334 | - | 30 | 3.8 | 6.0 | $M_L$ | 6 | 542 | $r_{epi}$ | 1 | U | 1 | A |
| Tsai et al. (2006) | Taiwan | 7123 | - | 744 | 4* | 7.3* | $M_L$ | 0* | 330* | $r_{hypo}$ | 1 | G | O | A |
| Zare and Sabzali (2006) | Iran | 89 | 89 | 55* | 2.7 | 7.4 | $M_w$ | 4 | 167 | $r_{hypo}$ | 4 | U | 1M & 2M | A |

*continued on next page*

[82] Also develops equations for Zagros using 98 records from an unknown number of earthquakes.
[83] Does not need to be multiplied by two.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Akkar and Bommer (2007b) | Europe & Middle East | 532 | - | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ | 3 | G | 1WM | A (N, S, R) |
| Amiri et al. (2007a) & Amiri et al. (2007b) | Alborz and central Iran[84] | 200* | 200* | 50* | 4.5* | 7.3* | $M_s$ ($m_b$) | 5* | 400* | $r_{hypo}$ | 2 | L | 1 | A |
| Aydan (2007) | Turkey | U | - | U | U | U | U | U | U | $r_{hypo}$ | C | U | U | A |
| Bindi et al. (2007) | NW Turkey | 4047 | 4047 | 528 | 0.5 | 5.9 | $M_L$[85] | 5* | 200* | $r_{hypo}$[86] | 2 | L | 1M | A |
| Bommer et al. (2007) | Europe and Middle East | 997 | - | 289 | 3 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | G | 1WM | A (N, S, R) |
| Boore and Atkinson (2007) & Boore and Atkinson (2008) | Worldwide shallow crustal | 1574 | - | 58 | 4.27[87] | 7.90[88] | $M_w$ | 0 | 280[89] | $r_{jb}$ | C | I50 | 2M | A (N, R, S, U) |
| Campbell and Bozorgnia (2007), Campbell and Bozorgnia (2008b) & Campbell and Bozorgnia (2008a) | Worldwide shallow crustal | 1561 | - | 64 | 4.27[90] | 7.90[91] | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW) |
| Danciu and Tselentis (2007a), Danciu and Tselentis (2007b) & Danciu (2006) | Greece | 335 | - | 151 | 4.5 | 6.9 | $M_w$ | 0* | 136 | $r_{epi}$ | 3 | A | 1M | A (ST, N) |
| Douglas (2007) | | | See text | | | | $M_w$ | See text | | $r_{jb}$ | See text | | 1 | A |
| Fukushima et al. (2007a) | Japan (central Honshu) | 8615 | - | 158 | 5.0 | 6.8 | $M_{JMA}$ | 18.1 | 448.4 | $r_{rup}$ | 1 | V | 1 | A |
| Graizer and Kalkan (2007, 2008) | Worldwide shallow crustal | 2583 | - | 47 | 4.9[92] | 7.9[93] | $M_w$ | 0.1 | 349.6[94] | $r_{rup}$ | C | U | O | A (R,SN) |
| Güllü and Erçelebi (2007) | Turkey | 210 | - | U | 3.2 | 7.4 | $M_w$ | 1 | 364 | $r_{epi}$ | 4 | V3 | 1 | A |

*continued on next page*

[84] Also develop models for the Zagros region of Iran using about 100 records.
[85] Also derive model using $M_w$.
[86] Also derive model using $r_{epi}$.
[87] Recommend that model is not extrapolated below 5 due to lack of data.
[88] Believe that model can be used to 8.0.
[89] Recommend that model is not used for distances $\geq 200$ km.
[90] Believe that model can be extrapolated down to 4.0.
[91] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[92] Graizer and Kalkan (2007) state that valid down to 4.5.
[93] Graizer and Kalkan (2007) state that valid up to 7.6.
[94] Graizer and Kalkan (2007) state that valid up to 200 km.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hong and Goda (2007) & Goda and Hong (2008) | California | 592 | - | 39 | 5* | 7.3* | $M_w$ | 0.2* | 100* | $r_{jb}$ | C | G, Q, R | 1M | A |
| Massa et al. (2007) | Central northern Italy | 1063 | - | 243 | 2.5 | 5.2 | $M_L$ | 0* | 300* | $r_{hypo}$ | 2 | L | 1 | A |
| Popescu et al. (2007) | Romania | U | - | 58 | 4* | 7.1 | $M_w$ | $\leq$ 70 | $\geq$ 227 | $r_{epi}$, $r_{hypo}$ | C | L | O | A |
| Sobhaninejad et al. (2007) | Europe & Middle East | 589 | 589 | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | L | O | A (N, T, S, O) |
| Tavakoli and Pezeshk (2007) | Taiwan | 424 | - | 48 | 4.3* | 7.3* | $M_L$ | 5* | 260* | $r_{hypo}$ | 1 | G | O | A |
| Tejeda-Jácome and Chávez-García (2007) | Colima, Mexico | 162 | 162 | 26 | 3.3 | 5.2 | $M_L$ | 5* | 175 | $r_{hypo}$ | 1 | G | 2M | A |
| Abrahamson and Silva (2008) & Abrahamson and Silva (2009) | Worldwide shallow crustal | 2754 | - | 135 | 4.27[95] | 7.9[96] | $M_w$ | 0.06* | 200* | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW) |
| Ágústsson et al. (2008) | South Iceland | 1085 | 1085 | 64 | 3.5 | 6.5 | $M_{Lw}$ | 3* | 350* | $r_{epi}$ | 1 | V3 | 1 | A |
| Aghabarati and Tehranizadeh (2008) | Worldwide shallow crustal | 646 | - | 54 | 5.2 | 7.9 | $M_w$ | 0 | 60 | $r_{rup}$[97] | C | G | 1M | A (N, R, S) |
| Al-Qaryouti (2008) | Dead Sea area | 57 | - | 30 | 3.7 | 6.2 | $M_L$ | 5.8 | 330.6 | $r_{epi}$ | 1 | L | 2 | A |
| Cauzzi and Faccioli (2008), Cauzzi (2008) & Cauzzi et al. (2008) | Worldwide shallow crustal | 1164 | 1132 | 60 | 5.0 | 7.2 | $M_w$ | 6* | 150* | $r_{hypo}$ | 4 & C | G | 2M | A (N, R, S) |
| Chen (2008) | China, Taiwan and Japan | 249 | 249 | 55 | 4.2 | 7.6 | $M_w$ ($M_L$, $M_s$) | 10 & 12 | 153 & 153 | $r_{epi}$ & $r_{hypo}$ | 2 | G & L | 2 | A |
| Chiou and Youngs (2008) | Worldwide shallow crustal | 1950 | - | 125 | 4.265[98] | 7.90[99] | $M_w$ | 0.2*[100] | 70*[101] | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW, AS) |

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[95] Recommend that model is not extrapolated below 5 due to lack of data.
[96] Believe that model can be reliably extrapolated to 8.5.
[97] Not clear from article if the authors mean $r_{rup}$ or $r_{jb}$.
[98] Believe that model can be extrapolated down to 4.0.
[99] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[100] Believe that model valid to 0 km.
[101] Believe that model valid to 200 km.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cotton et al. (2008) | Japan | 3894 | - | 337 | 4 | 7.3 | $M_w$ ($M_{\mathrm{JMA}}$) | 1* | 100* | $r_{rup}$ ($r_{hypo}$ for small) | 4[102] & 2[103] | G | 2M | A |
| Güllü et al. (2008) | Turkey | 210 | - | U | 3.2 | 7.4 | $M_w$ | 10* | 100* | $r_{epi}$ | 2 | L3 | 1 | A |
| Humbert and Viallet (2008) | Europe & Middle East | 960 | - | 138 | 4.0 | 7.4 | $M_s$ | U | U | $r_{hypo}$ | 1 | U | O | A |
| Idriss (2008) | Worldwide shallow crustal | 942 | - | 72 | 4.5 | 7.7 | $M_w$ | 0.3 | 199.3 | $r_{rup}$ | 2 | I50 | 1 | A (R/RO/NO, S/N) |
| Lin and Lee (2008) | NE Taiwan+10 foreign | 4244+139 | - | 44+10 | 4.1 (6.0) | 7.3 (8.1) | $M_w$ ($M_L$) | 15 | 630 | $r_{hypo}$ | 2 | G | 1W | A (B, F) |
| Massa et al. (2008) | Northern Italy | 306 | 306 | 82 | 3.5 & 4.0 | 6.3 & 6.5 | $M_w$ ($M_L$) & $M_L$ | 1* | 100* | $r_{epi}$ | 3 | L | 1M | A |
| Mezcua et al. (2008) | Spain | 250 | - | 149 | 3.1 | 5.3 | $M_w$ ($m_b(L_g)$) | 5* | 100* | $r_{hypo}$ | 1 | U | 1 | A |
| Morasca et al. (2008) | Molise | 3090 | 3090 | 100 | 2.7 | 5.7 | $M_L$ | 12* | 60* | $r_{hypo}$ | 2 | L | 1M | A |
| Slejko et al. (2008) | Caucasus (36–46°N, 38–52°E) | 200 | - | ≥21 | 4.0* | 8.1* | $M_s$ ($M_L$, $M_w$, $m_b$) | 2* | 100* | $r_{epi}$ | 1 | U | O | A |
| Srinivasan et al. (2008) | Kolar Gold Fields, India | 795 | - | 795 | 0.5 | 3.0 | $M_L$ | 1 | 4.76 | $r_{hypo}$ | 1 | G | 1 | A |
| Adnan and Suhatril (2009) | Lalaysia | 93 | - | 14 | 6.7 | 9.1 | $M_w$ | 466 | 2487 | $r_{rup}$ | 1 | G | 1M | F, B |
| Aghabarati and Tehranizadeh (2009) | Worldwide shallow crustal | 678 | 678 | 55 | 5.2 | 7.9 | $M_w$ | 0 | 60 | $r_{rup}$ | C | G | 1M | A (N, R, S) |
| Akyol and Karagöz (2009) | Western Anatolia | 168 | - | 49 | 4.03 | 6.40 | $M_w$ ($M_d$, $M_L$) | 15 | 200 | $r_{hypo}$ | 2 | L | 2M | A |
| Baruah et al. (2009) | Shillong plateau (India) | 82 | - | U | 2.5* | 5.0* | $M_s$ ($M_D$) | 3.5 | 144.5 | $r_{hypo}$ | 1 | A | 1 | A |
| Bindi et al. (2009a) | Italy | 241 | 241 | 27 | 4.8 | 6.9 | $M_w$ | 0 | 190 | $r_{jb}$ ($r_{epi}$ for small) | 3 | L, G | 1M | A (N, S, R) |
| Bindi et al. (2009b) | Italy | 235 | - | 27 | 4.6 | 6.9 | $M_w$ ($M_L$) | 0 | 183 | $r_{jb}$, $r_{epi}$ | 3 | L | 1M | A |
| Bragato (2009) | Italy | 922 | - | 116 | 2.7 | 4.5 | $M_L$ | 6 | 100 | $r_{epi}$ | I, 3, 1, C | U | 1 | A |
| Cabalar and Cevik (2009) | Turkey | 93[104] | - | 19 | 4.5 | 7.4 | $M_w$ | 1.20 | 150 | $r_{jb}$, $r_{epi}$ | 3 | L, R | O | A |
| Garcìa Blanco (2009) | Spain | U | - | 149 | U | 5.3 | U | 10* | 100* | $r_{epi}$ | 1 | U | 1 | A |

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[102]For stations on surface.
[103]For borehole stations.
[104]This is total number of horizontal components used. They come from 47 triaxial records.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Goda and Atkinson (2009) | Japan | 8557 (3410 shallow, 5147 deep) | - | 155 (51 shallow, 104 deep) | 5.5 | 7.9 | $M_w$ | 1.5* | 300* | $r_{rup}$ ($r_{hypo}$ for some $M < 6.5$) | C | G | 2M | A (C/F, B) |
| Hong et al. (2009a) | Mexico (interface & inslab) | 418, 277 | -, - | 40, 16 | 5.0, 5.2 | 8.0, 7.4 | $M_w$ | U | U | $r_{rup}$ ($r_{hypo}$ for small) | 1 | G, R, Q | 1M | F, S |
| Hong et al. (2009b) | California | 592 | - | 39 | 5* | 7.3* | $M_w$ | 0.2* | 100* | $r_{jb}$ | C | G, R | 1M, 2M, O | A |
| Kuehn et al. (2009) | Worldwide | 2660 | - | 60 | 5.61 | 7.9* | $M_w$ | 0.1* | 200* | $r_{jb}$ | C | G | 1M (O) | A (N, R, S) |
| Li et al. (2009) | Yunnan, China | 240 | - | U | 3.0 | 7.9 | U | 5 | 25 | $r_{epi}$ | 1 | U | 1 | A |
| Mandal et al. (2009) | Gujarat, India | 248 | - | 33 | 3.1 | 7.7 | $M_w$ | 1* | 300* | $r_{jb}$ | 2 | L | 2 | A |
| Moss (2009) & Moss (2011) | Worldwide shallow crustal | 1950 | - | 125 | 4.265 | 7.90 | $M_w$ | 0.2* | 70* | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW, AS) |
| Pétursson and Vogfjörd (2009) | SW Iceland | 823 | 823 | 46 | 3.3 | 6.5 | $M_{Lw}$ | 3 | 380 | $r_{epi}$ | 1 | V3 | 1 | A |
| Rupakhety and Sigbjörnsson (2009) | South Iceland+others | 64+29 | - | 12 | 5.02 | 7.67 | $M_w$ | 1 | 97 | $r_{jb}$ ($r_{epi}$ for some) | 2 | L | 1 | S & O |
| Akkar and Bommer (2010) | Europe & Middle East | 532 | - | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ | 3 | G | 1M | A (N, S, R) |
| Akkar and Çağnan (2010) | Turkey | 433 | - | 137 | 5.0 | 7.6 | $M_w$ | 0* | 200* | $r_{jb}$ | C | G | 1M | A (N, S, R) |
| Arroyo et al. (2010) | Pacific coast of Mexico | 418 | - | 40 | 5.0 | 8.0 | $M_w$ | 20 | 400 | $r_{rup}$ ($r_{hypo}$ for $M_w < 6$) | 1 | U | O | F |
| Bindi et al. (2010) | Italy | 561 | 561 | 107 | 4.0 | 6.9 | $M_w$ | 1* | 100* | $r_{jb}$, $r_{epi}$ | 3 | L | 1M | A |
| Cua and Heaton (2010) | Southern California+other shallow crustal | 3588+1607 | - | 70 | 2 (5) | 7.3 (7.9) | $M_w$ | 0.8 (0.1)* | 200 (200)* | $r_{jb}$ ($r_{epi}$ for $M < 5$) | 2 | G | 1 | A |
| Douglas and Halldórsson (2010) | Europe & Middle East | 595 | - | 135 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | L | 1WM | A (N, T, S, O, AS) |
| Faccioli et al. (2010) | Worldwide shallow crustal | 1499 | - | $\leq 60$ | 4.5 | 7.6 | $M_w$ | 0.2* | 200* | $r_{rup}$ ($r_{hypo}$ for small) | 4 & C | G | 1M | A (N, R, S) |
| Graizer et al. (2010) & Graizer et al. (2013) | Worldwide | 13992 | - | 245 | 4.2 | 7.9 | $M_w$ | 0.1* | 500* | $r_{rup}$ | C | U | O | A (SN, R) |

*continued on next page*

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hong and Goda (2010) | California[105] | 592 | - | 39 | 5.0 | 7.28 | $M_w$ | 0.2* | 100* | $r_{jb}$ | C | 1, 2 | 1M | A |
| Iervolino et al. (2010) | Italy | 95 | - | 17 | 4.6 | 6.8 | $M_w$ | 1.5, 1.5 | 179, 180 | $r_{jb}$ & $r_{epi}$ | 3 | L | 1 | A |
| Jayaram and Baker (2010) | Worldwide shallow crustal | 1561 | - | 64 | 4.27 | 7.90 | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | I50 | O | A (N, R, S, HW) |
| Montalva (2010) & Rodriguez-Marek et al. (2011) | Japan | 3894 | - | 337 | 4 | 7.3 | $M_w$ ($M_{\mathrm{JMA}}$) | 1 | 100 | $r_{rup}$ ($r_{hypo}$ for small) | C, I | G | O (1M) | A |
| Ornthammarath et al. (2010), Ornthammarath (2010) & Ornthammarath et al. (2011) | South Iceland | 81 | - | 6 | 5.1 | 6.5 | $M_w$ | 1* | 80* | $r_{jb}$ ($r_{epi}$ for $M_w < 6$) | 2 | G | 1M | S |
| Sokolov et al. (2010) | Taiwan | 4656 | - | 66 | 4.6* | 7.6* | $M_w$ ($M_L$) | 5* | 220* | $r_{hypo}$ | 1 | G | 1, 2M | A |
| Ulutaş and Özer (2010) | Marmara region, Turkey | 751 | - | 78 | 4.0 | 7.4 | $M_w$ ($M_d$) | 0.1 | 196.8 | $r_{jb}$[106] ($r_{epi}$ for small events) | 1 | L | 1 | SN |
| Alavi et al. (2011) | Worldwide shallow crustal | 2252 | - | U | 5.1* | 7.9* | $M_w$ | 0.2* | 350* | $r_{rup}$ | C | U | O | A (Rake) |
| Anderson and Uchiyama (2011) | Guerrero, Mexico | 293 | 293 | 27 | 5.05 | 7.96 | $M_w$ | 10* | 390* | $r_{rup}$ | 1 | M, V, V3 | O | A |
| Arroyo and Ordaz (2011) | Worldwide shallow crustal | 906 | - | 44 | U | U | $M_w$ | U | U | $r_{rup}$ | 1 | I50 | 1M | A (R/RO/NO, S/N) |
| Beauducel et al. (2011) | Guadeloupe (France) | 1430 | - | 400* | 1* | 6.3 | $M_d$ for $M < 4.5$, $M_w$ otherwise | 2* | 500* | $r_{hypo}$ | 1 | V | 1W | A |
| Bindi et al. (2011a) | Italy | 769 | - | 99 | 4.1 | 6.9 | $M_w$ | 0* | 200* | $r_{jb}$ | 5 | G, V | 1M | A (S, R, N, U) |
| Emolo et al. (2011) | Campania-Lucania, Italy | 875 | - | 123 | 1.5 | 3.2 | $M_L$ | 3 | 100* | $r_{hypo}$ | 2 | L | 1 | A |
| Gehl et al. (2011) | Japan | 3874 | - | 335 | 4.0 | 7.3 | $M_w$ | 0* | 340* | $r_{rup}$ | C | G | 1M, O | A |
| Joshi et al. (2011) & Joshi et al. (2012) | Kumaon Himalaya (India) | 130 | - | 82 | 3.5 | 5.3 | $M_w$ | 4 | 151 | $r_{hypo}$ | 1 | L | 1 | A |

*continued on next page*

[105] Also derive models for inslab (273 records from 16 earthquakes) and interface (413 records from 40 earthquakes) Mexican earthquakes.
[106] Not entirely clear in the article if $r_{rup}$ was actually used.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kayabali and Beyaz (2011) | Turkey | 482[107] | - | U | 4 | 7.4 | $M_w$ ($M_s$, $M_L$, $M_D$) | 0* | 200* | $r_{epi}$ | 1 | B | 1 | A |
| Luzi et al. (2011) | Italy | U | - | U | 4.0* | 6.9* | $M_w$ | 0* | 300* | $r_{jb}$ ($r_{epi}$ for $M_w <$ 5.5), $r_{hypo}$ | 5 | G | 1M | A (S, N, R) |
| Lin et al. (2011b) | Taiwan + 8 foreign events | 5181+87 | - | 44+8 | 3.5 (6.0) | 7.6 (7.4) | $M_w$ ($M_L$) | 1 | 240 | $r_{rup}$ ($r_{hypo}$) | 2 | G | 1 | A (HW) |
| Yilmaz (2011) | SW Turkey | 66 | - | 44 | 2.9 | 6.04 | $M_d$ | 1.11 | 145 | $r_{epi}$ & $r_{hypo}$ | 2+C | U | O | A |
| Yuen and Mu (2011) | Tangshan, Xinjiang and Guangdong (China) | 266 | - | 147 | 3.6* | 7.2* | U | 4* | 600* | $r_{hypo}$ | 3 | U | O | A |
| Chang et al. (2012) | Taiwan | 302 | - | 58 | 5.5 | 7.3 | $M_L$ | 0* | 170* | $r_{hypo}$ ($r_{rup}$ for some) | 1 | G | 1 | A |
| Contreras and Boroschek (2012) | Chile | 117 | - | 13 | 6.5 | 8.8 | $M_w$ | 30* | 600* | $r_{rup}$, $r_{hypo}$ for 4 events | 2 | G | 1M | F |
| Convertito et al. (2012) | Geysers, N. California | U[108] | - | 220 | 1.0 | 3.5 | $M_w$ ($M_D$) | 0.5 | 20 | $r_{hypo}$ | 2 | L | 1M | G |
| Cui et al. (2012) | Sichuan-Yunnan (China) | 962 | - | >21 | 4.5 | 6.5 | $M_s$ | 0* | 110* | $r_{epi}$ | 2 | G | 1, 1W | A |
| Di Alessandro et al. (2012) | Italy | 602 | - | 120 | 4.0 | 6.8 | $M_w$ | 2* | 200* | $r_{hypo}$ | 7 | G | 1M | A |
| Gómez-Bernal et al. (2012) | Mexico | 607 | 607 | 17[109] | 6.0 | 8.1 | $M_w$ | 20* | 600* | $r_{rup}$ | 1 | L | 2 | A (F, B, C) |
| Hamzehloo and Mahood (2012) | East central Iran | 258 | - | 109[110] | 4.9* | 7.4 | $M_w$ | 1* | 200* | $r_{jb}$ | 1 | G | 2M | A |
| Hung and Kiyomiya (2012) | Japan & northern Vietnam and Yunnan (China) | 447 + 22 | - | 7 | 3.9 (2.7) | 6.9 (6.4) | $M_w$ ($M_s$) | 3* | 300* | $r_{jb}$ ($r_{epi}$) | C | U | 1 | S |
| Laouami and Slimani (2012) | Algeria + Europe & USA | 633 + 528 & 155[111] | - | 82+17* & 7* | 3 (5*) | 6.8 (7.3*) | $M_s$ | 6* (10*) | 140* (150*) | $r_{hypo}$ | 2 | B | 2 | A |
| Mohammadnejad et al. (2012) | Worldwide shallow crustal | 2252 | - | U | 5.2 | 7.9 | $M_w$ | 0.07 | 366.03 | $r_{rup}$ | C | I50 | O | A (R, S, N) |

*continued on next page*

[107] Authors also state that 516 records were used. Not clear which is the correct total.
[108] Probably roughly 5500 based on Sharma et al. (2013).
[109] Taken from their Table 3.1. Elsewhere in the article the total is given as 23 and 25.
[110] Or 106. Both are given.
[111] Do not need to multiply by 2.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Nabilah and Balendra (2012) | Peninsular Malaysia & Singapore | 35 | - | 9 | 7.2 | 9.1 | $M_w$ | 508 | 1021 | $r_{epi}$ | 1 | L | 2 | F |
| Nguyen et al. (2012) | Northern Vietnam | 330 | - | 53 | 1.6 | 4.6 | $M_L$ | 5* | 500* | $r_{epi}$ | 1 | L3 | 1 | A |
| Saffari et al. (2012) | Iran | 351 | - | 78 | 5.0 | 7.4 | $M_w$ | 4 | 190* | $r_{rup}$ ($r_{hypo}$ for $M_w < 6.5$) | 3 | U | 2M | A |
| Shah et al. (2012) | N. Pakistan/N. India | 128 | - | 25 | 4.1 | 7.6 | U | 8 | 265 | $r_{epi}$ | 1 | U | 1 | A |
| Abrahamson et al. (2013, 2014) | Worldwide shallow crustal | 15750 | - | 326 | 3 | 7.9[112] | $M_w$ | 0 | 300 | $r_{rup}$ + others for HW | C | D50 | 1M | A (S, N, R, HW) |
| Boore et al. (2013, 2014) | Worldwide shallow crustal | 15000* | - | 350* | 3.0 | 7.9[113] | $M_w$ | 0 | 400 | $r_{jb}$ | C | D50 | 2M | A (S, N, R, U) |
| Campbell and Bozorgnia (2013, 2014) | Worldwide shallow crustal | 15521 | - | 322 | 3.0[114] | 7.9[115] | $M_w$ | 0* | 300* | $r_{rup}$ | C | D50 | 1M | A (S, R, N, HW) |
| Chiou and Youngs (2013, 2014) | Worldwide shallow crustal | 12244 | - | 300 | 3.1*[116] | 7.9*[117] | $M_w$ | 0.3* | 400*[118] | $r_{rup}$ | C | D50 | 1M | A (S, R, N, HW) |
| Douglas et al. (2013) | Mainly geothermally-related | 3968 | - | 535 | 1* | 4* | $M_w$ ($M_L$, $M_D$) | 0* | 20* | $r_{hypo}$ | 1 | G | 1M | G |
| Edwards and Douglas (2013) | Cooper Basin (Australia) | 2089 | - | 427 | 1.7 | 3.1 | $M_w$ | 2.4 | 7.8 | $r_{hypo}$ | 1 | G | 1M | G |
| Idriss (2013, 2014) | Worldwide shallow crustal | 2353 | - | 151 | 4.5[119] | 7.9[120] | $M_w$ | 0.2 | 175 | $r_{rup}$ | C | D50 | 1 | A |
| Joshi et al. (2013a) | Uttarakhand Himalaya (India) | U, 29 | - | U, U | 3.5, 3.5 | 5.3, 5.3 | $M_w$ | 15, 20 | 100, 210 | $r_{hypo}$ | 1 | U | 1 | A |
| Laurendeau et al. (2013) | Japan | 2357 | - | 132 | 4.5 | 6.9 | $M_w$ | 3* | 300* | $r_{rup}$ ($r_{hypo}$ for small) | C | G | 1M | A |
| Morikawa and Fujiwara (2013) | Japan | 21681 | - | 333 | 5.5 | 9.0 | $M_w$ | 1* | 200 | $r_{rup}$ | C | V | 2W | A (C, B, F) |

*continued on next page*

[112] State model applicable up to 8.5.
[113] State model applicable up to $M_w 8.5$ for strike-slip and reverse and $M_w 7$ for normal earthquakes.
[114] State model applicable for $M_w \geq 3.3$ in California and $M_w \geq 5.5$ globally.
[115] State model applicable to $M_w 8.5$ for strike-slip, $M_w 8$ for reverse/reverse-oblique and $M_w 7.5$ for normal/normal-oblique.
[116] State applicable for $M_w \geq 3.5$.
[117] State applicable for $M_w \leq 8.5$ for strike-slip and $M_w \leq 8$ for reverse and normal earthquakes.
[118] State applicable up to 300 km
[119] Recommends model for $M_w \geq 5$.
[120] Recommends model up to $M_w 8$.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pacific Earthquake Engineering Research Center (2013) | Worldwide shallow crustal | - | | 4 vertical models | | | $M_w$ | 4 vertical models | | | C | - | 1M | A (N, S, R, HW) |
| Segou and Voulgaris (2013) | Europe & Middle East | 327 | - | 164 | 4.1 | 6.6 | $M_w$ ($m_b$) | 1* | 150* | $r_{epi}$ | 3 | I50 | O | A (S, R, N) |
| Sharma et al. (2013) | Geysers, N. California | 5451 | - | 212 | 1.3 | 3.3 | $M_w$ ($M_D$) | 0.5 | 20 | $r_{hypo}$ | 3 | L | 1M | G |
| Skarlatoudis et al. (2013) | Hellenic Arc (Greece) | 743 | - | 21 | 4.4 | 6.7 | $M_w$ ($m_b$, $M_L$) | 65* | 850* | $r_{hypo}$ | 3 | D50 | 1M | F, B |
| Villalobos-Escobar and Castro (2013) | Medellìn and Aburrà Valley (Colombia) | 596 | - | 17 | 2.8 | 6.5 | $M_L$ | 10* | 290 | $r_{epi}$ | I | U | 1M | A |
| Akkar et al. (2014b,c) | Europe & Middle East | 1041 | - | 221 | 4.0 | 7.6[121] | $M_w$ | 0 | 200 | $r_{jb}$, $r_{epi}$ & $r_{hypo}$ | C | G | 1M | A (S, N, R) |
| Ansary (2014) | Himalaya, India | R: 229, S: 187 | - | 150* | 2.5* | 7.8 | U | 2* | 2000* | $r_{hypo}$ | 2 | U | 1 | A |
| Bindi et al. (2014a,b) | Europe & Middle East | 1224, 2126 | - | 225, 365 | 4.0 | 7.6 | $M_w$ | 0 | 300 | $r_{jb}$ ($r_{epi}$ for $M_w \leq 5$ and $r_{epi} \geq 10$) & $r_{hypo}$ | C, 4 | G | 1M | A (S, N, R) |
| Derras et al. (2014) | Europe & Middle East | 1088 | - | 320 | 3.6[122] | 7.6[123] | $M_w$ | 1[124] | 547[125] | $r_{jb}$ | C | G | O | A |
| Ghofrani and Atkinson (2014) | Japan | > 1000 | - | 6 | 7.0 | 9.0 | $M_w$ | 30* | 1000* | $r_{rup}$ | C | G | O | F |
| Gianniotis et al. (2014) | Various Eurasian areas | | | See text | | | $M_w$ | See text | | $r_{hypo}$ | C | G | O | A (NS, R) |
| Kurzon et al. (2014) | San Jacinto fault zone (S. California, USA) | 29474 | - | 809 | 1.5 | 5.9 | $M_L$ | 0 | 150 | $r_{epi}$ | 1 | G | 1M | A |
| Luzi et al. (2014) | Italy | 829, 2805, 401 | - | 146, 658, 41 | 4, 4, 3.5 | 6.9, 6.9, 6.3 | $M_w$ ($M_L$) | 0* | 200* | $r_{jb}$ ($r_{epi}$ for $M < 5.5$) | 5 | G | 1M | A |
| Rodríguez-Pérez (2014) | Cen. and S. Mexico | 75 (F), 121 (B) | - | 8 F, 25 B | 5.1 (F), 5.0 (B) | 8.0 (F), 7.2 (B) | $M_w$ | 50* (F), 70* (B) | 580* (F), 540* (B) | $r_{rup}$ ($r_{hypo}$ for $M_w < 6.5$) | 1 | G | 1M | F, B |

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[121] Believe model can be used up to $M_w8$.
[122] Recommend never using model below 4.
[123] Recommend never using model above 7.
[124] Recommend never using model for $r_{jb} < 5$.
[125] Recommend never using model for $r_{jb} > 200$.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Vacareanu et al. (2014) | 9 events from Vrancea (Romania) + 17 foreign events | 233+198 | - | 9+17 | 5.2 (5.6)[126] | 7.4 (7.8)[127] | $M_w$ | 105[128] | 650*[129] | $r_{hypo}$ | 1 | G | 1M | B |
| Atkinson (2015) | California | U | - | U | 3* | 6* | $M_w$ | 2* | 40 | $r_{hypo}$ | 1 | G | 1M | A |
| Breska et al. (2015) | Worldwide | 3550 for $r_{jb}$ & 3083 for $r_{rup}$ | - | 173 | 4.2 | 7.9 | $M_w$ | 0 | 200* | $r_{jb}$ & $r_{rup}$ | C | G | 1 | A (R, N, S) |
| Cauzzi et al. (2015b) | Worldwide shallow active crustal | 1880 | - | 98 | 4.5 | 7.9 | $M_w$ | 0* | 150* | $r_{rup}$ ($r_{hypo}$ for $M_w \leq 5.7$) | C | G | 2M | A (S, N, R) |
| Emolo et al. (2015) | South Korea | 11129 | - | 222 | 2.0 | 4.9 | $M_L$ | 1.4 | 600* | $r_{epi}$ | I | L | 1M | A |
| Graizer and Kalkan (2015) & Graizer and Kalkan (2016) | Worldwide shallow crustal | 2583 | - | 47 | 4.9[130] | 7.9[131] | $M_w$ | 0.2 | 250 | $r_{rup}$ | C | U | O | A (R,SN) |
| Haendel et al. (2015) | Northern Chile | 1094 | - | 138 | 5* | 8.1 | $M_w$ | 40* | 300* | $r_{rup}$ | 2 | G | 1M | B, F |
| Jaimes et al. (2015) | Ciudad Universitaria, Mexico City[132] | 22 | - | 22 | 5.2 | 7.4 | $M_w$ | 103 | 464 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ for $M_w \leq 6.5$ | 1 | G | 1B | B |
| Kale et al. (2015) | Turkey & Iran | 1198 | - | 313 | 4 | 7.6[133] | $M_w$ | 0 | 200 | $r_{jb}$ | C | G | 1MW | A (S, N, R) |
| Kuehn and Scherbaum (2015) | Europe & Middle East | 835 | - | 279 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | G | O | A (R, N, S) |
| Pacific Earthquake Engineering Research Center (2015) — Al Noman and Cramer | Cen. and E. N. America + foreign | 6061[134] | - | 78[135] | 2.5 | 7.6[136] | $M_w$ | 1* | 2000* | $r_{rup}$ | C | D50 | 2M | A (R, S, U) |

*continued on next page*

[126] Believe can be used to 5.0.
[127] Believe can be used to 8.0.
[128] Believe can be used for $r_{epi} \geq 10$ km.
[129] Believe can be used for $r_{epi} \leq 300$ km.
[130] State that valid down to 5.0.
[131] State that valid up to 8.0 except for normal faulting where limit is 7.0.
[132] Also derive models for two other sites (SCT and CDAO) in Mexico City.
[133] Recommend model up to $M_w 8$
[134] Also use 1921 macroseismic intensities.
[135] Macroseismic intensities from 6 events.
[136] 7.7 by including macroseismic data.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pacific Earthquake Engineering Research Center (2015) — Graizer & Graizer (2016) | Cen. and E. USA | 5026 | - | 48 | 3.75[137] | 6.8[138] | $M_w$ | 4[139] | 1000* | $r_{rup}$ | C | D50 | O | A |
| Vacareanu et al. (2015b) | Vrancea, Romania + foreign intermediate-depth | 344+360 | - | 9+29 | 5.2 (5.1) | 7.4 (8.0) | $M_w$ | 2 ($r_{epi}$) | 399 ($r_{epi}$) | $r_{hypo}$ | 3 | G | 1M | A |
| Vuorinen et al. (2015) | Fennoscandian shield | U | - | 2239 | U | U | U | U | U | U | U | U | 1 | A |
| Wan Ahmad et al. (2015) | Malaysia | 130 | - | 10 | 3.5 | 6.7 | $M_w$ | U | U | $r_{hypo}$ | 1 | M | 1 | S |
| Zhao et al. (2015) | Japan + some overseas | 16362 | - | 335 + 62 | 4.9* | 9.1* | $M_w$ | 0* | 300* | $r_{rup}$ if available, $r_{hypo}$ otherwise | 4 + C | G | 1M | A (B, F, R, N, S) |
| Abrahamson et al. (2016) & BC Hydro (2012) | Worldwide subduction | 2590 for B, 953 for F | - | 63 for B, 43 for F | 5.0 for B, 6.0 for F | 7.9 for B, 8.4 for F | $M_w$ | 12* | 300* | $r_{rup}$ ($r_{hypo}$) for F, $r_{hypo}$ for B | C | G | 1M | B, F |
| Bozorgnia and Campbell (2016b) | Worldwide shallow crustal | - | 15161 | 321 | 3.0[140] | 7.9[141] | $M_w$ | 0* | 500*[142] | $r_{rup}$ | C | - | 1M | A (R, S, N) |
| Kaveh et al. (2016) | Worldwide shallow crustal | 2252 | - | U | 5.2 | 7.9 | $M_w$ | 0.07 | 360 | $r_{rup}$ | C | U | O | A |
| Kotha et al. (2016a,b) | Europe & Middle East | 1251 | - | U | 4 | 7.6 | $M_w$ | 0* | 300*[143] | $r_{jb}$ ($r_{epi}$ for some $M_w \leq 5$) | C | G | O | A |
| Kuehn and Scherbaum (2016) | Europe & Middle East | 1261 | - | 362 | 4.1 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | G | O | A (R, N, S) |
| Landwehr et al. (2016) | California & Nevada | 10692 | - | 221 | 3.0* | 7.3* | $M_w$ | 1* | 300* | $r_{jb}$ | C | U[144] | O | A (S, N, R) |
| Lanzano et al. (2016) | Po Plain & NE Italy | 2489 | - | 94 | 4.0 | 6.4 | $M_w$ | 0* | 200* | $r_{jb}$ | 5 | G | 1M | A (R, N, U) |
| Mu and Yuen (2016) | Tangshan, China | 132 | - | 72 | 4.0* | 7.8* | $M_w$ | 2* | 500* | $r_{hypo}$ | 1 | U | O | A |

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[137] Recommends use down to 4.0.
[138] Believes applies up to 8.2.
[139] Believes applies down to 0 km.
[140] Believe applicable down to 3.3 for California and down to 5.5 globally.
[141] Believe valid to 8.5 for strike-slip, 8.0 for reverse and 7.5 for normal.
[142] Believe applicable to 300 km.
[143] Recommend model up to 200 km
[144] Probably D50.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Noor et al. (2016) & Nazir et al. (2016) | Malaysia | 130 | - | 11 | 3.53 | 8.6 | $M_w$ | 204 | 1720 | $r_{hypo}$ | 1 | M | 1 | S |
| Sedaghati and Pezeshk (2016) | Europe & Middle East | 350 | - | 85 | 5.0 | 7.6 | $M_w$ | 1* | 100* | $r_{jb}$ | 4 | G | 1, 1W, 1M, 2, 2M, 2O and O | A |
| Shoushtari et al. (2016) | Malaysia, Japan and Iran | 531 | - | 13 | 5.0 | 7.7 | $M_w$ | 120* | 1400* | $r_{hypo}$ | 4 | G | 1 | B |
| Stewart et al. (2016) | Worldwide shallow crustal | - | 17089 | U | 3 | 7.9[145] | $M_w$ | 0 | 300 | $r_{jb}$ | C | - | 2M | A (R, S, N, U) |
| Sung and Lee (2016) | Taiwan | 19887 | - | 150 | 4.01 | 7.62 | $M_w$ ($M_L$) | 0.32 | 291.59 | $r_{hypo}$, $r_{rup}$ for Chi-Chi | C | U | 1M, O | A (S, N, R) |
| Tusa and Langer (2016) | Mount Etna, Italy | 1158 (shallow), 1957 (deep) | 1158 (shallow), 1957 (deep) | 38 (shallow), 53 (deep) | 3.0 | 4.3 (shallow), 4.8 (deep) | $M_L$ | 0.5 | 100 | $r_{epi}$ | 3 | G | 1 | V |
| Wang et al. (2016) | Offshore NE Taiwan | 832 | - | 13 | 4.0 | 5.9 | $M_w$ | 20* | 300* | $r_{hypo}$ | C | G | 1 | N |
| Zhao et al. (2016a) | Japan | 4555+155 | - | 125+11 | 5.0* | 7.92 (8.25) | $M_w$ | 25* | 300* | $r_{rup}$, $r_{hypo}$ for most | 4 | G | 1M | B |
| Zhao et al. (2016b) | Japan | 3111+463 | - | 76 | 5.0* | 9.0 | $M_w$ | 20* | 300* | $r_{rup}$, $r_{hypo}$ for most | 4 | G | 1M | F |
| Zhao et al. (2016c) | Japan + some foreign | 5957 | - | 117 | 4.9 | 7.2* | $M_w$ | 0* | 280* | $r_{rup}$, $r_{hypo}$ for most | 4 | G | 1M | C (N), UM (R, NS) |
| Ameri et al. (2017) | Europe & Middle East | 2355 | - | 384 | 3 | 7.6 | $M_w$ | 0* | 200* | $r_{epi}$, $r_{jb}$ | 4 | G | 1M | A (N, R, S) |
| Baltay et al. (2017) | San Jacinto fault (USA) | 14840 | - | 3200 | 1.15 | 3 | $M_w$ ($M_L$) | 0* | 20* | $r_{hypo}$ | C | G | 1M | A |
| Bindi et al. (2017) | Worldwide shallow crustal | 4692 | - | 242 | 3* | 7.9* | $M_w$ | 4* | 300* | $r_{hypo}$, $r_{jb}$ | C | G | 1M | A |
| Çağnan et al. (2017a,b) | Europe & Middle East | - | 1041 | 221 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | V | 1M | A (S, N, R) |
| Derras et al. (2017) | Japan | 977 | - | 214 | 3.7 | 6.9 | $M_w$ | 3.65 | 440.63 | $r_{jb}$ | C × C | G | O | A |

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[145]Recommend model for use up to 8.0 for strike-slip and reverse and 7.0 for normal earthquakes.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| García-Soto and Jaimes (2017) | Mexico (Pacific coast) | 418 | 418 | 40 | 5.0 | 8.0 | $M_w$ | 17 | 400 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | V | 1M | F |
| Gülerce et al. (2017) | Worldwide shallow crustal | - | 15597 | 326 | 3 | 7.9[146] | $M_w$ | 0 | 300 | $r_{rup}$ + others for HW | C | V | 1M | A (S, N, R, HW) |
| Idini et al. (2017) | Chile | 114 for B, 369 for F | - | 38 for B, 65 for F | 5.5 | 7.8 for B, 8.8 for F[147] | $M_w$ | 61 for B, 31 for F | 386 for B, 391 for F | $r_{hypo}$ ($r_{rup}$ for F and $M_w \geq$ 7.7) | C | U | 2M | B,F |
| Institute of Seismology at the University of Helsinki (2017) cited by Ader et al. (2019) | Finland | U | - | U | -0.9 | 4.1 | $M_L$ | 1.5 | 78 | $r_{hypo}$ | U | U | 1 | A |
| Kumar et al. (2017) | NE India | 216 | - | 24 | 4.0 | 6.8 | U | 25* | 950* | $r_{hypo}$ | 1 | U | 2 | A |
| Montalva et al. (2017a,c,b) | Chile | 2461 for F, 1313 for S | - | 281 for F, 192 for B | 4.5* | 8.8 for F, 7.8* for B | $M_w$ ($M_L$) | 25* for F, 60* for B | 1000* for F, 500* for B | $r_{rup}$ for F, $r_{hypo}$ for B | C | G | 1M | F, B |
| Liew et al. (2017) | Malaysia | 111, 65, 82 | - | 10, 5, 7 | U, U, U | 7.0*, 6.0*, U | $M_w$ and $m_b$ | U | U | $r_{epi}$, $r_{epi}$, $r_{hypo}$ and $r_{epi}$ | 1 | V[148] | 1 | F, B, C |
| Oth et al. (2017) | Japan | 118102 | - | 1905 | 2.7 | 7.2 | $M_w$ | 0.8* | 250 | $r_{hypo}$ ($r_{rup}$ for $M_w \geq 6$) | 1 | G | 1M | A |
| Peruzza et al. (2017) | Mount Etna, Italy | 1158 | - | 38 | 3.0 | 4.3 | $M_L$ | 0.5 | 100 | $r_{hypo}$ | 3 | G | 1 | V |
| Sedaghati and Pezeshk (2017) | Iran | 688 | 688 | 152 | 4.7 | 7.4 | $M_w$ | 1* | 250* | $r_{jb}$ | C | 1M | G | A |
| Shahidzadeh and Yazdani (2017) | Iran | 289 | - | 136 | 5.0* | 7.4* | $M_w$ | 0* | 190* | $r_{jb}$, $r_{epi}$ for some | 3 | L | O | A (S, R, N) |
| Soghrat and Ziyaeifar (2017) | N Iran | 325 | 325 | 55 | 4.1 | 7.3 | $M_w$ (U) | 5.3 | 303.1 | $r_{jb}$, $r_{epi}$ for some | 4, C | G | 1M | A (S, R, U) |
| Zuccolo et al. (2017) | Southwest Italy | 2270 | - | 319 | 1.5 | 4.2 | $M_L$ | 3 | 100* | $r_{hypo}$ | 1 | B | 1W | A |

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[146] State model applicable up to 8.5.
[147] Recommend use for $M_w \leq 9$ for interface and $M_w \leq 8$ for intraslab.
[148] Call it 'diagonal'.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ameur et al. (2018) | Worldwide shallow crustal | 2335 | - | 137 | 3.2[149] | 7.9[150] | $M_w$ | 0.01[151] | 358[152] | $r_{jb}$ | C | G | O | A |
| Bajaj and Anbazhagan (2018) | Himalaya | 512 | - | 66 | 4.0 | 7.8 | $M_w$ | 5* | 500* | $r_{hypo}$ | 1 | U | 1 | A |
| Chousianitis et al. (2018) | Greece | 652 | - | 72 | 4.0* | 6.8 | $M_w$ | 0.3* | 200* | $r_{epi}$ | 2 | G | 2M | A (R/S, N) |
| D'Amico et al. (2018a) | S Calabria & Sicily (S Italy) | 840 | - | 48 | 4.0 | 6.0 | $M_w$ ($M_L$) | 2* | 200* | $r_{jb}$ ($r_{epi}$ for most) | 4 | G | 1M | A |
| Erken et al. (2018) | NW Turkey + foreign | 369 + 33 | - | 19 + 7 | 4.1 + 6.6[153] | 7.4 + 7.6[154] | $M_w$ | 1 | 344[155] | $r_{jb}$ | 2 | U | 1 | A |
| Felicetta et al. (2018) | Italy | 769 | - | 99 | 4.1 | 6.9 | $M_w$ | 0* | 200* | $r_{jb}$ | 5, 6 | G | 1M | A (S, R, N, U) |
| Javan-Emrooz et al. (2018) | N Iran, E Turkey, Armenia & Georgia | 463 | 463 | 107 | 4.5 | 7.4 | $M_w$ ($m_b$) | 2 | 100 | $r_{epi}$ | 2 | V | O | A (R, S) |
| Ktenidou et al. (2018) | Euroseistest (N Greece) | 691 | - | 74 | 2.0 | 5.6 | $M_L$ | 5 | 220 | $r_{rup}$ | 1, 2, C, I | D50 | 1M | A |
| Laouami et al. (2018a,b) | Algeria + Europe + W. USA | 556+494+158 | - | 82 + 58 + 8 | 3.0 + 5.3 + 5.9 | 6.8 + 7.6 + 7.2 | $M_w$ ($M_s$) | 6* | 230* | $r_{hypo}$ | 3 | B | 2 | A |
| Mahani and Kao (2018) | Graham and Septimus areas (BC, Canada) | U, U | - | 129, 90 | 1.5, 1.5 | 3.8, 3.0 | $M_L$ | 2.3, 1.6 | 19, 42 | $r_{hypo}$ | 1 | G | 1M | W |
| Rahpeyma et al. (2018) | Hveragerdi (S Iceland) | 4620 | - | 610 | 0.42 | 4.75 | $M_L$ | 1.6 | 18* | $r_{hypo}$ | I | G | O | A |
| Sahakian et al. (2018) | Anza, S California | >120 000 | - | >10 000 | 0.5 | 4.5 | $M_w$ | 0* | 180 | $r_{hypo}$ | C, I | G | 1M | A |
| Sharma and Convertito (2018) | The Geysers, USA | 261711 | - | 10974 | 0.7 | 3.3 | $M_w$ ($M_D$) | 0.1 | 73 | $r_{hypo}$ | I | L | 1M | G |
| Shoushtari et al. (2018) | Japan + Malay Peninsula | 651 + 77 | - | 11 + 14 | 5.0 + 6.7 | 9.1 + 9.0 | $M_w$ | 120* + 500* | 1300* + 1000* | $r_{hypo}$ | 4 | G | 1 | F |
| Wen et al. (2018) | Sichuan region (China) | 1644 | - | 186 | 4.0 | 6.7 | $M_s$ | 2 | 200 | $r_{jb}$ | C | D50 | 1M | A |

*continued on next page*

[149] Believe applicable $\geq 3.6$.
[150] Believe applicable $\leq 7.6$.
[151] Believe applicable $\geq 6$ km.
[152] Believe applicable $\leq 200$ km.
[153] Recommend for use $M_w \geq 5.0$.
[154] Recommend for use for $M_w \leq 7.0$
[155] Recommend for use for $r_{jb} \leq 200$ km.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zafarani et al. (2018) | Iran | 1551 | - | 200 | 4.0 | 7.3 | $M_w$ ($M_L$) | 0.6* | 200* | $r_{jb}$ ($r_{epi}$) | 4 | G | 1M | A (R, S, U) |
| Ashadi and Kaka (2019) | Java (Indonesia) | 1825 | - | 95, 57 | 4.4[156] | 8.6[157] | $M_w$ ($M_L$, $m_b$) | 33.0, 83.4[158] | 994.3, 994.0[159] | $r_{hypo}$ | 2 | G | 1 | B, F |
| Darzi et al. (2019) | Iran | 1350 | - | 370 | 4.5 | 7.4 | $M_w$ ($M_s$, $m_b$) | 1* | 200* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ & $r_{rup}$ | 3 | G | 2M | A (S, R, U) |
| Farajpour et al. (2019) | Iran | 1356[160] | - | 208 | 4.8 | 7.5 | $M_w$ | 1.5* | 350* | $r_{rup}$ | C | G | 1M | A (R, S, N) |
| Huang and Galasso (2019) | Italy | 7843 | - | 233 | 4.0 | 6.9 | $M_w$ | 1* | 250* | $r_{jb}$ ($r_epi$) | 3 | D50 | O | A (R, S, N) |
| Konovalov et al. (2019) | Sakhalin (Russia) | 115 | 115 | 15 | 4.4 | 6.1 | $M_w$ | 15 | 650 | $r_{rup}$ | 1 | L3 | 1W | A |
| Lanzano et al. (2019a,b) | Italy + 12 foreign events | 4965 + 823[161] | - | 144 + 12 | 3.5 + 6.07 | 6.87 + 8.0 | $M_w$ | 0* | 200* | $r_{jb}$ ($r_{epi}$ for $M < 5.5$), $r_{rup}$ ($r_{hypo}$ for $M < 5.5$) | C | D50 | 1M | A (N, R, S) |
| Laouami (2019) | Algeria + Europe + W. USA | - | 257 + 247 + 79 | U | 3.0 | 7.4 | $M_w$ ($M_s$) | 5 | 150 | $r_{hypo}$ | 3 | - | 2 | A |
| Podili and Raghukanth (2019) | Japan | 96880 | - | 1340 | 5.0 | 9.0 | $M_w$ | 5 | 350 | $r_{rup}$ ($r_{hypo}$ for some) | C | A | 2 | A (S, R, N, U, B, C) |
| Stafford (2019) | Worldwide shallow crustal | 924–8548 | - | 103–384 | 3* | 7.9* | $M_w$ | 0* | 200* | $r_{rup}$ | C | D50 | O | A (S, N, R) |
| Sung and Lee (2019) | Taiwan | 20006 | - | 497 | 4.01 | 7.62 | $M_w$ ($M_L$) | 0.63 | 200 | $r_{rup}$ ($r_{hypo}$ for $M_w <$ 4.8) | C, I | G | 1M | A (S, N, R) |
| Zolfaghari and Darzi (2019a) | Iran | - | 1350 | 370 | 4.5 | 7.4 | $M_w$ ($M_s$, $m_b$) | 1* | 200* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ & $r_{rup}$ | 3 | - | 2M | A (S, R, U) |
| Chao et al. (2020) | Taiwan | 40892 | - | 316 | 3.5 | 7.6[162] | $M_w$ | 0.07 | 437.10 | $r_{rup}$ | C | D50 | O | A (N, S, R, F, B, AS) |

*continued on next page*

[156] State only applicable from $M_w$4.8 or 5.0.
[157] State only applicable to $M_w$8.0.
[158] State only applicable from 100 km.
[159] State only applicable to 800 km.
[160] Could be 1288 records.
[161] This is the total in the Electronic Supplement listing all the data used. In the article it is stated that 5607 records from 146 earthquakes are used.
[162] Believe model applicable up to 8.0 for crustal and intraslab events and 9.0 for interface events.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cremen et al. (2020) | Lancashire + N. Nottinghamshire (UK) | 195+192 | - | 29+48 | (0.1*) | (2.9*) | $M_w$ ($M_L$) | 1.5* | 7* | $r_{hypo}$ | 1 | G | O | E + M |
| Hu et al. (2020) | Sagami Bay, Japan | 738 (off-shore)[163], 3775 (on-shore) | 738 (off-shore), 3775 (on-shore) | 233, 223 (on-shore) | 4.0 | 6.8 | $M_w$ | 5* | 300* | $r_{hypo}$ | I, 4 | D50 | 1M | A (C, F, B) |
| Jaimes and García-Soto (2020) | Mexico | 366 | 366 | 23 | 5.2 | 8.2 | $M_w$ | 22 | 400 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | G[164] | 1M | B |
| Kotha et al. (2020) | Europe & Mediterranean | 18222 | - | 927 | 3.0 | 7.4 | $M_w$ | 0 | 545 | $r_{jb}$ ($r_{epi}$) | I | D50 | O | A |
| Kowsari et al. (2020) | South Iceland | 83 | - | 6 | 5.1 | 6.5 | $M_w$ | 0* | 80* | $r_{jb}$ | 2 | D50 | O | S |
| Kuehn et al. (2020b) | Separate models for Taiwan & Iran | 13236 & 2775 | - | 108 & 480 | 4* & 3 | 7.6* & 7.37 | $M_w$ | 1* & 2.5 | 300* & 300 | $r_{jb}$ & $r_{hypo}$ | C & 1 | D50 | 1M, O | A |
| Lanzano and Luzi (2020) | Volcanic areas, Italy | 615 | - | 41 | 3.0 | 4.9 | $M_w$ ($M_L$) | 2* | 200* | $r_{hypo}$ | 3 | G | 1M | V |
| Li et al. (2020) | Sichuan-Yunnan (China) + global | 250 + 276 | - | 7 + 22 | 6.0 + 6.1 | 7.9 + 7.68 | $M_w$ | 0* | 200* | $r_{rup}$ | C | D50 | 1M | A |
| Phung et al. (2020a) | Taiwan + Japan | 3314 + 3376 | - | 51 + 25 | 4.5 + 6.5 | 7.1 + 9.1 | $M_w$ ($M_L$) | 1 + 26 | 280 + 345 | $r_{rup}$ | C | D50 | O | A (B, F) |
| Phung et al. (2020b) | Taiwan + other shallow crustal | 11375 + 2040 | - | 157 + 30 | 3.5 + 6.46 | 7.65 + 7.9 | $M_w$ ($M_L$) | 0.1* | 200* | $r_{rup}$ | C | D50 | O | A (N, S, R, HW) |
| Ramkrishnan et al. (2022) | NE India | 204 | - | 24 | 4.2 | 6.9 | $M_w$ | 42 | 640 | $r_{hypo}$ | 1 | L | 2M | A |
| Tusa et al. (2020) | Mt Etna, Italy | 1600 | 1600 | 49 | 3.0 | 4.8 | $M_L$ | 0.5 | 100 | $r_{hypo}$ | 3 | G | 1M | V |
| Abdelfattah et al. (2021) | Jazan (Saudi Arabia) | 638 | - | 72 | 2.0 | 5.1 | $M_L$ | 4 | 200* | $r_{hypo}$ | 1 | A | 1 | A |
| Boore et al. (2021) | Greece | 1500* | - | 150* | 4.0* | 7.0* | $M_w$ | 0.1* | 300* | $r_{jb}$ | C | D50 | O | A (S, R, N) |
| Gao et al. (2021) | S. Taiwan | 338 | - | 61 | 4.2 | 7.6 | $M_w$ ($M_L$) | 3.6 | 300 | $r_{rup}$, $r_{hypo}$ for some events | 1 | D50 | 1M | A |
| Kumar et al. (2021) | Uttarakhand, India | 116 | - | 9 | 5.0 | 6.8 | $M_w$ | 10* | 430* | $r_{hypo}$ | 1 | L | 2W | A |

*continued on next page*

[163] May be 742 as this is stated in Table 4 of article.
[164] Call it 'quadratic mean', which is assumed to be geometric mean.

Table 3.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lanzano et al. (2021) & Caramenti et al. (2022) | Italy | 4784 | - | 137 | 3.5 | 6.9 | $M_w$ | 0.3* | 200* | $r_{jb}$ | C | D50 | O | A (N, R, S) |
| Ramkrishnan et al. (2021) | N. and Cen. Himalaya | 278 | - | 33 | 4.1 | 7.8 | $M_w$ | 16 | 1560 | $r_{hypo}$ | 1 | U | O | A |
| Yao et al. (2021) | Wenchuan (China) aftershocks | 99 | - | 13 | 5.4 | 6.4 | $M_w$ | 20* | 180* | $r_{hypp}$ | 1 | EW | 2W | AS |
| Akhani and Pezeshk (2022) | Taiwan | 424 | - | 48 | 4.3 | 7.3 | $M_L$ | 5* | 260* | $r_{hypo}$ | 1 | G | O | A |
| Allen (2022) | N. Australia | U | - | U | 5.3* | 7.6*[165] | $M_w$ | 75*[166] | 1750*[167] | $r_{hypo}$ | C | G | O | B, F |
| Miyazawa et al. (2022) | NE Japan | 213, 159 | - | 3, 2 | 7.51, 8.3 | 7.81, 9.1 | 50* | 300* | $r_{SMGA}$, $r_{rup}$ | 1 | D50 | 1M | F | |
| Zeiß et al. (2022) | SW Germany | 19100* | - | 1200* | 1.4* (0.9) | 3.7* (4.0) | $M_w$ ($M_L$) | 5* | 200* | $r_{hypo}$ | I | V | O | A |
| Zhang et al. (2022) | SW China | 1324 | - | 70 | 4.2 | 7.9[168] | $M_w$ | 0.06[169] | 299.95[170] | $r_{rup}$ | C | D50 | 1M | A (N, S, R) |
| Gogoi et al. (2023) | NE India | 113 | 113 | 24 | 4.4 | 6.8 | $M_w$ (unknown) | 20 | 525 | $r_{epi}$ | 1 | EW, NS, All | 1 | A |
| Khansefid et al. (2023) | Worldwide geothermal sites | 664 | 664 | 110 | 2.75[171] | 5.60[172] | $M_w$ ($M_L$, $M_D$) | 1* | 150*[173] | $r_{hypo}$ | C | U | 1M | G |

[165] Recommend model up to $M_w 8$.
[166] Recommend model from 500 km.
[167] Recommend model to 1500 km.
[168] Recommend model for $M_w \leq 6.1$ for strike-slip, $M_w \leq 7.9$ for reverse and $M_w \leq 6.5$ for normal faulting.
[169] Recommend model from 10 km.
[170] Recommend model to 200 km.
[171] Recommend for use to $M_w 2.5$.
[172] Recommend for use to $M_w 5.5$.
[173] Recommend for use to 100 km.

# Chapter 4

# Summary of published GMPEs for spectral ordinates

## 4.1 Johnson (1973)

- Ground-motion model is:

$$\text{PSRV} = C10^{\alpha m_b} R^m$$

- Response parameter is pseudo-velocity for 5% damping.
- Most (76%) records from $R < 70$ km.
- Uses only shallow focus earthquakes of 'normal' or less depth, to minimize variables, except for one record from deeper earthquake ($m_b = 6.5$, $R = 61.1$ km) which produces no distortion in statistical calculations.

## 4.2 McGuire (1974) & McGuire (1977)

- See Section 2.11.
- Response parameter is pseudo-velocity for 0, 2, 5 and 10% damping.
- Residuals pass Kolmogorov-Smirnov goodness-of-fit test at 5% significance level for normal distribution, so it is concluded that pseudo-velocities are lognormally distributed.
- Feels that using 16 natural periods presents a very good picture of spectral trends throughout entire period range.
- Only gives graphs of coefficients not actual calculated values.

## 4.3 Kobayashi and Nagahashi (1977)

- Ground-motion model is:

$$\log_{10} S_{V0} = a(\omega)M - b(\omega)\log_{10} x - c(\omega)$$

- Response parameter is velocity for unspecified[1] damping.

[1] It is probably 5%.

- Do regression iteratively. Assume $a(\omega)$, $b(\omega)$ and $c(\omega)$. Find amplification factors, $G_i(\omega)$, for each response spectra, $R_i(\omega)$: $G_i = R_i(\omega)/S_{V0}$. Calculate amplification factor, $G$, for each site: $G = \sqrt[n]{\prod_{i=1}^{n} G_i(\omega)}$. Estimate bedrock spectrum, $B_i(\omega)$, for each record: $B_i(\omega) = R_i(\omega)/G(\omega)$. Find $a(\omega)$, $b(\omega)$ and $c(\omega)$ by least squares. Repeat these steps until convergence. Hence find attenuation relation for bedrock and amplification function for each site.

## 4.4 Trifunac (1977) & Trifunac and Anderson (1977)

- Ground-motion model is:

$$\begin{aligned}\log_{10}[\mathrm{SA}(T), p] &= M + \log_{10} A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v \\ &\quad - f(T)M^2 - g(T)R\end{aligned}$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of $M_L$, $p$ is confidence level and $v$ is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Uses three site categories:

  $s = 0$ Alluvium. 63% of data.

  $s = 1$ Intermediate. 23% of data.

  $s = 2$ Basement rock. 8% of data.

- Response parameter is acceleration for 0, 2, 5, 10 and 20% damping.

- Note that do not believe the chosen independent parameters are the best physical characterization of strong shaking but they are based on instrumental and qualitative information available to the engineering community in different parts of the USA and the world.

- Data from free-field stations and basements of tall buildings, which assume are not seriously affected by the surroundings of the recording station. Note that detailed investigations will show that data from basements of tall buildings or adjacent to some other large structure are affected by the structures but do not consider these effects.

- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace $f(T)M^2$ by $f(T)(M - M_{\max})^2$ and for $M < M_{\min}$ replace $M$ by $M_{\min}$ everywhere to right of $\log_{10} A_0(R)$.

- Use almost same data as Trifunac (1976a). See Section 2.16.

- Use same regression method as Trifunac (1976a). See Section 2.16.

- Note that need to examine extent to which computed spectra are affected by digitization and processing noise. Note that routine band-pass filtering with cut-offs of 0.07 and 25 Hz or between 0.125 and 25 Hz may not be adequate because digitisation noise does not have constant spectral amplitudes in respective frequency bands and because noise amplitudes depend on total length of record.

- Find approximate noise spectra based on 13 digitisations of a diagonal line processed using the same technique used to process the accelerograms used for the regression. Linearly interpolate noise spectra for durations of 15, 30, 60 and 100 s to obtain noise spectra for duration of record and then subtract noise spectrum from record spectrum. Note that since $\mathrm{SA}(y_1 + y_2) \neq \mathrm{SA}(y_1) + \mathrm{SA}(y_2)$ this subtraction is an approximate method to eliminate noise which, empirically, decreases the distortion by noise of the SA spectra when the signal-to-noise ratio is small.

- Note that $p$ is not a probability but for values of $p$ between 0.1 and 0.9 it approximates probability that $\mathrm{SA}(T)_{,p}$ will not be exceeded given other parameters of the regression.
- $-g(T)R$ term represents a correction to average attenuation which is represented by $\log_{10} A_0(R)$.
- Do not use data filtered at 0.125 Hz in regression for $T > 8$ s.
- Due to low signal-to-noise ratio for records from many intermediate and small earthquakes only did regression up to 12 s rather than 15 s.
- Smooth coefficients using an Ormsby low-pass filter along the $\log_{10} T$ axis.
- Only give coefficients for 11 selected periods. Give graphs of coefficients for other periods.
- Note that due to the small size of $g(T)$ a good approximation would be $\log A_0(R) + R/1000$.
- Note that due to digitisation noise, and because subtraction of noise spectra did not eliminate all noise, $b(T)$, $c(T)$ and $f(T)$ still reflect considerable noise content for $T > 1--2$ s for $M \approx 4.5$ and $T > 6--8$ s for $M \approx 7.5$. Hence predicted spectra not accurate for periods greater than these.
- Note that could apply an optimum band-pass filter for each of the accelerograms used so that only selected frequency bands remain with a predetermined signal-to-noise ratio. Do not do this because many data points would have been eliminated from analysis which already has only a marginal number of representative accelerograms. Also note that such correction procedures would require separate extensive and costly analysis.
- Note that low signal-to-noise ratio is less of a problem at short periods.
- Compare predicted spectra with observed spectra and find relatively poor agreement. Note that cannot expect using only magnitude to characterise source will yield satisfactory estimates in all cases, especially for complex earthquake mechanisms. Additional parameters, such as a better distance metric than epicentral distance and inclusion of radiation pattern and direction and velocity of propagating dislocation, could reduce scatter. Note, however, that such parameters could be difficult to predict *a priori* and hence may be desirable to use equations no more detailed than those proposed so that empirical models do not imply smaller uncertainties than those associated with the input parameters.
- Plot fraction of data points, $p_a$ which are smaller than spectral amplitude predicted for $p$ values between 0.1 and 0.9. Find relationship between $p_a$ and $p$. Note that response spectral amplitudes should be nearly Rayleigh distributed, hence $p_a(T) = \{1 - \exp[-\exp(\alpha(T)p + \beta(T)]\}^{N(T)}$. Find $\alpha$, $\beta$ and $N$ by regression and smoothed by eye. $N(T)$ should correspond to the number of peaks of the response of a single-degree-of-freedom system with period $T$ but best-fit values are smaller than the value of $N(T)$ derived from independent considerations.

## 4.5 Faccioli (1978)

- See Section 2.23.
- Response parameter is pseudo-velocity for 5% damping.
- Plots all spectra. 2 records have abnormally high values in long period range, so remove and repeat. Results practically unaffected so leave them in.
- Notes that due to small size of sample, site and source correlation can introduce some error in coefficients because all data treated as statistically independent. Assume correlations are small so neglect error.

## 4.6 McGuire (1978a)

- See Section 2.25.
- Response parameter is pseudo-velocity for 2% damping.

## 4.7 Trifunac (1978) & Trifunac and Anderson (1978a)

- Ground-motion model is (from definition of local magnitude scale):

$$\begin{aligned}\log[\mathrm{PSV}(T)_{,p}] &= M + \log A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v \\ &\quad - f(T)M^2 - g(T)R\end{aligned}$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of $M_L$, $p$ is confidence level and $v$ is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses three site categories:

$s = 0$ Alluvium. 63% of data.

$s = 1$ Intermediate. 23% of data. Notes that ideally would not need but had to be introduced because in some cases difficult to make a choice in complex geological environment or because of insufficient data.

$s = 2$ Basement rock. 8% of data.

- Use same data as Trifunac and Anderson (1977). See Section 4.4.
- Use same regression method as Trifunac and Anderson (1977). See Section 4.4.
- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace $M$ by $M_{\max}$ everywhere and for $M < M_{\min}$ replace $M$ by $M_{\min}$ in $b(T)M$ and $f(T)M^2$. This gives linear growth for $M < M_{\min}$, parabolic growth for $M_{\min} \leq M \leq M_{\max}$ and constant amplitude for $M > M_{\max}$.
- 98 records from San Fernando earthquake (9/2/1971) but regression method eliminated 70% of these before computing the coefficients.
- Epicentral distance used for simplicity, consistency with earlier studies and for lack of significantly better choice. Distance measure chosen has small effect whenever epicentral distance greater than several source dimensions.
- Notes that recording and processing noise in signal means that quality of coefficients diminishes for $T > 2$ s. Equations not recommended for periods longer than those for which selected spectral amplitudes plotted.
- Notes that equations should be considered only as preliminary and an empirical approximation to a complicated physical problem.
- Notes that data are limited to narrow magnitude interval, most data comes from alluvium sites and about half comes from one earthquake.
- Only gives coefficients for 11 periods. Graphs of coefficients for other periods.

## 4.8 Trifunac and Anderson (1978b)

- Ground-motion model is (from definition of local magnitude scale):

$$\begin{aligned}\log[\mathrm{PSV}(T)_{,p}] &= M + \log A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v \\ &\quad - f(T)M^2 - g(T)R\end{aligned}$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of $M_L$, $p$ is confidence level and $v$ is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Response parameter is velocity for 0, 2, 5, 10 and 20% damping.

- Uses three site categories:

$s = 0$ Alluvium. 63% of data.

$s = 1$ Intermediate. 23% of data. Notes that ideally would not need but had to be introduced because in some cases difficult to make a choice in complex geological environment or because of insufficient data.

$s = 2$ Basement rock. 8% of data.

- Use same data as Trifunac and Anderson (1977). See Section 4.4.

- Use same regression method as Trifunac and Anderson (1977). See Section 4.4.

- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace $M$ by $M_{\max}$ everywhere and for $M < M_{\min}$ replace $M$ by $M_{\min}$ in $b(T)M$ and $f(T)M^2$. This gives linear growth for $M < M_{\min}$, parabolic growth for $M_{\min} \leq M \leq M_{\max}$ and constant amplitude for $M > M_{\max}$.

- Only gives coefficients for 11 periods. Graphs of coefficients for other periods.

## 4.9 Cornell et al. (1979)

- See Section 2.27.

- Response parameter is pseudo-velocity for 0, 2 and 10% damping.

- Consider different paths, e.g. going through intensities, Fourier spectra and PGA, to predict PSV. Note that direct paths have minimum variance but that going through intermediate steps does not significantly increase prediction uncertainty provided that intermediate parameters are representative of frequency band of structural system.

- Do not give coefficients.

## 4.10 Faccioli and Agalbato (1979)

- See Section 2.29.

- Response parameter is pseudo-velocity for 5% damping.

## 4.11 Trifunac and Lee (1979)

- Ground-motion model is:

$$\log_{10} \mathrm{PSV}(T) = M + \log_{10} A_0(R) - b(T)M - c(T) - d(T)h - e(T)v - f(T)M^2 - g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of $M_L$ and $v$ is component direction ($v = 0$ for horizontal 1 for vertical).

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Use depth of sedimentary deposits, $h$, to characterise local geology.
- Depths of sedimentary and alluvial deposits at stations used are between 0 and about 6 km and most are less than about 4 km.
- Use data and regression technique of Trifunac and Anderson (1977), see Section 4.4.
- Note no obvious physical reason why dependence of PSV on $h$ should be linear. Try including terms with $h^2$, $h^3$ and higher powers of $h$ but they lead to values which are undistinguishable from zero at 95% confidence level.
- Approximate significance tests show that coefficients are significantly different from zero in large subregions of the complete period range.
- Only give coefficients for 11 periods. Graphs of coefficients for other periods.
- Note results are only preliminary.
- Note amount of data too small to include more sophisticated independent parameters.

## 4.12 Ohsaki et al. (1980a)

- Ground-motion model is:

$$\log S_v = a'M - b' \log x - c'$$

- Response parameter is velocity for 5% damping.
- Use two soil conditions:

Group A Hard rock: geology consists of granite, andesite and shale of Miocene or earlier geological age, having S wave velocity $\gtrsim 1500$ m/s or P wave velocity $\gtrsim 3000$ m/s, 60 records

Group B Rather soft rock: geology consists of mudstone of Pliocene or late Miocene age, having S wave velocity of about 500–1000 m/s, 35 records.

- Use records where geological and geotechnical conditions investigated in detail and considered to represent free-field rock motions. Exclude records suspected to be amplified by surface soil or affected by high topographical relief.
- Most records from $\geq 30$ km.
- Do regression on both site categories separately and give graphs of coefficients not tables.

## 4.13 Ohsaki et al. (1980b)

- See Section 2.34.
- Response parameter is velocity for 5% damping.
- Also give smoothed results using correction factors based on derived PGV equation.

## 4.14 Trifunac (1980)

- Ground-motion model is:

$$\log_{10} \mathrm{PSV}(T) = \begin{cases} M - \log_{10} A_0(R) - b(T)M_{\min} - c(T) - d(T)h - e(T)v \\ \quad - f(T)M_{\min}^2 - g(T)R \\ \quad \text{for} \quad M \leq M_{\min} \\ M - \log_{10} A_0(R) - b(T)M - c(T) - d(T)h - e(T)v \\ \quad - f(T)M^2 - g(T)R \\ \quad \text{for} \quad M_{\min} < M < M_{\max} \\ M_{\max} - \log_{10} A_0(R) - b(T)M_{\max} - c(T) - d(T)h - e(T)v \\ \quad - f(T)M_{\max}^2 - g(T)R \\ \quad \text{for} \quad M \geq M_{\max} \end{cases}$$

  where $\log_{10} A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of $M_L$, $v$ is component direction ($v = 0$ for horizontal and 1 for vertical), $M_{\min} = -b(T)/(2f(T))$ and $M_{\max} = (1 - b(T))/(2f(T))$.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Characterises site condition by depth of sedimentary and alluvial deposits beneath station, $h$. Uses records with $0 \leq h \leq 6$ km, with most $< 4$ km.
- Performs analysis to minimize possible bias due to uneven distribution of data among magnitude, site conditions and from abundance of data for some earthquakes.
- Tries terms with higher powers of $h$ but coefficients are undistinguishable from zero at 95% confidence level.
- Assumes probability that $\log_{10} \mathrm{PSV}(T) - \log_{10} \bar{\mathrm{PSV}}(T) \leq \epsilon$, where $\log_{10} \mathrm{PSV}(T)$ is measured PSV and $\bar{\mathrm{PSV}}(T)$ is predicted PSV and $\epsilon$ is a probability, can be expressed as $p(\epsilon, T) = [1 - \exp(-\exp(\alpha(T)\epsilon(T) + \beta(T)))]^{N(T)}$. This assumption passes Kolmogorov-Smirnov and $\chi^2$ tests at 95% level.
- Finds $a(T)$ through $g(T)$ significantly different than zero for large subregions of whole period range. $d(T)$ is only significantly different than zero for $T \gtrsim 0.3$ s.
- Gives coefficients of smoothed results for 11 periods.
- Notes only preliminary. Improvements should be based on physical nature of phenomenon using a functional form predicted by theory and experiment but due to lack of data cannot be done.

## 4.15 Devillers and Mohammadioun (1981)

- Ground-motion model is:

$$V(f) = C 10^{\alpha M} R^n$$

- Response parameter is pseudo-velocity for 2, 5, 10 and 20% damping.
- Most records from between 20 and 40 km. No records from $R < 10$ km so equation does not apply there.
- Eliminate suspect and/or redundant (San Fernando) records.
- Split data into intensity groups: VI (126 records), VII (56 records), V+VI (186 records), VI+VII (182 records) and VII+$\geq$ VIII (70 records) and calculates coefficients for each group.
- Note not adjusted for local site conditions. Try to distinguish effect but correlations do not reveal significant variations. Notes very few records on hard rock.
- Do not give coefficients only graphs of results.

## 4.16 Joyner and Boore (1982a)

- Ground-motion model is:

$$\begin{aligned}\log y &= \alpha + \beta M_p \log r + br + cS \\ r &= (d^2 + h^2)^{1/2}\end{aligned}$$

- Response parameter is pseudo-velocity for 5% damping.
- Use two site classes:

Rock $S = 1$

Soil $S = 0$

- Test magnitude dependence of $h$ by selecting data from $< 10$ km and plot residuals against $M$. Do not find any systematic relationship so conclude that data does not support a magnitude-dependent shape.
- Smooth coefficients using unspecified method.
- No data from rock sites with $d < 8$ km and $M > 6$ so suggest caution in applying equations for rock sites at shorter distances and larger magnitudes. Also suggest caution in applying equations for $d < 25$ km and $M > 6.6$ for either soil or rock because no data in this range. Also do not recommend equations for $M > 7.7$.

## 4.17 Joyner and Boore (1982b)

- See Section 2.41.
- Response parameter is pseudo-velocity for 5% damping.
- Use same data and method as Joyner and Boore (1982a).
- Restrict regressions to $T \leq 4$ s to avoid problems due to record-processing errors.
- Find that coefficient for quadratic term is not statistically significant at 90% level for most periods but the values obtained at different periods are sufficiently consistent to warrant inclusion of this term. Note that maximum difference with and without quadratic term is about 20%.
- Include soil term at short periods even though not significant at 90% level.
- Smooth coefficients by plotting them against $\log T$ and drawing smooth curves.

## 4.18 Kobayashi and Midorikawa (1982)

- Ground-motion model is:

$$\begin{aligned}
\log \mathrm{Sv}_0(T) &= a(T)(\log M_0 - c) - b(T)\log X + d \\
\text{where } a(T) &= a_1 + a_2 \log T \\
\text{and: } b(T)) &= \begin{cases} b_1(\log T)^2 + b_2 \log T + b_3 & \text{for: } \quad 0.1 \le T \le 0.3\,\mathrm{s} \\ b_4 - b_5 \log T & \text{for: } \quad 0.3 \le T \le 5\,\mathrm{s} \end{cases}
\end{aligned}$$

- Response parameter is velocity for 5% damping.
- Magnitudes converted to seismic moment, $M_0$, by using empirical formula.
- Observed surface spectra divided by amplification over bedrock (assumed to have shear-wave velocity of 3 km/s), calculated for each of the 9 sites.
- Note equation not for near field because earthquake is not a point source.

## 4.19 Joyner and Fumal (1984), Joyner and Fumal (1985) & Joyner and Boore (1988)

- See Section 2.46.
- Use data from Joyner and Boore (1982b).
- Response parameter is pseudo-velocity for 5% damping.
- shear-wave velocity not significant, at 90%, for periods 0.1, 0.15 and 0.2 s but significant for longer periods.
- Regression using shear-wave velocity and depth to rock shows significant correlation (decreasing ground motion with increasing depth) for long periods but small coefficients. Short periods do not show significant correlation.
- State inappropriate to use depth to rock for present data due to limited correlation and because San Fernando data is analysed on its own does not show significant correlation.

## 4.20 Kawashima et al. (1984)

- See Section 2.47.
- Response parameter is acceleration for 5% damping.

## 4.21 Kawashima et al. (1985)

- See section 2.52.
- Response parameter is acceleration for 5% damping.
- Variation of $a$ and $b$ with respect to $T$ is due to insufficient number of records.

## 4.22 Trifunac and Lee (1985b)

- Ground-motion models are (if define site in terms of local geological site classification):

$$\log \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + b_3(T)v + b_5(T) + b_6(T)M^2$$

  or (if define site in terms of depth of sediment):

$$\log \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)h + b_3(T)v + b_5(T) + b_6(T)M^2$$

  where

$$\begin{aligned}
\mathrm{Att}(\Delta, M, T) &= \begin{cases} A_0(T)\log_{10}\Delta & \text{for} \quad R \leq R_{\max} \\ A_0(T)\log_{10}\Delta_{\max} - (R - R_{\max})/200 & \text{for} \quad R > R_{\max} \end{cases} \\
\Delta &= S\left(\ln \frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2}\right)^{-1/2} \\
\Delta_{\max} &= \Delta(R_{\max}, H, S) \\
R_{\max} &= \frac{1}{2}(-\beta + \sqrt{\beta^2 - 4H^2})
\end{aligned}$$

  $S_0 = S_0(T)$ represents the coherence radius of the source and can be approximated by $S_0 \sim C_s T/2$, $C_s$ is shear-wave velocity in source region (taken to be 1 km/s), $T$ is period, $S$ is 'source dimension' approximated by $S = 0.2$ for $M < 3$ and $S = -25.34 + 8.151M$ for $3 \leq M \leq 7.25$ and $v$ is component direction ($v = 0$ for horizontal 1 for vertical).

- Use two types of site parameter:
  - Local geological site classification:
    $s = 0$ Sites on sediments.
    $s = 1$ Intermediate sites.
    $s = 2$ Sites on basement rock.
  - Depth of sediments from surface to geological basement rock beneath site, $h$.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.

- Equations only apply in range $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_1(T)/(2b_6(T))$ and $M_{\max} = -(1 + b_1(T))/(2b_6(T))$. For $M < M_{\min}$ use $M$ only in first term of equation and $M_{\min}$ elsewhere and for $M > M_{\max}$ using $M_{\max}$ everywhere.

- Screen data to minimize possible bias in the model, which could result from uneven distribution of data among the different magnitude ranges and site conditions, or from excessive contribution to the database from several abundantly recorded earthquakes.

- Originally include a term linear in $\Delta$, i.e. $b_4(T)\Delta/100$, but find that $b_4(T)$ is insignificant for most periods so deleted it.

- Use method of Trifunac and Anderson (1977) for residuals, see Section 4.4.

## 4.23 Kamiyama and Yanagisawa (1986)

- Ground-motion model is:

$$\log_{10} V(T) = a(T)M_J - b(T)\log_{10}(\Delta + 30) - d(T)D - c(T) + A_1(T)S_1 + \ldots + A_{N-1}(T)S_{N-1}$$

  where $S_i = 1$ for $i$th site and 0 otherwise.

- Response parameters are acceleration, velocity and displacement for 0, 2, 5 and 10% damping
- Model site amplification of each of the 26 sites individually by using $S_i$. Choose one site as bed rock site, which has S-wave velocity of about 1000 m/s.
- Use records with PGA> 20gal ($0.2\,\mathrm{m/s^2}$).
- Focal depths, $D$, between 0 and 130 km, with most between 10 and 50 km.
- Find no significant differences between site amplification spectra for different response parameters or different damping levels.
- Compare amplification spectra from regression for different sites with those predicted using S-wave theory and find good agreement.
- Coefficients only given for velocity for 5% damping.

## 4.24 C.B. Crouse (1987) reported in Joyner and Boore (1988)

- See Section 2.58.
- Response parameter is pseudo-velocity for 5% damping.

## 4.25 Lee (1987) & Lee (1993)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10}[\widehat{\mathrm{PSV}}(T)] &= M_< + \mathrm{Att}(\Delta, M, T) + \hat{b}_1(T)M_{<>} + \hat{b}_2(T)h + \hat{b}_3(T)v \\
&\quad + \hat{b}_4(T)hv + \hat{b}_5(T) + \hat{b}_6(T)M_{<>}^2 + \hat{b}_7^{(1)}(T)S_L^{(1)} + \hat{b}_7^{(2)}(T)S_L^{(2)} \\
\text{where } M_< &= \min(M, M_{\max}) \\
M_{<>} &= \max(M_{\min}, M_<) \\
M_{\min} &= -\hat{b}_1/(2\hat{b}_6(T)) \\
M_{\max} &= -(1+\hat{b}_1(T))/(2\hat{b}_6(T))
\end{aligned}
$$

where $v = 0$ for horizontal component, 1 for vertical, $h$ is depth of sedimentary deposits beneath recording station and $\mathrm{Att}(\Delta, M, T)$ is same as Trifunac and Lee (1989) (see Section 4.35).

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses three site categories:

$S_L = 0$ Rock: 1 sediment site ($h > 0$), 11 intermediate sites ($h \sim 0$) and 13 bedrock sites ($h = 0$) $\Rightarrow S_L^{(1)} = 0$ & $S_L^{(2)} = 0$.

$S_L = 1$ Stiff soil ($\leq 45 - 60$ m deep): 37 sediment sites ($h > 0$), 24 intermediate sites ($h \sim 0$) and 3 bedrock sites ($h = 0$) $\Rightarrow S_L^{(1)} = 1$ & $S_L^{(2)} = 0$.

$S_L = 2$ Deep soil: 44 sediment sites ($h > 0$) and 2 intermediate sites ($h \sim 0$) $\Rightarrow S_L^{(1)} = 0$ & $S_L^{(2)} = 1$.

- For $M > 6.5$ uses different (unspecified) magnitude scales because for seismic risk analysis often catalogues do not specify scale and often estimates are not homogeneous.
- Free-field records with both soil and alluvial depth information.

- Screens data to minimize possible bias due to uneven distribution of soil classification or excessive contribution from several abundantly recorded earthquakes.
- Gives smoothed coefficients for 12 periods.
- Uses method of Trifunac (1980) for uncertainties.
- Also uses method where site coefficients, $\hat{b}_7^{(1)}$ & $\hat{b}_7^{(2)}$, are found from residues from equation without site coefficients; find similar results.

## 4.26 K. Sadigh (1987) reported in Joyner and Boore (1988)

- See Section 2.61.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.27 Annaka and Nozawa (1988)

- See Section 2.64.
- Response parameter is acceleration for 5% damping.
- Give only graphs of coefficients.

## 4.28 Crouse et al. (1988)

- Ground-motion model is:
$$\ln[\mathrm{PSV}(T)] = a + bM + c\ln[R] + dh$$
- Most data from shallow stiff soil and sedimentary deposits between about 5 and 25 m deep on Tertiary or older bedrock.
- Response parameter is pseudo-velocity for 5% damping.
- All earthquakes from Benioff-Wadati zones.
- Exclude data with magnitudes or distances well outside range of most selected records.
- Focal depths, $h$ between 14 and 130 km.
- No strong correlations between $h$, $R$ and $M$.
- Try terms $eM^2$ and $fR$ but find not significant (using t-test).
- Try term $R + C_1 \exp(C_2 M)$ instead of $R$; find similar standard errors.
- Find $d$ is insignificant for 0.6 to 2 s; find $d$ does not significantly reduce standard errors.
- Find residuals are normally distributed (by plotting on normal probability paper and by Kolmogorov-Smirnov test).
- Split data by fault mechanism (thrust: 49 records, normal: 11 records, strike-slip: 4 records) and find attenuation equation for each subset; results are not significantly different (at 95% using F test). Also check by examining normal deviates (normalised residuals) for each subset and period; find no significant differences.

- Use 131 records from six other subduction zones (Nankai, Kuril, Alaska, Peru/N. Chile, Mexico and New Britain/Bougainville) to examine whether ground motions from all subduction zones are similar.
- Examine normal deviates for residuals between other zones' ground motion and N. Honshu equation. Find no significant differences (although obtain significant results for some periods and focal mechanisms) between N. Honshu, Kuril and Nankai motions. Find differences for Alaskan and Mexican data but could be due to site effects (because some data from soft soil sites). Find differences for Peru/N. Chile and New Britain/Bougainville which are probably source effects.
- Plot seismotectonic data (age, convergence rate, dip, contact width, maximum subduction depth, maximum historical earthquake ($M_w$), maximum rupture length, stress drop and seismic slip) against decreasing ground motion at stiff sites for $T > 0.8$ s. Find weak correlations for stress drop and $M_w$ (if ignore Mexican data) but due to variability in stress drop estimates note lack of confidence in results.

## 4.29 Petrovski and Marcellini (1988)

- See Section 2.68.
- Response parameter is relative pseudo-velocity for 0.5%, 2%, 5% and 10% damping.

## 4.30 PML (1988)

- See Section 2.69.
- Response parameter is pseudo-velocity for 5% damping.
- Plot residuals w.r.t. $R$ for 0.1 s. Confirm (using a 20% significance level) using Kolmogorov-Smirnov test that residuals are drawn from a lognormal distribution. Note that the normal distribution may not explain the tails of the data but insufficient data to test these.

## 4.31 Yokota et al. (1988)

- Ground-motion model is:
$$\log S_v(T) = a(T)M + b(T)\log X + c(T)$$
- Response parameter is velocity for 5% damping.
- Focal depths between about 20 and 100 km.
- Records from two stations in lowlands of Tokyo 3.7 km apart.
- Also analyse another region, using 26 records from 17 earthquakes with distances between 95 and 216 km. Note difference in results between regions.
- Analyses vertical spectra from three small regions separately, one with 24 records with $4.0 \leq M \leq 6.1$ and $60 \leq X \leq 100$ km, one with 22 records with $4.2 \leq M \leq 6.0$ and $68 \leq X \leq 99$ km and one with 5 records with $4.4 \leq M \leq 6.0$ and $59 \leq X \leq 82$ km.
- Give no coefficients, only results.

## 4.32 Youngs et al. (1988)

- See Section 2.72.
- Ground-motion model is:

$$\ln(S_v/a_{\max}) = C_6 + C_7(C_8 - M_w)^{C_9}$$

- Response parameter, $S_v$, is velocity[2] for 5% damping
- Develop relationships for ratio $S_v/a_{\max}$ because there is a much more data for PGA than spectral ordinates and use of ratio results in relationships that are consistent over full range of magnitudes and distances.
- Calculate median spectral shapes from all records with $7.8 \leq M_w \leq 8.1$ (choose this because abundant data) and $R < 150$ km and one for $R > 150$ km. Find significant difference in spectral shape for two distance ranges. Since interest is in near-field ground motion use smoothed $R < 150$ km spectral shape. Plot ratios $[S_v/a_{\max}(M_w)]/[S_v/a_{\max}(M_w = 8)]$ against magnitude. Fit equation given above, fixing $C_8 = 10$ (for complete saturation at $M_w = 10$) and $C_9 = 3$ (average value obtained for periods $> 1$ s). Fit $C_7$ by a linear function of $\ln T$ and then fix $C_6$ to yield calculated spectral amplifications for $M_w = 8$.
- Calculate standard deviation using residuals of all response spectra and conclude standard deviation is governed by equation derived for PGA.

## 4.33 Kamiyama (1989)

- Ground-motion model is:

$$\log_{10} V(\omega) = \log_{10} M_0 - a(\omega)\log_{10} r + b(\omega)\log_{10} L + e(\omega)r + c(\omega) + \sum_{j=1}^{N-1} A_j(\omega)S_j$$

  where $S_j = 1$ for site $j$ and $S_j = 0$ otherwise.

- Response parameter is velocity for 0% damping.
- Uses same data as Kamiyama and Yanagisawa (1986).
- Uses same regression method as Kamiyama and Yanagisawa (1986).
- Focal depths between 0 and 130 km.
- Uses fault length, $L$, for 52 records. For others where such data does not exist uses $M_0 = 10^{(1.5\log_{10} S + 22.3)}$, $S = 10^{M-4.07}$ and $L = \sqrt{S/2}$ where $S$ is fault area in km$^2$.
- Chooses hard slate site with shear-wave velocity of 1–2 km/s as 'basic site'.
- Does not give coefficients, only graphs of coefficients.

## 4.34 Sewell (1989)

- Ground-motion model is:

$$\begin{aligned} \ln y &= \alpha + \beta M - \ln r - qr + cS \\ \text{where} \quad r &= \sqrt{d^2 + h^2} \end{aligned}$$

[2]In paper conversion is made between $S_v$ and spectral acceleration, $S_a$, suggesting that it is pseudo-velocity.

- Use 2 site classes:

$S = 0$ Rock

$S = 1$ Soil

- Response parameter is acceleration for 5% damping. Also derives models for various nonlinear response parameters.
- Uses similar data to Joyner and Boore (1981) and Campbell (1981).
- Notes data reasonably well distributed except for lack of data for $M_w > 7$, $r_{jb} < 10$ km and small earthquakes at long distances. Notes that model most reliable for small-to-moderate earthquakes at moderate-to-large distances, where data is densest.
- Compares observations (grouped by magnitude ranges) and predictions against distance.

## 4.35 Trifunac and Lee (1989)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10}[\mathrm{PSV}(T)] &= M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)h + b_3(T)v + b_5(T) \\
&\quad + b_6(T)M^2 \\
\text{where } \mathrm{Att}(\Delta, M, T) &= A_0(T)\log_{10}\Delta \\
A_0(T) &= \begin{cases} -0.732025 \quad \text{for:} \quad T > 1.8\,\mathrm{s} \\ -0.767093 + 0.271556\log_{10}T - 0.525641(\log_{10}T)^2 \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{for:} \quad T < 1.8\,\mathrm{s} \end{cases} \\
\Delta &= S\left(\ln\frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2}\right)^{-1/2} \\
S &= 0.2 + 8.51(M - 5)
\end{aligned}
$$

  where $v = 0$ for horizontal component and 1 for vertical, $\Delta$ is representative distance, $S_0$ is correlation radius of source function (or coherence size of source) (which can be approximated by $C_sT/2$, where $C_s$ is shear wave velocity), $h$ is depth of sedimentary deposits beneath recording station and $H$ is focal depth.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Screen data to minimize possible bias due to uneven distribution of data among different magnitude ranges and site conditions or from excessive contribution to database from several abundantly recorded earthquakes.
- Include term, $b_4(T)\Delta/100$, but insignificant for most periods so remove.
- Equation only applies for $M_{\min} \leq M \leq M_{\max}$, where $M_{\min} = -b_1(T)/(2b_6(T))$ and $M_{\max} = -(1 + b_1(T))/(2b_6(T))$. For $M \leq M_{\min}$ use $M_{\min}$ everywhere except first term. For $M \geq M_{\max}$ use $M_{\max}$ everywhere.
- Use method of Trifunac (1980) for uncertainties.
- Note estimates should only be used where signal to noise ratio (based on estimated digitisation noise) not much less than unity or slope in log-log scale is not significantly greater than $-1$.
- Also fit data to $\log_{10}\mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + b_3(T)v + b_5(T) + b_6(T)M^2$ (where $s = 0$ for sediment sites, 1 for intermediate sites and 2 for basement rock sites) because depth of sediment not always known.

## 4.36 Atkinson (1990)

- Ground-motion model is:

$$\log y = c_1 + c_2(\mathbf{M} - 6) + c_3(\mathbf{M} - 6)^2 - \log R - c_4 R$$

- Response parameter is pseudo-velocity for 5% damping.
- All data from rock sites.
- Includes only if a reliable seismic moment estimate exists.
- Converts ECTN vertical seismograms to equivalent horizontal component by multiplying by 1.4.
- Includes Nahanni (western Canada) earthquakes because exhibit dominant characteristics of eastern North American shocks (low seismicity area, high horizontal compressive stress, thrust mechanisms dominant, no surface ruptures despite shallow focus and rocks have high seismic velocity).
- Excludes US digital strong-motion Saguenay records due to low resolution. Two effects on response spectra: i) high frequencies contaminated by a 'mathematical noise' floor, ii) significant errors in amplitudes of low to intermediate frequencies (severity dependent on resolution degree). Inclusion of such data could lead to significant misinterpretation of these earthquakes.
- Most records (66, 65%) from $R \geq 111$ km and $\mathbf{M} \leq 5.22$.
- Examines residuals from equations. Finds no persistent trends except for Saguenay data ($\mathbf{M} = 6$) between $63 \leq R \leq 158$ km.
- Notes data very limited in large magnitude range and that one or two earthquakes are controlling predictions.
- Notes different regression technique could change predictions for large magnitudes but i) data too limited to warrant more sophisticated analysis and ii) may be other factors, in addition to number of recordings, which should be considered in weighting each earthquake.

## 4.37 Campbell (1990)

- See Section 2.79.
- Response parameter is pseudo-velocity for 5% damping.

## 4.38 Dahle et al. (1990b) & Dahle et al. (1990a)

- See Section 2.80.
- Response parameter is pseudo-velocity for 5% damping.
- Coefficients only given for 7 periods; graphs for others.

## 4.39 Tamura et al. (1990)

- Ground-motion model is:

$$S_A(T_i, \mathrm{GC}) = a(T_i, \mathrm{GC})10^{b(T_i,\mathrm{GC})M}(\Delta + 30)^{C(T_i,\mathrm{GC})}$$

- Response parameter is acceleration for 2 and 5% damping.

- Use three site categories (GC) for which perform separate regression:

Group 1 Ground characteristic index $\lesssim 0.67$, 29 records.

Group 2 Ground characteristic index between about 0.67 and 1.50, 46 records.

Group 3 Ground characteristic index $\gtrsim 1.50$, 22 records.

  where the ground characteristic index is calculated from statistical analysis of amplitude of records. Thought to reflect the characteristic of deep soil deposits at site (1.0 means amplification is average for Japan, $< 1.0$ or $> 1.0$ means amplification is lower or greater, respectively, than average for Japan).

- Records from JMA low-magnification mechanical seismographs (natural period 6 s, damping ratio 0.55) which were instrument corrected (because sensitivity for periods $> 10$ s is substantially suppressed) , filtered (cut-offs 1.3–2 s and 20–30 s chosen from a study of recording accuracy of instruments) and differentiated in frequency domain to find ground velocity and acceleration. Hence limit analysis to 2 to 20 s.

- Do not use resultant of two horizontal components because two components not synchronous.

- Find difference in predicted ground motion using derived equations and those from earlier equations for short periods. Find that $b$ for earlier equations increases almost linearly with logarithm of natural period, $T$, so find equation, by least squares, connecting $b$ and $\log T$. Assume this equation holds for 2 to 20 s and so fix $b$ and recalculate $a$ and $c$; find predictions now agree.

- Only give graphs for original coefficients for 5% damping. Give tables of coefficients for preferred second analysis.

## 4.40 Tsai et al. (1990)

- See Section 2.84.

- Response parameter is acceleration for 5% damping.

- Also give equations for average acceleration for 2 period bands 0.12–0.33 s and 0.07–0.2 s.

## 4.41 Crouse (1991)

- See Section 2.86.

- Response parameter is pseudo-velocity for 5% damping.

- Focal depths, $h$, between 10 and 238 km.

- Notes that spectral database is biased to higher ground motions (because only higher ground motions are digitised). Suggest either using a different form of equation or impose constraints. Do not do either because (1) consider sample adequate for regression and (2) although overestimate smaller, more distant motion, it would properly estimate larger motions which are of greater concern for design applications.

- Sets $p_3$, $p_5$ and $p_6$ to those for PGA equation after trial regressions; does not appreciably affect standard deviation.
- Finds relatively larger standard deviation for 3.0 and 4.0 s which suggests form of equation may be inappropriate for longer periods.
- Plots normalised residuals (not shown) which show uniform distribution.

## 4.42 Dahle et al. (1991)

- Ground-motion model is:

$$
\begin{aligned}
\ln A &= c_1 + c_2 M + c_4 R + \ln G(R, R_0) \\
\text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \leq R_0 \\
\text{and: } G(R, R_0) &= R_0^{-1} \left(\frac{R_0}{R}\right)^{5/6} \quad \text{for} \quad R > R_0
\end{aligned}
$$

  this equation assumes spherical spreading (S waves) to $R_0$ and cylindrical spreading with dispersion (Lg waves) for larger distances.
- Response parameter is pseudo-velocity for 5% damping.
- All data from solid rock sites.
- Follow-on study to Dahle et al. (1990b) and Dahle et al. (1990a) but remove Chinese and Friuli data and data from border zone of Eurasian plate, so data is a more genuine intraplate set.
- Use 395 records from Norwegian digital seismograms. Require that the Lg displacement amplitude spectra should have a signal-to-noise ratio of a least 4 in the frequency range 1–10 Hz, when compared to the noise window preceding the P-wave arrival.
- For the selected seismograms the following procedure was followed. Select an Lg window, starting at a manually picked arrival time and with a length that corresponds to a group velocity window between 2.6 and 3.6 km/s. Apply a cosine tapering bringing the signal level down to zero over a length corresponding to 5% of the data window. Compute a Fast Fourier Transform (FFT). Correct for instrument response to obtain true ground motion displacement spectra. Bandpass filter the spectra to avoid unreasonable amplification of spectral estimates outside the main response of the instruments. Passband was between 0.8 Hz and 15 or 20 Hz, dependent on sampling rate. The amplitude spectra obtained using the direct method, using $A = \Delta t \sqrt{ZZ^*}$ where $\Delta t$ is time step and $Z$ is Fourier transformed time-history and $Z^*$ is its complex conjugate. Convert instrument corrected displacement Lg Fourier transforms to acceleration by double differentiation and an inverse FFT.
- Use 31 accelerograms from eastern N. America, N. Europe and Australia.
- Use $R_0 = 100$ km although note that $R_0$ may be about 200 km in Norway.
- Correlation in magnitude-distance space is 0.20.
- Use a variant of the two-stage method to avoid an over-representation of the magnitude scaling terms at small magnitudes. Compute average magnitude scaling coefficients within cells of 0.2 magnitude units before the second stage.
- Resample data to make sure all the original data is used in a variant of the one-stage method. Compute new (resampled) data points as the average of one or more original points within a grid of cells 160 km by 0.4 magnitude units. Correlation in resampled magnitude-distance space is 0.10.

- Find estimated ground motions from one-stage method systematically higher than those from two-stage method particularly at short distances and large magnitudes. Effect more significant for low frequencies. Find that this is because one-stage method gives more weight to supplementary accelerograph data from near field of large earthquakes.
- Standard deviations similar for one- and two-stage equations.
- Scatter in magnitude scaling coefficients from first stage of two-stage method is greater for strong-motion data.
- Try fixing the anelastic decay coefficient ($c_4$) using a previous study's results. Find almost identical results.
- Remove 1 record from Nahanni earthquake ($M_s = 6.9$) and recompute; only a small effect.
- Remove 17 records from Saguenay earthquake ($M_s = 5.8$) and recompute; find significant effect for large magnitudes but effect within range of variation between different regression methods.

## 4.43 Geomatrix Consultants (1991), Sadigh et al. (1993) & Sadigh et al. (1997)

- See Section 2.88
- Ground-motion model for deep soil is:

$$\ln y = C_1 + C_2 M - C_3 \ln(r_{\mathrm{rup}} + C_4 \mathrm{e}^{C_5 M}) + C_6 + C_7 (8.5 - M)^{2.5}$$

  where $C_6$ is different for reverse and strike-slip earthquakes.

  Ground-motion model for rock is:

$$\ln y = C_1 + C_2 M + C_3 (8.5 - M)^{2.5} + C_4 \ln(r_{\mathrm{rup}} + \exp(C_5 + C_6 M)) + C_7 \ln(r_{\mathrm{rup}} + 2)$$

  where $C_1$ is different for reverse and strike-slip earthquakes.

  Vertical equations do not include $C_7$.
- Response parameter is acceleration for 5% damping.
- Perform analysis on spectral amplification ln(SA/PGA).
- Give smooth coefficients.
- Find standard errors to be dependent on magnitude and fit to a linear relation.

## 4.44 I.M. Idriss (1991) reported in Idriss (1993)

- See section 2.90.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.45 Loh et al. (1991)

- See Section 2.91.
- Response parameters are acceleration, velocity and displacement for 5% damping.
- Only give coefficients for acceleration for periods $\geq 0.1$ s.

## 4.46 Matuschka and Davis (1991)

- See Section 2.92.
- Response parameter is acceleration for 5% damping.

## 4.47 Mohammadioun (1991)

- Ground-motion model is:

$$\log \mathrm{PSV}(f) = k(f) + a(f)M + n(f)R$$

- Response parameter is pseudo-velocity for 5%.
- Records not baseline corrected so no equations for periods $> 2$ s.
- Does not split up data into subsets by intensity because risk of creating data populations which are not statistically significant.
- Notes that could be inconsistency with using both $r_{hypo}$ and $r_{rup}$.
- Notes that results are preliminary.
- Also analyses wide range of Californian data for 96 periods between 0.013 and 5 s split into two intensity dependent subsets: those records with site intensities VI-VII (326 records) and those with site intensities VII+ (156 records). Uses $r_{rup}$ except for Imperial Valley earthquake where uses $r_E$. Does not use include soil or other variables because poorly defined and lead to selection of records that are not statistically valid.

## 4.48 Stamatovska and Petrovski (1991)

- See Section 2.95.
- Response parameter is pseudo-velocity for 0, 0.5, 1, 2, 5, 7, 10 and 20% damping.

## 4.49 Benito et al. (1992)

- Ground-motion model is:

$$\ln \begin{array}{c}\mathrm{PSA}\\ \mathrm{PSV}\end{array} = c_1 + c_2 M + c_3 \ln(R + R_0) + c_4(R + R_0)$$

- Response parameters are pseudo-acceleration, PSA, and pseudo-velocity, PSV, for 5% damping[3].
- Use three soil conditions (revised when cross hole information was available):

$S = 0$ Hard and rock sites, 50 records.

$S = 1$ Intermediate soil, 10 records.

$S = 2$ Soft soil, 12 records.

- Use $M_L$ because most suitable for distance range of majority of records.

[3] Although coefficients should only differ by a constant because PSA = $(2\pi/T)$PSV they do not; hence response parameters are probably not those stated.

- Try including $c_5 S$ term but find low significance values for $c_5$. Repeat regression for each soil category separately. Give results when coefficient of determination $R^2 > 0.80$, standard errors $< 25\%$ and coefficients have high significance levels.
- For PSA for $S = 0$ give coefficients for all periods, for $S = 1$ give coefficients for 0.17 to 0.2 s and for $S = 2$ give coefficients for 1 to 10 s.
- Also consider Friuli records ($4.2 \leq M_L \leq 6.5$, epicentral distances between 2 and 192 km, 14 records for $S = 0$, 23 records for $S = 1$ and 16 records for $S = 2$).
- Note need to include term in model reflecting explicitly local amplification dependent on natural period of soil as well as predominant period of incident radiation to bed rock.

## 4.50 Niazi and Bozorgnia (1992)

- See Section 2.93.
- Response parameter is pseudo-velocity for 5% damping.
- For some periods (0.20 s for vertical and 0.10 and 0.111 s for horizontal) constrain $c_2$ to zero so that predicted amplitude would not decrease with increasing magnitude at zero distance. Note that does not affect uncertainty.
- Note that long period filter cutoff may be too long for records from small shocks but if a shorter period was used then information on long period spectral ordinates would be lost. Note that insufficient data for well constrained results at $M = 5$ or $M > 7$.
- Find evidence for long period noise in $d$ and in Degree of Magnitude Saturation (DMS $= -(c_2 d/b) * 100$).
- Examine median and normalized standard deviation (coefficient of variation) and find evidence for decreasing uncertainty with increasing magnitude.

## 4.51 Silva and Abrahamson (1992)

- See Section 2.101.
- Response parameter is pseudo-acceleration for 5% damping.
- Ground-motion model for PSA to PGA ratio is:

$$\ln(\mathrm{Sa}/\mathrm{pga}) = c_1 + c_3 r + c_4\{1 - \tanh[(r^{1.1} - 10)/3]\}(1 - F)$$

- Regress on ratio of PSA to PGA ratio because more stable than regression on absolute values.
- Choice of functional form guided by numerical simulations and previous empirical studies. Numerical simulations suggest that strike-slip events maybe more likely to show near-field directivity effects at long periods than dip-slip events.
- Data does not allow magnitude dependency to be reliably determined hence not modelled.
- Judge whether long period motion is realistic based on consistency of amplitudes and timing of long period energy and that of higher frequency motions. Expect that seismic ground motions have consistent phase structure at long periods whereas noise will have random phase. Examine the analytical derivative of the phase with respect to frequency and chose the upper period of reliable PSAs based on the period at which the phase derivative becomes more random.

- Only use PSAs for frequencies greater than 1.25 times the high-pass filter corner frequency and for periods less than the shortest period at which phase derivative is not well behaved. Note that these criteria tend to bias regression to larger spectral values because these will be above noise level more often than smaller motions. Do not try to correct for this bias.

- For $\geq 10$ s insufficient data to yield stable coefficients. Based on numerical simulations, find response spectra are approximately flat for $> 8$ s and $M < 7.5$ and, therefore, extend model to 20 s by assuming constant spectral displacement. Note that may not be appropriate for $M > 7.5$.

- Note that Loma Prieta is major contributor to dataset, which may explain strong distance dependency of spectral shape.

## 4.52 Tento et al. (1992)

- See Section 2.103.

- Response parameter is pseudo-velocity for 5% damping.

- Note that correction procedure significantly affects results for $T > 2$ s. Correction procedure introduces dishomogeneity and errors due to subjectivity of choice of low frequency filter limits.

## 4.53 Abrahamson and Silva (1993)

- See Section 2.105.

- Response parameter is pseudo-acceleration for 5% damping.

- Ground-motion model for PSA to PGA ratio is:

$$\begin{aligned}
\text{For } M > 6.5&: \\
\ln(\text{Sa}/\text{pga})_{soil} &= c_1 + c_2(8.5 - M)^{c_8} + c_6 r + c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1) \\
\text{For } M > 6.5&: \\
\ln(\text{Sa}/\text{pga})_{rock} &= c_3 + c_4(8.5 - M)^{c_8} + c_7 r + c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1) \\
\text{For } 6 \leq M \leq 6.5&: \\
\ln(\text{Sa}/\text{pga})_{soil} &= c_1 + c_2(8.5 - M)^{c_8} + c_6 r \\
&\quad + 2(M - 6)c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1) \\
\text{For } 6 \leq M \leq 6.5&: \\
\ln(\text{Sa}/\text{pga})_{rock} &= c_3 + c_4(8.5 - M)^{c_8} + c_7 r \\
&\quad + 2(M - 6)c_5\{1 - \tanh[(r - c_9)/c_{10}]\}(1 - F_1)
\end{aligned}$$

- Regress on ratio of PSA to PGA ratio because more stable than regression on absolute values.

- Choice of functional form guided by numerical simulations and previous empirical studies. Numerical simulations suggest that strike-slip events maybe more likely to show near-field directivity effects at long periods than dip-slip events.

- Interested in long-period motions. Apply new accelerogram processing procedure to evaluate reliable long-period range based on Fourier phase spectra. Apply high-pass filter in frequency domain and a polynomial baseline correction in time domain. Judge whether long period motion is realistic based on consistency of amplitudes and timing of long period energy and that of higher frequency motions. Expect that seismic ground motions have consistent phase structure at long periods whereas noise will have random phase. Examine the analytical derivative of the phase with respect to frequency and chose the upper period of reliable PSAs based on the period at which the phase derivative becomes more random.

- Only use PSAs for frequencies greater than 1.25 times the high-pass filter corner frequency and for periods less than the shortest period at which phase derivative is not well behaved. Note that these criteria tend to bias regression to larger spectral values because these will be above noise level more often than smaller motions. Do not try to correct for this bias.
- For $\geq 10$ s insufficient data to yield stable coefficients. Based on numerical simulations, find response spectra are approximately flat for $> 8$ s and $M < 7.5$ and, therefore, extend model to 20 s by assuming constant spectral displacement. Note that may not be appropriate for $M > 7.5$.
- Compare predictions to spectrum of Landers 1992 ($M_w$7.5) recorded at Lucerne station. Find that model overpredicts observation.

## 4.54 Boore et al. (1993) & Boore et al. (1997)

- See Section 2.106
- Response parameter is pseudo-velocity for 2, 5, 10 and 20% damping.
- Cutoff distance is lesser of distance to first digitized record triggered by S wave, distance to closest non-digitized recording, and closest distance to an operational nontriggered instrument.
- Note that can only use response spectral values between 0.1 and 2 s because of low sampling rate of older data (sometimes only 50 samples/sec) and low signal to noise ratios and filter cutoffs.
- Site categories same as in Section 2.106 but due to smaller dataset number of records in each category is less. Class A: 12 records, B: 51 records, C: 49 records.
- Smoothed coefficients using a least-squares fit of a cubic polynomial.

## 4.55 Caillot and Bard (1993)

- Ground-motion model is:
$$\ln y = \beta_1 + \beta_2 M + \beta_3 \ln \mathrm{HYPO} + \beta_4 S_1$$
- Response parameter is acceleration for 5% damping.
- Consider three site conditions but only retain two:
    1. Rock: ENEA/ENEL S0 classification $\Rightarrow S_1 = 0$, 49 records.
    2. Thin alluvium: depth of soil between 5 and 20 m,ENEA/ENEL S1 classification $\Rightarrow S_1 = 1$, 34 records.
- Selected records have $d_e < 60$ km and focal depth less than 30 km. Data selected so that mean and standard deviation of magnitude and hypocentral distance in each site category are equal, in this case 5.1 and 20 km respectively.
- All records processed using common procedure. High pass filtered with $f_l = 0.5$ Hz, instrument corrected and low pass filtered with $f_h = 30$ Hz.
- Considered three things when choosing method of analysis:

1. Attenuation equation must have some physical basis.
2. Parameters must be available for original data set.
3. Attenuation equation must be easy to use in a predictive manner.

- Hypocentral distance used because rupture not known for most earthquakes. Note that only important for magnitudes greater than about 6.5 and distances less than about 15 km.
- Originally included another set of data (32 records) from thick soil with depth greater than about 20 m (ENEA/ENEL classification S2) but note that results for this category are much more uncertain, possibly due to diversity of geotechnical characteristics of soils. Therefore excluded.
- Regression was done using two-stage algorithm (Joyner and Boore, 1981) and a weighted one-stage method. Weight by splitting the magnitude and distance ranges into four intervals and weighting data in each interval inversely proportionally to number of points in the bin. Thus gives roughly equal weight to each part of magnitude-distance space.
- Note that results from two-stage regression for this set of data may be misleading because for some periods it does not bring any 'explanation' to the variance of initial data. The two-stage and normal one-stage and weighted one-stage yield significant changes in predictions.
- Repeat analysis using only S0 subset and using only S1 subset but no significant changes in magnitude or distance scaling between the two subsets so consider complete set and include a constant scaling between rock and shallow soil. If set is reduced to 53 records with similar spread of magnitude, distance and sites then difference between shallow soil and rock is not significant.
- Note that confidence interval should be given by formula in Weisburg (1985) not normal way of simply using standard deviation.

## 4.56 Campbell (1993)

- See Section 2.107.
- Response parameter is pseudo-acceleration for 5% damping.
- Notes that equation can predict smaller pseudo-acceleration than PGA for short periods, which is impossible in practice. Hence pseudo-acceleration for periods $\leq 0.2$ s should be constrained to be $\geq$ PGA.

## 4.57 Electric Power Research Institute (1993a)

- Ground-motion model is:

$$\ln[y(f)] = C_1 + C_2(M-6) + C_3(M-6)^2 + C_4 \ln(R) + C_5 R + C_6 Z_{SS} + C_7 Z_{IS} + C_8 Z_{DS}$$

- Response parameter is acceleration for 5% damping.
- Use three site classes

SS Shallow soil (depth to rock < 20 m). $Z_{SS} = 1$, $Z_{IS} = 0$ and $Z_{DS} = 0$.

IS Intermediate soil (depth to rock between 20 and 100 m). Very limited data. $Z_{IS} = 1$, $Z_{SS} = 0$ and $Z_{DS} = 0$.

DS Deep soil (depth to rock more than 100 m). $Z_{DS} = 1$, $Z_{SS} = 0$ and $Z_{IS} = 0$.

Cannot also examine effect of rock type (hard crystalline; hard sedimentary; softer, weathered; soft over hard) because of lack of data from non-crystalline sites in SS and IS classes.

- Collect all data from strong-motion instruments in eastern North America (ENA) and all seismographic network data from $m_b \geq 5.0$ at $\leq 500$ km. Also include some data from Eastern Canadian Telemetered Network (ECTN).
- Most data from $M < 5$ and $> 10$ km.
- Roughly half the data from aftershocks or secondary earthquakes in sequences.
- Limit analysis to $M \geq 4$ because focus is on ground motions of engineering interest.
- Use geometric mean to avoid having to account for correlation between two components.
- Note the large error bars on $C_3$, $C_5$ shows that data does not provide tight constraints on magnitude scaling and attenuation parameters.
- Do not provide actual coefficients only graphs of coefficients and their error bars.
- Find smaller inter-event standard deviations when using $m_{Lg}$ than when using $M_w$.
- Examine effect on standard deviation of not including site terms. Compute the statistical significance of the reduction using the likelihood ratio test. Conclude that the hypothesis that the site terms are zero cannot be rejected at any period.
- Split data by region: the Gulf Coast (no records), the rest of ENA or a subregion of ENA that may have marginally different attenuation characteristics. Add dummy variable to account for site location in one of the two zones with data and another dummy variable for earthquake and site in different zones. Neither variable is statistically significant due to the limited and scattered data.
- Try fitting a bilinear geometric spreading term but find that the reduction in standard deviation is minimal.

## 4.58 Sun and Peng (1993)

- See section 2.115.
- Response parameter is acceleration for 5% damping.
- Coefficients not given.

## 4.59 Boore et al. (1994a), Boore et al. (1997) & Boore (2005)

- See Section 2.117
- Find no evidence for magnitude dependent uncertainty for spectral values.
- Find no evidence for amplitude dependent uncertainty for spectral values.
- Note that effect of basin-generated surface waves can have an important effect but probably not at periods between 0.1 and 2 s.

## 4.60 Climent et al. (1994)

- Inspect observed and predicted values and conclude no clear difference between upper-crustal and subduction zone ground motions. Equations are for region regardless of earthquake source type.

## 4.61 Fukushima et al. (1994) & Fukushima et al. (1995)

- See Section 2.120.
- Response parameter is pseudo-velocity for 5% damping.
- Only give graphs of coefficients.
- Note possible noise contamination, for periods $< 0.1$ s, in coefficients.

## 4.62 Lawson and Krawinkler (1994)

- See Section 2.121.
- Response parameter is acceleration for 5% damping.

## 4.63 Lee and Manić (1994) & Lee (1995)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10}\widehat{\mathrm{PSV}} &= M_< + \mathrm{Att} + b_1 M_{<>} + b_2^{(1)} S^{(1)} + b_2^{(2)} S^{(2)} + b_3 v + b_4 + b_5 M_{<>}^2 \\
&\quad + b_6^{(1)} S_L^{(1)} \\
M_< &= \min(M, M_{\max}) \\
\text{where } M_{\max} &= \frac{-(1+b_1)}{2b_5} \\
M_{<>} &= \max(M_<, M_{\min}) \\
\text{where } M_{\min} &= \frac{-b_1}{2b_5} \\
\mathrm{Att} &= \begin{cases} A_0 \log_{10}\Delta & \text{for} \quad R \leq R_0 \\ A_0 \log_{10}\Delta_0 - \frac{(R-R_0)}{200} & \text{for} \quad R > R_0 \end{cases} \\
\text{with: } A_0 &= \begin{cases} -0.761 & \text{for} \quad T \geq 1.8\,\mathrm{s} \\ -0.831 + 0.313\log_{10} T - 0.161(\log_{10} T)^2 & \text{for} \quad T < 1.8\,\mathrm{s} \end{cases} \\
\Delta &= S\left[\ln\left(\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)\right]^{-\frac{1}{2}} \\
\Delta_0 &= \Delta(R_0) \\
\text{where } R_0 &= \frac{1}{2}\left\{\frac{-200A_0(1-S_0^2/S^2)}{\ln 10} + \left[\left[\frac{200A_0(1-S_0^2/S^2)}{\ln 10}\right]^2 - 4H^2\right]\right\}
\end{aligned}
$$

where $\Delta$ is 'representative' distance, $S$ is 'size' of fault, $S_0$ is coherence radius of source and $v$ is component orientation ($v = 0$ for horizontal, $v = 1$ for vertical).

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Consider three geological site conditions:

$s = 0$ Sediment: $\Rightarrow S^{(1)} = 0, S^{(2)} = 0$, 151 records.

$s = 1$ Intermediate sites: $\Rightarrow S^{(1)} = 1, S^{(2)} = 0$, 106 records.

$s = 2$ Basement rock: $\Rightarrow S^{(1)} = 0, S^{(2)} = 1$, 54 records.

- Consider three local site categories but only retain two:

$s_L = 0$ Rock: $\Rightarrow S_L^{(1)} = 0$, 100 records.

$s_L = 1$ Stiff soil: $\Rightarrow S_L^{(1)} = 1$, 205 records.

- Cannot include those records from deep soil sites ($s_L = 2$) because only six records.
- Most earthquakes are shallow, depth $H < 25$ km.
- Most records have epicentral distances, $R < 50$ km.
- Most have magnitudes between 3 and 6.
- Only use records with high signal-to-noise ratio. Quality of records is not adequate for response spectrum calculation outside range 0.04 to 2 s.
- Analysis performed using residue 2-step method. In first step use only records from $M \geq 4.25$ to force a concave form to magnitude scaling (if all records used then find a convex parabola), $s_L$ parameter is not included. In second step find $s_L$ dependence from residuals of first stage including all magnitudes.
- Give expressions to describe distribution of residuals so that can find confidence limits, unlike normal standard deviation based method, see Trifunac (1980).
- Note difference between western USA and Yugoslavian ground motions.

## 4.64 Mohammadioun (1994a)

- Ground-motion model is:
$$\log \mathrm{SR}(f) = k(f) + \alpha(f)M + n(f)\log R$$
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses records from rock sites ($V_s \geq 750$ m/s).
- Half of records from $R < 30$ km and significant number from $R < 10$ km.
- Most (82%) records from earthquakes with $6.2 \leq M \leq 7.0$.
- Coefficients not given, only results.

## 4.65 Mohammadioun (1994b)

- Ground-motion model is:
$$\log V(f) = k(f) + \alpha(f)M + n(f)\log R$$
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Choose W. USA to make data as homogeneous as possible in terms of seismotectonic context and parameter quality.
- Notes recording site-intensities may only be average intensity values, thereby neglecting possible microzoning effects.
- Uses $M_L$ because generally available and uniformly determined. Notes may not be best choice.

- Records from free-field and typical of different intensity classes.
- Does regression for records associated with three different intensities: V (184 records, $5.5 \lesssim R \lesssim 200$ km), VI (256 records, $3 \lesssim R \lesssim 250$ km, VII (274 records, $1 \lesssim R \lesssim 150$ km) and four different intensity groups: V-VI, VI-VII, VII and more (extra 25 records, $1 \lesssim R \lesssim 100$ km) and V and less (extra 30 records, $25 \lesssim R \lesssim 350$ km.
- Graph of $\alpha(f)$ given for horizontal component for the four intensity groups and graph of $n(f)$ for vertical component for intensity VI.

## 4.66 Musson et al. (1994)

- See section 2.123.
- Response parameter is pseudo-velocity for 5% damping.
- More data because use analogue records as well.

## 4.67 Theodulidis and Papazachos (1994)

- Use same data, equation and procedure as Theodulidis and Papazachos (1992), see Section 2.104.
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Note lack of near-field data ($R < 20$ km, $M > 6.2$) to constrain $R_0$.
- Only give graphs of original coefficients but give table of smoothed (using a ($\frac{1}{4}+\frac{1}{2}+\frac{1}{4}$ running average along $\log T$) coefficients for 13 periods and all 5 damping levels.
- Note large residuals for $T > 0.5$ s due mainly to different digitising and processing procedures which significantly affect long period spectral values.
- Check histograms of residuals for 0.1, 0.3, 0.5, 1, 3 and 5 s and find similar to normal distribution.
- Note no data from $R < 30$ km for $M > 6.5$ so state caution is required for use of equations in that range. Also suggest do not use equations for $M > 7.5$ or for $R > 130$ km.
- Note may not apply for very soft soils.
- Note lack of data.

## 4.68 Dahle et al. (1995)

- See Section 2.129.
- Derive spectral attenuation relations for almost double number of periods given. Coefficients smoothed using a third degree polynomial.

## 4.69 Lee and Trifunac (1995)

- Based on Lee et al. (1995). See Section 2.130.
- Response parameter is pseudo-velocity for 5% damping (also use 0, 2, 10 and 20% damping but do not report results).
- Before regression, smooth the actual response spectral amplitudes along the $\log_{10} T$ axis to remove the oscillatory ('erratic') nature of spectra.
- State that for small earthquakes ($M \approx 3$) equations only valid up to about 1 s because recorded spectra are smaller than recording noise for longer periods.
- Only give coefficients for 0.04, 0.06, 0.10, 0.17, 0.28, 0.42, 0.70, 1.10, 1.90, 3.20, 4.80 and 8.00 s but give graphs for rest.
- Assume that distribution of residuals from last step can be described by probability function:

$$p(\epsilon, T) = [1 - \exp(-\exp(\alpha(T) + \beta(T)))]^{n(T)}$$

where $p(\epsilon, T)$ is probability that $\log \mathrm{PSV}(T) - \log \widehat{\mathrm{PSV}}(T) \leq \epsilon(T)$, $n(T) = \min[10, [25/T]]$, $[25/T]$ is integral part of $25/T$. Arrange residuals in increasing order and assign an 'actual' probability of no exceedance, $p^*(\epsilon, T)$ depending on its relative order. Estimate $\alpha(T)$ and $\beta(T)$ by least-squares fit of $\ln(-\ln(1 - p^{1/n(T)})) = \alpha(T)\epsilon(T) + \beta(T)$. Test quality of fit between $\hat{p}(\epsilon, T)$ and $p^*(\epsilon, T)$ by $\chi^2$ and Kolmogorov-Smirnov tests. For some periods the $\chi^2$ test rejects the fit at the 95% level but the Kolmogorov-Smirnov test accepts it.

## 4.70 Ambraseys et al. (1996) & Simpson (1996)

- See Section 2.134.
- Response parameter is acceleration for 5% damping.
- Do no smoothing because if plotted on a normal scale then smoothing should be done on $T$, but if on log-log plot then smoothing should be done on $\log T$.

## 4.71 Ambraseys and Simpson (1996) & Simpson (1996)

- See Section 2.135.
- Response parameter is acceleration for 5% damping.

## 4.72 Bommer et al. (1996)

- See section 2.137.
- Response parameter is pseudo-velocity for unspecified damping.

## 4.73 Crouse and McGuire (1996)

- See section 2.138.
- Response parameter is pseudo-velocity for 5% damping.
- Find $k_1$ not significantly different than 1 for $T \leq 0.15$ s and $k_2$ not significantly different than 1 for $T \leq 0.50$ s.

## 4.74 Free (1996) & Free et al. (1998)

- See Section 2.139.
- Response parameter is acceleration for 5% damping.
- Finds including focal depth, $h$, explicitly has dramatic effect on predicted spectra at short distances but insignificant effect at large distances.
- Repeats analysis using only E. N. American data. Finds significantly larger amplitudes than predictions from combined set for short and intermediate distances for periods $> 0.3$ s but similar spectra for large distances.

## 4.75 Molas and Yamazaki (1996)

- Based on Molas and Yamazaki (1995), see Section 2.88 of Douglas (2001b).
- Response parameters are absolute acceleration and relative velocity for 5% damping.

## 4.76 Ohno et al. (1996)

- See Section 2.141.
- Response parameter is acceleration for 5% damping.
- Plot amplitude factors from first stage against $M_w$; find well represented by linear function.
- Do not give table of coefficients only graphs of coefficients.

## 4.77 Sabetta and Pugliese (1996)

- Ground-motion model used is:

$$\log_{10} Y = a + bM - \log_{10} \sqrt{d^2 + h^2} + e_1 S_1 + e_2 S_2$$

- Response parameter, $Y$, is pseudo-velocity for 5% damping
- Use data from Sabetta and Pugliese (1987).
- Remove anelastic decay term because it was not significant at $\alpha = 0.1$ and sometimes it was positive. Originally geometrical decay coefficient $c$ was allowed to vary but find it is close to $-1$ so constrain.
- Use three site categories:

$S_1 = 1, S_2 = 0$ Shallow: depth $H \leq 20$ m alluvium $400 \leq V_s \leq 800$ m/s.

$S_1 = 0, S_2 = 1$ Deep: depth $H > 20$ m alluvium $400 \le V_s \le 800$ m/s.

$S_1 = 0, S_2 = 0$ Stiff: $V_s > 800$ m/s.

- Accelerograms digitised at 400 samples/sec. Bandpass frequencies chosen by an analysis of signal and fixed trace Fourier spectra. $f_{\min}$ between 0.2 and 0.7 Hz most about 0.3 Hz and $f_{\max}$ between 20 and 35 Hz most about 25 Hz. Instrument correction applied.
- Use one-stage method although two-stage method yields similar results.
- Also present smoothed coefficients.

## 4.78 Spudich et al. (1996) & Spudich et al. (1997)

- See Section 2.145
- Response parameter is pseudo-velocity for 5% damping.
- Only use spectral values within the passband of the filter used to correct records hence number of records used for each period varies, lowest number is 99 for periods between 1.7 and 2.0 s.
- Smooth coefficients using cubics or quadratics.

## 4.79 Abrahamson and Silva (1997)

- Ground-motion model is[4]:

$$\begin{aligned}
\ln \mathrm{Sa} &= f_1 + F f_3 + HW f_{HW}(M) f_{HW}(R_{\mathrm{rup}}) + S f_5 \\
f_1 &= \begin{cases} a_1 + a_2(M - c_1) + a_{12}(8.5 - M)^n + [a_3 + a_{13}(M - c_1)] \ln R & \text{for } M \le c_1 \\ a_1 + a_4(M - c_1) + a_{12}(8.5 - M)^n + [a_3 + a_{13}(M - c_1)] \ln R & \text{for } M > c_1 \end{cases} \\
\text{where } R &= \sqrt{r_{\mathrm{rup}} + c_4^2} \\
f_3 &= \begin{cases} a_5 & \text{for } M \le 5.8 \\ a_5 + \frac{a_6 - a_5}{c_1 - 5.8}(M - 5.8) & \text{for } 5.8 < M < c_1 \\ a_6 & \text{for } M \ge c_1 \end{cases} \\
f_{HW}(M) &= \begin{cases} 0 & \text{for } M \le 5.5 \\ M - 5.5 & \text{for } 5.5 < M < 6.5 \\ 1 & \text{for } M \ge 6.5 \end{cases} \\
f_{HW}(r_{\mathrm{rup}}) &= \begin{cases} 0 & \text{for } r_{\mathrm{rup}} < 4 \\ a_9 \frac{r_{\mathrm{rup}} - 4}{4} & \text{for } 4 < r_{\mathrm{rup}} < 8 \\ a_9 & \text{for } 8 < r_{\mathrm{rup}} < 18 \\ a_9 \left(1 - \frac{r_{\mathrm{rup}} - 18}{7}\right) & \text{for } 18 < r_{\mathrm{rup}} < 24 \\ 0 & \text{for } r_{\mathrm{rup}} > 25 \end{cases} \\
f_5 &= a_{10} + a_{11} \ln(\widehat{\mathrm{PGA}} + c_5)
\end{aligned}$$

  where $\widehat{\mathrm{PGA}}$ is expected peak acceleration on rock as predicted by the attenuation equation with $S = 0$.

[4] $f_3$ given in Abrahamson and Silva (1997) was modified to ensure homogeneity and a linear variation in $f_3$ with magnitude.

- Response parameter is acceleration for unspecified[5] damping.
- Use two site categories:

$S = 0$ Rock: rock ($V_s > 600$ m/s), very thin soil ($< 5$ m) over rock or soil 5 to 20 m thick over rock.

$S = 1$ Deep soil: deep soil in narrow canyon (soil $> 20$ m thick and canyon $< 2$ km wide) or deep soil in broad canyon (soil $> 20$ m thick and canyon $> 2$ km wide).

- All records reprocessed using common procedure. Interpolated to 400 samples/sec, low-pass filtering with corner frequency selected for each record based on visual examination of Fourier amplitude spectrum, instrument corrected, decimated to 100 to 200 samples/sec depending on low-pass corner frequency, baseline correction using 0 to 10 degree polynomial, high-pass filtered based on integrated displacements.
- Only use response spectral data within frequency band $1.25 f_h$ to $0.8 f_l$ to avoid effects of filter roll-off. Hence number of records used for regression at each period varies, minimum number is less than 100 records for 0.01 s.
- Well distributed dataset in terms of magnitude and distance.
- Supplement data with records from Gazli, Friuli, Tabas, Taiwan, Nahanni and Spitak.
- Consider source mechanism: reverse $\Rightarrow F = 1$, reverse/oblique $\Rightarrow F = 0.5$, others (strike-slip and normal) $\Rightarrow F = 0$).
- Consider hanging wall effect: if over hanging wall $HW = 1$, otherwise $HW = 0$.
- Note that interpretation of $c_4$ is not clear for their distance measure but yields better fit.
- Model nonlinear soil response by $f_5$.
- Model uncertainty as magnitude dependent.
- Fix some coefficients to be independent of period so that response spectral values vary smoothly with distance, magnitude and period.
- Smooth coefficients using piecewise continuous linear fits on log period axis. For highly correlated coefficients, smooth one coefficient and re-estimate other coefficients.

## 4.80 Atkinson (1997)

- Ground-motion model used is:

$$\begin{aligned}\log \mathrm{PSA} &= c_0 + c_1(M_w - 6) + c_2(M_w - 6)^2 + c_3 h - c_{a_1} \log R - c_{a_2} R + c_s S \\ \text{with: } c_{a_2} &= c_{a_3} + c_{a_4} h\end{aligned}$$

- Response parameter is pseudo-acceleration for 5% damping.
- Uses two site categories (no soil profiles were available for Cascadia region):

$S = 0$ Rock: average $V_s$ assumed to be about 2000 m/s

$S = 1$ Soil: average $V_s$ assumed to be about 255 m/s (although includes some soft soil sites with average $V_s$ about 125 m/s).

[5] It is probably 5%.

- Tectonic type of earthquakes used: crustal, subcrustal and subduction
- Most Cascadia data is from seismograms. Converts vertical measurements from these to one horizontal component.
- Supplements in large magnitude range ($6.7 < M_w \leq 8.2$) with data from 9 subduction earthquakes in Alaska, Mexico, Japan and Chile
- Most magnitudes below 5.3 and no data between 6.8 and 7.5.
- Focal depths between 1 and 60 km
- Only uses events recorded at 3 or more stations. Improves ability of regression to distinguish between magnitude and distance dependencies in data.
- Most low magnitude events were recorded on rock and most high magnitude events were on soil. Thus to stabilize regression takes the coefficients $c_s$ from Boore et al. (1994a) and not derived from this data.
- Magnitude partitioning, in first step, into 0.5 unit intervals gave evidence for magnitude dependent attenuation. Uses $c_{a_1} = 1$ for $4.1 \leq M_w \leq 6.7$ and $c_{a_1} = 0.5$ (largest which yielded positive $c_{a_2}$) for $M_w \geq 7.5$. Thought to show breakdown of point source assumption.
- Demonstrates depth dependence in anelastic decay by performing regression in four 15 km deep subsets for range $4.1 \leq M_w \leq 6.7$. $c_{a_3}$ and $c_{a_4}$ then finds by regression for each period. No depth dependence for $M_w \geq 7.5$ because of lack of different depths.
- Includes depth dependence in second step because gave better fit for short periods.
- Checks dependence on crustal, interface and intra-slab events; finds no dependence.

## 4.81 Campbell (1997), Campbell (2000) & Campbell (2001)

- See Section 2.148
- Ground-motion model (horizontal component) is:

$$\begin{aligned}
\ln \mathrm{SA}_H &= \ln A_H + c_1 + c_2 \tanh[c_3(M - 4.7)] + (c_4 + c_5 M) R_{\mathrm{SEIS}} + 0.5 c_6 S_{\mathrm{SR}} \\
&\quad + c_6 S_{\mathrm{HR}} + c_7 \tanh(c_8 D)(1 - S_{\mathrm{HR}}) + f_{\mathrm{SA}} \\
f_{\mathrm{SA}} &= \begin{cases} 0 & \text{for} \quad D \geq 1\,\mathrm{km} \\ c_6(1 - S_{\mathrm{HR}})(1 - D)(1 - 0.5 S_{\mathrm{SR}}) & \text{for} \quad D < 1\,\mathrm{km} \end{cases}
\end{aligned}$$

- Ground-motion model (vertical component) is:

$$\begin{aligned}
\ln \mathrm{SA}_V &= \ln \mathrm{SA}_H + c_1 + b_2 M + c_2 \tanh[d_1(M - 4.7)] + c_3 \tanh[d_2(M - 4.7)] \\
&\quad + b_3 \ln[R_{\mathrm{SEIS}} + b_4 \exp(b_5 M)] + b_6 \ln[R_{\mathrm{SEIS}} + b_7 \exp(b_8 M)] + b_9 F \\
&\quad + [c_4 \tanh(d_3 D) + c_5 \tanh(d_4 D)](1 - S_{\mathrm{SR}})
\end{aligned}$$

- Response parameter is pseudo-acceleration for 5% damping.
- Notes importance of depth to basement rock, $D$, for modelling long period site response. For shallow sediments defines $D$ as depth to top of Cretaceous or older deposits, for deep sediments determine $D$ from crustal velocity profiles where define basement as crystalline basement rock or sedimentary deposits having a P-wave velocity $\geq 5$ km/s or shear-wave velocity $\geq 3$ km/s (called 'seismic basement' by geophysicists).

- Uses different data than for PGA equations hence: reverse (3), thrust (H:9, V:6), reverse-oblique (2) and thrust-oblique (0), total (H:14, V:11) (H:140 records, V:85 records), strike-slip (H:124 records, V:88 records). Only two normal faulting earthquakes in horizontal set of records (contributing 2 records) so a difference in not modelled although $F = 0.5$ is given as first approximation (later revised to $F = 0$) to use as for PGA case.
- Only excludes records from toe and base of dams, included those from buildings and bridge columns which were excluded from PGA study, because of lack of data.
- Uses weighted regression analysis. Assigns recordings from a given earthquake that fell within the same distance interval (ten logarithmical spaced) same weight as those recordings from other earthquakes that fell within the same distance interval. Gives recordings from a given earthquake that occurred at the same site location the same cumulative weight as a single recording at that distance, thus reducing the bias.
- Performs analysis on spectral ratio ln(PSA/PGA) because of unacceptably large period-to-period variability in regression coefficients when direct regression is applied and strongly correlated coefficients. Notes that are too many regression coefficients so it was necessary to perform analysis in many steps, at each step different coefficients are determined and detrended and residuals examined to find appropriate functional forms for trends present. Yields more stable results.
- No consideration of nontriggering instruments made, unlike PGA study.

## 4.82 Schmidt et al. (1997)

- See Section 2.152.
- Response parameter is pseudo-velocity for 5% damping.

## 4.83 Youngs et al. (1997)

- See Section 2.153.
- Ground-motion model used is:

$$\ln(\mathrm{SA}/\mathrm{PGA}) = B_1 + B_2(10 - \mathbf{M})^3 + B_3 \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{\alpha_1+\alpha_2\mathbf{M}}\right]$$

  where $\alpha_1$ and $\alpha_2$ are set equal to $C_4$ and $C_5$ of appropriate PGA equation.
- Response parameter, SA, is acceleration for 5% damping.
- Do analysis on response spectral amplification because digitised and processed accelerograms used for spectral attenuation is only a subset of PGA database and they are often those with strongest shaking. Hence analysis directly on spectral accelerations may be biased.
- Smooth coefficients.

## 4.84 Bommer et al. (1998)

- Ground-motion model is:

$$\begin{aligned} \log(\mathrm{SD}) &= C_1 + C_2 M + C_4 \log r + C_A S_A + C_S S_S \\ r &= \sqrt{d^2 + h_0^2} \end{aligned}$$

- Response parameter is displacement for 5, 10, 15, 20, 25 and 30% damping.
- Use three site conditions:

  R Rock: $V_s > 750$ m/s, $S_A = 0$, $S_S = 0$, 30–45 records.

  A Stiff soil: $360 < V_s \leq 750$ m/s, $S_A = 1$, $S_S = 0$, 56–92 records.

  S Soft soil: $180 < V_s \leq 360$ m/s, $S_A = 0$, $S_S = 1$, 32–43 records.

- Use subset of data of Ambraseys et al. (1996) (see 2.134) data with a few changes and exclusion of records from earthquakes with $M_s < 5.5$ because ground motion at long periods was of interest and to increase likelihood of acceptable single-to-noise ratio at longer periods.
- Each record individually filtered. Firstly filter record with sharp low cut-off at 0.1 Hz and plot velocity and displacement time-histories. Check, visually, whether contaminated by noise and if so increase cutoff frequency by small amount and repeat procedure until resulting velocity and displacement time-histories are deemed acceptable and no significant improvement is observed by further increase of cutoff frequency. Instrument correction not applied because high frequency distortion caused by transducer characteristics not important for displacement spectra. Only use each record for regression for periods up to 0.1 s less than filter cutoff used for that record to avoid distortion by filter, hence as period increases number of data points decreases.
- Regression procedure same as Ambraseys et al. (1996), see 2.134.

## 4.85 Perea and Sordo (1998)

- Ground-motion model is:

$$\ln \mathrm{Pa} = \beta_1 + \beta_2 M + \beta_3 \ln(R + 25)$$

- Response parameter is pseudo-acceleration for 5% damping.
- All records from five medium soft soil sites.
- Use $m_b$ for $M < 6$ and $M_s$ otherwise, because $m_b$ is more representative of released energy for small earthquakes and $M_s$ better represents energy release for large earthquakes because $m_b$ saturates starting from $M > 6$.
- Try including anelastic decay term, $\beta_4 R$ but it does not significantly affect standard deviation.
- Also repeat analysis for three other zones. Zone 1: 3 earthquakes, 3 records ($5.0 \leq M \leq 6.4$, $80 \leq R \leq 156$ km) for which conclude has too limited data for reliable equation. Zone 3[6]: 11 earthquakes, 13 records ($4.5 \leq M \leq 7.7$, $251 \leq R \leq 426$ km) for which find fits spectra of medium sized shocks better than large shocks because of lack of data for large earthquakes. Zone 4: 4 earthquakes, 7 records ($5.1 \leq M \leq 6.2$, $356 \leq R \leq 573$ km) for which find $\beta_2$ is negative and $\beta_3$ is positive for some periods (which is nonphysical) which state is due to limited number of earthquakes and their similar epicentral distances.
- Find fit spectra of medium sized earthquakes than large earthquakes because of lack of data from large earthquakes.
- Only give graphs of coefficients.

[6] The following values are from their Table 1 which does not match with their Figure 3.

## 4.86 Reyes (1998)

- See Section 2.159.
- Response parameter is acceleration for 5% damping.

## 4.87 Shabestari and Yamazaki (1998)

- Ground-motion model is:

$$\log y(T) = b_0(T) + b_1(T)M + b_2(T) - \log r + b_4(T)h + c_i(T)$$

  where $c_i(T)$ is the station coefficient, reflecting relative site effect for each period, assuming zero mean for all stations.

- Response parameters are acceleration and velocity for 5% damping.
- Include at least five earthquakes with $M_{\text{JMA}} \geq 7.2$.
- Exclude earthquakes with focal depths, $h$, equal to 0 km or greater than 200 km.
- Exclude records with vectorial composition of PGA less than $0.01\,\text{m/s}^2$.
- Use three-stage iterative partial regression method.
- For $T \geq 6$ s constrain horizontal anelastic coefficient to zero because get positive coefficient.
- See Yamazaki et al. (2000) for examination of station coefficients.

## 4.88 Chapman (1999)

- See Section 2.168.
- Response parameter is pseudo-velocity for 2, 5 and 10% damping.

## 4.89 Spudich et al. (1999) & Spudich and Boore (2005)

- See Section 2.173.
- Response parameter is pseudo-velocity for 5% damping.
- Use only use response spectral data within frequency band $1.25f_h$ to $0.75f_l$ to avoid effects of filter roll-off. Eight records were not processed like the rest so use only response spectral values within 0.1 to 1 s. Hence number of records used for regression at each period varies, minimum number used is 105 records for 2 s.
- Give smoothed coefficients using cubic function.

## 4.90 Ambraseys and Douglas (2000), Douglas (2001a) & Ambraseys and Douglas (2003)

- See Section 2.176.
- Response parameter is acceleration for 5% damping.
- Find $b_2$ and $b_3$ significantly different than 0 at 5% level for all periods but $b_A$ and $b_S$ not significant for many periods (especially for vertical component).
- Find deamplification for vertical component on soft and stiff soil compared with rock. Check by removing all 34 Northridge records (many of which were on soft soil) and repeat analysis; find little change.
- Also derive equations for horizontal response under influence of vertical acceleration using a bending SDOF model; find little change in response.

## 4.91 Bozorgnia et al. (2000)

- See Section 2.177.
- Response parameter is acceleration for 5% damping.
- Different set of data than for PGA hence: strike-slip: 20 earthquakes (including one normal faulting shock), reverse: 7 earthquakes and thrust: 6 earthquakes.
- Find considerable period-to-period variability in coefficients causing predicted spectra to be very jagged near limits of magnitude and distance ranges so carried out partial smoothing of coefficients.

## 4.92 Campbell and Bozorgnia (2000)

- See Section 2.178.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.93 Chou and Uang (2000)

- Ground-motion model is:

$$\log Y = a + b(M-6) + c(M-6)^2 + d\log(D^2+h^2)^{1/2} + eG_c + fG_d$$

- Response parameter is pseudo-velocity for 5% damping.
- Use three site categories (based on average shear-wave velocity, $V_s$, over top 30 m):

Classes A+B Hard rock or rock: $V_s > 760$ m/s, $G_c = 0$, $G_d = 0$, 35 records.

Class C Very dense soil and soft rock: $360 < V_s \leq 760$ m/s, $G_c = 1$, $G_d = 0$, 97 records.

Class D Stiff soil: $180 \leq V_s \leq 360$ m/s, $G_c = 0$, $G_d = 1$, 141 records.

- Records from free-field or ground level of structures no more than two storeys in height.
- Smooth coefficients using cubic polynomial.
- Do not give coefficients for all periods.
- Find cannot use equation to predict near-field ground motions.

## 4.94 Field (2000)

- See Section 2.179.
- Distribution w.r.t. site class for 3.0 s is: B, 10 records; BC, 27 records; C, 13 records; CD, 119 records; D, 187 records; DE, 1 record.
- Response parameter is acceleration for 5% damping.
- Constrains $b_3$ for 1.0 and 3.0 s to zero because originally finds positive value.
- 151 records have basin-depth estimates.
- Does not find significant slopes for residuals w.r.t. predicted ground motion at BC sites.
- Plots squared residuals w.r.t. $V_s$ and finds small significant trends for 1.0 and 3.0 s.

## 4.95 Kawano et al. (2000)

- Ground-motion model is:

$$\log S_i(T) = a(T)M - \{b(T)X_{eq} + \log X_{eq}\} + c_i(T)$$

  where $c_i(T)$ is an individual site amplification factor for each of 12 stations.
- Response parameter is acceleration for 5% damping.
- Focal depths between 0 and 60 km.
- Use data either recorded at ground surface where $0.5 \leq V_s \leq 2.7$ km/s ($1.7 \leq V_p \leq 5.5$ km/s) or obtained by analytically removing effects of uppermost surface layers of ground from underground observation data (or by stripping-off analysis) using underground structure.
- Use only ground motion after arrival of first S wave because most important for aseismic design.
- Do not give table of coefficients, only graphs of coefficients.
- Define amplification factors, $d_i(T) = c_i(T) - c_0(T)$ for horizontal motion and $d_i(T) = c_{v,i}(T) - c_0(T)$ for vertical motion, where $c_0(T)$ is the regression coefficient for data observed at ground layer equivalent to seismic bedrock.
- Find $S_h(T) = S_b(T)\alpha_h(T)\beta_h(T)$ where $S_b(T)$ is $S_0(T)$. $\alpha_h(T) = (V_s/V_{s,b})^{-\delta_h(T)}$ for $T \leq T_{s,1}$ and $\alpha_h(T) = \alpha_h(T_{s,1})$ for $T > T_{s,1}$ where $T_{s,1}$ is the primary predominant period of surface layer. $\beta_h(T) = 1$ for $T \leq T_{s,1}$, $\beta_h(T) = (T/T_{s,1})^{-\log(\alpha_h(T_{s,1}))}$ for $10T_{s,1} > T > T_{s,1}$ and $\beta_h(T) = 10^{-\log(\alpha_h(T_{s,1}))}$ for $T \geq 10T_{s,1}$. $V_{s,b} = 2.2$ km/s. Similar relationships are defined for vertical motion, $S_v(T)$.
- Note that relation does not include effect of source mechanism or rupture propagation, so probably less valid in near-fault region.

## 4.96 Kobayashi et al. (2000)

- See Section 2.181.
- Response parameter is pseudo-velocity for 5% damping.
- Use significantly less records for $T > 1.5$ s.

## 4.97 McVerry et al. (2000)

- Ground-motion model for crustal earthquakes is (using form from Abrahamson and Silva (1997), see Section 4.79):

$$
\begin{aligned}
\ln \mathrm{SA}'(T) \quad = \quad & C_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C_5(T)r \\
& + (C_8(T) + C_{6AS}(M-6))\ln(r^2 + C_{10AS}^2(T))^{1/2} + C_{46}(T)r_{\mathrm{VOL}} \\
& + \{C_2(T)r + C_{44}(T) + (C_9(T) + C_7(T)(M-6))(\ln(r^2 + C_{10AS}^2(T))^{1/2} \\
& - \ln C_{10AS})\} \\
& + \{C_{29}(T)\} \\
& + \{C_{30AS}(T)\ln(\mathrm{PGA}'_{WA} + 0.03) + C_{43}(T)\} \\
& + C_{32}\mathrm{CN} + C_{33AS}(T)\mathrm{CR}
\end{aligned}
$$

  Also add on hanging wall term, see Section 4.79. Subscript $AS$ denotes those coefficients from Abrahamson and Silva (1997). Three parts of equation within $\{\ldots\}$ are for site conditions MA/SA, Class B and Class C respectively. $\mathrm{PGA}'_{WA}$ is the predicted PGA ($\mathrm{SA}'(0)$) for weak rock category. $\mathrm{CN} = -1$ for normal mechanism and 0 otherwise. $\mathrm{CR} = 0.5$ for reverse/oblique, 1.0 for reverse and 0 otherwise. Ground-motion model for subduction zone earthquakes is (using form from Youngs et al. (1997), see Section 4.83):

$$
\begin{aligned}
\ln \mathrm{SA}'(T) \quad = \quad & C_{11}(T) + [C_{12Y} + (C_{17Y}(T) - C_{17}(T))C_{19Y}] \\
& + C_{13Y}(T)(10-M)^3 + C_{17}(T)\ln(r + C_{18Y}\exp(C_{19Y}M)) + C_{20}(T)H_C \\
& + C_{24}(T)\mathrm{SI} + C_{46}(T)r_{\mathrm{VOL}}(1-\mathrm{DS}) \\
& + \{C_{44}(T) + C_{16}(T)(\ln(r + C_{18Y}\exp(C_{19Y}M)) \\
& - \ln(C_{18Y}\exp(C_{19Y}M)))\} \\
& + \{C_{29}(T)\} \\
& + \{C_{30Y}(T)\ln(\mathrm{PGA}'_{WA} + 0.03) + C_{43}(T)\}
\end{aligned}
$$

  Subscript $Y$ denotes those coefficients from Youngs et al. (1997). Three parts of equation within $\{\ldots\}$ are for site conditions MA/SA, Class B and Class C respectively. $\mathrm{SI} = 1$ for subduction interface and 0 otherwise. $\mathrm{DS} = 1$ for deep slab and 0 otherwise. $r_{\mathrm{VOL}}$ is length of path that lies in the volcanic zone.

- Response parameter is acceleration for 5% damping.

- Use four site conditions (mostly based on geological descriptions rather than measured shear-wave velocity):

  WA Weak rock sites, or sites with soil layer of thickness $\leq 3$ m overlying weak rock.

  MA/SA Moderate-strength or strong rock sites, or sites with soil layer of thickness $\leq 3$ m overlying moderate-strength or strong rock.

  Class B Intermediate soil sites or sites with soil layer of thickness $> 3$ m overlying rock.

  Class C Flexible or deep soil sites with natural periods $> 0.6$ s.

  Justify soil categories using statistical studies of residuals at early stage. Exclude response spectra from very soft soil sites ($V_s < 150$ m/s for depths of $\gtrsim 10$ m).

- Use data for PGA equation from Zhao et al. (1997), see Section 2.154.

- Exclude records from bases of buildings with >4 storeys.

- Use less records for long periods because noise.

- Lack of data prevent development of robust model purely from NZ data. Plot residuals of predicted response using published attenuation relations (base models) for other areas to find relations which gave good representations of NZ data. Then modify some coefficients to improve match; imposing constraints so that the selected models control behaviour at short distances where NZ data lacking. Require crustal and subduction zone expressions for rock sites to match magnitude dependence of base models at $r = 0$ km. Constrain coefficients that occur nonlinearly and nonlinear site response coefficient for Class C to base model values.

- Find anelastic attenuation term and additive terms for shallow slab earthquakes for subduction earthquakes not statistically significant. Also differences in attenuation rates for shallow slab, deep slab and interface earthquakes not statistically significant.

- Exclude deep slab earthquakes because of high attenuation in mantle; note equation should not be used for such earthquakes.

- Different attenuation rate for site category MA/SA because of magnitude dependence apparent in residuals for simpler model.

- Eliminate nonlinear site response term for Class B because find unacceptable (positive) values of coefficient and constraining to negative values produces poorer fit.

- Predicted PGA ($\mathrm{SA}'(0)$) from response spectrum set of records considerably smaller than those, SA(0), from the complete PGA set of records. Thus scale $\mathrm{SA}'(T)$ by ratio $\mathrm{SA}(0)/\mathrm{SA}'(0)$.

- Standard error has a magnitude dependent intra-event component and a magnitude independent inter-event component.

- Note lack of data for large magnitude subduction zone earthquakes and large magnitude near source data for crustal earthquakes.

- Do not give coefficients, only predictions.

## 4.98 Monguilner et al. (2000b)

- Ground-motion model is:

$$\log S_A(T) = A(\Delta, T) + M + b_1(T) + b_2(T)M + b_3(T)s + b_4(T)v + b_5(T)M^2 + e_p(i)$$

  where $A(\mathrm{DE}, H, S, T) = A_0(T) \log \Delta(\mathrm{DE}, H, M)$, $\Delta = (\mathrm{DE}^2 + H^2 + S^2)^{\frac{1}{2}}$, $H$ is focal depth, $p$ is the confidence level, $s$ is from site classification (details not given in paper) and $v$ is component direction (details not given in paper although probably $v = 0$ for horizontal direction and $v = 1$ for vertical direction).

- Response parameter is pseudo-acceleration for unknown damping level.

- Use same data and weighting method as Monguilner et al. (2000a) (see Section 2.182).

- Find $A_0(T)$ by regression of the Fourier amplitude spectra of the strong-motion records.

- Estimate fault area, $S$, using $\log S = M_s + 8.13 - 0.6667 \log(\sigma \Delta\sigma/\mu)$.

- Equation only valid for $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_2/(2b_5(T))$ and $M_{\max} = -(1+b_2(T))/(2b_5(T))$. For $M < M_{\min}$ use $M$ for second term and $M = M_{\min}$ elsewhere. For $M > M_{\max}$ use $M = M_{\max}$ everywhere.

- Examine residuals, $\epsilon(T) = \log S_A(T) - \log S'_A(T)$ where $S'_A(T)$ is the observed pseudo-acceleration and fit to the normal probability distribution,
$p(\epsilon, T) = \int \exp[-(x - \mu(T))/\sigma(T)]^2/(\sigma(T)\sqrt{2\pi})$, to find $\mu(T)$ and $\sigma(T)$. Find that the residuals fit the theoretical probably distribution at the 5% level using the $\chi^2$ and KS[7] tests.

- Do not give coefficients, only graphs of coefficients.

## 4.99 Paciello et al. (2000)

- See Section 2.183.

- Response parameter is acceleration for 5% damping.

## 4.100 Shabestari and Yamazaki (2000)

- Ground-motion model is:

$$\log y(T) = b_0(T) + b_1(T)M + b_2(T) - \log r + b_4(T)h + c_i(T)$$

  where $c_i(T)$ is the station coefficient, reflecting the relative site effect for each period, assuming zero mean for all stations.

- Response parameters are acceleration and velocity for 5% damping.

- Depths between 1 (includes earthquakes with depths reported as 0 km) and 158 km. Exclude earthquakes with focal depths greater than 200 km.

- Exclude records with vectorial composition of PGA less than $0.01\,\mathrm{m/s^2}$.

- Exclude data from stations which have recorded less than two records, because the station coefficient could not be determined adequately. Use records from 823 stations.

- Most records from distances between 50 and 300 km.

- Use three-stage iterative partial regression method.

- For $T \geq 5$ s constrain horizontal anelastic coefficient to zero because get positive coefficient.

## 4.101 Smit et al. (2000)

- See Section 2.185.

- Response parameter is acceleration for 5% damping.

## 4.102 Takahashi et al. (2000)

- See Section 2.186.

- Response parameter is pseudo-velocity for 5% damping.

- For periods $\geq 1$ s long period noise in records leads to reduction in number of records.

[7]Probably this is Kolmogorov-Smirnov.

- Set $b$ and $e$ to zero at long periods because estimates not statistically significant.
- Find that soft soil site correction terms may be affected by different processing procedures for data from different sources.

## 4.103 Lussou et al. (2001)

- See Section 2.191.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.104 Das et al. (2002, 2006)

- Ground-motion model is:

$$\log[PSV(T)] = c_1(T) + c_2(T)M + c_3(T)h + c_4(T)\log(\sqrt{R^2+h^2}) + c_5(T)v$$

  where $v = 0$ for horizontal and 1 for vertical.
- Response spectral parameter is pseudo-velocity for 5% damping.
- Use records from stiff soil/rock sites.
- Focal depths between 15 and 122 km.
- Use square-root-of-sum-of-squares (SRSS) to combine horizontal components to reduce strong azimuthal dependence of ground motions. Note that dividing predicted spectra by 1.41 gives spectrum for each component separately.
- Do not derive equations for $T > 1$ s because of baseline problems and noise in accelerograms at longer periods.
- Try more complex functional forms but not enough data to constrain all parameters to physically-realistic values.
- Smooth coefficients using unspecified technique.
- Report residual spectra for different probability levels not $\sigma$.

## 4.105 Gülkan and Kalkan (2002)

- See Section 2.196.
- Response parameter is acceleration for 5% damping.

## 4.106 Khademi (2002)

- See Section 2.198.
- Response parameter is acceleration for 5% damping.

## 4.107 Manic (2002)

- Ground-motion model is:

$$\begin{aligned} \log \mathrm{PSV}(T) &= c_1(T) + c_2(T)M + c_3(T)\log(R) + c_4(T)S_A \\ \text{where } R &= (d^2 + d_0^2)^{1/2} \end{aligned}$$

- Response parameter is pseudo-velocity for 5% damping,
- Uses two site categories:

$S_A = 0$ Rock, $V_{s,30} > 750$ m/s.

$S_A = 1$ Stiff soil, $360 < V_{s,30} \leq 750$ m/s.

Soft soil sites ($V_s \leq 360$ m/s) do not exist in set of records.

- Use technique of Ambraseys et al. (1996) to find the site coefficient $c_4(T)$, i.e. use residuals from regression without considering site classification.
- Derives separate equations for $M_s$ and $M_L$ and for $r_{jb}$ and $r_{epi}$.

## 4.108 Schwarz et al. (2002)

- See Section 2.201.
- Response parameter is acceleration for 5% damping.

## 4.109 Zonno and Montaldo (2002)

- See Section 2.204.
- Response parameter is pseudo-velocity for 5% damping.

## 4.110 Alarcón (2003)

- See Section 2.205.
- Response parameter is acceleration for 0, 5 and 10% damping but only report coefficients for 5% damping.
- Derive equations for 84[8] periods but only reports coefficients for 11 periods.

## 4.111 Atkinson and Boore (2003)

- See Section 2.207.
- Response parameter is pseudo-acceleration for 5% damping.

[8]On page 8 of paper it says 88 periods.

## 4.112 Berge-Thierry et al. (2003)

- Ground-motion model is:

$$\log_{10} \mathrm{PSA}(f) = a(f)M + b(f)d - \log_{10} d + c_1(f) + c_2(f)$$

  where $c_1(f)$ is for rock sites and $c_2(f)$ is for alluvium sites.

- Use two site categories based on $V_s$ where $V_s$ is the average shear-wave velocity in top 30 m:

  1. Rock, $V_s > 800$ m/s.
  2. Alluvium, $300 < V_s < 800$ m/s.

  Note that some uncertainty in site classification due to lack of $V_s$ values at many stations.

- Response parameter is spectral acceleration for 5%, 7%, 10% and 20% damping.

- Note that not enough data to derive an equation using only French data so had to use European and US data.

- Use only records from earthquakes with focal depth $\leq 30$ km so as to be consistent with shallow crustal earthquakes in France.

- Predominately use corrected data from Ambraseys et al. (2000).

- Supplement European data with some data from western USA to improve the magnitude and distance distribution.

- Exclude records from Ambraseys et al. (2000) from earthquakes with $M_s < 4$.

- Exclude records from Ambraseys et al. (2000) with record lengths $< 10$ s.

- Exclude records from Ambraseys et al. (2000) with poor visual quality.

- Exclude records from Ambraseys et al. (2000) from non-free-field stations or those inside a building on the third floor or higher.

- Exclude records from Ambraseys et al. (2000) from stations with unknown or very soft soil site conditions.

- Processing procedure of records from Ambraseys et al. (2000) is: baseline correct uncorrected record, resample record to 0.01 s time-step and bandpass filtered using a elliptical filter with cut-offs of 0.25 and 25 Hz because most instruments were SMA-1s with natural frequency of 25 Hz and damping of 60%. No instrument correction was applied because instrument characteristics are not known.

- Only use US records from earthquakes with $M > 6$.

- Use the already corrected records from USGS and CDMG.

- Most data from rock sites is from earthquakes with $M < 6$.

- 49.7% of data is from Italy and 16.9% is from USA. All other countries contribute less than 10% each.

- Use hypocentral distance because believe it accounts for both point and extended sources.

- Use uniformly calculated $M_s$ for data from Ambraseys et al. (2000) and $M_w$ for data from W. USA, which believe is equivalent for $M_s$ for $M_w > 6$.

- Coefficients only reported for horizontal spectral acceleration for 5% damping.

- Note that recent data, e.g. Chi-Chi, shows saturation of ground motions at short distances but data used only contains a few records at close distances so data not sufficient to model such phenomenon.
- Obtain positive $b(f)$ coefficients for periods $> 1s$ which believe is due to low frequency noise and surface waves.
- Believe that small difference between estimated rock and alluvium motions could be due to incorrect site classification at some stations.
- Repeat regression using a randomly selected half of the data. Find very small differences between predicted ground motions using half or complete data set so believe equation is stable.
- Repeat regression excluding data from W. USA and find very small differences between predicted ground motions so believe equation is not influenced by data from W. USA.
- Repeat regression using $M_w$ rather than $M_s$ if available and find that predicted ground motions are different but that the predictions using $M_s$ are higher than those using $M_w$ so note that equation using $M_s$ is conservative hence it is useful in a nuclear safety assessment.
- Repeat regression using $r_{rup}$ rather than $r_{hypo}$ and find that predicted ground motions using $r_{hypo}$ are higher than when $r_{rup}$ is used because using $r_{hypo}$ places source further from source of energy.
- Plot residuals for 0.03 and 2 s and find not systematic bias in residuals.

## 4.113 Bommer et al. (2003)

- See Section 2.209.
- Response parameter is acceleration for 5% damping.

## 4.114 Campbell and Bozorgnia (2003d,a,b,c) & Bozorgnia and Campbell (2004b)

- See Section 2.210.
- Response parameter is pseudo-acceleration for 5% damping.
- To make regression analysis more stable set $c_2$ equal to value from better-constrained regression of uncorrected PGAs.
- Do limited amount of smoothing of regression coefficients to reduce the considerable amount of period-to-period variability in the regression coefficients that caused variability in predicted pseudo-acceleration especially for small distances and large magnitudes.

## 4.115 Fukushima et al. (2003)

- Ground-motion model is:

$$\log \mathrm{Sa}(f) = a(f)M - \log(R + d(f)10^{e(f)M}) + b(f)R + c_1\delta_1 + c_2\delta_2$$

- Use two site categories:
  1. Rock sites with $V_s > 800$ m/s. $\delta_1 = 1$ and $\delta_2 = 0$.

2. Soil sites with $V_s < 800\,\mathrm{m/s}$. $\delta_2 = 1$ and $\delta_1 = 0$.

Note that some data (Turkish and Japanese) are associated with liquefaction phenomena and so probably $V_s < 300\,\mathrm{m/s}$.

- Choose functional form to include effect of amplitude saturation close to source.
- Note that negative Q values obtained in some ground motion estimation equations may be due to the lack of amplitude saturation terms.
- Do not investigate effect of rupture mechanism, directivity, and the hanging wall effect because of a lack of data.
- Use same set of data as Berge-Thierry et al. (2003) but with the addition of records from the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes, which are used to help constrain the near-source characteristics. In total use 399 records from west Eurasia, 162 from USA, 154 from Hyogo-ken Nanbu and 25 from Kocaeli.
- Remove records from distances greater than the distance at which the predicted PGA is less than $10\,\mathrm{cm/s^2}$ (the average trigger level plus the standard error of observation) as predicted by a previously derived ground motion prediction equation that agrees well with the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes although they note the process should be iterative.
- Use only records from earthquakes with $M \geq 5.5$ so as to allow the use of a linear magnitude dependence.
- Due to the nonlinear functional form adopt a iterative method to find $d(f)$ and $e(f)$. However, due to the lack of near-source data an accurate value of $e(f)$ cannot be found therefore set $e(f)$ to 0.42, which gives accelerations that agree with the observed peak accelerations in the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes.
- Bandpass filter records with cut-offs of 0.25 and 25 Hz. Note that due to the presence of many records from analogue instruments the results for frequencies higher than 10 Hz are less reliable than those for lower frequencies.
- Find that for frequencies $> 0.4$ Hz the $b(f)$ coefficient corresponds to positive Q values. For lower frequencies the value of $b(f)$ correspond to negative Q values, which note could be due to instrumental noise or the effect of surface waves that are not well represented by the functional form adopted.
- Note that the small difference between predicted rock and soil motions may be due to intrinsic rock amplification due to rock weathering or inappropriate site classification for some records (e.g. those from the 1999 Kocaeli earthquake, which are all considered to be on soil).
- Plot residuals with respect to regional origin (Hyogo-ken Nanbu, USA, western Eurasian and Kocaeli) and find no clear bias or trend.
- Note that most of the used near-fault records come from strike-slip earthquakes and so the equation may be only should be used for prediction of strike-slip motions.
- Note that the site classification scheme adopted is very basic but lack information for more sophisticated method.

## 4.116 Kalkan and Gülkan (2004a)

- See Section 2.225.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.117 Kalkan and Gülkan (2004b) and Kalkan and Gülkan (2005)

- See Section 2.226.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.118 Matsumoto et al. (2004)

- Ground-motion model is (for $r_{rup}$):

$$\log SA(T) = C_m(T)M + C_h(T)H_c - C_d(T)\log[R + 0.334\exp(0.653M)] + C_o(T)$$

  Ground-motion model is (for $r_q$):

$$\log SA(T) = C_m(T)M + C_h(T)H_c - C_d(T)X_{\text{eq}} - \log X_{\text{eq}} + C_o(T)$$

  $H_c = h$ for $h < 100$ km and $H_c = 100$ km for $h > 100$ km.

- Response parameter is acceleration for 5% damping.
- Data from at 91 dam sites with rock foundations. Most instruments in inspection gallery at lowest elevation (for concrete dams) and in bottom inspection gallery (for embankment dams). Note that $1.8 \leq V_p \leq 4.5$ km/s for bedrock of many concrete dams and $1.5 \leq V_p \leq 3.0$ km/s for bedrock of embankment dams, which convert to $0.7 \leq V_s \leq 1.5$ km/s.
- Select data from $M > 5$, $d_e < 200$ km and focal depth $h < 130$ km.
- Most records from $h < 60$ km.
- Most records from $d < 100$ km.
- Classify earthquakes into three types:

| | |
|---|---|
| Shallow crustal | Epicentres located inland at shallow depths. 175 records[9]. |
| Inter-plate | Epicentres located in ocean with $h < 60$ km. 55 records. |
| Deep intra-slab | Epicentres located inland with $h > 60$ km. 63 records. |

- Know fault source mechanism for 12 earthquakes.
- Adopt $0.334\exp(0.653M)$ from earlier Japanese study.
- Derive coefficients regardless of earthquake type. Then derive correction factors for each earthquake type.
- Do not report coefficients only graphs of coefficients against period.
- Find good agreement between predicted spectra and observed spectra for two stations that recorded the magnitude 8.0 Tokati-oki 2003 earthquake.

## 4.119 Özbey et al. (2004)

- See Section 2.230.
- Response parameter is acceleration for 5% damping.

[9]The authors also give number of 'sets' as 81 for shallow crustal, 29 for inter-plate and 29 for deep intra-slab

## 4.120 Pankow and Pechmann (2004) and Pankow and Pechmann (2006)

- See Section 2.231.
- Response parameter is pseudo-velocity for 5% damping.

## 4.121 Sunuwar et al. (2004)

- See Section 2.233.
- Response parameter is pseudo-acceleration for 5% damping.
- Developed equations up to 5 s but do not think results for 4 and 5 s are satisfactory.

## 4.122 Takahashi et al. (2004)

- Ground-motion model is:

$$\begin{aligned}\log[y(T)] &= aM - bx - \log r + e(h - h_c)\delta_h + S_R + S_I + S_S + S_k \\ r &= x + c\exp(dM)\end{aligned}$$

  Use $S_R$ only for crustal reverse events, $S_I$ only for interface events, $S_S$ only for subduction slab events and $S_k$ for each of the site classes ($k = 1, \ldots, 4$). $\delta_h = 0$ for $h < h_c$ and 1 otherwise. For $h > 125$ km use $h = 125$ km.

- Use four site categories:

  SC I Rock, natural period $T < 0.2$ s, $V_{s,30} > 600$ m/s, approximately NEHRP classes A and B. 1381 records.

  SC II Hard soil, natural period $0.2 \leq T < 0.4$ s, $300 < V_{s,30} \leq 600$ m/s, approximately NEHRP class C. 1425 records.

  SC III Medium soil, natural period $0.4 \leq T < 0.6$ s, $200 < V_{s,30} \leq 300$ m/s, approximately NEHRP class D. 594 records.

  SC IV Soft soil, natural period $T \geq 0.6$ s, $V_{s,30} \leq 200$ m/s, approximately NEHRP classes E and F. 938 records.

  Site classification unknown for 62 records. Prefer using site classes rather than individual coefficients for each station because avoids possibility of source effects being shifted into site terms and can be used when there are only a few records per station.

- Response parameter is acceleration for 5% damping.
- Classify earthquakes into three types:

Crustal Focal depths $\leq 25$ km. 81 earthquakes, 1497 records.

Interface 88 earthquakes, 1188 records.

Slab 101 earthquakes. 1715 records.

- Classify earthquakes into four mechanisms:

Reverse 160 earthquakes (28 crustal), 1969 records (373 crustal).

Strike-slip 82 earthquakes (39 crustal), 1674 records (1100 crustal).

Normal 26 earthquakes (4 crustal), 749 records (24 crustal).

Unknown 2 earthquakes (0 crustal), 8 records (0 crustal).

Consider differences between reverse and strike-slip motions for crustal earthquakes because enough data but note there is not enough data to consider normal earthquakes as a separate group.

- Focal depths, $h$, between about 0 and 162 km with most $< 60$ km.
- Exclude data from distances greater than a specified limit for a given magnitude in order to eliminate bias due to untriggered instruments. For subduction slab events, fix maximum distance as 300 km.
- Note that there is little near-source data from Japan from within 30 km. All Japanese data from within 10 km is from two earthquakes (Kobe 1995 and Tottori 2000). Add data from with 40 km from earthquakes in western USA ($h < 20$ km) and from the Tabas 1978 (Iran) earthquake to help constrain near-source behaviour of derived equations. Use data from: Japan (61 crustal earthquakes, 1301 records; 87 interface earthquakes, 1176 records; 101 slab earthquakes, 1715 records) and Iran and western USA (20 crustal earthquakes; 196 records; 1 interface earthquake, 12 records).
- Note that reasonably good distribution of data for all magnitudes and focal depths.
- Note strong correlation between focal depth and distance.
- Use ISC relocations rather than JMA locations because find that they are more reliable.
- Use $M_w$ values from Harvard CMT unless value from special study is available.
- Prefer the one-stage maximum-likelihood method to the two-stage method because when there many events with only a small number of records and many individual site terms, the coefficients must be determined using an iterative method and hence their reliability is questionable.
- Find that, by residual analysis (not shown), that equations predict unbiased ground motions for crustal and interface events but biased ground motions for slab events with bias that depends on distance. Apply this magnitude-independent path modification factor SF for slab events: $\log(\mathrm{SF}) = S_{\mathrm{SL}}[\log(\sqrt{x^2 + R_a^2}) - \log(R_c)]$ where $R_a = 90.0$ km and $R_c = 125.0$ km.
- Find that, because of lack of near-source data, it is not possible to find reliable estimates of $c$ and $d$ so use a iterative method to find $d$ by fixing $c$.
- Estimate site coefficient, $S_H$, for hard rock sites ($V_{s,30} = 1500$ m/s) from 10 stations with $1020 \leq V_{s,30} \leq 2200$ m/s with 1436 records, based on residuals.
- Examine residuals w.r.t. magnitude, distance and focal depth for all three source types and find no significant bias. Find that PGAs from two events on east coast of Hokkaido are under-estimated and note that investigation needed to see if it is a regional anomaly. Also find that ground motions from 2003 Miyagi ($M_w$7.0) event are under-estimated, which note is due to a known regional anomaly.
- Believe model more robust than other models for subduction events due to lower prediction errors.
- Note that predictions for near-source ground motion for subduction events are largely constrained by data from shallow crustal events from western USA hence adding subduction records from $< 50$ km could result in improvements.

## 4.123 Wang et al. (2004)

- Ground-motion model is:
$$\log Y = a_1 + a_2(M-6) + a_3 \log \sqrt{r_{jb}^2 + h^2}$$
- Response parameter is pseudo-velocity for 5% damping.
- Use data from class D (soil) sites (Lee et al., 2001).
- Note that little confidence in $a_2$ because of limited magnitude range of data.

## 4.124 Yu and Hu (2004)

- Ground-motion model is:
$$\log Y = c_1 + c_2 M + c_3 \log(R + c_4 e^{c_5 M})$$
- Response parameter is acceleration for 5% damping.
- Use data from 377 sites with $V_{s,30} > 500$ m/s.
- Use data from the Trinet broadband high and low gain channels (BH and HL). BH are STS-1 and STS-2 instruments and HL are mainly FBA-23 instruments. Use BH data when not clipped and otherwise HL data.
- Eliminate DC offset for each record. Convert ground motions into acceleration while applying a high-pass filter with cut-off of 40 s. Display recovered acceleration, velocity and displacement time-histories from a $M_L 5.1$ earthquake from the BH and HL data. Note that they are similar and hence that reliable ground motion can be recovered from these data.
- Display the signal and noise Fourier amplitude spectra for one record and find that the signal-to-noise ratio is higher in the BH channel than in the HL channel. State that the signal-to-noise ratio is still $> 1$ for periods of 20 s for both types of data.
- Compute acceleration and relative displacement response spectra for both channels. Find that for periods $> 0.3$ s the response spectra from the two channels are very close. State that the difference for short periods is due to the low sampling rate (20 sps) for the BH channel and the higher (80 or 100 sps) sampling rate for HL channel.
- Conclude that reliable ground motions up to 20 s can be recovered from these data.
- Use a two-stage regression method where first determine $c_4$ and $c_5$ and then the other coefficients.
- Most data from digital instruments from $M \leq 5.5$ and $R < 300$ km. Most data from analogue instruments from $6.0 \leq M \leq 7.0$ and $10 < R < 100$ km.
- Use data from analogue instruments for short-period range (0.04–3 s) and data from Trinet instruments for long-period range (1–20 s). Connect the two sets of coefficients at 1.5 s after confirming that the predictions match at this period.
- Do not give coefficients only predictions.

## 4.125 Yu and Wang (2004)

- See Section 2.235.
- Response parameter is pseudo-acceleration for 5% damping.
- Use analogue data for spectral ordinates 0.04–2 s and data from broadband digital instruments for 1.5–6 s. Broadband data from mainly from $> 100$ km.
- Derive two separate models and then connect at $T = 2$ s (details not given).

## 4.126 Ambraseys et al. (2005a)

- See Section 2.237.
- Response parameter is acceleration for 5% damping.
- Only use spectral accelerations within passband of filter ($1.25 f_l$ and $f_h$) where $f_l$ is the low cut-off frequency and $f_h$ is the high roll-off frequency.
- Note that after 0.8 s the number of records available for regression analysis starts to decrease rapidly and that after 4 s there are few records available. Only conduct regression analysis up to 2.5 s because for longer periods there are too few records to obtain stable results. Note that larger amplitude ground motions are better represented in the set for long-periods ($> 1$ s).
- Find that logarithmic transformation may not be justified for nine periods (0.26, 0.28 and 0.44–0.65 s) by using pure error analysis but use logarithmic transformation since it is justified for neighbouring periods.
- By using pure error analysis, find that for periods $> 0.95$ s the null hypothesis of a magnitude-independent standard deviation cannot be rejected so assume magnitude-independent $\sigma$. Note that could be because magnitude-dependent standard deviations are a short-period characteristic of ground motions or because the distribution of data w.r.t. magnitude changes at long periods due to filtering.
- Find that different coefficients are significant at different periods so try changing the functional form to exclude insignificant coefficients and then applying regression again. Find that predicted spectra show considerable variation between neighbouring periods therefore retained all coefficients for all periods even when not significant.
- Note that smoothing could improve the reliability of long-period ground-motion estimates because they were based on less data but that smoothing is not undertaken since the change of weighted to unweighted regression at 0.95 s means a simple function cannot fit both short- and long-period coefficients.

## 4.127 Ambraseys et al. (2005b)

- See Section 2.238.
- Response parameter is acceleration for 5% damping.
- By using pure error analysis, find that for periods 0.15–0.40, 0.60–0.65, 0.75 and 0.85 s the null hypothesis of a magnitude-independent standard deviation be rejected so use weighted regression for these periods.

## 4.128 Bragato and Slejko (2005)

- See Section 2.240.
- Response parameter is acceleration for 5% damping.

## 4.129 García et al. (2005)

- See Section 2.242.
- Response parameter is pseudo-acceleration for 5% damping.
- No coefficient smoothing performed because coefficients w.r.t. frequency show acceptable behaviour.

## 4.130 McGarr and Fletcher (2005)

- See Section 2.244.
- Response parameter is pseudo-velocity for 5% damping.
- Constrain $k$ to 0 for $T \geq 0.5$ s because otherwise positive.

## 4.131 Pousse et al. (2005)

- Ground-motion model is:

$$\log_{10}(\text{PSA}(f)) = a(f)M + b(f)X - \log_{10}(X) + S_k$$

  Select this form to compare results with Berge-Thierry et al. (2003).

- Use five Eurocode 8 categories:

  A $V_{s,30} > 800$ m/s, use $S_1$

  B $360 < V_{s,30} < 800$ m/s, use $S_2$

  C $180 < V_{s,30} < 360$ m/s, use $S_3$

  D $V_{s,30} < 180$ m/s, use $S_4$

  E Soil D or C underlain in first 20 m by a layer of $V_{s,30} > 800$ m/s, use $S_5$

  where $V_{s,30}$ is average shear-wave velocity in upper 30 m. Since soil profiles only available up to 20 m, use method of Atkinson and Boore (2003) to assign sites to categories using Kik-Net profiles to define probability curves. Generate five redistributions to test stability of results. Find coefficients and $\sigma$ relative stable (changes less than 10%) except for site class A (changes up to 50%.

- Response parameter is pseudo-acceleration for 5% damping.
- Use data from the K-Net and Kik-Net networks.
- Process records using non-causal 4 pole Butterworth filter with cut-offs of 0.25 and 25 Hz for consistency with earlier studies.
- Select records from events with $M_w > 4$ and with focal depth $< 25$ km to exclude records of subduction events and to remain close to tectonic conditions in France.

- Exclude records from distances greater than a the distance predicted by a magnitude-dependent equation predicting the location of a PGA threshold of $10\,\text{cm/s}^2$ (corresponding to trigger of older Japanese sensors) to prevent possible underestimation of attenuation rate.
- Visually inspect records to check for glitches and to use only main shock if multiple events present.
- Convert $M_{\text{JMA}}$ to $M_w$ to compare results with other studies.
- For 10 large earthquakes for which source dimensions are known use $r_{rup}$.
- Note good distribution w.r.t. $M_w$ and $r_{rup}$ except between 6.1 and 7.3 where only two events.
- Find that pseudo-acceleration at 0.01 s equals PGA.
- Also compute coefficients using geometric mean and find identical coefficients and standard deviations lower by 0.02.
- Find $\sigma$ lower when use five site classes than when no site information is used.
- Find peak in $\sigma$ at about 1 s. Peak also present when unfiltered data used. Also present when data from different magnitude ranges (4.0–4.5, 4.0–5.0, 4.0–5.5 and 4.0–6.0) are used.
- Note that results for site class E are uncertain due to limited number of records.
- Examine residuals w.r.t. distance and magnitude and find no significant bias.
- Examine quartile plots of residuals and find that residuals are normally distributed up to 2–4 $\sigma$s. All pass Kolmogorov-Smirnov test at 5% significance level for normality except at 0.01 s.
- Conducted sensitivity analysis by changing minimum magnitude, geographical area and minimum number of events recorded at each station. Find dependence of $\sigma$ on period was similar as were site coefficients. $b$ shows some variations.
- Coefficients not reported.

## 4.132 Takahashi et al. (2005), Zhao et al. (2006) and Fukushima et al. (2006)

- See Section 2.248.
- Response parameter is acceleration for 5% damping.

## 4.133 Wald et al. (2005)

- See Section 2.249.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.134 Atkinson (2006)

- See Section 2.250.
- Response parameter is pseudo-acceleration for 5% damping.

- Compares predictions to observations grouped into 1-unit magnitude bins at 0.3 and 1.0 s and finds equations are reasonable description of data. Also compares predictions to observations from large magnitudes events and from close distances and finds that equations would overestimate short-period motions from large events at close distances.

- Compares overall distribution of residuals for 0.3 s with normal distribution. Finds that residuals generally follow normal distribution but data shows greater number of large-residual observations that predicted by normal distribution, most of which come from a single event (22/02/2000 **M**3.24) recorded at $> 100$ km. Finds no evidence for truncation of residuals up to three standard deviations.

- For analysis of Landers events, regresses 0.3 s data for 10 stations with more than 50 records using same functional form without distance terms (since distances are almost constant) to get site-specific equations. Find on average $\sigma = 0.19 \pm 0.04$. Therefore concludes single station-single source standard deviations much lower (60%) than standard $\sigma$s.

- Notes that decreasing $\sigma$ with increasing period could be due to dominance of small events for which long-period motions are at the moment end of the spectrum, which should be correlated with **M** and independent of stress drop.

## 4.135 Beyer and Bommer (2006)

- See Section 2.251.
- Response parameter is acceleration for 5% damping.
- Use records only up to maximum usable period specified in NGA database.

## 4.136 Bindi et al. (2006)

- See Section 2.252.
- Response parameter is pseudo-velocity for 5% damping.
- Only use records from within passband of filter. For $T > 2$ s only use digital records.

## 4.137 Campbell and Bozorgnia (2006a) and Campbell and Bozorgnia (2006b)

- See Section 2.253.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.138 Hernandez et al. (2006)

- See Section 2.256.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.139 Jaimes et al. (2006)

- See Section 2.257.
- Response parameter is acceleration for an unknown damping ratio (probably 5%).

## 4.140 Kanno et al. (2006)

- See Section 2.259.
- Response parameter is acceleration for 5% damping.
- Note the poorer correlation between residuals and $V_{s,30}$ for short periods could be due to higher modal effects or to nonlinear effects (although note that few records where nonlinear effects are likely).

## 4.141 Kataoka et al. (2006)

- See Section 2.260.
- Response parameter is acceleration for 5% damping.

## 4.142 McVerry et al. (2006)

- See Section 2.264.
- Response parameter is acceleration for 5% damping.

## 4.143 Pousse et al. (2006)

- See Section 2.266.
- Response parameter is pseudo-acceleration for 5% damping.
- Coefficients not reported.

## 4.144 Sakamoto et al. (2006)

- Ground-motion model is:

$$\begin{aligned} \log \mathrm{SA}(T) &= a(T)M_w + b(T)X + g + d(T)D + c(T) \\ \text{where} \quad g &= -\log(X+e) \quad \text{for} \quad D \leq 30\,\mathrm{km} \\ g &= 0.4\log(1.7D+e) - 1.4\log(X+e) \quad \text{for} \quad D > 30\,\mathrm{km} \\ e &= 0.00610^{0.5M_w} \end{aligned}$$

- Soil characteristics known to bedrock for 571 (out of 1013) stations. Classify stations using NEHRP classification using $V_{s,30}$ or converted $N$-values:

  A $V_{s,30} > 1500\,\mathrm{m/s}$, 0 stations

  B $760 < V_{s,30} \leq 1500\,\mathrm{m/s}$, 0 stations

  C1 $460 < V_{s,30} \leq 760\,\mathrm{m/s}$, 174 stations

  C2 $360 < V_{s,30} \leq 460\,\mathrm{m/s}$, 193 stations

  D1 $250 < V_{s,30} \leq 360\,\mathrm{m/s}$, 300 stations

  D2 $180 < V_{s,30} \leq 250\,\mathrm{m/s}$, 230 stations

  E $V_{s,30} \leq 180\,\mathrm{m/s}$, 116 stations

Define nonlinear (based on PGA at bedrock) soil amplification model using nonlinear analyses of sampled soil conditions for each class of soils. Use this model to convert observed ground motion to motion at a C1 site.

- Response parameter is acceleration for 5% damping.
- Focal depths, $D$, between 3 and 122 km.
- Distribution with respective to earthquake type (based on mechanism, location and depth) is: crustal ($3 \leq D \lesssim 25$ km), 13; interplate ($10 \lesssim D \lesssim 70$ km), 23; and intraplate, 16 ($30 \lesssim D \leq 122$ km).
- PGA from 2 to 1114 cm/s$^2$.
- Try including different constant terms to model effect of earthquake type but find lower statistical confidences of results. Therefore remove these coefficients. Believe that modelling of focal-depth dependency may already include effect of earthquake type due to high correlation between depth and type.
- Fit fourth-degree polynomials (in $\log(T)$) through derived coefficients to generate smooth spectra.
- Compare inter- and intra-event residuals to normal distribution using Kolmogorov-Smirnov test and find that the intra-event residuals have a normal distribution and that the inter-event residuals almost have.
- Examine magnitude-dependence of the standard deviations using residuals binned within different magnitude ranges ($M_w < 6.0$, $6.0 \leq M_w < 6.5$, $6.5 \leq M_w < 7.0$ and $M_w \geq 7.0$) and do not find a clear trend for either inter- or intra-event residuals.
- Examine distance-dependence of the intra-event standard deviations and find that for some periods the standard deviations show some depth-dependence for short and long distances.
- Examine amplitude-dependence of the intra-event standard deviations and find some positive dependence ($\sigma$ increases for higher amplitude motions) for $T \leq 0.4$ s. Note that this may be due to a lack of small amplitude motions due to nontriggering of instruments.

## 4.145 Sharma and Bungum (2006)

- Ground-motion model is:

$$\ln(A) = c_2 M - b \ln(X + \exp(c_3 M))$$

- Response parameter is acceleration for an unspecified damping (but assumed to be 5%).
- Use two site classes:

  R Rock. Generally granite/quartzite/sandstone.

  S Soil. Sites with exposed soil cover with different levels of consolidation.

- Data from three strong-motion (SMA-1) arrays: Kangra, Uttar Pradesh and Shillong, in the Himalayas.
- Instruments generally from ground floors of buildings.
- Rotate components into NS and EW directions.
- Focal depths between 7 and 121 km.
- Note that distribution of records is uneven. Five events have less than 9 records and one earthquake has 43.

- Note that $M_w$ avoids magnitude saturation problems.

- Note that lack of near-field data (all but one record from $> 20$ km) means that results are not stable. Therefore introduce nine European records from seven reverse-faulting earthquakes for $M \geq 6.0$ and $d_e \leq 20$ km.

- Use method of Campbell (1981) to avoid problems due to correlation between magnitude and distance. Divide data into a number of subsets based on distance. For each interval, each earthquake is given equal weight by assigning a relative weight of $1/n_{j,l}$ to the record where $n_{j,l}$ is the total number of records from the $j$th earthquake within $i$th distance bin. Normalise weights so that they sum to total number of records. Use distance bins of 5 km wide up to 10 km and then bins of equal width w.r.t. logarithmic distance.

- Use $r_{hypo}$ rather than $r_{rup}$ because: a) large depth of some events and b) poorly known fault geometries. Note that $r_{hypo}$ has a reasonable seismological basis and can be reliably and easily determined for most significant (including hypothetical design) earthquakes.

- Regress all data using: $\ln(A) = c - b\ln(X)$ and find $b = 1.22 \pm 0.69$. Next regress using: $\ln(A) = aM - b\ln(X) + c$ and find $b = 0.515 \pm 0.081$. Conclude that this is due to correlation between magnitude and distance and hence conduct the first step of a two-step regression with dummy variables for each earthquake. Find a decay rate of $-1.20 \pm 0.036$. Use this fixed decay rate for rest of analysis.

- Try to regress on rock and soil data simultaneously by including a linear site term $c_4 S_{SR}$ but find that there are problems during the regression process. Hence regress separately on rock and soil data.

## 4.146 Sigbjörnsson and Elnashai (2006)

- This is the same as Ambraseys et al. (1996) (see Section 2.134) but provides coefficients up to 4 s.

- Response parameter is acceleration for 5% damping.

## 4.147 Tapia (2006) & Tapia et al. (2007)

- See Section 2.268.

- Response parameter is acceleration for 5% damping.

## 4.148 Uchiyama and Midorikawa (2006)

- Ground-motion model is:

$$
\begin{aligned}
\log \mathrm{SA} &= aM_w + br_{rup} + g + dH + c \\
g &= \begin{cases} -\log(r_{rup} + 0.00610^{0.5M}) & H \leq 30\,\mathrm{km} \\ -1.4\log(r_{rup} + 0.00610^{0.5M}) + 0.4\log(1.7H + 0.00610^{0.5M}) & H > 30\,\mathrm{km} \end{cases}
\end{aligned}
$$

  where $H$ is focal depth.

- Response parameter is acceleration for 5% damping.

- Use 1 site class of engineering bedrock ($V_{s,30}$ is about 500 m/s).

- Use data from 1968 to 2003.

## 4.149 Zare and Sabzali (2006)

- See Section 2.270.
- Response parameter is not given but assumed to be acceleration for 5% damping.

## 4.150 Akkar and Bommer (2007b)

- See Section 2.271.
- Response parameter is displacement for 2, 5, 10, 20 and 30% damping. Choose displacement because of aimed use of equations for displacement-based design.
- Only use records within their usable range, defined as a fraction of the cut-off frequency used and depending on instrument type (digital or analogue), magnitude and site class.
- Note that drop-off in available records from analogue instruments is much more rapid (starting around 1 s) than for records from digital instruments (starting around 3 s). Due to lack of data for longer periods limit regression to periods $\leq 4$ s.
- Due to jagged appearance of predicted response spectra, particularly at long periods where different data was used for each period, apply negative exponential smoothing. Try smoothing using low-order polynomials, to achieve very smooth spectra, but complex functional form means results are sensitive to trade-offs between smoothed coefficients. Find that for periods $> 3$ s spectra predicted from the raw and smoothed coefficients show differences, especially for low damping ratios.
- Find that coefficients $b_7$-$b_{10}$ weakly dependent on damping ratio so present these coefficients for 2 and 5% damping (combined), 10% and 20 and 30% damping (combined).

## 4.151 Bindi et al. (2007)

- See Section 2.274.
- Response parameter is acceleration for 5% damping.
- Display graphs of inter-, intra-event and total standard deviations against period when using $M_w$ or $M_L$.

## 4.152 Bommer et al. (2007)

- See Section 2.275.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive equations only up to 0.5 s because thought that ground motions reliable up to this limit and since equations developed only for comparative purposes. Note that usable period range of data could be extended to 2 s but since study is for exploring influence of lower magnitude limit short-period motions are the most important.

## 4.153 Boore and Atkinson (2007) & Boore and Atkinson (2008)

- See Section 2.276.
- Response parameter is pseudo-acceleration for 5% damping.
- Do not use pseudo-accelerations at periods $> T_{MAX}$, the inverse of the lowest useable frequency in the NGA Flatfile.
- Constant number of records to 1 s, slight decrease at 2 s and a rapid fall off in number of records for periods $> 2$ s.
- For long periods very few records for small earthquakes ($M < 6.5$) at any distance so magnitude scaling at long periods poorly determined for small events.
- Choi and Stewart (2005) do not provide coefficients for site amplification for periods $> 5$ s so linearly extrapolate $b_{lin}$ in terms of log period by assuming relative linear site amplification to decrease.
- To assign $c_3$ for entire period range fit quadratic to $c_3$s from four-event analysis with constraints for short and long periods.
- No data from normal-faulting events for 10 s so assume ratio of motions for normal and unspecified faults is same as for 7.5 s.
- Possible underprediction of long-period motions at large distances in deep basins.
- Chi-Chi data major controlling factor for predictions for periods $> 5$ s even for small events.

## 4.154 Campbell and Bozorgnia (2007), Campbell and Bozorgnia (2008b) & Campbell and Bozorgnia (2008a)

- See Section 2.277.
- Response parameter is pseudo-acceleration (PSA) for 5% damping.
- If PSA $<$ PGA for $T \leq 0.25$ s then set PSA equal to PGA, to be consistent with definition of PSA (occurs for large distances and small magnitudes).
- Due to cut-off frequencies used number of records available for periods $>$ 4–5 s falls off significantly. Majority of earthquakes at long periods are for $6.5 \leq M \leq 7.9$ and 70% are from 1999 Chi-Chi earthquake.
- To extend model to longer periods and small magnitudes constrain the magnitude-scaling term using empirical observations and simple seismological theory.

## 4.155 Danciu and Tselentis (2007a), Danciu and Tselentis (2007b) & Danciu (2006)

- See Section 2.278.
- Response parameter is acceleration for 5% damping.

## 4.156 Fukushima et al. (2007c) & Fukushima et al. (2007b)

- Ground-motion model is [same as Fukushima et al. (2003)]:

$$\log_{10}(\mathrm{Sa}(f)) = a(f)M - \log_{10}(R + d(f) \times 10^{e(f)M}) + b(f)R + \Sigma c_j(f)\delta_j$$

  $\delta_j = 1$ for $j$th site class and 0 otherwise.

- Use five site categories:

  SC-1 Site natural period $T_G < 0.2$ s, $V_{s,30} > 600$ m/s, NEHRP classes A+B. 23 sites.

  SC-2 Site natural period $0.2 \leq T_G < 0.6$ s, $200 \leq V_{s,30} < 600$ m/s, NEHRP classes C+D. 100 sites.

  SC-3 Site natural period $T_G \geq 0.6$ s, $V_{s,30} \leq 200$ m/s, NEHRP class E. 95 sites.

  SC-4 Unknown site natural period, $V_{s,30} > 800$ m/s, NEHRP classes A+B. 44 sites.

  SC-5 Unknown site natural period, $300 \leq V_{s,30} < 800$ m/s, NEHRP class C. 79 sites.

  Manually classify stations using the predominant period computed using average horizontal-to-vertical (H/V) response spectral ratios using similar approach to Zhao et al. (2006) and also mean residuals w.r.t. equations of Fukushima et al. (2003). Reclassify stations of Fukushima et al. (2003), who used rock/soil classes. Some (36%) stations cannot be classified (due to, e.g., broadband amplification) using this approach so retain rock/soil classes for these records. Use this approach since limited geotechnical data is available for most sites in their dataset. Only roughly 30% of stations have multiple records so the average H/V ratios are not statistically robust so do not use automatic classification approach. Each co-author independently classified stations. About 90% of classifications agreed. After discussion the stations were reclassified. Originally used same categories as Zhao et al. (2006) but find their class SC-III too narrow so combine it with their SC-II to form SC-2. Find similar average ratios for the different categories as Zhao et al. (2006).

- Response parameter is acceleration for 5% damping.

- Use data and regression method of Fukushima et al. (2003). Eliminate data from two stations of Fukushima et al. (2003) because of suspected soil-structure interaction.

- Coefficients not reported since focus of article is the site classification procedure and its impact on predicted response spectra and not to propose a new model for seismic hazard assessment.

- Records filtered with cut-offs at 0.25 and 25 Hz therefore present results up to 3 s to avoid filter effects.

- Find roughly 2% reduction in standard deviation using classification scheme compared to rock/soil scheme.

## 4.157 Hong and Goda (2007) & Goda and Hong (2008)

- See Section 2.283.

- Response parameter is pseudo-acceleration for 5% damping.

- Select the period range of usable PSA values based on cut-off frequencies of the high-pass filters used to correct records.

- Develop an orientation-dependent ground-motion measure based on maximum resultant response and ratio between response of an (arbitrarily) oriented SDOF system and maximum resultant response.

- Derive equations for the probability of exceedance for SDOF systems designed for different ways of combining the two horizontal components subjected to ground motions from an unknown direction.

- Investigate record-to-record variability of response and implied exceedance probability using a set of 108 records used by Boore et al. (1997) for 0.2 and 1.0 s. Conclude that when using common methods for combining two horizontal components (such as geometric mean) that meaning of the return period of uniform hazard spectra is not clear because the major and minor axes of shaking are unknown before an event.

- Investigate SA resolved for different directions normalized by SA along the major axis for all selected records. Conclude that knowing SA along the major axis and the normalized SA for different direction completely defines the response in any direction. Derive empirical equation for the normalized SA w.r.t. angle and its probability distribution.

- Only report coefficients for 0.2, 0.3, 1, 2 and 3 s in article. Provide coefficients for other periods as electronic supplement.

## 4.158 Massa et al. (2007)

- See Section 2.284.

- Response parameter is acceleration for 5% damping.

## 4.159 Tejeda-Jácome and Chávez-García (2007)

- See Section 2.288.

- Response parameter is pseudo-acceleration for 5% damping.

- Signal-to-noise ratios mean analysis limited to 1 s for horizontal and 0.8 s for vertical.

## 4.160 Abrahamson and Silva (2008) & Abrahamson and Silva (2009)

- See Section 2.289.

- Response parameter is pseudo-acceleration for 5% damping.

- Records only used for spectral frequencies 1.25 times the high-pass corner frequency used in the record processing. Therefore, number of records and earthquakes available for regression decreases with increasing period.

- Fix $a_2$, $a_{12}$, $a_{13}$, $a_{16}$ and $a_{18}$ at their values for 2–4 s for $T > 5$ s because they could not be constrained by data.

- Smooth coefficients in several steps.

## 4.161 Aghabarati and Tehranizadeh (2008)

- See Section 2.291.

- Response parameter is pseudo-acceleration for 5% damping.

## 4.162 Cauzzi and Faccioli (2008), Cauzzi (2008) & Cauzzi et al. (2008)

- See Section 2.293.
- Response parameter is displacement for 5, 10, 20 and 30% damping.
- Coefficients reported as Electronic Supplementary Material.
- Try replacing site terms: $a_B$, $a_C$ and $a_D$ by $b_4 10^{b_5 M_w}$, $b_6 10^{b_7 M_w}$ and $b_8 10^{b_9 M_w}$ but do not report coefficients since did not lead to reduction in standard deviation.
- Compare predictions and observations for Parkfield 2004 earthquake. Find good match.
- Study residuals for site classes B, C and D w.r.t. predicted ground motion to check for nonlinear site response. Find some evidence for moderate nonlinear effects in limited period ranges.

## 4.163 Chen and Yu (2008a)

- Ground-motion model is:

$$\log \mathrm{Sa} = C_1 + C_2 M + C_3 M^2 + C_4 \log[R + C_5 \exp(C_6 M)]$$

- Use records from sites with $V_{s,30} \geq 500\,\mathrm{m/s}$.
- Use the NGA Flatfile.
- Response parameter is acceleration for 5% damping.
- Data divided into magnitude intervals of: 5.0–5.4, 5.5–5.9, 6.0–6.4, 6.5–6.9 and 7.0–7.5 and distance intervals of: 0–2.9 km, 3.0–9.9 km, 10–29.9 km, $30 - 59.9$ km, 60-99.9 km, 100–200 km and $> 200$ km. Use weighted regression with weights given by inverse of number of records in each magnitude-distance bin since most data from moderate earthquakes at intermediate distances.
- Compute $C_5$ and $C_6$ using data from six earthquakes: 1979 Imperial Valley ($M6.53$), 1980 Livermore ($M5.42$), 1989 Loma Prieta ($M6.93$), 1992 Landers ($M7.28$), 1999 Hector Mine ($M7.13$) and 2004 Parkfield ($M5.9$).

## 4.164 Chen and Yu (2008b)

- Response parameter is acceleration for 0.5, 2, 7, 10 and 20% damping.
- Continuation of Chen and Yu (2008a) (Section 4.163) for other damping levels.

## 4.165 Chiou and Youngs (2008)

- See Section 2.295.
- Response parameter is pseudo-acceleration for 5% damping.
- Coefficients developed through iterative process of performing regressions for entire spectral period range with some parts of model fixed, developing smoothing models for these coefficients with period, and then repeating analysis to examine variation of remaining coefficients. Note noticeable steps in $c_1$ at 0.8, 1.1, 1.6, 4.0 and 8.0 s, where there is large reduction in usable data. Suggest that this could indicate bias due to systematic removal of weaker motions from data set. To correct this bias and to smooth $c_1$ impose smooth variation in slope of $c_1$ w.r.t. period. Also examine shape of displacement spectra for $M \geq 6.5$ to verify that constant displacement reached at periods expected by design spectra.

## 4.166 Cotton et al. (2008)

- See Section 2.296.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.167 Dhakal et al. (2008)

- Ground-motion model is:

$$\log_{10} Y(T) = c + aM_w + hD - \log_{10} R - b_1 R_1 - b_2 R_2$$

- Response parameter is pseudo-velocity for 5% damping.
- Use $R_1$, distance from hypocentre to volcanic front, and $R_2$, distance from volcanic front to site, to model anelastic attenuation.
- Use data from K-Net. Select earthquakes that: 1) have $M_w > 5$ and 2) have more than 50 available records. To remove bias due to large number of records from fore-arc site compared to back-arc, select only those earthquakes with 40% of the available records within 300 km are from back-arc region. Use both interplate and intraslab events occurring in fore-arc region so that effect of low $Q$ zone is clearly seen. Only use records up to 300 km so that peaks are due to S-wave motions. Exclude records from $M_w 8$ earthquakes because these events radiate strong surface waves so assumption of S-wave peaks may not be valid.
- Focal depths, $D$, of intraslab earthquakes between 59 and 126 km and for interface[10] earthquakes between 21 and 51 km.
- Also derive model using: $\log_{10} Y(T) = c + aM_w + hD - \log_{10} R - bR$. Find lower $\sigma$s for functional form using $R_1$ and $R_2$ for periods $< 1$ s. Examine residuals w.r.t. $r_{hypo}$ for 0.1 and 1.0 s with grey scale indicating ratio $R_1/(R_1 + R_2)$ for this functional form. Note that fore-arc sites have positive residuals and back-arc sites negative residuals. Also plot residuals for selected functional form and find that residuals do not show difference between fore-arc and back-arc sites.
- Regress separately for intraslab and interface earthquakes because source characteristics significantly different.
- Find that the coefficients for anelastic attenuation for fore-arc and back-arc different for periods $< 2$ s.
- Convert computed anelastic coefficients to $Q$ models and find that can relate observations to different $Q$ models for fore-arc and back-arc regions.

## 4.168 Hancock et al. (2008) & Hancock (2006)

- Ground-motion model is:

$$\log y = c_1 + c_2 M + c_3 M^2 + c_4 \log \sqrt{r_{jb}^2 + c_6^2} + c_5 \sqrt{r_{jb}^2 + c_6^2} + c_7 S_1 + c_8 S_2 + c_9 F_1 + c_{10} F_2$$

- Response parameter is pseudo-acceleration for 1, 5 10 and 20% damping.
- Use 3 site classes:

[10] Authors call them 'interplate'.

Rock $V_{s,30} > 760$ m/s. $S_1 = S_2 = 0$.

Stiff soil $360 \leq V_{s,30} \leq 760$ m/s. $S_2 = 1$, $S_1 = 0$.

Soft soil $V_{s,30} < 360$ m/s. $S_1 = 1$, $S_2 = 0$.

- Use 3 fault mechanisms:

  1. Strike-slip. $F_1 = F_2 = 0$.
  2. Normal. $F_1 = 1$, $F_2 = 0$.
  3. Reverse/reverse-oblique. $F_2 = 1$, $F_1 = 0$.

  Classify using rake angles. Find reverse/reverse/oblique motions similar based on residuals so combine into single class.

- Derive model for use in study on number of scaled and matched accelerograms required for inelastic dynamic analyses of structures.

- Use PEER NGA West database (Chiou et al., 2008). Only use data with known $M_w$, $r_{jb}$ and site class. Exclude records from Taiwan to reduce database and prevent the 1813 accelerograms from the 1999 Chi-Chi sequence dominating results. Exclude records where either horizontal component was filtered with high-pass cut-off $> 0.33$ Hz.

- Most records from strike-slip earthquakes, followed by reverse and lastly normal, for which limited data available and over magnitude range $5.6 \leq M_w \leq 6.9$.

- Note that model is not for general use and hence coefficients not reported in journal article.

## 4.169 Idriss (2008)

- See Section 2.299.

- Response parameter is pseudo-acceleration for 5% damping.

- Uses all records (including those from Chi-Chi) to constrain coefficients for $1.5 \leq T \leq 5$ s because influence of Chi-Chi records decreases with increasing period.

- Uses smoothed plots to obtain coefficients for $T > 5$ s because of lack of records.

## 4.170 Kataoka et al. (2008)

- Ground-motion model is:

$$\log_{10} Y = a_1 M_w - bX + c_0 - d \log_{10}(X + p10^{qM_w}) + c_j$$

- Response parameter is acceleration for 1% and 5% damping.

- Follow-up study to Kataoka et al. (2006) for periods $\geq 2$ s.

- Derive separate models using data from crustal (focal depth $\leq 16$ km) earthquakes and subduction (focal depths 0 to 59 km) earthquakes.

## 4.171 Lin and Lee (2008)

- See Section 2.300.
- Response parameter is acceleration for 5% damping.

## 4.172 Massa et al. (2008)

- See Section 2.301.
- Response parameters are acceleration and pseudo-velocity for 5% damping.

## 4.173 Morasca et al. (2008)

- See Section 2.303.
- Response parameter is pseudo-velocity for 5% damping.

## 4.174 Yuzawa and Kudo (2008)

- Ground-motion model is:

$$\log S(T) = a(T)M - [\log X_{eq} + b(T)X_{eq}] + c(T)$$

- Response parameter is acceleration for 5% damping.
- Use data from KiK-Net at hard rock sites with shear-wave velocity $V_s \geq 2.0$ km/s at surface and/or in borehole. Select records from 161 sites (out of 670 sites of KiK-Net) where spectral ratio between surface and borehole records $\leq 2$ at periods $> 1$ s. Note that preferable to use higher velocity (3.0 km/s) but as velocity increases number of available sites rapidly decreases: 43 sites with $V_s = 2.0$–$2.2$ km/s, 33 with $V_s = 2.2$–$2.4$, 27 with $V_s = 2.4$–$2.6$, 31 with $V_s = 2.6$–$2.8$, 16 with $V_s = 2.8$–$3.0$, 8 with $V_s = 3.0$–$3.2$ and 3 with $V_s > 3.2$ km/s.
- Select earthquakes based on their magnitudes, horizontal locations and depths and types (crustal, interface and intraslab). Note that geographical distribution is not homogeneous but it covers whole of Japan.
- Focal depths between 8.58 and 222.25 km.
- Also derive model using $M_w$. Find predictions similar so use prefer $M_{JMA}$ for convenience of application in Japan.
- Only graphs of coefficients presented.

## 4.175 Aghabarati and Tehranizadeh (2009)

- See Section 2.307.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.176 Akyol and Karagöz (2009)

- See Section 2.308.
- Response parameter is acceleration for 5% damping.
- Observe nonlinear site effects in residuals for periods $\leq 0.27$ s, which model using site coefficient correction terms.

## 4.177 Bindi et al. (2009a)

- See Section 2.310.
- Response parameter is acceleration for 5% damping.

## 4.178 Bindi et al. (2009b)

- See Section 2.311.
- Response parameter is acceleration for 5% damping.

## 4.179 Bragato (2009)

- See Section 2.312.
- Response parameter is acceleration for 5% damping.
- Coefficients not reported, only $\sigma$s.

## 4.180 Ghasemi et al. (2009)

- Ground-motion model is:

$$\log_{10} \mathrm{Sa} = a_1 + a_2 M + a_3 \log_{10}(R + a_4 10^{a_5 M}) + a_6 S_1 + a_7 S_2$$

  after trying various other functional forms. Fix $a_5$ to 0.42 from previous study due to lack of near-field data and unstable regression results.

- Use two site classes:

  Rock $V_{s,30} \geq 760$ m/s. $S_1 = 1$, $S_2 = 0$.

  Soil $V_{s,30} < 760$ m/s. $S_2 = 1$, $S_1 = 0$.

  Classify station using $V_{s,30}$ and surface geology data, if available. Otherwise use empirical H/V classification scheme.

- Response parameter is acceleration for 5% damping.
- Investigate differences in ground motions between Alborz-Central Iran and Zagros regions using analysis of variance (ANOVA) (Douglas, 2004b) to check whether data can be combined into one dataset. Find that for only one magnitude-distance interval out of 30 is there a significant difference in ground motions between the two regions. Hence, combine two datasets.

- Check that data from West Eurasia and Kobe from Fukushima et al. (2003) can be combined with data from Iran using ANOVA. Find that for only one magnitude-distance interval is there a significant difference in ground motions and, therefore, the datasets are combined.
- Only retain data from $R < 100$ km to avoid bias due to non-triggered instruments and because data from greater distances is of low engineering significance.
- Process uncorrected records by fitting quadratic to velocity data and then filtering acceleration using a fourth-order acausal Butterworth filter after zero padding. Choose filter cut-offs by using the signal-to-noise ratio using the pre-event noise for digital records and the shape of the Fourier amplitude spectra for analogue records. Only use records for periods within the passband of the filters applied.
- Exclude data from earthquakes with $M_w < 5$ because of risk of misallocating records to the wrong small events and because small events can be poorly located. Also records from earthquakes with $M_w < 5$ are unlikely to be of engineering significance.
- Cannot find negative anelastic coefficients for periods $> 1$ s and therefore exclude this term for all periods.
- Try including a $M^2$ term but find that it is not statistically significant so remove it.
- Examine residuals (display graphs for 0.1 and 1 s) w.r.t. $M$ and $R$. Find no significant (at 5% level) trends.
- Examine histograms of residuals for 0.1 and 1 s and find that expected normal distribution fits the histograms closely.

## 4.181 Goda and Atkinson (2009)

- See Section 2.315.
- Response parameter is pseudo-acceleration for 5% damping.
- Report coefficients for 8 periods but others available on request to authors.
- Plot total residuals for 0.2 and 1.0 s w.r.t. $M_w$ and $H$ and compute averages for events and plot intra-event residuals w.r.t. $r_{rup}$ and add a moving average. Find no significant trends.
- Plot intra-event residuals (with moving average) w.r.t. $r_{rup}$ for 6 individual well-recorded events: 2001 Geiyo ($M_w$6.8, $H = 51$ km), 2003 Tokachi-Oki ($M_w$7.9, $H = 42$ km), 2004 Kii Hantou Nansei-oki ($M_w$7.5, $H = 44$ km), 2004 mid-Niigata-ken ($M_w$6.6, $H = 13$ km), 2007 Niigata-ken Chuetsu ($M_w$6.6, $H = 17$ km) and 2008 Iwate-Miyagi ($M_w$6.9, $H = 8$ km) for 0.2 and 10 s and conclude residuals are unbiased.

## 4.182 Hong et al. (2009a)

- See Section 2.316.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.183 Hong et al. (2009b)

- See Section 2.317.
- Response parameter is pseudo-acceleration for 5% damping.
- Only report coefficients for three periods (0.3, 1 and 3 s).

## 4.184 Kuehn et al. (2009)

- See Section 2.318.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data up to highest usable period.
- Note that could choose different functional form for each period separate but believe effect would be small so use the same for all periods.

## 4.185 Moss (2009) & Moss (2011)

- See Section 2.321.
- Response parameter is pseudo-acceleration for 5% damping.
- Finds maximum decrease in $\sigma$ is 9% at 3 s.

## 4.186 Rupakhety and Sigbjörnsson (2009)

- See Section 2.323.
- Response parameter is acceleration for 5% damping.
- Also provide coefficients for constant-ductility inelastic spectral ordinates and structural behaviour factors for application within Eurocode 8.
- Coefficients only reported for 29 periods — graphs for rest.
- Note that coefficients are not smooth functions w.r.t. period, which is undesirable for practical purposes. Smooth coefficients using Savitzky-Golay procedure with a span of 19 and a quadratic polynomial and then recomputed $\sigma$. Verify that smoothing does not disturb inherent correlation between model parameters by comparing correlation matrix of coefficients before and after smoothing. Find that smoothing has little effect on matrix nor on $\sigma$.

## 4.187 Sharma et al. (2009)

- Ground-motion model is:

$$\log A = b_1 + b_2 M_w + b_3 \log \sqrt{R_{JB}^2 + b_4^2} + b_5 S + b_6 H$$

- Response parameter is acceleration for 5% damping.
- Use two site classes:

$S = 1$ Rock. 69 records.

$S = 0$ Soil. 132 records.

- Focal depths between 5 and 33 km for Iranian events and 19 and 50 km for Indian earthquakes.
- Use two fault mechanisms:

$H = 0$ Reverse. 8 earthquakes and 123 records.

$H = 1$ Strike-slip. 8 earthquakes and 78 records.

- Seek to develop model for Indian Himalayas. Due to lack of near-source data from India include data from the Zagros region of Iran, which has comparable seismotectonics (continental compression). Note that some differences, in particular the higher dip angles of reverse events in the Zagros compared to those in the Himalayas.
- Use data from three strong-motion arrays in Indian Himalayas: Kangra array in Himachal Pradesh, Uttar Pradesh and Shillong array in Meghalaya and Assam, and from Iran Strong-Motion Network. Note that records from at least three significant Himalayan earthquakes have not yet been digitized.
- Use some non-Zagros data from Iran because of similar focal mechanisms and since no significant difference in ground motions between these events are those in the Zagros was observed.
- Note that data seems to be adequate between $M_w 5$ and 7 and up to 100 km.
- To exclude data from earthquakes that show anomalous behaviour, the PGAs for each earthquake individually were plotted against distance. Find that decay rates for 6/2/1988 and 14/3/1998 earthquakes were different than rest so data from these events were excluded.
- Also exclude data from two earthquakes (6/8/1988, 10/1/1990 and 6/5/1995) due to their great hypocentral depths ($> 90$ km).
- Also exclude data from eight earthquakes (9/1/1990, 24/3/1995, 14/12/2005, 29/11/2006, 10/12/2006, 9/6/2007, 18/10/2007 and 25/11/2007) because no focal mechanisms published.
- Prefer $r_{jb}$ partly because of lack of reliable depths for most Himalayan earthquakes.
- Estimate $r_{jb}$ for some earthquakes by using reported focal mechanism and relationships of Wells and Coppersmith (1994).
- Use explicit weighting method of Campbell (1981) with equal weights given to records falling into three ranges: $\leq 10$ km, 10–100 km and more than 100 km.
- Note that high standard deviations partly due to low quality of site information, large uncertainties in source-to-site distances and simple functional form.

## 4.188 Akkar and Bommer (2010)

- See Section 2.324.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive equations up to 4 s but only report coefficients to 3 s because of a significant drop in available data at this period and because of the related issue of a sudden change in $\sigma$ (particularly intra-event $\sigma$) at 3.2 s.

## 4.189 Akkar and Çağnan (2010)

- See Section 2.325.
- Response parameter is pseudo-acceleration for 5% damping.
- Data become scarce for $T > 2$ s due to cut-off frequencies used and, therefore, do not derive equations for longer periods. Limit of 0.03 s is based on Nyquist (sampling rates are generally $\geq 100$ Hz) and high-cut filtering used (generally $> 30$ Hz). Note that this conservative choice is based on the study of Douglas and Boore (2011).

## 4.190 Amiri et al. (2009)

- Ground-motion model is:

$$\log(\mathrm{SA}) = C_1 + C_2 M_s + C_3 \log(R)$$

- Use two site classes that are consistent with Iranian design code and derive equations for each separately:

  Soil $V_s < 375$ m/s.

  Rock $V_s > 375$ m/s.

- Response parameter is acceleration for 5% damping.
- Focal depths between 5 and 59 km but most 10 km.
- Based on Amiri et al. (2007a) (see Section 2.272) but using larger and reappraised dataset.
- Derive models for Zagros and Alborz-Central Iran separately.
- Note the poor quality of some Iranian strong-motion data. Selected data based on accuracy of independent parameters.
- State that faulting mechanism is known for only a small proportion of data. Therefore, it is not considered.
- Use $M_s$ because it is the most common scale for Iranian earthquakes.
- Most data from $M_s < 6.5$ and $5 < r_{hypo} < 200$ km. Note lack of near-source data from $M_s > 6$.
- Because of small and moderate size of most earthquakes used and since causative faults are not known for many earthquakes use $r_{hypo}$, which compute using S-P method because of uncertainty in reported hypocentral locations.
- Data from SMA-1 (about 210 records on soil and 130 on rock) and SSA-2 (about 220 records on soil and 170 on rock).
- Bandpass filter records using cut-off frequencies chosen based on instrument type and data quality. Cut-offs chosen by trial and error based on magnitude and distance of record and obtained velocity. Generally cut-offs are: 0.15–0.20 Hz and 30–33 Hz for SSA-2 on rock, 0.15–0.25 Hz and 20–23 Hz for SMA-1 on rock, 0.07–0.20 Hz and 30–33 Hz for SSA-2 on soil and 0.15–0.20 Hz and 20–23 Hz for SMA-1 on soil.
- Choose functional form after many tests (not shown) and because it is simple but physically justified.
- Note that predictions show peaks and valleys since no smoothing applied.
- Report that residual analysis (not shown) shows predictions are unbiased w.r.t. magnitude, distance and site conditions.

## 4.191 Arroyo et al. (2010)

- See Section 2.326.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.192 Bindi et al. (2010)

- See Section 2.327.
- Response parameter is acceleration for 5% damping.

## 4.193 Bozorgnia et al. (2010)

- Ground-motion model is same as Campbell and Bozorgnia (2007, 2008b) (see Section 2.253) except that do not apply constraints to computed regression coefficients and for geometric mean.

- Model derived for comparison with models for inelastic response spectral ordinates, which are derived in same study.

- For elastic spectra recommend model of Campbell and Bozorgnia (2007, 2008b).

## 4.194 Das and Gupta (2010)

- Ground-motion model is:

$$
\begin{aligned}
\log_{10}[\mathrm{PSV}(T)] &= a_1(T)M + a_4(T)\log_{10} D + a_5(T)h + (a_6(T) + a_7(T)M)s + a_8(T) \\
D &= \sqrt{r_{rup}^2 + D_{sat}^2} \\
D_{sat} &= 0.0072410^{0.507M}
\end{aligned}
$$

- Use 3 site classes:

  1. Soil soil. $s = 0$
  2. Stiff soil. $s = 1$
  3. Rock or very dense soil. $s = 2$

- Response parameter is pseudo-velocity for 5% damping.

- Derive model for comparison with conditional scaling model for prediction of PSV in aftershocks given PSV in mainshock.

- Use data from 1999 Chi-Chi earthquake ($M7.3$, $h = 10.33$ km, 93 records) and its 15 largest aftershocks ($4.99 \leq M \leq 6.80$, between 3 and 51 records per event, 405 records in total). Records from 93 stations, which did not contribute equal numbers of records. Select records with $r_{epi} \leq 50$ km since aftershock motions are very weak at larger distances. Did not use data from stations that did not trigger in mainshock.

- Focal depths $1.0 \leq h \leq 16.8$ km.

- Exclude data from 11 records for $T > 5s$ because of noise in PSV spectra.

- Original include $a_2(T)M^2$ and $a_3(T)D$ terms but these are removed because $a_2(T)$ and $a_3(T)$ are positive, which is unphysical. Conclude insufficient data to constrain these coefficients.

- Compare coefficients and $\sigma$s from conditional and unconditional models and conclude that can roughly obtain conditional model from unconditional one.

- Do not report coefficients.

## 4.195 Douglas and Halldórsson (2010)

- See Section 2.329.

- Response parameter is acceleration for 5% damping.

## 4.196 Faccioli et al. (2010)

- See Section 2.330.
- Response parameter is displacement for 5% damping.
- Coefficients only given for a subset of periods for which analysis conducted.
- Site terms particularly important for $T \geq 0.25$ s, where reduction in $\sigma$ is between 5% and 15%.

## 4.197 Hong and Goda (2010)

- See Section 2.332.
- Response parameter is pseudo-acceleration for 5% damping.
- Present correlation models between ground motions at different periods.

## 4.198 Jayaram and Baker (2010)

- See Section 2.334.
- Response parameter is pseudo-acceleration for 5% damping.
- Report coefficients only for 1 s.

## 4.199 Montalva (2010) & Rodriguez-Marek et al. (2011)

- See Section 2.335.
- Response parameter is pseudo-acceleration for 5% damping.
- Residual analysis shown for 0.03, 0.2, 0.6, 1.0 and 1.4 s.

## 4.200 Ornthammarath et al. (2010), Ornthammarath (2010) & Ornthammarath et al. (2011)

- See Section 2.336.
- Response parameter is acceleration for 5% damping.

## 4.201 Rodriguez-Marek and Montalva (2010)

- Ground-motion model is a simplified version of Boore and Atkinson (2008), because it is the simplest NGA functional form[11]:

$$
\begin{aligned}
\ln(\bar{y}) &= F_m + F_d + F_{site}(S_{surface}) + [F_{100}(S_{100}) + F_{200}(S_{200})](1 - S_{surface}) \\
F_d &= [c_1 + c_2(M - M_{ref})]\ln(R/R_{ref}) + c_3(R - R_{ref}) \\
R &= \sqrt{R^2 + h^2} \\
F_m &= e_1 + e_5(M - M_h) + e_6(M - M_h)^2 \quad \text{for} \quad M < M_h \\
F_m &= e_1 + e_7(M - M_h) \quad \text{for} \quad M > M_h \\
F_{site} &= b_{lin}\ln(V_{s,30}/V_{ref}) \\
F_{100} &= a_{100} + b_{100}\ln(V_{s,30}/V_{ref}) + c_{100}\ln(V_{s,hole}/3000) \\
F_{200} &= a_{200} + b_{200}\ln(V_{s,30}/V_{ref}) + c_{200}\ln(V_{s,hole}/3000)
\end{aligned}
$$

- Sites characterized by $V_{s,30}$, $V_{s,hole}$ (shear-wave velocity at depth of instrument), $S_{surface}$ (1 for surface record, 0 otherwise), $S_{100}$ (1 for borehole record from $< 150$ m depth, 0 otherwise) and $S_{200}$ (1 for borehole record from $> 150$ m depth, 0 otherwise).

- Response parameter is pseudo-acceleration for 5% damping.

- Use the same data as Cotton et al. (2008) (see Section 2.296).

- Develop GMPEs for use in the estimation of single-station $\sigma$.

- Note that functional form assumes that magnitude and distance dependency are the same for both surface and borehole records. Also assume that site amplification is linear, which note appears to be true for most records but not all but insufficient data to constrain nonlinearity using purely empirical method so ignore it.

- For regression: use only surface data to constrain $b_{lin}$, use both surface and borehole records to compute inter-event $\sigma$s and assume intra-event $\sigma$s independent of magnitude. Note that final assumption is somewhat limiting but use residual analysis to examine dependency of intra-event terms on depth, $V_{s,30}$ and magnitude.

- Compute single-station $\sigma$s based on residuals from the 44 stations that recorded $\geq 15$ earthquakes. Averaged these 44 $\sigma$s to obtain a single estimate of single-station $\sigma$. Note that more work on these $\sigma$s is being undertaken. Find single-station $\sigma$s are on average 25% lower than total $\sigma$. Find that total $\sigma$s obtained for borehole stations lower than those at surface but the single-station $\sigma$s are not considerable different on the surface and in boreholes.

## 4.202 Sadeghi et al. (2010)

- Ground-motion model is:

$$
\begin{aligned}
\log A &= a(f) + b(f)M - c_1(f)\log R - k(f)R \quad \text{for} \quad R \leq R_1 \\
\log A &= a(f) + b(f)M - c_1(f)\log R_1 - c_2(f)\log(R/R_1) - k(f)R \quad \text{for} \quad R_1 < R \leq R_2 \\
\log A &= a(f) + b(f)M - c_1(f)\log R_1 - c_2(f)\log(R_2/R_1) - c_3(f)\log(R/R_2) - k(f)R \\
&\quad \text{for} \quad R > R_2
\end{aligned}
$$

  Functional form chosen to enable modelling of effect of reflections off Moho and surface wave attenuation.

[11]Number of typographic errors in report so this may not be correct functional form.

- Use two site classes:

  Soil $V_{s,30} < 750$ m/s or, for 30 stations classified using H/V ratios, $f_0 < 7.5$ Hz where $f_0$ is peak frequency. 556 records.

  Rock $V_{s,30} > 750$ m/s or , for 30 stations classified using H/V ratios, $f_0 > 7.5$ Hz. 213 records.

  Develop models for all data and only soil records.

- Data from 573 different stations.

- Response parameter is acceleration for 5% damping.

- Also develop separate models for regions of Alborz (20 earthquakes and 423 records), Zagros (27 earthquakes and 198 records), East (32 earthquakes and 262 records) and Central South (20 earthquakes and 175 records). Note that regionalization is limited by lack of data for other regions.

- Use data recorded by National Strong Motion Network of Iran from 1987 to 2007.

- Select data by criterion of earthquake having being recorded by $\geq 3$ stations within 350 km.

- Most data from $M_w < 6.5$ and $r < 150$ km.

- Insufficient data to constrain model for $R > R_2$ therefore set geometric spreading coefficient to 0.5.

- Use Monte Carlo technique to find coefficients.

- Fit $a$ and $b$ to functional forms: $a_1 + a_2 \exp(-a_3 T)$ and $b_1 + b_2 T + b_3 T^2 + b_4 T^3$ respectively. Also present model assuming $a = a_1 + a_2 T + a_3 T + a_4 T^3$.

- Plot residuals against $r_{epi}$.

- Believe model can be applied for $5 < M < 7.5$ and $r_{epi} < 200$ km.

## 4.203 Saffari et al. (2010)

- Ground-motion model is:

$$\log A = a(T)M_w - \log[X + d(T)10^{0.5M_w}] - b(T)X + c_{Rock}L_R + c_{Soil}L_S$$

- Use two site classes:

  Rock $L_R = 1$, $L_S = 0$.

  Soil $L_S = 1$, $L_R = 0$.

- Focal depths between 7 and 72 km with most between 10 and 30 km.

- Response parameter is acceleration for 5% damping.

- Use data from Iranian Strong-Motion Network run by Building and Housing Research Centre.

- Select data based on these criteria: $M_w \geq 5$, record on ground surface (free-field) and two orthogonal horizontal components available. Apply a $M_w$-dependent distance filter. After first regression data again truncated based on the median plus one $\sigma$ model and a trigger level of 10 gal.

- Examine data binned by $M_w$ w.r.t. distance and remove earthquakes with irregular distributions (due to tectonic or other reasons).

- Baseline correct and bandpass filter (cut-offs of 0.2 and 20 Hz) data based on characteristics of instruments (SSA-2 and SMA-1).
- Use rock data to define all coefficients and then compute $c_{Soil}$ and $\sigma_{Soil}$ using soil data and the coefficients defined from rock data (details not given).
- Smooth coefficients using fifth-degree polynomial based on logarithm of period.
- Derive coefficients for central Iran and Zagros separately.

## 4.204 Anderson and Uchiyama (2011)

- See Section 2.340.
- Response parameter is acceleration for 5% damping.

## 4.205 Arroyo and Ordaz (2011)

- See Section 2.341.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.206 Bindi et al. (2011a)

- See Section 2.343.
- Response parameter is acceleration for 5% damping.

## 4.207 Buratti et al. (2011)

- Ground-motion model is[12]:

$$\log y = c_1 + c_2 M + c_3 M^2 + c_4 \log \sqrt{r_{jb}^2 + c_6^2} + c_5 \sqrt{r_{jb}^2 + c_6^2} + c_7 V_{s,30}$$

- Use $V_{s,30}$ to characterise sites.
- Find that effect of faulting mechanism is not statistically significant and hence do not include such terms.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive model for use in study on number of scaled and matched accelerograms required for inelastic dynamic analyses of structures. Similar goal to Hancock et al. (2008) (see Section 4.168).
- Use PEER NGA West database (Chiou et al., 2008). Only use data with known $M_w$, $r_{jb}$ and $V_{s,30}$. Exclude records from Taiwan to reduce database and prevent the 1813 accelerograms from the 1999 Chi-Chi sequence dominating results. Exclude records with only one component or where either horizontal component was filtered with high-pass cut-off > 0.33 Hz. Dataset is similar to that of Hancock et al. (2008) (see Section 4.168).
- Note that model is not for general use and hence coefficients not reported.

[12]The actual functional form is not reported in the article but it is stated that it is like the form of Hancock et al. (2008).

## 4.208 Cauzzi et al. (2011)

- Ground-motion model is:

$$\log_{10} \mathrm{DRS} = c_1 + m_1 M_w + m_2 M_w^2 + (r_1 + r_2 M_w) \log_{10}(R + r_3 10^{r_4 M_w}) + s_1 S_B + s_2 S_C + s_3 S_D$$

- Response parameter is displacement for 5% damping.

- Use Eurocode 8 site classes to characterise sites:

Class A Most data from Swiss stations. $S_B = S_C = S_D = 0$.

Class B Few data from Swiss stations. $S_B = 1$.

Class C Few data from Swiss stations. $S_C = 1$.

Class D Few data from Swiss stations. $S_D = 1$.

Also derive model using $V_{s,30}$ (available for 87% of records) with term $b_v \log_{10}(V_{s,30}/V_a)$ (and term where $V_a$ constrained to 800 m/s to ensure consistency between approaches) replacing site terms using EC8 classes. Use weighted regression on residuals to derive this term.

Also derive model using $V_{s,QWL}$, where $V_{s,QWL}$ is the quarter-wavelength velocity, and term $b_{v,QWL} \log_{10}(V_{s,QWL}/V_{a,QWL})$, where $V_{a,QWL}$ is taken from generic Swiss velocity profile.

- Update of Faccioli et al. (2010) (see Section 2.330) by extending data below $M_w 5$ by adding Swiss records. Also add data from 2009 L'Aquila (Italy), 2010 Christchurch (New Zealand), 2002 Denali (USA) and 2008 Wenchuan (China) events. Majority of data from $M_w < 4.5$ is from Switzerland (with some from Italy and Japan) and majority of data for higher $M_w$ from elsewhere (mainly Japan). Gap in Swiss data for $3.8 \leq M_w \leq 4.3$.

- All data from digital instruments (mainly 24-bit). Also use Swiss data from on-scale broadband velocity sensors to improve $M$-$R$ range of rock site data.

- Process records by removing pre-event offset from entire time-history or filter with high-pass 4th-order acausal ($f_c = 0.05$ Hz) after cosine tapering and zero padding. For low-magnitude data main noise source is microseismal peaks. Find for $2 < T < 20$ s and records not dominated by microseismic noise that spectral displacements are independent of correction technique and that spectral displacements remain constant after $T > 2$ s. Hence uniformly filter $M_w < 4.5$ data with 4th-order acausal ($f_c = 0.5$ Hz) filter so that number of records does not change with period.

- Find inclusion of $r_2 M_w$ term has no impact on $\sigma$ but required to stabilise regressions for $T > 5$ s. Find that when using only strong-motion part of database that had to assume $r_2 = 0$ for $T > 2$ s. Believe this explained by increase in $M$ dependency for weak-motion data because of, e.g., decrease in stress drop for Swiss earthquakes for $M_w < 4$.

- Did not include anelastic term because of limited distance range and long periods of interest. Note residual plots confirm this assumption *a posteriori*.

- Derive model using entire database and only part from $M_w > 4.4$. Find similar predictions. Moderate changes only for rock sites and near-field predictions for class D sites.

- Find higher residuals for weak-motion contribution to database, especially at long periods.

- Compare predictions and observations for some records not used to derive model. Find some large differences, which relate to site effects.

- Find that using $V_{s,30}$ or $V_{s,QWL}$ results in similar predictions and $\sigma$.

## 4.209 Chopra and Choudhury (2011)

- Ground-motion model is:

$$\log(\text{PSA}) = a + bM + cR + dS$$

- Use 2 site classes based (32 sites in total):

  Rock 27 stations. 385 records. $S = 0$.

  Soil 5 stations. 22 records. $S = 1$.

  Also classify sites by geology: mesozoic (19 stations), tertiary (7 stations), quaternary (4 stations) and proterozoic (2 stations). 5 stations provide majority of records.

- Response parameter is pseudo-acceleration for 5% damping.
- Instruments are 18-bit digital sensors either installed in vaults or on concrete platforms.
- Most records from $10 \leq r_{hyp} \leq 100$ km and $M_w \leq 5$.
- Examine residuals w.r.t. distance and find large residuals for $r_{hyp} > 200$ km, which suggest may indicate that model does not apply at such distances.
- Compare observations and predictions for a $M_w$4.6 earthquake and find fair agreement.

## 4.210 Gehl et al. (2011)

- See Section 2.345.
- Response parameter is acceleration for 5% damping.
- Only report coefficients for 1 s.

## 4.211 Lin et al. (2011b)

- See Section 2.348.
- Response parameter is acceleration for 5% damping.
- Do not apply any constraints to coefficients unlike for PGA.

## 4.212 Chang et al. (2012)

- See Section 2.352.
- Response parameter is pseudo-acceleration for 5% damping.
- Only report coefficients for 2 periods: 0.3 and 1.0 s.
- Compare predicted and observed response spectra for various $M$-$R$ bins and find good match except at long periods, where model overestimates observations.

## 4.213 Contreras and Boroschek (2012)

- See Section 2.353.
- Response parameter is pseudo-acceleration for 5% damping.
- Use periods up to slightly short of $1/f_{min}$.
- Difficult to apply filtering procedure for analogue records and hence limit model to 2 s.
- Plot predicted and observed spectra for some records and find good match.

## 4.214 Cui et al. (2012)

- See Section 2.355.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.215 Di Alessandro et al. (2012)

- See Section 2.356.
- Response parameter is pseudo-acceleration for 5% damping.
- Only consider $T \leq 2$ s to maintain consistent dataset and to reduce influence of filter cut-offs.

## 4.216 Hamzehloo and Mahood (2012)

- See Section 2.358.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.217 Mohammadnejad et al. (2012)

- See Section 2.361.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.218 Saffari et al. (2012)

- See Section 2.364.
- Response parameter is acceleration for 5% damping.
- Smooth coefficients using 5-degree polynomial.

## 4.219 Abrahamson et al. (2013, 2014)

- See Section 2.366.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data for spectral frequencies > 1.25 times the high-pass corner frequency used for filtering.

## 4.220 Boore et al. (2013, 2014)

- See Section 2.367.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use PSAs for $T \leq$ reciprocal of lowest usable frequency. Do not exclude PSAs based on high-frequency filter.
- At long periods few records in range $5 \leq M_w \leq 6$.
- Note few PSAs from small events at long periods and hence magnitude-scaling here less well constrained.
- Very few records from NS events at long periods.
- Coefficients generally smooth except for large and small magnitudes at $T > 2$ s, probably due to fewer records. Hence smoothed $h$ and re-regressed model. Finally computed 11-point running means of resulting coefficients.
- Note that increase in $\tau$ near 0.08 s, which is stable in all subsets except Class 1 Californian events for $M_w > 5.5$. Do not adjust model because of limited number of large Californian events in database.

## 4.221 Campbell and Bozorgnia (2013, 2014)

- See Section 2.368.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.222 Chiou and Youngs (2013, 2014)

- See Section 2.369.
- Response parameter is pseudo-acceleration for 5% damping.
- Model underpredicts at 3 s for $M_w < 3.5$.
- For $r_{rup} > 250$ km predicted PSA for $T \leq 0.3$ s should be set equal to PGA when falls below predicted PGA.

## 4.223 Douglas et al. (2013)

- See Section 2.370.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.224 Idriss (2013, 2014)

- See Section 2.372.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.225 Laurendeau et al. (2013)

- See Section 2.374.
- Response parameter is acceleration for 5% damping.

## 4.226 Morikawa and Fujiwara (2013)

- See Section 2.375.
- Response parameter is acceleration for 5% damping.
- Smooth coefficients to avoid rough spectra.

## 4.227 Pacific Earthquake Engineering Research Center (2013)

- See Section 2.376.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.228 Segou and Voulgaris (2013)

- See Section 2.377.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data within 1.25 $\times$ lower and upper cut-off frequencies.

## 4.229 Sharma et al. (2013)

- See Section 2.378.
- Response parameter is acceleration for 5% damping.

## 4.230 Skarlatoudis et al. (2013)

- See Section 2.379.
- Response parameter is pseudo-acceleration for 5% damping.
- Use data within period range defined by $1.25T_{Nyquist}$–$0.67T_{c,low}$, where $T_{Nyquist}$ is the Nyquist period and $T_{c,low}$ is the period of the low cut-off filter.

## 4.231 Akkar et al. (2014b,c)

- See Section 2.381.
- Response parameter is pseudo-acceleration for 5% damping.
- Present coefficients for a selection of 18 periods in article. Electronic supplement contains all.

- Only use data within passband of high-pass filtering (Akkar and Bommer, 2006) hence number of records per $T$ decreases. For $T > 4$ s sharp decrease in number of data, because of large proportion of analogue records, and hence do not derive models for longer $T$.
- Do not exclude records based on low-pass filtering effects because it did not significantly affect number of records available.
- Do not smooth or truncate because of unexpected jagged variations in predictions from previous model.

## 4.232 Ansary (2014)

- See Section 2.382.
- Response parameters are acceleration and velocity for 5% damping.

## 4.233 Bindi et al. (2014a,b)

- See Section 2.383.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data within passband of high-pass filtering $f_{hp} \leq 1/(1.25T)$ hence number of records per $T$ decreases.
- Based on distribution of $f_{hp}$ with $M_w$, conclude that some noise may still be present in records from small events. Also note large event term for 2004 Baladeh (Iran, $M_w 6.2$) that relate to poor filtering.
- Coefficient $b_3$ is not significantly different than zero for 0.15–1.5 s and $c_3$ is only significantly different than zero for 0.04–0.4 s.
- Sharp drop in $\sigma$ for $T > 3$ s, which believe is not reliable. Hence do not report coefficients for $T > 3$ s.

## 4.234 Derras et al. (2014)

- See Section 2.384.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.235 Ghofrani and Atkinson (2014)

- See Section 2.385.
- Response parameter is pseudo-acceleration for 5% damping.
- log amplitudes averaged within each frequency bin centered about the given frequency.

## 4.236 Kurzon et al. (2014)

- See Section 2.387.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.237 Luzi et al. (2014)

- See Section 2.388.
- Response parameter is acceleration for 5% damping.

## 4.238 Rodríguez-Pérez (2014)

- See Section 2.389.
- Response parameter is pseudo-acceleration for 5% damping.
- Smooth coefficients using weighted 3-point scheme.

## 4.239 Stafford (2014)

- Ground-motion model is:

$$\begin{aligned}
\ln y &= \beta_1 + \beta_M(M-6.75) + \beta_4(8.5-M)^2 + [\beta_5 + \beta_6(M-6.75)] \ln \sqrt{r_{rup}^2 + \beta_h^2} \\
&\quad + \beta_7 r_{rup} + \beta_8 \ln\left(\frac{V_{s,30}}{760}\right) + \beta_9 F_{NM} + \beta_1 0 F_{RV} + \beta_1 1 F_{AS} \\
\beta_M &= \begin{cases} \beta_2 & M \leq 6.75 \\ \beta_3 & M > 6.75 \end{cases}
\end{aligned}$$

- Uses $V_{s,30}$ to characterise sites.
- Uses 3 mechanisms:

Strike-slip $F_{NM} = F_{RV} = 0$.

Normal $F_{NM} = 1$, $F_{RV} = 0$.

Reverse $F_{RV} = 1$, $F_{NM} = 0$.

- Uses 2 earthquake types:

Mainshock $F_{AS} = 0$.

Aftershock $F_{AS} = 1$.

- Response parameter is acceleration[13] for 5% damping.
- Develops model to demonstrate use of implicitly nested, partially crossed, mixed-effects regression, which addresses limitations of multistage additive random-effects approach to obtain single-station $\sigma$s. Also considers the influence of uncertainties in input variables ($M_w$ and $V_{s,30}$) by using Bayesian influence to derive model. Focus is on estimation of variance components. Selects a sufficiently flexible functional form to enable reasonable estimates of these components to be made.
- Uses data from the NGA West database (Chiou et al., 2008). Data from 15 countries but heavily dominated by earthquakes in California and Taiwan. Uses random effects for each country not because ground motions recognize politcal borders but as a demonstration of mixed-effect regressions accounting for geographical differences. Approach does not try to solve directly for the country random effects but to quantify their variance.

[13] Probably pseudo-acceleration since uses NGA West database.

- Finds that some of the coefficients are not significant (e.g. quadratic magnitude-scaling and mechanism terms), by applying traditional approaches, but retains all coefficients so that same functional form applies to all periods.
- Finds that coefficients vary greatly when considering different sets of random effects, which demonstrates difficulty in removing ergodic assumption in a series of steps. Although notes for (overparameterized) models that predictions from models may be similar, except at edges of data.
- Finds country-to-country (or regional) variance is nontrivial.
- Finds that when accounting for uncertainties in $M_w$ and $V_{s,30}$ that magnitude dependence of model changes and the variance components reduce.
- Develops model that allows removal of ergodic assumption by including additional country-dependent random effects for magnitude-dependence of geometric spreading, anelastic attenuation and $V_{s,30}$ scaling. Finds that many of the random effects are not well constrained and hence could remove them.
- Finally proposes model for intra-event site-corrected $\sigma$ ($\phi_{SS}$) based on combining analyses.

## 4.240 Vacareanu et al. (2014)

- See Section 2.390.
- Response parameter is acceleration for 5% damping.

## 4.241 Atkinson (2015)

- See Section 2.391.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.242 Cauzzi et al. (2015b)

- See Section 2.393.
- Response parameter is displacement for 5% damping.
- Limit $b_v$ to lower than $-0.1$ to avoid divergence in $V_A$ for periods 0.05–0.1 s.

## 4.243 Emolo et al. (2015)

- See Section 2.394.
- Response parameter is acceleration for 5% damping.

## 4.244 Haendel et al. (2015)

- See Section 2.396.
- Response parameter is acceleration for 5% damping.
- For long periods, use data up to $1.25f_c$, where $f_c$ is cut-off frequency, for high-pass filtering and for short periods, irrespective of the cut-off frequency.

## 4.245 Jaimes et al. (2015)

- See Section 2.397.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.246 Kale et al. (2015)

- See Section 2.398.
- Response parameter is pseudo-acceleration for 5% damping.
- Number of records used reduces at longer periods because using individual cut-offs.
- Only report coefficients in paper for 18 periods. Others are in an electronic supplement.

## 4.247 Kuehn and Scherbaum (2015)

- See Section 2.399.
- Response parameter is acceleration for 5% damping.
- Coefficients and covariances reported in electronic supplement.

## 4.248 Pacific Earthquake Engineering Research Center (2015) — Al Noman and Cramer

- See Section 2.400.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.249 Vacareanu et al. (2015b)

- See Section 2.402.
- Response parameter is acceleration for 5% damping.

## 4.250 Vuorinen et al. (2015)

- See Section 2.403.
- Response parameter is acceleration for unknown (but probably 5%) damping.

## 4.251 Zhao et al. (2015)

- See Section 2.405.
- Response parameter is acceleration for 5% damping.

## 4.252 Abrahamson et al. (2016) & BC Hydro (2012)

- See Section 2.406.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.253 Bommer et al. (2016)

- Ground-motion model is:

$$\ln Y = c_1 + c_2 M_w + c_4 \ln \sqrt{R_{epi}^2 + [\exp(c_5 M + c_6)]^2}$$

- Response parameter is acceleration for 5% damping.
- Data from 18 instruments on ground surface.
- All station have roughly $180 \leq V_{s,30} \leq 210\,\mathrm{m/s}$. Do not include explicit site response term because site conditions at all stations not available.
- Assume that $M_L$ from KNMI are equivalent to $M_w$ in the magnitude range considered.
- Derive model for comparison with model from stochastic simulations, for use within a risk assessment, and to constrain the aleatory variability components.
- Records of induced seismicity within gas reservoir (thickness 150–300 m) located at depth of 3 km.
- Use $r_{epi}$ rather than $r_{hypo}$ because all earthquakes at same depth.
- Earthquakes either normal or strike-slip but reliable fault-plane solutions not available so do not consider the effect of mechanism.
- Do not include term for anelastic attenuation because of limited distance range.
- Find unphysical combinations of $c_5$ and $c_6$ at longer periods. Hence regress for all periods simultaneously with the constraint of common values for these two coefficients.
- Do not report coefficients.
- Find model fits data well but that it would not extrapolate reliably to larger magnitudes because of linear magnitude scaling.
- Examine intra- and inter-event residuals. Find no trends in inter-event residuals w.r.t. $M_w$ but some patterns in intra-event residuals w.r.t. $r_{epi}$, which relate to unusual velocity structure above gas reservoir.

## 4.254 Bozorgnia and Campbell (2016b)

- See Section 2.407.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.255 Kotha et al. (2016a,b)

- See Section 2.409.
- Response parameter is acceleration for 5% damping.
- For oscillator frequency $f$ only use records with high-pass corner frequency $f_{hp} \leq 0.8f$ (Abrahamson and Silva, 1997).

## 4.256 Landwehr et al. (2016)

- See Section 2.411.
- Response parameter is acceleration for 5% damping.

## 4.257 Lanzano et al. (2016)

- See Section 2.412.
- Response parameter is acceleration for 5% damping.
- Only use spectral ordinates within the usable frequency band defined by bandpass frequencies. Reduces number of records by about 5% for $T > 1$ s and 8% for $T < 0.07$ s.

## 4.258 Sedaghati and Pezeshk (2016)

- See Section 2.415.
- Response parameter is acceleration for 5% damping.

## 4.259 Shoushtari et al. (2016)

- See Section 2.416.
- Response parameter is pseudo-acceleration for 5% damping.
- Use sample rate of record to determine minimum usable period and Akkar and Bommer (2006) to define maximum usable period based on filter cut-off period.
- Compare predicted and observed response spectra for 5 Sumatra/Java earthquakes. Find good match.

## 4.260 Stewart et al. (2016)

- See Section 2.417.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.261 Sung and Lee (2016)

- See Section 2.418.
- Response parameter is acceleration for 5% damping.

## 4.262 Tusa and Langer (2016)

- See Section 2.419.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.263 Wang et al. (2016)

- See Section 2.420.
- Response parameter is pseudo-acceleration for 5% damping.
- Number of records available starts to drop off from about $T = 0.3$ s. Fewer than half records retained for $T > 3$ s and almost no records for $T > 7$ s.

## 4.264 Zhao et al. (2016a)

- See Section 2.421.
- Response parameter is acceleration for 5% damping.

## 4.265 Zhao et al. (2016b)

- See Section 2.422.
- Response parameter is acceleration for 5% damping.

## 4.266 Zhao et al. (2016c)

- See Section 2.423.
- Response parameter is acceleration for 5% damping.

## 4.267 Ameri et al. (2017)

- See Section 2.424.
- Response parameter is pseudo-acceleration for 5% damping.
- Dramatic decrease in available data $> 1$ s. Hence only derive model to 3 s.
- Heteroscedastic $\tau$ not statistically significant for $T > 1$ s so $\tau_1 = \tau_2$.

## 4.268 Bindi et al. (2017)

- See Section 2.426.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.269 Çağnan et al. (2017a,b)

- See Section 2.427.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.270 Derras et al. (2017)

- See Section 2.428.
- Response parameter is pseudo-acceleration for 5% damping.
- Compute percentage decrease in $\sigma^2$, $\tau^2$ and $\phi^2$ by using SCPs over base model using no SCPs. Find $V_{s,30}$ is best SCP for $T < 0.6$ s and $f_0$ and $H_{800}$ are better at long periods. Find $V_{s,30}$-$H_{800}$ and $f_0$-slope are best SCP pairs.

## 4.271 García-Soto and Jaimes (2017)

- See Section 2.429.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.272 Gülerce et al. (2017)

- See Section 2.430.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data for spectral frequencies $> 1.25$ times the high-pass corner frequency used for filtering. Significant drop in number of records $> 2$ s so model not well constrained at longer periods.

## 4.273 Hassani et al. (2017)

- Ground-motion model is:

$$\log Y = a_1 + a_2 M_w + a_3 \log \sqrt{d_{epi}^2 + a_4^2} + a_5 S_S + a_6 S_A$$

- Use 3 site classes:
  1. Rock. $V_{s,30} \geq 750$ m/s. About 300 records. $S_S = S_A = 0$.
  2. Stiff soil. $375 \leq V_{s,30} < 750$ m/s. About 350 records. $S_A = 1$, $S_S = 0$.
  3. Soft soil. $V_{s,30} < 375$ m/s. About 150 records. $S_S = 1$, $S_A = 0$
- Response parameter is displacement for 5% damping.
- Data from analogue (SMA-1, about 150 records) and digital (SSA-2, about 650 records) instruments. Exclude some analogue records from before 1994 because of their low quality.
- Use $r_{epi}$ because of lack of information on causative faults from which to compute $r_{jb}$ and because using $r_{hypo}$ may introduce error due to errors in depths. Earthquakes mainly from $M_w \leq 6$ so $r_{epi}$ and $r_{jb}$ similar.
- Most data from $10 \leq r_{epi} \leq 200$ km. Few records from $r_{epi} < 30$ km for $M_w \geq 6.5$ hence advise model used with caution there.

- Do not consider effect of faulting mechanism as lack of data for most earthquakes.
- Data from two regions: Zagros (about 375 records) and Alborz-central Iran (about 425 records).
- Individually baseline correct and bandpass filter all records according to the instrument type.
- Examine (not shown) residuals w.r.t. $r_{epi}$ and $M_w$ and as a histogram and find no trends by fitting best-fit lines.

## 4.274 Idini et al. (2017)

- See Section 2.431.
- Response parameter is acceleration for 5% damping.
- Use approach of Akkar and Bommer (2006) to determine longest usable period. Use fewer records at long periods because of filtering.

## 4.275 Montalva et al. (2017a,c,b)

- See Section 2.435.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.276 Peruzza et al. (2017)

- See Section 2.437.
- Response parameter is acceleration for 5% damping.

## 4.277 Sedaghati and Pezeshk (2017)

- See Section 2.438.
- Response parameter is pseudo-acceleration for 5% damping.
- Number of records for each period varies due to filter cut-offs. For $> 4$ s too few records to obtain robust model.

## 4.278 Shahidzadeh and Yazdani (2017)

- See Section 2.439.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data within passband of $1.25 f_l$ to $f_h$, where $f_l$ is low cut-off frequency and $f_h$ is roll-off frequency.
- Compare predicted and observed spectra for some records and find good match.

## 4.279 Soghrat and Ziyaeifar (2017)

- See Section 2.440.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.280 Zuccolo et al. (2017)

- See Section 2.441.
- Response parameter is acceleration for 5% damping.

## 4.281 Ameur et al. (2018)

- See Section 2.442.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.282 D'Amico et al. (2018a)

- See Section 2.445.
- Response parameter is acceleration for 5% damping.
- Consider periods often used for ShakeMap purposes.

## 4.283 Felicetta et al. (2018)

- See Section 2.445.
- Response parameter is acceleration for 5% damping.

## 4.284 Gupta and Trifunac (2018a)

- Ground-motion model is:

$$\begin{aligned}
\log_{10}\mathrm{PSV} &= M + A_0\log_{10}\Delta + C_1 + C_2M + C_3M^2 + C_4v + C_5s + C_6^0S_L^0 + C_6^1S_L^1 + C_6^2S_L^2 \\
\Delta &= S\left(\ln\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)^{-\frac{1}{2}} \\
S_0 &= \min\left(\frac{\beta T}{2}, \frac{S}{2}\right) \\
S &= \begin{cases} 0.2 & M \leq 3.0 \\ -13.557 + 4.586M & 3.0 < M \leq 6.0 \\ 13.959 & M > 6.0 \end{cases}
\end{aligned}$$

  where $R$ is $r_{epi}$, $v = 0$ for horizontal and $v = 1$ for vertical components (believe both components should have identical dependency on magnitude, distance and site conditions), $S_0$ is correlation radius of source, $\beta$ is shear-wave velocity at earthquake source (assume as 3.5 km/s for NE India and 3.3 km/s in W Himalaya), $S$ is fault size in km and $A_0$ is frequency-dependent attenuation function from previous study.

- Model only valid for $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_2/(2b_5(T))$ and $M_{\max} = -(1+b_2(T))/(2b_5(T))$. For $M < M_{\min}$ use $M = M_{\min}$ in $C_2M + C_3M^2$ terms. For $M > M_{\max}$ use $M = M_{\max}$ everywhere.
- Consider three geological site conditions (thick strata of order of km):

$s = 0$ Sediment: 193 records.

$s = 1$ Intermediate sites or complex geological environments that cannot be categorized unambiguously: 26 records.

$s = 2$ Basement rock: 146 records.

- Consider three local site categories (top 100–200 m):

$s_L = 0$ Rock ($V_s < 800$ m/s only in top 10 m): 35 records.

$s_L = 1$ Stiff soil ($V_s < 800$ m/s in top roughly 75 m): 72 records.

$s_L = 2$ Deep soil ($V_s < 800$ m/s in top 150–200 m): 258 records.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Develop model only for 0.04 to 3 s to minimize the effect of noise in the data. Extend model to shorter and longer periods by theoretical methods.
- 217 (of which $\tilde{3}5$ are analogue and rest digital) records from 47 earthquakes and 80 stations in western Himalaya and 148 (of which $\tilde{5}5$ are analogue and rest digital) records from 36 earthquakes and 56 stations in northeastern India. Analogue data from local networks (of 40-50 stations) of IIT Roorkee in Kangra, Garhwal-Kumaon areas and Shillong Plateau (1986–1999), which correct for instrument response and filter. Digital data from National Strong Motion Instrumentation Network of $\tilde{3}00$ stations (since 2005), which filter.
- Select data from $M \leq 4.0$ and $r_{hypo} \leq 350$ km because weaker data contaminated by noise, lower magnitude estimates are unreliable and more distant attenuation difficult to constrain.
- Most data from W Himalaya from $4.5 \leq M_w \leq 5.5$ and $10 \leq r_{hypo} \leq 185$ km (mean recording distance is 100 km) and most data from NE India from $5.5 \leq M_w \leq 6.0$ and $35 \leq r_{hypo} \leq 205$ km (mean recording distance is 150 km).
- Focal depths ($H$) in W Himalaya between roughly 5 and 65 km with most $\geq 30$ km, and in NE India between roughly 5 and 55 km with most $\leq 20$ km.
- Assume common model for both region but different attenuation functions $A_0$, which find consistent with the data.
- Use decimation scheme before regress to eliminate possible bias due to non-uniform data distribution. All 1095 spectral amplitudes for each $T$ are grouped into magnitudes 4.0–4.9, 5.0–5.9 and 6.0–6.9. Amplitudes in each group are separately sequentially per component and geology and soil categories. Arrange amplitudes in each of the 54 sub-divisions are arranged in increasing order. Select maximum of 33 values from each group for regression corresponding to serial numbers closest to 3rd, 6th, ..., 96th and 99th percentiles. Number of data points varies with $T$ due to cut-off periods for each accelerogram.
- Regress using a two-step weighted method.
- Smooth coefficients to obtained predicted spectra that are physically realistic.
- Fit models to residuals to obtain probability distributions for variability rather than $\sigma$.
- Compare predicted and observed spectra for some example records and find a good match.

## 4.285 Kotha et al. (2018a,b)

- Ground-motion model is (form based on non-parametric analyses and previous studies):

$$
\begin{aligned}
\ln \mathrm{PSA} &= f_R + f_M \\
f_R &= \begin{cases} c_1 \ln \sqrt{R_{JB}^2 + h^2} & R_{JB} < 100\,\mathrm{km} \\ c_1 \ln \sqrt{100^2 + h^2} + c_2 \ln(R_{JB}/100) + c_3(R_{JB} - 100) & R_{JB} \geq 100\,\mathrm{km} \end{cases} \\
\ln h &= 2.303 \max(-0.05 + 0.15 M_w, -1.72 + 0.43 M_w) \\
f_M &= \begin{cases} a + b_1(M_w - M_{ref}) & M_w < M_{ref} \\ a + b_2(M_w - M_{ref}) & M_{ref} \leq M_w < M_h \\ a + b_2(M_h - M_{ref}) + b_3(M_w - M_h) & M_h \leq M_w \end{cases} \\
M_{ref} &= 4.5
\end{aligned}
$$

  Equation for $\ln h$ from Yenier and Atkinson (2015a).

- Response parameter is pseudo-acceleration for 5% damping.

- $V_{s,30}$ between 106 and 2100 m/s.

- Only include data from earthquakes with most reliable locations and magnitudes from a master database of about 157 000 records from the KiK-net network from October 1997 to December 2011. Exclude subduction events and those with focal depth $> 35$ km. Only include surface records with measured $V_{s,30}$. Only consider records within their individual conservative passband and those records with signal-to-noise ratios $\geq 3$ within this passband. Exclude data from earthquakes with $< 3$ usable records.

- Derive model to propose via a data-driven approach a better site classification than one based on $V_{s,30}$.

- Data from 644 different sites.

- Data distribution dominated by distant $> 50$ km records and events with $M_w < 5$. Hence site terms capture linear site response.

- Use multi-step mixed-effects regression technique to estimate $\tau$ (inter-event), $\phi_{S2S}$ (inter-site) and $\phi_0$ (residual) variabilities. Firstly calibrate $f_R$ then use distance-corrected observations to find $f_M$. This is done to ensure coefficients unbiased by a few well-observed earthquakes or sites. Do not include site term in the original function.

- Do not include a term related to faulting mechanism because did not find significant dependency within non-parametric analyses on mechanism.

- Examine the intermediate residuals w.r.t. $M_w$, $V_{s,30}$ and $r_{jb}$. Compute mean, 15th and 85th percentiles of residuals within 10 magnitude bins and 10 distance bins. Find no significant trends.

- Plot predicted and observed (from within small magnitude bins) ground motions for 0.02, 0.2 and 2 s w.r.t. distance. Plot observations colour-coded by distance and predictions w.r.t. magnitude. Find good match.

- Classify the 588 stations with $\delta S2S$ available at all periods into 8 site clusters (number specified *a priori*) with distinct mean site amplification functions and within-cluster site-to-site variability about 50% smaller than overall $\phi_{S2S}$ using a spectral (k-means) clustering analysis (a type of unsupervised machine learning). Choose 8 as number of clusters based on consideration of total within sum of squares (WSS) and the gap statistic comparing the WSS change with that expected under an appropriate null reference distribution of the data. Examine average site amplifications within each cluster and find clear separation. Compare classification with previous classifications. Examine distribution of $T_G$ (predominant period) $V_{s,10}$, $V_{s,30}$ and $H_{800}$ (depth to horizon with $V_s = 800$ m/s) within each class. Find that some combinations of these parameters can be used to classify stations into the 8 classes.

## 4.286 Ktenidou et al. (2018)

- See Section 2.449.
- Response parameter is acceleration for 5% damping.

## 4.287 Laouami et al. (2018a,b)

- See Section 2.450.
- Response parameter is pseudo-acceleration for 5% damping.
- Due to positive $b$ coefficients for $T = 0.9$ and 1 s constrain $b$ to zero.
- Believe the large $\sigma$ for $T > 0.23$ s is due to large amount of small magnitude data.
- Find trends in residuals for $> 100$ km and $T = 2$ s.

## 4.288 Laurendeau et al. (2018)

- Ground-motion model is:

$$\ln \mathrm{SA} = a_1 + a_2 M_w + a_3 M_w^2 + b_1 R_{RUP} - \ln R_{RUP} + c_1 \ln(V_s/1000)$$

- Response parameter is acceleration for 5% damping.
- Use $V_s$, which is either $V_{s,30}$ for the control set DATA_surf or the shear-wave velocity at downhole sensor $V_{SDH}$ for the other datasets, which assume to be very close to the $V_{s,30}$ immediately below the downhole sensor. Use only data from sites with $500 \leq V_{s,30} \leq 1350$ m/s (only 13 sites have $V_{s,30} > 1000$ m/s).
- Use subset of KiK-net data from Laurendeau et al. (2013) (see Section 2.374).
- Originally use data from 164 different stations but reduce this down by application of criteria.
- Derive model for hard rock sites with $V_{s,30} \geq 1500$ m/s. Use numerical simulations to deconvolve site response from the surface records to obtain estimates of the outcropping hard rock motions. Apply 2 approaches: 1) correct downhole records for depth or within motion effects (DHcor, 1031 records) and 2) correct surface records using known velocity profile (SURFcor, 765 records). Also derive models for original surface (DATA_surf, same 1031 records as DHcor) and downhole (DATA_dh, same 1031 records as DHcor) data as a control. Discuss and test various aspects of these correction procedures (details not given here due to lack of space).
- Due to limited data in near field of large events and focus on site term use a simple functional form.
- Provide coefficients for the 4 different models in an electronic supplement.

## 4.289 Mahani and Kao (2018)

- See Section 2.451.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.290 Sharma and Convertito (2018)

- See Section 2.454.
- Response parameter is acceleration for 5% damping.

## 4.291 Shoushtari et al. (2018)

- See Section 2.455.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data within their passband so number of records available for each period may change.
- Compare predicted and observed response spectra for 12 example records. Find good match.

## 4.292 Wen et al. (2018)

- See Section 2.456.
- Response parameter is pseudo-acceleration for 5% damping.
- Limit period range considered so same number of records for all periods.
- Using unit covariances, conclude that the magnitude-distance dependence and source terms may be exhibiting trade-offs, which relate to limited magnitude range of data and lack of near-source records.

## 4.293 Zafarani et al. (2018)

- See Section 2.457.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.294 Ashadi and Kaka (2019)

- See Section **??**.
- Response parameter is acceleration for 5 damping.

## 4.295 Bindi et al. (2019)

- Ground-motion model is:

$$\begin{aligned}
\log Y &= e_1 + F + G \\
F &= \begin{cases} b_1(M - M_{ref}) & M \leq M_H \\ b_1(M_H - M_{ref}) + b_3(M - M_H) & M > M_H \end{cases} \\
G &= \begin{cases} c_{1A} \log R_{hypo} & R_{hypo} \leq R_H \\ c_{1A} \log R_H + c_{1B} \log(R_{hypo}/R_H) + c_3 R_{hypo} & R_{hypo} > R_H \end{cases}
\end{aligned}$$

  where $M_{ref} = 4.5$, $M_H = 6$ and $R_H = 15\,\text{km}$. Include a country-to-country random effect (Italy, Turkey, Romania, Greece and other) on $e_1$ or $c_3$.

- Used piece-wise linear function in $\log R$ with hinge at 15 km to avoid trends in residuals for shorter distances. Note that hinge distance may depend on $M$ and $T$.

- Account for site effects through between-station residuals.

- Response parameters are acceleration and displacement for unknown damping (almost certainly 5%).

- Only use data from focal depths $\leq 40$ km, with $R < 300$ km and from earthquakes with $\geq 2$ records. Only use data from surface (sensor depth $< 10$ m) instruments and on the ground floor of buildings or in the free-field.

- Bandpass filter records. Only use data for periods with $T \leq 0.8 f_{HP}$, where $f_{HP}$ is the high-pass corner frequency of the filter.

- Derive model as part of a consistency check of the 2018 flatfile taken from the Engineering Strong Motion database.

- Do not report exact coefficients only provide graphs of them w.r.t. $T$.

- Find positive $c_3$ for $T \geq 1.5$ s. Believe means more complex distance terms are required to capture late-arrivals on long-period motion.

- Believe regressions unstable for $T > 8$ s due to lack of records.

- Use within-model statistical estimate of epistemic uncertainty in the median to find magnitude-period ranges where model is not reliable.

- Plot event- and station-corrected residuals and do not find trends w.r.t. $M$ or $R$.

- Plot inter-event residuals and find trend w.r.t. $M$ for $M_w < 4.5$. Do not find dependency on faulting mechanism or country.

- Plot inter-station random effects and find trend with $V_{s,30}$ for short periods, which can fit with a piece-wise linear function. Find weaker relation w.r.t. $V_{s,30}$ estimated from topographic gradient.

- Identify events, stations and records with largest deviations ($> 3$ standard deviations from the mean) from the median predictions of the model.

- Examine trends in components of aleatory variability. Find peak in $\phi_{S2S}$ at $T = 0.1$ s. Find between-country terms are small.

- Find that when a country-to-country random effect is included in $c_3$ that it is statistically significant (with small standard errors), suggesting considerable differences in anelastic attenuation between regions (Italy and Greece have strong attenuation and Turkey weaker attenuation).

- Compare inter-event residuals obtained using two different sources of $M_w$. At long periods find considerable differences, which note shows the importance of reliable magnitudes.

- Find similar results for acceleration and displacement.

## 4.296 Darzi et al. (2019)

- See Section 2.459.

- Response parameter is acceleration for 5% damping.

## 4.297 Farajpour et al. (2019)

- See Section 2.460.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.298 Huang and Galasso (2019)

- See Section 2.461.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.299 Lanzano et al. (2019a,b)

- See Section 2.463.
- Response parameter is acceleration for 5% damping.
- Individual processing means number of records drops at longer periods.

## 4.300 Laouami (2019)

- See Section 2.464.
- Response parameter is pseudo-acceleration for 5% damping.
- Constrains $b$ to zero for $T > 0.75$ s because obtain non-physical positive values.
- Finds trends in residuals for $T = 2$ s for $R > 100$ km, which relate to lack of data.

## 4.301 Sung and Lee (2019)

- See Section 2.467.
- Response parameter is acceleration for unknown damping (almost certainly 5%).

## 4.302 Zolfaghari and Darzi (2019a)

- See Section 2.468.
- Response parameter is acceleration for 5% damping.

## 4.303 Chao et al. (2020)

- See Section 2.469.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data at spectral frequency $f$ with high-pass filter frequency $f_{hp} > 1.25f$ to avoid influence of filter. Number of data reduces at long periods.

## 4.304 Cremen et al. (2020)

- See Section 2.470.
- Response parameter is acceleration for 5% damping.

## 4.305 Hu et al. (2020)

- See Section 2.471.
- Response parameter is acceleration for 5% damping.

## 4.306 Jaimes and García-Soto (2020)

- See Section 2.472.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.307 Kotha et al. (2020)

- See Section 2.473.
- Response parameter is acceleration for 5% damping.
- Only use data at spectral period $T$ with high-pass filter frequency $f_{hp} \leq 0.8/T$ to avoid influence of filter. Number of data reduces at long periods. Data from 1341 stations used at 8 s.
- Observe kink in predicted spectra between 3.5 and 4.5 s due to the loss of about 3000 records. Choose not to smooth coefficients so as to preserve consistency of coefficients and variance-covariance matrices.

## 4.308 Kowsari et al. (2020)

- See Section 2.474.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.309 Kuehn et al. (2020b)

- See Section 2.476.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.310 Lanzano and Luzi (2020)

- See Section 2.477.
- Response parameter is acceleration for 5% damping.
- Individual processing means number of records drops significantly at longer periods so limit analysis to 5 s.

## 4.311 Li et al. (2020)

- See Section 2.478.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use records for frequencies up to 1.25 times the cut-off frequency. Hence number of records in global subset reduces at long periods.

## 4.312 Phung et al. (2020a)

- See Section 2.480.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data at spectral frequency $f$ with high-pass filter frequency $f_{hp} > 1.25f$ to avoid influence of filter. Number of data reduces at long periods.

## 4.313 Phung et al. (2020b)

- See Section 2.481.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data at spectral frequency $f$ with high-pass filter frequency $f_{hp} > 1.25f$ to avoid influence of filter. Number of data reduces at long periods. About half records used at 10 s.

## 4.314 Tusa et al. (2020)

- See Section 2.484.
- Response parameter is pseudo-acceleration for 5% damping.

## 4.315 Boore et al. (2021)

- See Section 2.486.
- Response parameter is pseudo-acceleration for 5% damping.
- Only use data with $T \leq T_{highest}$, which is the maximum usable period in the database flatfile. This leads to rapid drop in available data at long periods.

## 4.316 Gandomi et al. (2021)

- Ground-motion models are the following.

  Using MOGP-R:

$$\ln S_a = C_0 + C_1\sqrt{T/M} - C_s\sqrt{T}/M^{3/2} - C_3 \ln[\exp(-Z_{TOR})] + \sqrt{R} + C_4 T/M^2 + C_5\sqrt{\delta\sqrt{T}/V_{s30}}$$

Using GEP-MADS:

$$
\begin{aligned}
\ln S_a &= C_0 + C_1 \cos\{C_2 + [C_3 \tan^{-1}(T)^2]\} + C_4 M/R^{0.22} + C_5 \cos\{C_6 \sin M - C_6 \tan^{-1}(T)]^2\} \\
&\quad + C_7 \cos(\cos\{\sin[\cos(C_8 M - C_9)]\}) + C_{10} F_{NM} - C_{11} T^{0.4} + C_{12} - C_{13} \sqrt[3]{V_{s30}}
\end{aligned}
$$

where $T$ is spectral period.

- Response parameter is acceleration for 5% damping.
- Characterise sites using $V_{s,30}$.
- Use 2 faulting mechanisms:

Normal[14] $F_{NM} = 1$
Other $F_{NM} = 0$

- Characterise source using $Z_{TOR}$ (depth to top of rupture) and $\delta$ (fault dip).
- Derive models by multi-objective genetic programming and regression (MOGP-R) and gene expression programming with mesh adaptive direct search (GEP-MADS).
- Provide details of algorithms (not given here due to lack of space).
- Use data from Pacific Earthquake Engineering Research Center (PEER). Use selection criteria of Campbell and Bozorgnia (2008b). Train model on 21,885 records and test model using 3,862 records.
- Compute 3 statistical measures to assess fit to data for 0.2 s, 1 s and 3 s: root mean square error, mean absolute error and correlation coefficient. Compare these against values for published regression-based models and find similar results.
- Compute inter- and intra-event residuals. Compare these against residuals for published regression-based models. Find no clear trends.
- Assess Nash-Sutcliffe model efficiency coefficient (E), log-likelihood (LLH) and Euclidean distance-based ranking. Compare these against values for published regression-based models and find similar results.
- Plot observations against predictions.

## 4.317 Huang et al. (2021a)

- Ground-motion model is:

$$
\begin{aligned}
y &= a + F_M + F_D + F_{sof} + F_s + F_{Basin} \\
F_M &= b_1(M - M_r) + b_2(M - M_r)^2 \\
F_D &= [c_{1,k} + c_{2,k}(M - M_r)] \log_{10}(\sqrt{r_{jb}^2 + c_3^2}/R_h) \\
F_{sof} &= f_1 F_N + f_2 F_T \\
F_s &= s_1 S_B + s_2 S_C \\
F_{Basin} &= \delta_{Basin} I
\end{aligned}
$$

$M_r = 5.0$ and $R_h = 70$.

- Response parameter is displacement for 5% damping.

- Use 4 site classes based on Eurocode 8:

  A $V_{s,30} > 800$ m/s. About 15% of data. $S_B = 0 = S_C = 0$. $I = 1$.

  B $360 < V_{s,30} \leq 800$ m/s. About 30% of data. $S_B = 1$, $S_C = 0$. $I = 1$.

  C $180 < V_{s,30} \leq 360$ m/s and not in alluvium basin. About 20% of data. $S_C = 1$, $S_B = 0$. $I = 1$.

  C1 $180 < V_{s,30} \leq 360$ m/s and in alluvium basin (Po Plain or smaller basin in Appennies). 37% of data. $S_C = 1$, $S_B = 0$. $I = 1$.

- Use 3 faulting mechanisms:

  Normal $F_N = 1$, $F_T = 0$

  Thrust $F_T = 1$, $F_N = 0$

  Unspecified $F_N = F_T = 0$

- Use regression technique of Ming et al. (2019) that explicitly accounts for spatial correlation (exponential, stationary and isotropic) between intra-event residuals.

- Use data of Lanzano et al. (2016) from north Italy (Po Plain and surrounding area, roughly 8–15°E and 42–47°N). Most data from 2012 Emila and 1976-1977 Friuli sequences. Remove data from collocated stations and events with < 2 free-field records. Data from 290 different stations.

- Focal depths $\leq 30$ km.

- 80% of events and 70% of records from $M < 5.0$. Median $r_{jb}$ is 60 km.

- Use separate distance coefficients ($k$ index in $c_{1,k}$ and $c_{2,k}$) to distinguish between Po Plain and eastern Alps (PEA) and northern Apennines (NA). $k = 1$: site in PEA and $R \leq R_h$. $k = 2$: site in PEA and $R > R_h$. $k = 3$: site in NA and $R \leq R_h$. $k = 4$: site in NA and $R > R_h$.

- Fit preliminary model to verify using standard techniques that the assumptions of normality, stationarity and isotropy for spatial correlation are valid. Although for some cases the stationarity and isotrophy assumptions are found not be valid at a 5% significance level, the general conclusion is that they are so retain these assumptions. Use Bayesian Information Criteria (BIC) values to choose the exponential spatial correlation model as the most appropriate.

- Examine residuals and find no obvious bias or trends w.r.t. independent variables.

## 4.318 Gao et al. (2021)

- See Section 2.487.

- Response parameter is acceleration for 5% damping.

## 4.319 Lanzano et al. (2021)

- See Section 2.490.

- Response parameter is acceleration for 5% damping.

- Show observed and predicted spectra for four example records using both the non-stationary and stationary models. Find that the non-stationary version generally matches the observations more closely.

## 4.320 Allen (2022)

- See Section 2.494.
- Response parameter is pseudo-acceleration for 5% damping.
- Excludes data outside the frequency bounds determined by signal-to-noise ratios.
- Believes higher short-period predictions for deeper events may be due to smaller ruptures and higher stress drops at depth.
- Compares predicted spectra for 2 events at 2 sites and finds a close match.

## 4.321 Jiang et al. (2022)

- Ground-motion model is:

$$\begin{aligned}\ln Y &= a_1 + a_2 M + a_3 M^2 + (a_4 M + a_5)\ln(R + a_6) + a_7 R \\ &\quad + a_8 F_{RV} + a_9 \ln[\max(V_1, V_{s,30})/V_{LIN}]\end{aligned}$$

- Response parameter is acceleration for 5% damping.
- Data from Yunnan, Sichuan, Gansu and Shanxi provinces. Select data based on based on these criteria: 1) free-field records only, 2) all 3 components available, 3) $M_w > 4.5$, 4) $r_{rup}$ or $r_{hypo} < 300$ km and 5) $V_{s,30}$ is known.
- Characterise stations using $V_{s,30}$. Data from 144 different stations. Do not use data from deep soft sites so believe that $V_{s,30}$ is sufficient to model site response. Data with $V_{s,30}$ between about 200 m/s and 650 m/s.
- Classify events into 2 faulting mechanisms:

Reverse $F_{RV} = 1$.

Non-reverse Strike-slip and normal. These are combined as few normal events. $F_{RV} = 0$.

Check, using mean inter-event residuals, before final regression that the style-of-faulting term has an impact on residuals. Verify that this term leads to zero mean inter-event residuals when split by mechanism.

- Investigate impact of $Z_{TOR}$ (depth to top of rupture) on inter-event residuals. Find very limited effect as evidenced by residuals, correlation coefficients and inter-event standard deviations so do not include $Z_{TOR}$ term to limit the number of coefficients to determine. Note, however, that more accurate estimates of $Z_{TOR}$ could lead to different conclusions.
- Examine relationship between intra-event residuals and $V_{s,30}$ without including a $V_{s,30}$ term in the model. Find clear dependencies, which motivated the form of this term.
- Examine intra-event residuals w.r.t. reference PGA for evidence of soil nonlinearity. Find limited evidence so do not include in the final model. Note, however, that nonlinear soil terms could be constrained using observations and simulations.
- Baseline correct and bandpass filter records using cut-offs of 0.05 and 35 Hz. Check Fourier amplitude spectra and displacement time histories of processed records and find limited evidence of noise in processed records.

- Note the lack of earthquakes with $6.6 < M_w < 7.9$ from W. China so include data from NGA-West2 within this magnitude range where lacking data. Believe the events have similar stress drops. Examine this assumption using inter-event residuals.

- Determine $r_{rup}$ and $Z_{TOR}$ using finite fault models (for larger events), and focal mechanisms and global relationships between magnitude, fault dimensions and hypocentral locations.

- Because only use data within passband of filter for NGA-West2 records number of records decreases for $T \geq 2$ s but remains above 1000 to $T = 10$ s.

- Examine inter-event residuals w.r.t. $M_w$ and find no trends. Find no clear difference in the residuals for the Chinese and NGA-West2 events. Similarly find no clear trends in intra-event residuals w.r.t. $r_{rup}$, except for $r_{rup} > 270$ km where they are slightly negative, and $V_{s,30}$.

- Compare predictions and 2 observations (soil and rock sites) from 2019 Changning ($M_s$6.0) earthquake (not included in the dataset used to develop model).

## 4.322 Miyazawa et al. (2022)

- See Section 2.498.

- Response parameter is pseudo-acceleration for 5 damping.

- Consider model tentative as difficult to assign frequency-domain parameters to an SMGA unlike time-domain parameters, such as PGA, and assume that the SMGA locations remain the same for each period.

## 4.323 Zhang et al. (2022)

- See Section 2.502.

- Response parameter is acceleration for 5% damping.

- Number of records varies with period due to record-specific cut-offs used for filtering. Only use spectral accelerations at periods $< 1/(1.25 \times f_{hp}$, where $f_{hp}$ is the record-specific highpass cut-off frequency. Because only 46 records available for $T > 8$ s limit analysis to shorter periods.

- Observe that intra-event residuals for $200 \leq r_{rup} \leq 300$ km for $T \geq 1$ s are on average positive, which could be because of basin effects. Therefore, do not recommend model for $r_{rup} > 200$ km.

## 4.324 Khansefid et al. (2023)

- See Section 2.505.

- Response parameters are acceleration and velocity for 5% damping.

# Chapter 5

# General characteristics of GMPEs for spectral ordinates

Table 5.1 gives the general characteristics of published attenuation relations for spectral ordinates. The columns are the same as in Table 3.1 with three extra columns:

$T$s Number of periods for which attenuation equations are derived

$T_{\mathrm{min}}$ Minimum period for which attenuation equation is derived

$T_{\mathrm{max}}$ Maximum period for which attenuation equation is derived

Table 5.1: Characteristics of published spectral relations

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Johnson (1973) | W. USA | 41 | - | 23 | 5.3 | 7.7 | $m_b$ | 6.3 | 149.8 | $r_{epi}$ | 1 | 14 | 0.055 | 2.469 | M | 1 | A |
| Kobayashi and Nagahashi (1977) | Japan | U | - | U | 5.4* | 7.9* | U | 60* | 210* | $r_{hypo}$ | I | U | 0.1 | 5 | R[1] | O | A |
| McGuire (1977) | W. USA | 34 | - | 22 | 5.3 | 7.6 | $M_L$ | 14 | 125 | $r_{hypo}$ | 1 | 16 | 0.1 | 8 | B | U | A |
| Trifunac (1977) & Trifunac and Anderson (1977) | W. USA | 182 | 182 | 46 | 3.8 | 7.7 | Mostly $M_L$ | 6[2]* | 400[3]* | $r_{epi}$ | 3 | 91 | 0.04 | 12 | B | O | A |
| Faccioli (1978) | W. USA, Japan, Papua New Guinea, Mexico & Greece | 26[4] | - | 11 | 5.3 | 7.8 | U | 15 | 342 | $r_{hypo}$ | 1 | 15 | 0.1 | 4 | B | U | A |
| McGuire (1978a) | W. USA | 70 | - | 17+* | 4.5* | 7.7 | U[5] | 11* | 210* | $r_{hypo}$ | 2 | 1 | 1 | 1 | B | U | A |
| Trifunac (1978) & Trifunac and Anderson (1978a) | W. USA | 182 | 182 | 46 | 3.8 | 7.7 | Mostly $M_L$ | 6[6]* | 400[7]* | $r_{epi}$ | 3 | 91 | 0.04 | 12 | B | O | A |
| Trifunac and Anderson (1978b) | W. USA | 182 | 182 | 46 | 3.8 | 7.7 | Mostly $M_L$ | 6[8]* | 400[9]* | $r_{epi}$ | 3 | 91 | 0.04 | 12 | B | O | A |
| Cornell et al. (1979) | W. USA | 70 | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | 7 | 0.17 | 5 | C | U | A |
| Faccioli and Agalbato (1979) | Friuli, Italy | 38 | - | 14 | 3.7 | 6.3 | $M_L$ | 5 ($r_{epi}$) | 190 ($r_{epi}$) | $r_{hypo}$ | 2 | 1 | 1 | 1 | B | 1 | A |

*continued on next page*

[1]They state it is two dimensional response spectrum which assume to be resolved component.
[2]Note only valid for $R \geq 20$ km
[3]Note only valid for $R \leq 200$ km
[4]Total earthquake components (does not need to be multiplied by two)
[5]Idriss (1978) finds magnitudes to be mixture of $M_L$, $m_b$ and $M_s$.
[6]Note only valid for $R \geq 20$ km
[7]Note only valid for $R \leq 200$ km
[8]Note only valid for $R \geq 20$ km
[9]Note only valid for $R \leq 200$ km

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trifunac and Lee (1979) | W. N. America | U | U | U | U | U | U | U | U | $r_{epi}$ | 3 | 91 | 0.04 | 15 | U | U | A |
| Ohsaki et al. (1980a) | Japan | 95 | - | 29+ | 3.9* | 7.2* | U | 3* | 500* | $r_{hypo}$ | 2 | 86 | 0.02 | 5 | U | 1 | A |
| Ohsaki et al. (1980b) | Japan | 75 | - | U | 4 | 7.4 | U | 6 | 500 | $r_{hypo}$ | 1 | U | 0.02 | 5 | U | 1 | A |
| Trifunac (1980) | W. USA | U | - | U | U | U | U | U | U | $r_{epi}$ | C | 91 | 0.04 | 7.5 | U | U | A |
| Devillers and Mohammadioun (1981) | W. USA | 186 | - | U | 3.3* | 7.7* | U | $\geq$ 10 | 250* | $r_{hypo}$ | 1 | 46 | 0.04 | 10 | U | 1 | A |
| Joyner and Boore (1982a) | W. N. America | 64 | - | 12 | 5.3* | 7.7 | $M_w$ | 0.6* | 110* | $r_{jb}$ | 2 | 12 | 0.1 | 4 | L | 2 | A |
| Joyner and Boore (1982b) | W. N. America | 64 | - | 12 | 5.3* | 7.7 | $M_w$ | 0.6* | 110* | $r_{jb}$ | 2 | 12 | 0.1 | 4 | L, R | 2 | A |
| Kobayashi and Midorikawa (1982) | Japan | 45 | - | U | 5.1 | 7.5 | U | 50 | 280 | $r_{hypo}$ | 1 | U | 0.1 | 5 | U | O | A |
| Joyner and Fumal (1984), Joyner and Fumal (1985) & Joyner and Boore (1988) | W. N. America | U | - | U | 5.0 | 7.7 | $M_w(M_L)$ | U | U | $r_{jb}$ | C | 12 | 0.1 | 4 | L | U | A |
| Kawashima et al. (1984) | Japan | 197 | - | 90 | 5.0 | U | $M_{\mathrm{JMA}}$ | U | U | $r_{epi}$ | 3 | 10 | 0.1 | 3 | R | 1 | A |
| Kawashima et al. (1985) | Japan | - | 119 | 90* | 5.0* | 7.5* | $M_{\mathrm{JMA}}$ | 5* | 500* | $r_{epi}$ | 3 | 10 | 0.1 | 3 | - | 1 | A |
| Trifunac and Lee (1985b) | W. N. America | 438 | 438 | 104 | U | U | U | U | U | $r_{hypo}$ | 3, C | 91 | 0.04 | 15 | U | U | A |
| Kamiyama and Yanagisawa (1986) | Japan | 228 | - | 69 | 4.5 | 7.9 | $M_{\mathrm{JMA}}$ | 3 | 323 | $r_{epi}$ | I | 45 | 0.1 | 10 | U | 1 | A |
| C.B. Crouse (1987)[10] | S. California | U | - | U | U | U | $M_s$ | U | U | $r_{rup}$ | 1 | 10 | 0.05 | 6 | B | U | A |
| Lee (1987) & Lee (1993) | Mostly California | 494 | 494 | 106 | U | U | $M_L$ for $M \lesssim 6.5$, others for $M > 6.5$ | U | U | $r_{epi}$ | 3 | 91 | 0.04 | 15 | B | U | A |
| K. Sadigh (1987)[11] | W. USA + others | U | - | U | U | U | $M_w$ | U | U | $r_{rup}$ | 2 | 7 | 0.1 | 4 | B | U | A (S, R) |

*continued on next page*

[10]Reported in Joyner and Boore (1988).
[11]Reported in Joyner and Boore (1988).

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Annaka and Nozawa (1988) | Japan | U | - | 45 | U | U | U | U | U | U | 1 | U | 0.04* | 4* | U | 1 | A |
| Crouse et al. (1988) | N. Honshu | 64 | - | U | 5.1 | 8.2 | $M_w$, $M_s$ & $M_{\mathrm{JMA}}$ for $< 7.5$ | 42 | 407 | $r_E$, $r_{hypo}$ for $M < 7.5$ | 1 | 10 | 0.1 | 4 | B | 1 | A |
| Petrovski and Marcellini (1988) | Europe | 120 | 120 | 46 | 3 | 7 | U | 8 | 200 | $r_{hypo}$ | 1 | 26 | 0.02 | 5 | L | 1 | A |
| PML (1988)[12] | USA + Europe + others | 162 | 124 | 30* | 3.0* | $\geq 7.0$ | $M_s$ | 10* | $\geq$ 150 | $r_{hypo}$ | 3 | 20 | 0.025 | 1 | A | | |
| Yokota et al. (1988) | Tokyo | 154 | 24 | 75 (U) | 4.0 | 6.1 | $M_{\mathrm{JMA}}$ | 59 (60) | 206 (100) | $r_{hypo}$ | 1 | U | 0.1 (0.05) | 10 (5) | U | U | A |
| Youngs et al. (1988) | Worldwide subduction zones | 20 + 197 + 389 | - | 16* (60) | 5.6* (5) | 8.1* (8.1, 8.2)[13] | $M_w$ ($M_s$, $m_b$) | U (15*, 20*) | U (450*, 450*) | $r_{rup}$, $r_{hypo}$ for $M_w \lesssim 7.5$ | 1 | 15 | 0.07 | 4 | G | 1W | A (B,F) |
| Kamiyama (1989) | Japan | 228 | - | U | 4.1 | 7.9 | $M_{\mathrm{JMA}}$ | 3 | 350 | $r_{epi}$ | I | U | 0.05* | 10* | U | 1 | A |
| Sewell (1989) | California + 7 other events | 112 | - | 24 | 5.0 | $7.7M_w$ ($M_L$, $M_s$) | 0.6 | 211 | $r_{jb}$ ($r_{epi}$ for some) | 2 | 20 | 0.07 | 2 | C | 2 | A | |
| Trifunac and Lee (1989) | Mostly California | 438 | 438 | 104 | U | U | U | U | U | $r_{epi}$ | C | 12 | 0.04 | 14 | B | U | A |
| Atkinson (1990) | E. N. America + 10 others | 92+10[14] | - | 8+3 | 3.60 (5.16) | 6.00 (6.84) | $M_w$ | 8 (8) | 1215 (23) | $r_{hypo}$ | 1 | 4 | 0.1 | 1 | B | 2 | A |
| Campbell (1990) | Unknown | U | - | U | U | U | $M_L$ for $M < 6$, $M_s$ for $M \geq 6$ | U | U | $r_{seis}$ | 1 | 15 | 0.04 | 4 | U | U | A |
| Dahle et al. (1990b) & Dahle et al. (1990a) | Worldwide intraplate regions | 87 | - | 56 | 2.9 | 7.8 | $M_s$ ($M_L$, $m_b$, $M_{CL}$ | 6 | 1300 | $r_{hypo}$ | 1 | 89 | 0.025 | 4 | L | 2 | A |
| Tamura et al. (1990) | Japan | 97 | - | 7 | 7.1 | 7.9 | $M_{\mathrm{JMA}}$ | U | U | $r_{epi}$ | 3 | 13 | 2 | 20 | L | 1, O | A |
| Tsai et al. (1990) | Worldwide | <88 | - | <51 | 4.9* | 7.4 | $M_w$ | 3* | 150* | $r_{rup}$ | 1 | 14 | 0.07 | 1 | U | M | T (S,O) |

*continued on next page*

[12]Details of dataset are given in tables but quality of scan too poor to clearly see digits.
[13]Consider equations valid for $M_w \leq 8$
[14]Total earthquake components (does not need to be multiplied by two). 79+10 records for 0.1 s equation.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crouse (1991) | Worldwide subduction zones | 235 | - | U | 5.1 | 8.2 | $M_w$ ($M_s$, $M_{\mathrm{JMA}}$) | >8 | >469 | $r_E$, $r_{hypo}$ for $M < 7.5$ | 1 | 10 | 0.1 | 4 | B | 1 | A |
| Dahle et al. (1991) | Intraplate (particularly Norway) | 395+31 | - | 136+11 | 2.4*(4.1) | 5.2*(6.9) | $M_s$ ($M_L$,$M_{CL}$) | 20* (9.7) | 1200* (1300) | $r_{hypo}$ | 1 | 4[15] | 0.1 | 1 | L | O | A |
| I.M. Idriss (1991)[16] | Unknown | 572 | - | 30* | 4.6 | 7.4 | $M_L$ for $M < 6$, $M_s$ for $M \geq 6$ | 1 | 100 | $r_{rup}$, $r_{hypo}$ for $M < 6$ | 1 | 23 | 0.03 | 5 | U | U | A |
| Loh et al. (1991) | Taiwan | 112 | - | 63 | 4.0 | 7.1 | $M_L$ | 5.0 | 178.3 | $r_{hypo}$ | 1 | 11 | 0.04 | 10 | L | U | A |
| Matuschka and Davis (1991) | New Zealand | 80 | 80 | 30 | U | U | U | U | U | U | 3 | 16 | 0.04 | 4 | B | U | A |
| Mohammadioun (1991) | Italy | 144 | - | 46 | 3.0 | 6.5 | U | 6 | 186 | $r_{hypo}$, 1 eq. with $r_{rup}$ | 1 | 81 | 0.013 | 1.95 | B | U | A |
| Stamatovska and Petrovski (1991) | Mainly Italy and former Yugoslavia | 489[17] | - | 78 | 3* | 8* | $M_L$ | 10* | 500* | $r_{hypo}$ | 1 | 23 | 0.05 | 5 | B | 1 | A |
| Niazi and Bozorgnia (1992) | SMART-1 array, Taiwan | 236 | 234 | 12 | 3.6 | 7.8 | $M_L$ ($M_D$) for $M_L < 6.6$, else $M_s$ | 3.1[18] | 119.7[18] | $r_{hypo}$ | 1 | 23 | 0.03 | 10 | M | 2W | A |
| Benito et al. (1992) | Campano Lucano | 84 | - | U | 4.7 | 6.5 | $M_L$ | 3.4* | 142* | $r_{hypo}$ | 3 | 15 | 0.04 | 10 | L | 1 | A |
| Silva and Abrahamson (1992) | W. USA with 4 foreign | U–136 | - | U–12 | 6.1 | 7.4 | $M_w$ | 3* | 100* | $r_{seis}$ | 2 | 10 | 1 | 20 | G | 1M | A (S,R) |
| Tento et al. (1992) | Italy | 137 | - | 40 | 4 | 6.6 | $M_L$ | 3.2 | 170 | $r_{jb}$ for $M_L \geq 5.7$, $r_{epi}$ otherwise | 1 | 12 | 0.04 | 2.75 | L | 2 | A |

*continued on next page*

[15] Consider more than 4 natural periods but results not reported.
[16] Reported in Idriss (1993).
[17] Does not need to be multiplied by two.
[18] Distance to centre of array

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abrahamson and Silva (1993) | W. USA with 4 foreign | 22–201 | - | 1–18 | 6.0 | 7.4 | $M_w$ | 0.6* | 100* | $r_{rup}$ | 2 | 10 | 1 | 20 | G | 1M | A (S, R) |
| Boore et al. (1993) & Boore et al. (1997) | W. N. America | 112 | - | 14 | 5.30 | 7.70 | $M_w$ | 0 | 109 | $r_{jb}$ | 3 | 46 | 0.1 | 2 | L, G | 2M | A |
| Caillot and Bard (1993) | Italy | 83 | - | $\leq 40$ | 3.2 | 6.8 | $M_s$ if $M_L$ & $M_s \geq 6.0$ else $M_L$ | 10 | 63 | $r_{hypo}$ | 2 | 25 | 0.05 | 1.98 | U | 2, 1W | A |
| Campbell (1993) | Worldwide | U | - | U | U[19] | U | $M_L$ for $M < 6.0$ and $M_s$ otherwise | U | U[20] | $r_{seis}$ | 2 | 15 | 0.04 | 4 | M | O | A (T,S) |
| Sadigh et al. (1993) & Sadigh et al. (1997) | California with 4 foreign | 960+4 | U | 119+2 | 3.8 (6.8) | 7.4 (7.4) | $M_w$ | 0.1 (3) | 305 (172)[21] | $r_{rup}$ for some, $r_{hypo}$ for small ones | 2 | 21 | 0.05[22] | 7.5[23] | G | U | A(R,S) |
| Electric Power Research Institute (1993a) | Eastern North America | 66 | 132 | U | 4* | 6.8* | $M_w$, $m_{Lg}$ | 5* | 1000* | $r_{hypo}$ ($r_{rup}$ for largest) | 3 | 10 | 0.03 | 1 | G | 1M | A |
| Sun and Peng (1993) | W. USA with 1 foreign | 150+1 | - | 42+1 | 4.1 | 7.7 | $M_L$ for $M < 6$, else $M_s$ | 2* | 150* | $r_{epi}$ | C | U | 0.04 | 10 | R | 1 | A |
| Boore et al. (1994a) & Boore et al. (1997) | W. N. America | 112 (70) | - | 14 (9) | 5.30 | 7.70 (7.40) | $M_w$ | 0 | 109 | $r_{jb}$ | C | 46 | 0.1 | 2 | L, G | 1M, 2M | A (R,S)[24] |
| Climent et al. (1994) | Central America & Mexico | 280 | U | 72 | U | U | U | U | U | U | U | U | 0.05* | $\geq 2$ | U | U | A |
| Fukushima et al. (1994) & Fukushima et al. (1995) | 3 vertical arrays in Japan | 285 | 284 | 42 | 5.0 | 7.7 | $M_{\mathrm{JMA}}$ | 60* | 400* | $r_{hypo}$ | I | U | 0.05 | 2 | B | 1,2 | A |

*continued on next page*

[19] Considers equation valid for $M \geq 4.7$.
[20] Considers equation valid for $d \leq 300$ km.
[21] Equations stated to be for distances up to 100 km
[22] Minimum period for vertical equations is 0.04 s.
[23] Maximum period for vertical equations is 3 s.
[24] Coefficients given in Boore et al. (1994b).

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{min}$ | $M_{max}$ | $M$ scale | $r_{min}$ | $r_{max}$ | $r$ scale | S | $T$s | $T_{min}$ | $T_{max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lawson and Krawinkler (1994) | W. USA | 250+ | - | 11 | 5.8 | 7.4 | $M_w$ | U | 100 | $r_{jb}$ | 3 | 38 | 0.1 | 4 | U | 1M | A |
| Lee and Manić (1994) & Lee (1995) | Former Yugoslavia | 313 | 313 | 183 | 3.75 | 7.0 | U | 4 | 250 | $r_{epi}$ | 6 | 12 | 0.04 | 2 | U | 2R | A |
| Mohammadioun (1994a) | California | 108[25] | 56 | 23 | 5.3 | 7.7 | $M_L$ | 3 | 136 | Often $r_{rup}$, $r_{hypo}$ in far field | 1 | 96 | 0.013 | 5 | B | 1 | A |
| Mohammadioun (1994b) | W. USA | 530[26] | $\approx 265$ | U | U | U | $M_L$ | 1 | 250 | $r_{rup}$, $r_E$ if more appropriate, $r_{hypo}$ in far field | 1 | 96 | 0.013 | 5 | B | 1 | A |
| Musson et al. (1994) | UK + 28* foreign | 88*+28*[27] | - | 15+16 | 3 (3.7) | 4.1 (6.4) | $M_L$ | 70* (>1.3) | >477.4 (200*) | $r_{hypo}$ | 1 | 4 | 0.1 | 1 | U[28] | O | A |
| Theodulidis and Papazachos (1994) | Greece+16 foreign | 105+16[29] | - | 36+4 | 4.5 (7.2) | 7.0 (7.5) | $M_s$, $M_w$, $M_{\mathrm{JMA}}$ | 1 (48) | 128 (236) | $r_{epi}$ | 2 | 73 | 0.05 | 5 | B | O | A |
| Dahle et al. (1995) | Cen. America | 280 | - | 72 | 3* | 8* | $M_w$ ($M_s$, $m_b$, $M_D$) | 6* | 490* | $r_{hypo}$ | 2 | 8 | 0.025 | 4 | L | 1B | A |
| Lee and Trifunac (1995) | W. N. America | 1926 | 1926 | 297 | 1.7 | 7.7 | Usually $M_L$ for $M \leq 6.5$ and $M_s$ for $M > 6.5$ | 2 | 200+ | $r_{hypo}$ | 9, 3 × C | 91 | 0.04 | 15 | U | 1 | A |
| Ambraseys et al. (1996) | Europe & Mid. East | 422 | - | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M > 6.0$, $r_{epi}$ otherwise | 3 | 46 | 0.1 | 2 | L | 2 | A |
| Ambraseys and Simpson (1996) | Europe & Mid. East | - | 417 | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M > 6.0$, $r_{epi}$ otherwise | 3 | 46 | 0.1 | 2 | L | 2 | A |
| Bommer et al. (1996) | El Salvador & Nicaragua | 36 | - | 20 | 3.7 | 7.0 | $M_s$ | 62 | 260 | $r_{hypo}$ | 1 | 10 | 0.1 | 2 | L | U | A |

*continued on next page*

[25] Total number, does not need to be multiplied by two.
[26] Total number, does not need to be multiplied by two.
[27] There are 116 records in total.
[28] Free (1996) believes it is largest horizontal component.
[29] Total number of components does not need to be multiplied by two

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Crouse and McGuire (1996) | Cen. & S. California | 238 | - | 16 | 6.0 | 7.7 | $M_s$ | 0.1 | 211 | $r_{rup}$ | 4 | 14 | 0.04 | 14 | G | 1W | R,S (R,S) |
| Free (1996) & Free et al. (1998) | Stable continental regions | 399–410 | 347–477 | H: 137–138, V: 126–132 | 1.5 | 6.8 | $M_w$ | 0 | 820 | $r_{jb}$ for some, $r_{epi}$ for most | 2 | 52 | 0.04 | 2 | L | 1 | A |
| Molas and Yamazaki (1996) | Japan | 2166 | - | 387 | 4.1 | 7.8 | $M_{\text{JMA}}$ | 8* | 1000* | $r_{rup}$ for 2 earthquakes, $r_{hypo}$ otherwise | I | 12 | 0.1 | 4 | L | O | A |
| Ohno et al. (1996) | California | 248 | - | 17 | 5.0 | 7.5 | $M_w$ ($M_L$) | 7.2 | 99.6 | $r_q$ for $M > 5.3$, $r_{hypo}$ otherwise | 2 | U | 0.02 | 2 | B | 2M | A |
| Sabetta and Pugliese (1996) | Italy | 95 | 95 | 17 | 4.6 | 6.8 | $M_s$ if $M_L$ & $M_s \geq 5.5$ else $M_L$ | 1.5, 1.5 | 179, 180[30] | Both $r_{jb}$ & $r_{epi}$ | 3 | 14 | 0.04 | 4 | L | 1 | A |
| Spudich et al. (1996) & Spudich et al. (1997) | Worldwide extensional regimes | 99–118 | - | 27–29 | 5.10 | 6.90 | $M_w$ | 0 | 102.1 | $r_{jb}$ | 2 | 46 | 0.1 | 2 | G, C | 2M | NS |
| Abrahamson and Silva (1997) | California with some others | $\leq 655$* | $\leq 650$* | $\leq 58$ | 4.4 | 7.4 | U | 0.1 | 220* | $r_{rup}$ | 2 | 28 | 0.01 | 5 | G | 1M | A (S,O,T) |
| Atkinson (1997) | Cascadia with some foreign | U | - | 11+9 | 4.1 | 6.7(8.2) | $M_w$ | 20* | 580* | $r_c$ for some, $r_{hypo}$ for small ones | 2 | 12 | 0.1 | 2 | B | 2 | A |
| Campbell (1997), Campbell (2000) & Campbell (2001) | Worldwide | 266 [31] | 173 | H:30, V:22 | 4.7 | 8.1 | $M_s$ for $M_s \geq 6$, $M_L$ for $M_s < 6$ | 3 | 50 | $r_{seis}$ | 3 | 13 | 0.05 | 4 | G | IW | A (S,R,N) |
| Schmidt et al. (1997) | Costa Rica | 200 | - | 57 | 3.3 | 7.6 | $M_w$ ($M_s$, $m_b$, $M_D$) | 6.1 | 182.1 | $r_{hypo}$ | 3 | 7 | 0.025 | 4 | L, B | O | A |

*continued on next page*

[30]State equations should not be used for distances $> 100$ km

[31]Typographic error in Table 3 of Campbell (1997) does not match number of recordings in Table 4

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Youngs et al. (1997) | Worldwide subduction zones | $\leq 476$ | - | $\leq 164$ | 5.0 | 8.2 | $M_w$ ($M_s$,$m_b$) | 8.5 | 550.9 | $r_{rup}$, $r_{hypo}$ for some | 2 | 11 | 0.075 | 3 | G | 1M | NT (N,T) |
| Bommer et al. (1998) | Europe & Mid. East | 121–183 | - | 34–43 | 5.5 | 7.9 | $M_s$ | 3 | 260 | $r_{jb}$ for most, $r_{epi}$ otherwise | 3 | 66 | 0.04 | 3 | L | 2 | A |
| Perea and Sordo (1998) | Urban area of Puebla, Mexico | 10[32] | - | 8 | 5.8 | 8.1 | $m_b$ for $M < 6$, $M_s$ otherwise | 274 | 663 | $r_{epi}$ | 1 | 195 | 0.01 | 3.5 | L | 1 | A |
| Reyes (1998) | University City, Mexico City | 20+ | - | 20+ | U | U | $M_w$ | U | U | $r_{rup}$ | I | 2 | 1.0 | 3.0 | S | U | A |
| Shabestari and Yamazaki (1998) | Japan | 3990 | - | 1020 | U | 8.1 | $M_{\mathrm{JMA}}$ | U | U | $r_{rup}$ | U | 35 | 0.04 | 10 | L | O | A |
| Chapman (1999) | W. N. America | 304 | - | 23 | 5.0 | 7.7 | $M_w$ | 0.1 | 189.4 | $r_{jb}$ | 3 | 24 | 0.1 | 2 | G | 2M | A |
| Spudich et al. (1999) | Worldwide extensional regimes | 105–132 | - | $\leq 38$ | 5.1 | 7.2 | $M_w$ | 0 | 99.4 | $r_{jb}$ | 2 | 46 | 0.1 | 2 | G | 1M | NS |
| Ambraseys and Douglas (2000), Douglas (2001a) & Ambraseys and Douglas (2003) | Worldwide | 186 | 183 | 44 | 5.83 | 7.8 | $M_s$ | 0 | 15 | $r_{jb}$ | 3 | 46 | 0.1 | 2 | L | 1 | A |
| Bozorgnia et al. (2000) | Worldwide | 1308 | 1308 | 33 | U | U | $M_w$ | U | $\leq 60$ | $r_{seis}$ | 4 | U | 0.05 | 4 | G | U | A (R,S,T) |
| Campbell and Bozorgnia (2000) | Worldwide | 275–435 | 274–434 | $\leq 36$ | $\geq 4.7$ | $\leq 7.7$ | $M_w$ | $\geq 1$* | $\leq 60$* | $r_{seis}$ | 4 | 14 | 0.05 | 4 | G | 1 | A (S,R,T) |
| Chou and Uang (2000) | California | 273 | - | 15 | 5.6 | 7.4 | $M_w$ | 0* | 120 | $r_{jb}$ | 3 | 25 | 0.1 | 3 | G | 2M | A |
| Field (2000) | S California | 357–447 | - | 28 | 5.1 | 7.5 | $M_w$ | 0 | 148.9 | $r_{jb}$ | C (6) | 3 | 0.3 | 3.0 | G | 1M | A (R, S, O) |
| Kawano et al. (2000) | Japan | 107 | 107 | 44 | 5.5 | 7.0 | $M_{\mathrm{JMA}}$ | 27 | 202 | $r_q$ | I, C | U | 0.02 | 5 | U | O | A |

*continued on next page*

[32]Typographical error in Figure 3b) of Perea and Sordo (1998) because it does not match their Table 1.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kobayashi et al. (2000) | Japan | U | - | U | 5.0 | 7.8 | $M_w$ | 0.9* | 400* | U | 4 | 17 | 0.1 | 5 | B | 1M | A |
| McVerry et al. (2000) | NZ with 66 foreign | $\leq$ 224 (461+66) | - | (51+17) | (5.08) | (7.23(7.41)) | $M_w$ | (0.1) | (573) | ($r_{rup}$ for some, $r_c$ for most) | 4 | U | 0.01* | 4* | U | O | A (N, R, RO) |
| Monguilner et al. (2000b) | W. Argentina | 54 | 54 | 10 | 4.3 | 7.4 | $M_s$ if $M_L$ & $M_s > 6$, $M_L$ otherwise | 11 | 350 | $r_{hypo}$ | 2 | 200 | 0.1 | 6 | U | 1W | A |
| Paciello et al. (2000) | Greece & Italy | 115 | - | 18 | 4.5* | U | $M_w$ or $M_s$ | U | U | $r_{epi}$ | 3 | 2 | 0.2 | 1 | B | 1 | A (N) |
| Shabestari and Yamazaki (2000) | Japan | 6017 | - | 94 | 5.0 | 6.6 | $M_{\mathrm{JMA}}$ | 7* | 950* | $r_{rup}$ | I | 35 | 0.04 | 10 | L | O | A |
| Smit et al. (2000) | Caucasus | 84 | - | 26 | 4.0 | 7.1 | $M_s$ | 4 | 230 | $r_{hypo}$ | 1 | 22 | 0.05 | 1 | L | 2 | A |
| Takahashi et al. (2000) | Japan+166 foreign | $\leq$1332 | - | U+7* | 5* (5.8*) | 8.3* (8*) | $M_w$ | 1* (0.1*) | 300* (100*) | $r_{rup}$, $r_{hypo}$ for some | 4 | 20 | 0.05 | 5 | G | O | A |
| Lussou et al. (2001) | Japan | 3011 | 3011 | 102 | 3.7 | 6.3 | $M_{\mathrm{JMA}}$ | 4* | 600* | $r_{hypo}$ | 4 | 63 | 0.02 | 10 | B | 2 | A |
| Das et al. (2002, 2006) | NE India | 174 | - | 6 | 5.5 | 7.2 | $M_s$ | 53.51* | 153.91* | $r_{hypo}$ | 1 | 20 | 0.04 | 1 | V | 2 | A |
| Gülkan and Kalkan (2002) | Turkey | 93[33] | - | 19 | 4.5 | 7.4 | $M_w$ | 1.20 | 150 | $r_{jb}$, $r_{epi}$ | 3 | 46 | 0.1 | 2 | L, R | 1 | A |
| Khademi (2002) | Iran | 160 | 160 | 28* | 3.4* | 7.4 | $M_w$ ($m_b$ for $M_s < 5$ and $M_s$ otherwise) | 0.1* | 180* | $r_{jb}$, $r_{epi}$ for $M < 5.9$ | 2 | 13 | 0.05 | 4 | L | O | A |
| Manic (2002) | Former Yugoslavia | 153[34] | 77 | 19 | 4.0 and 4.2 | 6.9 and 7.0 | $M_s$ and $M_L$ | 0 and 0 | 110 and 150 | $r_{jb}$ and $r_{epi}$ | 2 | 14 | 0.04 | 4 | B | 1 | A |
| Schwarz et al. (2002) | N.W. Turkey | 683 | 683 | U | 0.9* | 7.2 | $M_L$ | 0* | 250* | $r_{epi}$ | 3 | 11 | 0.01 | 2 | U | 1 | A |
| Zonno and Montaldo (2002) | Umbria-Marche | 161 | - | 15 | 4.5 | 5.9 | $M_L$ | 2* | 100* | $r_{epi}$ | 2 | 14 | 0.04 | 4 | L | 2 | N, O |
| Alarcón (2003) | Colombia | 45 or 47 | - | U | 4.0 | 6.7 | $M_s$ | 49.7 | 322.4 | $r_{hypo}$ | 1 | 84 | 0.05 | 3 | U | U | A |
| Atkinson and Boore (2003) | Subduction zones | 1200+ | - | 43* | 5.5 | 8.3 | $M_w$ | 11* | 550* | $r_{rup}$ | 4 | 7 | 0.04 | 3 | C | 1M | F, B |

*continued on next page*

[33] This is total number of horizontal components used. They come from 47 triaxial records.
[34] This is total number of components. Does not need to be multiplied by two.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Berge-Thierry et al. (2003) | Europe & Mid. East+163 from W. USA | 802+163[35] | 403+82[36] | 130+8 | 4.0 (5.8) | 7.9 (7.4) | $M_s$ ($M_w$ for W. USA) | 4 | 330 | $r_{hypo}$ | 2 | 143 | 0.03 | 10 | B | 2 | A |
| Bommer et al. (2003) | Europe & Mid. East | 422 | - | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M_s > 6.0$, $r_{epi}$ otherwise | 3 | 46 | 0.1 | 2 | L | 1M | A (S, R, N) |
| Campbell and Bozorgnia (2003d), Campbell and Bozorgnia (2003a) & Bozorgnia and Campbell (2004b) | Worldwide | 443 | 439 | 36[37] | 4.7 | 7.7 | $M_w$ | 2* | 60* | $r_{seis}$ | 4 | 14 | 0.05 | 4 | G | 1 | A (S & N, R, T) |
| Fukushima et al. (2003) | Mainly west Eurasia+some US and Japanese | 399+341 | - | 40+10 | 5.5 | 7.4 | $M_w$ ($M_s$) | 0.5 | 235 | $r_{hypo}$ ($r_{rup}$ for 2 earthquakes) | 2 | 11 | 0.03 | 2 | B | 2 | A |
| Kalkan and Gülkan (2004a) | Turkey | - | 95–100[38] | 47 | 4.2 | 7.4 | $M_w$ (unspecified scales) | 1.2 | 250 | $r_{jb}$, $r_{epi}$ for small events | 3 | 46 | 0.1 | 2 | - | 1 | A |
| Kalkan and Gülkan (2004a) | Turkey | 112 | - | 57 | 4.0 | 7.4 | $M_w$ (unspecified scales) | 1.2 | 250.0 | $r_{jb}$, $r_{epi}$ for small events | 3 | 46 | 0.1 | 2 | L[39] | 1 | A |
| Matsumoto et al. (2004) | Japan | 293[40] | - | 63 | 5.0* | 7.6* | $M_{\mathrm{JMA}}$ | 0* | 195* | $r_{rup}$ & $r_q$ | 1 | U | 0.02* | 4* | M | 1M | A (B, C, F) |
| Özbey et al. (2004) | NW Turkey | 195 | - | 17 | 5.0 | 7.4 | $M_w$ ($M_L$) | 5* | 300* | $r_{jb}$ | 3 | 31 | 0.10 | 4.0 | G | 1M | NS |

*continued on next page*

[35]Total number of records. Does not need to be multiplied by two.
[36]485 records in total but do not state number of vertical records from W. USA.
[37]For horizontal corrected records. There are 34 for vertical corrected records.
[38]Authors do not state reason for different number of records used for different periods.
[39]The caption of their Table 2 states that reported coefficients are for mean.
[40]The authors also report that they used 139 'sets', which could refer to number of records rather than the 293 'components' that they also report.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pankow and Pechmann (2004) and Pankow and Pechmann (2006) | Worldwide extensional regimes | 142 | - | 39 | 5.1 | 7.2 | $M_w$ | 0 | 99.4 | $r_{jb}$ | 2 | 46 | 0.1 | 2.0 | G, O | 1M | NS |
| Sunuwar et al. (2004) | Okhotsk-Amur plate boundary | 667 | 667 | 42 | 4.0 | 5.6 | $M_{\mathrm{JMA}}$ | >3 | >264 | $r_{hypo}$ | 1 | 19 | 0.05 | 3.0 | L | 2M | A |
| Takahashi et al. (2004) | Mainly Japan+W USA+Iran | 4400 | - | 270 | 4.9* | 8.3* | $M_w$ | 0.3* | 300 | $r_{rup}$ for some, $r_{hypo}$ for rest | 4 | 21 | 0.02 | 5.0 | G | 1M | A (B, F, R, S) |
| Wang et al. (2004) | Chi-chi aftershocks (Taiwan) | 200* | - | 4 | 5.8 | 6.3 | $M_w$ | 20* | 80* | $r_{jb}$ | 1 | 14 | 0.1 | 5 | G | 1M | R |
| Yu and Hu (2004) | W USA | 522+187[41] | - | 38+14* | 5.0 | 7.5 | $M_s$ | 1.5* | 575* | $r_{epi}$ | 1 | U | 0.04 | 20 | B | O | A |
| Yu and Wang (2004) | W USA | 187 for $T < 1.5$ s, 754 for $T > 1.5$ s | - | >17 | 5.0* (5.0*) | 7.8* (7.5*) | U | 2* | 200* (600*) | $r_{epi}$ | 1 | 30 | 0.04 | 6.0 | B | O | A |
| Ambraseys et al. (2005a) | Europe & Middle East | 207–595 | - | 59–135 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | 61 | 0.05 | 2.5 | L | 1M | A (N, T, S, O) |
| Ambraseys et al. (2005b) | Europe & Middle East | - | 207–595 | 59–135 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | 61 | 0.05 | 2.5 | - | 1M | A (N, T, S, O) |
| Bragato and Slejko (2005) | E Alps (45.6–46.8°N & 12–14°E) | 1402 | 3168 | 240 | 2.5 | 6.3 | $M_L$ | 0 | 130 | $r_{jb}$ & $r_{epi}$ | 1 | 47 | 0.05 | 2.0 | R | O | A |
| García et al. (2005) | Central Mexico | 277 | 277 | 16 | 5.2 | 7.4 | $M_w$ | 4* | 400* | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | 15 | 0.04 | 5 | G[42] | 1M | B |

*continued on next page*

[41] Does not need to be multiplied by two.
[42] Call it 'quadratic mean', which is assumed to be geometric mean.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| McGarr and Fletcher (2005) | Central Utah coal-mining areas | 31–72 | - | 12 | 0.98 | 4.2 | $M_w$ ($M_{CL}$) | 0.5* | 10* | $r_{hypo}$ | 2 | 5 | 0.1 | 2.0 | L | 2M | M |
| Pousse et al. (2005) | Japan | 6812 | - | 591 | 4.1 | 7.3 | $M_w$ ($M_{\mathrm{JMA}}$) | 5.5 | 303 | $r_{hypo}$ ($r_{rup}$ for 10 events) | 5 | U | 0.01 | 4.0 | B | 2 | A |
| Takahashi et al. (2005), Zhao et al. (2006) and Fukushima et al. (2006) | Japan+208 overseas | 2763–4518+208 | - | <249+20 | 5.0 | 8.3 | $M_w$ | 0* | 300* | $r_{rup}$ | 5 | 20 | 0.05 | 5 | G | 1M | C (R, S/N) & F, B |
| Wald et al. (2005) | California | U | - | U | U | 5.3* | $M_w$ | U | U | $r_{jb}$ | 1 | 3 | 0.3 | 3 | L | U | A |
| Atkinson (2006) | Los Angeles region | 461–4973 | - | 509+ | 3.1* | 7.1* | $M_w$ | 5* | 350* | $r_{epi}$ ($r_{jb}$ for some) | 3 | 0.3 | 3.0 | I, C | B | 1 | A |
| Beyer and Bommer (2006) | Shallow crustal (USA, Taiwan, Turkey and others) | 949 | - | 103 | 4.3* | 7.9* | $M_w$ | 6* | 200* | $r_{hypo}$ | U | 77 | 0.01 | 5.0 | 1, 2, A, B, C, D50, G, I50, L, N, P, R | 1M | A (U) |
| Bindi et al. (2006) | Umbria-Marche | 144–239 | - | $\leq$ 45 | 4.0 | 5.9 | $M_L$ | 1* | 100* | $r_{epi}$ & $r_{hypo}$ | 4 | 14 | 0.04 | 4 | L | 1M | NS |
| Campbell and Bozorgnia (2006a) and Campbell and Bozorgnia (2006b) | Worldwide | 1500+ | - | 60+ | 4.2 | 7.9 | $M_w$ | 0 | 200 | $r_{rup}$ | C | U | U | 10 | G | 2M | A |
| Hernandez et al. (2006) | Haulien LSTT (Taiwan) | 456 | 456 | 51 | 5 | 7.3 | $M_L$ | 13.7 | 134.8 | $r_{hypo}$ | 5 | 143 | 0.03 | 10 | B | 1 | A |

*continued on next page*

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jaimes et al. (2006) | Ciudad Universitaria station, Mexico City | 21 | - | 21 | 6.0 | 8.1 | $M_w$ | 285 | 530 | $r_{rup}$ | 1 | 30 | 0.2 | 6 | U | 1B | F |
| Kanno et al. (2006) | Japan+some foreign | 3205–3392+331–377 (shallow) & 7721–8150 (deep) | - | 70–73+10 & 101–111 | 5.0* (6.1) & 5.5* | 8.2* (7.4) & 8.0* | $M_w$ ($M_{\mathrm{JMA}}$) | 1* (1.5*) & 30* | 450* (350*) & 450* | $r_{rup}$ ($r_{hypo}$ for some) | C | 37 | 0.05 | 5 | R | 2M | A |
| Kataoka et al. (2006) | Japan | 5160 | - | 47 | 4.8* | 6.9* | $M_w$ | 1* | 200* | U | 1 | 18 | 0.1 | 5 | U | U | C |
| McVerry et al. (2006) | New Zealand | 435 | - | 49 | 5.08 | 7.09 | $M_w$ | 6 | 400 | $r_c$ ($r_{rup}$) | 3 | 11 | 0.075 | 3 | L, G | 1M | C (R, OR, S & N) & F, B |
| Pousse et al. (2006) | Japan | 9390[43] | - | U | 4.1 | 7.3 | ($M_w$) | 5* | 250* | $r_{hypo}$ ($r_{rup}$ for some) | 5 | U | 0.01 | 3 | B | 2M | A |
| Sakamoto et al. (2006) | Japan | 3198 | - | 52 | 5.5 | 8.3 | $M_w$ | 1 | 300 | $r_{rup}$ | 5 | U | 0.02 | 5 | M | 1M | A |
| Sharma and Bungum (2006) | Indian Himalayas+9 European records | 175+9 | - | 12+7 | 4.5 (6.0) | 7.2 (7.4) | $M_w$ ($m_b$) | 10 | 200 | $r_{hypo}$ | 2 | 13 | 0.04 | 2.5 | G | 1W | A |
| Sigbjörnsson and Elnashai (2006) | Europe & Mid. East | 422 | - | 157 | 4.0 | 7.9 | $M_s$ (unspecified) | 0 | 260 | $r_{jb}$ for $M > 6.0$, $r_{epi}$ otherwise | 3 | 52 | 0.1 | 4 | L | 2 | A |
| Tapia (2006) & Tapia et al. (2007) | Western Mediterranean | 334 | - | 30 | 3.8 | 6.0 | $M_L$ | 6 | 542 | $r_{epi}$ | 1 | 5 | 0.1 | 2.0 | U | 1 | A |
| Uchiyama and Midorikawa (2006) | Japan | 3198 | - | 52 | 5.5 | 8.3 | $M_w$ | U | U | $r_{rup}$ | 1 | U | 0.02 | 5 | G | 2M | A (C/F, B) |
| Zare and Sabzali (2006) | Iran | 89 | 89 | 55* | 2.7 | 7.4 | $M_w$ | 4 | 167 | $r_{hypo}$ | 4 | 21 | 0.10 | 4 | U | 1M & 2M | A |

*continued on next page*

[43] Does not need to be multiplied by two.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Akkar and Bommer (2007b) | Europe & Middle East | 532 | - | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ | 3 | 80 | 0.05 | 4 | G | 1WM | A (N, S, R) |
| Bindi et al. (2007) | NW Turkey | 4047 | 4047 | 528 | 0.5 | 5.9 | $M_L$[44] | 5* | 200* | $r_{hypo}$[45] | 2 | 8 | 0.1 | 1[46] | L | 1M | A |
| Bommer et al. (2007) | Europe and Middle East | 997 | - | 289 | 3 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | 10 | 0.05 | 0.50 | G | 1WM | A (N, S, R) |
| Boore and Atkinson (2007) & Boore and Atkinson (2008) | Worldwide shallow crustal | 600*–1574 | - | 18*–58 | 4.27–5.00[47] | 7.90[48] | $M_w$ | 0 | 280[49] | $r_{jb}$ | C | 21 | 0.01 | 10 | I50 | 2M | A (N, R, S, U) |
| Campbell and Bozorgnia (2007), Campbell and Bozorgnia (2008b) & Campbell and Bozorgnia (2008a) | Worldwide shallow crustal | 506–1561 | - | 21–64 | 4.27[50] | 7.90[51] | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | 21 | 0.01 | 10 | I50 | 1M | A (N, R, S, HW) |
| Danciu and Tselentis (2007a), Danciu and Tselentis (2007b) & Danciu (2006) | Greece | 335 | - | 151 | 4.5 | 6.9 | $M_w$ | 0* | 136 | $r_{epi}$ | 3 | 31 | 0.10 | 4 | A | 1M | A (N, ST) |

*continued on next page*

[44] Also derive model using $M_w$.
[45] Also derive model using $r_{epi}$.
[46] Their Figure 2 present $\sigma$s up to 2 s but the coefficients of the model are not given beyond 1 s.
[47] Recommend that model is not extrapolated below 5 due to lack of data.
[48] Believe that model can be used to 8.0.
[49] Recommend that model is not used for distances $\geq 200$ km.
[50] Believe that model can be extrapolated down to 4.0.
[51] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fukushima et al. (2007c) & Fukushima et al. (2007b) | Mainly west Eurasia+some US and Japanese | 399+339 | - | 40+10 | 5.5 | 7.4 | $M_w$ ($M_s$) | 0.5 | 235 | $r_{hypo}$ ($r_{rup}$ for 2 earthquakes) | 5 | U | 0.03 | 3 | B | 2M | A |
| Hong and Goda (2007) & Goda and Hong (2008) | California | 484–592 | - | 34–39 | 5* | 7.4* | $M_w$ | 0.2* | 100* | $r_{jb}$ | C | 27 | 0.1 | 3 | G, Q, R | 1M | A |
| Massa et al. (2007) | Central northern Italy | 1063 | - | 243 | 2.5 | 5.2 | $M_L$ | 0* | 300* | $r_{hypo}$ | 2 | 8 | 0.1 | 1.5 | L | 1 | A |
| Tejeda-Jácome and Chávez-García (2007) | Colima, Mexico | 162 | 162 | 26 | 3.3 | 5.2 | $M_L$ | 5* | 175 | $r_{hypo}$ | 1 | H:10, V:9 | 0.07 | H:0.99, V:0.80 | G | 2M | A |
| Abrahamson and Silva (2008) & Abrahamson and Silva (2009) | Worldwide shallow crustal | 500*–2754 | - | 64–135 | 4.27[52] | 7.9[53] | $M_w$ | 0.06* | 200* | $r_{rup}$ | C | 22 | 0.01 | 10 | I50 | 1M | A (N, R, S, HW) |
| Aghabarati and Tehranizadeh (2008) | Worldwide shallow crustal | 646 | 646 | 54 | 5.2 | 7.9 | $M_w$ | 0 | 60 | $r_{rup}$ | C | 26 | 0.025 | 10 | G | 1M | A (N, R, S) |
| Cauzzi and Faccioli (2008) & Cauzzi (2008) | Worldwide shallow crustal | 1164 | 1132 | 60 | 5.0 | 7.2 | $M_w$ | 6* | 150* | $r_{hypo}$ | 4 & C | 400 | 0.05 | 20 | G | 2M | A (N, S, R) |
| Chen and Yu (2008a) | Worldwide shallow crustal | 130 | - | U | 5.0* | 7.5* | $M_w$ | 0* | 200* | U | 1 | U | 0.04 | 10 | B | 1 | A |
| Chen and Yu (2008b) | Worldwide shallow crustal | 130 | - | U | 5.0* | 7.5* | $M_w$ | 0* | 200* | U | 1 | U | 0.04 | 10 | B | 1 | A |

*continued on next page*

[52]Recommend that model is not extrapolated below 5 due to lack of data.
[53]Believe that model can be reliably extrapolated to 8.5.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chiou and Youngs (2008) | Worldwide shallow crustal | ≤1950[54] | - | ≤125 | 4.265[55] | 7.90[56] | $M_w$ | 0.2*[57] | 70*[58] | $r_{rup}$ | C | 22 | 0.01 | 10 | I50 | 1M | A (N, R, S, HW, AS) |
| Cotton et al. (2008) | Japan | 3894 | - | 337 | 4 | 7.3 | $M_w$ ($M_{\mathrm{JMA}}$) | 1 | 100 | $r_{rup}$ ($r_{hypo}$ for small) | 4[59] & 2[60] | 23 | 0.01 | 3.33 | G | 2M | A |
| Dhakal et al. (2008) | Northern Japan | 772 (B), 1749 (F) | - | 10 (B), 20 (F) | 5.4 (B), 5.1 (F) | 7.0 (B), 7.3 (F) | $M_w$ | 70* | 300* | $r_{hypo}$ | 1 | 16 | 0.1 | 5 | V | 2 | B, F |
| Hancock et al. (2008) | Worldwide shallow crustal | U | - | U | 5.6* | 7.9* | $M_w$ | 0.1* | 400* | $r_{jb}$ | 3 | U | 0* | 2.5* | U | 1M | A (S, N, R/RO) |
| Idriss (2008) | Worldwide shallow crustal | 942 | - | 72 | 4.5 | 7.7 | $M_w$ | 0.3 | 199.3 | $r_{rup}$ | 2 | 31 | 0.01 | 10 | I50 | 1 | A (R/RO/NO, S/N) |
| Kataoka et al. (2008) | Japan | 1880 (crustal), 2374 (subduction) | - | 11 (crustal), 14 (subduction) | 5.8 (crustal), 6.1 | 6.9 (crustal), 8.2 (subduction) | $M_w$ | 0.1* (crustal), 10* (subduction) | 600* (crustal), 900* (subduction) | U | 1 | 19 | 2 | 20 | U | U | C, BF |
| Lin and Lee (2008) | NE Taiwan+10 foreign | 4244+139 | - | 44+10 | 4.1 (6.0) | 7.3 (8.1) | $M_w$ ($M_L$) | 15 | 630 | $r_{hypo}$ | 2 | 27 | 0.01 | 5 | G | 1W | A (B, F) |
| Massa et al. (2008) | Northern Italy | 306 | 306 | 82 | 3.5 & 4.0 | 6.3 & 6.5 | $M_w$ ($M_L$) & $M_L$ | 1* | 100* | $r_{epi}$ | 3 | 12 & 14 | 0.04 | 2 & 4 | L | 1M | A |
| Morasca et al. (2008) | Molise | 3090 | 3090 | 100 | 2.7 | 5.7 | $M_L$ | 12* | 60* | $r_{hypo}$ | 2 | 12 | 0.04 | 2 | L | 1M | A |
| Yuzawa and Kudo (2008) | Japan | 1988 | - | 18 | 5.9, 5.7 | 8.0, 7.9 | $M_{JMA}$, $M_w$ | U | U | $r_q$ | 1 | 45 | 1 | 10 | U | 2 | A |
| Ghasemi et al. (2009) | Iran+West Eurasia | 716+177 | - | 200 | 5.0 | 7.4 | $M_w$ | 0.5 | 100 | $r_{rup}$ ($r_{hypo}$ for small events) | 2 | 17 | 0.05 | 3 | I50 | 1M | A |

*continued on next page*

[54] Due to filtering number of records and earthquakes depends on period.
[55] Believe that model can be extrapolated down to 4.0.
[56] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[57] Believe that model valid to 0 km.
[58] Believe that model valid to 200 km.
[59] For stations on surface.
[60] For borehole stations.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aghabarati and Tehranizadeh (2009) | Worldwide shallow crustal | 678 | 678 | 55 | 5.2 | 7.9 | $M_w$ | 0 | 60 | $r_{rup}$ | C | 26 | 0.025 | 10 | G | 1M | A (N, R, S) |
| Akyol and Karagöz (2009) | Western Anatolia | 168 | - | 49 | 4.03 | 6.40 | $M_w$ ($M_d$, $M_L$) | 15 | 200 | $r_{hypo}$ | 2 | 30 | 0.05 | 2 | L | 2M | A |
| Bindi et al. (2009a) | Italy | 241 | 241 | 27 | 4.8 | 6.9 | $M_w$ | 0 | 190 | $r_{jb}$ | 3 | 18 | 0.03 | 2 | L, G | 1M | A (N, S, R) |
| Bindi et al. (2009b) | Italy | 235 | - | 27 | 4.6 | 6.9 | $M_w$ ($M_L$) | 0 | 183 | $r_{jb}$, $r_{epi}$ | 3 | 19 | 0.03 | 3 | L | 1M | A |
| Bragato (2009) | Italy | 922 | - | 116 | 2.7 | 4.5 | $M_L$ | 6 | 100 | $r_{epi}$ | I, 3, 1, C | 3 | 0.3 | 3 | U | 1 | A |
| Goda and Atkinson (2009) | Japan | 8557 (3410 shallow, 5147 deep) | - | 155 (51 shallow, 104 deep) | 5.5 | 7.9 | $M_w$ | 1.5* | 300* | $r_{rup}$ ($r_{hypo}$ for some $M < 6.5$) | C | U | 0.1 | 5 | G | 2M | A (C/F, B) |
| Hong et al. (2009a) | Mexico (interface & inslab) | 418, 277 | -, - | 40, 16 | 5.0, 5.2 | 8.0, 7.4 | $M_w$ | U | U | $r_{rup}$ ($r_{hypo}$ for small) | 1 | 27 | 0.1 | 3 | G, R, Q | 1M | F, S |
| Hong et al. (2009b) | California | 484–592 | - | 34–39 | 5* | 7.4* | $M_w$ | 0.2* | 100* | $r_{jb}$ | C | 27 | 0.1 | 3 | G, R | 1M, 2M, O | A |
| Kuehn et al. (2009) | Worldwide | 2660 | - | 60 | 5.61 | 7.9* | $M_w$ | 0.1* | 200* | $r_{jb}$ | C | 39 | 0.01 | 3 | G | 1M (O) | A (N, R, S) |
| Moss (2009) & Moss (2011) | Worldwide shallow crustal | 1950 | - | 125 | 4.265 | 7.90 | $M_w$ | 0.2* | 70* | $r_{rup}$ | C | 5 | 0.1 | 7.5 | I50 | 1M | A (N, R, S, HW, AS) |
| Rupakhety and Sigbjörnsson (2009) | South Iceland+others | 64+29 | - | 12 | 5.02 | 7.67 | $M_w$ | 1 | 97 | $r_{jb}$ ($r_{epi}$ for some) | 2 | 66 | 0.04 | 2.5 | L | 1 | SO |
| Sharma et al. (2009) | Indian Himalayas+Zagros | 58+143 | - | 6+10 | 5.5 & 5.9 | 6.8 & 6.6 | $M_w$ | 5* & 10* | 190* & 200* | $r_{jb}$ | 1 | 13 | 0.04 | 2.5 | G | O | A (S, R) |
| Akkar and Bommer (2010) | Europe & Middle East | 532 | - | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ | 3 | 60 | 0.05 | 3 | G | 1M | A (N, S, R) |
| Akkar and Çağnan (2010) | Turkey | 433 | - | 137 | 5.0 | 7.6 | $M_w$ | 0* | 200* | $r_{jb}$ | C | 14 | 0.03 | 2 | G | 1M | A (N, S, R) |

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Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Amiri et al. (2009) | Alborz and central Iran[61] | 416 | - | 189 | 3.2[62] | 7.7 | $M_s$ ($m_b$) | 5* | 400* | $r_{hypo}$ | 2 | 15 | 0.1 | 4 | L | 1M | A |
| Arroyo et al. (2010) | Pacific coast of Mexico | 418 | - | 40 | 5.0 | 8.0 | $M_w$ | 20 | 400 | $r_{rup}$ ($r_{hypo}$ for $M_w < 6$) | 1 | 56 | 0.04 | 5 | U | O | F |
| Bindi et al. (2010) | Italy | 561 | 561 | 107 | 4.0 | 6.9 | $M_w$ | 1* | 100* | $r_{jb}$, $r_{epi}$ | 3 | 21 | 0.03 | 2 | L | 1M | A |
| Bozorgnia et al. (2010) | Worldwide shallow crustal | 506–1561 | - | 21–64 | 4.27 | 7.90 | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | 21 | 0.01 | 10 | G | 1M | A (N, R, S, HW) |
| Das and Gupta (2010) | Chi-Chi region (Taiwan) | 487–498 | - | 16 | 4.99 | 7.3 | $M_w$ ($M_L$) | 0* | 50* | $r_{rup}$ | 3 | 16 | 0.04* | 10 | G | 1M | A |
| Douglas and Halldórsson (2010) | Europe & Middle East | 595 | - | 135 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ ($r_{epi}$ for small events) | 3 | 61 | 0.05 | 2.5 | L | 1WM | A (N, T, S, O, AS) |
| Faccioli et al. (2010) | Worldwide shallow crustal | 1499 | - | $\leq 60$ | 4.5 | 7.6 | $M_w$ | 0.2* | 200* | $r_{rup}$ ($r_{hypo}$ for small) | 4 & C | 22 | 0.05 | 20 | G | 1M | A (N, R, S) |
| Hong and Goda (2010) | California[63] | 484–592 | - | 34–39 | 5.0 | 7.28 | $M_w$ | 0.2* | 100* | $r_{jb}$ | C | 6 | 0.2 | 3 | 1, 2 | 1M | A |
| Jayaram and Baker (2010) | Worldwide shallow crustal | 1561 | - | 64 | 4.27 | 7.90 | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | 21 | 0.01 | 10 | I50 | O | A (N, R, S, HW) |
| Montalva (2010) & Rodriguez-Marek et al. (2011) | Japan | 3894 | - | 337 | 4 | 7.3 | $M_w$ ($M_{\mathrm{JMA}}$) | 1 | 100 | $r_{rup}$ ($r_{hypo}$ for small) | C, I | 21 | 0.0384 | 1.3622 | G | O (1M) | A |
| Ornthammarath et al. (2010), Ornthammarath (2010) & Ornthammarath et al. (2011) | South Iceland | 81 | - | 6 | 5.1 | 6.5 | $M_w$ | 1* | 80* | $r_{jb}$ ($r_{epi}$ for $M_w < 6$) | 2 | 4 | 0.2 | 2 | G | 1M | S |

*continued on next page*

[61] Also develop models for the Zagros region of Iran using 309 records from 190 earthquakes.
[62] State that only use data with $M_s \geq 4$ but one earthquake in their Appendix A has $M_s 3.2$.
[63] Also derive models for inslab (273 records from 16 earthquakes) and interface (413 records from 40 earthquakes) Mexican earthquakes.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rodriguez-Marek and Montalva (2010) | Japan | 3894 | - | 337 | 4 | 7.3 | $M_w$ ($M_{\mathrm{JMA}}$) | 1 | 100 | $r_{rup}$ ($r_{hypo}$ for small) | C | 7 | 0.01 | 1.3622 | G | 2M | A |
| Sadeghi et al. (2010) | Iran | 883 | - | 79 | 5 | 7.4* | $M_w$ | 0* | 340* | $r_{epi}$ | 2 | 8 | 0.1 | 3 | U | O | A |
| Saffari et al. (2010) | Central Iran & Zagros | 627 | - | 110 | 5 | 7.4* | $M_w$ | 5* | 200* | $r_{rup}$ ($r_{hypo}$ for $M_w$ < 6.5) | 2 | 19 | 0.05 | 5 | U | 2M | A |
| Anderson and Uchiyama (2011) | Guerrero, Mexico | 293 | 293 | 27 | 5.05 | 7.96 | $M_w$ | 10* | 390* | $r_{rup}$ | 1 | 5 | 0.1 | 3 | M, V, V3 | O | A |
| Arroyo and Ordaz (2011) | Worldwide shallow crustal | 906, 458 | - | 44, 28 | U | U | $M_w$ | U | U | $r_{rup}$ | 1 | 1 | 3 | 3 | I50 | 1M | A (R/RO/NO, S/N) |
| Bindi et al. (2011a) | Italy | 769 | - | 99 | 4.1 | 6.9 | $M_w$ | 0* | 200* | $r_{jb}$ | 5 | 20 | 0.04 | 2 | G, V | 1M | A (S, R, N, U) |
| Buratti et al. (2011) | Worldwide shallow crustal | 1666 | - | U | 5.6* | 7.9* | $M_w$ | 0.1* | 400* | $r_{jb}$ | 3 | U | 0.06* | 3* | U | 1M | A |
| Cauzzi et al. (2011) | Global | U | - | U | 3 | 7.9 | $M_w$ | 0* | 150* | $r_{rup}$ ($r_{hypo}$) | C, 4 | 10 | 1 | 10 | B | 1M | A |
| Chopra and Choudhury (2011) | Gujarat (India) | 407 | 407 | >70 | 3.5 | 5.7 | $M_w$ | 0* | 300* | $r_{hypo}$ | 2 | 6 | 0.05 | 1 | G | 1 | A |
| Gehl et al. (2011) | Japan | 3874 | - | 335 | 4.0 | 7.3 | $M_w$ | 0* | 340* | $r_{rup}$ | C | 5 | 0.1 | 2 | G | 1M, O | A |
| Lin et al. (2011b) | Taiwan+8 foreign events | 5181+87 | - | 44+8 | 3.5 (6.0) | 7.6 (7.4) | $M_w$ ($M_L$) | 1 | 240 | $r_{rup}$ ($r_{hypo}$) | 2 | 15 | 0.01 | 5 | G | 1 | A (HW) |
| Chang et al. (2012) | Taiwan | 302 | - | 58 | 5.5 | 7.3 | $M_L$ | 0* | 170* | $r_{hypo}$ ($r_{rup}$ for some) | 1 | U | 0.01 | 10 | G | 1 | A |
| Contreras and Boroschek (2012) | Chile | 117 | - | 13 | 6.5 | 8.8 | $M_w$ | 30* | 600* | $r_{rup}$, $r_{hypo}$ for 4 events | 2 | 23 | 0.04 | 2 | G | 1M | F |
| Cui et al. (2012) | Sichuan-Yunnan (China) | 962 | - | >21 | 4.5 | 6.5 | $M_s$ | 0* | 110* | $r_{epi}$ | 2 | 5 | 0.04 | 6 | G | 1, 1W | A |
| Di Alessandro et al. (2012) | Italy | 602 | - | 120 | 4.0 | 6.8 | $M_w$ | 2* | 200* | $r_{hypo}$ | 7 | 58 | 0.033 | 2.01 | G | 1M | A |

*continued on next page*

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hamzehloo and Mahood (2012) | East central Iran | 258 | - | 109[64] | 4.9* | 7.4 | $M_w$ | 1* | 200* | $r_{jb}$ | 1 | 14 | 0.1 | 5 | G | 2M | A |
| Laouami and Slimani (2012) | Algeria + Europe & USA | 633 + 528 & 155[65] | - | 82+17* & 7* | 3 (5*) | 6.8 (7.3*) | $M_s$ | 6* (10*) | 140* (150*) | $r_{hypo}$ | 2 | U | 0.01 | 3* | B | 2 | A |
| Saffari et al. (2012) | Iran | 351 | - | 78 | 5.0 | 7.4 | $M_w$ | 4 | 190* | $r_{rup}$ ($r_{hypo}$ for $M_w < 6.5$) | 3 | 20 | 0.05 | 5 | U | 2M | A |
| Abrahamson et al. (2013, 2014) | Worldwide shallow crustal | 15750–4000* | - | 326–70* | 3 | 7.9[66] | $M_w$ | 0 | 300 | $r_{rup}$ + others for HW | C | 22 | 0.01 | 10 | D50 | 1M | A (S, N, R, HW, AS) |
| Boore et al. (2013, 2014) | Worldwide shallow crustal | 15000*–5000* | - | 350*–100* | 3.0 | 7.9[67] | $M_w$ | 0 | 400 | $r_{jb}$ | C | 105 | 0.01 | 10 | D50 | 2M | A (S, N, R, U) |
| Campbell and Bozorgnia (2013, 2014) | Worldwide shallow crustal | 15521–U* | - | 322–U* | 3.0[68] | 7.9[69] | $M_w$ | 0* | 300* | $r_{rup}$ | C | 21 | 0.01 | 10 | D50 | 1M | A (S, R, N, HW) |
| Chiou and Youngs (2013, 2014) | Worldwide shallow crustal | 12244–4200* | - | 300–U* | 3.1*[70] | 7.9*[71] | $M_w$ | 0.3* | 400*[72] | $r_{rup}$ | C | 24 | 0.01 | 10 | D50 | 1M | A (S, R, N, HW) |
| Douglas et al. (2013) | Mainly geothermally-related | 3968 | - | 535 | 1* | 4* | $M_w$ ($M_L$, $M_D$) | 0* | 20* | $r_{hypo}$ | 1 | 104 | 0.01 | 0.5 | G | 1M | G |
| Idriss (2013, 2014) | Worldwide shallow crustal | 2353 | - | 151 | 4.5[73] | 7.9[74] | $M_w$ | 0.2 | 175 | $r_{rup}$ | C | 22 | 0.01 | 10 | D50 | 1 | A |
| Laurendeau et al. (2013) | Japan | 2357 | - | 132 | 4.5 | 6.9 | $M_w$ | 3* | 300* | $r_{rup}$ ($r_{hypo}$ for small) | C | 23 | 0.02 | 1.3622 | G | 1M | A |

*continued on next page*

[64] Or 106. Both are given.
[65] Do not need to multiply by 2.
[66] State model applicable up to 8.5.
[67] State model applicable up to $M_w$8.5 for strike-slip and reverse and $M_w$7 for normal earthquakes.
[68] State model applicable for $M_w \geq 3.3$ in California and $M_w \geq 5.5$ globally.
[69] State model applicable to $M_w$8.5 for strike-slip, $M_w$8 for reverse/reverse-oblique and $M_w$7.5 for normal/normal-oblique.
[70] State applicable for $M_w \geq 3.5$.
[71] State applicable for $M_w \leq 8.5$ for strike-slip and $M_w \leq 8$ for reverse and normal earthquakes.
[72] State applicable up to 300 km
[73] Recommends model for $M_w \geq 5$.
[74] Recommends model up to $M_w$8.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{min}$ | $M_{max}$ | $M$ scale | $r_{min}$ | $r_{max}$ | $r$ scale | S | $T$s | $T_{min}$ | $T_{max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Morikawa and Fujiwara (2013) | Japan | 21681 | - | 333 | 5.5 | 9.0 | $M_w$ | 1* | 200 | $r_{rup}$ | C | 47 | 0.05 | 10 | V | 2W | A (C, B, F) |
| Pacific Earthquake Engineering Research Center (2013) | Worldwide shallow crustal | - | | 4 vertical models | | | $M_w$ | 4 vertical models | | | C | | 0.01 | 3 | - | 1M | A (N, S, R, HW) |
| Segou and Voulgaris (2013) | Europe & Middle East | 327 | - | 164 | 4.1 | 6.6 | $M_w$ ($m_b$) | 1* | 150* | $r_{epi}$ | 3 | 41 | 0.05 | 2 | I50 | O | A (S, R, N) |
| Sharma et al. (2013) | Geysers, N. California | 5451 | - | 212 | 1.3 | 3.3 | $M_w$ ($M_D$) | 0.5 | 20 | $r_{hypo}$ | 3 | 3 | 0.2 | 1 | L | 1M | G |
| Skarlatoudis et al. (2013) | Hellenic Arc (Greece) | ≤743 | - | ≤21 | 4.4 | 6.7 | $M_w$ ($m_b$, $M_L$) | 65* | 850* | $r_{hypo}$ | 3 | 9 | 0.01 | 4 | D50 | 1M | F, B |
| Akkar et al. (2014b,c) | Europe & Middle East | 1041–600* | - | 221 | 4.0 | 7.6[75] | $M_w$ | 0 | 200 | $r_{jb}$ | C | 62 | 0.01 | 4 | G | 1M | A (S, N, R) |
| Ansary (2014) | Himalaya, India | R: 229, S: 187 | - | 150* | 2.5* | 7.8 | U | 2* | 2000* | $r_{hypo}$ | 2 | 3 | 0.3 | 2 | U | 1 | A |
| Bindi et al. (2014a,b) | Europe & Middle East | 1224–800*, 2126–1460 | - | 225–150*, 365–226 | 4.0 | 7.6 | $M_w$ | 0 | 300 | $r_{jb}$ ($r_{epi}$ for $M_w \leq 5$ and $r_{epi} \geq 10$) & $r_{hypo}$ | C, 4 | 23[76] | 0.02 | 3 | G | 1M | A (S, N, R) |
| Derras et al. (2014) | Europe & Middle East | 1088 | - | 320 | 3.6[77] | 7.6[78] | $M_w$ | 1[79] | 547[80] | $r_{jb}$ | C | 62 | 0.01 | 4 | G | O | A |
| Ghofrani and Atkinson (2014) | Japan | > 1000 | - | 6 | 7.0 | 9.0 | $M_w$ | 30* | 1000* | $r_{rup}$ | C | 23 | 0.07 | 9.09 | G | O | F |

*continued on next page*

[75]Believe model can be used up to $M_w 8$.
[76]In text says 27 periods but coefficients only reported for 23.
[77]Recommend never using model below 4.
[78]Recommend never using model above 7.
[79]Recommend never using model for $r_{jb} < 5$.
[80]Recommend never using model for $r_{jb} > 200$.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kurzon et al. (2014) | San Jacinto fault zone (S. California, USA) | 29474 | - | 809 | 1.5 | 5.9 | $M_L$ | 0 | 150 | $r_{epi}$ | 1 | 12 | 0.03 | 1 | G | 1M | A |
| Luzi et al. (2014) | Italy | 829, 2805, 401 | - | 146, 658, 41 | 4, 4, 3.5 | 6.9, 6.9, 6.3 | $M_w$ ($M_L$) | 0* | 200* | $r_{jb}$ ($r_{epi}$ for $M < 5.5$) | 5 | 23 | 0.04 | 4 | G | 1M | A |
| Rodríguez-Pérez (2014) | Cen. and S. Mexico | 75 (F), 121 (B) | - | 8 F, 25 B | 5.1 (F), 5.0 (B) | 8.0 (F), 7.2 (B) | $M_w$ | 50* (F), 70* (B) | 580* (F), 540* (B) | $r_{rup}$ ($r_{hypo}$ for $M_w < 6.5$) | 1 | 15 | 0.04 | 5 | G | 1M | F, B |
| Stafford (2014) | Worldwide shallow crustal | U | - | U | U | U | $M_w$ | U | U | $r_{rup}$ | C | U | 0.01 | 2 | G | 1M, O | A (S, N, R, AS) |
| Vacareanu et al. (2014) | 9 events from Vrancea (Romania) + 17 foreign events | 233+198 | - | 9+17 | 5.2 (5.6)[81] | 7.4 (7.8)[82] | $M_w$ | 105[83] | 650*[84] | $r_{hypo}$ | 1 | 19 | 0.1 | 4 | G | 1M | B |
| Atkinson (2015) | California | U | - | U | 3* | 6* | $M_w$ | 2* | 40 | $r_{hypo}$ | 1 | 10 | 0.03 | 5 | G | 1M | A |
| Cauzzi et al. (2015b) | Worldwide shallow active crustal | 1880 | - | 98 | 4.5 | 7.9 | $M_w$ | 0* | 150* | $r_{rup}$ ($r_{hypo}$ for $M_w \leq 5.7$) | C | 208 | 0.02 | 10 | G | 2M | A (S, N, R) |
| Emolo et al. (2015) | South Korea | 11129 | - | 222 | 2.0 | 4.9 | $M_L$ | 1.4 | 600* | $r_{epi}$ | I | 13 | 0.055 | 5 | L | 1M | A |
| Haendel et al. (2015) | Northern Chile | 1094 | - | 138 | 5* | 8.1 | $M_w$ | 40* | 300* | $r_{rup}$ | 2 | 9 | 0.03 | 3 | G | 1M | B, F |
| Jaimes et al. (2015) | Ciudad Universitaria, Mexico City[85] | 22 | - | 22 | 5.2 | 7.4 | $M_w$ | 103 | 464 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ for $M_w \leq 6.5$ | 1 | 25 | 0.2 | 5 | G | 1B | B |

*continued on next page*

[81] Believe can be used to 5.0.
[82] Believe can be used to 8.0.
[83] Believe can be used for $r_{epi} \geq 10$ km.
[84] Believe can be used for $r_{epi} \leq 300$ km.
[85] Also derive models for two other sites (SCT and CDAO) in Mexico City.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kale et al. (2015) | Turkey & Iran | 1198 | - | 313 | 4 | 7.6[86] | $M_w$ | 0 | 200 | $r_{jb}$ | C | 62 | 0.01 | 4 | G | 1MW | A (S, N, R) |
| Kuehn and Scherbaum (2015) | Europe & Middle East | 835 | - | 279 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | 8 | 0.01 | 4 | G | O | A (R, N, S) |
| Pacific Earthquake Engineering Research Center (2015) — Al Noman and Cramer | Cen. and E. N. America + foreign | 6061[87] | - | 78[88] | 2.5 | 7.6[89] | $M_w$ | 1* | 2000* | $r_{rup}$ | C | 21 | 0.1 | 10 | D50 | 2M | A (R, S, U) |
| Vacareanu et al. (2015b) | Vrancea, Romania + foreign intermediate-depth | 344+360 | - | 9+29 | 5.2 (5.1) | 7.4 (8.0) | $M_w$ | 2 ($r_{epi}$) | 399 ($r_{epi}$) | $r_{hypo}$ | 3 | 19 | 0.1 | 4 | G | 1M | A |
| Vuorinen et al. (2015) | Fennoscandian shield | U | - | 2239 | U | U | U | U | U | U | U | U | U | U | U | 1 | A |
| Zhao et al. (2015) | Japan + some overseas | 16362 | - | 335 + 62 | 4.9* | 9.1* | $M_w$ | 0* | 300* | $r_{rup}$ if available, $r_{hypo}$ otherwise | 4 + C | 24 | 0.05* | 5* | G | 1M | A (B, F, R, N, S) |
| Abrahamson et al. (2016) & BC Hydro (2012) | Worldwide subduction | 2590 for B, 953 for F | - | 63 for B, 43 for F | 5.0 for B, 6.0 for F | 7.9 for B, 8.4 for F | $M_w$ | 12* | 300* | $r_{rup}$ ($r_{hypo}$) for F, $r_{hypo}$ for B | C | 22 | 0.02 | 10 | G | 1M | B, F |
| Bommer et al. (2016) | Groningen, Netherlands (induced seismicity) | 85 | - | 12 | 2.6 | 3.6 | $M_w$ | 0.5* | 19.5* | $r_{epi}$ | 1 | 5 | 0.01 | 2 | G | 1M | E |
| Bozorgnia and Campbell (2016b) | Worldwide shallow crustal | - | 15161 | 321 | 3.0[90] | 7.9[91] | $M_w$ | 0* | 500*[92] | $r_{rup}$ | C | 21 | 0.01 | 10 | - | 1M | A (R, S, N) |

*continued on next page*

[86] Recommend model up to $M_w 8$

[87] Also use 1921 macroseismic intensities.

[88] Macroseismic intensities from 6 events.

[89] 7.7 by including macroseismic data.

[90] Believe applicable down to 3.3 for California and down to 5.5 globally.

[91] Believe valid to 8.5 for strike-slip, 8.0 for reverse and 7.5 for normal.

[92] Believe applicable to 300 km.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Kotha et al. (2016a,b) | Europe & Middle East | 1251 | - | U | 4 | 7.6 | $M_w$ | 0* | 300*[93] | $r_{jb}$ ($r_{epi}$ for some $M_w \leq 5$) | C | 17 | 0.01 | 4 | G | O | A |
| Landwehr et al. (2016) | California & Nevada | 10692 | - | 221 | 3.0* | 7.3* | $M_w$ | 1* | 300* | $r_{jb}$ | C | 7 | 0.02 | 4 | U[94] | O | A (S, N, R) |
| Lanzano et al. (2016) | Po Plain & NE Italy | 2489 | - | 94 | 4.0 | 6.4 | $M_w$ | 0* | 200* | $r_{jb}$ | 5 | 24 | 0.04 | 4 | G | 1M | A (R, N, U) |
| Sedaghati and Pezeshk (2016) | Europe & Middle East | 350 | - | 85 | 5.0 | 7.6 | $M_w$ | 1* | 100* | $r_{jb}$ | 4 | 2 | 0.2 | 1.0 | G | 1, 1W, 1M, 2, 2M, 2O and O | A |
| Shoushtari et al. (2016) | Malaysia, Japan and Iran | 531 | - | 13 | 5.0 | 7.7 | $M_w$ | 120* | 1400* | $r_{hypo}$ | 4 | 19 | 0.1 | 5 | G | 1 | B |
| Stewart et al. (2016) | Worldwide shallow crustal | - | 17089 | U | 3 | 7.9[95] | $M_w$ | 0 | 300 | $r_{jb}$ | C | 105 | 0.01 | 10 | - | 2M | A (R, S, N, U) |
| Sung and Lee (2016) | Taiwan | 19887 | - | 150 | 4.01 | 7.62 | $M_w$ ($M_L$) | 0.32 | 291.59 | $r_{hypo}$, $r_{rup}$ for Chi-Chi | C | 3 | 0.3 | 3 | U | 1M, O | A (S, N, R) |
| Tusa and Langer (2016) | Mount Etna, Italy | 1158 (shallow), 1957 (deep) | 1158 (shallow), 1957 (deep) | 38 (shallow), 53 (deep) | 3.0 | 4.3 (shallow), 4.8 (deep) | $M_L$ | 0.5 | 100 | $r_{epi}$ | 3 | 23[96] | 0.1 | 10 | G | 1 | V |
| Wang et al. (2016) | Offshore NE Taiwan | 20*–832 | - | 13 | 4.0 | 5.9 | $M_w$ | 20* | 300* | $r_{hypo}$ | C | 105 | 0.01 | 10 | G | 1 | N |
| Zhao et al. (2016a) | Japan | 4555+155 | - | 125+11 | 5.0* | 7.92 (8.25) | $M_w$ | 25* | 300* | $r_{rup}$, $r_{hypo}$ for most | 4 | 36 | 0.01 | 5.0 | G | 1M | B |
| Zhao et al. (2016b) | Japan | 3111+463 | - | 76 | 5.0* | 9.0 | $M_w$ | 20* | 300* | $r_{rup}$, $r_{hypo}$ for most | 4 | 36 | 0.01 | 5.0 | G | 1M | F |

*continued on next page*

[93]Recommend model up to 200 km
[94]Probably D50.
[95]Recommend model for use up to 8.0 for strike-slip and reverse and 7.0 for normal earthquakes.
[96]Authors state 28 but coefficients only reported for 23.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zhao et al. (2016c) | Japan + some foreign | 5957 | - | 117 | 4.9 | 7.2* | $M_w$ | 0* | 280* | $r_{rup}$, $r_{hypo}$ for most | 4 | 36 | 0.01 | 5 | G | 1M | C (N), UM (R, NS) |
| Ameri et al. (2017) | Europe & Middle East | 2355 | - | 384 | 3 | 7.6 | $M_w$ | 0* | 200* | $r_{epi}$, $r_{jb}$ | 4 | 26 | 0.01 | 3 | G | 1M | A (N, R, S) |
| Bindi et al. (2017) | Worldwide shallow crustal | 4692 | - | 242 | 3* | 7.9* | $M_w$ | 4* | 300* | $r_{hypo}$, $r_{jb}$ | C | 89 | 0.02 | 4 | G | 1M | A |
| Çağnan et al. (2017a,b) | Europe & Middle East | - | 1041 | 221 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | 18 | 0.01 | 4 | V | 1M | A (S, N, R) |
| Derras et al. (2017) | Japan | 977 | - | 214 | 3.7 | 6.9 | $M_w$ | 3.65 | 440.63 | $r_{jb}$ | C × C | 18 | 0.01 | 4.0 | G | O | A |
| García-Soto and Jaimes (2017) | Mexico (Pacific coast) | 418 | 418 | 40 | 5.0 | 8.0 | $M_w$ | 17 | 400 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | 70[97] | 0.01 | 5 | V | 1M | F |
| Gülerce et al. (2017) | Worldwide shallow crustal | - | 15597–4000* | 326–70* | 3 | 7.9[98] | $M_w$ | 0 | 300 | $r_{rup}$ + others for HW | C | 21 | 0.02 | 10 | V | 1M | A (S, N, R, HW, AS) |
| Hassani et al. (2017) | Iran[99] | 806 | - | 330 | 4.0 | 7.3 | $M_w$ ($m_b$, $M_s$, $M_L$) | 1* | 280* | $r_{epi}$ | 3 | 16 | 0.06 | 4 | L | 1M | A |
| Idini et al. (2017) | Chile | 100*–114 for B, 150–369 for F | - | U–38 for B, U–65 for F | 5.5 | 7.8 for B, 8.8 for F[100] | $M_w$ | 61 for B, 31 for F | 386 for B, 391 for F | $r_{hypo}$ ($r_{rup}$ for F and $M_w \geq 7.7$) | C | 21 | 0.01 | 10 | U | 2M | B,F |
| Montalva et al. (2017a,c,b) | Chile | 2461 for F, 1313 for S | - | 281 for F, 192 for B | 4.5* | 8.8 for F, 7.8* for B | $M_w$ ($M_L$) | 25* for F, 60* for B | 1000* for F, 500* for B | $r_{rup}$ for F, $r_{hypo}$ for B | C | 22 | 0.02 | 10 | G | 1M | F, B |
| Peruzza et al. (2017) | Mount Etna, Italy | 1158 | - | 38 | 3.0 | 4.3 | $M_L$ | 0.5 | 100 | $r_{hypo}$ | 3 | 11 | 0.1 | 10 | G | 1 | V |

*continued on next page*

[97] Report coefficients for only 37 periods.
[98] State model applicable up to 8.5.
[99] Also develop separate models for Zagros and Alborz-central Iran.
[100] Recommend use for $M_w \leq 9$ for interface and $M_w \leq 8$ for intraslab.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sedaghati and Pezeshk (2017) | Iran | ≤688 | ≤688 | ≤152 | 4.7 | 7.4 | $M_w$ | 1* | 250* | $r_{jb}$ | C | 13 | 0.05 | 4 | 1M | G | A |
| Shahidzadeh and Yazdani (2017) | Iran | 289 | - | 136 | 5.0* | 7.4* | $M_w$ | 0* | 190* | $r_{jb}$, $r_{epi}$ for some | 3 | 14 | 0.05 | 2.5 | L | O | A (S, R, N) |
| Soghrat and Ziyaeifar (2017) | N Iran | 325 | 325 | 55 | 4.1 | 7.3 | $M_w$ (U) | 5.3 | 303.1 | $r_{jb}$, $r_{epi}$ for some | 4, C | 30 | 0.01 | 4.0 | G | 1M | A (S, R, U) |
| Zuccolo et al. (2017) | Southwest Italy | 2270 | - | 319 | 1.5 | 4.2 | $M_L$ | 3 | 100* | $r_{hypo}$ | 1 | 11 | 0.1 | 3 | B | 1W | A |
| Ameur et al. (2018) | Worldwide shallow crustal | 2335 | - | 137 | 3.2[101] | 7.9[102] | $M_w$ | 0.01[103] | 358[104] | $r_{jb}$ | C | 17 | 0.01 | 4.0 | G | O | A |
| D'Amico et al. (2018a) | S Calabria & Sicily (Italy) | 832–840 | - | 48 | 4.0 | 6.0 | $M_w$ ($M_L$) | 2* | 200* | $r_{jb}$ ($r_{epi}$ for most) | 4 | 3 | 0.3 | 3.0 | G | 1M | A |
| Felicetta et al. (2018) | Italy | 769 | - | 99 | 4.1 | 6.9 | $M_w$ | 0* | 200* | $r_{jb}$ | 5, 6 | 20 | 0.04 | 2 | G | 1M | A (S, R, N, U) |
| Gupta and Trifunac (2018a) | W Himalaya and NE India | 365 | 365 | 83 | 4.0* | 6.9* | U | 5* | 340* | $r_{hypo}$ | 3 × 3 | 13 | 0.04 | 3.0 | B, V | O | A |
| Ktenidou et al. (2018) | Euroseistest (N Greece) | 691 | - | 74 | 2.0 | 5.6 | $M_L$ | 5 | 220 | $r_{rup}$ | 1, 2, C, I | U | 0.01 | 2 | D50 | 1M | A |
| Kotha et al. (2018a) | Japan | 6462–15896 | - | U–850 | 3.4 | 7.3 | $M_w$ | 0 | 543 | $r_{JB}$ | I, 8 | 33 | 0.01 | 2 | G | O | A |
| Laouami et al. (2018a,b) | Algeria + Europe + W. USA | 556 + 494 + 158 | - | 82 + 58 + 8 | 3.0 + 5.3 + 5.9 | 6.8 + 7.6 + 7.2 | $M_w$ ($M_s$) | 6* | 230* | $r_{hypo}$ | 3 | 58 | 0.02 | 4.0 | B | 2 | A |
| Laurendeau et al. (2018) | Japan | 1031, 765 | - | 80, 75 | 4.5*, 4.5* | 6.9* | $M_w$ | 4* | 290* | $r_{rup}$ | C | 20 | 0.03 | 2.0 | G | 1M | A |
| Mahani and Kao (2018) | Graham and Septimus areas (BC, Canada) | U, U | - | 129, 90 | 1.5, 1.5 | 3.8, 3.0 | $M_L$ | 2.3, 1.6 | 19, 42 | $r_{hypo}$ | 1 | 5 | 0.1 | 1 | G | 1M | W |

*continued on next page*

[101] Believe applicable $\geq 3.6$.
[102] Believe applicable $\leq 7.6$.
[103] Believe applicable $\geq 6$ km.
[104] Believe applicable $\leq 200$ km.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sharma and Convertito (2018) | The Geysers, USA | 261711 | - | 10974 | 0.7 | 3.3 | $M_w$ ($M_D$) | 0.1 | 73 | $r_{hypo}$ | I | 5 | 0.05 | 1.0 | L | 1M | G |
| Shoushtari et al. (2018) | Japan + Malay Peninsula | 651 + 77 | - | 11 + 14 | 5.0 + 6.7 | 9.1 + 9.0 | $M_w$ | 120* + 500* | 1300* + 1000* | $r_{hypo}$ | 4 | 19 | 0.1 | 5 | G | 1 | F |
| Wen et al. (2018) | Sichuan region (China) | 1644 | - | 186 | 4.0 | 6.7 | $M_s$ | 2 | 200 | $r_{jb}$ | C | 16 | 0.04 | 2 | D50 | 1M | A |
| Zafarani et al. (2018) | Iran | 1551 | - | 200 | 4.0 | 7.3 | $M_w$ ($M_L$) | 0.6* | 200* | $r_{jb}$ ($r_{epi}$) | 4 | 24 | 0.04 | 4 | G | 1M | A (R, S, U) |
| Ashadi and Kaka (2019) | Java (Indonesia) | 1825 | - | 95, 57 | 4.4[105] | 8.6[106] | $M_w$ ($M_L$, $m_b$) | 33.0, 83.4[107] | 994.3, 994.0[108] | $r_{hypo}$ | 2 | 3 | 0.2 | 1 | G | 1 | B, F |
| Bindi et al. (2019) | Europe & Middle East | 2767–18859 | - | U–2179 | 3.5 | 7.8 | $M_w$ ($M_L$) | 1.5* | 300* | $r_{hypo}$ | I | U | 0.01 | 10 | D50 | 1M | A |
| Darzi et al. (2019) | Iran | 1350 | - | 370 | 4.5 | 7.4 | $M_w$ ($M_s$, $m_b$) | 1* | 200* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ & $r_{rup}$ | 3 | 60 | 0.01 | 10 | G | 2M | A (S, R, U) |
| Farajpour et al. (2019) | Iran | 1356[109] | - | 208 | 4.8 | 7.5 | $M_w$ | 1.5* | 350* | $r_{rup}$ | C | 18 | 0.04 | 4.0 | G | 1M | A (R, S, N) |
| Huang and Galasso (2019) | Italy | 7843 | - | 233 | 4.0 | 6.9 | $M_w$ | 1* | 250* | $r_{jb}$ ($r_epi$) | 3 | 29 | 0.01 | 4 | D50 | O | A (R, S, N) |
| Lanzano et al. (2019a,b) | Italy + 12 foreign events | 4965 + 823[110]–4100* | - | 144 + 12 | 3.5 + 6.07 | 6.87 + 8.0 | $M_w$ | 0* | 200* | $r_{jb}$ ($r_{epi}$ for $M < 5.5$), $r_{rup}$ ($r_{hypo}$ for $M < 5.5$) | C | 36 | 0.01 | 10 | D50 | 1M | A (N, R, S) |
| Laouami (2019) | Algeria + Europe + W. USA | - | 257 + 247 + 79 | U | 3.0 | 7.4 | $M_w$ ($M_s$) | 5 | 150 | $r_{hypo}$ | 3 | 58 | 0.02 | 4.0 | - | 2 | A |
| Sung and Lee (2019) | Taiwan | 20006 | - | 497 | 4.01 | 7.62 | $M_w$ ($M_L$) | 0.63 | 200 | $r_{rup}$ ($r_{hypo}$ for $M_w < 4.8$) | C, I | 3 | 0.3 | 3 | G | 1M | A (S, N, R) |

*continued on next page*

105 State only applicable from $M_w$4.8 or 5.0.
106 State only applicable to $M_w$8.0.
107 State only applicable from 100 km.
108 State only applicable to 800 km.
109 Could be 1288 records.
110 This is the total in the Electronic Supplement listing all the data used. In the article it is stated that 5607 records from 146 earthquakes are used.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zolfaghari and Darzi (2019a) | Iran | - | 1350 | 370 | 4.5 | 7.4 | $M_w$ ($M_s$, $m_b$) | 1* | 200* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ & $r_{rup}$ | 3 | 60 | 0.01 | 10 | - | 2M | A (S, R, U) |
| Chao et al. (2020) | Taiwan | ≤40892 | - | ≤316 | 3.5 | 7.6[111] | $M_w$ | 0.07 | 437.10 | $r_{rup}$ | C | 19 | 0.01 | 5 | D50 | O | A (N, S, R, F, B, AS) |
| Cremen et al. (2020) | Lancashire + N. Nottinghamshire (UK) | 195+192 | - | 29+48 | (0.1*) | (2.9*) | $M_w$ ($M_L$) | 1.5* | 7* | $r_{hypo}$ | 1 | 3 | 0.05 | 0.2 | G | O | E + M |
| Hu et al. (2020) | Sagami Bay, Japan | 738 (off-shore)[112], 3775 (on-shore) | 738 (off-shore), 3775 (on-shore) | 233, 223 (on-shore) | 4.0 | 6.8 | $M_w$ | 5* | 300* | $r_{hypo}$ | I, 4 | 20 | 0.05 | 5 | D50 | 1M | A (C, F, B) |
| Jaimes and García-Soto (2020) | Mexico | 366 | 366 | 23 | 5.2 | 8.2 | $M_w$ | 22 | 400 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | 18 | 0.01 | 5 | G[113] | 1M | B |
| Kotha et al. (2020) | Europe & Mediterranean | 18222–9698 | - | 927–491 | 3.0 | 7.4 | $M_w$ | 0 | 545 | $r_{jb}$ ($r_{epi}$) | I | 34 | 0.01 | 8 | D50 | O | A |
| Kowsari et al. (2020) | South Iceland | 83 | - | 6 | 5.1 | 6.5 | $M_w$ | 0* | 80* | $r_{jb}$ | 2 | 40 | 0.05 | 3 | D50 | O | S |
| Kuehn et al. (2020b) | Separate models for Taiwan & Iran | 13236 & 2775 | - | 108 & 480 | 4* & 3 | 7.6* & 7.37 | $M_w$ | 1* & 2.5 | 300* & 300 | $r_{jb}$ & $r_{hypo}$ | C & 1 | 1 | 0.2 | 0.2 | D50 | 1M, O | A |
| Lanzano and Luzi (2020) | Volcanic areas, Italy | 615–550* | - | 41 | 3.0 | 4.9 | $M_w$ ($M_L$) | 2* | 200* | $r_{hypo}$ | 3 | 30 | 0.025 | 5 | G | 1M | V |
| Li et al. (2020) | Sichuan-Yunnan (China) + global | 250 + 276–250 + 140* | - | 7 + 22–7 + 10* | 6.0 + 6.1 | 7.9 + 7.68 | $M_w$ | 0* | 200* | $r_{rup}$ | C | 21 | 0.01 | 10 | D50 | 1M | A |
| Phung et al. (2020a) | Taiwan + Japan | 3314 + 3376 | - | 51 + 25 | 4.5 + 6.5 | 7.1 + 9.1 | $M_w$ ($M_L$) | 1 + 26 | 280 + 345 | $r_{rup}$ | C | 20 | 0.01 | 5 | D50 | O | A (B, F) |

*continued on next page*

[111] Believe model applicable up to 8.0 for crustal and intraslab events and 9.0 for interface events.
[112] May be 742 as this is stated in Table 4 of article.
[113] Call it ‘quadratic mean’, which is assumed to be geometric mean.

Table 5.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | $T$s | $T_{\min}$ | $T_{\max}$ | C | R | M |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Phung et al. (2020b) | Taiwan + other shallow crustal | $\leq$ 11375 + 2040 | - | $\leq$ 157 + 30 | 3.5 + 6.46 | 7.65 + 7.9 | $M_w$ ($M_L$) | 0.1* | 200* | $r_{rup}$ | C | 24 | 0.01 | 10 | D50 | O | A (N, S, R, HW) |
| Tusa et al. (2020) | Mt Etna, Italy | 1600 | 1600 | 49 | 3.0 | 4.8 | $M_L$ | 0.5 | 100 | $r_{hypo}$ | 3 | 21 | 0.05 | 4 | G | 1M | V |
| Boore et al. (2021) | Greece | 1500–1000* | - | 150–30* | 4.0* | 7.0* | $M_w$ | 0.1* | 300* | $r_{jb}$ | C | 105 | 0.01 | 10 | D50 | O | A (S, R, N) |
| Gandomi et al. (2021) | Global | 25747 | - | U | U | U | $M_w$ | U | U | $r_{rup}$ | C | 21 | 0.01 | 10 | U | O | A (N) |
| Huang et al. (2021a) | N. Italy | 2427 | - | 85 | 4.0 | 6.4 | $M_w$ | 1* | 200* | $r_{jb}$ | 4 | 36 | 0.04 | 4 | G | O | A (N, T, U) |
| Gao et al. (2021) | S. Taiwan | 338 | - | 61 | 4.2 | 7.6 | $M_w$ ($M_L$) | 3.6 | 300 | $r_{rup}$, $r_{hypo}$ for some events | 1 | 27 | 0.01 | 5 | D50 | 1M | A |
| Lanzano et al. (2021) & Caramenti et al. (2022) | Italy | 4784 | - | 137 | 3.5 | 6.9 | $M_w$ | 0.3* | 200* | $r_{jb}$ | C | 36 | 0.01 | 10 | D50 | O | A (N, R, S) |
| Allen (2022) | N. Australia | U | - | U | 5.3* | 7.6*[114] | $M_w$ | 75*[115] | 1750*[116] | $r_{hypo}$ | C | 20 | 0.1 | 10 | G | O | B, F |
| Jiang et al. (2022) | W. China + foreign | - | 1317 + 630 | 73+19 | 4.5 | 7.9 | $M_w$ | 8* | 300* | $r_{rup}$ | C | 19 | 0.01 | 10 | V | 1M | A (R, SS/N) |
| Miyazawa et al. (2022) | NE Japan | 213, 159 | - | 3, 2 | 7.51, 8.3 | 7.81, 9.1 | 50* | 300* | $r_{SMGA}$, $r_{rup}$ | 1 | 21 | 0.01 | 10 | D50 | 1M | F | |
| Zhang et al. (2022) | SW China | 300*–1324 | - | 45*–70 | 4.2 | 7.9[117] | $M_w$ | 0.06[118] | 299.95[119] | $r_{rup}$ | C | 21 | 0.033 | 8.0 | D50 | 1M | A (N, S, R) |
| Khansefid et al. (2023) | Worldwide geothermal sites | 664 | 664 | 110 | 2.8*[120] | 5.6*[121] | $M_w$ ($M_L$, $M_D$) | 1* | 150*[122] | $r_{hypo}$ | C | 15 | 0.02 | 4.00 | D50 | 1M | G |

[114] Recommend model up to $M_w 8$.
[115] Recommend model from 500 km.
[116] Recommend model to 1500 km.
[117] Recommend model for $M_w \leq 6.1$ for strike-slip, $M_w \leq 7.9$ for reverse and $M_w \leq 6.5$ for normal faulting.
[118] Recommend model from 10 km.
[119] Recommend model to 200 km.
[120] Recommend for use to $M_w 2.5$.
[121] Recommend for use to $M_w 5.5$.
[122] Recommend for use to 100 km.

# Chapter 6

# List of other ground-motion models

Published ground-motion models for the prediction of PGA and/or response spectral ordinates that were derived by methods other than regression analysis on strong-motion data are listed below in chronological order. Note that deciding on how a model should be categorised is not always straightforward. Therefore, it is recommended to consult the original reference.

Table 6.1: GMPEs derived based on simulated ground motions, often the stochastic method

| | |
|---|---|
| Herrmann and Goertz (1981) | Eastern North America |
| Faccioli (1983) | Italy |
| Herrmann and Nuttli (1984) & Nuttli and Herrmann (1987) | Eastern North America |
| Boore and Atkinson (1987) and Atkinson and Boore (1990) | Eastern North America |
| Toro and McGuire (1987) | Eastern North America |
| Electric Power Research Institute (1988) | Eastern North America |
| Boore and Joyner (1991) | Eastern North America |
| Bungum et al. (1992) | Intraplate regions |
| Midorikawa (1993b) | Japan |
| Electric Power Research Institute (1993b) | Central and eastern USA |
| Savy et al. (1993) | Central and eastern USA |
| Atkinson and Boore (1995) & Atkinson and Boore (1997a) | Eastern North America |
| Winter (1995) | United Kingdom |
| Frankel et al. (1996) & Electric Power Research Institute (2004, Appendix B) | Central and eastern USA |
| Jonathan (1996) | Southern Africa |
| Wong et al. (1996) | Eastern Idaho, USA |
| Atkinson and Boore (1997b) | Cascadia subduction zone |
| Hwang and Huo (1997) | Eastern USA |
| Ólafsson and Sigbjörnsson (1999) | Iceland |
| Atkinson and Silva (2000) | California |
| Somerville et al. (2001) | Central and eastern USA |
| Toro and Silva (2001) | Central USA |
| Balendra et al. (2002) | Singapore |
| Gregor et al. (2002b) | Cascadia subduction zone |

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Table 6.1: *continued*

| | |
|---|---|
| Silva et al. (2002) | Central and eastern USA |
| Toro (2002) | Central and eastern USA |
| Megawati et al. (2003) | Sumatran subduction zone |
| Electric Power Research Institute (2004) (model clusters) | Central and eastern USA |
| Iyengar and Raghu Kanth (2004) | Peninsular India |
| Silva et al. (2004) | South Carolina |
| Zheng and Wong (2004) | Southern China |
| Megawati et al. (2005) | Sumatran subduction zone |
| Motazedian and Atkinson (2005) | Puerto Rico |
| Nath et al. (2005b,a) | Sikkim Himalaya |
| Yun and Park (2005) & Yun (2006) | Korea |
| Atkinson and Boore (2006) | Eastern North America |
| Böse (2006) | Marmara, Turkey |
| Collins et al. (2006) | Intermountain West, USA |
| Raghu Kanth and Iyengar (2006, 2007) | Peninsular India |
| Convertito et al. (2007) | Campania, Italy |
| Megawati (2007) | Hong Kong |
| Tuluka (2007) | African Western Rift Valley |
| Carvalho (2008) | Portugal |
| Jin et al. (2008)[1] | Fujian region, China |
| Liang et al. (2008) | Southwest Western Australia |
| Sokolov et al. (2008) | Vrancea, Romania |
| Atkinson and Macias (2009) | Cascadia subduction zone |
| Kang and Jin (2009)[2] | Sichuan region, China |
| Nath et al. (2009) | Guwahati, NE India |
| Somerville et al. (2009b,a) | Australia |
| Hamzehloo and Bahoosh (2010) | Tehran region, Iran |
| Megawati and Pan (2010) | Sumatran subduction zone |
| National Disaster Management Authority (2010) | Separate models for 7 regions of India |
| Deif et al. (2011) | Aswan area, Egypt |
| Allen (2012) | Southeastern Australia |
| Hamzehloo and Mahood (2012) | East central Iran |
| Nath et al. (2012) | Shillong region, India |
| Anbazhagan et al. (2013)[3] | Himalaya |
| Douglas et al. (2013) | Geothermally-induced events |
| Joshi et al. (2013b) | Kutch region, India |
| Rietbrock et al. (2013) | United Kingdom |
| Yazdani and Kowsari (2013) | Northern Iran |
| Bora et al. (2014) | Europe and Middle East |
| Harbindu et al. (2014) | Garhwal Himalaya, India |
| Raghukanth and Kavitha (2014) | India (active regions) |

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[1]This may be an empirical GMPE because it is based on broadband velocity records from which acceleration time-histories are generated by 'real-time simulation'. This could just mean differentiation.

[2]This may be an empirical GMPE because it is based on broadband velocity records from which acceleration time-histories are generated by 'real-time simulation'. This could just mean differentiation.

[3]This model is derived from both observations and simulations but most of the data, especially for large magnitudes, are simulated hence listed here.

Table 6.1: *continued*

| | |
|---|---|
| Bora et al. (2015) | Europe and Middle East |
| Cauzzi et al. (2015a) | Switzerland (Foreland and Alps) |
| Drouet and Cotton (2015) & Drouet (2017) | French Alps |
| Gamage (2015) | Sri Lanka |
| Pacific Earthquake Engineering Research Center (2015) | Central and eastern North America |
| Wong et al. (2015) | Hawaii |
| Yenier (2015) and Yenier and Atkinson (2015b) | Central and eastern North America |
| Adhikari and Nath (2016) | Darjeeling-Sikkim Himalaya, India |
| Bommer et al. (2016) | Groningen, Netherlands (induced seismicity) |
| Yazdani et al. (2016) | Alborz, Iran |
| Bommer et al. (2017) | Groningen, Netherlands (induced seismicity) |
| Bydlon et al. (2017)[4] | North-central Oklahoma and south-central Kansas |
| D'Amico et al. (2018a) | Southern Italy |
| Hassani and Atkinson (2018) | California |
| Jeong and Lee (2018) | South Korea |
| Novakovic et al. (2018) | Oklahoma |
| Bajaj and Anbazhagan (2019a) | Peninsular India |
| Bajaj and Anbazhagan (2019b) | Himalaya |
| Bydlon et al. (2019) | Oklahoma and Kansas (induced seismicity) |
| Rietbrock and Edwards (2019) | United Kingdom |
| Convertito et al. (2020) | Generic fluid injection site |
| Jee and Han (2021)[5] | South Korea |
| Sokolov et al. (2021) | Western Saudi Arabia |
| Bommer et al. (2022) | Groningen, Netherlands (induced seismicity) |
| Tang et al. (2022) | Low-to-moderate seismicity regions |
| Wong et al. (2022) | Hawaii |

Table 6.2: Complete (source, path and site terms) stochastic models that could be used within the stochastic method (e.g. Boore, 2003)

| | |
|---|---|
| De Natale et al. (1988) | Campi Flegrei, Italy |
| Atkinson (1996) | Cascadia |
| Atkinson and Silva (1997) | California |
| Gusev et al. (1997) | Kamchatka |
| Sokolov (1997) | Northern Caucasus |
| Sokolov (1998) | Caucasus |
| Raoof et al. (1999) | Southern California |
| Malagnini and Herrmann (2000) | Umbria-Marche, Italy |
| Malagnini et al. (2000a) | Apennines, Italy |
| Malagnini et al. (2000b) | Central Europe |
| Sokolov et al. (2000) | Taiwan |

*continued on next page*

[4]This model is derived from both observations and simulations but most of the data are simulated hence listed here.

[5]This model is derived from both observations and simulations but most of the data are simulated hence listed here.

Table 6.2: *continued*

| | |
|---|---|
| Akinci et al. (2001) | Erzincan, Turkey |
| Parvez et al. (2001) | Himalaya |
| Junn et al. (2002) | South Korea |
| Malagnini et al. (2002) | Northeastern Italy |
| Bay et al. (2003) | Switzerland |
| Singh et al. (2003) | India |
| Bodin et al. (2004) | Kachchh basin, India |
| Jeon and Herrmann (2004) | Utah and Yellowstone, USA |
| Halldorsson and Papageorgiou (2005) | Intraplate and interplate |
| Scognamiglio et al. (2005) | Eastern Sicily, Italy |
| Sokolov et al. (2005) | Vrancea, Romania |
| Akinci et al. (2006) | Marmara, Turkey |
| Allen et al. (2006) | Southwest Western Australia |
| Chung (2006) | Southwestern Taiwan |
| Morasca et al. (2006) | Western Alps |
| Malagnini et al. (2007) | San Francisco, USA |
| Meirova et al. (2008) | Israel |
| Zafarani et al. (2008) | Iran |
| Edwards and Rietbrock (2009) | Kanto, Tokai and Chubu regions, Japan |
| Hao and Gaull (2009) | Perth, Australia |
| D'Amico et al. (2012) | Taiwan |
| Òlafsson and Sigbjörnsson (2012) | Iceland |
| Zafarani and Soghrat (2012) | Zagros, Iran |
| Akinci et al. (2013) | Western Turkey |
| Edwards and Fäh (2013b) | Switzerland (Foreland and Alps) |
| Edwards and Fäh (2013a) | Europe and Middle East |
| Akinci et al. (2014) | Lake Van region, Turkey |
| Bernal et al. (2014) | Colombia |
| Galluzzo et al. (2016) | Campi Flegrei |
| Pacific Earthquake Engineering Research Center (2015) | Central and eastern North America |
| Yenier and Atkinson (2015a) | California |
| Pacor et al. (2016) | L'Aquila region, Italy |
| Tao et al. (2016) | Sichuan and Yunnan regions, SW China |
| Bora et al. (2017) | Europe and Middle East, Turkey and Italy |
| Jeong and Lee (2017) | South Korea |
| Boore (2018) | Eastern North America |
| D'Amico et al. (2018b) | Sicily Channel and surrounding region, S Italy |
| Ólafsson et al. (2018) | South Iceland Seismic Zone |
| Sokolov and Zahran (2018) | Saudi Arabia |
| Wang et al. (2018) | Wenchuan, China |
| Zandieh et al. (2018) | Worldwide shallow crustal |
| Tang et al. (2019) | South-eastern Australia and south-eastern China |
| Tang and Mai (2023) | South-eastern Australia |

Table 6.3: GMPEs derived using the hybrid stochastic-empirical method (e.g. Campbell, 2003b)

| | |
|---|---|
| Atkinson (2001) | Eastern North America |
| Abrahamson and Silva (2002) | Central and eastern USA |
| Campbell (2003b) | Eastern North America |
| Atkinson (2005) | Cascadia |
| Tavakoli and Pezeshk (2005) | Eastern North America |
| Douglas et al. (2006) | Southern Norway |
| Douglas et al. (2006) | Southern Spain |
| Campbell (2007) | Central and eastern USA |
| Pezeshk et al. (2011) | Eastern North America |
| Pacific Earthquake Engineering Research Center (2015) | Central and eastern North America |
| Shahjouei and Pezeshk (2016) | Central and eastern North America |
| Tsereteli et al. (2016) | Georgia (no regression performed) |
| Pezeshk et al. (2018) | Central and eastern North America |
| Pezeshk et al. (2021) | Gulf Coast, southern USA |

Table 6.4: GMPEs derived by converting equations for the prediction of macroseismic intensity to the prediction of PGA and/or response spectral ordinates

| | |
|---|---|
| Båth (1975) | Worldwide |
| Battis (1981) | Eastern North America |
| Hasegawa et al. (1981) | Canada |
| Ben-Menahem et al. (1982) | Israel |
| Gaull et al. (1990) | Australia (NE and W and SE) |
| Huo et al. (1992) | China |
| Malkawi and Fahmi (1996) | Jordan |
| Al-Homoud and Fandi Amrat (1998) | Jordan and Israel |
| Nguyen and Tran (1999) | Vietnam |
| Yu and Wang (2004) | NE Tibet |

Table 6.5: GMPEs derived using the referenced-empirical method (e.g. Atkinson, 2008) that adjusts coefficients of published GMPEs for one region to provide a better match to observations from another

| | |
|---|---|
| Dost et al. (2004) | Netherlands |
| Bommer et al. (2006) | El Salvador |
| Atkinson (2008) | Eastern North America |
| Scasserra et al. (2009) | Italy |
| Atkinson (2009, 2010) | Hawaii |
| Gupta (2010) | Indo-Burmese subduction zone |
| Lin et al. (2011a) | Taiwan |

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Table 6.5: *continued*

| | |
|---|---|
| Bourne et al. (2015) | Groningen, Netherlands |
| Hassani and Atkinson (2015) | Eastern North America |
| Pacific Earthquake Engineering Research Center (2015) | Central and eastern North America |
| Vuorinen et al. (2015) | Fennoscandian shield |
| Gülerce et al. (2016) | Turkey |
| Gupta et al. (2017) | Central and eastern USA |
| Kaski (2017) & Kaski and Atkinson (2017) | Alberta, Canada |
| Zafarani et al. (2017) | Northern Iran |
| Obaid et al. (2019) | Sharjah, United Arab Emirates |
| Kiuchi et al. (2019, 2023) | Western Saudi Arabia |
| Zalachoris and Rathje (2019) | Texas, Oklahoma, and Kansas |
| Edwards et al. (2021) | Preston New Road, Blackpool, UK |
| Farajpour and Pezeshk (2021) | Central and eastern USA (induced events) |
| Sokolov et al. (2021) | Western Saudi Arabia |

Table 6.6: Studies where one or more coefficients of previously published GMPEs are altered following additional analysis (completely new GMPEs are not derived in these studies)

| | |
|---|---|
| Twesigomwe (1997) | Modifies coefficients of Krinitzsky et al. (1988) |
| Lee et al. (2000) | New $\sigma$ for Abrahamson and Silva (1997), Boore et al. (1997), Campbell (1997), Sadigh et al. (1997) and Lee and Trifunac (1995) |
| Eberhart-Phillips and McVerry (2003) | New terms for McVerry et al. (2000) |
| Petersen et al. (2004) | Modified distance dependence of Youngs et al. (1997) for $> 200$ km |
| Chen (2008) & Chen and Faccioli (2013) | New $\sigma$ for Faccioli et al. (2010) |
| Wang and Takada (2009) | Adjustment of Si and Midorikawa (1999, 2000) for stations HKD100 and CHB022 |
| Bradley (2010, 2013) | Modified coefficients of Chiou and Youngs (2008) |
| Chiou et al. (2010) | New terms for Chiou and Youngs (2008) |
| Zhao (2010) & Zhao and Gerstenberger (2010) | New terms for Zhao et al. (2006) |
| Atkinson and Boore (2011) | New terms for Boore and Atkinson (2008), Atkinson and Boore (2006) and Atkinson (2008) |
| Bommer et al. (2012) | Coefficients for Akkar and Bommer (2010) for 6 periods from 0.00 to 0.05 s |
| McVerry and Holden (2014) | Modified terms for McVerry et al. (2006) |
| Pasyanos (2015) | Introduces 2D attenuation variations into Atkinson and Boore (2006) |
| Lee et al. (2016b) | Modify Lee (1995) for Vrancea earthquakes using model of Lee et al. (2016a) |
| Graizer (2017) | Modifies Graizer (2016) using more physically justified approach |
| Skarlatoudis (2017) | Modifies Abrahamson et al. (2016) and Zhao et al. (2006) for inslab Greek earthquakes |

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| | |
|---|---|
| Zalachoris and Rathje (2017) | Modifies Hassani and Atkinson (2015) for Texas, Oklahoma and Kansas |
| Abrahamson et al. (2018) | Introduces regional terms in Abrahamson et al. (2016) for Cascadia, Central America, Japan, New Zealand, South America and Taiwan |
| Graizer (2018) | Extends Graizer and Kalkan (2015, 2016) using the NGA-West2 database and adding new terms and more complex modelling[6] |
| Gupta and Trifunac (2018b) | Modifies Gupta and Trifunac (2018a) for deep-focus Hindu Kush earthquakes |
| Gupta and Trifunac (2018c) | Modifies Gupta and Trifunac (2018a) for Burmese subduction zone earthquakes |
| Erdem et al. (2019) | Modifies Boore et al. (2013, 2014) for Sacramento-San Joaquin Delta (California) |
| Gupta and Trifunac (2019) | Modifies Gupta and Trifunac (2018a) for National Capital Region (includes Delhi) of India |
| Sahakian et al. (2019) | Introduces additional path terms to Sahakian et al. (2018) |
| Fülöp et al. (2020) | Modifies Graizer (2016) for Fennoscandia (Sweden and Finland) |
| Kowsari et al. (2020) | Modifies for Iceland the coefficients of 4 ground-motion models from other regions using Bayesian inference |
| Walling et al. (2021) | Modifies Abrahamson et al. (2014) for potentially-induced earthquakes in Oklahoma (non-ergodic model) |
| Bodda et al. (2022) | Modifies Bindi et al. (2014a) for $3 \leq M_w \leq 5.2$ using Bayesian inference |
| Schiappapietra et al. (2022) | Modifies Cauzzi et al. (2015b) to account for the contribution of the fling-step at long periods |
| Arteta et al. (2023) | Modifies Abrahamson et al. (2014) for northern South America (Colombia, Ecuador, and Venezuela) |

Table 6.7: Non-parametric ground-motion models, i.e. models without an associated close-form equation, which are more difficult to use within seismic hazard assessments. These are often derived using machine learning/artificial intelligence/neural networks.

| | |
|---|---|
| Schnabel and Seed (1973) | Western North America |
| Katayama (1982) | Japan |

*continued on next page*

[6]This model is not included in the main body of the report as it is not clear from text (particularly Figure 3) whether a model for PGA can be expressed in the normal way.

Table 6.7: *continued*

| | |
|---|---|
| Anderson and Lei (1994) | Guerrero, Mexico |
| Lee et al. (1995) | California |
| Emami et al. (1996) | Western North America |
| Anderson (1997) | Guerrero, Mexico |
| Fajfar and Perus (1997) | Europe & Middle East |
| Garcia and Romo (2006) | Subduction zones |
| Pathak et al. (2006) | India |
| Güllü and Erçelebi (2007) | Turkey |
| Ahmad et al. (2008) | Europe & Middle East |
| Günaydın and Günaydın (2008) | Northwestern Turkey |
| Cabalar and Cevik (2009) | Turkey |
| Perus and Fajfar (2009, 2010) | Worldwide |
| Kuehn et al. (2011) | Worldwide shallow crustal |
| Tezcan and Cheng (2012) | Worldwide shallow crustal |
| Hermkes et al. (2014) | Europe & Middle East |
| Yerlikaya-Özkurt et al. (2014) | Turkey |
| Gandomi et al. (2016) | Iran |
| Thomas et al. (2016a) | Worldwide shallow crustal |
| Thomas et al. (2016b) | Worldwide shallow crustal |
| Derras et al. (2016) | Worldwide shallow crustal and Europe & Middle East |
| Oth et al. (2017) | Japan |
| Dhanya and Raghukanth (2018) | Worldwide shallow crustal |
| Goulet et al. (2018) | Central and eastern North America |
| Hamze-Ziabari and Bakhshpoori (2018) | Worldwide shallow crustal |
| Kaveh et al. (2018) | Worldwide shallow crustal |
| Khosravikia et al. (2018) | Texas, Oklahoma and Kansas |
| Tezcan et al. (2018) | Western North America |
| Derakhshani and Foruzan (2019) | Worldwide shallow crustal |
| Dhanya et al. (2019) | Worldwide shallow crustal |
| Wiszniowski (2019) | Legnica-Głogów Copper District, Poland District |
| Dhanya and Raghukanth (2020) | Himalaya |
| Ghalehjough and Mahinroosta (2020) | Iran |
| Huang et al. (2021b) | North India |
| Ji et al. (2021) | Worldwide shallow crustal |
| Kashani et al. (2021) | Worldwide shallow crustal |
| Khosravikia and Clayton (2021) | Texas, Oklahoma and Kansas |
| Klimasewski et al. (2021) | S California |
| Raghucharan et al. (2021) | Indo-Gangetic Plains (N. India) |
| Gök and Kaftan (2022) | Western Turkey near Izimir |

Table 6.8: Backbone ground-motion models (Atkinson et al., 2014a)

| | |
|---|---|
| Toro et al. (1997) | Central and eastern North America |
| Electric Power Research Institute (2004, 2013) | Central and eastern North America |

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Table 6.8: *continued*

| | |
|---|---|
| Petersen et al. (2008, 2014) | Western USA |
| Atkinson (2011) | Canada |
| Atkinson and Adams (2013) | Various regions of Canada |
| Al Atik and Youngs (2014) | Western USA |
| Coppersmith et al. (2014) | Hanford, USA |
| Bommer et al. (2015) | Thyspunt, South Africa |
| GeoPentech (2015) | Diablo Canyon and Palo Verde, USA |
| García-Fernández et al. (2016), Gehl (2017) | |
| & García-Fernández et al. (2019) | Europe & Middle East |
| Goulet et al. (2017) | Central and eastern USA |
| Douglas (2018b) | Europe & Middle East |
| Goulet et al. (2018) | Central and eastern North America |
| Phung et al. (2018) | Taiwan |
| de Almeida et al. (2019) | SE Brazil |
| Kowsari et al. (2019) | Iran |
| Weatherill and Cotton (2020) | Stable cratonic region of Europe |
| Weatherill et al. (2020) | Europe & Middle East |
| Akkar et al. (2021) | Central and eastern North America |
| Atkinson (2022, 2024) | New Zealand |
| Stafford (2022) | New Zealand |

Chapter 7

# General characteristics of GMPEs for intensity measures other than PGA and elastic spectral ordinates

The following table is an updated and extended version of Table 1 of Douglas (2012), where: AI is Arias intensity, CAV is cumulative absolute velocity, FSA is Fourier spectral amplitudes, IE is maximum absolute unit elastic input energy [often expressed in terms of equivalent velocity (Chapman, 1999)], ISO is inelastic response spectral ordinates, JMA is Japanese Meterological Agency seismic intensity, MI is macroseismic intensity (these models are often now as intensity prediction equations), MP is mean period (Rathje et al., 2004), PGV is peak ground velocity, PGD is peak ground displacement, RSD is relative significant duration, SI is (Housner) spectral intensity and VH is vertical-to-horizontal response spectral ratio. For consistency with the rest of this report only empirical models are listed [Table 1 of Douglas (2012) included hybrid and simulation-based models as well as empirical GMPEs].

Table 7.1: Characteristics of GMPEs for AI, CAV, FSA, IE, ISO, JMA, MI, MP, PGV, PGD, RSD and VH

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Esteva and Rosenblueth (1964) | W. USA | 46* | - | U | U | U | U | 15* | 450* | $r_{hypo}$ | 1 | U | U | A | PGV, MI |
| Orphal and Lahoud (1974) | California | 140 | - | 31 | 4.1 | 7.0 | $M_L$ | 15 | 350 | $r_{hypo}$ | 1 | U | O | A | PGV, PGD |
| Nazarov and Shebalin (1975) | Kazakhstan & Kirgizstan | U | - | U | U | U | U | U | U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Trifunac and Brady (1975a),Trifunac (1976a) & Trifunac and Brady (1976) | W. USA | 181 | 181 | 57 | 3.8 | 7.7 | Mostly $M_L$ | 6[1]* | 400[2]* | $r_{epi}$ | 3 | B | O | A | PGV, PGD |
| Trifunac and Brady (1975b) | W. USA | 188 | 188 | 48 | 3.8 | 7.7 | Mostly $M_L$ | 6* | 400* | $r_{epi}$ | 3 | B | O | A | AI, RSD |
| Trifunac (1976b) | W. USA | 182 | 182 | 46 | 3.8 | 7.7 | Mostly $M_L$ | 6* | 400* | $r_{epi}$ | 3 | B | O | A | FSA |
| Gürpinar (1977) | California | 64, 34, 13 | - | U | U | U | $M_L$ | 28* | 70* | $r_{hypo}$ | 3 | B | 1 | A | PGV, PGD |
| McGuire (1977) | W. USA | 34 | - | 22 | 5.3 | 7.6 | $M_L$ | 14 | 125 | $r_{hypo}$ | 1 | B | U | A | PGV, PGD |
| Oskorbin (1977) | Sakhalin (Russia) | U | - | U | U | U | $M_s$[3] | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Dobry et al. (1978) | W. USA | 84 | - | 14 | 4.7 | 7.6 | $M_L$ | 0.1 | 130 | $r_{rup}$ | 2 | B | 1 | A | RSD |
| McGuire (1978a) | W. USA | 70 | - | 17+* | 4.5* | 7.7 | U[4] | 11* | 210* | $r_{hypo}$ | 2 | B | U | A | PGV, PGD |
| McGuire (1978b) | W. USA | 70 | - | 17+* | 4.5* | 7.7 | U[5] | 11* | 210* | $r_{hypo}$ | 1 | B | U | A | FSA |
| Sadigh et al. (1978a) | W. USA | U | - | U | U | U | U | U | U | U | U | U | 1 | A | PGV, PGD |
| Trifunac and Lee (1978) | W. N. America | U | U | U | U | U | U | U | U | $r_{epi}$ | 3 | U | U | A | FSA |
| McGuire and Barnhard (1979) | W. USA | 50 | - | U | U | U | U | U | U | $r_{rup}$ ($r_{epi}$ for some) | 2 | B | 1 | A | RSD |
| Cornell et al. (1979) | W. USA | 70 | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | C | U | A | PGV, PGD, FSA |
| Båth (1980) | Sweden | U | - | U | U | U | U | U | U | $r_{epi}$ | 1 | - | 1 | A | MI |

*continued on next page*

[1] Note only valid for $R \geq 20$ km
[2] Note only valid for $R \leq 200$ km
[3] Called $M_{LH}$ so may be $M_L$.
[4] Idriss (1978) finds magnitudes to be mixture of $M_L$, $m_b$ and $M_s$.
[5] Idriss (1978) finds magnitudes to be mixture of $M_L$, $m_b$ and $M_s$.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Goto et al. (1981) | Japan | 84 | - | 28 | 4.3* | 7.8* | U[6] | 11* | 300* | $r_{epi}$ | 1, C | L | 1 | A | PGV, PGD |
| Joyner and Boore (1981) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | 2 | L | 2 | A | PGV |
| Campbell (1984) & K.W. Campbell (1988)[7] | Worldwide | U | - | U | $\geq 5$ | U | $M_L$ for $M < 6.0$ and $M_s$ otherwise | U | <50 | $r_{seis}$ | 2 | M | U | A (S, R) | PGV |
| Joyner and Fumal (1984) and Joyner and Fumal (1985) | W. N. America | 182 | - | 23 | 5.0 | 7.7 | $M_w$ ($M_L$) | 0.5 | 370 | $r_{jb}$ | C | L | 2 | A | PGV |
| Kamiyama (1984) | Japan | 192 | - | U | 4.1 | 7.9 | $M_{JMA}$ | 10 | 310 | $r_{epi}$ | I | B | 1 | A | RSD |
| Kawashima et al. (1984) & Kawashima et al. (1986) | Japan | 197 | - | 90 | 5.0 | 7.9 | $M_{\mathrm{JMA}}$ | 5* | 550* | $r_{epi}$ | 3 | R | 1 | A | PGV, PGD |
| Erdik et al. (1985) | Turkey | U | - | 114 | 5.1 | 7.75 | U | U | U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Trifunac and Lee (1985a) | W. N. America | 438 | 438 | 104 | U | U | U | U | U | $r_{hypo}$ | 3, C | U | U | A | FSA |
| Wilson and Keefer (1985) | W. USA | 30 | - | 20 | 5.0 | 7.4 | $M_w$ | 6 | 130 | $r_{jb}$ | 1 | A | 1 | A | AI |
| Woo (1985) | UK | U | - | U | U | U | $M_s$ | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Jibson (1987) | W. USA | 31 | - | 21 | 5.0 | 7.4 | $M_w$ | 6 | 130 | $r_{jb}$ | 1 | A | 1 | A | AI |
| Gaull (1988) | S.W. W. Australia | 25+ | - | 12+ | 2.6 | 6.9 | $M_L$ | 2.5 | 175 | $r_{hypo}$ | 1 | U | O | A | PGV |
| Hiehata et al. (1988) | 3 sites in Tokyo | 85 | - | 27* | 4.2* | 7.5* | $M_{JMA}$ | 40* | 400* | $r_{hypo}$ | 1 | B[8] | 1 | A | FSA |
| Huo (1989) | W. USA & S. China | U | - | U | U | U | U | U | U | U | 1 | G | 1 | A | PGV |
| Sewell (1989) | California + 7 other events | 112 | - | 24 | 5.0 | 7.7 | $M_w$ ($M_L$, $M_s$) | 0.6 | 211 | $r_{jb}$ ($r_{epi}$ for some) | 2 | C | 2 | A | ISO |
| Campbell (1990) | Unknown | U | - | U | U | U | $M_L$ for $M < 6$, $M_s$ for $M \geq 6$ | U | U | $r_{seis}$ | 1 | U | U | A | PGV |
| Gaull et al. (1990) | SE Australia | U | - | U | U | U | $M_s$ | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |

*continued on next page*

[6]Probably $M_{JMA}$
[7]Reported in Joyner and Boore (1988).
[8]Does not need to be multiplied by two.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Niazi and Bozorgnia (1991) | SMART-1 array, Taiwan | 236 | 234 | 12 | 3.6 | 7.8 | $M_L$ ($M_D$) for $M_L < 6.6$, else $M_s$ | 3.1[9] | 119.7[9] | $r_{hypo}$ | 1 | M | 2W | A | PGV, PGD |
| Dowrick (1992) | New Zealand | U | - | 30 | 5.0 | 7.8 | $M_w$ ($M_L$, $M_s$) | U | U | $r_c$ | 1 | - | 1 | A | MI |
| Kamiyama et al. (1992) & Kamiyama (1995) | Japan | 357 | - | 82 | 4.1 | 7.9 | $M_{\mathrm{JMA}}$ | 3.4 | 413.3 | $r_{hypo}$ | I | B | O | A | PGV, PGD |
| Theodulidis and Papazachos (1992) | Greece+16 foreign | 105+16[10] | - | 36+4 | 4.5 (7.2) | 7.0 (7.5) | $M_s$, $M_w$, $M_{\mathrm{JMA}}$ | 1 (48) | 128 (236) | $r_{epi}$ | 2 | B | O | A | PGV, PGD |
| Midorikawa (1993a) | Japan | U | - | U | 6.5 | 7.8 | $M_w$ | U | U | $r_{rup}$ | C | M | 1 | A | PGV |
| Benouar (1994) | Atlas Mountains | 123 | - | 32 | 4.2 | 7.45 | $M_s$ | U | U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Lee et al. (1995) | W. N. America | 1926 | 1926 | 297 | 1.7 | 7.7 | Usually $M_L$ for $M \leq 6.5$ and $M_s$ for $M > 6.5$ | 2 | 200+ | $r_{hypo}$ | 9, $3 \times C$ | U | 1 | A | PGV, PGD |
| Molas and Yamazaki (1995) | Japan | 2166 | - | 387 | 4.1* | 7.8* | $M_{\mathrm{JMA}}$ | 8* | 1000* | $r_{rup}$ for 2 earthquakes, $r_{hypo}$ otherwise | I | L | O | A | PGV |
| Abrahamson and Silva (1996) | California with some others | U | U | U | 4.7 | 7.4 | $M_w$ | 0.1 | 220* | $r_{rup}$ | 2 | G | 1M | A | RSD |
| Ambraseys and Simpson (1996) & Simpson (1996) | Worldwide shallow crustal | 90–113 | 90–113 | U–34 | 6.0 | 7.6 | $M_s$ | 0 | 15 | $r_{jb}$ | 1 | L | 1 | A, R, S | VH |
| Musson and Winter (1996) | UK | U | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Sabetta and Pugliese (1996) | Italy | 95 | 95 | 17 | 4.6 | 6.8 | $M_s$ if $M_L$ & $M_s \geq 5.5$ else $M_L$ | 1.5, 1.5 | 179, 180[11] | Both $r_{jb}$ & $r_{epi}$ | 3 | L | 1 | A | PGV, AI |
| Singh et al. (1996) | Himalayas | 86 | - | 5 | 5.7 | 7.2 | $m_b$ | 33.15 | 340.97 | $r_{hypo}$ | 1 | U | 1 | A | PGV |

*continued on next page*

[9] Distance to centre of array
[10] Total number of components does not need to be multiplied by two
[11] State equations should not be used for distances > 100 km

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SSB (1996) | E China, W China | U, U | - | U, U | U, U | U, U | $M_s$ | U, U | U, U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Atkinson and Silva (1997) | California | 1000 | - | 43 | 4.4 | 7.4 | $M_w$ | 1* | 200* | $r_{rup}$ | 2 | G | O | A | FSA |
| Bakun and Wentworth (1997, 1999) | Cen. California | 4344 | - | 22 | 4.4 | 6.9 | $M_w$ ($M_L$) | 0* | 600* | $r_{epi}$ | 1 | - | 1 | A | MI |
| Campbell (1997), Campbell (2000), Campbell (2001) & Campbell and Bozorgnia (1994) | Worldwide | 645 | 225 | H:47, V:26 | 4.7 | H:8.0, V:8.1 | $M_w$ | 3 | 60 | $r_{seis}$ | 3 | G | 1 | A(S,R,N) | PGV |
| Gregor and Bolt (1997) | California | 110 | 110 | 12 | 5.4 | 7.2 | $M_w$ | 6* | 200* | $r_{slip}$ | 2 | T, V | 1 | R, S | PGD |
| Kayen and Mitchell (1997) | W. USA | 66 | - | U | U | U | $M_w$ | 1* | 100* | $r_{rup}$ | 3 | G | 1 | A | AI |
| Shabestari and Yamazaki (1997) | Japan | 2166 | - | 387 | 4.1* | 7.8 | $M_{JMA}$ | U | U | $r_{rup}$ | 1 | V | 2 | A | JMA |
| Rathje et al. (1998) | California | 306 | - | 20 | 5.7 | 7.3 | $M_w$ | 0.5* | 200* | $r_{rup}$ | 2 | O | 1M | A | MP |
| Rinaldis et al. (1998) | Italy & Greece | 137* | - | 24* | 4.5 | 7 | $M_s$ or $M_w$ | 7 | 138 | $r_{epi}$ | 2 | U | O | A (N, ST) | PGV |
| Sadigh and Egan (1998) | California with 4 foreign | 960+4 | - | 119+2 | 3.8 | 7.4 | $M_w$ | 0.1 | 305[12] | $r_{rup}$ for some, $r_{hypo}$ for small ones | 2 | G | U | A(R,SN) | PGV, PGD |
| Sarma and Srbulov (1998) | Worldwide | 690[13] | - | 113 | 3.9 | 7.7 | $M_s$ (U) | 0 | 197 | $r_{jb}$, $r_{epi}$ | 2 | B | 1 | A | AI |
| Somerville (1998) | 15 mainly W. USA+12 simulated | 27 | - | 13 | 6.2 | 7.5 | $M_w$ | 0.1 | 10 | $r_{rup}$ | 1 | N | 1 | A | PGV |
| Theodulidis et al. (1998) | Kozani-Grevena (Greece) | 232[14] | - | >23 | 3.1 | 6.6 | $M_w$ | 1 | 140* | $r_{epi}$ | 1 | B | O | A | PGV |
| Chapman (1999) | W. N. America | 304 | - | 23 | 5.0 | 7.7 | $M_w$ | 0.1 | 189.4 | $r_{jb}$ | 3 | G | 2M | A | PGV, IE |
| Dowrick and Rhoades (1999) | New Zealand | U | - | 85 | 5.0 | 8.2 | $M_w$ | 4* | 450* | $r_c$ | 1 | - | 1 | A (S, R, N) | MI |
| Jiménez et al. (1999) | Portugal | U | - | U | U | U | U | U | U | U | 1 | - | 1 | A | MI |

*continued on next page*

[12] Equations stated to be for distances up to 100 km.
[13] Total number of components do not need to be multiplied by two.
[14] Total number of components do not need to be multiplied by two.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ólafsson and Sigbjörnsson (1999) | Iceland | 88[15] | - | 17 | 4.0 | 5.9 | $M_w$ | 2 | 112 | $r_{epi}$ | 1 | B | 1 | A | RSD |
| Alavi and Krawinkler (2000) | 15 mainly W USA+12 simulated | 27 | - | 13 | 6.2 | 7.5 | $M_w$ | 0.1 | 10 | $r_{rup}$ | 1 | N | 1 | A | PGV |
| Bommer et al. (2000) | Europe & Middle East | 183 | - | 43 | 5.5 | 7.9 | $M_s$ | 3 | 260 | $r_{jb}$ | 3 | L | 1 | A | PGV, PGD |
| Ambraseys and Douglas (2000), Douglas (2001a) & Ambraseys and Douglas (2003) | Worldwide | 186 | 183 | 44 | 5.83 | 7.8 | $M_s$ | 0 | 15 | $r_{jb}$ | 3; 1 | L | 1 | A; A, N, R, S | IE; VH |
| Hernandez and Cotton (2000) | Italy & California | 272[16] | - | 40* | 3.2 | 7.4 | $M_L$ for $M < 6$, $M_s$ otherwise | 1 | 109 | $r_{rup}$ | 2 | B | 1 | A | RSD |
| Musson (2000) | Turkey | U | - | U | U | U | $M_s$ | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Paciello et al. (2000) | Greece & Italy | 115 | - | 18 | 4.5 | U | $M_w$ or $M_s$ | U | U | $r_{epi}$ | 2 | B | 1 | A (N) | PGV, PGD, AI |
| Si and Midorikawa (1999, 2000) | Japan | 856 | - | 21 | 5.8 | 8.3 | $M_w$ | 0* | 280* | Both $r_q$ & $r_{rup}$ | 2 | L | O | A | PGV |
| Hinzen and Oemisch (2001) | N Rhine area | 4375 | - | 14 | 2.9 | 5.9 | $M_L$ | 0* | 675* | $r_{epi}$ | 1 | - | 1 | A | MI |
| Wu et al. (2001) | Taiwan | 1941 | - | 60 | 4.8 | 7.6 | $M_w$ ($M_L$) | 0.05* | 400* | $r_{rup}$ ($r_{epi}$ for some) | 1 & I | U | U | A | PGV |
| Chandler and Lam (2002) | S China | 264 | - | 76 | 3.3 | 8.0 | $M_w$ ($M_L$) | 1.9 | 289 | $r_{epi}$ | 1 | - | 1 | A | MI |
| Gregor et al. (2002a) | Shallow crustal worldwide (mainly California) | 993 | 993 | 68 | 4.4 | 7.4 | $M_w$ | 0.1 | 267.3 | $r_{rup}$ | 2 | U | 1M | A (S, R/O, T) | PGV, PGD |
| Margaris et al. (2002b) & Margaris et al. (2002a) | Greece | 744 | - | 142 | 4.5 | 7.0 | $M_w$ | 1 | 150 | $r_{epi}$ | 3 | B | O | A | PGV, PGD |
| Tromans and Bommer (2002) | Europe | 249 | - | 51 | 5.5 | 7.9 | $M_s$ | 1 | 359 | $r_{jb}$ | 3 | L | 2 | A | PGV, PGD |

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[15]Total number of components do not need to be multiplied by two.
[16]Total number of components do not need to be multiplied by two.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zonno and Montaldo (2002) | Umbria-Marche | 161 | - | 15 | 4.5 | 5.9 | $M_L$ | 2* | 100* | $r_{epi}$ | 2 | L | 2 | N, O | PGV, AI |
| Bakun et al. (2003) | E N America | 14198 | - | 28 | 3.7 | 7.3 | $M_w$ | 0* | 2000* | $r_{epi}$ | 1 | - | 1 | A | MI |
| Boatwright et al. (2003) | N California | 4028 | - | 104 | 3.3 | 7.1 | Mainly $M_w$, $M_L$ for some | 1* | 370* | $r_{hypo}$ | 4 | U | O | A | PGV |
| Skarlatoudis et al. (2003) | Greece | 1000 | - | 225 | 4.5 | 7.0 | $M_w$ ($M_L$) | 1.5* | 150* | $r_{epi}$ | 2 | U | O | A (N, ST) | PGV, PGD |
| Travasarou et al. (2003) | Mainly W USA | 1208 | - | 75 | 4.7 | 7.6 | $M_w$ | 0.1* | 200* | $r_{rup}$ | 3 | A | 1M | A (N, R) | AI |
| Zaré and Memarian (2003) | Iran | 470 | - | U | 3.0 | 7.4 | Mixed scales | U | U | $r_{epi}$ | 1, 2 | - | 1 | A | MI |
| Atkinson (2004) | SE Canada & NE USA | U | 1700 | 186 | 2.1* | 5.1* | $m_1$ | 7* | 2000* | $r_{hypo}$ | 1 | G | 1M | A | FSA |
| Bozorgnia and Campbell (2004b) | Worldwide | 443 | 439 | 36[17] | 4.7 | 7.7 | $M_w$ | 2* | 60* | $r_{seis}$ | 4 | G | 1 | A (S & N, R, T) | VH |
| Bray and Rodriguez-Marek (2004) | Worldwide | 54 | - | 13 | 6.1 | 7.6 | $M_w$ | 0.1 | 17.6 | $r_{rup}$ | 2 | N | 1M | A | PGV |
| Horike and Nishimura (2004) | Japan | U | - | U | U | U | $M_{JMA}$ | U | U | $r_{hypo}$ | U | U | 1 | A | PGV |
| Hwang et al. (2004) | Chi-Chi (Taiwan) | 221[18] | - | 4 | 6.2 | 7.7 | $M_w$ | U | U | $r_{jb}$ | 1 | A | 2M | A | AI |
| Kalkan and Gülkan (2004a) | Turkey | 96–100 | 96–100 | 47 | 4.2 | 7.4 | $M_w$ (unspecified scales) | 1.2 | 250 | $r_{jb}$, $r_{epi}$ for small events | 3 | L | 1 | A | VH |
| Lin and Lee (2004) | Taiwan | U | - | 41 | U | U | U | U | U | $r_{rup}$ | 1 | U | 1 | A | AI |
| Mezcua et al. (2004) | Iberia | 375 | - | 5 | 4.8 | 7.9 | $M_w$ | 0* | U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Midorikawa and Ohtake (2004) | Japan | 3335 | - | 33 | 5.5 | 8.3 | $M_w$ | 0* | 300* | $r_{rup}$ | 2 | L | 1 | A (C, B, F) | PGV |
| Moradi et al. (2004) | Iran | U | - | 22 | U | U | $M_s$ | U | U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Pankow and Pechmann (2004) and Pankow and Pechmann (2006) | Worldwide extensional regimes | 142 | - | 39 | 5.1 | 7.2 | $M_w$ | 0 | 99.4 | $r_{jb}$ | 2 | G, O | 1M | NS | PGV |

*continued on next page*

[17] For horizontal corrected records. There are 34 for vertical corrected records.
[18] Three other equations for site classes B, D and E.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rathje et al. (2004) | Worldwide shallow crustal | 835 | - | 44 | 4.9 | 7.6 | $M_w$ | 0.1* | 200* | $r_{rup}$ | 3 | O | 1M | A | MP |
| Yu and Wang (2004) | NE Tibet | U, U | - | 31 | 5.0 | 8.5 | $M_s$ | U, U | U, U | $r_{epi}$ | 1 | - | 1 | A | MI |
| Atkinson (2005) | Cascadia | - | U | U | 2.5* | 6.2* | $m_1$ | 20* | 600* | $r_{hypo}$ | 1 | G | 1M | C, B, F | FSA |
| Bragato and Slejko (2005) | E Alps (45.6–46.8°N & 12–14°E) | 1402 | 3168 | 240 | 2.5 | 6.3 | $M_L$ | 0 | 130 | $r_{jb}$ & $r_{epi}$ | 1 | R | O | A | PGV, AI, FSA |
| Dowrick and Rhoades (2005) | New Zealand | U | - | 89 | 4.6 (5.2 for B) | 8.2 (7.3 for B) | $M_w$ | 1* | 450* | $r_c$ | 1 | - | 1 | A (S, R, N), B | MI |
| Frisenda et al. (2005) | NW Italy | 6899[19] | - | >1152 | 0.0* | 5.1[20] | $M_L$ | 0 | 300[21] | $r_{hypo}$ | 2 | B | 1 | A | PGV |
| García et al. (2005) | Central Mexico | 277 | 277 | 16 | 5.2 | 7.4 | $M_w$ | 4* | 400* | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | G[22] | 1M | B | PGV |
| Gong and Xie (2005) | California | 266 | - | 15 | 5.6* | 7.4* | $M_w$ | 0* | 120* | $r_{jb}$ | 3 | G | 2M | A | IE |
| Kostov (2005) | Europe & Middle East | 967 | - | U | 4 | 7.8 | $M_s$ | 2* | 401* | $r_{hypo}$ | 1 | U | 1 | A | CAV |
| Liu and Tsai (2005) | Taiwan | 7907 | 7907 | 51 | 4.05 | 7.10 | $M_w$ ($M_L$) | 5* | 300* | $r_{hypo}$ | 1 | M | 2M | A | PGV |
| McGarr and Fletcher (2005) | Central Utah coal-mining areas | 72 | - | 12 | 0.98 | 4.2 | $M_w$ ($M_{CL}$) | 0.5* | 10* | $r_{hypo}$ | 2 | L | 2M | M | PGV |
| Musson (2005) | UK | 727 | - | U | U | U | $M_L$ | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Tselentis et al. (2005) | Greece | U | - | U | U | U | $M_w$ | U | U | $r_{epi}$ | U | A | 1M | A | AI |
| Wald et al. (2005) | California | U | - | U | U | 5.3* | $M_w$ | U | U | $r_{jb}$ | 1 | L | U | A | PGV |
| Bakun (2006a) | S California | 3234 | - | 13 | 5.6 | 7.1 | $M_w$ | 0* | 550* | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Bakun (2006b) | Basin & Range, USA | U | - | 9 | 6.1 | 7.3 | $M_w$ | 0* | 600* | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Bindi et al. (2006) | Umbria-Marche | 239 | - | 45 | 4.0 | 5.9 | $M_L$ | 1* | 100* | $r_{epi}$ & $r_{hypo}$ | 4 | L | 1M | NS | PGV |
| Bakun and Scotti (2006) | N France, S France | 13996, 4373 | - | 15, 11 | 4* | 5.5* | $M_w$ | 0* | 400* | $r_{hypo}$ | 1 | - | 1 | A | MI |

*continued on next page*

[19] Authors state in text that 'more than 14 000' values were used but their Table 1 gives $2 \times 6899$.
[20] State equations valid to 4.5.
[21] State equations valid up to 200 km.
[22] Call it 'quadratic mean', which is assumed to be geometric mean.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Faccioli and Cauzzi (2006) | Europe & Middle East | 75 | - | 26 | 3.8 | 6.9 | $M_w$ ($M_L$) | 1.5 | 71 | $r_{jb}$ ($r_{epi}$ for $M_w<5.5$) | 1 | - | 1 | A | MI |
| Gómez-Soberón et al. (2006) | Mexico | 1983 | - | 109 | 4.5* | 8.1* | $M_w$ ($M_s$ if $M>6$, $m_b$ if $M<6$) | 5* | 800* | $r_{hypo}$ ($r_{rup}$ for some) | 1 | U | 2 | F | PGD |
| Hwang (2006) | Taiwan | U | - | U | U | U | U | U | U | U | U | U | 1 | A | AI |
| Jaimes et al. (2006) | Ciudad Universitaria station, Mexico City | 21 | - | 21 | 6.0 | 8.1 | $M_w$ | 285 | 530 | $r_{rup}$ | 1 | U | 1B | F | FSA |
| Kanno et al. (2006) | Japan+some foreign | 3392+377 (shallow) & 8150 (deep) | - | 73+10 & 111 | 5.0* (6.1) & 5.5* | 8.2* (7.4) & 8.0* | $M_w$ ($M_{\mathrm{JMA}}$) | 1* (1.5*) & 30* | 450* (350*) & 450* | $r_{rup}$ ($r_{hypo}$ for some) | C | R | 2M | A | PGV |
| Kataoka et al. (2006) | Japan | 5160 | - | 47 | 4.8* | 6.9* | $M_w$ | 1* | 200* | U | 1 | U | U | C | PGV, JMA |
| Kempton and Stewart (2006) | Worldwide shallow crustal | 1559 | - | 73 | 5.0* | 7.6* | $M_w$ | 0* | 200* | $r_{rup}$ | C | G | 1M | A | RSD |
| Pousse et al. (2006) | Japan | 9390[23] | - | U | 4.1 | 7.3 | ($M_w$) | 5* | 250* | $r_{hypo}$ ($r_{rup}$ for some) | 5 | B | 2M | A | AI, RSD |
| Stafford (2006) & Stafford et al. (2006) | New Zealand + foreign | 265–484 | - | 59–93 | 5* | 7.4* | $M_w$ | 0.3* | 300* | $r_{rup}$ | 3 | G | 1M | A (S/N, R) | FSA |
| Akkar and Bommer (2007b) | Europe & Middle East | 532 | - | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ | 3 | G | 1WM | A (N, S, R) | PGV |
| Amiri et al. (2007a) & Amiri et al. (2007b) | Alborz and central Iran[24] | 200* | 200* | 50* | 4.5* | 7.3* | $M_s$ ($m_b$) | 5* | 400* | $r_{hypo}$ | 2 | L | 1 | A | PGV |
| Atkinson and Wald (2007) | California, Cen. E US | U | - | U | 2.4*, 2.0* | 7.8*, 7.8* | $M_w$ | 2*, 7* | 500*, 1000* | $r_{rup}$ | 1 | - | 1M | A | MI |
| Bindi et al. (2007) | NW Turkey | 4047 | 4047 | 528 | 0.5 | 5.9 | $M_L$[25] | 5* | 200* | $r_{hypo}$[26] | 2 | L | 1M | A | PGV |

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[23] Does not need to be multiplied by two.
[24] Also develop models for the Zagros region of Iran using about 100 records.
[25] Also derive model using $M_w$.
[26] Also derive model using $r_{epi}$.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boore and Atkinson (2007) & Boore and Atkinson (2008) | Worldwide shallow crustal | 1574 | - | 58 | 4.27[27] | 7.90[28] | $M_w$ | 0 | 280[29] | $r_{jb}$ | C | I50 | 2M | A (N, R, S, U) | PGV |
| Campbell and Bozorgnia (2007), Campbell and Bozorgnia (2008b) & Campbell and Bozorgnia (2008a) | Worldwide shallow crustal | 1561 | - | 64 | 4.27[30] | 7.90[31] | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW) | PGV, PGD |
| Danciu and Tselentis (2007a), Danciu and Tselentis (2007b) & Danciu (2006) | Greece | 335 | - | 151 | 4.5 | 6.9 | $M_w$ | 0* | 136 | $r_{epi}$ | 3 | A | 1M | A (ST, N) | PGV, PGD, AI, IE, SI |
| Fukushima et al. (2007a) | Japan | 8615 | - | 158 | 5.0 | 6.8 | $M_{JMA}$ | 18.1 | 448.4 | $r_{rup}$ | 1 | V | 1 | A | PGV |
| Mahdavifar et al. (2007) | Alborz and central Iran | 22 | - | 19 | U | U | U | U | U | $r_{hyp}$ | 1 | U | 1 | A | AI |
| Abrahamson and Silva (2008) & Abrahamson and Silva (2009) | Worldwide shallow crustal | 2754 | - | 135 | 4.27[32] | 7.9[33] | $M_w$ | 0.06* | 200* | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW) | PGV |
| Al-Qaryouti (2008) | Dead Sea area | 26 | - | 19 | 4.0 | 6.2 | $M_L$ | 5.8 | 330.6 | $r_{epi}$ | 1 | L | 2 | A | PGV |
| Chen (2008) | China, Taiwan and Japan | 249 | 249 | 55 | 4.2 | 7.6 | $M_w$ ($M_L$, $M_s$) | 10 & 12 | 153 & 153 | $r_{epi}$ & $r_{hypo}$ | 2 | G & L | 2 | A | PGV |

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[27]Recommend that model is not extrapolated below 5 due to lack of data.
[28]Believe that model can be used to 8.0.
[29]Recommend that model is not used for distances $\geq 200$ km.
[30]Believe that model can be extrapolated down to 4.0.
[31]Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[32]Recommend that model is not extrapolated below 5 due to lack of data.
[33]Believe that model can be reliably extrapolated to 8.5.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chiou and Youngs (2008) | Worldwide shallow crustal | 1950 | - | 125 | 4.265[34] | 7.90[35] | $M_w$ | 0.2*[36] | 70*[37] | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW, AS) | PGV |
| Jin et al. (2008) | Fujian (China) | 1974 | 1974 | 94 | 2.8 | 4.9 | $M_L$ | 13 | 462 | $r_{epi}$ | 1 | U | O | A | PGV |
| Massa et al. (2008) | Northern Italy | 306 | 306 | 82 | 3.5 & 4.0 | 6.3 & 6.5 | $M_w$ ($M_L$) & $M_L$ | 1* | 100* | $r_{epi}$ | 3 | L | 1M | A | PGV, AI, SI |
| Mezcua et al. (2008) | Spain | 250 | - | 149 | 3.1 | 5.3 | $M_w$ ($m_b(L_g)$) | 5* | 100* | $r_{hypo}$ | 1 | U | 1 | A | PGV |
| Pasolini et al. (2008) | Italy | 21932 | - | 470* | 4.4* | 7.4* | $M_w$ | 0* | 300* | $r_{epi}$ | 1 | - | O | A | MI |
| Snæbjörnsson and Sigbjörnsson (2008) | Europe & Middle East | 71 | - | 13 | 5.0* | 7.6* | $M_w$ | 0* | 100* | $r_{jb}$ | 1 | U | 1 | SS | RSD |
| Bindi et al. (2009a) | Italy | 241 | 241 | 27 | 4.8 | 6.9 | $M_w$ | 0 | 190 | $r_{jb}$ ($r_{epi}$ for small) | 3 | L, G | 1M | A (N, S, R) | PGV |
| Bindi et al. (2009b) | Italy | 235 | - | 27 | 4.6 | 6.9 | $M_w$ ($M_L$) | 0 | 183 | $r_{jb}$, $r_{epi}$ | 3 | L | 1M | A | PGV |
| Bommer et al. (2009) | Worldwide shallow crustal | 2406 | - | 114 | 4.8 | 7.9 | $M_w$ | 1.5* | 100* | $r_{rup}$ | C | B | O | A | RSD |
| Lee (2009), Lee and Green (2008) & Lee and Green (2014) | W. USA[38] | 324 | 324 | 49 | 5.0 | 7.6 | $M_w$ | 0.1 | 199.1 | $r_{rup}$ | 2 | A | 1M | A | AI, MP, RSD |
| Rupakhety and Sigbjörnsson (2009) | South Iceland+others | 64+29 | - | 12 | 5.02 | 7.67 | $M_w$ | 1 | 97 | $r_{jb}$ ($r_{epi}$ for some) | 2 | L | 1 | S/O | ISO |
| Sørensen et al. (2009) | Marmara Sea, Turkey | 121195 | - | 7 | 5.9 | 7.4 | $M_w$ | 0* | 350* | $r_{jb}$, $r_{epi}$ | 1 | - | 1W | A | MI |
| Stafford et al. (2009) | New Zealand + foreign | 144+241 & 144+200 | - | 23+41 | 5.08 | 7.51 | $M_w$ | 0.07 | 300 | $r_{jb}$ & $r_{rup}$ | 3 | L, O, G, A | 1M | A (S/N, R) | AI |
| Akkar and Bommer (2010) | Europe & Middle East | 532 | - | 131 | 5.0 | 7.6 | $M_w$ | 0 | 99 | $r_{jb}$ | 3 | G | 1M | A (N, S, R) | PGV |
| Akkar and Çağnan (2010) | Turkey | 433 | - | 137 | 5.0 | 7.6 | $M_w$ | 0* | 200* | $r_{jb}$ | C | G | 1M | A (N, S, R) | PGV |

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[34] Believe that model can be extrapolated down to 4.0.
[35] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[36] Believe that model valid to 0 km.
[37] Believe that model valid to 200 km.
[38] Also model for Central USA using 14 records and 296 scaled records

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Amiri et al. (2009) | Alborz and central Iran[39] | 416 | - | 189 | 3.2[40] | 7.7 | $M_s$ ($m_b$) | 5* | 400* | $r_{hypo}$ | 2 | L | 1M | A | AI |
| Beauval et al. (2010) | Sierra of Ecuador | 453 | - | 4 | 5.3 | 7.1 | $M_w$ | 10* | 200* | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Bindi et al. (2010) | Italy | 561 | 561 | 107 | 4.0 | 6.9 | $M_w$ | 1* | 100* | $r_{jb}$, $r_{epi}$ | 3 | L | 1M | A | PGV |
| Bozorgnia et al. (2010) | Worldwide shallow crustal | 1561 | - | 64 | 4.27 | 7.90 | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | G | 1M | A (N, R, S, HW) | ISO |
| Campbell and Bozorgnia (2011) & Campbell and Bozorgnia (2010a) | Worldwide shallow crustal | 1561 | - | 64 | 4.27 | 7.90 | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | G | 1M | A (N, R, S, HW) | JMA |
| Campbell and Bozorgnia (2010b) & Campbell and Bozorgnia (2010a) | Worldwide shallow crustal | 1561 | - | 64 | 4.27 | 7.90 | $M_w$ | 0.07 | 199.27 | $r_{rup}$ | C | G | 1M | A (N, R, S, HW) | CAV |
| Chiou et al. (2010)[41] | S & N California | 15684 | - | U | 3* | 6* | $M_w$ | 5* | 200* | $r_{rup}$ | C | I50 | 1M | A (N, R, S, HW, AS) | PGV |
| Iervolino et al. (2010) | Italy | 95 | - | 17 | 4.6 | 6.8 | $M_w$ | 1.5, 1.5 | 179, 180 | $r_{jb}$ & $r_{epi}$ | 3 | L | 1 | A | PGV, AI |
| Rajabi et al. (2010) | Zagros, Iran | 37 | - | 35 | 4.1 | 7.0 | $M_w$ | 5 | 150 | $r_{epi}$ | 1, 3 & 4 | L | 1 | A | AI |
| Sørensen et al. (2010a) | Campania, Italy | 2985 | - | 9 | 6.3 | 7.0 | $M_w$ | 0* | 650* | $r_{jb}$, $r_{epi}$ | 1 | - | 1W | A | MI |
| Sørensen et al. (2010b) | Vrancea, Romania | 4058 | - | 5 | 6.4 | 7.7 | $M_w$ | 0* | 550* | $r_{jb}$, $r_{epi}$, $r_{rup}$ | 1 | - | 1W | A | MI |
| Szeliga et al. (2010) | India | U | - | 29 | 4* | 8* | $M_w$ ($m_b$) | 7* | 2000* | $r_{hypo}$ | 1 | - | 1M | A | MI |

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[39] Also develop models for the Zagros region of Iran using 309 records from 190 earthquakes.
[40] State that only use data with $M_s \geq 4$ but one earthquake in their Appendix A has $M_s 3.2$.
[41] Adjustment of GMPE of Chiou and Youngs (2008) for $M_w < 6$

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Boore and Atkinson (2007) & Boore and Atkinson (2008) modified by Atkinson and Boore (2011) | Worldwide shallow crustal | 1574 | - | 58 | 4.27 | 7.90[42] | $M_w$ | 0 | 280[43] | $r_{jb}$ | C | I50 | 2M | A (N, R, S, U) | PGV |
| Alavi et al. (2011) | Worldwide shallow crustal | 2252 | - | U | 5.1* | 7.9* | $M_w$ | 0.2* | 350* | $r_{rup}$ | C | U | O | A (Rake) | PGV, PGD |
| Anderson and Uchiyama (2011) | Guerrero, Mexico | 293 | 293 | 27 | 5.05 | 7.96 | $M_w$ | 10* | 390* | $r_{rup}$ | 1 | M, V, V3 | O | A | PGV, PGD |
| Bindi et al. (2011b) | Central Asia | 6000* | - | 66 | 4.6 | 8.3 | $M_s$ | 0.1* | 600* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ | 1 | - | 1 | A | MI |
| Bommer et al. (2011) | Europe & Middle East | 1267 | 1267 | 392 | 4.5 | 7.6 | $M_w$ | 0 | 100* | $r_{jb}$ | 3 | G | 1M | A (N, R, S) | VH |
| De Luca et al. (2011) & De Luca (2011) | Italy | 725 | - | U | 4.1 | 6.9 | $M_w$ | 0 | 200 | $r_{jb}$ | 5 | G | 1M | A | ISO |
| Emolo et al. (2011) | Campania-Lucania, Italy | 875 | - | 123 | 1.5 | 3.2 | $M_L$ | 3 | 100* | $r_{hypo}$ | 2 | L | 1 | A | PGV |
| Ghanat (2011) | Worldwide shallow crustal | 2690 | - | 129 | 4.8 | 7.9 | $M_w$ | 0.2* | 200* | $r_{rup}$ | C | G | 1M | A | RSD |
| Ghosh and Mahajan (2011) | NW Himalaya | U | - | 10 | 4.3 | 7.8 | $M_s$ | 10* | 2000* | $r_{epi}$ | 1 | - | 1 | A | MI |
| Gülerce and Abrahamson (2011) | Worldwide shallow crustal | 2684 | 2684 | 127 | 4.27[44] | 7.9[45] | $M_w$ | 0.06* | 200* | $r_{rup}$ | C | I50 | 1M | A (N, R, S) | VH |
| Luzi et al. (2011) | Italy | U | - | U | 4.0* | 6.9* | $M_w$ | 0* | 300* | $r_{jb}$ ($r_{epi}$ for $M_w <$ 5.5), $r_{hypo}$ | 5 | G | 1M | A (S, N, R) | PGV |
| Rupakhety et al. (2011) | Worldwide shallow crustal | 93 | - | 29 | 5.56 | 7.6 | $M_w$ | 0 | 74.16 | $r_{jb}$ | 1 | N | 1M | A | PGV |
| Allen et al. (2012) | Worldwide shallow crustal | 13077 | - | U | 5.0 | 7.9 | $M_w$ | 5* | 315 | $r_{hypo}$ & $r_{rup}$ | C | - | 1 | A | MI |
| Cui et al. (2012) | Sichuan-Yunnan (China) | 962 | - | >21 | 4.5 | 6.5 | $M_s$ | 0* | 110* | $r_{epi}$ | 2 | G | 1, 1W | A | PGV |
| Foulser-Piggott and Stafford (2012) | Worldwide shallow crustal | 2406 | - | 114 | 4.79 | 7.9 | $M_w$ | 0.07 | 100 | $r_{rup}$ | C | A | 1M | A (S/N, R) | AI |

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[42]Believe that model can be used to 8.0.
[43]Recommend that model is not used for distances $\geq 200$ km.
[44]Recommend that model is not extrapolated below 5 due to lack of data.
[45]Believe that model can be reliably extrapolated to 8.5.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gómez-Bernal et al. (2012) | Mexico | 607 | 607 | 17[46] | 6.0 | 8.1 | $M_w$ | 20* | 600* | $r_{rup}$ | 1 | L | 2 | A (F, B, C) | PGV, AI |
| Lee et al. (2012) | Taiwan | 6570 | - | 62 | 3.93 | 7.62 | $M_w$ | 0.3 | 205 | $r_{rup}$ | C | A | 1M | A (S, N, R) | AI |
| Mohammadnejad et al. (2012) | Worldwide shallow crustal | 2252 | - | U | 5.2 | 7.9 | $M_w$ | 0.07 | 366.03 | $r_{rup}$ | C | I50 | O | A (R, S, N) | PGV, PGD |
| Nguyen et al. (2012) | Northern Vietnam | 330 | - | 53 | 1.6 | 4.6 | $M_L$ | 5* | 500* | $r_{epi}$ | 1 | L3 | 1 | A | PGV |
| Saffari et al. (2012) | Iran | 351 | - | 78 | 5.0 | 7.4 | $M_w$ | 4 | 190* | $r_{rup}$ ($r_{hypo}$ for $M_w < 6.5$) | 3 | U | 2M | A | PGV |
| Abrahamson et al. (2013, 2014) | Worldwide shallow crustal | 15750 | - | 326 | 3 | 7.9[47] | $M_w$ | 0 | 300 | $r_{rup}$ + others for HW | C | D50 | 1M | A (S, N, R, HW) | PGV |
| Boore et al. (2013, 2014) | Worldwide shallow crustal | 15000* | - | 350* | 3.0 | 7.9[48] | $M_w$ | 0 | 400 | $r_{jb}$ | C | D50 | 2M | A (S, N, R, U) | PGV |
| Campbell and Bozorgnia (2013, 2014) | Worldwide shallow crustal | 15521 | - | 322 | 3.0[49] | 7.9[50] | $M_w$ | 0* | 300* | $r_{rup}$ | C | D50 | 1M | A (S, R, N, HW) | PGV |
| Chiou and Youngs (2013, 2014) | Worldwide shallow crustal | 12244 | - | 300 | 3.1*[51] | 7.9*[52] | $M_w$ | 0.3* | 400*[53] | $r_{rup}$ | C | D50 | 1M | A (S, R, N, HW) | PGV |
| Crowell et al. (2013) | Japan & California | 118 | 118 | 5 | 5.3 | 8.3 | $M_w$ | 10* | 700* | $r_{hyp}$ | 1 | L3 | 1 | A | PGD |
| Douglas et al. (2013) | Mainly geothermally-related | 3968 | - | 535 | 1* | 4* | $M_w$ ($M_L$, $M_D$) | 0* | 20* | $r_{hypo}$ | 1 | G | 1M | G | PGV |
| Du and Wang (2013) | Worldwide shallow crustal | 1390 | - | 62 | 4.26 | 7.9 | $M_w$ | 0.07 | 200 | $r_{rup}$ | 3 | G | 1M | A (N, R, S) | CAV |
| Ghosh and Mahajan (2013) | NW Himalaya | U | - | 10 | 4.3 | 7.8 | $M_s$ | 0* | 1600* | $r_{epi}$ | 1 | - | 1 | A | MI |

*continued on next page*

[46]Taken from their Table 3.1. Elsewhere in the article the total is given as 23 and 25.
[47]State model applicable up to 8.5.
[48]State model applicable up to $M_w 8.5$ for strike-slip and reverse and $M_w 7$ for normal earthquakes.
[49]State model applicable for $M_w \geq 3.3$ in California and $M_w \geq 5.5$ globally.
[50]State model applicable to $M_w 8.5$ for strike-slip, $M_w 8$ for reverse/reverse-oblique and $M_w 7.5$ for normal/normal-oblique.
[51]State applicable for $M_w \geq 3.5$.
[52]State applicable for $M_w \leq 8.5$ for strike-slip and $M_w \leq 8$ for reverse and normal earthquakes.
[53]State applicable up to 300 km

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Idriss (2013, 2014) | Worldwide shallow crustal | 2353 | - | 151 | 4.5[54] | 7.9[55] | $M_w$ | 0.2 | 175 | $r_{rup}$ | C | D50 | 1 | A | PGV |
| Morikawa and Fujiwara (2013) | Japan | 21681 | - | 333 | 5.5 | 9.0 | $M_w$ | 1* | 200 | $r_{rup}$ | C | V | 2W | A (C, B, F) | PGV |
| Musson (2013) | UK | 446 | - | 161 | 2.5* | 4.3* | $M_w$ | U | U | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Pacific Earthquake Engineering Research Center (2013) | Worldwide shallow crustal | - | | 4 vertical models | | | $M_w$ | 4 vertical models | | | C | V | 1M | A (N, S, R, HW) | PGV |
| Segou and Voulgaris (2013) | Europe & Middle East | 327 | - | 164 | 4.1 | 6.6 | $M_w$ ($m_b$) | 1* | 150* | $r_{epi}$ | 3 | I50 | O | A (S, R, N) | PGV |
| Sharma et al. (2013) | Geysers, N. California | 5451 | - | 212 | 1.3 | 3.3 | $M_w$ ($M_D$) | 0.5 | 20 | $r_{hypo}$ | 3 | L | 1M | G | PGV |
| Skarlatoudis et al. (2013) | Hellenic Arc (Greece) | 743 | - | 21 | 4.4 | 6.7 | $M_w$ ($m_b$, $M_L$) | 65* | 850* | $r_{hyp}$ | 3 | D50 | 1M | F, B | PGV |
| Villalobos-Escobar and Castro (2013) | Medellìn and Aburrà Valley (Colombia) | 596 | - | 17 | 2.8 | 6.5 | $M_L$ | 10* | 290 | $r_{epi}$ | I | U | 1M | A | PGV |
| Akkar et al. (2014b,c) | Europe & Middle East | 1041 | - | 221 | 4.0 | 7.6[56] | $M_w$ | 0 | 200 | $r_{jb}$, $r_{epi}$ & $r_{hypo}$ | C | G | 1M | A (S, N, R) | PGV |
| Akkar et al. (2014a) | Europe & Middle East | 1041 | - | 221 | 4.0 | 7.6[57] | $M_w$ | 0 | 200 | $r_{jb}$ | C | G | 1M | A (S, N, R) | VH |
| Ansary (2014) | Himalaya, India | R: 229, S: 187 | - | 150* | 2.5* | 7.8 | U | 2* | 2000* | $r_{hyp}$ | 2 | U | 1 | A | PGV, PGD |
| Atkinson et al. (2014b) | California, Cen. E USA | U | - | U | 4* | 7.5* | $M_w$ | 1* | 400* | $r_{epi}$ | 1 | - | 1M | A | MI |
| Bindi et al. (2014a,b) | Europe & Middle East | 1224, 2126 | - | 225, 365 | 4.0 | 7.6 | $M_w$ | 0 | 300 | $r_{jb}$ ($r_{epi}$ for $M_w \leq 5$ and $r_{epi} \geq 10$) & $r_{hypo}$ | C, 4 | G | 1M | A (S, N, R) | PGV |
| Bora et al. (2014) | Europe & Middle East | 1232 | - | 369 | 4.0 | 7.6 | $M_w$ | 0* | 200* | $r_{jb}$ | C | G | 1M | A | FSA |
| Boyd and Cramer (2014) | Cen. & E USA | 21398* | - | 1143 | 2.5* | 7.2* | $M_w$ | 0* | 1500* | $r_{hypo}$ | 1 | - | O | A | MI |
| Cheng et al. (2014) & Cheng (2013) | Worldwide shallow crustal | 1550 | - | 63 | 4.26 | 7.9 | $M_w$ | 0.1 | 199.3 | $r_{rup}$ | C | G | 1M | A (N, R, S) | IE |

*continued on next page*

[54]Recommends model for $M_w \geq 5$.
[55]Recommends model up to $M_w 8$.
[56]Believe model can be used up to $M_w 8$.
[57]Believe model can be used up to $M_w 8$.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chousianitis et al. (2014) | Greece | 133[58] | - | 37 | 3.2 | 6.7 | $M_w$ | 1 | 195 | $r_{epi}$ | 4 | L | 2M | A (S/T, N) | AI |
| Derras et al. (2014) | Europe & Middle East | 1088 | - | 320 | 3.6[59] | 7.6[60] | $M_w$ | 1[61] | 547[62] | $r_{jb}$ | C | G | O | A | PGV |
| Foulser-Piggott and Goda (2014) | Japan | 13703 | - | 158 | 5.5 | 9.0 | $M_w$ | 2* | 300* | $r_{rup}$ | C | G | 1M | A (B) | AI, CAV |
| Ghofrani and Atkinson (2014) | Japan | > 1000 | - | 6 | 7.0 | 9.0 | $M_w$ | 30* | 1000* | $r_{rup}$ | C | G | O | F | PGV |
| Le Goff et al. (2014) | Mainland Portugal | | - | 25 | 4.4 | 6.2 | $M_w$ | 5* | 800* | $r_{epi}$ | 1 | - | 1 | A | MI |
| Rodríguez-Pérez (2014) | Cen. and S. Mexico | 75 (F), 121 (B) | - | 8 F, 25 B | 5.1 (F), 5.0 (B) | 8.0 (F), 7.2 (B) | $M_w$ | 50* (F), 70* (B) | 580* (F), 540* (B) | $r_{rup}$ ($r_{hypo}$ for $M_w$ < 6.5) | 1 | G | 1M | F, B | PGV |
| Yaghmaei-Sabegh et al. (2014) | Iran | 286 | - | 141 | 3.7 | 7.7 | $M_w$ | 0.6 | 294 | $r_{rup}$ | 4 | G | 1 | A | RSD |
| Atkinson (2015) | California | U | - | U | 3* | 6* | $M_w$ | 2* | 40 | $r_{hypo}$ | 1 | G | 1M | A | PGV |
| Bora et al. (2015) | Europe & Middle East | 1232 | - | 369 | 4.0 | 7.6 | $M_w$ | 0* | 200* | $r_{jb}$ | C | G | 1M | A | FSA |
| Bozorgnia and Campbell (2016b) | Worldwide shallow crustal | - | 15161 | 321 | 3.0[63] | 7.9[64] | $M_w$ | 0* | 500*[65] | $r_{rup}$ | C | V | 1M | A (R, S, N) | PGV |
| Bozorgnia and Campbell (2016a) | Worldwide shallow crustal | 15521 | 15161 | 321–322 | 3.0[66] | 7.9[67] | $M_w$ | 0* | 500*[68] | $r_{rup}$ | C | D50 | 1M | A (R, S, N) | VH |
| Cauzzi et al. (2015b) | Worldwide shallow active crustal | 1880 | - | 98 | 4.5 | 7.9 | $M_w$ | 0* | 150* | $r_{rup}$ ($r_{hypo}$ for $M_w$ ≤ 5.7) | C | G | 2M | A (S, N, R) | PGV |

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[58] Use an additional 60 records to validate model.
[59] Recommend never using model below 4.
[60] Recommend never using model above 7.
[61] Recommend never using model for $r_{jb} < 5$.
[62] Recommend never using model for $r_{jb} > 200$.
[63] Believe applicable down to 3.3 for California and down to 5.5 globally.
[64] Believe valid to 8.5 for strike-slip, 8.0 for reverse and 7.5 for normal.
[65] Believe applicable to 300 km.
[66] Believe applicable down to 3.3 for California and down to 5.5 globally.
[67] Believe valid to 8.5 for strike-slip, 8.0 for reverse and 7.5 for normal.
[68] Believe applicable to 300 km.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Emolo et al. (2015) | South Korea | 11129 | - | 222 | 2.0 | 4.9 | $M_L$ | 1.4 | 600* | $r_{epi}$ | I | L | 1M | A | PGV, PGD |
| Foulser-Piggott and Goda (2015) | Japan | 68567 | - | 661 | 5.0 | 9.0 | $M_w$ | 2* | 300* | $r_{rup}$ | C | G | 1M | A (R, S, N, F, B) | AI, CAV |
| Jaimes et al. (2015) | Ciudad Universitaria, Mexico City[69] | 22 | - | 22 | 5.2 | 7.4 | $M_w$ | 103 | 464 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ for $M_w \leq 6.5$ | 1 | G | 1B | B | PGV |
| Kale et al. (2015) | Turkey & Iran | 1198 | - | 313 | 4 | 7.6[70] | $M_w$ | 0 | 200 | $r_{jb}$ | C | G | 1MW | A (S, N, R) | PGV |
| Kuehn and Scherbaum (2015) | Europe & Middle East | 835 | - | 279 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | G | O | A (R, N, S) | PGV |
| Leonard (2015) | Australia | | | Adjusts model of Allen et al. (2012) using data from 6 $M_w \geq 5.5$ earthquakes | | | | | | | | | | | MI |
| Melgar et al. (2015) | Worldwide | 1321 | 1321 | 10 | 5.9 | 9.1 | $M_w$ | 10* | 1000* | $r_{hyp}$ | 1 | V3 | 1 | A | PGD |
| Pacific Earthquake Engineering Research Center (2015) — Al Noman and Cramer | Cen. and E. N. America + foreign | 6061[71] | - | 78[72] | 2.5 | 7.6[73] | $M_w$ | 1* | 2000* | $r_{rup}$ | C | D50 | 2M | A (R, S, U) | PGV |
| Pacific Earthquake Engineering Research Center (2015) — Graizer | Cen. and E. USA | 5026 | - | 48 | 4.0 | 6.8[74] | $M_w$ | 4[75] | 1000* | $r_{rup}$ | C | D50 | O | A | PGV |
| Pacific Earthquake Engineering Research Center (2015) — Hollenback et al. | Cen. and E. USA | U | - | U | 2.5[76] | 6.8[77] | $M_w$ | 0 | 300 | $r_{rup}$ | C | D50 | O | A | FAS |

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[69]Also derive models for two other sites (SCT and CDAO) in Mexico City.
[70]Recommend model up to $M_w 8$
[71]Also use 1921 macroseismic intensities.
[72]Macroseismic intensities from 6 events.
[73]7.7 by including macroseismic data.
[74]Believes applies up to 8.2.
[75]Believes applies down to 0 km.
[76]Recommends use down to 4.0.
[77]Believes applies up to 8.2.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ullah et al. (2015) | Central Asia | 6000* | - | 66 | 4.6 | 8.3 | $M_s$ | 0.1* | 600* | $r_{epi}$ | 1 | - | 1 | A | MI |
| Vacareanu et al. (2015a) | Vrancea, Romania | 9718 | - | 6 | 6.0 | 7.7 | $M_w$ | 0* | 1000* | $r_{epi}$ | 1 | - | 1M | A | MI |
| Yaghmaei-Sabegh (2015) | Iran | 575 | - | 40 | 3.7 | 7.7 | $M_w$ | 0.7 | 293 | $r_{jb}$ | 3 | O | 1 | A | MP |
| Afshari and Stewart (2016) | Worldwide shallow crustal | 11195 | - | | 3.0 | 7.9 | $M_w$ | 0* | 300* | $r_{rup}$ | C | G | 1M | A (R, S, N, U) | RSD |
| Alıcı and Sucuoğlu (2016) | Worldwide shallow crustal | 1442 | - | 104 | 5.50 | 7.90 | $M_w$ | 0.4 | 189.7 | $r_{epi}$ | 2 | G | 1M | A (N, R, S) | IE |
| Galluzzo et al. (2016) | Campi Flegrei, Italy | 120* | - | 20 | 0.8 | 2.4 | $M_w$ | 1* | 12 | $r_{hypo}$ | 1 | L | 1 | A | PGV |
| Ibrahim et al. (2016) | Japan | 409 | - | 20 | 6.0 | 9.1 | $M_w$ | 10* & 10* | 300* & 550* | $r_{rup}$ & $r_q$ | 1 | V | 2 | A (C, F, B) | PGV, PGD |
| Kaveh et al. (2016) | Worldwide shallow crustal | 2252 | - | U | 5.2 | 7.9 | $M_w$ | 0.07 | 360 | $r_{rup}$ | C | U | O | A | PGV, PGD |
| Kotha et al. (2016a,b) | Europe & Middle East | 1251 | - | U | 4 | 7.6 | $M_w$ | 0* | 300*[78] | $r_{jb}$ ($r_{epi}$ for some $M_w \leq 5$) | C | G | O | A | PGV |
| Lanzano et al. (2016) | Po Plain & NE Italy | 2489 | - | 94 | 4.0 | 6.4 | $M_w$ | 0* | 200* | $r_{jb}$ | 5 | G | 1M | A (R, N, U) | PGV |
| Lee et al. (2016a) | Serbia (Vrancea events) | 91 | 91 | 4 | 6.4 | 7.4 | $M_w$ | 84.7 | 554.2 | $r_{hypo}$ | 1 | B | 1 | A | FSA |
| Nekooei and Babaei (2016) | Iran | 484 | - | $\geq 25$ | 4.5 | 7.4 | $M_w$ | 1 | 149 | $r_{rup}$ | C | L, G | 1 | A | PGV |
| Shoushtari et al. (2016) | Malaysia, Japan and Iran | 531 | - | 13 | 5.0 | 7.7 | $M_w$ | 120* | 1400* | $r_{hypo}$ | 4 | G | 1 | B | PGV |
| Stewart et al. (2016) | Worldwide shallow crustal | - | 17089 | U | 3 | 7.9[79] | $M_w$ | 0 | 300 | $r_{jb}$ | C | V | 2M | A (R, S, N, U) | PGV |
| Tusa and Langer (2016) | Mount Etna, Italy | 1158 (shallow), 1957 (deep) | 1158 (shallow), 1957 (deep) | 38 (shallow), 53 (deep) | 3.0 | 4.3 (shallow), 4.8 (deep) | $M_L$ | 0.5 | 100 | $r_{epi}$ | 3 | G, V | 1 | V | PGV |
| Çağnan et al. (2017a) | Europe & Middle East | - | 1041 | 221 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$ | C | V | 1M | A (S, N, R) | PGV |
| Cameletti et al. (2017) | Italy | 6723 | - | 1917 | 2 | 5.9 | $M_L$ | U | U | $r_{hypo}$ | 1 | - | O | A | MI |

*continued on next page*

[78]Recommend model up to 200 km

[79]Recommend model for use up to 8.0 for strike-slip and reverse and 7.0 for normal earthquakes.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cremen et al. (2017) | Cen. and E. USA | 104023 | - | 972 | 3.0 | 5.8 | $M_w$ | 0* | > 50 | $r_{epi}$ | 1 | - | 1 | A (E/G/M/W) | MI |
| Du (2017) | Worldwide shallow crustal | 8491 | - | 263 | 3.05 | 7.9 | $M_w$ | 0.1 | 499.5 | $r_{rup}$ | C | V | 1M | A | MP |
| Derras et al. (2017) | Japan | 977 | - | 214 | 3.7 | 6.9 | $M_w$ | 3.65 | 440.63 | $r_{jb}$ | C $\times$ C | G | O | A | PGV |
| García-Soto and Jaimes (2017) | Mexico (Pacific coast) | 418 | 418 | 40 | 5.0 | 8.0 | $M_w$ | 17 | 400 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | V | 1M | F | PGV |
| Gupta and Trifunac (2017) | W Himalaya & NE India | 365 | 365 | 113 | 3.0 | 6.9 | $M_s$ or $M_w$ for $M \geq 6.5$ & $m_b$, $M_L$ or $M_s$ for $M < 6.5$ | 8* | 500* | $r_{hypo}$ | 9 | B | 1 | A | FSA |
| Haji-Soltani et al. (2017) | Gulf Coast (USA) | 943 | 943 | 30 | 3.40 | 5.74 | $M_w$ | 18* | 1000* | $r_{rup}$ | C | D50 | 1M | A | VH |
| Hassani et al. (2017) | Iran[80] | 806 | - | 330 | 4.0 | 7.3 | $M_w$ ($m_b$, $M_s$, $M_L$) | 1* | 280* | $r_{epi}$ | 3 | L | 1M | A | ISO |
| Oth et al. (2017) | Japan | 118102 | - | 1905 | 2.7 | 7.2 | $M_w$ | 0.8* | 250 | $r_{hypo}$ ($r_{rup}$ for $M_w \geq 6$) | 1 | G | 1M | A | JMA |
| Sandıkkaya and Akkar (2017) | Europe & Middle East | 1041 | - | 221 | 4.0 | 7.6 | $M_w$ | 0 | 200 | $r_{jb}$, $r_{epi}$ & $r_{hypo}$ | C | G | 1M | A (S, N, R) | AI, CAV, RSD |
| Sedaghati and Pezeshk (2017) | Iran | 688 | 688 | 152 | 4.7 | 7.4 | $M_w$ | 1* | 250* | $r_{jb}$ | C | 1M | G | A | PGV |
| Ameur et al. (2018) | Worldwide shallow crustal | 2335 | - | 137 | 3.2[81] | 7.9[82] | $M_w$ | 0.01[83] | 358[84] | $r_{jb}$ | C | G | O | A | PGV |
| Baumont et al. (2018) | France + Italy | U | - | 30 + 11 | 3.6 | 7.1 | $M_w$ | U | U | $r_{hypo}$ | 1 | - | 1M | A | MI |
| Bayless and Abrahamson (2018, 2019) | Worldwide shallow crustal | 13346 | - | 232 | 4.0* | 7.9* | $M_w$ | 0.2* | 300* | $r_{rup}$ | C | Q | 1M | A (N) | FSA |

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[80] Also develop separate models for Zagros and Alborz-central Iran.
[81] Believe applicable $\geq 3.6$.
[82] Believe applicable $\leq 7.6$.
[83] Believe applicable $\geq 6$ km.
[84] Believe applicable $\leq 200$ km.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Chousianitis et al. (2018) | Greece | 652 | - | 72 | 4.0* | 6.8 | $M_w$ | 0.3* | 200* | $r_{epi}$ | 2 | G | 2M | A (R/S, N) | PGV, MP, CAV |
| Ganas et al. (2018) | Greece | 64 | - | 11 | 5.5 | 6.9 | $M_w$ | 2 | 132 | $r_{hypo}$ | 1 | A, V | O | A | PGD |
| Javan-Emrooz et al. (2018) | N Iran, E Turkey, Armenia & Georgia | 463 | 463 | 107 | 4.5 | 7.4 | $M_w$ ($m_b$) | 2 | 100 | $r_{epi}$ | 2 | V | O | A (R, S) | PGV, PGD |
| Mahani and Kao (2018) | Graham and Septimus areas (BC, Canada) | U, U | - | 129, 90 | 1.5, 1.5 | 3.8, 3.0 | $M_L$ | 2.3, 1.6 | 19, 42 | $r_{hypo}$ | 1 | G | 1M | W | PGV, FAS |
| Sharma and Convertito (2018) | The Geysers, USA | 261711 | - | 10974 | 0.7 | 3.3 | $M_w$ ($M_D$) | 0.1 | 73 | $r_{hypo}$ | I | L | 1M | G | PGV |
| Shoushtari et al. (2018) | Japan + Malay Peninsula | 651 + 77 | - | 11 + 14 | 5.0 + 6.7 | 9.1 + 9.0 | $M_w$ | 120* + 500* | 1300* + 1000* | $r_{hypo}$ | 4 | G | 1 | F | PGV |
| Yaghmaei-Sabegh (2018) | Iran | 560 | - | 113 | 4.1 | 7.4 | $M_w$ | 1 | 405 | $r_{epi}$ | 1 | - | 1 | A | MI |
| Zafarani et al. (2018) | Iran | 1551 | - | 200 | 4.0 | 7.3 | $M_w$ ($M_L$) | 0.6* | 200* | $r_{jb}$ ($r_{epi}$) | 4 | G | 1M | A (R, S, U) | VH |
| Ahmadzadeh et al. (2019) | Iran | 111[85] | - | 31 | 5.1 | 7.4 | $M_w$ | 2.51 | 125.52[86] | $r_{epi}$ | 1 | - | 1 | A | MI |
| Bindi et al. (2019) | Europe & Middle East | 2767–18859 | - | U–2179 | 3.5 | 7.8 | $M_w$ ($M_L$) | 1.5* | 300* | $r_{hypo}$ | I | G | 1M | A | FSA |
| Campbell and Bozorgnia (2019) | Worldwide shallow crustal | 15521 | - | 322 | 3.0[87] | 7.9[88] | $M_w$ | 0* | 300* | $r_{rup}$ | C | G | 1M | A (S, R, N, HW) | AI, CAV |
| Darzi et al. (2019) | Iran | 1350 | - | 370 | 4.5 | 7.4 | $M_w$ ($M_s$, $m_b$) | 1* | 200* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ & $r_{rup}$ | 3 | G | 2M | A (S, R, U) | PGV |
| Huang and Galasso (2019) | Italy | 7843 | - | 233 | 4.0 | 6.9 | $M_w$ | 1* | 250* | $r_{jb}$ | 3 | D50 | O | A (R, S, N) | PGV |
| Lanzano et al. (2019a,b) | Italy + 12 foreign events | 4965 + 823[89] | - | 144 + 12 | 3.5 + 6.07 | 6.87 + 8.0 | $M_w$ | 0* | 200* | $r_{jb}$ ($r_{epi}$ for $M < 5.5$), $r_{rup}$ ($r_{hypo}$ for $M < 5.5$) | C | D50 | 1M | A (N, R, S) | PGV |

*continued on next page*

[85] Isoseismals not intensity data points.

[86] Table 1 includes a radius of 171.98 km but this looks like a typo.

[87] State model applicable for $M_w \geq 3.3$ in California and $M_w \geq 5.5$ globally.

[88] State model applicable to $M_w 8.5$ for strike-slip, $M_w 8$ for reverse/reverse-oblique and $M_w 7.5$ for normal/normal-oblique.

[89] This is the total in the Electronic Supplement listing all the data used. In the article it is stated that 5607 records from 146 earthquakes are used.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Podili and Raghukanth (2019) | Japan | 96880 | - | 1340 | 5.0 | 9.0 | $M_w$ | 5 | 350 | $r_{rup}$ ($r_{hypo}$ for some) | C | A | 2 | A (S, R, N, U, B, C) | AI, CAV, PGV, PGD, RSD, VH |
| Quadros et al. (2019) | Brazil | 497 | - | 20 | 3.5 | 6.2 | $m_b$ | 5* | 720* | $r_{hypo}$ | 1 | - | 1 | A | MI |
| Ruhl et al. (2019) | Worldwide | 3433 | 3433 | 29 | 6.0 | 9.0 | $M_w$ | 7* | 1000* | $r_{hyp}$ | 1 | V3 | 1W | A | PGD |
| Xu et al. (2019) | Taiwan (shallow + deep) | 17171 + 7496 | - | 310 | 4.8 | 7.9 | $M_w$ | 1* | 200* | $r_{epi}$ | C + 5 | G | 1M | C, B | CAV |
| Zolfaghari and Darzi (2019a) | Iran | - | 1350 | 370 | 4.5 | 7.4 | $M_w$ ($M_s$, $m_b$) | 1* | 200* | $r_{epi}$, $r_{hypo}$, $r_{jb}$ & $r_{rup}$ | 3 | - | 2M | A (S, R, U) | PGV |
| Zolfaghari and Darzi (2019b) | Iran | 1350 | 1350 | 370 | 4.5 | 7.4 | $M_w$ | 1.5* | 200* | $r_{epi}$, $r_{hypo}$, $r_{rup}$, $r_{jb}$ | 3 | G | 1M | A (R, S) | VH |
| Bullock et al. (2020) | Worldwide shallow crustal | 10093 | - | U | 3.0* | 7.9* | $M_w$ | 0* | 300* | $r_{rup}$ | C | D50 | 2M | A (R, S, N) | CAV |
| Chao et al. (2020) | Taiwan | 40892 | - | 316 | 3.5 | 7.6[90] | $M_w$ | 0.07 | 437.10 | $r_{rup}$ | C | D50 | O | A (N, S, R, F, B, AS) | PGV, PGD |
| Cremen et al. (2020) | Lancashire + N. Nottinghamshire (UK) | 195+192 | - | 29+48 | (0.1*) | (2.9*) | $M_w$ ($M_L$) | 1.5* | 7* | $r_{hypo}$ | 1 | G | O | E + M | PGV |
| Huang et al. (2020) | Italy | 5703 | - | 138 | 4.0 | 6.5 | $M_w$ | 1* | 220* | $r_{jb}$ ($r_epi$) | 3 | D50 | O | A (R, S, N) | RSD, CAV, AI |
| Jaimes and García-Soto (2020) | Mexico | 366 | 366 | 23 | 5.2 | 8.2 | $M_w$ | 22 | 400 | $r_{rup}$ for $M_w > 6.5$, $r_{hypo}$ otherwise | 1 | G[91] | 1M | B | PGV, VH |
| Kotha et al. (2020) | Europe & Mediterranean | 18222 | - | 927 | 3.0 | 7.4 | $M_w$ | 0 | 545 | $r_{jb}$ ($r_{epi}$) | I | D50 | O | A | PGV |
| Lanzano and Luzi (2020) | Volcanic areas, Italy | 615 | - | 41 | 3.0 | 4.9 | $M_w$ ($M_L$) | 2* | 200* | $r_{hypo}$ | 3 | G | 1M | V | PGV |
| Matsu'ura et al. (2020) | Japan | 33788 | - | 78 | 5.4 | 8.7 | $M_w$ | 6* | 1000* | $r_{hypo}$ | C | U | O | F, I, C | JMA |
| Tusa et al. (2020) | Mt Etna, Italy | 1600 | 1600 | 49 | 3.0 | 4.8 | $M_L$ | 0.5 | 100 | $r_{hypo}$ | 3 | G | 1M | V | PGV |

*continued on next page*

[90] Believe model applicable up to 8.0 for crustal and intraslab events and 9.0 for interface events.
[91] Call it 'quadratic mean', which is assumed to be geometric mean.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Abdelfattah et al. (2021) | Jazan (Saudi Arabia) | 638 | - | 72 | 2.0 | 5.1 | $M_L$ | 4 | 200* | $r_{hypo}$ | 1 | A | 1 | A | PGV |
| Bahrampouri et al. (2021a) | Japan | 17077 crustal, 21159 subduction | - | 984 crustal, 1028 subduction | 4 | 7.5* crustal, 9.0* subduction | $M_w$ | 2* | 1000* | $r_{rup}$ | C | G | 1M | C, (F, I) | AI |
| Bahrampouri et al. (2021b) | Japan | 22111 crustal, 74820 subduction | - | 873 crustal, 2249 subduction | 4 | 7.5* crustal, 9.0* subduction | $M_w$ | 2* | 500* | $r_{rup}$ | C | G | 1M | C, (F, I) | RSD |
| Boore et al. (2021) | Greece | 1500* | - | 150* | 4.0* | 7.0* | $M_w$ | 0.1* | 300* | $r_{jb}$ | C | D50 | O | A (S, R, N) | PGV |
| Fang et al. (2021) | Worldwide | 1434 | 1434 | 22 | 6.0 | 9.1 | $M_w$ | 10* | 1000* | $r_{hypo}$ | 1 | V3 | 1 | A | PGV |
| Huang et al. (2021a) | N. Italy | 2427 | - | 85 | 4.0 | 6.4 | $M_w$ | 1* | 200* | $r_{jb}$ | 4 | G | O | A (N, T, U) | ISO |
| Jaimes and García-Soto (2021) | Mexico | 418, 366 | - | 40, 23 | 5.0, 5.2 | 8.0, 8.2 | $M_w$ | 17, 22 | 400, 400 | $r_{rup}$ | 1 | Q | 1M | F, B | RSD |
| Lanzano et al. (2021) & Caramenti et al. (2022) | Italy | 4784 | - | 137 | 3.5 | 6.9 | $M_w$ | 0.3* | 200* | $r_{jb}$ | C | D50 | O | A (N, R, S) | PGV |
| Ramadan et al. (2021) | Italy + foreign | 5778 | 5778 | 156 | 3.5 | 8.0 | $M_w$ | 0* | 200* | $r_{jb}$ | C | D50 | 1M | A (N, R, S) | VH |
| Allen (2022) | N. Australia | U | - | U | 5.3* | 7.6*[92] | $M_w$ | 75*[93] | 1750*[94] | $r_{hypo}$ | C | G | O | B, F | PGV |
| Bommer et al. (2022) | Groningen, Netherlands | 1787 | - | 76 | 1.8 | 3.6 | $M_L$ | 0* | 36* | $r_{epi}$ | C | G, L, R, V | 1M | E | PGV |
| Céspedes et al. (2022) | Chile | 1048 | - | 288 | 4.5 | 8.8 | $M_w$ | 22.1 | 1026 | $r_{rup}$ | 2 | A, G | O | Z (B, F) | AI, RSD |
| Convertito et al. (2022) | The Geysers (USA), St Gallen (Switzerland) | U | - | 745, 346 | 0.3, -1.2 | 2.7, 3.5 | $M_w$ | 1*, 5* | 15*, 15* | $r_{hypo}$ | 1 | U | 1 | G | PGV |
| Miyazawa et al. (2022) | NE Japan | 213, 159 | - | 3, 2 | 7.51, 8.3 | 7.81, 9.1 | 50* | 300* | $r_{SMGA}$, $r_{rup}$ | 1 | D50 | 1M | F | PGV | |

*continued on next page*

[92]Recommend model up to $M_w 8$.
[93]Recommend model from 500 km.
[94]Recommend model to 1500 km.

Table 7.1: *continued*

| Reference | Area | H | V | E | $M_{\min}$ | $M_{\max}$ | $M$ scale | $r_{\min}$ | $r_{\max}$ | $r$ scale | S | C | R | M | IM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zhang et al. (2022) | SW China | 1324 | - | 70 | 4.2 | 7.9[95] | $M_w$ | 0.06[96] | 299.95[97] | $r_{rup}$ | C | D50 | 1M | A (N, S, R) | PGV |
| Campbell and Bozorgnia (2023) | Worldwide shallow crustal | 8985 | - | <322 | 3.0 | 7.9 | $M_w$ | 0.05 | 300 | $r_{rup}$ | C | D50 | O, 1M | A (N, R, S) | SI |
| Gogoi et al. (2023) | NE India | 113 | 113 | 24 | 4.4 | 6.8 | $M_w$ (unknown) | 20 | 525 | $r_{epi}$ | 1 | EW, NS, All | 1 | A | AI, CAV, PGV, SI |
| Khansefid et al. (2023) | Worldwide geothermal sites | 664 | 664 | 110 | 2.8*[98] | 5.6*[99] | $M_w$ ($M_L$, $M_D$) | 1* | 150*[100] | $r_{hypo}$ | C | U | 1M | G | AI, PGV, RSD, VH |
| Lavrentiadis et al. (2023) | California | 8916 | - | 188 | 3.1 | 7.3 | $M_w$ | 0.1 | 300 | $r_{rup}$ | C | G | O | A | FSA |
| Meimandi-Parizi et al. (2023) | Iran | 2228 | - | 749 | 4.5 | 7.6 | $M_w$ | 5* | 190* | $r_{rup}$ | C | G | 1M | A (N, R, S) | FSA |
| Zafarani and Soghrat (2023) | Iran | 2383 | - | 589 | 3.5* | 7.7* | $M_w$ | 1* | 300* | $r_{jb}$ | C | G | 1M | A (R, S, U) | AI, CAV, RSD |

[95] Recommend model for $M_w \leq 6.1$ for strike-slip, $M_w \leq 7.9$ for reverse and $M_w \leq 6.5$ for normal faulting.
[96] Recommend model from 10 km.
[97] Recommend model to 200 km.
[98] Recommend for use to $M_w 2.5$.
[99] Recommend for use to $M_w 5.5$.
[100] Recommend for use to 100 km.

# Bibliography


J. A. Abdalla, Y. E.-A. Mohamedzein, and A. A. Wahab. Probabilistic seismic hazard assessment of Sudan and its vicinity. *Earthquake Spectra*, 17(3), Aug 2001.

A. K. Abdelfattah, A. Al-amri, K. Abdelrahman, M. Fnais, and S. Qaysi. Attenuation relationships of peak ground motions in the jazan region. *Arabian Journal of Geosciences*, 14(139), 2021. doi: 10.1007/s12517-020-06442-z.

N. Abrahamson and W. Silva. Summary of the Abrahamson & Silva NGA ground-motion relations. *Earthquake Spectra*, 24(1):67–97, 2008. doi: 10.1193/1.2924360.

N. Abrahamson and W. Silva. Errata for "Summary of the Abrahamson and Silva NGA ground-motion relations" by Abrahamson, N. A. and W. J. Silva. Published on PEER NGA website, Aug 2009.

N. Abrahamson, N. Gregor, and K. Addo. BC Hydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra*, 32(1):23–44, Feb 2016. doi: 10.1193/051712EQS188MR.

N. Abrahamson, N. Kuehn, Z. Gulerce, N. Gregor, Y. Bozorgnia, G. Parker, J. Stewart, B. Chiou, I. M. Idriss, K. Campbell, and R. Youngs. Update of the BC Hydro subduction ground-motion model using the NGA-Subduction dataset. Technical Report 2018/02, Pacific Earthquake Engineering Research Center, Jun 2018.

N. A. Abrahamson and J. J. Litehiser. Attenuation of vertical peak acceleration. *Bulletin of the Seismological Society of America*, 79(3):549–580, Jun 1989.

N. A. Abrahamson and K. M. Shedlock. Overview. *Seismological Research Letters*, 68(1):9–23, Jan/Feb 1997.

N. A. Abrahamson and W. J. Silva. Attenuation of long period strong ground motions. In *Proceedings of Conference of American Society of Mechanical Engineers*, 1993.

N. A. Abrahamson and W. J. Silva. Empirical ground motion models. Technical report, 1996. Report to Brookhaven National Laboratory. Cited in Stewart et al. (2001).

N. A. Abrahamson and W. J. Silva. Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters*, 68(1):94–127, Jan/Feb 1997.

N. A. Abrahamson and W. J. Silva. Hybrid model — empirical attenuation relations for central and eastern U.S. hard and soft rock and deep soil site conditions. In *CEUS Ground Motion Project Workshop*, Sep 2002. Not seen. Cited in Electric Power Research Institute (2004). Only a presentation. Never officially published.

N. A. Abrahamson and R. R. Youngs. A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America*, 82(1):505–510, Feb 1992.

N. A. Abrahamson, W. J. Silva, and R. Kamai. Update of the AS08 ground-motion prediction equations based on the NGA-West2 data set. Technical Report 2013/04, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2013.

N. A. Abrahamson, W. J. Silva, and R. Kamai. Summary of the ASK14 ground motion relation for active crustal regions. *Earthquake Spectra*, 30(3):1025–1055, Aug 2014. doi: 10.1193/070913EQS198M.

T. Ader, M. Chendorain, M. Free, T. Saarno, P. Heikkinen, P. E. Malin, P. Leary, G. Kwiatek, G. Dresen, F. Blümle, and T. Vuorinen. Setting up traffic light system thresholds for geothermal stimulation in Helsinki, Finland. In *2019 SECED Conference*, Sep 2019.

M. D. Adhikari and S. K. Nath. Site-specific next generation ground motion prediction models for Darjeeling-Sikkim Himalaya using strong motion seismometry. *Journal of the Indian Geophysical Union*, 20(2):151–170, Apr 2016.

A. Adnan and M. Suhatril. Derivation of attenuation equations for distant earthquake (sic) suitable for malaysia. Technical Report VOT 78266, Pusat Pengurusan Penyelidikan, Universiti Teknologi Malaysia, 2009.

A. Adnan, Hendriyawan, A. Marto, and M. Irsyam. Selection and development of appropriate attenuation relationship for Peninsular Malaysia. In *Proceedings of the Malaysian Science Technology Congress*, Kuala Lumpur, Malaysia, 2005. Not seen. Cited in Shoushtari et al. (2016).

K. Afshari and J. P. Stewart. Physically parameterized prediction equations for significant duration in active crustal regions. *Earthquake Spectra*, 32(4):2057–2081, 2016. doi: 10.1193/063015EQS106M.

H. Aghabarati and M. Tehranizadeh. Near-source attenuation relationship for the geometric mean horizontal component of peak ground acceleration and acceleration response spectra. *Asian Journal of Civil Engineering (Building and Housing)*, 9(3):261–290, 2008.

H. Aghabarati and M. Tehranizadeh. Near-source ground motion attenuation relationship for PGA and PSA of the vertical and horizontal components. *Bulletin of Earthquake Engineering*, 7(3):609–635, 2009. doi: 10.1007/s10518-009-9114-9.

K. Ágústsson, B. Þorbjarnardóttir, and K. Vogfjörð. Seismic wave attenuation for earthquakes in SW Iceland: First results. Technical Report 08005, Veðurstofa Íslands (Icelandic Meteorological Office), Apr 2008.

I. Ahmad, M. H. El Naggar, and A. N. Khan. Neural network based attenuation of strong motion peaks in Europe. *Journal of Earthquake Engineering*, 12(5):663–680, 2008. doi: 10.1080/13632460701758570.

S. Ahmadzadeh, G. J. Doloei, and H. Zafarani. New intensity prediction equation for Iran. *Journal of Seismology*, 2019. doi: 10.1007/s10950-019-09882-7.

L. Ahorner and W. Rosenhauer. Probability distribution of earthquake accelerations for the sites in Western Germany. In *Proceedings of Fifth European Conference on Earthquake Engineering*, 1975. Not seen. Reported in Makropoulos and Burton (1985).

M. Akhani and S. Pezeshk. Using metaheuristic algorithms to optimize a mixed model-based ground-motion prediction model and associated variance components. *Journal of Seismology*, 26:483–498, 2022. doi: 10.1007/s10950-022-10091-y.

A. Akinci, L. Malagnini, R. B. Herrmann, N. A. Pino, L. Scognamiglio, and H. Eyidogan. High-frequency ground motion in the Erzincan region, Turkey: Inferences from small earthquakes. *Bulletin of the Seismological Society of America*, 91(6):1446–1455, Dec 2001.

A. Akinci, L. Malagnini, R. B. Herrmann, R. Gok, and M. B. Sørensen. Ground motion scaling in the Marmara region, Turkey. *Geophysical Journal International*, 166(2):635–651, 2006. doi: 10.1111/j.1365-246X.2006.02971.x.

A. Akinci, S. D'Amico, L. Malagnini, and A. Mercuri. Scaling earthquake ground motions in western Anatolia, Turkey. *Physics and Chemistry of the Earth, Parts A/B/C*, 63:124–135, 2013. doi: 10.1016/j.pce.2013.04.013.

A. Akinci, L. Malagnini, R. B. Herrmann, and D. Kalafat. High-frequency attenuation in the Lake Van region, eastern Turkey. *Bulletin of the Seismological Society of America*, 104(3):1400–1409, May 2014. doi: 10.1785/0120130102.

S. Akkar and J. J. Bommer. Influence of long-period filter cut-off on elastic spectral displacements. *Earthquake Engineering and Structural Dynamics*, 35(9):1145–1165, Jul 2006.

S. Akkar and J. J. Bommer. Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East. *Bulletin of the Seismological Society of America*, 97(2):511–530, Apr 2007a. doi: 10.1785/0120060141.

S. Akkar and J. J. Bommer. Prediction of elastic displacement response spectra in Europe and the Middle East. *Earthquake Engineering and Structural Dynamics*, 36(10):1275–1301, 2007b. doi: 10.1002/eqe.679.

S. Akkar and J. J. Bommer. Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean region and the Middle East. *Seismological Research Letters*, 81(2):195–206, Mar/Apr 2010.

S. Akkar and Z. Çağnan. A local ground-motion predictive model for Turkey and its comparison with other regional and global ground-motion models. *Bulletin of the Seismological Society of America*, 100(6):2978–2995, Dec 2010.

S. Akkar, Z. Çağnan, E. Yenier, Ö Erdoğan, A. Sandıkkaya, and P. Gülkan. The recently compiled Turkish strong-motion database: Preliminary investigation for seismological parameters. *Journal of Seismology*, 14 (3):457–479, 2010. doi: 10.1007/s10950-009-9176-9.

S. Akkar, M. A. Sandıkkaya, and B. Ö Ay. Compatible ground motion prediction equations for damping scaling factors and vertical-to-horizontal spectral amplitude ratios for the broader Europe region. *Bulletin of Earthquake Engineering*, 12:517—-547, 2014a. doi: 10.1007/s10518-013-9537-1.

S. Akkar, M. A. Sandıkkaya, and J. J. Bommer. Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bulletin of Earthquake Engineering*, 12 (1):359–387, 2014b. doi: 10.1007/s10518-013-9461-4.

S. Akkar, M. A. Sandıkkaya, and J. J. Bommer. Erratum to: Empirical ground-motion models for point- and extended-source crustal earthquake scenarios in Europe and the Middle East. *Bulletin of Earthquake Engineering*, 12(1):389–390, 2014c. doi: 10.1007/s10518-013-9508-6.

S. Akkar, M. A. Sandıkkaya, M. Şenyurt, A. S. Azari, B. Ö Ay, P. Traversa, J. Douglas, F. Cotton, L. Luzi, B. Hernandez, and S. Godey. Reference database for seismic ground-motion in Europe (RESORCE). *Bulletin of Earthquake Engineering*, 12(1):311–339, 2014d. doi: 10.1007/s10518-013-9506-8.

S. Akkar, Ö Kale, M. A. Sandıkkaya, and E. Yenier. A procedure to develop a backbone ground-motion model: A case study for its implementation. *Earthquake Spectra*, 37(4):2523–2544, 2021. doi: 10.1177/87552930211014541.

N. Akyol and Ö Karagöz. Empirical attenuation relationships for western Anatolia, Turkey. *Turkish Journal of Earth Sciences*, 18:351–382, 2009. doi: 10.3906/yer-0705-2.

L. Al Atik and R. R. Youngs. Epistemic uncertainty for NGA-West2 models. *Earthquake Spectra*, 30(3):1301–1318, Aug 2014. doi: 10.1193/062813EQS173M.

A. S. Al-Homoud and A.-Q. Fandi Amrat. Comparison between recorded and derived horizontal peak ground accelerations in Jordan. *Natural Hazards*, 17:101–115, 1998.

M. Y. Al-Qaryouti. Attenuation relations of peak ground acceleration and velocity in the Southern Dead Sea Transform region. *Arabian Journal of Geosciences*, 1(2):111–117, Oct 2008. doi: 10.1007/s12517-008-0010-4.

J. E. Alarcón. Relaciones de atenuación a partir de espectros de respuesta para Colombia. In *Proceedings of the Second Colombian Conference on Earthquake Engineering*, 2003. In Spanish.

J. E. Alarcón. *Estimation of duration, number of cycles, peak ground velocity, peak ground acceleration and spectral ordinates for engineering design.* PhD thesis, University of London, Apr 2007.

A. H. Alavi, A. H. Gandomi, M. Modaresnezhad, and M. Mousavi. New ground-motion prediction equations using multi expression programing. *Journal of Earthquake Engineering*, 15(4):511–536, 2011. doi: 10.1080/13632469.2010.526752.

B. Alavi and H. Krawinkler. Consideration of near-fault ground motion effects in seismic design. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000.

A. Alchalbi, G. Costa, and P. Suhadolc. Strong motion records from Syria: A preliminary analysis. In *Skopje Earthquake 40 Years of European Earthquake Engineering (SE-40EEE)*, Aug 2003.

A. Aldea, R. Vacareanu, D. Lungu, F. Pavel, and C. Arion. GMPEs for Romania's Vrancea intermediate depth seismic source. In *Progresses in European Earthquake Engineering and Seismology. ECEES 2022*, pages 90–108. Springer, Cham, 2022. doi: 10.1007/978-3-031-15104-0_6.

C. S. Alfaro, A. S. Kiremidjian, and R. A. White. Seismic zoning and ground motion parameters for El Salvador. Technical Report 93, The John A. Blume Earthquake Engineering Center, Stanford University, 1990. Not seen. Reported in Bommer et al. (1996).

S. T. Algermissen, S. L. Hansen, and P. C. Thenhaus. Seismic hazard evaluation for El Salvador. Technical report, Report for the US Agency for International Development, 1988. Not seen. Reported in Bommer et al. (1996).

F. S. Alıcı and H. Sucuoğlu. Prediction of input energy spectrum: attenuation models and velocity spectrum scaling. *Earthquake Engineering and Structural Dynamics*, 45(13):2137–2161, Oct 2016. doi: 10.1002/eqe.2749.

T. I. Allen. Stochastic ground-motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters. Technical Report 2012/69, Geoscience Australia, Canberra, 2012.

T. I. Allen. A far-field ground-motion model for the north Australian craton from plate-margin earthquakes. *Bulletin of the Seismological Society of America*, 112(2):1041–1059, 2022. doi: 10.1785/0120210191.

T. I. Allen, T. Dhu, P. R. Cummins, and J. F. Schneider. Empirical attenuation of ground-motion spectral amplitudes in southwestern Western Australia. *Bulletin of the Seismological Society of America*, 96(2):572–585, Apr 2006.

T. I. Allen, D. J. Wald, and C. B. Worden. Intensity attenuation for active crustal regions. *Journal of Seismology*, 16(3):409–433, 2012. doi: 10.1007/s10950-012-9278-7.

A. Aman, U. K. Singh, and R. P. Singh. A new empirical relation for strong seismic ground motion for the Himalayan region. *Current Science*, 69(9):772–777, Nov 1995.

N. Ambraseys. Ground motions in the near field of small-magnitude earthquakes. In *Proceedings of the Commission on the Safety of Nuclear Installations, Organisation of Economic Cooperation in Europe*, volume 1, pages 113–136, Paris, 1975a. Not seen. Reported in Ambraseys (1978a).

N. Ambraseys and J. Douglas. Reappraisal of the effect of vertical ground motions on response. ESEE Report 00-4, Department of Civil and Environmental Engineering, Imperial College, London, Aug 2000.

N. Ambraseys, P. Smit, R. Berardi, D. Rinaldis, F. Cotton, and C. Berge. Dissemination of European Strong-Motion Data. CD-ROM collection, 2000. European Commission, Directorate-General XII, Environmental and Climate Programme, ENV4-CT97-0397, Brussels, Belgium.

N. N. Ambraseys. Trends in engineering seismology in Europe. In *Proceedings of Fifth European Conference on Earthquake Engineering*, volume 3, pages 39–52, 1975b.

N. N. Ambraseys. Middle East — a reappraisal of seismicity. *The Quarterly Journal of Engineering Geology*, 11 (1):19–32, 1978a.

N. N. Ambraseys. Preliminary analysis of European strong-motion data 1965–1978. *Bulletin of the European Association of Earthquake Engineering*, 4:17–37, 1978b.

N. N. Ambraseys. Uniform magnitude re-evaluation of European earthquakes associated with strong-motion records. *Earthquake Engineering and Structural Dynamics*, 19(1):1–20, Jan 1990.

N. N. Ambraseys. The prediction of earthquake peak ground acceleration in Europe. *Earthquake Engineering and Structural Dynamics*, 24(4):467–490, Apr 1995.

N. N. Ambraseys and J. J. Bommer. The attenuation of ground accelerations in Europe. *Earthquake Engineering and Structural Dynamics*, 20(12):1179–1202, 1991.

N. N. Ambraseys and J. J. Bommer. On the attenuation of ground accelerations in Europe. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 2, pages 675–678, 1992.

N. N. Ambraseys and J. J. Bommer. Attenuation relations for use in Europe: An overview. In A. S. Elnashai, editor, *Proceedings of Fifth SECED Conference on European Seismic Design Practice*, pages 67–74, 1995.

N. N. Ambraseys and J. Douglas. Near-field horizontal and vertical earthquake ground motions. *Soil Dynamics and Earthquake Engineering*, 23(1):1–18, 2003.

N. N. Ambraseys and K. A. Simpson. Prediction of vertical response spectra in Europe. *Earthquake Engineering and Structural Dynamics*, 25(4):401–412, 1996.

N. N. Ambraseys and M. Srbulov. Attenuation of earthquake-induced ground displacements. *Earthquake Engineering and Structural Dynamics*, 23(5):467–487, 1994.

N. N. Ambraseys, J. J. Bommer, and S. K. Sarma. A review of seismic ground motions for UK design. ESEE Report 92-8, Department of Civil Engineering, Imperial College, London, Nov 1992.

N. N. Ambraseys, K. A. Simpson, and J. J. Bommer. Prediction of horizontal response spectra in Europe. *Earthquake Engineering and Structural Dynamics*, 25(4):371–400, 1996.

N. N. Ambraseys, P. Smit, J. Douglas, B. Margaris, R. Sigbjörnsson, S. Ólafsson, P. Suhadolc, and G. Costa. Internet site for European strong-motion data. *Bollettino di Geofisica Teorica ed Applicata*, 45(3):113–129, Sep 2004.

N. N. Ambraseys, J. Douglas, S. K. Sarma, and P. M. Smit. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, 3(1):1–53, 2005a. doi: 10.1007/s10518-005-0183-0.

N. N. Ambraseys, J. Douglas, S. K. Sarma, and P. M. Smit. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Vertical peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, 3(1):55–73, 2005b. doi: 10.1007/s10518-005-0186-x.

G. Ameri, S. Drouet, P. Traversa, D. Bindi, and F. Cotton. Toward an empirical ground motion prediction equation for France: accounting for regional differences in the source stress parameter. *Bulletin of Earthquake Engineering*, 15(11):4681–4717, Nov 2017. doi: 10.1007/s10518-017-0171-1.

M. Ameur, B. Derras, and D. Zendagui. Ground motion prediction model using adaptive neuro-fuzzy inference systems: An example based on the NGA-West 2 data. *Pure and Applied Geophysics*, 175(3):1019–1034, 2018. doi: 10.1007/s00024-017-1743-3.

G. G. Amiri, A. Mahdavian, and F. M. Dana. Attenuation relationships for Iran. *Journal of Earthquake Engineering*, 11(4):469—-492, 2007a. doi: 10.1080/13632460601034049.

G. G. Amiri, A. Mahdavian, and F. M. Dana. Response on the Discussion of 'Attenuation relationships for Iran'. *Journal of Earthquake Engineering*, 11(6):1036—-1037, 2007b. doi: 10.1080/13632460701647476.

G. G. Amiri, M. Khorasani, R. M. Hessabi, and S. A. R. Amrei. Ground-motion prediction equations of spectral ordinates and Arias intensity for Iran. *Journal of Earthquake Engineering*, 14(1):1–29, 2009. doi: 10.1080/13632460902988984.

P. Anbazhagan, A. Kumar, and T. G. Sitharam. Ground motion prediction equation considering combined dataset of recorded and simulated ground motions. *Soil Dynamics and Earthquake Engineering*, 53:92–108, 2013. doi: 10.1016/j.soildyn.2013.06.003.

T. D. Ancheta, R. B. Darragh, J. P. Stewart, E. Seyhan, W. J. Silva, B. S. J. Chiou, K. E. Wooddell, R. W. Graves, A. R. Kottke, D. M. Boore, T. Kishida, and J. L. Donahue. NGA-West2 database. *Earthquake Spectra*, 30(3):989–1005, Aug 2014. doi: 10.1193/070913EQS197M.

J. G. Anderson. Nonparametric description of peak acceleration above a subduction thrust. *Seismological Research Letters*, 68(1):86–93, Jan/Feb 1997.

J. G. Anderson and S. E. Hough. A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. *Bulletin of the Seismological Society of America*, 74(5):1969–1993, Oct 1984.

J. G. Anderson and Y. Lei. Nonparametric description of peak acceleration as a function of magnitude, distance, and site in Guerrero, Mexico. *Bulletin of the Seismological Society of America*, 84(4):1003–1017, 1994.

J. G. Anderson and Y. Uchiyama. A methodology to improve ground-motion prediction equations by including path corrections. *Bulletin of the Seismological Society of America*, 101(4):1822–1846, 2011. doi: 10.1785/0120090359.

T. Annaka and Y. Nozawa. A probabilistic model for seismic hazard estimation in the Kanto district. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 107–112, 1988.

A. M. Ansal. Istanbul icin tasarim deprem ozelliklerinin belirlenmesi. In *Proceedings of Prof. Dr. Rifat Yarar Symposium*, volume 1, pages 233–244, 1997. In Turkish. Not seen. Cited in Güllü and İyisan (2016).

M. A. Ansary. Engineering characteristics of ground motions recorded by northeast Indian strong motion instrumentation network from 2005 to 2013. In *Proceedings of the Tenth U.S. National Conference on Earthquake Engineering*, Jul 2014.

F. Aptikaev and J. Kopnichev. Correlation between seismic vibration parameters and type of faulting. In *Proceedings of Seventh World Conference on Earthquake Engineering*, volume 1, pages 107–110, 1980.

D. Arroyo and M. Ordaz. On the forecasting of ground-motion parameters for probabilistic seismic hazard analysis. *Earthquake Spectra*, 27(1):1–21, Feb 2011. doi: 10.1193/1.3525379.

D. Arroyo, D. García, M. Ordaz, M. A. Mora, and S. K. Singh. Strong ground-motion relations for Mexican interplate earthquakes. *Journal of Seismology*, 14(4):769–785, Oct 2010. doi: 10.1007/s10950-010-9200-0.

C. A. Arteta, C. A. Pajaro, V. Mercado, J. Montejo, M. Arcila, and N. A. Abrahamson. Ground-motion model (GMM) for crustal earthquakes in northern South America (NoSAm crustal GMM). *Bulletin of the Seismological Society of America*, 113(1):186–203, 2023. doi: 10.1785/0120220168.

A. L. Ashadi and S. I. Kaka. Ground-motion relations for subduction-zone earthquakes in Java island, Indonesia. *Arabian Journal for Science and Engineering*, 44:449–465, 2019. doi: 10.1007/s13369-018-3563-x.

G. M. Atkinson. A comparison of eastern North American ground motion observations with theoretical predictions. *Seismological Research Letters*, 61(3–4):171–180, Jul–Dec 1990.

G. M. Atkinson. The high-frequency shape of the source spectrum for earthquakes in eastern and western Canada. *Bulletin of the Seismological Society of America*, 86(1A):106–112, Feb 1996.

G. M. Atkinson. Empirical ground motion relations for earthquakes in the Cascadia region. *Canadian Journal of Civil Engineering*, 24:64–77, 1997.

G. M. Atkinson. An alternative to stochastic ground-motion relations for use in seismic hazard analysis in eastern North America. *Seismological Research Letters*, 72:299–306, 2001.

G. M. Atkinson. Empirical attenuation of ground-motion spectral amplitudes of southeastern Canada and the northeastern United States. *Bulletin of the Seismological Society of America*, 94(3):1079–1095, Jun 2004.

G. M. Atkinson. Ground motions for earthquakes in southwestern British Columbia and northwestern Washington: Crustal, in-slab, and offshore events. *Bulletin of the Seismological Society of America*, 95(3):1027–1044, Jun 2005. doi: 10.1785/0120040182.

G. M. Atkinson. Single-station sigma. *Bulletin of the Seismological Society of America*, 96(2):446–455, Apr 2006. doi: 10.1785/0120050137.

G. M. Atkinson. Ground-motion prediction equations for eastern North America from a referenced empirical approach: Implications for epistemic uncertainty. *Bulletin of the Seismological Society of America*, 98(3): 1304–1318, Jun 2008. doi: 10.1785/0120070199.

G. M. Atkinson. Ground motion prediction equations for Hawaii from a referenced empirical approach. Final technical report 08HQGR0020, Mar 2009.

G. M. Atkinson. Ground motion prediction equations for Hawaii from a referenced empirical approach. *Bulletin of the Seismological Society of America*, 100(2):751–761, Apr 2010. doi: 10.1785/0120090098.

G. M. Atkinson. An empirical perspective on uncertainty in earthquake ground motion prediction. *Canadian Journal of Civil Engineering*, 38(9):1002–1015, 2011. doi: 10.1139/L10-120.

G. M. Atkinson. Ground-motion prediction equation for small-to-moderate events at short hypocentral distances, with application to induced-seismicity hazards. *Bulletin of the Seismological Society of America*, 105(2A):981–992, Apr 2015. doi: 10.1785/0120140142.

G. M. Atkinson. Backbone ground-motion models for crustal, interface and slab earthquakes in New Zealand. GNS Science Report 2022/11, GNS Science, Lower Hutt, New Zealand, 2022. 61 pp.

G. M. Atkinson. Backbone ground-motion models for crustal, interface, and slab earthquakes in New Zealand from equivalent point-source concepts. *Bulletin of the Seismological Society of America*, 2024. doi: 10.1785/0120230144. In press.

G. M. Atkinson and J. Adams. Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps. *Canadian Journal of Civil Engineering*, 40(10):988–998, 2013. doi: 10.1139/cjce-2012-0544.

G. M. Atkinson and D. M. Boore. Recent trends in ground motion and spectral response relations for North America. *Earthquake Spectra*, 6(1):15–35, Feb 1990.

G. M. Atkinson and D. M. Boore. Ground-motion relations for eastern North America. *Bulletin of the Seismological Society of America*, 85(1):17–30, Feb 1995.

G. M. Atkinson and D. M. Boore. Some comparisons between recent ground-motion relations. *Seismological Research Letters*, 68(1), 1997a.

G. M. Atkinson and D. M. Boore. Stochastic point-source modeling of ground motions in the Cascadia region. *Seismological Research Letters*, 68(1):74–85, 1997b.

G. M. Atkinson and D. M. Boore. Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. *Bulletin of the Seismological Society of America*, 93(4):1703–1729, 2003.

G. M. Atkinson and D. M. Boore. Earthquake ground-motion prediction equations for eastern North America. *Bulletin of the Seismological Society of America*, 96(6):2181–2205, 2006. doi: 10.1785/0120050245.

G. M. Atkinson and D. M. Boore. Modifications to existing ground-motion prediction equations in light of new data. *Bulletin of the Seismological Society of America*, 101(3):1121–1135, Jun 2011. doi: 10.1785/0120100270.

G. M. Atkinson and M. Macias. Predicted ground motions for great interface earthquakes in the Cascadia subduction zone. *Bulletin of the Seismological Society of America*, 99(3):1552–1578, 2009.

G. M. Atkinson and W. Silva. An empirical study of earthquake source spectra for California earthquakes. *Bulletin of the Seismological Society of America*, 87(1):97–113, Feb 1997.

G. M. Atkinson and W. Silva. Stochastic modeling of California ground motion. *Bulletin of the Seismological Society of America*, 90(2):255–274, Apr 2000.

G. M. Atkinson and D. J. Wald. "Did You Feel It?" intensity data: A surprisingly good measure of earthquake ground motion. *Seismological Research Letters*, 78(3):362–368, May/Jun 2007.

G. M. Atkinson, J. J. Bommer, and N. A. Abrahamson. Alternative approaches to modeling epistemic uncertainty in ground motions in probabilistic seismic-hazard analysis. *Seismological Research Letters*, 85(6):1141–1144, Oct 2014a. doi: 10.1785/0220140120.

G. M. Atkinson, C. B. Worden, and D. J. Wald. Intensity prediction equation for North America. *Bulletin of the Seismological Society of America*, 104(6):3084–3093, Dec 2014b. doi: 10.1785/0120140178.

Ö. Aydan. Istanbul Bogazi denizalti gecisi icin tup tünel ile kalkan tünelin uygunlugunun karsilastirilmasi. *Jeoloji Mühendisligi*, 25(1):1–17, 2001. In Turkish. Not seen. Reported in Ulusay et al. (2004).

Ö. Aydan. Inference of seismic characteristics of possible earthquakes and liquefaction and landslide risks from active faults. In *The 6th National Conference on Earthquake Engineering of Turkey*, volume 1, pages 563–574, 2007. Not seen. In Turkish.

Ö. Aydan, M. Sedaki, and R. Yarar. The seismic characteristics of Turkish earthquakes. In *Proceedings of Eleventh World Conference on Earthquake Engineering*, 1996. Paper no. 1270.

C.-E. Baag, S.-J. Chang, N.-D. Jo, and J.-S. Shin. Evaluation of seismic hazard in the southern part of Korea. In *Proceedings of the Second International Symposium on Seismic Hazards and Ground Motion in the Region of Moderate Seismicity*, 1998. Not seen. Reported in Nakajima et al. (2007).

M. Bahrampouri, A. Rodriguez-Marek, and R. A. Green. Ground motion prediction equations for Arias intensity using the Kik-net database. *Earthquake Spectra*, 37(1):428–448, Feb 2021a. doi: 10.1177/8755293020938815.

M. Bahrampouri, A. Rodriguez-Marek, and R. A. Green. Ground motion prediction equations for significant duration using the Kik-net database. *Earthquake Spectra*, 37(2):903–920, May 2021b. doi: 10.1177/8755293020970971.

S. Bai and J. X. Zhao. Ground motion prediction equations for the vertical ground motions from subduction interface earthquakes in Japan using site period or $V_{S30}$ as the site-effect parameters. *Bulletin of the Seismological Society of America*, 112(5):2499–2519, 2022. doi: 10.1785/0120220054.

K. Bajaj and P. Anbazhagan. Determination of GMPE functional form for an active region with limited strong motion data: Application to the Himalayan region. *Journal of Seismology*, 22(1):161–185, 2018. doi: 10.1007/s10950-017-9698-5.

K. Bajaj and P. Anbazhagan. Regional stochastic ground-motion model for low to moderate seismicity area with variable seismotectonic: Application to peninsular India. *Bulletin of Earthquake Engineering*, 17:3661–3680, 2019a. doi: 10.1007/s10518-019-00646-9.

K. Bajaj and P. Anbazhagan. Regional stochastic GMPE with available recorded data for active region — Application to the himalayan region. *Soil Dynamics and Earthquake Engineering*, 126:105825, 2019b. doi: 10.1016/j.soildyn.2019.105825.

W. H. Bakun. Estimating locations and magnitudes of earthquakes in southern California from Modified Mercalli Intensities. *Bulletin of the Seismological Society of America*, 96(4A):1278–1295, Aug 2006a. doi: 10.1785/0120050205.

W. H. Bakun. MMI attenuation and historical earthquakes in the basin and range province of western North America. *Bulletin of the Seismological Society of America*, 96(6):2206–2220, Dec 2006b. doi: 10.1785/0120060045.

W. H. Bakun and O. Scotti. Regional intensity attenuation models for France and the estimation of magnitude and location of historical earthquakes. *Geophysical Journal International*, 164:596–610, 2006.

W. H. Bakun and C. M. Wentworth. Estimating earthquake location and magnitude from seismic intensity data. *Bulletin of the Seismological Society of America*, 87(6):1502–1521, Dec 1997.

W. H. Bakun and C. M. Wentworth. Erratum for "Estimating earthquake location and magnitude from seismic intensity data". *Bulletin of the Seismological Society of America*, 89(2):557, Apr 1999.

W. H. Bakun, A. C. Johnston, and M. G. Hopper. Estimating locations and magnitudes of earthquakes in eastern North America from Modified Mercalli intensities. *Bulletin of the Seismological Society of America*, 93(1):190–202, 2003.

T. Balendra, N. T. K. Lam, J. L. Wilson, and K. H. Kong. Analysis of long-distance earthquake tremors and base shear demand for buildings in singapore. *Engineering Structures*, 24(1):99–108, Jan 2002.

A. S. Baltay, T. C. Hanks, and N. A. Abrahamson. Uncertainty, variability, and earthquake physics in ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 107(4):1754–1772, Aug 2017. doi: 10.1785/0120160164.

S. Baruah, S. Baruah, N. K. Gogoi, O. Erteleva, F. Aptikaev, and J. R. Kayal. Ground motion parameters of Shillong plateau: One of the most seismically active zones of northeastern India. *Earthquake Science*, 22(3): 283–291, Jun 2009. doi: 10.1007/s11589-009-0285-2.

J. Battis. Regional modification of acceleration attenuation functions. *Bulletin of the Seismological Society of America*, 71(4):1309–1321, Aug 1981.

D. Baumont, K. Manchuel, P. Traversa, C. Durouchoux, E. Nayman, and G. Ameri. Intensity predictive attenuation models calibrated in *mw* for metropolitan France. *Bulletin of Earthquake Engineering*, 16(6): 2285–2310, Jun 2018. doi: 10.1007/s10518-018-0344-6.

F. Bay, D. Fäh, L. Malagnini, and D. Giardini. Spectral shear-wave ground-motion scaling in Switzerland. *Bulletin of the Seismological Society of America*, 93(1):414–429, 2003.

J. Bayless and N. A. Abrahamson. An empirical model for Fourier amplitude spectra using the NGA-West2 database. PEER Report 2018/07, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, USA, 2018.

J. Bayless and N. A. Abrahamson. Summary of the BA18 ground-motion model for fourier amplitude spectra for crustal earthquakes in California. *Bulletin of the Seismological Society of America*, 109(5):2088–2105, 2019. doi: 10.1785/0120190077.

BC Hydro. Probabilistic seismic hazard analysis (PSHA) model, volumes 1, 2, 3 and 4. Technical Report E658, BC Hydro Engineering, Nov 2012. Not seen. Cited in Abrahamson et al. (2016).

F. Beauducel, S. Bazin, and M. Bengoubou-Valerius. Loi d'atténuation B-cube pour l'évaluation rapide des intensités sismiques probables dans l'archipel de Guadeloupe. Internal report OVSG-IPGP-UAG, Observatoire Volcanologique et Sismologique de Guadeloupe, Dec 2004.

F. Beauducel, S. Bazin, M. Bengoubou-Val'érius, M.-P. Bouin, A. Bosson, C. Anténor-Habazac, V. Clouard, and J.-B. de Chabalier. Empirical model for rapid macroseismic intensities prediction in Guadeloupe and Martinique/modèle empirique pour la prédiction rapide des intensités macrosismiques en Guadeloupe et Martinique. *Comptes Rendus Geoscience*, 343(11–12):717–728, 2011. doi: 10.1016/j.crte.2011.09.004.

C. Beauval, H. Yepes, W. H. Bakun, J. Egred, A. Alvarado, and J.-C. Singaucho. Locations and magnitudes of historical earthquakes in the Sierra of Ecuador (1587–1996). *Geophysical Journal International*, 181:1613–1633, 2010. doi: 10.1111/j.1365-246X.2010.04569.x.

A. Ben-Menahem, M. Vered, and D. Brooke. Earthquake risk in the Holy Land. *Bollettino di Geofisica Teorica ed Applicata*, XXIV:175–203, 1982. Not seen. Reported in Al-Homoud and Fandi Amrat (1998).

B. Benito and J. M. Gaspar-Escribano. Ground motion characterization and seismic hazard assessment in Spain: Context, problems and recent developments. *Journal of Seismology*, 11(4):433–452, 2007. doi: 10.1007/s10950-007-9063-1.

B. Benito, D. Rinaldis, V. Gorelli, and A. Paciello. Influence of the magnitude, distance and natural period of soil in the strong ground motion. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 2, pages 773–779, 1992.

B. Benito, L. Cabañas, M. E. Jiménez, C. Cabañas, M. López, P. Gómez, and S. Alvarez. Caracterización del movimiento del suelo en emplazamientos de la península ibérica y evaluación del daño potencial en estructuras. proyecto daños. In Consejo de Seguridad Nuclear, editor, *Monografia ref. 19.2000*. 2000. In Spanish. Not seen.

D. Benouar. Magnitude-intensity and intensity-attenuation relationships for Atlas region and Algerian earthquakes. *Earthquake Engineering and Structural Dynamics*, 23(7):717–727, Jul 1994. doi: 10.1002/eqe.4290230703.

C. Berge-Thierry, F. Cotton, O. Scotti, D.-A. Griot-Pommera, and Y. Fukushima. New empirical response spectral attenuation laws for moderate European earthquakes. *Journal of Earthquake Engineering*, 7(2): 193–222, 2003.

G. Bernal, O.-D. Cardona, A. Barbat, and M. Salgado. Strong motion attenuation relationships for Colombia. In *Proceedings of Second European Conference on Earthquake Engineering and Seismology (a joint event of the 15th ECEE & 31st General Assembly of the ESC*, Aug 2014. Paper no. 556.

T. Beyaz. *Development of a new attenuation relationship of seismic energy for Turkey using the strong motion records free of soil effect.* PhD thesis, Ankara University, Turkey, 2004. In Turkish. Cited in Selcuk et al. (2010).

K. Beyer and J. J. Bommer. Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion. *Bulletin of the Seismological Society of America*, 96(4A): 1512–1522, Aug 2006. doi: 10.1785/0120050210.

D. Bindi, L. Luzi, F. Pacor, G. Franceshina, and R. R. Castro. Ground-motion predictions from empirical attenuation relationships versus recorded data: The case of the 1997—1998 Umbria-Marche, central Italy, strong-motion data set. *Bulletin of the Seismological Society of America*, 96(3):984–1002, 2006. doi: 10.1785/0120050102.

D. Bindi, S. Parolai, H. Grosser, C. Milkereit, and E. Durukal. Empirical ground-motion prediction equations for northwestern Turkey using the aftershocks of the 1999 Kocaeli earthquake. *Geophysical Research Letters*, 34(L08305), 2007. doi: 10.1029/2007GL029222.

D. Bindi, L. Luzi, and F. Pacor. Interevent and interstation variability computed for the Italian Accelerometric Archive (ITACA). *Bulletin of the Seismological Society of America*, 99(4):2471–2488, Aug 2009a. doi: 10.1785/0120080209.

D. Bindi, L. Luzi, F. Pacor, F. Sabetta, and M. Massa. Towards a new reference ground motion prediction equation for Italy: Update of the Sabetta-Pugliese (1996). *Bulletin of Earthquake Engineering*, 7(3):591–608, 2009b. doi: 10.1007/s10518-009-9107-8.

D. Bindi, L. Luzi, M. Massa, and F. Pacor. Horizontal and vertical ground motion prediction equations derived from the Italian Accelerometric Archive (ITACA). *Bulletin of Earthquake Engineering*, 8(5):1209–1230, 2010. doi: 10.1007/s10518-009-9130-9.

D. Bindi, F. Pacor, L. Luzi, R. Puglia, M. Massa, G. Ameri, and R. Paolucci. Ground motion prediction equations derived from the Italian strong motion database. *Bulletin of Earthquake Engineering*, 9:1899–1920, 2011a. doi: 10.1007/s10518-011-9313-z.

D. Bindi, S. Parolai, A. Oth, K. Abdrakhmatov, A. Muraliev, and J. Zschau. Intensity prediction equations for central Asia. *Geophysical Journal International*, 187:327–337, 2011b. doi: 10.1111/j.1365-246X.2011.05142.x.

D. Bindi, M. Massa, L. Luzi, G. Ameri, F. Pacor, R. Puglia, and P. Augliera. Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset. *Bulletin of Earthquake Engineering*, 12(1):391–430, 2014a. doi: 10.1007/s10518-013-9525-5.

D. Bindi, M. Massa, L. Luzi, G. Ameri, F. Pacor, R. Puglia, and P. Augliera. Erratum to: Pan-European ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods up to 3.0 s using the RESORCE dataset. *Bulletin of Earthquake Engineering*, 12(1): 431–448, 2014b. doi: 10.1007/s10518-014-9589-x.

D. Bindi, F. Cotton, S. R. Kotha, C. Bosse, D. Stromeyer, and G. Grünthal. Application-driven ground motion prediction equation for seismic hazard assessments in non-cratonic moderate-seismicity areas. *Journal of Seismology*, 2017. doi: 10.1007/s10950-017-9661-5.

D. Bindi, S.-R. Kotha, G. Weatherill, G. Lanzano, L. Luzi, and F. Cotton. The pan-European engineering strong motion (ESM) flatfile: Consistency check via residual analysis. *Bulletin of Earthquake Engineering*, 17 (2):583–602, Feb 2019. doi: 10.1007/s10518-018-0466-x.

J. A. Blume. The SAM procedure for site-acceleration-magnitude relationships. In *Proceedings of Sixth World Conference on Earthquake Engineering*, volume I, pages 416–422, 1977.

J. A. Blume. Distance partitioning in attenuation studies. In *Proceedings of Seventh World Conference on Earthquake Engineering*, volume 2, pages 403–410, 1980.

J. Boatwright, H. Bundock, J. Luetgert, L. Seekins, L. Gee, and P. Lombard. The dependence of PGA and PGV on distance and magnitude inferred from northern California ShakeMap data. *Bulletin of the Seismological Society of America*, 93(5):2043–2055, Oct 2003.

S. S. Bodda, M. Keller, A. Gupta, and G. Senfaute. A methodological approach to update ground motion prediction models using Bayesian inference. *Pure and Applied Geophysics*, 179:247–264, 2022. doi: 10.1007/s00024-021-02915-8.

P. Bodin, L. Malagnini, and A. Akinci. Ground-motion scaling in the Kachchh basin, India, deduced from aftershocks of the 2001 $M_w$7.6 Bhuj earthquake. *Bulletin of the Seismological Society of America*, 94(5): 1658–1669, Oct 2004.

B. A. Bolt and N. A. Abrahamson. New attenuation relations for peak and expected accelerations of strong ground motion. *Bulletin of the Seismological Society of America*, 72(6):2307–2321, Dec 1982.

J. J. Bommer. Empirical estimation of ground motion: Advances and issues. In *Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, pages 115–135, 2006. Paper number: KN 8.

J. J. Bommer and J. E. Alarcón. The prediction and use of peak ground velocity. *Journal of Earthquake Engineering*, 10(1):1–31, 2006.

J. J. Bommer and A. Martínez-Pereira. The effective duration of earthquake strong motion. *Journal of Earthquake Engineering*, 3(2):127–172, 1999.

J. J. Bommer and F. Scherbaum. The use and misuse of logic trees in probabilistic seismic hazard analysis. *Earthquake Spectra*, 24(4):997–1009, Nov 2008.

J. J. Bommer, D. A. Hernández, J. A. Navarrete, and W. M. Salazar. Seismic hazard assessments for El Salvador. *Geofísica Internacional*, 35(3):227–244, 1996.

J. J. Bommer, A. S. Elnashai, G. O. Chlimintzas, and D. Lee. Review and development of response spectra for displacement-based seismic design. ESEE Report 98-3, Department of Civil Engineering, Imperial College, London, Mar 1998.

J. J. Bommer, A. S. Elnashai, and A. G. Weir. Compatible acceleration and displacement spectra for seismic design codes. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper no. 207.

J. J. Bommer, J. Douglas, and F. O. Strasser. Style-of-faulting in ground-motion prediction equations. *Bulletin of Earthquake Engineering*, 1(2):171–203, 2003.

J. J. Bommer, S. Oates, J. M. Cepeda, C. Lindholm, J. Bird, R. Torres, G. Marroquín, and J. Rivas. Control of hazard due to seismicity induced by a hot fractured rock geothermal project. *Engineering Geology*, 83: 287–306, 2006. doi: 10.1016/j.enggeo.2005.11.002.

J. J. Bommer, P. J. Stafford, J. E. Alarcón, and S. Akkar. The influence of magnitude range on empirical ground-motion prediction. *Bulletin of the Seismological Society of America*, 97(6):2152–2170, 2007. doi: 10.1785/0120070081.

J. J. Bommer, P. J. Stafford, and J. E. Alarcón. Empirical equations for the prediction of the significant, bracketed, and uniform duration of earthquake ground motion. *Bulletin of the Seismological Society of America*, 99(6):3217–3233, Dec 2009. doi: 10.1785/0120080298.

J. J. Bommer, J. Douglas, F. Scherbaum, F. Cotton, H. Bungum, and D. Fäh. On the selection of ground-motion prediction equations for seismic hazard analysis. *Seismological Research Letters*, 81(5):783–793, 2010. doi: 10.1785/gssrl.81.5.783.

J. J. Bommer, S. Akkar, and Ö Kale. A model for vertical-to-horizontal response spectral ratios for Europe and the Middle East. *Bulletin of the Seismological Society of America*, 101(4):1783–1806, Aug 2011. doi: 10.1785/0120100285.

J. J. Bommer, S. Akkar, and S. Drouet. Extending ground-motion prediction equations for spectral accelerations to higher response frequencies. *Bulletin of Earthquake Engineering*, 10(2):379–399, 2012. doi: 10.1007/s10518-011-9304-0.

J. J. Bommer, K. J. Coppersmith, R. T. Coppersmith, K. L. Hanson, A. Mangongolo, J. Neveling, E. M. Rathje, A. Rodriguez-Marek, F. Scherbaum, R. Shelembe, P. J. Stafford, and F. O. Strasser. A SSHAC level 3 probabilistic seismic hazard analysis for a new-build nuclear site in South Africa. *Earthquake Spectra*, 31 (2):661–698, May 2015. doi: 10.1193/060913EQS145M.

J. J. Bommer, B. Dost, B. Edwards, P. J Stafford, J. van Elk, D. Doornhof, and M. Ntinalexis. Developing an application-specific ground-motion model for induced seismicity. *Bulletin of the Seismological Society of America*, 106(1):158–173, 2016. doi: 10.1785/0120150184.

J. J. Bommer, P. J. Stafford, B. Edwards, B. Dost, E. van Dedem, A. Rodriguez-Marek, P. Kruiver, J. van Elk, D. Doornhof, and M. Ntinalexis. Framework for a ground-motion model for induced seismic hazard and risk analysis in the Groningen gas field, The Netherlands. *Earthquake Spectra*, 33(2):481–498, May 2017. doi: 10.1193/082916EQS138M.

J. J. Bommer, P. J. Stafford, E. Ruigrok, A. Rodriguez-Marek, M. Ntinalexis, P. P. Kruiver, B. Edwards, B. Dost, and J. van Elk. Ground-motion prediction models for induced earthquakes in the Groningen gas field, the Netherlands. *Journal of Seismology*, 26:1157–1184, 2022. doi: 10.1007/s10950-022-10120-w.

D. M. Boore. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *Bulletin of the Seismological Society of America*, 73(6):1865–1894, Dec 1983.

D. M. Boore. Simulation of ground motion using the stochastic method. *Pure and Applied Geophysics*, 160(3–4): 635–676, Mar 2003. doi: 10.1007/PL00012553.

D. M. Boore. Estimating $vs30$ (or NEHRP site classes) from shallow velocity models (depths $\leq 30\,\mathrm{m}$). *Bulletin of the Seismological Society of America*, 94(2):591—-597, 2004.

D. M. Boore. Erratum: Equations for estimating horizontal response spectra and peak acceleration from western north american earthquakes: A summary of recent work. *Seismological Research Letters*, 76(3):368–369, May/Jun 2005.

D. M. Boore. Ground-motion models for very-hard-rock sites in eastern North America: An update. *Seismological Research Letters*, 89(3):1172–1184, May/Jun 2018. doi: 10.1785/0220170218.

D. M. Boore and G. M. Atkinson. Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America. *Bulletin of the Seismological Society of America*, 77(22):440–467, Apr 1987.

D. M. Boore and G. M. Atkinson. Boore-Atkinson NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters. PEER Report 2007/01, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2007.

D. M. Boore and G. M. Atkinson. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra*, 24(1): 99–138, 2008. doi: 10.1193/1.2830434.

D. M. Boore and W. B. Joyner. The empirical prediction of ground motion. *Bulletin of the Seismological Society of America*, 72(6):S43–S60, Dec 1982. Part B.

D. M. Boore and W. B. Joyner. Estimation of ground motion at deep-soil sites in eastern North America. *Bulletin of the Seismological Society of America*, 81(6):2167–2185, Dec 1991.

D. M. Boore, W. B. Joyner, and T. E. Fumal. Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report. Open-File Report 93-509, U.S. Geological Survey, 1993. 70 pages.

D. M. Boore, W. B. Joyner, and T. E. Fumal. Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report. Part 2. Open-File Report 94-127, U.S. Geological Survey, 1994a.

D. M. Boore, W. B. Joyner, and T. E. Fumal. Ground motion estimates for strike- and reverse-slip faults. Provided to the Southern California Earthquake Center and widely distributed as an insert in Boore et al. (1994a). Not seen. Reported in Boore et al. (1997)., 1994b.

D. M. Boore, W. B. Joyner, and T. E. Fumal. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. *Seismological Research Letters*, 68(1):128–153, Jan/Feb 1997.

D. M. Boore, J. Watson-Lamprey, and N. A. Abrahamson. Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America*, 96(4A):1502–1511, Aug 2006. doi: 10.1785/0120050209.

D. M. Boore, E. M. Thompson, and H. Cadet. Regional correlations of $V_{S30}$ and velocities averaged over depths less than and greater than 30 meters. *Bulletin of the Seismological Society of America*, 101(6):3046–3059, 2011.

D. M. Boore, J. P. Stewart, E. Seyhan, and G. M. Atkinson. NGA-West2 equations for predicting response spectral accelerations for shallow crustal earthquakes. Technical Report 2013/05, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2013.

D. M. Boore, J. P. Stewart, E. Seyhan, and G. M. Atkinson. NGA-West 2 equations for predicting PGA, PGV, and 5%-damped PSA for shallow crustal earthquakes. *Earthquake Spectra*, 30(3):1057–1085, Aug 2014. doi: 10.1193/070113EQS184M.

D. M. Boore, J. P. Stewart, A. A. Skarlatoudis, E. Seyhan, B. Margaris, N. Theodoulidis, E. Scordilis, I. Kalogeras, N. Klimis, and N. S. Melis. A ground-motion prediction model for shallow crustal earthquakes in Greece. *Bulletin of the Seismological Society of America*, 111(2):857–874, 2021. doi: 10.1785/0120200270.

S. S. Bora, F. Scherbaum, N. Kuehn, and P. J. Stafford. Fourier spectral- and duration models for the generation of response spectra adjustable to different source-, propagation-, and site conditions. *Bulletin of Earthquake Engineering*, 12(1):467–493, 2014. doi: 10.1007/s10518-013-9482-z.

S. S. Bora, F. Scherbaum, N. Kuehn, P. Stafford, and B. Edwards. Development of a response spectral ground-motion prediction equation (GMPE) for seismic-hazard analysis from empirical Fourier spectral and duration models. *Bulletin of the Seismological Society of America*, 105(4):2192–2218, Aug 2015. doi: 10.1785/0120140297.

S. S. Bora, F. Cotton, F. Scherbaum, B. Edwards, and P. Traversa. Stochastic source, path and site attenuation parameters and associated variabilities for shallow crustal European earthquakes. *Bulletin of Earthquake Engineering*, 15(11):4531–4561, Nov 2017. doi: 10.1007/s10518-017-0167-x.

R. D. Borcherdt. Estimates of site-dependent response spectra for design (methodology and justification). *Earthquake Spectra*, 10(4):617–653, 1994.

M. Böse. *Earthquake early warning for Istanbul using artifical neural networks*. PhD thesis, Fakultät für Physik der Universität, Karlsruhe, Germany, 2006.

Y. Bouhadad, N. Laouami, R. Bensalem, and S. Larbes. Seismic hazard estimation in the central Tell Atlas of Algeria (Algiers-Kabylia). In *Proceedings of Eleventh European Conference on Earthquake Engineering*, 1998.

S. J. Bourne, S. J. Oates, J. J. Bommer, B. Dost, J. van Elk, and D. Doornhof. Monte Carlo method for probabilistic hazard assessment of induced seismicity due to conventional natural gas production. *Bulletin of the Seismological Society of America*, 105(3):1721–1738, Jun 2015. doi: 10.1785/0120140302.

O. S. Boyd and C. H. Cramer. Estimating earthquake magnitudes from reported intensities in the central and eastern United States. *Bulletin of the Seismological Society of America*, 104(4):1709–1722, Aug 2014. doi: 10.1785/0120120352.

Y. Bozorgnia and K. W. Campbell. Engineering characterization of ground motion. In Y. Bozorgnia and V. Bertero, editors, *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*, chapter 5. CRC Press, Boca Raton, FL, 2004a.

Y. Bozorgnia and K. W. Campbell. The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and the vertical design spectra. *Journal of Earthquake Engineering*, 8(2): 175–207, 2004b.

Y. Bozorgnia and K. W. Campbell. Ground motion model for the vertical-to-horizontal (V/H) ratios of PGA, PGV, and response spectra. *Earthquake Spectra*, 32:951—-978, 2016a. doi: 10.1193/100614EQS151M.

Y. Bozorgnia and K. W. Campbell. Vertical ground motion model for PGA, PGV, and linear response spectra using the NGA-West2 database. *Earthquake Spectra*, 32(2):979–1004, May 2016b. doi: 10.1193/072814EQS121M.

Y. Bozorgnia, M. Niazi, and K. W. Campbell. Characteristics of free-field vertical ground motion during the Northridge earthquake. *Earthquake Spectra*, 11(4):515–525, Nov 1995.

Y. Bozorgnia, K. W. Campbell, and M. Niazi. Observed spectral characteristics of vertical ground motion recorded during worldwide earthquakes from 1957 to 1995. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 2671.

Y. Bozorgnia, M. M. Hachem, and K. W. Campbell. Ground motion prediction equation (“attenuation relationship”) for inelastic response spectra. *Earthquake Spectra*, 26(1):1–23, Feb 2010. doi: 10.1193/1.3281182.

B. A. Bradley. NZ-specific pseudo-spectral acceleration ground motion prediction equations based on foreign models. University of Canterbury Research Report 2010-03, Department of Civil and Natural Resources Engineering, University of Canterbury, Sep 2010. 319pp.

B. A. Bradley. A New Zealand-specific pseudo-spectral acceleration ground-motion prediction equation for active shallow crustal earthquakes based on foreign models. *Bulletin of the Seismological Society of America*, 103 (3):1801–1822, 2013. doi: 10.1785/0120120021.

P. L. Bragato. Regression analysis with truncated samples and its application to ground-motion attenuation studies. *Bulletin of the Seismological Society of America*, 94(4):1369–1378, Aug 2004.

P. L. Bragato. Estimating an upper limit probability distribution for peak ground acceleration using the randomly clipped normal distribution. *Bulletin of the Seismological Society of America*, 95(6):2058–2065, Dec 2005. doi: 10.1785/0120040213.

P. L. Bragato. Assessing regional and site-dependent variability of ground motions for ShakeMap implementation in Italy. *Bulletin of the Seismological Society of America*, 99(5):2950–2960, Oct 2009. doi: 10.1785/0120090020.

P. L. Bragato and D. Slejko. Empirical ground-motion attenuation relations for the eastern Alps in the magnitude range 2.5–6.3. *Bulletin of the Seismological Society of America*, 95(1):252–276, Feb 2005. doi: 10.1785/0120030231.

M. Båth. Seismicity of the Tanzania region. *Tectonophysics*, 27:353–379, 1975.

M Båth. Intensity relations for Swedish earthquakes. *Tectonophysics*, 67:163–173, 1980.

J. D. Bray and A. Rodriguez-Marek. Characterization of forward-directivity ground motions in the near-fault region. *Soil Dynamics and Earthquake Engineering*, 24(11):815–828, 2004. doi: 10.1016/j.soildyn.2004.05.001.

M. Breska, I. Perus, and V. Stankovski. Refitting equations for peak ground acceleration in light of the PF-L database. *International Journal of Environmental, Ecological, Geological and Geophysical Engineering*, 9(2): 66–70, 2015.

D. R. Brillinger and H. K. Preisler. An exploratory analysis of the Joyner-Boore attenuation data. *Bulletin of the Seismological Society of America*, 74(4):1441–1450, 1984.

D. R. Brillinger and H. K. Preisler. Further analysis of the Joyner-Boore attenuation data. *Bulletin of the Seismological Society of America*, 75(2):611–614, 1985.

Z. Bullock, A. B. Liel, S. Dashti, and K. A. Porter. A suite of ground motion prediction equations for cumulative absolute velocity in shallow crustal earthquakes including epistemic uncertainty. *Earthquake Spectra*, 37(2): 937–958, 2020. doi: 10.1177/8755293020957342.

H. Bungum, A. Dahle, G. Toro, R. McGuire, and O.T. Gudmestad. Ground motions from intraplate earthquakes. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 2, pages 611–616, 1992.

N. Buratti, P. J. Stafford, and J. J. Bommer. Earthquake accelerogram selection and scaling procedures for estimating the distribution of drift response. *Journal of Structural Engineering, ASCE*, 137(3):345–357, Mar 2011. doi: 10.1061/(ASCE)ST.1943-541X.0000217.

S. A. Bydlon, A. Gupta, and E. M. Dunham. Using simulated ground motions to constrain near-source ground-motion prediction equations in areas experiencing induced seismicity. *Bulletin of the Seismological Society of America*, 107(5):2078–2093, Oct 2017. doi: 10.1785/0120170003.

S. A. Bydlon, K. B. Withers, and E. M. Dunham. Combining dynamic rupture simulations with ground-motion data to characterize seismic hazard from $m_w$ 3 to 5.8 earthquakes in Oklahoma and Kansas. *Bulletin of the Seismological Society of America*, 109(2):652–671, Apr 2019. doi: 10.1785/0120180042.

A. F. Cabalar and A. Cevik. Genetic programming-based attenuation relationship: An application of recent earthquakes in Turkey. *Computers and Geosciences*, 35:1884–1896, 2009. doi: 10.1016/j.cageo.2008.10.015.

L. Cabañas, B. Benito, C Cabañas, M. López, P. Gómez, M. E. Jiménez, and S. Alvarez. Banco de datos de movimiento fuerte del suelo mfs. aplicaciones. In Complutense, editor, *Física de la Tierra*, volume 11, pages 111–137. 1999. In Spanish with English abstract.

L. Cabañas, M. Lopez, B. Benito, and M. E. Jiménez. Estimation of PGA attenuation laws for Spain and Mediterranean region. Comparison with other ground motion models. In *Proceedings of the XXVII General Assembly of the European Seismological Commission (ESC)*, Sep 2000.

V. Caillot and P. Y. Bard. Magnitude, distance and site dependent spectra from Italian accelerometric data. *European Earthquake Engineering*, VII(1):37–48, 1993.

M. Cameletti, V. De Rubeis, C. Ferrari, P. Sbarra, and P. Tosi. An ordered probit model for seismic intensity data. *Stochastic Environmental Research and Risk Assessment*, 31(7):1593–1602, Sep 2017. doi: 10.1007/s00477-016-1260-4.

K. W. Campbell. Near-source attenuation of peak horizontal acceleration. *Bulletin of the Seismological Society of America*, 71(6):2039–2070, Dec 1981.

K. W. Campbell. Near-source attenuation of strong ground motion for moderate to large earthquakes: An update and suggested application to the Wasatch fault zone of north-central Utah. In *Proceedings of Conference XXVI: A Workshop on Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah*, pages 483–499. US Geological Survey, 1984. Open-File Report 84-763.

K. W. Campbell. Strong motion attenuation relations: A ten-year perspective. *Earthquake Spectra*, 1(4):759–804, Aug 1985.

K. W. Campbell. The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small-magnitude earthquakes in California and eastern North America. *Bulletin of the Seismological Society of America*, 79(5):1311–1346, Oct 1989.

K. W. Campbell. Empirical prediction of near-source soil and soft-rock ground motion for the Diablo Canyon power plant site, San Luis Obispo county, California. Technical report, Dames & Moore, Evergreen, Colorado, Sep 1990. Prepared for Lawrence Livermore National Laboratory. Not seen. Reported in Idriss (1993).

K. W. Campbell. Empirical prediction of near-source ground motion from large earthquakes. In *Proceedings of the International Workshop on Earthquake Hazard and Large Dams in the Himalaya*. Indian National Trust for Art and Cultural Heritage, New Delhi, India, Jan 1993.

K. W. Campbell. Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, 68(1):154–179, Jan/Feb 1997.

K. W. Campbell. Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, 71(3):352–354, May/Jun 2000.

K. W. Campbell. Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, 72(4):474, Jul/Aug 2001.

K. W. Campbell. Engineering models of strong ground motion. In W. F. Chen and C. Scawthorn, editors, *Handbook of Earthquake Engineering*, chapter 5. CRC Press, Boca Raton, FL, USA, 2003a.

K. W. Campbell. Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America. *Bulletin of the Seismological Society of America*, 93(3):1012–1033, 2003b.

K. W. Campbell. Strong-motion attenuation relations. In W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger, editors, *International Handbook of Earthquake and Engineering Seismology*, chapter 60. Academic Press, London, 2003c.

K. W. Campbell. Validation and update of hybrid empirical ground motion (attenuation) relations for the CEUS. Final technical report, ABS Consulting, Inc. (EQECAT), Beaverton, USA, Sep 2007. NEHRP External Grants Program, U.S. Geological Survey Award Number: 05HQGR0032.

K. W. Campbell and Y. Bozorgnia. Near-source attenuation of peak horizontal acceleration from worldwide accelerograms recorded from 1957 to 1993. In *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, volume III, pages 283–292, Jul 1994.

K. W. Campbell and Y. Bozorgnia. New empirical models for predicting near-source horizontal, vertical, and $V/H$ response spectra: Implications for design. In *Proceedings of the Sixth International Conference on Seismic Zonation*, Nov 2000.

K. W. Campbell and Y. Bozorgnia. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, 93(3):1413, 2003a.

K. W. Campbell and Y. Bozorgnia. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, 93(4):1872, 2003b.

K. W. Campbell and Y. Bozorgnia. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, 94(6):2417, 2003c.

K. W. Campbell and Y. Bozorgnia. Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, 93(1):314–331, 2003d.

K. W. Campbell and Y. Bozorgnia. Campbell-Bozorgnia Next Generation Attenuation (NGA) relations for PGA, PGV and spectral acceleration: A progress report. In *Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*, Apr 2006a. Paper no. 906.

K. W. Campbell and Y. Bozorgnia. Next Generation Attenuation (NGA) empirical ground motion models: Can they be used in Europe? In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, Sep 2006b. Paper no. 458.

K. W. Campbell and Y. Bozorgnia. Campbell-Bozorgnia NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters. PEER Report 2007/02, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2007.

K. W. Campbell and Y. Bozorgnia. Empirical ground motion model for shallow crustal earthquakes in active tectonic environments developed for the NGA project. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008a. Paper no. 03-02-0004.

K. W. Campbell and Y. Bozorgnia. NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthquake Spectra*, 24(1):139–171, 2008b. doi: 10.1193/1.2857546.

K. W. Campbell and Y. Bozorgnia. Analysis of cumulative absolute velocity (CAV) and JMA instrumental seismic intensity ($i_{\mathrm{jma}}$) using the PEER-NGA strong motion database. Technical Report 2010/102, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, Feb 2010a.

K. W. Campbell and Y. Bozorgnia. A ground motion prediction equation for the horizontal component of cumulative absolute velocity (CAV) based on the PEER-NGA strong motion database. *Earthquake Spectra*, 26(3):635–650, Aug 2010b. doi: 10.1193/1.3457158.

K. W. Campbell and Y. Bozorgnia. A ground motion prediction equation for JMA instrumental seismic intensity for shallow crustal earthquakes in active tectonic regimes. *Earthquake Engineering and Structural Dynamics*, 40(4):413–427, Apr 2011. doi: 10.1002/eqe.1027.

K. W. Campbell and Y. Bozorgnia. NGA-West2 Campbell-Bozorgnia ground motion model for the horizontal components of PGA, PGV, and 5%-damped elastic pseudo-acceleration response spectra for periods ranging from 0.01 to 10 sec. Technical Report 2013/06, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2013.

K. W. Campbell and Y. Bozorgnia. NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5%-damped linear acceleration response spectra. *Earthquake Spectra*, 30(3):1087–1115, Aug 2014. doi: 10.1193/062913EQS175M.

K. W. Campbell and Y. Bozorgnia. Ground motion models for the horizontal components of Arias intensity (AI) and cumulative absolute velocity (CAV) using the NGA-West2 database. *Earthquake Spectra*, 35(3): 1289–1310, Aug 2019. doi: 10.1193/090818EQS212M.

K. W. Campbell and Y. Bozorgnia. Ground-motion model for Housner's spectrum intensity based on a novel hybrid-scenario approach. *Earthquake Spectra*, 39(3):1558–1577, 2023. doi: 10.1177/87552930231173451.

J. V. Cantavella, M. Herraiz, M. J. Jiménez, and M. García. Seismic attenuation in the SE of the Iberian peninsula. In *Proceedings of the Asamblea Hispano-Portuguesa de Geodesia y Geofísica*, 2004. S07.23. Not seen. Cited by Tapia et al. (2007).

L. Caramenti, A. Menafoglio, S. Sgobba, and G. Lanzano. Multi-source geographically weighted regression for regionalized ground-motion models. *Spatial Statistics*, 47:100610, 2022. doi: 10.1016/j.spasta.2022.100610.

A. Carvalho. *Modelação Estocástica da acção sísmica em Portugal continental*. PhD thesis, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal, 2008. In Portuguese. Not seen.

C. Cauzzi and E. Faccioli. Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records. *Journal of Seismology*, 12(4):453–475, Oct 2008. doi: 10.1007/s10950-008-9098-y.

C. Cauzzi and E. Faccioli. Anatomy of sigma of a global predictive model for ground motions and response spectra. *Bulletin of Earthquake Engineering*, 16(5):1887–1905, May 2018a. doi: 10.1007/s10518-017-0278-4.

C. Cauzzi and E. Faccioli. Correction to: Anatomy of sigma of a global predictive model for ground motions and response spectra. *Bulletin of Earthquake Engineering*, 16(5):1907–1907, May 2018b. doi: 10.1007/s10518-017-0286-4.

C. Cauzzi, E. Faccioli, R. Paolucci, and M. Villani. Long-period ground motion evaluation from a large worldwide digital strong motion database. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008. Paper no. S10-047.

C. Cauzzi, E. Faccioli, V. Poggi, D. Fäh, and B. Edwards. Prediction of long-period displacement response spectra for low-to-moderate seismicity regions: Merging the Swiss earthquake waveform archive with a global fully digital strong-motion dataset. In *Fourth IASPEI/IAEE International Symposium: Effects of surface geology on seismic motion*, University of California Santa Barbara, USA, Aug 2011.

C. Cauzzi, B. Edwards, D. Fäh, J. Clinton, S. Wiemer, P. Kästli, G. Cua, and D. Giardini. New predictive equations and site amplification estimates for the next-generation Swiss ShakeMaps. *Geophysical Journal International*, 200:421–438, 2015a. doi: 10.1093/gji/ggu404.

C. Cauzzi, E. Faccioli, M. Vanini, and A. Bianchini. Updated predictive equations for broadband (0.01–10 s) horizontal response spectra and peak ground motions, based on a global dataset of digital acceleration records. *Bulletin of Earthquake Engineering*, 13(6):1587–1612, Jun 2015b. doi: 10.1007/s10518-014-9685-y.

C. V. Cauzzi. *Broadband empirical prediction of displacement response spectra based on worldwide digital records*. PhD thesis, Politecnico di Milano, Apr 2008.

Z. Çağnan, S. Akkar, and P. Gülkan. A predictive ground-motion model for Turkey and its comparison with recent local and global GMPEs. In *Earthquake Data in Engineering Seismology: Predictive models, data management and networks*, pages 39–52. Springer, Dordrecht, 2011. doi: 10.1007/978-94-007-0152-6_4.

Z. Çağnan, S. Akkar, Ö Kale, and A. Sandıkkaya. A model for predicting vertical component peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudospectral acceleration (PSA) for Europe and the Middle East. *Bulletin of Earthquake Engineering*, 15(7):2617–2643, Jul 2017a. doi: 10.1007/s10518-016-0063-9.

Z. Çağnan, S. Akkar, Ö Kale, and A. Sandıkkaya. Erratum to: A model for predicting vertical component peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudospectral acceleration (PSA) for Europe and the Middle East. *Bulletin of Earthquake Engineering*, 15(12):5623–5624, Dec 2017b. doi: 10.1007/s10518-017-0209-4.

S. Céspedes, R. Boroschek, and R. O. Ruiz. Strong motion models for duration and arias intensity for strong motion records in Chile. *Journal of Earthquake and Tsunami*, 16(4):2250010, 2022. doi: 10.1142/S1793431122500105.

A. M. Chandler and N. T. K. Lam. Intensity attenuation relationship for the south China region and comparison with the component attenuation model. *Journal of Asian Earth Sciences*, 20(7):775–790, 2002.

T.-Y. Chang, F. Cotton, and J. Angelier. Seismic attenuation and peak ground acceleration in Taiwan. *Bulletin of the Seismological Society of America*, 91(5):1229–1246, Oct 2001.

Y.-W. Chang, W.-Y. Jean, and C.-H. Loh. A comparison of NGA ground-motion prediction models with Taiwan models and data. In *Proceedings of Fifteenth World Conference on Earthquake Engineering*, 2012. Paper no. 4994.

S.-H. Chao and Y.-H. Chen. A novel regression analysis method for randomly truncated strong motion data. *Earthquake Spectra*, 35(2):977–1001, May 2019. doi: 10.1193/022218EQS044M.

S.-H. Chao, B. Chiou, C.-C. Hsu, and P.-S. Lin. A horizontal ground-motion model for crustal and subduction earthquakes in Taiwan. *Earthquake Spectra*, 36(2):463–506, May 2020. doi: 10.1177/8755293020919415.

M. C. Chapman. On the use of elastic input energy for seismic hazard analysis. *Earthquake Spectra*, 15(4): 607–635, Nov 1999.

L. Chen. Ground motion attenuation relationships based on Chinese and Japanese strong ground motion data. Master's thesis, ROSE School, Pavia, Italy, May 2008.

L. Chen and E. Faccioli. Single-station standard deviation analysis of 2010–2012 strong-motion data from the Canterbury region, New Zealand. *Bulletin of Earthquake Engineering*, 11(5):1617–1632, Oct 2013. doi: 10.1007/s10518-013-9454-3.

S.-Z. Chen and G. M. Atkinson. Global comparison of earthquake source spectra. *Bulletin of the Seismological Society of America*, 92(3):885–895, 2002.

Y. Chen and Y.-X. Yu. The development of attenuation relations in the rock sites for periods ($T = 0.04 \sim 10\,\mathrm{s}$, $\xi = 0.05$) based on NGA database. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008a. Paper no. 03-02-0017.

Y. Chen and Y.-X. Yu. The development of attenuation relations in the rock sites for periods ($T = 0.04 \sim 10\,\mathrm{s}$, $\xi = 0.005$, 0.02, 0.07, 0.1 & 0.2) based on NGA database. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008b. Paper no. 03-02-0029.

Y.-H. Chen and C.-C. P. Tsai. A new method for estimation of the attenuation relationship with variance components. *Bulletin of the Seismological Society of America*, 92(5):1984–1991, 2002.

Y. Cheng. *Intensity measures for seismic response prediction and associated ground motion selection and modification*. PhD thesis, Sapienza University of Rome, Sep 2013.

Y. Cheng, A. Lucchini, and F. Mollaioli. Proposal of new ground-motion prediction equations for elastic input energy spectra. *Earthquakes and Structures*, 7(4):485–510, 2014. doi: 10.12989/eas.2014.7.4.485.

C. Chiaruttini and L. Siro. The correlation of peak ground horizontal acceleration with magnitude, distance, and seismic intensity for Friuli and Ancona, Italy, and the Alpide belt. *Bulletin of the Seismological Society of America*, 71(6):1993–2009, Dec 1981.

B. Chiou, R. Darragh, N. Gregor, and W. Silva. NGA project strong-motion database. *Earthquake Spectra*, 24 (1):23–44, Feb 2008. doi: 10.1193/1.2894831.

B. Chiou, R. Youngs, N. Abrahamson, and K. Addo. Ground-motion attenuation model for small-to-moderate shallow crustal earthquakes in California and its implications on regionalization of ground-motion prediction models. *Earthquake Spectra*, 26(4):907–926, 2010. doi: 10.1193/1.3479930.

B. S.-J. Chiou and R. R. Youngs. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 24(1):173–215, 2008. doi: 10.1193/1.2894832.

B. S. J. Chiou and R. R. Youngs. Update of the Chiou and Youngs NGA ground motion model for average horizontal component of peak ground motion and response spectra. Technical Report 2013/07, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2013.

B. S.-J. Chiou and R. R. Youngs. Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 30(3):1117–1153, Aug 2014. doi: 10.1193/072813EQS219M.

I.-K. Choi, M. Nakajima, Y.-S. Choun, and Y. Ohtori. Development of the site-specific uniform hazard spectra for Korean nuclear power plant sites. *Nuclear Engineering and Design*, 239:790–799, 2009. doi: 10.1016/j.nucengdes.2008.12.026.

Y. Choi and J. P. Stewart. Nonlinear site amplification as function of 30 m shear wave velocity. *Earthquake Spectra*, 21(1):1–30, Feb 2005.

S. Chopra and P. Choudhury. A study of response spectra for different geological conditions in Gujarat, India. *Soil Dynamics and Earthquake Engineering*, 31(11):1551–1564, 2011. doi: 10.1016/j.soildyn.2011.06.007.

C.-C. Chou and C.-M. Uang. Establishing absorbed energy spectra — an attenuation approach. *Earthquake Engineering and Structural Dynamics*, 29(10):1441–1455, Oct 2000.

K. Chousianitis, V. Del Gaudio, I. Kalogeras, and A. Ganas. Predictive model of Arias intensity and Newmark displacement for regional scale evaluation of earthquake-induced landslide hazard in Greece. *Soil Dynamics and Earthquake Engineering*, 65:11–29, 2014. doi: 10.1016/j.soildyn.2014.05.009.

K. Chousianitis, V. Del Gaudio, P. Pierri, and G.-A. Tselentis. Regional ground-motion prediction equations for amplitude-, frequency response-, and duration-based parameters for Greece. *Earthquake Engineering and Structural Dynamics*, 47(11):2252–2274, Sep 2018. doi: 10.1002/eqe.3067.

J.-K. Chung. Prediction of peak ground acceleration in southwestern Taiwan as revealed by analysis of CHY array data. *Terrestrial Atmospheric and Oceanic Science*, 17(1):139–167, Mar 2006.

A. Climent, W. Taylor, M. Ciudad Real, W. Strauch, M. Villagrán, A. Dahle, and H. Bungum. Spectral strong motion attenuation in Central America. Technical Report 2-17, NORSAR, 1994.

S. W. Cole and P. W. Burton. Comparitive analysis of the seismic hazard of central China. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, Oct 2008.

S. W. Cole, Y. Xu, and P. W. Burton. Seismic hazard and risk in Shanghai and estimation of expected building damage. *Soil Dynamics and Earthquake Engineering*, 28(10–11):778–794, Oct–Nov 2008. doi: 10.1016/j.soildyn.2007.10.008.

N. Collins, R. Graves, G. Ichinose, and P. Somerville. Ground motion attenuation relations for the Intermountain West. Final report, U.S. Geological Survey, 2006. Award 05HQGR0031.

V. Contreras and R. Boroschek. Strong ground motion attenuation relations for Chilean subduction zone interface earthquakes. In *Proceedings of Fifteenth World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.

V. Convertito, R. De Matteis, A. Romeo, A. Zollo, and G. Iannaccone. A strong motion attenuation relation for early-warning application in the Campania region (southern Apennines). In P. Gasparini, G. Manfredi, and J. Zschau, editors, *Earthquake Early Warning Systems*, pages 132–152. Springer, 2007.

V. Convertito, N. Maercklin, N. Sharma, and A. Zollo. From induced seismicity to direct time-dependent seismic hazard. *Bulletin of the Seismological Society of America*, 102(6):2563–2573, 2012. doi: 10.1785/0120120036.

V. Convertito, R. De Matteis, R. Esposito, and P. Capuano. Using ground motion prediction equations to monitor variations in quality factor due to induced seismicity: A feasibility study. *Acta Geophysica*, 68: 723–735, 2020. doi: 10.1007/s11600-020-00441-0.

V. Convertito, R. De Matteis, O. Amoroso, and P. Capuano. Ground motion prediction equations as a proxy for medium properties variation due to geothermal resources exploitation. *Scientific Reports*, 12:12632, 2022. doi: 10.1038/s41598-022-16815-x.

K. Coppersmith, J. Bommer, K. Hanson, J. Unruh, R. Coppersmith, L. Wolf, B. Youngs, A. Rodriguez-Marek, L. Al Atik, G. Toro, and V. Montaldo-Falero. Hanford sitewide probabilistic seismic hazard analysis. Technical Report PNNL-23361, Pacific Northwest National Laboratory, Richland, Washington 99352, USA, Nov 2014.

C. A. Cornell, H. Banon, and A. F. Shakal. Seismic motion and response prediction alternatives. *Earthquake Engineering and Structural Dynamics*, 7(4):295–315, Jul–Aug 1979.

G. Costa, P. Suhadolc, and G. F. Panza. The Friuli (NE Italy) Accelerometric Network: Analysis of low-magnitude high-quality digital accelerometric data for seismological and engineering applications. In *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*, Oakland, USA, 1998. Earthquake Engineering Research Institute. Seattle, USA. 31 May–4 June.

G. Costa, P. Suhadolc, A. Delise, L. Moratto, E. Furlanetto, and F. Fitzko. Estimation of site effects at some stations of the Friuli (NE Italy) accelerometric network (RAF). In *Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, volume 1, pages 729–739, 2006. Paper number 089.

F. Cotton, F. Scherbaum, J. J. Bommer, and H. Bungum. Criteria for selecting and adjusting ground-motion models for specific target regions: Application to central Europe and rock sites. *Journal of Seismology*, 10(2): 137–156, Apr 2006. doi: 10.1007/s10950-005-9006-7.

F. Cotton, G. Pousse, F. Bonilla, and F. Scherbaum. On the discrepancy of recent European ground-motion observations and predictions from empirical models: Analysis of KiK-net accelerometric data and point-sources stochastic simulations. *Bulletin of the Seismological Society of America*, 98(5):2244–2261, Oct 2008. doi: 10.1785/0120060084.

W. J. Cousins, J. X. Zhao, and N. D. Perrin. A model for the attenuation of peak ground acceleration in New Zealand earthquakes based on seismograph and accelerograph data. *Bulletin of the New Zealand Society for Earthquake Engineering*, 32(4):193–220, Dec 1999.

G. Cremen, A. Gupta, and J. Baker. Evaluation of ground motion intensities from induced earthquakes using "Did you feel it?" data. In *Proceedings of Sixteenth World Conference on Earthquake Engineering*, Jan 2017. Paper no. 3365.

G. Cremen, M. J. Werner, and B. Baptie. A new procedure for evaluating ground-motion models, with application to hydraulic-fracture-induced seismicity in the United Kingdom. *Bulletin of the Seismological Society of America*, 110(5):2380–2397, 2020. doi: 10.1785/0120190238.

C. B. Crouse. Ground-motion attenuation equations for earthquakes on the Cascadia subduction zones. *Earthquake Spectra*, 7(2):201–236, 1991.

C. B. Crouse and J. W. McGuire. Site response studies for purpose of revising NEHRP seismic provisions. *Earthquake Spectra*, 12(3):407–439, Aug 1996.

C. B. Crouse, Y. K. Vyas, and B. A. Schell. Ground motion from subduction-zone earthquakes. *Bulletin of the Seismological Society of America*, 78(1):1–25, Feb 1988.

B. W. Crowell, D. Melgar, Y. Bock, J. S. Haase, and J. Geng. Earthquake magnitude scaling using seismogeodetic data. *Geophysical Research Letters*, 40:6089–6094, 2013. doi: 10.1002/2013GL058391.

G. Cua and T. H. Heaton. Characterizing average properties of southern California ground motion amplitudes and envelopes. *Bulletin of the Seismological Society of America*, 2010. Unpublished manuscript.

G. Cua, D. J. Wald, T. I. Allen, D. Garcia, C. B. Worden, M. Gerstenberger, K. Lin, and K. Marano. "Best practices" for using macroseismic intensity and ground motion intensity conversion equations for hazard and loss models in GEM1. Technical Report 2010-4, GEM Foundation, Pavia, Italy, Oct 2010.

J. W. Cui, J. G. Zhang, D. Gao, J. X. Duan, and T. Wang. The ground motion attenuation relation for the mountainous area in Sichuan and Yunnan. In *Proceedings of Fifteenth World Conference on Earthquake Engineering*, 2012. Paper no. 149.

A. Dahle, H. Bugum, and L. B. Kvamme. Attenuation modelling based on intraplate earthquake recordings. In *Proceedings of Ninth European Conference on Earthquake Engineering*, volume 4-A, pages 121–129, 1990a.

A. Dahle, H. Bungum, and L. B. Kvamme. Attenuation models inferred from intraplate earthquake recordings. *Earthquake Engineering and Structural Dynamics*, 19(8):1125–1141, Nov 1990b.

A. Dahle, H. Bungum, and L. B. Kvamme. Empirically derived PSV spectral attenuation models for intraplate conditions. *European Earthquake Engineering*, 3:42–52, 1991.

A. Dahle, A. Climent, W. Taylor, H. Bungum, P. Santos, M. Ciudad Real, C. Linholm, W. Strauch, and F. Segura. New spectral strong motion attenuation models for Central America. In *Proceedings of the Fifth International Conference on Seismic Zonation*, volume II, pages 1005–1012, 1995.

M. D'Amico, G. Lanzano, M. Santulin, R. Puglia, C. Felicetta, M. M. Tiberti, A. A. Gomez-Capera, and E. Russo. Hybrid GMPEs for region-specific PSHA in southern Italy. *Geosciences*, 8(217), 2018a. doi: 10.3390/geosciences8060217.

S. D'Amico, A. Akinci, and L. Malagnini. Predictions of high-frequency ground-motion in Taiwan based on weak motion data. *Geophysical Journal International*, 189(1):611–628, Apr 2012. doi: 10.1111/j.1365-246X.2012.05367.x.

S. D'Amico, A. Akinci, and M. Pischiutta. High-frequency ground-motion parameters from weak-motion data in the Sicily Channel and surrounding regions. *Geophysical Journal International*, 214(1):148–163, Jul 2018b. doi: 10.1093/gji/ggy107.

L. Danciu. *Development of a system to assess the earthquake damage potential for buildings: Intensiometer*. PhD thesis, Laboratory of Seismology, Department of Geology, University of Patras, Greece, 2006.

L. Danciu and G.-A. Tselentis. Engineering ground-motion parameters attenuation relationships for Greece. *Bulletin of the Seismological Society of America*, 97(1B):162–183, 2007a. doi: 10.1785/0120040087.

L. Danciu and G.-A. Tselentis. Engineering ground-motion parameters attenuation relationships for Greece. In *Proceedings of the International Symposium on Seismic Risk Reduction: The JICA Technical Cooperation Project in Romania*, pages 327–334, Apr 2007b. Paper ID 26.

A. Darzi, M. R. Zolfaghari, C. Cauzzi, and D. Fäh. An empirical ground-motion model for horizontal PGV, PGA, and 5% damped elastic response spectra (0.01–10 s) in Iran. *Bulletin of the Seismological Society of America*, 109(3):1041–1057, Jun 2019. doi: 10.1785/0120180196.

D. Das and V. K. Gupta. Scaling of response spectrum and duration for aftershocks. *Soil Dynamics and Earthquake Engineering*, 30:724–735, 2010. doi: 10.1016/j.soildyn.2010.03.003.

S. Das, I. D. Gupta, and V. K. Gupta. A new attenuation model for north-east India. In *Proceedings of the Twelfth Symposium of Earthquake Engineering, Roorkee, India*, pages 151–158, 2002.

S. Das, I. D. Gupta, and V. K. Gupta. A probabilistic seismic hazard analysis of northeast India. *Earthquake Spectra*, 22(1):1–27, Feb 2006. doi: 10.1193/1.2163914.

A. J. Davenport. A statistical relationship between shock amplitude, magnitude, and epicentral distance and its appplication to seismic zoning. Engineering Science Research Report BLWT-4-72, Western Ontario University, 1972. Not seen. Cited in Hays (1980).

H. M. Dawood, A. Rodriguez-Marek, J. Bayless, C. Goulet, and E. Thompson. A flatfile for the KiK-net database processed using an automated protocol. *Earthquake Spectra*, 32(2):1281—-1302, 2016.

A. A. D. de Almeida, M. Assump cão, J. J. Bommer, S. Drouet, C. Riccomini, and C. L. M. Prates. Probabilistic seismic hazard analysis for a nuclear power plant site in southeast Brazil. *Journal of Seismology*, 23(1):1–23, 2019. doi: 10.1007/s10950-018-9755-8.

F. De Luca. *Records, capacity curve fits and reinforced concrete damage states within a performance based earthquake engineering framework.* PhD thesis, University of Naples Federico II, Italy, 2011.

F. De Luca, I. Iervolino, G. Ameri, F. Pacor, and D. Bindi. Prediction equations for nonlinear SDOF response from the ITalian ACcelerometric Archive: Preliminary results. In *ANIDIS*, Bari, Italy, 2011.

G. De Natale, E. Faccioli, and A. Zollo. Scaling of peak ground motions from digital recordings of small earthquakes at Campi Flegrei, southern Italy. *Pure and Applied Geophysics*, 126(1):37–53, 1988.

A. Deif, A. Abed, K. Abdel-Rahman, and E. A. Moneim. Strong ground motion attenuation in Aswan area, Egypt. *Arabian Journal of Geosciences*, 4:855–861, 2011. doi: 10.1007/s12517-009-0103-8.

D. Denham and G. R. Small. Strong motion data centre: Bureau of mineral resources, Canada. *Bulletin of the New Zealand Society for Earthquake Engineering*, 4(1):15–30, Mar 1971.

D. Denham, G. R. Small, and I.B. Everingham. Some strong-motion results from Papua New Guinea 1967–1972. In *Proceedings of Fifth World Conference on Earthquake Engineering*, volume 2, pages 2324–2327, 1973.

A. Derakhshani and A. H. Foruzan. Predicting the principal strong ground motion parameters: A deep learning approach. *Applied Soft Computing Journal*, 80:192–201, Jul 2019. doi: 10.1016/j.asoc.2019.03.029.

B. Derras, F. Cotton, and P.-Y. Bard. Towards fully data driven ground-motion prediction models for Europe. *Bulletin of Earthquake Engineering*, 12(1):495–516, 2014. doi: 10.1007/s10518-013-9481-0.

B. Derras, P.-Y. Bard, and F. Cotton. Site-condition proxies, ground motion variability, and data-driven GMPEs: Insights from the NGA-West2 and RESORCE data sets. *Earthquake Spectra*, 32(4):2027–2056, Nov 2016. doi: 10.1193/060215EQS082M.

B. Derras, P.-Y. Bard, and F. Cotton. $v_{S30}$, slope, $h_{800}$ and $f_0$: Performance of various site-condition proxies in reducing ground-motion aleatory variability and predicting nonlinear site response. *Earth, Planets and Space*, 69(133), 2017. doi: 10.1186/s40623-017-0718-z.

C. Devillers and B. Mohammadioun. French methodology for determining site-adapted SMS (Séisme Majoré de Sécurité) spectra. In *Transactions of the 6th International Conference on Structural Mechanics in Reactor Technology*, volume K(a), 1981. K 1/9.

Y. P. Dhakal, N. Takai, and T. Sasatani. Path effects on prediction equations of pseudo-velocity response spectra in northern Japan. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008. Paper no. 03-02-0023.

J. Dhanya and S. T. G. Raghukanth. Ground motion prediction model using artificial neural network. *Pure and Applied Geophysics*, 175(3):1035–1064, 2018. doi: 10.1007/s00024-017-1751-3.

J. Dhanya and S. T. G. Raghukanth. Neural network-based hybrid ground motion prediction equations for western Himalayas and north-eastern India. *Acta Geophysica*, 68:303–324, 2020. doi: 10.1007/s11600-019-00395-y.

J. Dhanya, D. Sagar, and S. T. G. Raghukanth. Predictive models for ground motion parameters using artificial neural network. In A. Rama Mohan Rao and K. Ramanjaneyulu, editors, *Recent Advances in Structural Engineering*, volume 2 of *Lecture Notes in Civil Engineering 12.* Springer Nature Singapore Pte Ltd., 2019. doi: 10.1007/978-981-13-0365-4_8.

C. Di Alessandro, L. F. Bonilla, D. M. Boore, A. Rovelli, and O. Scotti. Predominant-period site classification for response spectra prediction equations in Italy. *Bulletin of the Seismological Society of America*, 102(2): 680–695, Apr 2012. doi: 10.1785/0120110084.

R. Dobry, I. M. Idriss, and E. Ng. Duration characteristics of horizontal components of strong-motion earthquake records. *Bulletin of the Seismological Society of America*, 68(5):1487–1520, 1978.

J. L. Donahue and N. A. Abrahamson. Simulation-based hanging wall effects. *Earthquake Spectra*, 30(3): 1269–1284, Aug 2014. doi: 10.1193/071113EQS200M.

N. C. Donovan. A statistical evaluation of strong motion data including the February 9, 1971 San Fernando earthquake. In *Proceedings of Fifth World Conference on Earthquake Engineering*, volume 1, pages 1252–1261, 1973.

N. C. Donovan and A. E. Bornstein. Uncertainties in seismic risk analysis. *Journal of The Geotechnical Engineering Division, ASCE*, 104(GT7):869–887, Jul 1978.

B. Dost, T. van Eck, and H. Haak. Scaling peak ground acceleration and peak ground velocity recorded in The Netherlands. *Bollettino di Geofisica Teorica ed Applicata*, 45(3):153–168, 2004.

J. Douglas. *A critical reappraisal of some problems in engineering seismology*. PhD thesis, University of London, Oct 2001a.

J. Douglas. A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000). ESEE Report 01-1, Department of Civil and Environmental Engineering, Imperial College, London, Jan 2001b.

J. Douglas. Errata of and additions to ESEE Report No. 01-1: 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)'. Dept. report, Department of Civil and Environmental Engineering, Imperial College, London, Oct 2002.

J. Douglas. Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground acceleration and response spectral ordinates. *Earth-Science Reviews*, 61(1–2): 43–104, 2003.

J. Douglas. Ground motion estimation equations 1964–2003: Reissue of ESEE Report No. 01-1: 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)' with corrections and additions. Technical Report 04-001-SM, Department of Civil and Environmental Engineering; Imperial College of Science, Technology and Medicine; London; U.K., Jan. 2004a. URL `http://www3.imperial.ac.uk/civilengineering/research/researchnewsandreports/researchreports`.

J. Douglas. An investigation of analysis of variance as a tool for exploring regional differences in strong ground motions. *Journal of Seismology*, 8(4):485–496, Oct 2004b.

J. Douglas. Errata of and additions to 'Ground motion estimation equations 1964–2003'. Intermediary report RP-54603-FR, BRGM, Orléans, France, Dec 2006. URL `http://www.brgm.fr/publication/rechRapportSP.jsp`.

J. Douglas. On the regional dependence of earthquake response spectra. *ISET Journal of Earthquake Technology*, 44(1):71–99, Mar 2007.

J. Douglas. Further errata of and additions to 'Ground motion estimation equations 1964–2003'. Final report RP-56187-FR, BRGM, Orléans, France, Dec 2008. URL `http://www.brgm.fr/publication/rechRapportSP.jsp`.

J. Douglas. Assessing the epistemic uncertainty of ground-motion predictions. In *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, 2010a. Paper no. 219.

J. Douglas. Consistency of ground-motion predictions from the past four decades. *Bulletin of Earthquake Engineering*, 8(6):1515–1526, 2010b. doi: 10.1007/s10518-010-9195-5.

J. Douglas. Ground-motion prediction equations 1964–2010. Final report RP-59356-FR, BRGM, Orléans, France, Jan 2011. URL `http://www.brgm.fr/publication/rechRapportSP.jsp`.

J. Douglas. Consistency of ground-motion predictions from the past four decades: Peak ground velocity and displacement, Arias intensity and relative significant duration. *Bulletin of Earthquake Engineering*, 10(5): 1339–1356, 2012. doi: 10.1007/s10518-012-9359-6.

J. Douglas. Preface of special issue: A new generation of ground-motion models for europe and the middle east. *Bulletin of Earthquake Engineering*, 12(1):307–310, 2014. doi: 10.1007/s10518-013-9535-3.

J. Douglas. Calibrating the backbone approach for the development of earthquake ground motion models. In *Best Practices in Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations: issues and challenges towards full Seismic Risk Analysis (2nd Best PSHANI)*, Cadarache Chateau, France, May 2018a.

J. Douglas. Capturing geographically-varying uncertainty in earthquake ground motion models or what we think we know may change. In K. Pitilakis, editor, *Recent Advances in Earthquake Engineering in Europe*, volume 46 of *Geotechnical, Geological and Earthquake Engineering*, pages 153–181. Springer International Publishing AG, 2018b. doi: 10.1007/978-3-319-75741-4_6.

J. Douglas and H. Aochi. A survey of techniques for predicting earthquake ground motions for engineering purposes. *Surveys in Geophysics*, 29(3):187–220, 2008. doi: 10.1007/s10712-008-9046-y.

J. Douglas and D. M. Boore. High-frequency filtering of strong-motion records. *Bulletin of Earthquake Engineering*, 9(2):395–409, 2011. doi: 10.1007/s10518-010-9208-4.

J. Douglas and B. Edwards. Recent and future developments in earthquake ground motion estimation. *Earth-Science Reviews*, 160:203–219, 2016. doi: 10.1016/j.earscirev.2016.07.005.

J. Douglas and H. Halldórsson. On the use of aftershocks when deriving ground-motion prediction equations. In *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, 2010. Paper no. 220.

J. Douglas and P. M. Smit. How accurate can strong ground motion attenuation relations be? *Bulletin of the Seismological Society of America*, 91(6):1917–1923, 2001.

J. Douglas, H. Bungum, and F. Scherbaum. Ground-motion prediction equations for southern Spain and southern Norway obtained using the composite model perspective. *Journal of Earthquake Engineering*, 10(1):33–72, 2006.

J. Douglas, B. Edwards, V. Convertito, N. Sharma, A. Tramelli, D. Kraaijpoel, B. M. Cabrera, N. Maercklin, and C. Troise. Predicting ground motion from induced earthquakes in geothermal areas. *Bulletin of the Seismological Society of America*, 103(3):1875–1897, Jun 2013. doi: 10.1785/0120120197.

J. Douglas, S. Akkar, G. Ameri, P.-Y. Bard, D. Bindi, J. J. Bommer, S. S. Bora, F. Cotton, B. Derras, M. Hermkes, N. M. Kuehn, L. Luzi, M. Massa, F. Pacor, C. Riggelsen, M. A. Sandikkaya, F. Scherbaum, P. J. Stafford, and P. Traversa. Comparisons among the five ground-motion models developed using RESORCE for the prediction of response spectral accelerations due to earthquakes in Europe and the Middle East. *Bulletin of Earthquake Engineering*, 12(1):341–358, 2014. doi: 10.1007/s10518-013-9522-8.

D. J. Dowrick. Attenuation of modified Mercalli intensity in New Zealand earthquakes. *Earthquake Engineering and Structural Dynamics*, 21(3):181–196, 1992.

D. J. Dowrick and D. A. Rhoades. Attenuation of modified Mercalli intensity in New Zealand earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, 32(4):55–89, 1999.

D. J. Dowrick and D. A. Rhoades. Revised models for attenuation of Modified Mercalli Intensity in New Zealand earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, 38(4):185–214, Dec 2005.

D. J. Dowrick and S. Sritharan. Attenuation of peak ground accelerations in some recent New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 26(1):3–13, 1993. Not seen. Reported in Stafford (2006).

N. R. Draper and H. Smith. *Applied Regression Analysis*. John Wiley & Sons, 2nd edition, 1981.

S. Drouet. Erratum to: Regional stochastic GMPEs in low-seismicity areas: Scaling and aleatory variability analysis — Application to the French Alps. *Bulletin of the Seismological Society of America*, 107(1):501, Feb 2017. doi: 10.1785/0120160234.

S. Drouet and F. Cotton. Regional stochastic GMPEs in low-seismicity areas: Scaling and aleatory variability analysis — Application to the French Alps. *Bulletin of the Seismological Society of America*, 105(4):1883–1902, Aug 2015. doi: 10.1785/0120140240.

W. Du. An empirical model for the mean period ($t_m$) of ground motions using the NGA-West2 database. *Bulletin of Earthquake Engineering*, 15:2673–2693, 2017. doi: 10.1007/s10518-017-0088-8.

W. Du and G. Wang. A simple ground-motion prediction model for cumulative absolute velocity and model validation. *Earthquake Engineering and Structural Dynamics*, 42:1189–1202, 2013. doi: 10.1002/eqe.2266.

D. Eberhart-Phillips and G. McVerry. Estimating slab earthquake response spectra from a 3D $Q$ model. *Bulletin of the Seismological Society of America*, 93(6):2649–2663, 2003.

B. Edwards and J. Douglas. Selecting ground-motion models developed for induced seismicity in geothermal areas. *Geophysical Journal International*, 195:1314–1322, 2013. doi: 10.1093/gji/ggt310.

B. Edwards and D. Fäh. Measurements of stress parameter and site attenuation from recordings of moderate to large earthquakes in Europe and the Middle East. *Geophysical Journal International*, 194(2):1190–1202, Aug 2013a. doi: 10.1093/gji/ggt158.

B. Edwards and D. Fäh. A stochastic ground-motion model for Switzerland. *Bulletin of the Seismological Society of America*, 103(1), 2013b. doi: 10.1785/0120110331.

B. Edwards and A. Rietbrock. A comparative study on attenuation and source-scaling relations in the Kanto, Tokai, and Chubu regions of Japan, using data from Hi-Net and KiK-Net. *Bulletin of the Seismological Society of America*, 99(4):2435–2460, Aug 2009. doi: 10.1785/0120080292.

B. Edwards, H. Crowley, R. Pinho, and J. J. Bommer. Seismic hazard and risk due to induced earthquakes at a shale gas site. *Bulletin of the Seismological Society of America*, 111(2):875–897, 2021. doi: 10.1785/0120200234.

Y. M. El Hassan. Structural response to earthquake ground motion in Sudan. Master's thesis, University of Khartoum, Sudan, 1994. Not seen. Reported in Abdalla et al. (2001).

Electric Power Research Institute. Engineering model of earthquake ground motion for eastern North America. Final report NP-6074, 1988. Research project 2556-16. Investigators: McGuire, R. K., Toro, G. R., W. J. Silva.

Electric Power Research Institute. Empirical ground motion data in eastern North America. In J. F. Schneider, editor, *Guidelines for determining design basis ground motions*, volume EPRI TR-102293. 1993a.

Electric Power Research Institute. Engineering model of strong ground motions from earthquakes in the central and eastern United States. In J. F. Schneider, editor, *Guidelines for determining design basis ground motions*, volume EPRI TR-102293. 1993b.

Electric Power Research Institute. CEUS ground motion project final report. Technical Report 1009684, EPRI, Palo Alto, CA, Dominion Energy, Glen Allen, VA, Entergy Nuclear, Jackson, MS, and Exelon Generation Company, Kennett Square, PA., Dec 2004.

Electric Power Research Institute. EPRI (2004, 2006) ground-motion model (GMM) review project. Technical Report 3002000717, EPRI, Palo Alto, CA, USA, 2013.

S. M. R. Emami, Y. Iwao, and T. Harada. A method for prediction of peak horizontal acceleration by artificial neural networks. In *Proceedings of Eleventh World Conference on Earthquake Engineering*, 1996. Paper no. 1238.

A. Emolo, V. Convertito, and L. Cantore. Ground-motion predictive equations for low-magnitude earthquakes in the Campania-Lucania area, southern Italy. *Journal of Geophysics and Engineering*, 8(1):46–60, 2011. doi: 10.1088/1742-2132/8/1/007.

A. Emolo, N. Sharma, G. Festa, A. Zollo, V. Convertito, J.-H. Park, H.-C. Chi, and I.-S. Lim. Ground-motion prediction equations for South Korea peninsula. *Bulletin of the Seismological Society of America*, 105(5): 2625–2640, Oct 2015. doi: 10.1785/0120140296.

E. R. Engdahl, R. van der Hilst, and R. Buland. Global teleseismic earthquake relocation with improved travel times procedures for depth determination. *Bulletin of the Seismological Society of America*, 88:722–743, 1998.

J. E. Erdem, J. Boatwright, and J. B. Fletcher. Ground-motion attenuation in the Sacramento–San Joaquin Delta, California, from 14 Bay Area earthquakes, including the 2014 M 6.0 South Napa earthquake. *Bulletin of the Seismological Society of America*, 109(3):1025–1033, Jun 2019. doi: 10.1785/0120180182.

M. Erdik, V. Doyuran, N. Akkas, and P. Gulkan. A probabilistic assessment of the seismic hazard in Turkey. *Tectonophysics*, 117:295–344, 1985.

A. Erken, G. Ş. Nomaler, and Z. Gündüz. The development of attenuation relationship for northwest Anatolia region. *Arabian Journal of Geosciences*, 11(21), 2018. doi: 10.1007/s12517-017-3359-4.

A. F. Espinosa. Attenuation of strong horizontal ground accelerations in the western United States and their relation to $M_L$. *Bulletin of the Seismological Society of America*, 70(2):583–616, Apr 1980.

L. Esteva. Seismic risk and seismic design. In R.J. Hansen, editor, *Seismic Design for Nuclear Power Plants*, pages 142–182. The M.I.T. Press, 1970.

L. Esteva. Geology and probability in the assessment of seismic risk. In *Proceedings of the 2nd International Conference of the Association of Engineering Geology*, Sao Paulo, 1974. Not seen. Reported in Ambraseys (1978a).

L. Esteva and E. Rosenblueth. Espectros de temblores a distancias moderadas y grandes. *Boletin Sociedad Mexicana de Ingenieria Sesmica*, 2:1–18, 1964. In Spanish.

L. Esteva and R. Villaverde. Seismic risk, design spectra and structural reliability. In *Proceedings of Fifth World Conference on Earthquake Engineering*, volume 2, pages 2586–2596, 1973.

E. Faccioli. Response spectra for soft soil sites. In *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, volume I, pages 441–456, Jun 1978.

E. Faccioli. Engineering seismic risk analysis of the Friuli region. *Bollettino di Geofisica Teorica ed Applicata*, XXI(83):173–190, Sep 1979.

E. Faccioli. Measures of strong ground motion derived from a stochastic source model. *Soil Dynamics and Earthquake Engineering*, 2(3):135–149, Jul 1983.

E. Faccioli and D. Agalbato. Attenuation of strong-motion parameters in the 1976 Friuli, Italy, earthquakes. In *Proceedings of the Second U.S. National Conference on Earthquake Engineering*, pages 233–242, 1979.

E. Faccioli and C. Cauzzi. Macroseismic intensities for seismic scenarios, estimated from instrumentally based correlations. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, 2006. Paper number 569.

E. Faccioli, A. Bianchini, and M. Villani. New ground motion prediction equations for $T > 1\,\mathrm{s}$ and their influence on seismic hazard assessment. In *Proceedings of the University of Tokyo Symposium on Long-Period Ground Motion and Urban Disaster Mitigation*, Mar 2010.

P. Fajfar and I. Perus. A non-parametric approach to attenuation relations. *Journal of Earthquake Engineering*, 1(2):319–340, 1997.

R. Fang, J. Zheng, J. Geng, Y. Shu, C. Shi, and J. Liu. Earthquake magnitude scaling using peak ground velocity derived from high-rate GNSS observations. *Seismological Research Letters*, 92(1):227–237, 2021. doi: 10.1785/0220190347.

Z. Farajpour and S. Pezeshk. A ground-motion prediction model for small-to-moderate induced earthquakes for central and eastern United States. *Earthquake Spectra*, 37(Issue 1 Supplement):1440–1459, 2021. doi: 10.1177/87552930211016014.

Z. Farajpour, S. Pezeshk, and M. Zare. A new empirical ground-motion model for Iran. *Bulletin of the Seismological Society of America*, 109(2):732–744, Apr 2019. doi: 10.1785/0120180139.

R. Fat-Helbary and Y. Ohta. Attenuation models of seismic intensity and peak ground acceleration in Egypt. In *Proceedings of the first Cairo Earthquake Engineering Symposium*, pages 55—-70, 1994. Not seen. Reported by Deif et al. (2011).

C. Felicetta, G. Lanzano, M. D'Amico, R. Puglia, L. Luzi, and F. Pacor. Ground motion model for reference rock sites in Italy. *Soil Dynamics and Earthquake Engineering*, 110:276–283, 2018. doi: 10.1016/j.soildyn.2018.01.024.

E. H. Field. A modified ground-motion attenuation relationship for southern California that accounts for detailed site classification and a basin-depth effect. *Bulletin of the Seismological Society of America*, 90(6B):S209–S221, Dec 2000.

R. Foulser-Piggott and K. Goda. New prediction equations of Arias intensity and cumulative absolute velocity for Japanese earthquakes. In *Proceedings of Second European Conference on Earthquake Engineering and Seismology (a joint event of the 15th ECEE & 31st General Assembly of the ESC*, Aug 2014. Paper no. 918.

R. Foulser-Piggott and K. Goda. Ground-motion prediction models for Arias intensity and cumulative absolute velocity for Japanese earthquakes considering single-station sigma and within-event spatial correlation. *Bulletin of the Seismological Society of America*, 105(4):1903–1918, Aug 2015. doi: 10.1785/0120140316.

R. Foulser-Piggott and P. J. Stafford. A predictive model for Arias intensity at multiple sites and consideration of spatial correlations. *Earthquake Engineering and Structural Dynamics*, 41(3):431—-451, Mar 2012. doi: 10.1002/eqe.1137.

A. Frankel, C. Mueller, T. Barnhard, D. Perkins, E. V. Leyendecker, N. Dickman, S. Hanson, and M. Hopper. National Seismic-Hazard Maps: Documentation June 1996. Open-File Report 96-532, U.S. Department of the Interior, U.S. Geological Survey, 1996.

M. W. Free. *The Attenuation of Earthquake Strong-Motion in Intraplate regions*. PhD thesis, University of London, 1996.

M. W. Free, N. N. Ambraseys, and S. K. Sarma. Earthquake ground-motion attenuation relations for stable continental intraplate regions. ESEE Report 98-1, Department of Civil Engineering, Imperial College, London, Feb 1998.

M. Frisenda, M. Massa, D. Spallarossa, G. Ferretti, and C. Eva. Attenuation relationships for low magnitude earthquakes using standard seismometric records. *Journal of Earthquake Engineering*, 9(1):23–40, 2005.

C. Frohlich and K. D. Apperson. Earthquake focal mechanisms, moment tensors, and the consistency of seismic activity near plate boundaries. *Tectonics*, 11(2):279–296, Apr 1992.

S. Fukushima, T. Hayashi, and H. Yashiro. Seismic hazard analysis based on the joint probability density function of PGA and PGV. In *Transactions, SMiRT 19*, Aug 2007a. Paper # M03/1.

Y. Fukushima and T. Tanaka. A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan. *Bulletin of the Seismological Society of America*, 80(4):757–783, 1990.

Y. Fukushima, T. Tanaka, and S. Kataoka. A new attenuation relationship for peak ground acceleration derived from strong-motion accelerograms. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 343–348, 1988.

Y. Fukushima, J.-C. Gariel, and R. Tanaka. Prediction relations of seismic motion parameters at depth using borehole data. In *Proceedings of Tenth European Conference on Earthquake Engineering*, volume 1, pages 417–422, 1994.

Y. Fukushima, J.-C. Gariel, and R. Tanaka. Site-dependent attenuation relations of seismic motion parameters at depth using borehole data. *Bulletin of the Seismological Society of America*, 85(6):1790–1804, Dec 1995.

Y. Fukushima, C. Berge-Thierry, P. Volant, D.-A. Griot-Pommera, and F. Cotton. Attenuation relation for western Eurasia determined with recent near-fault records from California, Japan and Turkey. *Journal of Earthquake Engineering*, 7(4):573–598, 2003.

Y. Fukushima, J. X. Zhao, J. Zhang, A. Asano, Y. Ohno, T. Oouchi, T. Takahashi, H. Ogawa, K. Irikura, Y. Fukushima, H. K. Thio, and P. G. Somerville. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, 2006. Paper number 683.

Y. Fukushima, F. Bonilla, O. Scotti, and J. Douglas. Impact of site classification on deriving empirical ground-motion prediction equations: Application to the west Eurasia dataset. In *7ème Colloque National AFPS 2007*, Jul 2007b.

Y. Fukushima, L. F. Bonilla, O. Scotti, and J. Douglas. Site classification using horizontal-to-vertical response spectral ratios and its impact when deriving empirical ground motion prediction equations. *Journal of Earthquake Engineering*, 11(5):712–724, 2007c. doi: 10.1080/13632460701457116.

L. Fülöp, V. Jussila, R. Aapasuo, T. Vuorinen, and P. Mäntyniemi. A ground=motion prediction equation for Fennoscandian nuclear installations. *Bulletin of the Seismological Society of America*, 110(3):1211–1230, Jun 2020. doi: 10.1785/0120190230.

M. Gallego. *Estimación del riesgo sísmico en la República de Colombia*. PhD thesis, Universidad Autónoma de México, Mexico City, Mexico, 2000. In Spanish. Not seen.

M. Gallego and M. Ordaz. Construcción de leyes de atenuación para Colombia a partir de espectros fuente y teoría de vibraciones aleatorias. *Revista internacional de ingeniería de estructuras*, 4(1):45–60, 1999. In Spanish. Not seen. Cited in Bernal et al. (2014).

D. Galluzzo, F. Bianco, M. La Rocca, and G. Zonno. Ground motion observations and simulation for local earthquakes in the Campi Flegrei volcanic area. *Bulletin of Earthquake Engineering*, 14(7):1903–1916, Jul 2016. doi: 10.1007/s10518-015-9770-x.

J. P. W. Gamage. *Earthquake Ground Motion Models for Sri Lanka*. PhD thesis, College of Engineering and Science, Victoria University, Sri Lanka, Aug 2015.

A. Ganas, N. Andritsou, C. Kosma, P. Argyrakis, V. Tsironi, and G. Drakatos. A 20-yr database (1997–2017) of co-seismic displacements from GPS recordings in the Aegean area and their scaling with mw and hypocentral distance. *Bulletin of the Geological Society of Greece*, 52(1):98–130, 2018. doi: 10.12681/bgsg.18070.

M. Gandomi, M. Soltanpour, M. R. Zolfaghari, and A. H. Gandomi. Prediction of peak ground acceleration of Iran's tectonic regions using a hybrid soft computing technique. *Geoscience Frontiers*, 7(1):75–82, Jan 2016. doi: 10.1016/j.gsf.2014.10.004.

M. Gandomi, A. R. Kashani, A. Farhadi, M. Akhani, and A. H. Gandomi. Spectral acceleration prediction using genetic programming based approaches. *Applied Soft Computing*, 106:107326, 2021. doi: 10.1016/j.asoc.2021.107326.

J.-C. Gao, C.-H. Chan, and C.-T. Lee. Site-dependent ground-motion prediction equations and uniform hazard response spectra. *Engineering Geology*, 292(106241), 2021. doi: 10.1016/j.enggeo.2021.106241.

D. García, S. K. Singh, M. Herráiz, M. Ordaz, and J. F. Pacheco. Inslab earthquakes of central Mexico: Peak ground-motion parameters and response spectra. *Bulletin of the Seismological Society of America*, 95(6):2272–2282, Dec 2005. doi: 10.1785/0120050072.

S. Garcia and M. Romo. Machine learning for ground-motion relations. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, Sep 2006. Paper no. 1438.

R. M. Garcìa Blanco. *Caracterización del potencial sísmico y su influencia en la determinación de la peligrosidad sìsmica probabilista*. PhD thesis, Polythecnical University of Madrid, 2009. In Spanish. Not seen. Reported by Mezcua et al. (2011).

M. Garcìa-Fernàndez and J. A. Canas. Estimation of regional values of peak ground acceleration from short-period seismograms. In *Proceedings of the Fourth International Conference on Seismic Zonation*, volume II, pages 533–539, 1991.

M. Garcia-Fernandez and J.A. Canas. Regional Lg-wave attenuation and estimates of peak ground acceleration in the Iberian peninsula. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 1, pages 439–443, 1992.

M. Garcia-Fernandez and J.A. Canas. Regional peak ground acceleration estimates in the Iberian peninsula. In *Proceedings of the Fifth International Conference on Seismic Zonation*, volume II, pages 1029–1034, 1995.

M. García-Fernández, P. Gehl, M. J. Jiménez, and D. D'Ayala. A pan-European representative ground motion model. In *35th General Assembly of the European Seismological Commission*, Sep 2016. Abstract only. Number ESC2016-527.

M. García-Fernández, P. Gehl, M. J. Jiménez, and D. D'Ayala. Modelling pan-European ground motions for seismic hazard applications. *Bulletin of Earthquake Engineering*, 17(6):2821–2840, Jun 2019. doi: 10.1007/s10518-019-00605-4.

A. D. García-Soto and M. A. Jaimes. Ground-motion prediction model for vertical response spectra from Mexican interplate earthquakes. *Bulletin of the Seismological Society of America*, 107(2):887–900, Apr 2017. doi: 10.1785/0120160273.

J. K. Gardner and L. Knopoff. Is the sequence of earthquakes in southern California, with aftershocks removed, Poissonian ? *Bulletin of the Seismological Society of America*, 64:1363—-1367, 1974.

B. A. Gaull. Attenuation of strong ground motion in space and time in southwest Western Australia. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 361–366, 1988.

B. A. Gaull, M. O. Michael-Leiba, and J. M. W. Rynn. Probabilistic earthquake risk maps of Australia. *Australian Journal of Earth Sciences*, 37:169–187, 1990. Not seen. Cited in Musson and Cecić (2002).

P. Gehl. *Bayesian Networks for the Multi-Risk Assessment of Road Infrastructure*. PhD thesis, University of London (University College London), 2017.

P. Gehl, L. F. Bonilla, and J. Douglas. Accounting for site characterization uncertainties when developing ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 101(3):1101–1108, Jun 2011. doi: 10.1785/0120100246.

Geomatrix Consultants. Seismic ground motion study for West San Francisco Bay Bridge. Report for caltrans, division of structures, sacramento, california, Mar 1991. Not seen. Cited in Idriss (1993).

GeoPentech. Southwestern United States ground motion characterization SSHAC Level 3. Technical Report Rev. 2, Mar 2015.

B. K. Ghalehjough and R. Mahinroosta. Peak ground acceleration prediction by fuzzy logic modeling for Iranian plateau. *Acta Geophysica*, 68:75–89, 2020. doi: 10.1007/s11600-019-00394-z.

S. Ghanat. *Duration characteristics of the mean horizontal component of shallow crustal earthquake records in active tectonic regions*. PhD thesis, Arizona State University, USA, 2011.

H. Ghasemi, M. Zare, Y. Fukushima, and K. Koketsu. An empirical spectral ground-motion model for Iran. *Journal of Seismology*, 13(4):499–515, Oct 2009. doi: 10.1007/s10950-008-9143-x.

H. Ghofrani and G. M. Atkinson. Ground-motion prediction equations for interface earthquake of M7 to M9 based on empirical data from Japan. *Bulletin of Earthquake Engineering*, 12(2):549–571, 2014. doi: 10.1007/s10518-013-9533-5.

G. K. Ghosh and A. K. Mahajan. Interpretation of intensity attenuation relation of 1905 Kangra earthquake with epicentral distance and magnitude in the northwest himalayan region. *Journal of the Geological Society of India*, 77:511–520, Jun 2011. doi: 10.1007/s12594-011-0058-8.

G. K. Ghosh and A. K. Mahajan. Intensity attenuation relation at Chamba-Garhwal area in north-west Himalaya with epicentral distance and magnitude. *Journal of Earth System Science*, 122(1):107–122, 2013.

N. Gianniotis, N. Kuehn, and F. Scherbaum. Manifold aligned ground motion prediction equations for regional datasets. *Computers and Geosciences*, 69:72–77, Aug 2014. doi: 10.1016/j.cageo.2014.04.014.

Y. Gitterman, Y. Zaslavsky, and A. Shapira. Analysis of strong records in Israel. In *Proceedings of XVIIth regional European seminar on earthquake engineering, Haifa, Israel*, Sep 1993. Not seen.

K. Goda and G. M. Atkinson. Probabilistic characterization of spatially correlated response spectra for earthquakes in Japan. *Bulletin of the Seismological Society of America*, 99(5):3003–3020, Oct 2009. doi: 10.1785/0120090007.

K. Goda and H. P. Hong. Spatial correlation of peak ground motions and response spectra. *Bulletin of the Seismological Society of America*, 98(1):354–365, Feb 2008. doi: 10.1785/0120070078.

A. Gogoi, S. Baruah, and S. Sharma. Regression analysis on ground motion parameters for the earthquakes ($Mw \geq 4.0$) in NE India with special emphasis on 3 jan 2016 M6.7, Tamenglong earthquake. *Physics and Chemistry of the Earth*, 129:103316, 2023. doi: 10.1016/j.pce.2022.103316.

E. Gök and İ Kaftan. Prediction of peak ground acceleration by artificial neural network and adaptive neuro-fuzzy inference system. *Annal of Geophysics*, 65(1):SE106, 2022. doi: 104401/ag-8659.

A. Golik and M. J. Mendecki. Ground-motion prediction equations for induced seismicity in the main anticline and main syncline, Upper Silesian Coal Basin, Poland. *Acta Geophysica*, 60(2):410–425, Apr 2012. doi: 10.2478/s11600-011-0070-9.

A. Gómez-Bernal, M. A. Lecea, and H. Juárez-García. Empirical attenuation relationship for Arias intensity in Mexico and their relation with the damage potential. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2012. Paper no. 3826.

C. Gómez-Soberón, A. Tena-Colunga, and M. Ordaz. Updated attenuation laws in displacement and acceleration for the Mexican Pacific coast as the first step to improve current design spectra for base-isolated structures in Mexico. In *Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*, Apr 2006. Paper no. 1010.

M.-S. Gong and L.-L. Xie. Study on comparison between absolute and relative input energy spectra and effects of ductility factor. *Acta Seismologica Sinica*, 18(6):717–726, Nov 2005.

H. Goto, H. Kameda, N. Imanishi, and O. Hashimoto. Statistical analysis of earthquake ground motion with the effect of frequency-content correction. In *5th Japan Earthquake Engineering Symposium*, volume 11, pages 49–56, 1978. In Japanese. Not seen. Cited in Goto et al. (1981).

H. Goto, H. Kameda, and M. Sugito. Attenuation and estimation of site-dependent earthquake motions. *Journal of Natural Disaster Science*, 3(1):15–31, 1981.

C. Goulet, Y. Bozorgnia, N. Abrahamson, N. Kuehn, L. Al Atik, R. Youngs, and R. Graves. Central and eastern north america ground-motion characterization — NGA-East final report. PEER Report 2018/08, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, USA, 2018.

C. A. Goulet, Y. Bozorgnia, N. Kuehn, L. Al Atik, R. R. Youngs, R. W. Graves, and G. M. Atkinson. NGA-East ground-motion models for the U.S. Geological Survey national seismic hazard maps. PEER Report 2017/03, Pacifi c Earthquake Engineering Research Center, University of California, Berkeley, USA, Mar 2017.

V. Graizer. Ground-motion prediction equations for central and eastern North America. *Bulletin of the Seismological Society of America*, 106(4):1600–1612, Aug 2016. doi: 10.1785/0120150374.

V. Graizer. Alternative (G-16v2) ground-motion prediction equations for central and eastern North America. *Bulletin of the Seismological Society of America*, 107(2):869–886, Apr 2017. doi: 10.1785/0120160212.

V. Graizer. GK17 ground-motion prediction equation for horizontal PGA and 5% damped PSA from shallow crustal continental earthquakes. *Bulletin of the Seismological Society of America*, 108(1):380–398, Feb 2018. doi: 10.1785/0120170158.

V. Graizer and E. Kalkan. Ground motion attenuation model for peak horizontal acceleration from shallow crustal earthquakes. *Earthquake Spectra*, 23(3):585–613, Aug 2007. doi: 10.1193/1.2755949.

V. Graizer and E. Kalkan. A novel approach to strong ground motion attenuation modeling. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008. Paper no. 02-0022.

V. Graizer and E. Kalkan. Update of the Graizer-Kalkan ground-motion prediction equations for shallow crustal continental earthquakes. Open-File Report 2015–1009, U.S. Geological Survey, 2015.

V. Graizer and E. Kalkan. Summary of the GK15 ground-motion prediction equation for horizontal PGA and 5% damped PSA from shallow crustal continental earthquakes. *Bulletin of the Seismological Society of America*, 106(2):687–707, Apr 2016. doi: 10.1785/0120150194.

V. Graizer, E. Kalkan, and K.-W. Lin. Extending and testing Graizer-Kalkan ground motion attenuation model based on Atlas database of shallow crustal events. In *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, 2010. Paper no. 568.

V. Graizer, E. Kalkan, and K.-W. Lin. Global ground motion prediction equation for shallow crustal regions. *Earthquake Spectra*, 29(3):777–791, Aug 2013. doi: 10.1193/1.4000140.

N. Gregor, W. Silva, and B. Darragh. Development of attenuation relations for peak particle velocity and displacement. A pearl report to pg&e/cec/caltrans., Pacific Engineering and Analysis, El Cerrito, U.S.A., Jun. 2002a. URL `http://www.pacificengineering.org/rpts\_page1.shtml`.

N. J. Gregor, W. J. Silva, I. G. Wong, and R. R. Youngs. Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model. *Bulletin of the Seismological Society of America*, 92(5):1923–1932, Jun 2002b.

N.J. Gregor and B.A. Bolt. Peak strong motion attenuation relations for horizontal and vertical ground displacements. *Journal of Earthquake Engineering*, 1(2):275–292, 1997.

Z. Gülerce and N. A. Abrahamson. Site-specific design spectra for vertical ground motion. *Earthquake Spectra*, 27(4):1023–1047, Nov 2011. doi: 10.1193/1.3651317.

Z. Gülerce, B. Kargıoğlu, and N. A. Abrahamson. Turkey-adjusted NGA-W1 horizontal ground motion prediction models. *Earthquake Spectra*, 32(1):75–100, Feb 2016. doi: 10.1193/022714EQS034M.

Z. Gülerce, R. Kamai, N. A. Abrahamson, and W. J. Silva. Ground motion prediction equations for the vertical ground motion component based on the NGA-W2 database. *Earthquake Spectra*, 33(2):499–528, May 2017. doi: 10.1193/121814EQS213M.

P. Gülkan and E. Kalkan. Attenuation modeling of recent earthquakes in Turkey. *Journal of Seismology*, 6(3): 397–409, Jul 2002.

H. Güllü and E. Erçelebi. A neural network approach for attenuation relationships: An application using strong ground motion data from Turkey. *Engineering Geology*, 93(3–4):65–81, Aug 2007.

H. Güllü and R. İyisan. A seismic hazard study through the comparison of ground motion prediction equations using the weighting factor of logic tree. *Journal of Earthquake Engineering*, 20(6):861–884, 2016. doi: 10. 1080/13632469.2015.1104752.

H. Güllü, A. M. Ansal, and A. Özbay. Seismic hazard studies for Gaziantep city in south Anatolia of Turkey. *Natural Hazards*, 44:19–50, 2008. doi: 10.1007/s11069-007-9140-3.

K. Günaydın and A. Günaydın. Peak ground acceleration prediction by artifical neural networks for northwestern Turkey. *Mathematical Problems in Engineering*, 2008. doi: 10.1155/2008/919420. Article ID 919420.

A. Gupta, J. W. Baker, and W. L. Ellsworth. Assessing ground-motion amplitudes and attenuation for small-to-moderate induced and tectonic earthquakes in the central and eastern United States. *Seismological Research Letters*, 88(5):1379–1389, Sep/Oct 2017. doi: 10.1785/0220160199.

I. D. Gupta. Response spectral attenuation relations for in-slab earthquakes in Indo-Burmese subduction zone. *Soil Dynamics and Earthquake Engineering*, 30(5):368–377, May 2010. doi: 10.1016/j.soildyn.2009.12.009.

I. D. Gupta and M. D. Trifunac. Scaling of Fourier spectra of strong earthquake ground motion in western Himalaya and northeastern India. *Soil Dynamics and Earthquake Engineering*, 102:137–159, 2017. doi: 10.1016/j.soildyn.2017.08.010.

I. D. Gupta and M. D. Trifunac. Empirical scaling relations for pseudo relative velocity spectra in western Himalaya and northeastern India. *Soil Dynamics and Earthquake Engineering*, 106:70–89, 2018a. doi: 10.1016/j.soildyn.2017.12.005.

I. D. Gupta and M. D. Trifunac. Attenuation of strong earthquake ground motion —- I: Dependence on geology along the wave path from the Hindu Kush subduction zone to western Himalaya. *Soil Dynamics and Earthquake Engineering*, 114:127–146, 2018b. doi: 10.1016/j.soildyn.2018.05.008.

I. D. Gupta and M. D. Trifunac. Attenuation of strong earthquake ground motion —- II: Dependence on geology along the wave paths from the Burmese subduction zone to northeastern India. *Soil Dynamics and Earthquake Engineering*, 112:256–276, 2018c. doi: 10.1016/j.soildyn.2018.05.009.

I. D. Gupta and M. D. Trifunac. Attenuation of Fourier amplitude and pseudo relative velocity spectra due to local earthquakes in the national capital region of India. *Soil Dynamics and Earthquake Engineering*, 116: 593–611, 2019. doi: 10.1016/j.soildyn.2018.10.004.

S. Gupta and I. D. Gupta. The prediction of earthquake peak ground acceleration in Koyna region, India. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 1437.

A. Gürpinar. A stable attenuation law based on RMS of strong motion acceleration. In *Proceedings of the Symposium of the Analysis of Seismicity and on Seismic Risk*, Oct 1977.

A. A. Gusev, E. I. Gordeev, E. M. Guseva, A. G. Petukhin, and V. N. Chebrov. The first version of the $A_{max}(m_w, r)$ relationship for Kamchatka. *Pure and Applied Geophysics*, 149(2):299–312, 1997.

A. Haendel, S. Specht, N. M. Kuehn, and F. Scherbaum. Mixtures of ground-motion prediction equations as backbone models for a logic tree: An application to the subduction zone in northern Chile. *Bulletin of Earthquake Engineering*, 13(2):483–501, 2015. doi: 10.1007/s10518-014-9636-7.

A. Haji-Soltani, S. Pezeshk, M. Malekmohammadi, and A. Zandieh. A study of vertical-to-horizontal ratio of earthquake components in the Gulf Coast region. *Bulletin of the Seismological Society of America*, 107(5): 2055–2066, Oct 2017. doi: 10.1785/0120160252.

B. Halldorsson and A. S. Papageorgiou. Calibration of the specific barrier model to earthquakes of different tectonic regions. *Bulletin of the Seismological Society of America*, 95(4):1276–1300, Aug 2005. doi: 10.1785/0120040157.

P. Halldórsson and B. I. Sveinsson. Dvínun hröðunar á Íslandi. Technical Report 03025, Veðurstofa Íslands (Icelandic Meteorological Office), Aug 2003.

S. M. Hamze-Ziabari and T. Bakhshpoori. Improving the prediction of ground motion parameters based on an efficient bagging ensemble model of M5 and CART algorithms. *Applied Soft Computing*, 68:147–161, 2018. doi: 10.1016/j.asoc.2018.03.052.

H. Hamzehloo and H. R. Bahoosh. Theoretical spectral attenuation relationship for Tehran region, Iran. In *Proceedings of Fourteenth European Conference on Earthquake Engineering*, 2010. Paper no. 821.

H. Hamzehloo and M. Mahood. Ground-motion attenuation relationship for east central Iran. *Bulletin of the Seismological Society of America*, 102(6):2677–2684, Dec 2012. doi: 10.1785/0120110249.

J. Hancock. *The influence of duration and the selection and scaling of accelerograms in engineering design and assessment*. PhD thesis, Imperial College London, United Kingdom, 2006.

J. Hancock and J. J. Bommer. The effective number of cycles of earthquake ground motion. *Earthquake Engineering and Structural Dynamics*, 34:637–664, 2005. doi: 10.1002/eqe.437.

J. Hancock, J. J. Bommer, and P. J. Stafford. Numbers of scaled and matched accelerograms required for inelastic dynamic analyses. *Earthquake Engineering and Structural Dynamics*, 37(14):1585–1607, 2008. doi: 10.1002/eqe.827.

H. Hao and B. A. Gaull. Estimation of strong seismic ground motion for engineering use in Perth Western Australia. *Soil Dynamics and Earthquake Engineering*, 29(5):909–924, May 2009. doi: 10.1016/j.soildyn.2008.10.006.

A. Harbindu, S. Gupta, and M. L. Sharma. Earthquake ground motion predictive equations for Garhwal Himalaya, India. *Soil Dynamics and Earthquake Engineering*, 66:135–148, Nov 2014. doi: 10.1016/j.soildyn.2014.06.018.

H. S. Hasegawa, P. W. Basham, and M. J. Berry. Attenuation relations for strong seismic ground motion in Canada. *Bulletin of the Seismological Society of America*, 71(6):1943–1962, Dec 1981.

B. Hassani and G. M. Atkinson. Referenced empirical ground-motion model for eastern North America. *Seismological Research Letters*, 86(2A):477–491, Mar/Apr 2015. doi: 10.1785/0220140156.

B. Hassani and G. M. Atkinson. Adjustable generic ground-motion prediction equation based on equivalent point-source simulations: Accounting for kappa effects. *Bulletin of the Seismological Society of America*, 108 (2):913–928, Apr 2018. doi: 10.1785/0120170333.

N. Hassani, G. G. Amiri, M. Bararnia, and F. Sinaeian. Ground motion prediction equation for inelastic spectral displacement in Iran. *Scientia Iranica — Transactions B: Mechanical Engineering*, 24(1):164–182, 2017.

G. P. Hayes, D. J. Wald, and R. L. Johnson. Slab1.0: A three-dimensional model of global subduction zone geometries. *Journal of Geophysical Research*, 117(B01302), 2012. doi: 10.1029/2011JB008524.

W. W. Hays. Procedures for estimating earthquake ground motions. Geological Survey Professional Paper 1114, US Geological Survey, 1980.

M. Herak, S. Markušić, and I. Ivančić. Attenuation of peak horizontal and vertical acceleration in the Dinarides area. *Studia Geophysica et Geodaetica*, 45(4):383–394, 2001.

M. Hermkes, N. M. Kuehn, and C. Riggelsen. Simulataneous quantification of epistemic and aleatory uncertainty in GMPEs using Gaussian process regression. *Bulletin of Earthquake Engineering*, 12(1):449–466, 2014. doi: 10.1007/s10518-013-9507-7.

B. Hernandez and F. Cotton. Empirical determination of the ground shaking duration due to an earthquake using strong motion accelerograms for engineering applications. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper no. 2254/4/A.

B. Hernandez, Y. Fukushima, R. Bossu, and J. Albaric. Seismic attenuation relation for Hualien (Taiwan) at the free surface and down to 52.6 m deep. In *Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, volume 1, pages 145–154, 2006. Paper number 008.

R. B. Herrmann and M. J. Goertz. A numerical study of peak ground motion scaling. *Bulletin of the Seismological Society of America*, 71(6):1963–1979, Dec 1981.

R. B. Herrmann and O. W. Nuttli. Scaling and attenuation relations for strong ground motion in eastern North America. In *Proceedings of Eighth World Conference on Earthquake Engineering*, volume II, pages 305–309, 1984.

S. Hiehata, M. Takemura, and T. Ohta. Regression analysis on Fourier amplitude spectra of seismic ground motions in terms of earthquake magnitude, hypocentral distance and site condition. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 319–324, Aug 1988. Paper 3-2-9.

K.-G. Hinzen and M. Oemisch. Location and magnitude from seismic intensity data of recent and historic earthquakes in the northern Rhine area, central Europe. *Bulletin of the Seismological Society of America*, 91 (1):40–56, Jan 2001. doi: 10.1785/0120000036.

H. P. Hong and K. Goda. Orientation-dependent ground-motion measure for seismic-hazard assessment. *Bulletin of the Seismological Society of America*, 97(5):1525–1538, Oct 2007. doi: 10.1785/0120060194.

H. P. Hong and K. Goda. Characteristics of horizontal ground motion measures along principal directions. *Earthquake Engineering and Engineering Vibration*, 9(1):9–22, Mar 2010. doi: 10.1007/s11803-010-9048-x.

H. P. Hong, A. Pozos-Estrada, and R. Gomez. Orientation effect on ground motion measurements for Mexican subduction earthquakes. *Earthquake Engineering and Engineering Vibration*, 8(1):1–16, Mar 2009a. doi: 10.1007/s11803-009-8155-z.

H. P. Hong, Y. Zhang, and K. Goda. Effect of spatial correlation on estimated ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 99(2A):928–934, Apr 2009b. doi: 10.1785/0120080172.

M. Horike and T. Nishimura. Attenuation relationships of peak ground velocity inferred from the Kyoshin network data. *Journal of Structural and Construction Engineering (Transactions of AIJ)*, 575:73—-79, 2004. In Japanese. Not seen. Cited in Edwards and Rietbrock (2009).

J. Hu, J. Tan, and J. X. Zhao. New gmpes for the Sagami Bay region in Japan for moderate magnitude events with emphasis on differences on site amplifications at the seafloor and land seismic stations of K-NET. *Bulletin of the Seismological Society of America*, 110(5):2577–2597, Oct 2020. doi: 10.1785/0120190305.

C. Huang and C. Galasso. Ground-motion intensity measure correlations observed in Italian strong-motion records. *Earthquake Engineering and Structural Dynamics*, 48:1634–1660, 2019. doi: 10.1002/eqe.3216.

C. Huang, K. Tarbali, and C. Galasso. Correlation properties of integral ground-motion intensity measures from Italian strong-motion records. *Earthquake Engineering and Structural Dynamics*, 49(15), 2020. doi: 10.1002/eqe.3318.

C. Huang, K. Tarbali, and C. Galasso. A region-specific ground-motion model for inelastic spectral displacement in northern Italy considering spatial correlation properties. *Seismological Research Letters*, 92(3):1979–1991, 2021a. doi: 10.1785/0220200249.

H. Huang, R. Ramkrishnan, S. Kolathayar, A. Garg, and J. S. Yadav. Development of region-specific new generation attenuation relations for north India using artificial neural networks. In *Proceedings of the 1st Indo-China Research Series in Geotechnical and Geoenvironmental Engineering*, pages 85–101. Springer, 2021b. doi: 10.1007/978-981-33-4324-5_6.

N. Humbert and E. Viallet. An evaluation of epistemic and random uncertainties included in attenuation relationship parameters. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008. Paper no. 07-0117.

T. V. Hung and O. Kiyomiya. Ground motion attenuation relationship for shallow strike-slip earthquakes in northern Vietnam based on strong motion records from Japan, Vietnam and adjacent regions. *Journal of Japan Society of Civil Engineers, Ser. A1 (Structural Engineering & Earthquake Engineering)*, 68(3):509–525, 2012.

J. Huo and Y. Hu. Attenuation laws considering the randomness of magnitude and distance. *Earthquake Research in China*, 5(1):17–36, 1991.

J. Huo and Y. Hu. Study on attenuation laws of ground motion parameters. *Earthquake Engineering and Engineering Vibration*, 12:1–11, 1992. Not see. Reported in Zhang et al. (1999).

J. Huo, Y. Hu, and Q. Feng. Study on estimation of ground motion from seismic intensity. *Earthquake Engineering and Engineering Vibration*, 12(3):1–15, 1992. In Chinese. Not seen.

J. R. Huo. *The characteristics of near field strong earthquake ground motion*. PhD thesis, Institute of Engineering and Mechanics, China Seismological Bureau, China, 1989. In Chinese. Not seen. Cited in Wang et al. (2002).

H. Hwang. Attenuation of Arias intensity based on data from the Chi-Chi earthquake. In *Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*, 2006. Paper No. 306. Not seen. Cited in Alarcón (2007).

H. Hwang and J.-R. Huo. Attenuation relations of ground motion for rock and soil sites in eastern United States. *Soil Dynamics and Earthquake Engineering*, 16(6):363–372, 1997.

H. Hwang, C. K. Lin, Y. T. Yeh, S. N. Cheng, and K. C. Chen. Attenuation relations of Arias intensity based on the Chi-Chi Taiwan earthquake data. *Soil Dynamics and Earthquake Engineering*, 24:509–517, 2004.

R. Ibrahim, H. Si, K. Koketsu, and H. Miyake. Long-period ground-motion prediction equations for moment magnitude estimation of large earthquakes in Japan. *Bulletin of the Seismological Society of America*, 106(1): 54–72, Feb 2016. doi: 10.1785/0120140244.

A. Içen and A. Sandikkaya. Region specific ground-motion predictive models for shallow active regions. *Journal of Earthquake Engineering*, 27(15):4449–4468, 2023. doi: 10.1080/13632469.2023.2167890.

B. Idini, F. Rojas, S. Ruiz, and C. Pastén. Ground motion prediction equations for the Chilean subduction zone. *Bulletin of Earthquake Engineering*, 15(5):1853–1880, May 2017. doi: 10.1007/s10518-016-0050-1.

I. M. Idriss. Characteristics of earthquake ground motions. In *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, volume III, pages 1151–1265, Jun 1978.

I. M. Idriss. Procedures for selecting earthquake ground motions at rock sites. Technical Report NIST GCR 93-625, National Institute of Standards and Technology, 1993.

I. M. Idriss. An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. *Earthquake Spectra*, 24(1):217–242, 2008. doi: 10.1193/1.2924362.

I. M. Idriss. NGA-West2 model for estimating average horizontal values of pseudo-absolute spectral accelerations generated by crustal earthquakes. Technical Report 2013/08, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, 2013.

I. M. Idriss. An NGA-West2 empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. *Earthquake Spectra*, 30(3):1155–1177, Aug 2014. doi: 10.1193/070613EQS195M.

I. Iervolino, M. Giorgio, C. Galasso, and G. Manfredi. Conditional hazard maps for secondary intensity measures. *Bulletin of the Seismological Society of America*, 100(6):3312–3319, 2010. doi: 10.1785/0120090383.

A. Iglesias, S. K. Singh, J. F. Pacheco, and M. Ordaz. A source and wave propagation study of the Copalillo, Mexico, earthquake of 21 July 2000 ($M_w$5.9): Implications for seismic hazard in Mexico City from inslab earthquakes. *Bulletin of the Seismological Society of America*, 92(3):1060–1071, Apr 2002. doi: 10.1785/0120010144.

E. Inan, Z. Colakoglu, N. Koc, N. Bayülke, and E. Coruh. Earthquake catalogs with acceleration records from 1976 to 1996. Technical report, General Directorate of Disaster Affairs, Earthquake Research Department, Ankara, Turkey, 1996. In Turkish. Not seen. Reported in Ulusay et al. (2004).

T. Iwasaki, K. Kawashima, and M. Saeki. Effects of seismic and geotechnical conditions on maximum ground accelerations and response spectra. In *Proceedings of Seventh World Conference on Earthquake Engineering*, volume 2, pages 183–190, 1980.

R. N. Iyengar and S. Ghosh. Microzonation of earthquake hazard in Greater Delhi area. *Current Science*, 87 (9):1193–1202, Nov 2004.

R. N. Iyengar and S. T. G. Raghu Kanth. Attenuation of strong ground motion in peninsular India. *Seismological Research Letters*, 75(4):530–540, Jul/Aug 2004. doi: 10.1785/gssrl.75.4.530.

K. H. Jacob, J.-C. Gariel, J. Armbruster, S. Hough, P. Friberg, and M. Tuttle. Site-specific ground motion estimates for New York City. In *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, volume 1, pages 587–596, May 1990.

M. A. Jaimes and A. D. García-Soto. Updated ground motion prediction model for Mexican intermediate-depth intraslab earthquakes including V/H ratios. *Earthquake Spectra*, 36(3):1298–1330, 2020. doi: 10.1177/8755293019899947.

M. A. Jaimes and A.-D. García-Soto. Ground-motion duration prediction model from recorded Mexican interplate and intermediate-depth intraslab earthquakes. *Bulletin of the Seismological Society of America*, 111(1): 258–273, 2021. doi: 10.1785/0120200196.

M. A. Jaimes, E. Reinoso, and M. Ordaz. Comparison of methods to predict response spectra at instrumented sites given the magnitude and distance of an earthquake. *Journal of Earthquake Engineering*, 10(6):887–902, 2006. doi: 10.1080/13632460609350622.

M. A. Jaimes, A. Ramirez-Gaytán, and E. Reinoso. Ground-motion prediction model from intermediate-depth intraslab earthquakes at the hill and lake-bed zones of Mexico City. *Journal of Earthquake Engineering*, 19 (8):1260–1278, 2015. doi: 10.1080/13632469.2015.1025926.

S. K. Jain, A. D. Roshan, J. N. Arlekar, and P. C. Basu. Empirical attenuation relationships for the Himalayan earthquakes based on Indian strong motion data. In *Proceedings of the Sixth International Conference on Seismic Zonation*, Nov 2000.

J. M. Jara-Guerrero, M. Jara-Diaz, and H. Hernández. Estimation of the pseudoacceleration response spectra in sites of Mexico. In *Proceedings of the International Symposium on Seismic Risk Reduction: The JICA Technical Cooperation Project in Romania*, pages 343–350, Apr 2007. Paper ID 13.

H. Javan-Emrooz, M. Eskandari-Ghadi, and N. Mirzaei. Prediction equations for horizontal and vertical PGA, PGV, and PGD in northern Iran using prefix gene expression programming. *Bulletin of the Seismological Society of America*, 108(4):2305–2332, 2018. doi: 10.1785/0120170155.

N. Jayaram and J. W. Baker. Considering spatial correlation in mixed-effects regression and the impact on ground-motion models. *Bulletin of the Seismological Society of America*, 100(6):3295–3303, Dec 2010. doi: 10.1785/0120090366.

W.-Y. Jean, Y.-W. Chang, K.-L. Wen, and C.-H. Loh. Early estimation of seismic hazard for strong earthquakes in Taiwan. *Natural Hazards*, 37:39–53, 2006. doi: 10.1007/s11069-005-4655-y.

H. W. Jee and S. W. Han. Regional ground motion prediction equation developed for the Korean peninsula using recorded and simulated ground motions. *Journal of Earthquake Engineering*, 2021. doi: 10.1080/13632469.2021.1871682.

Y.-S. Jeon and R. B. Herrmann. High-frequency earthquake ground-motion scaling in Utah and Yellowstone. *Bulletin of the Seismological Society of America*, 94(5):1644–1657, Oct 2004.

G. H. Jeong and H. S. Lee. An earthquake ground motion model (GMM) for Korean peninsula. In *The 2017 World Congress on Advances in Structural Engineering and Mechanics (ASEM17)*, 2017.

K.-H. Jeong and H.-S. Lee. Ground-motion prediction equation for South Korea based on recent earthquake records. *Earthquakes and Structures*, 15(1):29–44, 2018. doi: 10.12989/eas.2018.15.1.029. Not seen.

D. Ji, C. Li, C. Zhai, Y. Dong, E. I. Katsanos, and W. Wang. Prediction of ground-motion parameters for the NGA-West2 database using refined second-order deep neural networks. *Bulletin of the Seismological Society of America*, 111(6):3278–3296, 2021. doi: 10.1785/0120200388.

L. Jia, H. Li, and Z. Duan. Convex model for gross domestic product-based dynamic earthquake loss assessment method. *Natural Hazards*, 60(2):589–604, Jan 2012. doi: 10.1007/s11069-011-0028-x.

Z.-J. Jiang, L. Zhang, X.-Y. Song, and F. Zhang. Ground motion prediction equation for the vertical component of 5%-damped spectral acceleration (0.01-–10 s) in western China. *Journal of Seismology*, 26:1267–1293, 2022. doi: 10.1007/s10950-022-10118-4.

R. W. Jibson. Summary of research on the effects of topographic amplification of earthquakes shaking on slope stability. Open-File Report 87-268, US Geological Survey, Menlo Park, California, USA, 1987.

M.-J. Jiménez, M. García-Fernández, and the GSHAP Ibero-Maghreb Working Group. Seismic hazard assessment in the Ibero-Maghreb region. *Annali di Geofisica*, 42(6):1057–1065, Dec 1999.

X. Jin, L.-C. Kang, and Y.-P. Ou. Ground motion attenuation relation for small to moderate earthquakes in Fujian region, China. *Acta Seismologica Sinica*, 21(3):283–295, May 2008. doi: 10.1007/s11589-008-0283-4.

R. A. Johnson. An earthquake spectrum prediction technique. *Bulletin of the Seismological Society of America*, 63(4):1255–1274, Aug 1973.

A. Johnston et al. The earthquakes of stable continental regions, Vol. 1: Assessment of large earthquake potential. EPRI Report TR-102261, Electrical Power Research Institute, Palo Alto, 1994.

E. Jonathan. Some aspects of seismicity in Zimbabwe and eastern and southern Africa. Master's thesis, Institute of Solid Earth Physics, University of Bergen, Norway, 1996. 100 pp. Not seen. Cited in Midzi et al. (1999).

A. Joshi, A. Kumar, and A. Sinvhal. Attenuation relation for the Kumaon and Garhwal Himalaya, Uttarakhand, India. In *Proceeding of International Symposium on The 2001 Bhuj earthquake and advances in earthquake sciences — AES 2011*, ISR, Gandhinagar, Gujart, India, Jan 2011. Not seen. Reported in Joshi et al. (2012).

A. Joshi, A. Kumar, C. Lomnitz, H. Castanños, and S. Akhtar. Applicability of attenuation relations for regional studies. *Geofísica Internacional*, 51(4):349–363, 2012.

A. Joshi, A. Kumar, H. Castanos, and C. Lomnitz. Seismic hazard of the Uttarakhand Himalaya, India, from deterministic modeling of possible rupture planes in the area. *International Journal of Geophysics*, 2013a. doi: 10.1155/2013/825276. Article ID 825276.

A. Joshi, A. Kumar, K. Mohran, and B. K. Rastogi. Hybrid attenuation model for estimation of peak ground accelerations in the Kutch region, India. *Natural Hazards*, 68(2):249–269, 2013b. doi: 10.1007/s11069-012-0524-7.

W. B. Joyner and D. M. Boore. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bulletin of the Seismological Society of America*, 71(6):2011–2038, Dec 1981.

W. B. Joyner and D. M. Boore. Estimation of response-spectral values as functions of magnitude, distance, and site conditions. Open-File Report 82-881, U.S. Geological Survey, 1982a.

W. B. Joyner and D. M. Boore. Prediction of earthquake response spectra. Open-File Report 82-977, U.S. Geological Survey, 1982b.

W. B. Joyner and D. M. Boore. Measurement, characterization, and prediction of strong ground motion. In *Proceedings of Earthquake Engineering & Soil Dynamics II*, pages 43–102. Geotechnical Division, ASCE, Jun 1988.

W. B. Joyner and D. M. Boore. Methods for regression analysis of strong-motion data. *Bulletin of the Seismological Society of America*, 83(2):469–487, Apr 1993.

W. B. Joyner and D. M. Boore. Recent developments in strong motion attenuation relationships. In *Proceedings of the 28th Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resource Panel on Wind and Seismic Effects*, pages 101–116, Aug 1996.

W. B. Joyner and T. E. Fumal. Use of measured shear-wave velocity for predicting geologic site effects on strong ground motion. In *Proceedings of Eighth World Conference on Earthquake Engineering*, volume II, pages 777–783, 1984.

W. B. Joyner and T. E. Fumal. Predictive mapping of earthquake ground motion. In *Evaluating Earthquake Hazards in the Los Angeles Region — An Earth Science Perspective*, number 1360 in U.S. Geological Survey Professional Paper, pages 203–220. United States Government Printing Office, Washington, 1985.

J.-G. Junn, N.-D. Jo, and C.-E. Baag. Stochastic prediction of ground motions in southern Korea. *Geosciences Journal*, 6(3):203–214, Sep 2002.

Ö Kale, S. Akkar, A. Ansari, and H. Hamzehloo. A ground-motion predictive model for Iran and Turkey for horizontal PGA, PGV, and 5% damped response spectrum: Investigation of possible regional effects. *Bulletin of the Seismological Society of America*, 105(2A):963–980, Apr 2015. doi: 10.1785/0120140134.

E. Kalkan and P. Gülkan. Empirical attenuation equations for vertical ground motion in Turkey. *Earthquake Spectra*, 20(3):853–882, Aug 2004a.

E. Kalkan and P. Gülkan. Site-dependent spectra derived from ground motion records in Turkey. *Earthquake Spectra*, 20(4):1111–1138, Nov 2004b.

E. Kalkan and P. Gülkan. Erratum: Site-dependent spectra derived from ground motion records in Turkey. *Earthquake Spectra*, 21(1):283, Feb 2005.

R. Kamai, N. A. Abrahamson, and W. J. Silva. Nonlinear horizontal site amplification for constraining the NGA-West2 GMPEs. *Earthquake Spectra*, 30(3):1223–1240, Aug 2014. doi: 10.1193/070113EQS187M.

M. Kamiyama. Effects of subsoil conditions and other factors on the duration of earthquake ground shakings. In *Proceedings of Eighth World Conference on Earthquake Engineering*, volume II, pages 793–800, 1984.

M. Kamiyama. Regression analyses of strong-motion spectra in terms of a simplified faulting source model. In *Proceedings of the Fourth International Conference on Soil Dynamics and Earthquake Engineering*, pages 113–126, Oct 1989.

M. Kamiyama. An attenuation model for the peak values of strong ground motions with emphasis on local soil effects. In *Proceedings of the First International Conference on Earthquake Geotechnical Engineering*, volume 1, pages 579–585, 1995.

M. Kamiyama and E. Yanagisawa. A statisical model for estimating response spectra of strong earthquake ground motions with emphasis on local soil conditions. *Soils and Foundations*, 26(2):16–32, Jun 1986.

M. Kamiyama, M.J. O'Rourke, and R. Flores-Berrones. A semi-empirical analysis of strong-motion peaks in terms of seismic source, propagation path and local site conditions. Technical Report NCEER-92-0023, National Center for Earthquake Engineering Research, Sep 1992.

K. Kanai. Improved empirical formula for characteristics of stray [sic] earthquake motions. In *Proceedings of the Japanese Earthquake Symposium*, pages 1–4, 1966. Not seen. Reported in Trifunac and Brady (1975a).

L. Kang and X. Jin. Ground motion attenuation relations of small and moderate earthquakes in Sichuan region. *Earthquake Science*, 22:277–282, 2009. doi: 10.1007/s11589-009-0277-x.

L. Kang and J. X. Zhao. Ground-motion prediction equations for shallow-crustal and upper-mantle earthquakes in Japan using site class and segmented geometric attenuation functions for the horizontal component. *Bulletin of the Seismological Society of America*, 112(3):1502–1526, Jun 2022. doi: 10.1785/0120200383.

T. Kanno, A. Narita, N. Morikawa, H. Fujiwara, and Y. Fukushima. A new attenuation relation for strong ground motion in Japan based on recorded data. *Bulletin of the Seismological Society of America*, 96(3): 879–897, 2006. doi: 10.1785/0120050138.

A. R. Kashani, M. Akhani, C. V. Camp, and A. H. Gandomi. A neural network to predict spectral acceleration. In *Basics of Computational Geophysics*, chapter 18, pages 335–349. 2021. doi: 10.1016/B978-0-12-820513-6.00006-0.

K. M. Kaski. A comparison of ground motion characteristics from induced seismic events in Alberta with those in Oklahoma. Master's thesis, The University of Western Ontario, Canada, Dec 2017.

K. M. Kaski and G. M. Atkinson. A comparison of ground-motion characteristics from induced seismic events in Alberta with those in Oklahoma. *Seismological Research Letters*, 88(6):1570–1585, Nov 2017. doi: 10.1785/0220170064.

S. Kataoka, T. Satoh, S. Matsumoto, and T. Kusakabe. Attenuation relationships of ground motion intensity using short period level as a variable. *Doboku Gakkai Ronbunshuu A*, 62(4):740–757, 2006. doi: 10.2208/jsceja.62.740. In Japanese with English abstract.

S. Kataoka, S. Matsumoto, T. Kusakabe, and N. Toyama. Attenuation relationships and amplification map for ground motion in rather-long period range. *Doboku Gakkai Ronbunshuu A*, 64(4):721–738, 2008. doi: 10.2208/jsceja.64.721. In Japanese with English abstract.

T. Katayama. Statistical analysis of peak acceleration of recorded earthquake ground motions. *Seisan-Kenkyu*, 26(1):18–20, 1974. Not seen.

T. Katayama. An engineering prediction model of acceleration response spectra and its application to seismic hazard mapping. *Earthquake Engineering and Structural Dynamics*, 10(1):149–163, Jan/Feb 1982. doi: 10.1002/eqe.4290100111.

A. Kaveh, T. Bakhshpoori, and S. M. Hamzeh-Ziabari. Derivation of new equations for prediction of principal ground-motion parameters using M5' algorithm. *Journal of Earthquake Engineering*, 20(6):910–930, 2016. doi: 10.1080/13632469.2015.1104758.

A. Kaveh, S. M. Hamze-Ziabari, and T. Bakhshpoori. Feasibility of PSO-ANFIS-PSO and GA-ANFIS-GA models in prediction of peak ground acceleration. *International Journal of Optimization in Civil Engineering*, 8(1):1–14, 2018.

H. Kawano, K. Takahashi, M. Takemura, M. Tohdo, T. Watanabe, and S. Noda. Empirical response spectral attenuations on the rocks with VS = 0.5 to 3.0 km/s in Japan. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 0953.

K. Kawashima, K. Aizawa, and K. Takahashi. Attenuation of peak ground motion and absolute acceleration response spectra. In *Proceedings of Eighth World Conference on Earthquake Engineering*, volume II, pages 257–264, 1984.

K. Kawashima, K. Aizawa, and K. Takahashi. Attenuation of peak ground motions and absolute acceleration response spectra of vertical earthquake ground motion. *Proceedings of JSCE Structural Engineering/Earthquake Engineering*, 2(2):415–422, Oct 1985.

K. Kawashima, K. Aizawa, and K. Takahashi. Attenuation of peak ground acceleration, velocity and displacement based on multiple regression analysis of Japanese strong motion records. *Earthquake Engineering and Structural Dynamics*, 14(2):199–215, Mar–Apr 1986.

K. Kayabali and T. Beyaz. Strong motion attenuation relationship for Turkey —– a different perspective. *Bulletin of Engineering Geology and the Environment*, 70:467–481, 2011. doi: 10.1007/s10064-010-0335-6.

R. E. Kayen and J. K. Mitchell. Assessment of liquefaction potential during earthquakes by Arias intensity. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 123(12):1162–1175, 1997. Not seen.

J. J. Kempton and J. P. Stewart. Prediction equations for significant duration of earthquake ground motions considering site and near-source effects. *Earthquake Spectra*, 22(4):985–1013, 2006. doi: 10.1193/1.2358175.

M. H. Khademi. Attenuation of peak and spectral accelerations in the Persian plateau. In *Proceedings of Twelfth European Conference on Earthquake Engineering*, Sep 2002. Paper reference 330.

A. Khansefid, S. M. Yadollahi, G. Müller, and F. Taddei. Ground motion models for the induced earthquakes by the geothermal power plants activity. *Journal of Earthquake Engineering*, 27(5):1324–1353, 2023. doi: 10.1080/13632469.2022.2084475.

F. Khosravikia and P. Clayton. Machine learning in ground motion prediction. *Computers and Geosciences*, 148 (104700), 2021. doi: 10.1016/j.cageo.2021.104700.

F. Khosravikia, Y. Zeinali, Z. Nagy, P. Clayton, and E. M. Rathje. Neural network-based equations for predicting PGA and PGV in Texas, Oklahoma, and Kansas. In *Geotechnical Earthquake Engineering and Soil Dynamics V GSP 291*, pages 538–549, Jun 2018.

B. Kim and M. Shin. A model for estimating horizontal aftershock ground motions for active crustal regions. *Soil Dynamics and Earthquake Engineering*, 92:165–175, 2017. doi: 10.1016/j.soildyn.2016.09.040.

R. Kiuchi, W. D. Mooney, and H. M. Zahran. Ground-motion prediction equations for western Saudi Arabia. *Bulletin of the Seismological Society of America*, 109(6):2722–2737, 2019. doi: 10.1785/0120180302.

R. Kiuchi, W. D. Mooney, and H. M. Zahran. Ground-motion prediction equations for western Saudi Arabia. In T. W. Sisson, A. T. Calvert, and W. D. Mooney, editors, *Active Volcanism on the Arabian Shield—Geology, Volcanology, and Geophysics of Northern Harrat Rahat and Vicinity, Kingdom of Saudi Arabia*, number U.S. Geological Survey Professional Paper 1862; Saudi Geological Survey Special Report SGS–SP–2021–1, chapter 0. 2023.

A. Klimasewski, V. Sahakian, and A. Thomas. Comparing artificial neural networks with traditional ground-motion models for small-magnitude earthquakes in southern California. *Bulletin of the Seismological Society of America*, 111(3):1577–1589, Jun 2021. doi: 10.1785/0120200200.

H. Kobayashi and S. Midorikawa. A semi-empirical method for estimating response spectra of near-field ground motions with regard to fault rupture. In *Proceedings of Seventh European Conference on Earthquake Engineering*, volume 2, pages 161–168, 1982.

H. Kobayashi and S. Nagahashi. Response spectra on seismic bedrock during earthquake. In *Proceedings of Sixth World Conference on Earthquake Engineering*, volume I, pages 516–522, 1977.

S. Kobayashi, T. Takahashi, S. Matsuzaki, M. Mori, Y. Fukushima, J. X. Zhao, and P. G. Somerville. A spectral attenuation model for Japan using digital strong motion records of JMA87 type. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 2786.

A. V. Konovalov, K. A. Manaychev, A. A. Stepnov, and A. V. Gavrilov. Regional ground motion prediction equation for Sakhalin island. *Seismic Instruments*, 55(1):70—-77, 2019.

M. K. Kostov. Site specific estimation of cumulative absolute velocity. In *18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18)*, Aug 2005. Paper no. K03_4.

S. R. Kotha, D. Bindi, and F. Cotton. Partially non-ergodic region specific GMPE for Europe and Middle-East. *Bulletin of Earthquake Engineering*, 14(4):1245–1263, Apr 2016a. doi: 10.1007/s10518-016-9875-x.

S. R. Kotha, D. Bindi, and F. Cotton. Erratum to: Partially non-ergodic region specific GMPE for Europe and Middle-East. *Bulletin of Earthquake Engineering*, 14(8):2435–2435, Aug 2016b. doi: 10.1007/s10518-016-9940-5.

S. R. Kotha, F. Cotton, and D. Bindi. A new approach to site classification: Mixed-effects ground motion prediction equation with spectral clustering of site amplification functions. *Soil Dynamics and Earthquake Engineering*, 110:318–329, 2018a. doi: 10.1016/j.soildyn.2018.01.051.

S. R. Kotha, F. Cotton, and D. Bindi. Site classification derived from spectral clustering of empirical site amplification functions. In *Proceedings of Sixteenth European Conference on Earthquake Engineering*, 2018b.

S. R. Kotha, G. Weatherill, D. Bindi, and F. Cotton. A regionally-adaptable ground-motion model for shallow crustal earthquakes in Europe. *Bulletin of Earthquake Engineering*, 18:4091–4125, 2020. doi: 10.1007/s10518-020-00869-1.

M. Kowsari, S. Ghasemi, Z. Farajpour, and M. Zare. Capturing epistemic uncertainty in the Iranian strong-motion data on the basis of backbone ground motion models. *Journal of Seismology*, 2019. doi: 10.1007/s10950-019-09886-3.

M. Kowsari, T. Sonnemann, B. Halldorsson, B. Hrafnkelsson, J. Th. Snæbjörnsson, and S. Jónsson. Bayesian inference of empirical ground motion models to pseudo-spectral accelerations of south Iceland seismic zone earthquakes based on informative priors. *Soil Dynamics and Earthquake Engineering*, 132(106075), 2020. doi: 10.1016/j.soildyn.2020.106075.

E. L. Krinitzsky, F. K. Chang, and O. W. Nuttli. State-of-the-art for assessing earthquake hazards in the United States; report 26, Parameters for specifying magnitude-related earthquake ground motions. Technical report, U.S. Army Engineer Waterways Experimental Station, Sep 1987. Miscellaneous paper S-73-1.

E. L. Krinitzsky, F. K. Chang, and O. W. Nuttli. Magnitude-related earthquake ground motions. *Bulletin of the Association of Engineering Geologists*, XXV(4):399–423, 1988.

O.-J. Ktenidou, Z. Roumelioti, N. Abrahamson, F. Cotton, K. Pitilakis, and F. Hollender. Understanding single-station ground motion variability and uncertainty (sigma): Lessons learnt from EUROSEISTEST. *Bulletin of Earthquake Engineering*, 16:2311–2336, 2018. doi: 10.1007/s10518-017-0098-6.

N. Kuehn, Y. Bozorgnia, K. W. Campbell, and N. Gregor. Partially non-ergodic ground-motion model for subduction regions using the NGA-Subduction database. PEER Report 2020/04, Pacific Earthquake Engineering Research Center, Sep 2020a.

N. M. Kuehn and F. Scherbaum. Ground-motion prediction model: A multilevel approach. *Bulletin of Earthquake Engineering*, 13(9):2481–2491, Sep 2015. doi: 10.1007/s10518-015-9732-3.

N. M. Kuehn and F. Scherbaum. A partially non-ergodic ground-motion prediction equation for Europe and the Middle East. *Bulletin of Earthquake Engineering*, 14(10):2629–2642, 2016. doi: 10.1007/s10518-016-9911-x.

N. M. Kuehn, F. Scherbaum, and C. Riggelsen. Deriving empirical ground-motion models: Balancing data constraints and physical assumptions to optimize prediction capability. *Bulletin of the Seismological Society of America*, 99(4):2335–2347, Aug 2009. doi: 10.1785/0120080136.

N. M. Kuehn, C. Riggelsen, and F. Scherbaum. Modeling the joint probability of earthquake, site, and ground-motion parameters using Bayesian networks. *Bulletin of the Seismological Society of America*, 101(1):235–249, 2011. doi: 10.1785/0120100080.

N. M. Kuehn, T. Kishida, M. AlHamaydeh, G. Lavrentiadis, and Y. Bozorgnia. A Bayesian model for truncated regression for the estimation of empirical ground-motion models. *Bulletin of Earthquake Engineering*, 18: 6149–6179, 2020b. doi: 10.1007/s10518-020-00943-8.

A. Kumar, H. Mittal, R. Kumar, and R. S. Ahluwalia. Empirical attenuation relationship for peak ground horizontal acceleration for north-east Himalaya. *Vietnam Journal of Earth Sciences*, 39(1):47–57, 2017. doi: 10.15625/0866-7187/39/1/9183.

P. Kumar, B. P. Chamoli, A. Kumar, and A. Gairola. Attenuation relationship for peak horizontal acceleration of strong ground motion of Uttarakhand region of central Himalayas. *Journal of Earthquake Engineering*, 25 (12):2537–2554, 2021. doi: 10.1080/13632469.2019.1634161.

I. Kurzon, F. L. Vernon, Y. Ben-Zion, and G. Atkinson. Ground motion prediction equations in the San Jacinto fault zone: Significant effects of rupture directivity and fault zone amplification. *Pure and Applied Geophysics*, 171(11):3045–3081, Nov 2014. doi: 10.1007/s00024-014-0855-2.

N. Landwehr, N. M. Kuehn, T. Scheffer, and N. Abrahamson. A nonergodic ground-motion model for California with spatially varying coefficients. *Bulletin of the Seismological Society of America*, 106(6):2574–2583, Dec 2016. doi: 10.1785/0120160118.

G. Lanzano and L. Luzi. A ground motion model for volcanic areas in Italy. *Bulletin of Earthquake Engineering*, 18(1):57–76, 2020. doi: 10.1007/s10518-019-00735-9.

G. Lanzano, M. D'Amico, C. Felicetta, R. Puglia, L. Luzi, F. Pacor, and D. Bindi. Ground-motion prediction equations for region-specific probabilistic seismic-hazard analysis. *Bulletin of the Seismological Society of America*, 106(1):73–92, Feb 2016. doi: 10.1785/0120150096.

G. Lanzano, L. Luzi, F. Pacor, C. Felicetta, R. Puglia, S. Sgobba, and M. D'Amico. A revised ground-motion prediction model for shallow crustal earthquakes in Italy. *Bulletin of the Seismological Society of America*, 109(2):525–540, Apr 2019a. doi: 10.1785/0120180210.

G. Lanzano, L. Luzi, F. Pacor, R. Puglia, C. Felicetta, M. D'Amico, and S. Sgobba. Update of the ground motion predictions for Italy. In *Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions*. Associazione Geotecnica Italiana, 2019b. ISBN 978-0-367-14328-2.

G. Lanzano, S. Sgobba, L. Caramenti, and A. Menafoglio. Ground-motion model for crustal events in Italy by applying the multisource geographically weighted regression (MS-GWR) method. *Bulletin of the Seismological Society of America*, 111(6):3297–3313, Dec 2021. doi: 10.1785/0120210044.

N. Laouami. Vertical ground motion prediction equations and vertical-to-horizontal (V/H) ratios of PGA and PSA for Algeria and surrounding region. *Bulletin of Earthquake Engineering*, 17(7):3637–3660, Jul 2019. doi: 10.1007/s10518-019-00635-y.

N. Laouami and A. Slimani. Local vs. regional spectral ground-motion predictive equation for Algeria. In *Proceedings of Fifteenth World Conference on Earthquake Engineering*, 2012. Paper no. 316.

N. Laouami, A. Slimani, Y. Bouhadad, J.-L. Chatelain, and A. Nour. Evidence for fault-related directionality and localized site effects from strong motion recordings of the 2003 Boumerdes (Algeria) earthquake: Consequences on damage distribution and the Algerian seismic code. *Soil Dynamics and Earthquake Engineering*, 26(11): 991–1003, 2006.

N. Laouami, A. Slimani, and S. Larbes. Ground motion prediction equations for Algeria and surrounding region using site classification based H/V spectral ratio. *Bulletin of Earthquake Engineering*, 16(7):2653–2684, Jul 2018a. doi: 10.1007/s10518-018-0310-3.

N. Laouami, A. Slimani, and S. Larbes. Correction to: Ground motion prediction equations for Algeria and surrounding region using site classification based H/V spectral ratio. *Bulletin of Earthquake Engineering*, 16 (7):2685–2686, Jul 2018b. doi: 10.1007/s10518-018-0335-7.

A. Laurendeau, F. Cotton, O.-J. Ktenidou, L.-F. Bonilla, and F. Hollender. Rock and stiff-soil site amplification: Dependency on $V_{S30}$ and kappa ($\kappa_0$). *Bulletin of the Seismological Society of America*, 103(6):3131–3148, Dec 2013. doi: 10.1785/0120130020.

A. Laurendeau, P.-Y. Bard, F. Hollender, V. Perron, L. Foundotos, O.-J. Ktenidou, and B. Hernandez. Derivation of consistent hard rock ($1000 < V_S < 3000\,\mathrm{m/s}$) GMPEs from surface and down-hole recordings: Analysis of KiK-net data. *Bulletin of Earthquake Engineering*, 16:2253–2284, 2018. doi: 10.1007/s10518-017-0142-6.

G. Lavrentiadis, N. A. Abrahamson, and N. M. Kuehn. A non-ergodic effective amplitude ground-motion model for California. *Bulletin of Earthquake Engineering*, 21:5233–5264, 2023. doi: 10.1007/s10518-021-01206-w.

R. S. Lawson and H. Krawinkler. Cumulative damage potential of seismic ground motion. In *Proceedings of Tenth European Conference on Earthquake Engineering*, volume 2, pages 1079–1086, 1994.

B. Le Goff, J. F. Borges, and M. Bezzeghoud. Intensity-distance attenuation laws for the Portugal mainland using intensity data points. *Geophysical Journal International*, 199(2):1278–1285, Nov 2014. doi: 10.1093/gji/ggu317.

C. T. Lee, C. T. Cheng, C. W. Liao, and Y. B. Tsai. Site classification of taiwan free-field strong-motion stations. *Bulletin of the Seismological Society of America*, 91:1283—-1297, 2001.

C.-T. Lee, B.-S. Hsieh, C.-H. Sung, and P.-S. Lin. Regional Arias intensity attenuation relationship for Taiwan considering $V_{S30}$. *Bulletin of the Seismological Society of America*, 102(1):129–142, Feb 2012. doi: 10.1785/0120100268.

J. Lee. *Engineering charaterization of earthquake ground motions.* PhD thesis, University of Michigan, USA, 2009.

J. Lee and R. A. Green. Predictive relations for significant durations in stable continental regions. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008.

J. Lee and R. A. Green. An empirical significant duration relationship for stable continental regions. *Bulletin of Earthquake Engineering*, 12(1), Jan 2014. doi: 10.1007/s10518-013-9570-0.

V. W. Lee. Influence of local soil and geological site conditions on pseudo relative velocity spectrum amplitudes of recorded strong motion accelerations. Technical Report CE 87-06, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., Jul 1987.

V. W. Lee. Scaling PSV from earthquake magnitude, local soil, and geologic depth of sediments. *Journal of The Geotechnical Engineering Division, ASCE*, 119(1):108–126, Jan 1993.

V. W. Lee. Pseudo relative velocity spectra in former Yugoslavia. *European Earthquake Engineering*, IX(1): 12–22, 1995.

V. W. Lee and M. Manić. Empirical scaling of response spectra in former Yugoslavia. In *Proceedings of Tenth European Conference on Earthquake Engineering*, volume 4, pages 2567–2572, 1994.

V. W. Lee and M. D. Trifunac. Pseudo relative velocity spectra of strong earthquake ground motion in California. Technical Report CE 95-04, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., May 1995.

V. W. Lee, M. D. Trifunac, M. I. Todorovska, and E. I. Novikova. Empirical equations describing attenuation of peak of strong ground motion, in terms of magnitude, distance, path effects and site conditions. Technical Report CE 95-02, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., Apr 1995.

V. W. Lee, M. D. Trifunac, B. Bulajić, and M. Manić. A preliminary empirical model for frequency-dependent attenuation of Fourier amplitude spectra in Serbia from the Vrancea earthquakes. *Soil Dynamics and Earthquake Engineering*, 83:167–179, Apr 2016a. doi: 10.1016/j.soildyn.2015.12.004.

V. W. Lee, M. D. Trifunac, B. Đ. Bulajić, and M. I. Manić. Preliminary empirical scaling of pseudo relative velocity spectra in Serbia from the Vrancea earthquakes. *Soil Dynamics and Earthquake Engineering*, 86: 41–54, 2016b. doi: 10.1016/j.soildyn.2016.03.007.

Y. Lee, J. G. Anderson, and Y. Zeng. Evaluation of empirical ground-motion relations in southern California. *Bulletin of the Seismological Society of America*, 90(6B):S136–S148, Dec 2000.

M. Leonard. Consistent MMI area estimation for Australian earthquakes. In *Proceedings of the Tenth Pacific Conference on Earthquake Engineering: Building an Earthquake-Resilient Pacific*, Nov 2015. Paper number 170.

S. Li et al. Study on attenuation features of earthquake intensity in the Yunnan region. *Earthquake Research in China*, 19(3), 2003. Not seen. Cited in Li et al. (2009).

X. Li, G. Li, and C. Li. Analysis of ground motion parameters and ground liquefaction prediction using GIS for Kunming Basin, China. In *International Conference on Geo-spatial Solutions for Emergency Management and the 50th Anniversary of the Chinese Academy of Surveying and Mapping*, pages 78–83, Sep 2009.

X. Li, C. Zhai, W. Wen, and L. Xie. Ground motion prediction model for horizontal PGA, 5% damped response spectrum in Sichuan-Yunnan region of China. *Journal of Earthquake Engineering*, 24(11):1829–1866, 2020. doi: 10.1080/13632469.2018.1485600.

J. Liang, H. Hao, B. A. Gaull, and C. Sinadinovski. Estimation of strong ground motions in southwest Western Australia with a combined Green's function and stochastic approach. *Journal of Earthquake Engineering*, 12 (3):382–405, 2008.

M. S. Liew, K. U. Danyaro, M. Mohamad, L. E. Shawn, and A. Aulov. Ground motion prediction equations for Malaysia due to subduction zone earthquakes in Sumatran region. *IEEE Access*, 5:23920–23937, 2017. doi: 10.1109/ACCESS.2017.2748360.

Lin and Lee. Unknown. Original reference not seen. Cited in 'Attenuation Relationship of Arias Intensity for Taiwan' by Hsieh, P.-S. (2007), 2004.

P.-S. Lin and C.-T. Lee. Ground-motion attenuation relationships for subduction-zone earthquakes in northeastern Taiwan. *Bulletin of the Seismological Society of America*, 98(1):220–240, Feb 2008. doi: 10.1785/0120060002.

P.-S. Lin, B. Chiou, N. Abrahamson, M. Walling, C.-T. Lee, and C.-T. Cheng. Repeatable source, site, and path effects on the standard deviation for empirical ground-motion prediction models. *Bulletin of the Seismological Society of America*, 101(5):2281–2295, Oct 2011a. doi: 10.1785/0120090312.

P.-S. Lin, C.-T. Lee, C.-T. Cheng, and C.-H. Sung. Response spectral attenuation relations for shallow crustal earthquakes in Taiwan. *Engineering Geology*, 121(3–4):150–164, Aug 2011b.

K.-S. Liu and Y.-B. Tsai. Attenuation relationships of peak ground acceleration and velocity for crustal earthquakes in Taiwan. *Bulletin of the Seismological Society of America*, 95(3):1045–1058, Jun 2005. doi: 10.1785/0120040162.

C.-H. Loh, Y. T. Yeh, W.-Y. Jean, and Y.-H. Yeh. Probabilistic seismic risk analysis in the Taiwan area based on PGA and spectral amplitude attenuation formulas. *Engineering Geology*, 30(3–4):277–304, 1991.

Z. Lubkowski, J. Bommer, B. Baptie, J. Bird, J. Douglas, M. Free, J. Hancock, S. Sargeant, N. Sartain, and F. Strasser. An evaluation of attenuation relationships for seismic hazard assessment in the UK. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 1422.

D. Lungu, S. Demetriu, C. Radu, and O. Coman. Uniform hazard response spectra for Vrancea earthquakes in Romania. In *Proceedings of Tenth European Conference on Earthquake Engineering*, volume 1, pages 365–370, 1994.

D. Lungu, O. Coman, and T. Moldoveanu. Hazard analysis for Vrancea earthquakes. Application to Cernavoda NPP site in Romania. In *Proceedings of the 13th International Conference on Structural Mechanics in Reactor Technology*, Aug 1995a. Division K, Paper No. 538.

D. Lungu, T. Cornea, I. Craifaleanu, and A. Aldea. Seismic zonation of Romania based on uniform hazard response ordinates. In *Proceedings of the Fifth International Conference on Seismic Zonation*, volume I, pages 445–452, 1995b.

D. Lungu, T. Cornea, I. Craifaleanu, and S. Demetriu. Probabilistic seismic hazard analysis for inelastic structures on soft soils. In *Proceedings of Eleventh World Conference on Earthquake Engineering*, Jun 1996.

P. Lussou, P. Y. Bard, F. Cotton, and Y. Fukushima. Seismic design regulation codes: Contribution of K-Net data to site effect evaluation. *Journal of Earthquake Engineering*, 5(1):13–33, Jan 2001.

L. Luzi, P. Morasca, F. Zolezzi, D. Bindi, F. Pacor, D. Spallarossa, and G. Franceschina. Ground motion models for Molise region (southern Italy). In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, 2006. Paper number 938.

L. Luzi, M. Massa, D. Bindi, and F. Pacor. Strong-motion networks in Italy and their efficient use in the derivation of regional and global predictive models. In *Earthquake Data in Engineering Seismology: Predictive models, data management and networks*, pages 53–69. Springer, Dordrecht, 2011. doi: 10.1007/978-94-007-0152-6_5.

L. Luzi, D. Bindi, R. Puglia, F. Pacor, and A. Oth. Single-station sigma for Italian strong-motion stations. *Bulletin of the Seismological Society of America*, 104(1):467–483, 2014. doi: 10.1785/0120130089.

A. A. Lyubushin and I. A. Parvez. Map of seismic hazard of India using Bayesian approach. *Natural Hazards*, 55(2):543–556, 2010. doi: 10.1007/s11069-010-9546-1.

A. B. Mahani and H. Kao. Ground motion from $m1.5$ to 3.8 induced earthquakes at hypocentral distance $< 45$ km in the Montney Play of northest British Columbia, Canada. *Seismological Research Letters*, 89(1): 22–34, Jan 2018. doi: 10.1785/0220170119.

A. Mahdavian. Empirical evaluation of attenuation relations of peak ground acceleration in the Zagros and central Iran. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, 2006. Paper number 558.

M. R. Mahdavifar, M. K. Jafari, and M. R. Zolfaghari. The attenuation of Arias intensity in Alborz and central Iran. In *Proceedings of the Fifth International Conference on Seismology and Earthquake Engineering, Tehran, Iran*, 2007. Not seen. Cited in Chousianitis et al. (2014).

K. C. Makropoulos. *The statistics of large earthquake magnitude and an evaluation of Greek seismicity*. PhD thesis, University of Edinburgh, UK, 1978. Not seen.

K. C. Makropoulos and P. W. Burton. Seismic hazard in Greece. II. Ground acceleration. *Tectonophysics*, 117: 259–294, 1985.

L. Malagnini and R. B. Herrmann. Ground-motion scaling in the region of the 1997 Umbria-Marche earthquake (Italy). *Bulletin of the Seismological Society of America*, 90(4):1041–1051, Aug 2000.

L. Malagnini, R. B. Herrmann, and M. Di Bona. Ground-motion scaling in the Apennines (Italy). *Bulletin of the Seismological Society of America*, 90(4):1062–1081, Aug 2000a.

L. Malagnini, R. B. Herrmann, and K. Koch. Regional ground-motion scaling in central Europe. *Bulletin of the Seismological Society of America*, 90(4):1052–1061, Aug 2000b.

L. Malagnini, A. Akinci, R. B. Herrmann, N. A. Pino, and L. Scognamiglio. Characteristics of the ground motion in northeastern Italy. *Bulletin of the Seismological Society of America*, 92(6):2186–2204, Aug 2002.

L. Malagnini, K. Mayeda, R. Uhrhammer, A. Akinci, and R. B. Herrmann. A regional ground-motion excitation/attenuation model for the San Francisco region. *Bulletin of the Seismological Society of America*, 97(3): 843–862, Jun 2007. doi: 10.1785/0120060101.

A. I. H. Malkawi and K. J. Fahmi. Locally derived earthquake ground motion attenuation relations for Jordan and conterminous areas. *Quarterly Journal of Engineering Geology and Hydrogeology*, 29(4):309–319, 1996. doi: 10.1144/GSL.QJEGH.1996.029.P4.05.

P. Mandal, N. Kumar, C. Satyamurthy, and I. P. Raju. Ground-motion attenuation relation from strong-motion records of the 2001 Mw 7.7 Bhuj earthquake sequence (2001–2006), Gujarat, India. *Pure and Applied Geophysics*, 166(3):451–469, 2009. doi: 10.1007/s00024-009-0444-y.

E. F. Manea, C. O. Cioflan, and L. Danciu. Ground-motion models for Vrancea intermediate-depth earthquakes. *Earthquake Spectra*, 38(1):407–431, 2022. doi: 10.1177/87552930211032985.

M. I. Manic. A new site dependent attenuation model for prediction of peak horizontal acceleration in Northwestern Balkan. In *Proceedings of Eleventh European Conference on Earthquake Engineering*, 1998.

M. I. Manic. Empirical scaling of response spectra for the territory of north-western Balkan. In *Proceedings of Twelfth European Conference on Earthquake Engineering*, Sep 2002. Paper reference 650.

B. Margaris, C. Papazachos, C. Papaioannou, N. Theodulidis, I. Kalogeras, and A. Skarlatoudis. Ground motion attenuation relations for shallow earthquakes in Greece. In *Proceedings of Twelfth European Conference on Earthquake Engineering*, Sep 2002a. Paper reference 385.

B. Margaris, C. Papazachos, C. Papaioannou, N. Theodulidis, I. Kalogeras, and A. Skarlatoudis. Ground motion attenuation relations for shallow earthquakes in Greece. In *Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*, Sep 2002b.

S. Marin, J.-P. Avouac, M. Nicolas, and A. Schlupp. A probabilistic approach to seismic hazard in metropolitan France. *Bulletin of the Seismological Society of America*, 94(6):2137–2163, Dec 2004.

M. Massa, S. Marzorati, E. D'Alema, D. Di Giacomo, and P. Augliera. Site classification assessment for estimating empirical attenuation relationships for central-northern Italy earthquakes. *Journal of Earthquake Engineering*, 11(6):943—-967, 2007. doi: 10.1080/13632460701232675.

M. Massa, P. Morasca, L. Moratto, S. Marzorati, G. Costa, and D. Spallarossa. Empirical ground-motion prediction equations for northern Italy using weak- and strong-motion amplitudes, frequency content, and duration parameters. *Bulletin of the Seismological Society of America*, 98(3):1319–1342, Jun 2008. doi: 10.1785/0120070164.

N. Matsumoto, T. Sasaki, K. Inagaki, and T. Annaka. Attenuation relations of acceleration response spectra at dam foundations in Japan. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 689.

R. S. Matsu'ura, H. Tanaka, M. Furumura, T. Takahama, and A. Noda. A new ground-motion prediction equation of Japanese instrumental seismic intensities reflecting source type characteristics in Japan. *Bulletin of the Seismological Society of America*, 2020. doi: 10.1785/0120180337.

T. Matuschka. Assessment of seismic hazards in New Zealand. Technical Report 222, Department of Civil Engineering, School of Engineering, University of Auckland, 1980. Not seen. Reported in Stafford (2006).

T. Matuschka and B. K. Davis. Derivation of an attenuation model in terms of spectral acceleration for New Zealand. In *Pacific Conference on Earthquake Engineering*, 1991. Not seen. Reported in Stafford (2006).

SSB. *Zoning map of China*. Seismological Press, Beijing, China, 1996. In Chinese. Not seen. Cited in Cole and Burton (2008).

M. W. McCann Jr. and H. Echezwia. Investigating the uncertainty in ground motion prediction. In *Proceedings of Eighth World Conference on Earthquake Engineering*, volume II, pages 297–304, 1984.

K. McCue. Strong motion attenuation in eastern Australia. In *Earthquake Engineering Symposium*, National Conference Publication 86/15. Institution of Engineers Australia, Dec 1986. Not seen. Reported in Free (1996).

K. McCue, G. Gibson, and V. Wesson. Intraplate recording of strong motion in southeastern Australia. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 355–360, 1988.

A. McGarr and J. B. Fletcher. Development of ground-motion prediction equations relevant to shallow mining-induced seismicity in the Trail Mountain area, Emery County, Utah. *Bulletin of the Seismological Society of America*, 95(1):31–47, Feb 2005. doi: 10.1785/0120040046.

R. K. McGuire. Seismic structural response risk analysis, incorporating peak response regressions on earthquake magnitude and distance. Research Report R74-51, Massachusetts Institute of Technology, Department of Civil Engineering, Cambridge, USA, 1974. Not seen.

R. K. McGuire. FORTRAN computer program for seismic risk analysis. Open-File Report 76-67, United States Department of the Interior Geological Survey, 1976.

R. K. McGuire. Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response. *Earthquake Engineering and Structural Dynamics*, 5:211–234, 1977.

R. K. McGuire. Seismic ground motion parameter relations. *Journal of The Geotechnical Engineering Division, ASCE*, 104(GT4):481–490, Apr 1978a.

R. K. McGuire. A simple model for estimating Fourier amplitude spectra of horizontal ground acceleration. *Bulletin of the Seismological Society of America*, 68(3):803–822, 1978b.

R. K. McGuire and T. P. Barnhard. The usefulness of ground motion duration in prediction of severity of seismic shaking. In *Proceedings of the Second U.S. National Conference on Earthquake Engineering*, pages 713–722, 1979.

G. H. McVerry and C. Holden. A modified ground-motion prediction equation to accommodate spectra of simulated Hikurangi subduction interface motions for Wellington. Consultancy Report 2014/131, GNS Science, 2014.

G. H. McVerry, D. J. Dowrick, S. Sritharan, W. J. Cousins, and T. E. Porritt. Attenuation of peak ground accelerations in New Zealand. In *Proceedings of the International Workshop on Strong Motion Data*, volume 2, pages 23–38, 1993. Not seen. Cited in McVerry et al. (1995).

G. H. McVerry, D. J. Dowrick, and J. X. Zhao. Attenuation of peak ground accelerations in New Zealand. In *Pacific Conference on Earthquake Engineering*, volume 3, pages 287–292, November 1995.

G. H. McVerry, J. X. Zhao, N. A. Abrahamson, and P. G. Somerville. Crustal and subduction zone attenuation relations for New Zealand earthquakes. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 1834.

G. H. McVerry, J. X. Zhao, N. A. Abrahamson, and P. G. Somerville. New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, 39(4):1–58, Mar 2006.

C. Medel-Vera and T. Ji. A stochastic ground motion accelerogram model for Northwest Europe. *Soil Dynamics and Earthquake Engineering*, 82:170–195, 2016. doi: 10.1016/j.soildyn.2015.12.012.

K. Megawati. Hybrid simulations of ground motions from local earthquakes affecting Hong Kong. *Bulletin of the Seismological Society of America*, 97(4):1293–1307, 2007. doi: 10.1785/0120060129.

K. Megawati and T.-C. Pan. Ground-motion attenuation relationship for the Sumatran megathrust earthquakes. *Earthquake Engineering and Structural Dynamics*, 39:827–845, 2010. doi: 10.1002/eqe.967.

K. Megawati, T.-C. Pan, and K. Koketsu. Response spectral attenuation relationships for Singapore and the Malay peninsula due to distant Sumatran-fault earthquakes. *Earthquake Engineering and Structural Dynamics*, 32(14):2241–2265, Nov 2003.

K. Megawati, T.-C. Pan, and K. Koketsu. Response spectral attenuation relationships for Sumatran-subduction earthquakes and the seismic hazard implications to Singapore and Kuala Lumpur. *Soil Dynamics and Earthquake Engineering*, 25(1):11–25, 2005.

A. Meimandi-Parizi, A. Mahdavian, and H. Saffari. New empirical equations for determination of Fourier amplitude spectrum of acceleration. *Journal of Earthquake Engineering*, 27(10):2775–2795, 2023. doi: 10.1080/13632469.2022.2133031.

T. Meirova, R. Hofstetter, Z. Ben-Avraham, D. M. Steinberg, L. Malagnini, and A. Akinci. Weak-motion-based attenuation relationships for Israel. *Geophysical Journal International*, 175:1127–1140, 2008. doi: 10.1111/j.1365-246X.2008.03953.x.

D. Melgar, B. W. Crowell, J. Geng, R. M. Allen, Y. Bock, S. Riquelme, E. M. Hill, M. Protti, and A. Ganas. Earthquake magnitude calculation without saturation from the scaling of peak ground displacement. *Geophysical Research Letters*, 42:5197–5205, 2015. doi: 10.1002/2015GL064278.

J. Mezcua, J. Rueda, and R. M. García Blanco. Reevaluation of historic earthquakes in Spain. *Seismological Research Letters*, 75(1):75–81, Jan 2004. doi: 10.1785/gssrl.75.1.75.

J. Mezcua, R. M. García Blanco, and J. Rueda. On the strong ground motion attenuation in Spain. *Bulletin of the Seismological Society of America*, 98(3):1343–1353, Jun 2008. doi: 10.1785/0120070169.

J. Mezcua, J. Rueda, and R. M. Garcìa Blanco. A new probabilistic seismic hazard study of Spain. *Natural Hazards*, 59(2):1087–1108, Nov 2011. doi: 10.1007/s11069-011-9819-3.

W. V. Mickey. Strong motion response spectra. *Earthquake Notes*, XLII(1):5–8, Mar 1971.

S. Midorikawa. Preliminary analysis for attenuation of ground velocity on stiff site. In *Proceedings of the International Workshop on Strong Motion Data*, volume 2, pages 39–48, 1993a. Not seen.

S. Midorikawa. Semi-empirical estimation of peak ground acceleration from large earthquakes. *Tectonophysics*, 218:287–295, 1993b.

S. Midorikawa and Y. Ohtake. Variance of peak ground acceleration and velocity in attenuation relationships. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 0325.

V. Midzi, D. J. Hlatywayo, L. S. Chapola, F. Kebede, K. Atakan, D. K. Lombe, G. Turyomurugyendo, and F. A. Tugume. Seismic hazard assessment in eastern and southern Africa. *Annali di Geofisica*, 42(6):1067–1083, Dec 1999.

W. G. Milne. Seismic risk maps for Canada. In *Proceedings of Sixth World Conference on Earthquake Engineering*, volume I, page 930, 1977. 2-508.

W. G. Milne and A. G. Davenport. Distribution of earthquake risk in Canada. *Bulletin of the Seismological Society of America*, 59(2):729–754, Apr 1969.

D. Ming, C. Huang, G. W. Peters, and C. Galasso. An advanced estimation algorithm for ground-motion models with spatial correlation. *Bulletin of the Seismological Society of America*, 109(2):541–566, 2019. doi: 10.1785/0120180215.

M. Miyazawa, R. Kiuchi, and K. Koketsu. Attenuation characteristics of high-frequency ground motions from local sources caused by great subduction zone earthquakes in northeast Japan. *Seismological Research Letters*, 93(5):2686–2699, 2022. doi: 10.1785/0220210353.

B. Mohammadioun. The prediction of response spectra for the anti-seismic design of structures specificity of data from intracontinential environments. *European Earthquake Engineering*, V(2):8–17, 1991.

B. Mohammadioun. Prediction of seismic motion at the bedrock from the strong-motion data currently available. In *Proceedings of Tenth European Conference on Earthquake Engineering*, volume 1, pages 241–245, 1994a.

G. Mohammadioun. Calculation of site-adapted reference spectra from the statistical analysis of an extensive strong-motion data bank. In *Proceedings of Tenth European Conference on Earthquake Engineering*, volume 1, pages 177–181, 1994b.

A. K. Mohammadnejad, S. M. Mousavi, M. Torabi, M. Mousavi, and A. H. Alavi. Robust attenuation relations for peak time-domain parameters of strong ground motions. *Environmental Earth Sciences*, 67(1):53–70, Sep 2012. doi: 10.1007/s12665-011-1479-9.

G. L. Molas and F. Yamazaki. Attenuation of earthquake ground motion in Japan including deep focus events. *Bulletin of the Seismological Society of America*, 85(5):1343–1358, Oct 1995.

G. L. Molas and F. Yamazaki. Attenuation of response spectra in Japan using new JMA records. *Bulletin of Earthquake Resistant Structure Research Center*, 29:115–128, Mar 1996.

C. A. Monguilner, N. Ponti, and S. B. Pavoni. Relationships between basic ground motion parameters for earthquakes of the Argentine western region. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000a. Paper no. 1195.

C. A. Monguilner, N. Ponti, S. B. Pavoni, and D. Richarte. Statistical characterization of the response spectra in the Argentine Republic. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000b. Paper no. 1825.

G. A. Montalva. *Site-specific seismic hazard analyses*. PhD thesis, Washington State University, Aug 2010.

G. A. Montalva, N. Bastías, and A. Rodriguez-Marek. Ground-motion prediction equation for the Chilean subduction zone. *Bulletin of the Seismological Society of America*, 107(2):901–911, 2017a. doi: 10.1785/0120160221.

G. A. Montalva, N. Bastías, and A. Rodriguez-Marek. Single station sigma in Chile. In *Proceedings of Sixteenth World Conference on Earthquake Engineering*, 2017b. Paper no. 2799.

G. A. Montalva, N. Bastías, and A. Rodriguez-Marek. Erratum to Ground-motion prediction equation for the Chilean subduction zone. *Bulletin of the Seismological Society of America*, 107(5):2541, 2017c. doi: 10.1785/0120170189.

G. A. Montalva, N. Bastías, and F. Leyton. Strong ground motion prediction model for PGV and spectral velocity for the Chilean subduction zone. *Bulletin of the Seismological Society of America*, 112(1):348–360, Feb 2022. doi: 10.1785/0120210037.

A. S. Moradi, N. Mirzaei, and M. Rezapour. Attenuation relationships of seismic intensity in iran. *Journal of Earth and Space Physics*, 30(1):31, 2004. In Persian. Abstract in English.

P. Morasca, L. Malagnini, A. Akinci, D. Spallarossa, and R. B. Herrmann. Ground-motion scaling in the western Alps. *Journal of Seismology*, 10(3):315–333, 2006. doi: 10.1007/s10950-006-9019-x.

P. Morasca, F. Zolezzi, D. Spallarossa, and L. Luzi. Ground motion models for the Molise region (southern Italy). *Soil Dynamics and Earthquake Engineering*, 28(3):198–211, 2008.

N. Morikawa and H. Fujiwara. A new ground motion prediction equation for Japan applicable up to $M9$ mega-earthquake. *Journal of Disaster Research*, 8(5):878–888, 2013.

R. E. Moss. Reduced sigma of ground motion prediction equations through uncertainty propagation. *Bulletin of the Seismological Society of America*, 101(1):250–257, 2011.

R. E. S. Moss. Reduced uncertainty of ground motion prediction equations through Bayesian variance analysis. PEER Report 2009/105, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, USA, Nov 2009.

R. E. S. Moss and A. Der Kiureghian. Incorporating parameter uncertainty into attenuation relationships. In *Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*, Apr 2006. Paper no. 2010.

D. Motazedian and G. Atkinson. Ground-motion relations for Puerto Rico. In P. Mann, editor, *Special Paper 385: Active Tectonics and Seismic Hazards of Puerto Rico, the Virgin Islands, and Offshore Areas*, pages 61–80. The Geological Society of America, 2005.

H.-Q. Mu and K.-V. Yuen. Ground motion prediction equation development by heterogeneous Bayesian learning. *Computer-Aided Civil and Infrastructure Engineering*, 31(10):761–776, Oct 2016. doi: 10.1111/mice.12215.

C. G. Munson and C. H. Thurber. Analysis of the attenuation of strong ground motion on the island of Hawaii. *Bulletin of the Seismological Society of America*, 87(4):945–960, Aug 1997.

R. M. W. Musson. Intensity-based seismic risk assessment. *Soil Dynamics and Earthquake Engineering*, 20: 353–360, 2000.

R. M. W. Musson. Intensity attenuation in the UK. *Journal of Seismology*, 9(1):73–86, 2005.

R. M. W. Musson. Updated intensity attenuation for the UK. Open Report OR/13/029, British Geological Survey, 2013.

R. M. W. Musson and I. Cecić. Macroseismology. In W. H. K. Lee, H. Kanamori, P. C. Jennings, and C. Kisslinger, editors, *International Handbook of Earthquake and Engineering Seismology*, volume 81A, chapter 49, pages 807–822. Academic Press, San Diego, USA, 2002. ISBN 0-12-440652-1.

R. M. W. Musson and P. W. Winter. Seismic hazard of the U.K. Technology Report AEA/CS/16422000/ZJ745/005, AEA, 1996. Not seen. Cited in Musson (2005).

R. M. W. Musson, P. C. Marrow, and P. W. Winter. Attenuation of earthquake ground motion in the UK. Technical Report AEA/CS/16422000/ZJ745/004, AEA Technology Consultancy Services (SRD) and British Geological Survey, May 1994.

A. B. Nabilah and T. Balendra. Seismic hazard analysis for Kuala Lumpur, Malaysia. *Journal of Earthquake Engineering*, 16(7):1076–1094, 2012. doi: 10.1080/13632469.2012.685208.

M. Nakajima, I.-K. Choi, Y. Ohtori, and Y.-S. Choun. Evaluation of seismic hazard curves and scenario earthquakes for Korean sites based on probabilistic seismic hazard analysis. *Nuclear Engineering and Design*, 237(3):277–288, Feb 2007. doi: 10.1016/j.nucengdes.2006.04.028.

S. K. Nath, M. Vyas, I. Pal, and P. Sengupta. A seismic hazard scenario in the Sikkim Himalaya from seismotectonics, spectral amplification, source parameterization, and spectral attenuation laws using strong motion seismometry. *Journal of Geophysical Research*, 110(B01301), 2005a. doi: 10.1029/2004JB003199.

S. K. Nath, M. Vyas, I. Pal, A. K. Singh, S. Mukherjee, and P. Sengupta. Spectral attenuation models in the Sikkim Himalaya from the observed and simulated strong motion events in the region. *Current Science*, 88 (2):295–303, Jan 2005b.

S. K. Nath, A. Raj, K. K. S. Thingbaijam, and A. Kumar. Ground motion synthesis and seismic scenario in guwahati city — a stochastic approach. *Seismological Research Letters*, 80(2):233–242, Mar 2009. doi: 10.1785/gssrl.80.2.233.

S. K. Nath, K. K. S. Thingbaijam, S. K. Maiti, and A. Nayak. Ground-motion predictions in Shillong region, northeast India. *Journal of Seismology*, 16(3):475–488, Jun 2012. doi: 10.1007/s10950-012-9285-8.

National Disaster Management Authority. Development of probablistic seismic hazard map of India. Technical report, 2010.

A. G. Nazarov and N. V. Shebalin. *The Seismic Scale and Methods of Measuring Seismic Intensity*. Nauka, Moscow, USSR, 1975. In Russian. Not seen. Cited in Bindi et al. (2011b).

R. Nazir, H. Moayedi, R. B. M. Noor, and S. Ghareh. Development of new attenuation equation for subduction mechanisms in Malaysia water. *Arabian Journal of Geosciences*, 9(741), 2016. doi: 10.1007/s12517-016-2773-3.

M. Nekooei and H. Babaei. Attenuation relationships for horizontal component of PGV derived from strong-motion records from Iran. *Journal of Measurements in Engineering*, 4(2):112–116, Jun 2016.

D. X. Nguyen and T. M. T. Tran. Determination of an equation for acceleration ground motion by a strong earthquake in Vietnam. *Journal of Earth Sciences*, 21(3):207—-213, 1999. In Vietnamese. Not seen. Cited in Nguyen et al. (2012).

L. M. Nguyen, T.-L. Lin, Y.-M. Wu, B.-S. Huang, C.-H. Chang, W.-G. Huang, T. S. Le, Q. C. Nguyen, and V. T. Dinh. The first peak ground motion attenuation relationships for north of Vietnam. *Journal of Asian Earth Sciences*, 43(1):241–253, Jan 2012. doi: 10.1016/j.jseaes.2011.09.012.

M. Niazi and Y. Bozorgnia. Behaviour of near-source peak horizontal and vertical ground motions over SMART-1 array, Taiwan. *Bulletin of the Seismological Society of America*, 81(3):715–732, Jun 1991.

M. Niazi and Y. Bozorgnia. Behaviour of near-source vertical and horizontal response spectra at SMART-1 array, Taiwan. *Earthquake Engineering and Structural Dynamics*, 21:37–50, 1992.

T. Nishimura and M. Horike. The attenuation relationships of peak ground accelerations for the horizontal and the vertical components inferred from Kyoshin network data. *Journal of Structural and Construction Engineering (Transactions of AIJ)*, 571:63—-70, 2003. In Japanese. Not seen. Cited in Edwards and Rietbrock (2009).

R. M. Noor, S. W. Ahmad, A. Adnan, and R. Nazir. Attenuation function relationship of subduction mechanism and far field earthquake. *ARPN Journal of Engineering and Applied Sciences*, 11(4):2597–2601, Feb 2016.

M. Novakovic, G. M. Atkinson, and K. Assatourians. Empirically calibrated ground-motion prediction equation for Oklahoma. *Bulletin of the Seismological Society of America*, 108(5A):2444–2461, Oct 2018. doi: 10.1785/0120170331.

A. A. Nowroozi. Attenuation relations for peak horizontal and vertical accelerations of earthquake ground motion in Iran: A preliminary analysis. *Journal of Seismology and Earthquake Engineering*, 7(2):109–128, Summer 2005.

O. W. Nuttli and R. B. Herrmann. Ground motion relations for eastern North American earthquakes. In *Proceedings of the Third International Conference on Soil Dynamics & Earthquake Engineering*, volume II, pages 231–241, 1987.

L. Obaid, S. Alani, M. Omar, S. Barakat, M. Arab, M. Leblouba, A. Shanableh, and A. Tahmaz. The development of a local ground motion prediction equation from recorded data. In *Proceedings of the 4th World Congress on Civil, Structural, and Environmental Engineering*, Apr 2019. doi: 10.11159/icgre19.181. Paper no. ICGRE 181.

S. Ohno, T. Ohta, T. Ikeura, and M. Takemura. Revision of attenuation formula considering the effect of fault size to evaluate strong motion spectra in near field. *Tectonophysics*, 218:69–81, 1993.

S. Ohno, M. Takemura, M. Niwa, and K. Takahashi. Intensity of strong ground motion on pre-quaternary stratum and surface soil amplifications during the 1995 Hyogo-ken Nanbu earthquake, Japan. *Journal of Physics of the Earth*, 44(5):623–648, 1996.

Y. Ohsaki, Y. Sawada, K. Hayashi, B. Ohmura, and C. Kumagai. Spectral characteristics of hard rock motions. In *Proceedings of Seventh World Conference on Earthquake Engineering*, volume 2, pages 231–238, 1980a.

Y. Ohsaki, M. Watabe, and M. Tohdo. Analyses on seismic ground motion parameters including vertical components. In *Proceedings of Seventh World Conference on Earthquake Engineering*, volume 2, pages 97–104, 1980b.

S. Ólafsson and R. Sigbjörnsson. A theoretical attenuation model for earthquake-induced ground motion. *Journal of Earthquake Engineering*, 3(3):287–315, Jul 1999.

S. Òlafsson and R. Sigbjörnsson. Near-source decay of seismic waves in Iceland. In *Proceedings of Fifteenth World Conference on Earthquake Engineering*, 2012. Paper no. 4462.

S. Ólafsson, R. Sigbjörnsson, and R. Rupakhety. Determination of parameters for stochastic strong motion models representing earthquakes in the South Iceland Seismic Zone. In R. Rupakhety and S. Ólafsson, editors, *Earthquake Engineering and Structural Dynamics in Memory of Ragnar Sigbjörnsson*, volume 44 of *Geotechnical, Geological and Earthquake Engineering*, pages 193–207. Springer International Publishing AG, 2018. doi: 10.1007/978-3-319-62099-2_10.

D. Olszewska. Attenuation relations of ground motion acceleration response spectra for the Polkowice region. *Publications of the Institute of Geophysics of the Polish Academy of Sciences*, M-29(395), 2006.

M. Ordaz and C. Reyes. Earthquake hazard in Mexico City: Observations versus computations. *Bulletin of the Seismological Society of America*, 89(5):1379–1383, Oct 1999.

M. Ordaz, J. M. Jara, and S. K. Singh. Riesgo sísmico y espectros de diseño en el estado de Guerrero. Technical Report 8782/9745, UNAM Instituto de Ingeniería, 1989. In Spanish. Not seen, cited in Arroyo et al. (2010).

M. Ordaz, S. K. Singh, and A. Arciniega. Bayesian attenuation regressions: An application to Mexico City. *Geophysical Journal International*, 117(2):335–344, 1994.

T. Ornthammarath. *Influence of hazard modeling methods and the uncertainty of GMPEs on the results of probabilistic seismic hazard analysis*. PhD thesis, ROSE School, University of Pavia, Italy, 2010.

T. Ornthammarath, J. Douglas, R. Sigbjörnsson, and C. G. Lai. Assessment of strong ground motion variability in Iceland. In *Proceedings of Fourteenth European Conference on Earthquake Engineering*, 2010. Paper no. 1263.

T. Ornthammarath, J. Douglas, R. Sigbjörnsson, and C. G. Lai. Assessment of ground motion variability and its effects on seismic hazard analysis: A case study for Iceland. *Bulletin of Earthquake Engineering*, 9(4): 931–953, 2011. doi: 10.1007/s10518-011-9251-9.

D. L. Orphal and J. A. Lahoud. Prediction of peak ground motion from earthquakes. *Bulletin of the Seismological Society of America*, 64(5):1563–1574, Oct 1974.

L. S. Oskorbin. Equations of seismic field for sakhalin earthquakes. In *Seismicheskoe raionirovanie Sakhalina (Seismic Zoning of Sakhalin)*, pages 3–22. Nauch. Tsentr Akad. Nauk SSSR, 1977. Not seen. Cited in Konovalov et al. (2019).

A. Oth, H. Miyake, and D. Bindi. On the relation of earthquake stress drop and ground motion variability. *Journal of Geophysical Research: Solid Earth*, 122, 2017. doi: 10.1002/2017JB014026.

C. Özbey, A. Sari, L. Manuel, M. Erdik, and Y. Fahjan. An empirical attenuation relationship for northwestern Turkey ground motion using a random effects approach. *Soil Dynamics and Earthquake Engineering*, 24(2): 115–125, 2004.

A. Paciello, D. Rinaldis, and R. Romeo. Incorporating ground motion parameters related to earthquake damage into seismic hazard analysis. In *Proceedings of the Sixth International Conference on Seismic Zonation*, pages 321–326, 2000.

Pacific Earthquake Engineering Research Center. NGA-West2 ground motion prediction equations for vertical ground motions. Technical Report 2013/24, Pacific Earthquake Engineering Research Center, Headquarters at the University of California, Berkeley, USA, Sep 2013.

Pacific Earthquake Engineering Research Center. NGA-East: Median ground-motion models for the central and eastern North America region. Technical Report 2015/04, PEER, University of California, Berkeley, USA, Apr 2015.

F. Pacor, D. Spallarossa, A. Oth, L. Luzi, R. Puglia, L. Cantore, A. Mercuri, M. D'Amico, and D. Bindi. Spectral models for ground motion prediction in the L'Aquila region (central Italy): Evidence for stress-drop dependence on magnitude and depth. *Geophysical Journal International*, 204(2):697–718, Feb 2016. doi: 10.1093/gji/ggv448.

A. Pancha and J. J. Taber. Attenuation of weak ground motions: A report prepared for the New Zealand Earthquake Commission. Technical report, School of Earth Sciences, Victoria University of Wellington, New Zealand, 1997. Not seen. Reported in Stafford (2006).

K. L. Pankow and J. C. Pechmann. The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America*, 94(1):341–348, Feb 2004.

K. L. Pankow and J. C. Pechmann. Erratum: The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America*, 96(1):364, Feb 2006. doi: 10.1785/0120050184.

R. Paolucci, A. Rovelli, E. Faccioli, C. Cauzzi, D. Finazzi, M. Vanini, C. Di Alessandro, and G. Calderoni. On the reliability of long period spectral ordinates from digital accelerograms. *Earthquake Engineering and Structural Dynamics*, 37(5):697–710, 2008.

G. A. Parker, J. P. Stewart, D. M. Boore, G. M. Atkinson, and B. Hassani. NGA-Subduction global ground-motion models with regional adjustment factors. PEER Report 2020/03, Pacific Earthquake Engineering Research Center, Aug 2020.

G. A. Parker, J. P. Stewart, D. M. Boore, G. M. Atkinson, and B. Hassani. NGA-Subduction global ground motion models with regional adjustment factors. *Earthquake Spectra*, 38(1):456–493, 2022. doi: 10.1177/87552930211034889.

I. A. Parvez, A. A. Gusev, G. F. Panza, and A. G. Petukhin. Preliminary determination of the interdependence among strong-motion amplitude, earthquake magnitude and hypocentral distance for the Himalayan region. *Geophysical Journal International*, 144(3):577–596, 2001.

C. Pasolini, D. Albarello, P. Gasperini, V. D'Amico, and B. Lolli. The attenuation of seismic intensity in Italy, part II: Modeling and validation. *Bulletin of the Seismological Society of America*, 98(2):692–708, Apr 2008. doi: 10.1785/0120070021.

M. Pasyanos. Validation of attenuation models for ground motion applications in central and eastern North America. *Earthquake Spectra*, 31(4):2281–2300, Nov 2015. doi: 10.1193/052714EQS074M.

J. Pathak, D. K. Paul, and P. N. Godbole. ANN based attenuation relationship for estimation of PGA using Indian strong-motion data. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, Sep 2006. Paper no. 1132.

K. Peng, L. Xie, S. Li, D. M. Boore, W. D. Iwan, and T. L. Teng. The near-source strong-motion accelerograms recorded by an experimental array in Tangshan, China. *Physics of the Earth and Planetary Interiors*, 38: 92–109, 1985a.

K.-Z. Peng, F. T. Wu, and L. Song. Attenuation characteristics of peak horizontal acceleration in northeast and southwest China. *Earthquake Engineering and Structural Dynamics*, 13(3):337–350, May–Jun 1985b.

T. Perea and E. Sordo. Direct response spectrum prediction including local site effects. In *Proceedings of Eleventh European Conference on Earthquake Engineering*, 1998.

I. Perus and P. Fajfar. How reliable are the ground motion prediction equations? In *20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)*, Aug 2009. SMiRT 20-Division IV, Paper 1662.

I. Perus and P. Fajfar. Ground-motion prediction by a non-parametric approach. *Earthquake Engineering and Structural Dynamics*, 39(12):1395–1416, Oct 2010. doi: 10.1002/eqe.1007.

L. Peruzza, R. Azzaro, R. Gee, S. D'Amico, H. Langer, G. Lombardo, B. Pace, M. Pagani, F. Panzera, M. Ordaz, M. L. Suarez, and G. Tusa. When probabilistic seismic hazard climbs volcanoes: the Mt. Etna case, Italy – Part 2: Computational implementation and first results. *Natural Hazards and Earth System Sciences*, 17: 1999–2015, 2017. doi: 10.5194/nhess-17-1999-2017.

M. D. Petersen, J. Dewey, S. Hartzell, C. Mueller, S. Harmsen, A. D. Frankel, and K. Rukstales. Probabilistic seismic hazard analysis for Sumatra, Indonesia and across the southern Malaysian peninsula. *Tectonophysics*, 390(1–4):141–158, Oct 2004. doi: 10.1016/j.tecto.2004.03.026.

M. D. Petersen, A. D. Frankel, S. C. Harmsen, C. S. Mueller, K. M. Haller, R. L. Wheeler, R. L. Wesson, Y. Zeng, O. S. Boyd, D. M. Perkins, N. Luco, E. H. Field, C. J. Wills, and K. S. Rukstales. Documentation for the 2008 Update of the United States National Seismic Hazard Maps. Open-File Report 2008-1128, U.S. Department of the Interior, U.S. Geological Survey, 2008. 61 p.

M. D. Petersen, M. P. Moschetti, P. M. Powers, C. S. Mueller, K. M. Haller, A. D. Frankel, Y. Zeng, S. Rezaeian, S. C. Harmsen, O. S. Boyd, N. Field, R. Chen, K. S. Rukstales, N. Luco, R. L. Wheeler, R. A. Williams, and A. H. Olsen. Documentation for the 2014 Update of the United States National Seismic Hazard Maps. Open-File Report 2014-1091, U.S. Department of the Interior, U.S. Geological Survey, 2014. 243 pp.

D. Petrovski and A. Marcellini. Prediction of seismic movement of a site: Statisical approach. In *Proc. UN Sem. on Predict. of Earthquakes*, 1988. Lisbon, Portugal, 14–18 November.

G. G. Pétursson and K. S. Vogfjörd. Attenuation relations for near- and far-field peak ground motion (PGV, PGA) and new magnitude estimates for large earthquakes in SW-Iceland. Technical Report VÍ 2009-012, Icelandic Meteorological Office, Reykjavik, Iceland, 2009.

S. Pezeshk, A. Zandieh, and B. Tavakoli. Hybrid empirical ground-motion prediction equations for eastern North Amercia using NGA models and updated seismological parameters. *Bulletin of the Seismological Society of America*, 101(4):1859–1870, Aug 2011. doi: 10.1785/0120100144.

S. Pezeshk, A. Zandieh, K. W. Campbell, and B. Tavakoli. Ground-motion prediction equations for central and eastern North America using the hybrid empirical method and NGA-West2 empirical ground-motion models. *Bulletin of the Seismological Society of America*, 108(4):2278–2304, 2018. doi: 10.1785/0120170179.

S. Pezeshk, A. Zandieh, and A. Haji-Soltani. A ground-motion model for the Gulf coast region of the United States. *Bulletin of the Seismological Society of America*, 111(6):3261–3277, 2021. doi: 10.1785/0120210023.

V.-B. Phung, C.-H. Loh, S.-H. Chao, and N. A. Abrahamson. Analysis of epistemic uncertainty associated with GMPEs and their weight within the logic tree for PSHA: Application to Taiwan. *Terrestrial Atmospheric and Oceanic Science*, 29(6):611–633, Dec 2018.

V.-B. Phung, C. H. Loh, S. H. Chao, and N. A. Abrahamson. Ground motion prediction equation for Taiwan subduction zone earthquakes. *Earthquake Spectra*, 36(3):1331–1358, Aug 2020a. doi: 10.1177/8755293020906829.

V.-B. Phung, C. H. Loh, S. H. Chao, B. S. J. Chiou, and B.-S. Huang. Ground motion prediction equation for crustal earthquakes in Taiwan. *Earthquake Spectra*, 36(4):2129–2164, Nov 2020b. doi: 10.1177/8755293020919415.

V.-B. Phung, N. A. Abrahamson, B.-S. Huang, and C. H. Loh. Vertical ground-motion prediction equation and the vertical-to-horizontal spectral ratio for crustal earthquakes in Taiwan. *Earthquake Spectra*, 38(2): 1189–1222, 2022. doi: 10.1177/87552930211061168.

PML. British earthquakes. Technical Report 115/82, Principia Mechanica Ltd., London, 1982. Not seen. Reported in Ambraseys et al. (1992).

PML. Seismological studies for UK hazard analysis. Technical Report 346/85, Principia Mechanica Ltd., London, 1985. Not seen. Reported in Ambraseys et al. (1992).

PML. UK uniform risk spectra. Technical Report HPC-IP-096013, Principia Mechanica Ltd., London, Apr 1988. Report for National Nuclear Corporation.

B. Podili and S. T. G. Raghukanth. Ground motion prediction equations for higher order parameters. *Soil Dynamics and Earthquake Engineering*, 118:98–110, 2019. doi: 10.1016/j.soildyn.2018.11.027.

E. Popescu, C. O. Cioflan, M. Radulian, A. O. Placinta, and I. A. Moldovan. Attenuation relations for the seismic ground motion induced by Vrancea intermediate-depth earthquakes. In *International Symposium on Strong Vrancea Earthquakes and Risk Mitigation*, Oct 2007.

G. Pousse, C. Berge-Thierry, L. F. Bonilla, and P.-Y. Bard. Eurocode 8 design response spectra evaluation using the K-Net Japanese database. *Journal of Earthquake Engineering*, 9(4):547–574, Jul 2005. doi: 10.1142/S1363246905002067.

G. Pousse, L. F. Bonilla, F. Cotton, and L. Margerin. Non stationary stochastic simulation of strong ground motion time histories including natural variability: Application to the K-net Japanese database. *Bulletin of the Seismological Society of America*, 96(6):2103—-2117, Dec 2006. doi: 10.1785/0120050134.

L. Quadros, M. Assump cão, and A. P. Trindade de Souza. Seismic intensity attenuation for intraplate earthquakes in Brazil with the re-evaluation of historical seismicity. *Seismological Research Letters*, 90(6):2217–2226, 2019. doi: 10.1785/0220190120.

P. Quijada, E. Gajardo, M. Franke, M. Kozuch, and J. Grases. Analisis de amenaza sìsmica de Venezuela para nuevo mapa de zonificaciun con fines de ingenierìa. In *Memorias del Octavo Seminario Latinoamericano de Ingenierìa Sismo-reistente*, Merida, Mexico, 1993. In Spanish. Not seen. Used by Tanner and Shedlock (2004).

C. Radu, D. Lungu, S. Demetriu, and O. Coman. Recurrence, attenuation and dynamic amplification for intermediate depth Vrancea earthquakes. In *Proceedings of the XXIV General Assembly of the ESC*, volume III, pages 1736–1745, Sep 1994.

S. T. G. Raghu Kanth and R. N. Iyengar. Seismic hazard estimation for Mumbai city. *Current Science*, 91(11): 1486–1494, Dec 2006.

S. T. G. Raghu Kanth and R. N. Iyengar. Estimation of seismic spectral acceleration in peninsular India. *Journal of Earth System Science*, 116(3):199–214, Jun 2007.

M. C. Raghucharan, S. N. Somala, O. Erteleva, and E. Rogozhi. Seismic attenuation model for data gap regions using recorded and simulated ground motions. *Natural Hazards*, 107:423–446, 2021. doi: 10.1007/s11069-021-04589-w.

S. T. G. Raghukanth and B. Kavitha. Ground motion relations for active regions in India. *Pure and Applied Geophysics*, 171(9):2241–2275, Sep 2014. doi: 10.1007/s00024-014-0807-x.

S. Rahpeyma, B. Halldorsson, B. Hrafnkelsson, and S. Jónsson. Bayesian hierarchical model for variations in earthquake peak ground acceleration within small-aperture arrays. *Environmetrics*, 29(e2497), 2018. doi: 10.1002/env.2497.

A. M. Rajabi, M. Khamehchiyan, M. R. Mahdavifar, and V. Del Gaudio. Attenuation relation of Arias intensity for Zagros Mountains region (Iran). *Soil Dynamics and Earthquake Engineering*, 30:110–118, 2010. doi: 10.1016/j.soildyn.2009.09.008.

F. Ramadan, C. Smerzini, G. Lanzano, and F. Pacor. An empirical model for the vertical-to-horizontal spectral ratios for Italy. *Earthquake Engineering and Structural Dynamics*, 50:4121–4141, 2021. doi: 10.1002/eqe.3548.

H. R. Ramazi and V. Schenk. Preliminary results obtained from strong ground motion analzses [sic] of Iranian earthquakes. In *Proceedings of the XXIV General Assembly of the ESC*, volume III, pages 1762–1770, Sep 1994.

R. Ramkrishnan, K. Sreevalsa, and T. G. Sitharam. Development of new ground motion prediction equation for the north and central Himalayas using recorded strong motion data. *Journal of Earthquake Engineering*, 25 (10):1903–1926, 2021. doi: 10.1080/13632469.2019.1605318.

R. Ramkrishnan, K. Sreevalsa, and T. G. Sitharam. Strong motion data based regional ground motion prediction equations for north east India based on non-linear regression models. *Journal of Earthquake Engineering*, 26 (6):2927–2947, 2022. doi: 10.1080/13632469.2020.1778586.

M. Raoof, R. B. Herrmann, and L. Malagnini. Attenuation and excitation of three-component ground motion in southern California. *Bulletin of the Seismological Society of America*, 89(4):888–902, Aug 1999.

E. M. Rathje, N. A. Abrahamson, and J. D. Bray. Simplified frequency content estimates of earthquake ground motions. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 124(2):150–159, 1998. doi: 10.1061/(ASCE)1090-0241(1998)124:2(150.

E. M. Rathje, F. Faraj, S. Russell, and J. D. Bray. Empirical relationships for frequency content parameters of earthquake ground motions. *Earthquake Spectra*, 20(1):119–144, 2004.

C. Reyes. *El estado limite de servicio en el diseño sismico de edificios*. PhD thesis, School of Engineering, National Autonomous University of Mexico (UNAM), 1998. In Spanish. Not seen, reported in Ordaz and Reyes (1999).

D. A. Rhoades. Estimation of attenuation relations for strong-motion data allowing for individual earthquake magnitude uncertainties. *Bulletin of the Seismological Society of America*, 87(6):1674–1678, 1997.

C. F. Richter. *Elementary Seismology*. Freeman and Co., San Francisco, USA, 1958.

A. Rietbrock and B. Edwards. Update of the UK stochastic ground motion model using a decade of broadband data. In *2019 SECED Conference*, Sep 2019.

A. Rietbrock, F. Strasser, and B. Edwards. A stochastic earthquake ground-motion prediction model for the United Kingdom. *Bulletin of the Seismological Society of America*, 103(1):57–77, Feb 2013.

D. Rinaldis, R. Berardi, N. Theodulidis, and B. Margaris. Empirical predictive models based on a joint Italian & Greek strong-motion database: I, peak ground acceleration and velocity. In *Proceedings of Eleventh European Conference on Earthquake Engineering*, 1998.

A. Rodriguez-Marek and G. Montalva. Uniform hazard spectra for site-specific applications including uncertainties in site-response. Final technical report, Washington State University, USA, Feb 2010. USGS award number 08HQGR0086.

A. Rodriguez-Marek, G. A. Montalva, F. Cotton, and F. Bonilla. Analysis of single-station standard deviation using the KiK-net data. *Bulletin of the Seismological Society of America*, 101(3):1242–1258, Jun 2011. doi: 10.1785/0120100252.

Q. Rodríguez-Pérez. Ground-motion prediction equations for near-trench interplate and normal-faulting inslab subduction zone earthquakes in Mexico. *Bulletin of the Seismological Society of America*, 104(1):427–438, Feb 2014. doi: 10.1785/0120130032.

A. M. Rogers, D. M. Perkins, D. B. Hampson, and K. W. Campbell. Investigations of peak acceleration data for site effects. In *Proceedings of the Fourth International Conference on Seismic Zonation*, volume II, pages 229–236, 1991.

R. W. Romeo, G. Tranfaglia, and S. Castenetto. Engineering-developed relations derived from the strongest instrumentally-detected Italian earthquakes. In *Proceedings of Eleventh World Conference on Earthquake Engineering*, 1996. Paper no. 1466.

C. J. Ruhl, D. Melgar, J. Geng, D. E. Goldberg, B. W. Crowell, R. M. Allen, Y. Bock, S. Barrientos, S. Riquelme, J. C. Baez, E. Cabral-Cano, X. Pérez-Campos, E. M. Hill, M. Protti, A. Ganas, M. Ruiz, P. Mothes, P. Jarrín, J.-M. Nocquet, J.-P. Avouac, and E. D'Anastasio. A global database of strong-motion displacement GNSS recordings and an example application to PGD scaling. *Seismological Research Letters*, 90(1):271–279, 2019. doi: 10.1785/0220180177.

S. Ruiz and G. R. Saragoni. Formulas de atenuación para la subducción de Chile considerando los dos mecanismos de sismogenesis y los efectos del suelo. In *Congreso Chileno de Sismología e Ingeniería Antisísmica, Novenas Jornadas*, Nov 2005. No. 01-07. In Spanish.

R. Rupakhety and R. Sigbjörnsson. Ground-motion prediction equations (GMPEs) for inelastic response and structural behaviour factors. *Bulletin of Earthquake Engineering*, 7(3):637–659, Aug 2009. doi: 10.1007/s10518-009-9105-x.

R. Rupakhety, S. U. Sigurdsson, A. S. Papageorgiou, and R. Sigbjörnsson. Quantification of ground-motion parameters and response spectra in the near-fault region. *Bulletin of Earthquake Engineering*, 9:893–930, 2011. doi: 10.1007/s10518-011-9255-5.

F. Sabetta and A. Pugliese. Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records. *Bulletin of the Seismological Society of America*, 77(5):1491–1513, Oct 1987.

F. Sabetta and A. Pugliese. Estimation of response spectra and simulation of nonstationary earthquake ground motions. *Bulletin of the Seismological Society of America*, 86(2):337–352, Apr 1996.

H. Sadeghi, A. Shooshtari, and M. Jaladat. Prediction of horizontal response spectra of strong ground motions in Iran and its regions. In *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, 2010. Paper no. 861.

K. Sadigh, M. S. Power, and R. R. Youngs. Peak horizontal and vertical accelerations, velocities, and displacements on deep soil sites during moderately strong earthquakes. In *Proceedings of the Second International Conference on Microzonation for Safer Construction — Research and Application*, pages 801–811, 1978a. Not seen. Cited in Alarcón (2007).

K. Sadigh, R. R. Youngs, and M. S. Power. A study of attenuation of peak horizontal accelerations for moderately strong earthquakes. In *Proceedings of Sixth European Conference on Earthquake Engineering*, volume 1, pages 243–250, 1978b.

K. Sadigh, C.-Y. Chang, N. A. Abrahamson, S. J. Chiou, and M. S. Power. Specification of long-period ground motions: Updated attenuation relationships for rock site conditions and adjustment factors for near-fault effects. In *Proceedings of ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control*, pages 59–70, Mar 1993.

K. Sadigh, C.-Y. Chang, J. A. Egan, F. Makdisi, and R. R. Youngs. Attenuation relationships for shallow crustal earthquakes based on California strong motion data. *Seismological Research Letters*, 68(1):180–189, Jan/Feb 1997.

R. K. Sadigh and J. A. Egan. Updated relationships for horizontal peak ground velocity and peak ground displacement for shallow crustal earthquakes. In *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*, 1998.

M. Saeki, T. Katayama, and T. Iwasaki. Statistical characteristics of accelerograms recorded in japan. In *32th Annual Convention, JSCE*, volume Part I, pages 304–305, 1977. In Japanese. Not seen. Cited in Goto et al. (1981).

H. Saffari, Y. Kuwata, S. Takada, and A. Mahdavian. Spectral acceleration attenuation for seismic hazard analysis in Iran. In *Proceedings of the Ninth U.S. National and 10th Canadian Conference on Earthquake Engineering: Reaching Beyond Borders*, 2010. Paper no. 867.

H. Saffari, Y. Kuwata, S. Takada, and A. Mahdavian. Updated PGA, PGV, and spectral acceleration attenuation relations for Iran. *Earthquake Spectra*, 28(1):257–276, Feb 2012. doi: 10.1193/1.3673622.

V. Sahakian, A. Baltay, T. Hanks, J. Buehler, F. Vernon, D. Kilb, and N. Abrahamson. Decomposing leftovers: Event, path, and site residuals for a small-magnitude Anza region GMPE. *Bulletin of the Seismological Society of America*, 108(5A):2478–2492, Oct 2018. doi: 10.1785/0120170376.

V. Sahakian, A. Baltay, T. C. Hanks, J. Buehler, F. L. Vernon, D. Kilb, and N. A. Abrahamson. Ground motion residuals, path effects, and crustal properties: A pilot study in southern California. *Journal of Geophysical Research*, 124(6):5738–5753, Jun 2019. doi: 10.1029/2018JB016796.

S. Saini, M. L. Sharma, and S. Mukhopadhyay. Strong ground motion empirical attenuation relationship for seismic hazard estimation in Himalaya region. In *12th Symposium on Earthquake Engineering*, volume I, pages 143–150, Dec 2002.

S. Sakamoto, Y. Uchiyama, and S. Midorikawa. Variance of response spectra in attenuation relationship. In *Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*, Apr 2006. Paper no. 471.

A. R. Sanchez and J. M. Jara. Estimación del peligro sísmico de Morelia. *Ciencia Nicolaita*, 29:63–76, 2001. Not seen. Cited in Jara-Guerrero et al. (2007). In Spanish.

M. A. Sandıkkaya and S. Akkar. Cumulative absolute velocity, Arias intensity and significant duration predictive models from a pan-European strong-motion dataset. *Bulletin of Earthquake Engineering*, 15(5):1881–1898, 2017. doi: 10.1007/s10518-016-0066-6.

M. A. Sandikkaya, S. Akkar, and P.-Y. Bard. A nonlinear site amplifcation model for the new pan-European ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 103(1):19—-32, 2013.

R. Saragoni, M. Astroza, and S. Ruiz. Comparative study of subduction earthquake ground motion of North, Central and South America. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 104.

S. K. Sarma and M. W. Free. The comparison of attenuation relationships for peak horizontal acceleration in intraplate regions. In *Pacific Conference on Earthquake Engineering*, volume 2, pages 175–184, November 1995.

S. K. Sarma and M. Srbulov. A simplified method for prediction of kinematic soil-foundation interaction effects on peak horizontal acceleration of a rigid foundation. *Earthquake Engineering and Structural Dynamics*, 25 (8):815–836, Aug 1996.

S. K. Sarma and M. Srbulov. A uniform estimation of some basic ground motion parameters. *Journal of Earthquake Engineering*, 2(2):267–287, 1998.

J. B. Savy, A. C. Boussonnade, R. W. Mensing, and C. M. Short. Eastern U.S. seismic hazard characterization update. Technical Report UCRL-ID-115111, Lawrence Livermore National Laboratory, USA, Jun 1993.

G. Scasserra, J. P. Stewart, P. Bazzurro, G. Lanzo, and F. Mollaioli. A comparison of NGA ground-motion prediction equations to Italian data. *Bulletin of the Seismological Society of America*, 99(5):2961–2978, 2009. doi: 10.1785/0120080133.

V. Schenk. Peak particle ground motions in earthquake near-field. In *Proceedings of Seventh European Conference on Earthquake Engineering*, volume 2, pages 211–217, 1982.

V. Schenk. Relations between ground motions and earthquake magnitude, focal distance and epicentral intensity. *Engineering Geology*, 20(1/2):143–151, Mar 1984.

F. Scherbaum, F. Cotton, and P. Smit. On the use of response spectral-reference data for the selection and ranking of ground-motion models for seismic-hazard analysis in regions of moderate seismicity: The case of rock motion. *Bulletin of the Seismological Society of America*, 94(6):2164–2185, Dec 2004. doi: 10.1785/0120030147.

F. Scherbaum, E. Delavaud, and C. Riggelsen. Model selection in seismic hazard analysis: An information-theoretic perspective. *Bulletin of the Seismological Society of America*, 99(6):3234–3247, 2009. doi: 10.1785/0120080347.

F. Scherbaum, N. M. Kuehn, M. Ohrnberger, and A. Koehler. Exploring the proximity of ground-motion models using high-dimensional visualization techniques. *Earthquake Spectra*, 26(4):1117–1138, Nov 2010. doi: 10.1193/1.3478697.

E. Schiappapietra, G. Lanzano, and S. Sgobba. Empirical predictive models for fling step and displacement response spectra based on the NESS database. *Soil Dynamics and Earthquake Engineering*, 158, 2022. doi: 10.1016/j.soildyn.2022.107294.

V. Schmidt, A. Dahle, and H. Bungum. Costa Rican spectral strong motion attenuation. Technical report, NORSAR, Kjeller, Norway, Nov. 1997. Reduction of Natural Disasters in central America Earthquake Preparedness and Hazard Mitigation Phase II: 1996–2000, Part 2.

P. B. Schnabel and H. B. Seed. Accelerations in rock for earthquakes in the western United States. *Bulletin of the Seismological Society of America*, 63(2):501–516, Apr 1973.

J. Schwarz, C. Ende, J. Habenberger, D. H. Lang, M. Baumbach, H. Grosser, C. Milereit, S. Karakisa, and S. Zünbül. Horizontal and vertical response spectra on the basis of strong-motion recordings from the 1999 Turkey earthquakes. In *Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*, Sep 2002.

L. Scognamiglio, L. Malagnini, and A. Akinci. Ground-motion scaling in eastern Sicily, Italy. *Bulletin of the Seismological Society of America*, 95(2):568–578, Apr 2005. doi: 10.1785/0120030124.

F. Sedaghati and S. Pezeshk. Comparative study on parameter estimation method for attenuation relationships. *Journal of Geophysics and Engineering*, 13:912–927, 2016. doi: 10.1088/1742-2132/13/6/912.

F. Sedaghati and S. Pezeshk. Partially nonergodic empirical ground-motion models for predicting horizontal and vertical PGV, PGA, and 5% damped linear acceleration response spectra using data from the Iranian plateau. *Bulletin of the Seismological Society of America*, 107(2):934–948, Apr 2017. doi: 10.1785/0120160205.

H. B. Seed, R. Murarka, J. Lysmer, and I. M. Idriss. Relationships of maximum acceleration, maximum velocity, distance from source, and local site conditions for moderately strong earthquakes. *Bulletin of the Seismological Society of America*, 66(4):1323–1342, 1976.

M. Segou and N. Voulgaris. The use of stochastic optimization in ground motion prediction. *Earthquake Spectra*, 29(1):283–308, Feb 2013. doi: 10.1193/1.4000098.

L. Selcuk, A. S. Selcuk, and T. Beyaz. Probabilistic seismic hazard assessment for Lake Van basin, Turkey. *Natural Hazards*, 54(3):949–965, 2010. doi: 10.1007/s11069-010-9517-6.

M. K. Sen. Deep structural complexity and site response in Los Angeles basin. In *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, volume 1, pages 545–553, May 1990.

R. T. Sewell. *Damage effectiveness of earthquake ground motion: Characterizations based on the performance of structures and equipment*. PhD thesis, Stanford University, California, USA, 1989.

E. Seyhan and J. P. Stewart. Semi-empirical nonlinear site amplification from NGA-West 2 data and simulations. *Earthquake Spectra*, 30(3):1241–1256, Aug 2014. doi: 10.1193/063013EQS181M.

K. T. Shabestari and F. Yamazaki. Attenuation relation of JMA intensity based on JMA-87-type accelerometer records. In *Proceedings of the JSCE Earthquake Engineering Symposium*, volume 24, pages 169–172, 1997. doi: 10.11532/proee1997.24.169.

K. T. Shabestari and F. Yamazaki. Attenuation relation of response spectra in Japan considering site-specific term. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 1432.

T. K. Shabestari and F. Yamazaki. Attenuation of JMA seismic intensity using recent JMA records. In *Proceedings of the 10th Japan Earthquake Engineering Symposium*, volume 1, pages 529–534, 1998. Not seen. Reported in Shabestari and Yamazaki (2000).

H. C. Shah and M. Movassate. Seismic risk analysis — California state water project. In *Proceedings of Fifth European Conference on Earthquake Engineering*, 1975. Not seen. Reported in Makropoulos and Burton (1985).

M. A. Shah, T. Iqbal, M. Qaisar, N. Ahmed, and M. Tufail. Development of attenuation relationship for northern Pakistan. In *Proceedings of Fifteenth World Conference on Earthquake Engineering*, 2012. Paper no. 5447.

M. S. Shahidzadeh and A. Yazdani. A Bayesian updating applied to earthquake ground-motion prediction equations for Iran. *Journal of Earthquake Engineering*, 21(2):290–324, 2017. doi: 10.1080/13632469.2016.1158754.

A. Shahjouei and S. Pezeshk. Alternative hybrid empirical ground-motion model for central and eastern North America using hybrid simulations and NGA-West 2 models. *Bulletin of the Seismological Society of America*, 106(2):734–754, Apr 2016. doi: 10.1785/0120140367.

M. Sharma and H. Bungum. New strong ground-motion spectral acceleration relations for the Himalayan region. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, 2006. Paper number 1459.

M. L. Sharma. Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India. *Bulletin of the Seismological Society of America*, 88(4):1063–1069, Aug 1998.

M. L. Sharma. Attenuation relationship for estimation of peak ground vertical acceleration using data from strong motion arrays in India. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 1964.

M. L. Sharma, J. Douglas, H. Bungum, and J. Kotadia. Ground-motion prediction equations based on data from the Himalayan and Zagros regions. *Journal of Earthquake Engineering*, 13(8):1191–1210, 2009. doi: 10.1080/13632460902859151.

N. Sharma and V. Convertito. Update, comparison, and interpretation of the ground-motion prediction equation for "The Geysers" geothermal area in the light of new data. *Bulletin of the Seismological Society of America*, 108(6):3645–3655, Dec 2018. doi: 10.1785/0120170350.

N. Sharma, V. Convertito, N. Maercklin, and A. Zollo. Ground-motion prediction equations for The Geysers geothermal area based on induced seismicity records. *Bulletin of the Seismological Society of America*, 103 (1):117–130, Feb 2013. doi: 10.1785/0120120138.

S. Shi and J. Shen. A study on attenuation relations of strong earth movements in Shanghai and its adjacent area. *Earthquake Research in China*, 19:315–323, 2003. In Chinese. Not seen. Cited in Cole et al. (2008).

A. V. Shoushtari, A. B. Adnan, and M. Zare. On the selection of ground–motion attenuation relations for seismic hazard assessment of the Peninsular Malaysia region due to distant Sumatran subduction intraslab earthquakes. *Soil Dynamics and Earthquake Engineering*, 82:123–137, 2016. doi: 10.1016/j.soildyn.2015.11.012.

A. V. Shoushtari, A. Z. Adnan, and M. Zare. Ground motion prediction equations for distant subduction interface earthquakes based on empirical data in the Malay Peninsula and Japan. *Soil Dynamics and Earthquake Engineering*, 109:339–353, 2018. doi: 10.1016/j.soildyn.2018.03.024.

H. Si and S. Midorikawa. New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition. *Journal of Structural and Construction Engineering, AIJ*, 523:63–70, 1999. In Japanese with English abstract. Not seen.

H. Si and S. Midorikawa. New attenuation relations for peak ground acceleration and velocity considering effects of fault type and site condition. In *Proceedings of Twelfth World Conference on Earthquake Engineering*, 2000. Paper No. 0532.

H. Si, S. Midorikawa, and T. Kishida. Development of NGA-Sub ground-motion model of 5%-damped pseudo-spectral acceleration based on database for subduction earthquakes in Japan. PEER Report 2020/06, Pacific Earthquake Engineering Research Center, Dec 2020.

H. Si, S. Midorikawa, and T. Kishida. Development of NGA-Sub ground-motion prediction equation of 5%-damped pseudo-spectral acceleration based on database of subduction earthquakes in Japan. *Earthquake Spectra*, 38(4):2682–2706, 2022. doi: 10.1177/87552930221090326.

R. Sigbjörnsson. Strong motion measurements in Iceland and seismic risk assessment. In *Proceedings of Ninth European Conference on Earthquake Engineering*, volume 10-A, pages 215–222, 1990.

R. Sigbjörnsson and N. N. Ambraseys. Uncertainty analysis of strong ground motion. *Bulletin of Earthquake Engineering*, 1(3):321–347, 2003.

R. Sigbjörnsson and G. I. Baldvinsson. Seismic hazard and recordings of strong ground motion in Iceland. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 1, pages 419–424, Rotterdam, The Netherlands, 1992. A. A. Balkema. Madrid, Spain. 19–24 July.

R. Sigbjörnsson and A. S. Elnashai. Hazard assessment of Dubai, United Arab Emirates, for close and distant earthquakes. *Journal of Earthquake Engineering*, 10(5):749–773, 2006.

W. Silva and N. A. Abrahamson. Quantification of long period strong ground motion attenuation for engineering design. In M. J. Huang, editor, *Proceedings of (Strong Motion Instrumentation Program) SMIP92 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*. California Division of Mines and Geology, Sacramento, USA, May 1992.

W. Silva, N. Gregor, and R. Darragh. Development of regional hard rock attenuation relations for central and eastern North America. Technical report, Pacific Engineering and Analysis, Nov 2002.

W. Silva, N. Gregor, and R. Lee. Development of regional hard rock attenuation relations for South Carolina. Technical report, Sep 2004.

K. A. Simpson. *Attenuation of strong ground-motion incorporating near-surface foundation conditions*. PhD thesis, University of London, 1996.

R. P. Singh, A. Aman, and Y. J. J. Prasad. Attenuation relations for strong seismic ground motion in the Himalayan region. *Pure and Applied Geophysics*, 147(1):161–180, 1996.

S. K. Singh, E. Mena, R. Castro, and C. Carmona. Empirical prediction of ground motion in Mexico City from coastal earthquakes. *Bulletin of the Seismological Society of America*, 77(5):1862–1867, Oct 1987.

S. K. Singh, C. Gutierreez, J. Arboleda, and M. Ordaz. Peligro sísmico en El Salvador. Technical report, Universidad Nacional Autónoma de México, México, 1993. Not seen. Reported in Bommer et al. (1996).

S. K. Singh, B. K. Bansal, S. N. Bhattacharya, J. F. Pacheco, R. S. Dattatrayam, M. Ordaz, G. Suresh, Kamal, and S. E. Hough. Estimation of ground motion for Bhuj (26 January 2001; $m_w$7.6) and for future earthquakes in India. *Bulletin of the Seismological Society of America*, 93(1):353–370, Feb 2003.

A. Skarlatoudis, N. Theodulidis, C. Papaioannou, and Z. Roumelioti. The dependence of peak horizontal acceleration on magnitude and distance for small magnitude earthquakes in Greece. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 1857.

A. A. Skarlatoudis. Applicability of ground-motion prediction equations to a Greek within-slab earthquake dataset. *Bulletin of Earthquake Engineering*, 15(10):3987–4008, 2017. doi: 10.1007/s10518-017-0140-8.

A. A. Skarlatoudis, C. B. Papazachos, B. N. Margaris, N. Theodulidis, C. Papaioannou, I. Kalogeras, E. M. Scordilis, and V. Karakostas. Empirical peak ground-motion predictive relations for shallow earthquake in Greece. *Bulletin of the Seismological Society of America*, 93(6):2591–2603, Dec 2003.

A. A. Skarlatoudis, C. B. Papazachos, B. N. Margaris, C. Ventouzi, I. Kalogeras, and the EGELADOS Group. Ground-motion prediction equations of intermediate-depth earthquakes in the Hellenic Arc, southern Aegean subduction area. *Bulletin of the Seismological Society of America*, 103:1952–1968, Jun 2013. doi: 10.1785/0120120265.

D. Slejko, Z. Javakhishvili, A. Rebez, M. Santulin, M. Elashvili, P. L. Bragato, T. Godoladze, and J. Garcia. Seismic hazard assessment for the Tbilisi test area (eastern Georgia). *Bollettino di Geofisica Teorica ed Applicata*, 49(1):37–57, Mar 2008.

P. Smit. Strong motion attenuation model for central Europe. In *Proceedings of Eleventh European Conference on Earthquake Engineering*, Sep 1998. smisma.

P. Smit. Personal communication 4/12/2000, Dec 2000.

P. Smit, V. Arzoumanian, Z. Javakhishvili, S. Arefiev, D. Mayer-Rosa, S. Balassanian, and T. Chelidze. The digital accelerograph network in the Caucasus. In S. Balassanian, editor, *Earthquake Hazard and Seismic Risk Reduction — Advances in Natural and Technological Hazards Research*. Kluwer Academic Publishers, 2000. Presented at 2nd International Conference on Earthquake Hazard and Seismic Risk Reduction, Yerevan, Armenia, 15/9/1998–21/9/1998.

J. T. Snæbjörnsson and R. Sigbjörnsson. The duration characteristics of earthquake ground motions. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008.

G. Sobhaninejad, A. Noorzad, and A. Ansari. Genetic algorithm (GA): A new approach in estimating strong ground motion attenuation relations. In *Proceedings of the Fourth International Conference on Earthquake Geotechnical Engineering*, Jun 2007. Paper no. 1313.

M. R. Soghrat and M. Ziyaeifar. Ground motion prediction equations for horizontal and vertical components of acceleration in northern Iran. *Journal of Seismology*, 21(1):99–125, Jan 2017. doi: 10.1007/s10950-016-9586-4.

V. Sokolov. Empirical models for estimating Fourier-amplitude spectra of ground acceleration in the northern Caucasus (Racha seismogenic zone). *Bulletin of the Seismological Society of America*, 87(6):1401–1412, Dec 1997.

V. Sokolov and H. M. Zahran. Generation of stochastic earthquake ground motion in western Saudi Arabia as a first step in development of regional ground motion prediction model. *Arabian Journal of Geosciences*, 11 (38), 2018. doi: 10.1007/s12517-018-3394-9.

V. Sokolov, C.-H. Loh, and K.-L. Wen. Empirical model for estimating Fourier amplitude spectra of ground acceleration in Taiwan region. *Earthquake Engineering and Structural Dynamics*, 29(3):339–357, Mar 2000.

V. Sokolov, K.-P. Bonjer, M. Oncescu, and M. Rizescu. Hard rock spectral models for intermediate-depth Vrancea, Romania, earthquakes. *Bulletin of the Seismological Society of America*, 95(5):1749–1765, Oct 2005. doi: 10.1785/0120050005.

V. Sokolov, K.-P. Bonjer, F. Wenzel, B. Grecu, and M. Radulian. Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes. *Bulletin of Earthquake Engineering*, 6:367–388, 2008.

V. Sokolov, F. Wenzel, W.-Y. Jean, and K.-L. Wen. Uncertainty and spatial correlation of earthquake ground motion in Taiwan. *Terrestrial Atmospheric and Oceanic Science*, 21(6):905–921, Dec 2010. doi: 10.3319/TAO.2010.05.03.01(T).

V. Sokolov, R. Kiuchi, W. D. Mooney, and H. M. Zahran. Regional ground-motion prediction equations for western Saudi Arabia: merging stochastic and empirical estimates. *Bulletin of Earthquake Engineering*, 19: 1663–1686, 2021. doi: 10.1007/s10518-021-01048-6.

V. Y. Sokolov. Spectral parameters of the ground motions in Caucasian seismogenic zones. *Bulletin of the Seismological Society of America*, 88(6):1438–1444, Dec 1998.

P. Somerville, N. Collins, N. Abrahamson, R. Graves, and C. Saikia. Ground motion attenuation relations for the central and eastern United States. Technical report, Jun 2001. Research supported by the U.S. Geological Survey, under award number 99HQGR0098.

P. Somerville, R. Graves, N. Collins, S. G. Song, S. Ni, and P. Cummins. Source and ground motion models of Australian earthquakes. In *Proceedings of the 2009 Annual Conference of the Australian Earthquake Engineering Society*, Dec 2009a.

P. G. Somerville. Development of an improved representation of near fault ground motions. In *Proceedings of the SMIP98 Seminar on Utilization of Strong Motion Data*, pages 1–20, 1998.

P. G. Somerville, R. W. Graves, N. F. Collins, S. G. Song, and S. Ni. Ground motion models for australian earthquakes. Report to geoscience australia, Jun 2009b. Not seen.

M. B. Sørensen, D. Stromeyer, and G. Grünthal. Attenuation of macroseismic intensity: A new relation for the Marmara Sea region, northwest Turkey. *Bulletin of the Seismological Society of America*, 99(2A):538–553, 2009. doi: 10.1785/0120080299.

M. B. Sørensen, D. Stromeyer, and G. Grünthal. Intensity attenuation in the Campania region, southern Italy. *Journal of Seismology*, 14:209–223, 2010a. doi: 10.1007/s10950-009-9162-2.

M. B. Sørensen, D. Stromeyer, and G. Grünthal. A macroseismic intensity prediction equation for intermediate depth earthquakes in the Vrancea region, Romania. *Soil Dynamics and Earthquake Engineering*, 30(11): 1268–1278, 2010b. doi: 10.1016/j.soildyn.2010.05.009.

A. Souriau. Quantifying felt events: A joint analysis of intensities, accelerations and dominant frequencies. *Journal of Seismology*, 10(1):23–38, Jan 2006. doi: 10.1007/s10950-006-2843-1.

P. Spudich and D. M. Boore. Erratum: SEA99: A revised ground-motion prediction relation for use in extensional tectonic regimes. *Bulletin of the Seismological Society of America*, 95(3):1209, Jun 2005. doi: 10.1785/0120050026.

P. Spudich, J. Fletcher, M. Hellweg, J. Boatwright, C. Sullivan, W. Joyner, T. Hanks, D. Boore, A. McGarr, L. Baker, and A. Lindh. Earthquake ground motions in extensional tectonic regimes. Open-File Report 96-292, U.S. Geological Survey, 1996. Not seen. Reported in Spudich et al. (1997).

P. Spudich, J. B. Fletcher, M. Hellweg, J. Boatwright, C. Sullivan, W. B. Joyner, T. C. Hanks, D. M. Boore, A. McGarr, L. M. Baker, and A. G. Lindh. SEA96 — A new predictive relation for earthquake ground motions in extensional tectonic regimes. *Seismological Research Letters*, 68(1):190–198, Jan/Feb 1997.

P. Spudich, W. B. Joyner, A. G. Lindh, D. M. Boore, B. M. Margaris, and J. B. Fletcher. SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes. *Bulletin of the Seismological Society of America*, 89(5):1156–1170, Oct 1999.

C. Srinivasan, M. L. Sharma, J. Kotadia, and Y. A. Willy. Peak ground horizontal acceleration attenuation relationship for low magnitudes at short distances in south Indian region. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008. Paper no. 02-0135.

P. Stafford, J. Berrill, and J. Pettinga. New empirical predictive equations for the Fourier amplitude spectrum of acceleration and Arias intensity in New Zealand. In *Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC*, 2006. Paper number 820.

P. J. Stafford. *Engineering seismological studies and seismic design criteria for the Buller region, South Island, New Zealand.* PhD thesis, University of Canterbury, Christchurch, New Zealand, Feb 2006.

P. J. Stafford. Crossed and nested mixed-effects approaches for enhanced model development and removal of the ergodic assumption in empirical ground-motion models. *Bulletin of the Seismological Society of America*, 104(2):702–719, 2014. doi: 10.1785/0120130145.

P. J. Stafford. Continuous integration of data into ground-motion models using Bayesian updating. *Journal of Seismology*, 23(1):39–57, Jan 2019. doi: 10.1007/s10950-018-9792-3.

P. J. Stafford. A model for the distribution of response spectral ordinates from New Zealand crustal earthquakes based upon adjustments to the Chiou and Youngs (2014) response spectral model. GNS Science Report 2022/15, GNS Science, Lower Hutt, New Zealand, 2022. 97 pp.

P. J. Stafford, J. B. Berrill, and J. R. Pettinga. New predictive equations for Arias intensity from crustal earthquakes in New Zealand. *Journal of Seismology*, 13(1):31–52, 2009. doi: 10.1007/s10950-008-9114-2.

S. Stamatovska. A new azimuth dependent empirical strong motion model for Vranchea subduction zone. In *Proceedings of Twelfth European Conference on Earthquake Engineering*, Sep 2002. Paper reference 324.

S. Stamatovska and D. Petrovski. Ground motion parameters based on data obtained from strong earthquake records. In *National Progress Report of Yugoslavia, UNDP/UNESCO Project Rep/88/004, Task Group 3, Second Meeting*. Geophysical Institute, Zagreb, Yugoslavia, May 1991.

S. Stamatovska and D. Petrovski. Empirical attenuation acceleration laws for Vrancea intermediate earthquakes. In *Proceedings of Eleventh World Conference on Earthquake Engineering*, 1996. Paper no. 146.

V. V. Steinberg, M. V. Saks, F. F. Aptikaev, et al. Methods of seismic ground motion estimation (handbook). In *Voprosy Inzhenernoi Seismologii. Iss. 34. Nauka*, pages 5–97. 1993. In Russian. Not seen. Cited by Lyubushin and Parvez (2010).

J. P. Stewart, S.-J. Chiou, J. D. Bray, R. W. Graves, P. G. Somerville, and N. A. Abrahamson. Ground motion evaluation procedures for performance-based design. PEER Report 2001/09, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, USA, Sep 2001.

J. P. Stewart, J. Douglas, M. Javanbarg, N. A. Abrahamson, Y. Bozorgnia, D. M. Boore, K. W. Campbell, E. Delavaud, M. Erdik, and P. J. Stafford. Selection of ground motion prediction equations for the Global Earthquake Model. *Earthquake Spectra*, 31(1):19–45, 2015. doi: 10.1193/013013EQS017M.

J. P. Stewart, D. M. Boore, E. Seyhan, and G. M. Atkinson. NGA-West 2 equations for predicting vertical component PGA, PGV, and 5%-damped PSA from shallow crustal earthquakes. *Earthquake Spectra*, 32(2): 1005–1031, May 2016. doi: 10.1193/072114EQS116M.

F. Sun and K. Peng. Attenuation of strong ground motion in western U.S.A. *Earthquake Research in China*, 7 (1):119–131, 1993.

C.-H. Sung and C.-T. Lee. A new methodology for quantification of the systematic path effects on ground-motion variability. *Bulletin of the Seismological Society of America*, 106(6):2796–2810, Dec 2016. doi: 10. 1785/0120160038.

C.-H. Sung and C.-T. Lee. Improvement of the quantification of epistemic uncertainty using single-station ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 109(4):1358–1377, 2019. doi: 10.1785/0120180044.

C.-H. Sung, N. A. Abrahamson, and J.-Y. Huang. Conditional ground-motion models for horizontal peak ground displacement for active crustal regions. *Bulletin of the Seismological Society of America*, 111(3):1542–1562, 2021. doi: 10.1785/0120200299.

L. Sunuwar, C. Cuadra, and M. B. Karkee. Strong ground motion attenuation in the Sea of Japan (Okhotsk-Amur plates boundary) region. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 0197.

W. Szeliga, S. Hough, S. Martin, and R. Bilham. Intensity, magnitude, location, and attenuation in India for felt earthquakes since 1762. *Bulletin of the Seismological Society of America*, 100(2):570–584, Apr 2010. doi: 10.1785/0120080329.

T. Takahashi, S. Kobayashi, Y. Fukushima, J. X. Zhao, H. Nakamura, and P. G. Somerville. A spectral attenuation model for Japan using strong motion data base. In *Proceedings of the Sixth International Conference on Seismic Zonation*, Nov 2000.

T. Takahashi, A. Asano, T. Saiki, H. Okada, K. Irikura, J. X. Zhao, J. Zhang, H. K. Thio, P. G. Somerville, Y. Fukushima, and Y. Fukushima. Attenuation models for response spectra derived from Japanese strong-motion records accounting for tectonic source types. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 1271.

T. Takahashi, A. Asano, Y. Ono, H. Ogawa, J. X. Zhao, J. Zhang, Y. Fukushima, K. Irikura, H. K. Thio, P. G. Somerville, and Y. Fukushima. Attenuation relations of strong motion in Japan using site classification based on predominant period. In *18th International Conference on Structural Mechanics In Reactor Technology (SMiRT 18)*, Aug 2005. Paper SMiRT18-K02-1.

K. Tamura, Y. Sasaki, and K. Aizawa. Attenuation characteristics of ground motions in the period range of 2 to 20 seconds — for application to the seismic design of long-period structures. In *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, volume 1, pages 495–504, May 1990.

Y. Tang and P. M. Mai. Stochastic ground-motion simulation of the 2021 $M_w$5.9 Woods Point earthquake: Facilitating local probabilistic seismic hazard analysis in Australia. *Bulletin of the Seismological Society of America*, 113(5):2119–2143, 2023. doi: 10.1785/0120220260.

Y. Tang, N. Lam, H-H. Tsang, and E. Lumantarna. Use of macroseismic intensity data to validate a regionally adjustable ground motion prediction model. *Geosciences*, 9(422), 2019. doi: 10.3390/geosciences9100422.

Y. Tang, N. Lam, H.-H. Tsang, and E. Lumantarna. An adaptive ground motion prediction equation for use in low-to-moderate seismicity regions. *Journal of Earthquake Engineering*, 26(5):2567–2598, 2022. doi: 10.1080/13632469.2020.1784810.

J. G. Tanner and K. M. Shedlock. Seismic hazard maps of Mexico, the Caribbean, and Central and South America. *Tectonophysics*, 390(1–4):159–175, 2004.

Z. Tao, X. Tao, and A. Cui. Strong motion PGA prediction for southwestern China from small earthquake records. *Natural Hazards and Earth System Sciences*, 16:1145–1155, 2016. doi: 10.5194/nhess-16-1145-2016.

M. Tapia. *Desarrollo y aplicación de métodos avanzados para la caracterización de la respuesta sísmica del suelo a escala regional y local*. PhD thesis, Universidad Politécnica de Catalunya, Barcelona, Spain, 2006. In Catalan.

M. Tapia, T. Susagna, and X. Goula. Curvas predictivas del movimiento del suelo en el oeste del Mediterráneo. In *Asociación Espaõla de Ingeniería Sísmica*, Girona, Spain, May 2007. In Spanish with English abstract.

B. Tavakoli and S. Pezeshk. Empirical-stochastic ground-motion prediction for eastern North America. *Bulletin of the Seismological Society of America*, 95(6):2283–2296, Dec 2005. doi: 10.1785/0120050030.

B. Tavakoli and S. Pezeshk. A new approach to estimate a mixed model-based ground motion prediction equation. *Earthquake Spectra*, 23(3):665–684, Aug 2007. doi: 10.1193/1.2755934.

W. Taylor Castillo, P. Santos Lopez, A. Dahle, and H. Bungum. Digitization of strong motion data and estimation of PGA attenuation. Technical report, NORSAR, Kjeller, Norway, Nov. 1992. Reduction of Natural Disasters in central America Earthquake Preparedness and Hazard Mitigation Seismic Zonation and Earthquake Hazard Assessment.

J. Tejeda-Jácome and F. J. Chávez-García. Empirical ground-motion estimation equations in Colima from weak motion records. *ISET Journal of Earthquake Technology*, 44(3–4):409–420, Sep–Dec 2007.

A. Tento, L. Franceschina, and A. Marcellini. Expected ground motion evaluation for Italian sites. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 1, pages 489–494, 1992.

TERA Corporation. Evaluation of peak horizontal ground acceleration associated with the offshore zone of deformation at San Onofre Nuclear Generating Station. Technical report, TERA Corporation, Berkeley, California, USA, Aug 1980.

J. Tezcan and Q. Cheng. Support vector regression for estimating earthquake response spectra. *Bulletin of Earthquake Engineering*, 10(4):1205–1219, 2012. doi: 10.1007/s10518-012-9350-2.

J. Tezcan, Y. Dak Hazirbaba, and Q. Cheng. A kernel-based mixed effect regression model for earthquake ground motions. *Advances in Engineering Software*, 120:26–35, Jun 2018. doi: 10.1016/j.advengsoft.2016.06.002.

P. C. Thenhaus, S. T. Algermissen, D. M. Perkins, S. L. Hanson, and W. H. Diment. Probabilistic estimates of the seismic ground-motion hazard in western Saudi Arabia. Bulletin 1868, U.S. Geological Survey, 1989.

N. Theodulidis, V. Lekidis, B. Margaris, C. Papazachos, C. Papaioannou, and P. Dimitriu. Seismic hazard assessment and design spectra for the Kozani-Grevena region (Greece) after the earthquake of May 13, 1995. *Journal of Geodynamics*, 26(2–4):375–391, 1998.

N. P. Theodulidis. Peak ground acceleration attenuation of small earthquakes: Analysis of Euroseistest (Greece) data. In *Proceedings of the Second International Symposium on The Effects of Surface Geology on Seismic Motion: Recent Progress and New Horizon on ESG Study*, pages 1171–1176, Dec 1998.

N. P. Theodulidis and B. C. Papazachos. Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, peak horizontal acceleration, velocity and displacement. *Soil Dynamics and Earthquake Engineering*, 11:387–402, 1992.

N. P. Theodulidis and B. C. Papazachos. Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: II horizontal pseudovelocity. *Soil Dynamics and Earthquake Engineering*, 13(5):317–343, 1994.

S. Thomas, G. N. Pillai, and K. Pal. Prediction of peak ground acceleration using $\epsilon$-SVR, $\nu$-SVR and Ls-SVR algorithm. *Geomatics, Natural Hazards and Risk*, 2016a. doi: 10.1080/19475705.2016.1176604.

S. Thomas, G. N. Pillai, K. Pal, and P. Jagtap. Prediction of ground motion parameters using randomized ANFIS (RANFIS). *Applied Soft Computing*, 40:624–634, Mar 2016b. doi: 10.1016/j.asoc.2015.12.013.

H. Tong and T. Katayama. Peak acceleration attenuation by eliminating the ill-effect of the correlation between magnitude and epicentral distance. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 349–354, 1988.

G. R. Toro. Modification of the Toro et al. (1997) attenuation equations for large magnitudes and short distances. Technical report, Risk Engineering, Jun 2002.

G. R. Toro and R. K. McGuire. An investigation into earthquake ground motion characteristics in eastern North America. *Bulletin of the Seismological Society of America*, 77(2):468–489, Apr 1987.

G. R. Toro and W. J. Silva. Scenario earthquakes for Saint Louis, MO, and Memphis, TN, and seismic hazard maps for the central United States region including the effect of site conditions. Technical report, Jan 2001. Research supported by the U.S. Geological Survey (USGS), under award number 1434-HQ-97-GR-02981.

G. R. Toro, N. A. Abrahamson, and J. F. Schneider. Model of strong ground motions from earthquake in central and eastern North America: Best estimates and uncertainties. *Seismological Research Letters*, 68(1):41–57, Jan/Feb 1997.

T. Travasarou, J. D. Bray, and N. A. Abrahamson. Empirical attenuation relationship for Arias intensity. *Earthquake Engineering and Structural Dynamics*, 32:1133–1155, 2003. doi: 10.1002/eqe.270.

M. D. Trifunac. Preliminary analysis of the peaks of strong earthquake ground motion – dependence of peaks on earthquake magnitude, epicentral distance, and recording site conditions. *Bulletin of the Seismological Society of America*, 66(1):189–219, Feb 1976a.

M. D. Trifunac. Preliminary empirical model for scaling Fourier amplitude spectra of strong ground acceleration in terms of earthquake magnitude, source-to-station distance, and recording site conditions. *Bulletin of the Seismological Society of America*, 66(4):1343–1373, Aug 1976b.

M. D. Trifunac. Forecasting the spectral amplitudes of strong earthquake ground motion. In *Proceedings of Sixth World Conference on Earthquake Engineering*, volume I, pages 139–152, 1977.

M. D. Trifunac. Response spectra of earthquake ground motions. *Journal of The Engineering Mechanics Division, ASCE*, 104(EM5):1081–1097, Oct 1978.

M. D. Trifunac. Effects of site geology on amplitudes of strong motion. In *Proceedings of Seventh World Conference on Earthquake Engineering*, volume 2, pages 145–152, 1980.

M. D. Trifunac and J. G. Anderson. Preliminary empirical models for scaling absolute acceleration spectra. Technical Report 77-03, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., 1977.

M. D. Trifunac and J. G. Anderson. Preliminary empirical models for scaling pseudo relative velocity spectra. Technical Report 78-04, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., 1978a.

M. D. Trifunac and J. G. Anderson. Preliminary empirical models for scaling relative velocity spectra. Technical Report 78-05, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., 1978b.

M. D. Trifunac and A. G. Brady. On the correlation of peak acceleration of strong motion with earthquake magnitude, epicentral distance and site conditions. In *Proceedings of the U.S. National Conference on Earthquake Engineering*, pages 43–52, 1975a.

M. D. Trifunac and A. G. Brady. A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America*, 65(3):581–626, Jun 1975b.

M. D. Trifunac and A. G. Brady. Correlations of peak acceleration, velocity and displacement with earthquake magnitude, distance and site conditions. *Earthquake Engineering and Structural Dynamics*, 4(5):455–471, Jul–Sep 1976.

M. D. Trifunac and V. W. Lee. Dependence of the Fourier amplitude spectra of strong motion acceleration on depth of sedimentary deposits. Technical Report 78-14, Department of Civil Engineering, University of Southern California, Los Angeles, California, USA, 1978.

M. D. Trifunac and V. W. Lee. Dependence of pseudo relative velocity spectra of strong motion acceleration on depth of sedimentary deposits. Technical Report 79-02, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., 1979.

M. D. Trifunac and V. W. Lee. Preliminary empirical model for scaling fourier amplitude spectra of strong ground acceleration in terms of earthquake magnitude, source to station distance, site intensity and recording site conditions. Technical Report 85-03, Department of Civil Engineering, University of Southern California, Los Angeles, California, USA, 1985a.

M. D. Trifunac and V. W. Lee. Preliminary empirical model for scaling pseudo relative velocity spectra of strong earthquake acceleration in terms of magnitude, distance, site intensity and recording site condition. Technical Report 85-04, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A., 1985b.

M. D. Trifunac and V. W. Lee. Empirical models for scaling pseudo relative velocity spectra of strong earthquake accelerations in terms of magnitude, distance, site intensity and recording site conditions. *Soil Dynamics and Earthquake Engineering*, 8(3):126–144, Jul 1989.

I. Tromans. *Behaviour of buried water supply pipelines in earthquake zones*. PhD thesis, University of London, Jan 2004.

I. J. Tromans and J. J. Bommer. The attenuation of strong-motion peaks in Europe. In *Proceedings of Twelfth European Conference on Earthquake Engineering*, Sep 2002. Paper no. 394.

C.-C. P. Tsai, Y.-H. Chen, and C.-H. Liu. The path effect in ground-motion variability: An application of the variance-components technique. *Bulletin of the Seismological Society of America*, 96(3):1170–1176, Jun 2006. doi: 10.1785/0120050155.

Y. B. Tsai, F. W. Brady, and L. S. Cluff. An integrated approach for characterization of ground motions in PG&E's long term seismic program for Diablo Canyon. In *Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, volume 1, pages 597–606, May 1990.

G.-A. Tselentis, L. Danciu, and F. Gkika. Empirical Arias intensity attenuation relationships for seismic hazard analysis of Greece. In C. A. Brebbia, D. E. Beskos, G. D. Manolis, and C. C. Spyrakos, editors, *Earthquake Resistant Engineering Structures V*. WIT Press, 2005. doi: 10.2495/ERES050041.

N. Tsereteli, A. Askan, and H. Hamzehloo. Hybrid-empirical ground motion estimations for Georgia. *Acta Geophysica*, 64(5):1225–1256, Oct 2016. doi: 10.1515/acgeo-2016-0048.

M. Tuluka. An estimate of the attenuation relationship for strong ground motion in the Kivu Province, Western Rift Valley of Africa. *Physics of the Earth and Planetary Interiors*, 162:13–21, 2007.

G. Tusa and H. Langer. Prediction of ground motion parameters for the volcanic area of Mount Etna. *Journal of Seismology*, 20(1):1–42, 2016. doi: 10.1007/s10950-015-9508-x.

G. Tusa, H. Langer, and R. Azzaro. Localizing ground-motion models in volcanic terranes: Shallow events at Mt. Etna, Italy, revisited. *Bulletin of the Seismological Society of America*, 110(6):2843–2861, Dec 2020. doi: 10.1785/0120190325.

E. Twesigomwe. *Probabilistic seismic hazard assessment of Uganda*. PhD thesis, Department of Physics, Makarere University, Uganda, 1997. Not seen. Cited in Midzi et al. (1999).

Y. Uchiyama and S. Midorikawa. Attenuation relationship for response spectra on engineering bed rock considering effects of focal depth. *Journal of Structural and Construction Engineering, Architectural Institute of Japan*, 606:81—-88, 2006. In Japanese. Not seen. Cited in Goda and Atkinson (2009).

S. Ullah, D. Bindi, M. Pilz, L. Danciu, G. Weatherill, E. Zuccolo, A. Ischuk, N. N. Mikhailova, K. Abdrakhmatov, and S. Parolai. Probabilistic seismic hazard assessment for central Asia. *Annals of Geophysics*, 58(1):S0103, 2015. doi: 10.4401/ag-6687.

R. Ulusay, E. Tuncay, H. Sonmez, and C. Gokceoglu. An attenuation relationship based on Turkish strong motion data and iso-acceleration map of Turkey. *Engineering Geology*, 74(3-4):265–291, 2004.

E. Ulutaş and M. F. Özer. Attenuation relationship for estimation of peak ground horizontal acceleration in eastern Marmara region of Turkey. In *EGS-AGU-EUG Joint Assembly*, Nice, France, Apr 2003. Not seen. Cited in Güllü and İyisan (2016).

E. Ulutaş and M. F. Özer. Empirical attenuation relationship of peak ground acceleration for eastern Marmara region in Turkey. *The Arabian Journal for Science and Engineering*, 35(1A):187–203, Jan 2010.

R. Vacareanu, S. Demetriu, D. Lungu, F. Pavel, C. Arion, M. Iancovici, A. Aldea, and C. Neagu. Empirical ground motion model for Vrancea intermediate-depth seismic source. *Earthquakes and Structures*, 6(2):141–161, 2014. doi: 10.12989/eas.2014.6.2.141.

R. Vacareanu, M. Iancovici, C. Neagu, and F. Pavel. Macroseismic intensity prediction equations for Vrancea intermediate-depth seismic source. *Natural Hazards*, 79(3):2005–2031, Dec 2015a. doi: 10.1007/s11069-015-1944-y.

R. Vacareanu, M. Radulian, M. Iancovici, F. Pavel, and C. Neagu. Fore-arc and back-arc ground motion prediction model for Vrancea intermediate depth seismic source. *Journal of Earthquake Engineering*, 19(3): 535—562, 2015b. doi: 10.1080/13632469.2014.990653.

G. P. Villalobos-Escobar and R. R. Castro. Empirical ground-motion relations using moderate earthquakes recorded in Medellín-Aburrá valley (Colombia) strong-motion networks. *Bulletin of Earthquake Engineering*, 11:863–884, 2013. doi: 10.1007/s10518-012-9408-1.

V. Vives and J.A. Canas. Anelastic attenuation and pseudoacceleration relations in eastern Iberia. In *Proceedings of Tenth World Conference on Earthquake Engineering*, volume 1, pages 299–304, 1992.

T. Vuorinen, T. Tiira, and B. Lund. New Fennoscandian shield empirical ground motion characterization models. In *EGU General Assembly, Geophysical Research Abstracts*, volume 17, 2015. EGU2015-11784-1.

D. J. Wald and T. I. Allen. Topographic slope as a proxy for seismic site conditions and amplification. *Bulletin of the Seismological Society of America*, 97(5):1379–1395, 2007. doi: 10.1785/0120060267.

D. J. Wald, B. C. Worden, V. Quitoriano, and K. L. Pankow. ShakeMap ® manual. Technical Manual, users guide, and software guide Version 1.0, USGS Techniques and Methods 12-A1, 2005. URL `http://pubs.usgs.gov/tm/2005/12A01/`.

M. Walling, W. Silva, and N. Abrahamson. Nonlinear site amplification factors for constraining the NGA models. *Earthquake Spectra*, 24(1):243–255, Feb 2008. doi: 10.1193/1.2934350.

M. Walling, N. Kuehn, and N. Abrahamson. An induced seismicity non-ergodic ground motion prediction (GMPE) in the Oklahoma region. Final technical report, U.S. Geological Survey, 2021. NEHRP Grant G18AP00076. Award Period August 2018 to August 2019.

S. Wan Ahmad, A. Adnan, R. Mohd Noor, K. Muthusamy, S. M. S. Razak, A. Taib, and M. Z. A. Mohd Zahid. Attenuation function relationship for far field earthquake considered by strike slip mechanism. *Applied Mechanics and Materials*, 754–755:897–901, 2015. doi: 10.4028/www.scientific.net/AMM.754-755.897.

B.-Q. Wang, F. T. Wu, and Y.-J. Bian. Attenuation characteristics of peak acceleration in north China and comparison with those in the eastern part of North America. *Acta Seismologica Sinica*, 12(1):26–34, 1999. doi: 10.1007/s11589-999-0004-7.

G. Wang and X. Tao. A new two-stage procedure for fitting attenuation relationship of strong ground motion. In *Proceedings of the Sixth International Conference on Seismic Zonation*, Nov 2000.

G.-Q. Wang, X.-Y. Zhou, P.-Z. Zhang, and H. Igel. Characteristics of amplitude and duration for near fault strong ground motion from the 1999 Chi-Chi, Taiwan earthquake. *Soil Dynamics and Earthquake Engineering*, 22:73–96, 2002.

G.-Q. Wang, D. M. Boore, H. Igel, and X.-Y. Zhou. Comparisons of ground motions from five aftershocks of the 1999 Chi-Chi, Taiwan, earthquake with empirical predictions largely based on data from California. *Bulletin of the Seismological Society of America*, 94(6):2198–2212, Dec 2004.

H. Wang, Y. Ren, and R. Wen. Source parameters, path attenuation and site effects from strong-motion recordings of the Wenchuan aftershocks (2008-2013) using a nonparametric generalized inversion technique. *Geophysical Journal International*, 212(2):872–890, 2018. doi: 10.1093/gji/ggx447.

M. Wang and T. Takada. A Bayesian framework for prediction of seismic ground motion. *Bulletin of the Seismological Society of America*, 99(4):2348–2364, Aug 2009. doi: 10.1785/0120080017.

S. Y. Wang et al. Development of attenuation relations for ground motion in China. *Earthquake Research in China*, 16:99–106, 2000. In Chinese. Not seen. Reported in Jia et al. (2012).

Y.-J. Wang, Y.-T. Lee, K.-F. Ma, and Y.-C. Wu. New attenuation relationship for peak ground and pseudo-spectral acceleration of normal-faulting earthquakes in offshore northeast Taiwan. *Terrestrial Atmospheric and Oceanic Science*, 27(1):43–58, Feb 2016. doi: 10.3319/TAO.2015.08.17.01(T).

G. Weatherill and F. Cotton. A ground motion logic tree for seismic hazard analysis in the stable cratonic region of europe: regionalisation, model selection and development of a scaled backbone approach. *Bulletin of Earthquake Engineering*, 2020. doi: 10.1007/s10518-020-00940-x.

G. Weatherill, S. R. Kotha, and F. Cotton. A regionally-adaptable “scaled backbone” ground motion logic tree for shallow seismicity in europe: Application to the 2020 European seismic hazard model. *Bulletin of Earthquake Engineering*, 18:5087–5117, 2020. doi: 10.1007/s10518-020-00899-9.

S. Weisburg. *Applied Linear Regression*. John Wiley & Sons, 2nd edition, 1985.

D. L. Wells and K. J. Coppersmith. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, 84(4):974–1002, Aug 1994.

R. Wen, P. Xu, H. Wang, and Y. Ren. Single-station standard deviation using strong-motion data from Sichuan region, China. *Bulletin of the Seismological Society of America*, 108(4):2237–2247, Aug 2018. doi: 10.1785/0120170276.

J. H. Wiggins, Jr. Construction of strong motion response spectra from magnitude and distance data. *Bulletin of the Seismological Society of America*, 54(5):1257–1269, Oct 1964.

C. J. Wills, M. Petersen, W. A. Bryant, M. Reichle, G. J. Saucedo, S. Tan, G. Taylor, and J. Treiman. A site-conditions map for California based on geology and shear-wave velocity. *Bulletin of the Seismological Society of America*, 90(6B):S187–S208, Dec 2000.

R. C. Wilson and D. K. Keefer. Predicting areal limits of earthquake-induced landsliding. In *Evaluating earthquake hazards in the Los Angeles region; an earth-science perspective*, number 1360 in Professional Paper, pages 317–345. US Geological Survey, 1985.

P. W. Winter. A stochastic ground motion model for UK earthquakes. Technical Report GNSR(DTI)/P(96)275 Milestone ECS 0263, AEA/16423530/R003, AEA Technology, 1995. Not seen. Written communication R. M. W. Musson (2016).

J. Wiszniowski. Estimation of a ground motion model for induced events by Fahlman's cascade correlation neural network. *Computers and Geosciences*, 131:23–31, 2019. doi: 10.1016/j.cageo.2019.06.006.

I. Wong, R. Darragh, S. Smith, Q. Wu, W. Silva, and T. Kishida. Ground motion models for shallow crustal and deep earthquakes in Hawaii and analyses of the 2018 M 6.9 Kalapana sequence. *Earthquake Spectra*, 38 (1):579–614, 2022. doi: 10.1177/87552930211044521.

I. G. Wong, W. J. Silva, R. R. Youngs, and C. L. Stark. Numerical earthquake ground motion modeling and its use in microzonation. In *Proceedings of Eleventh World Conference on Earthquake Engineering*, 1996. Paper no. 701.

I. G. Wong, W. J. Silva, R. Darragh, N. Gregor, and M. Dober. A ground motion prediction model for deep earthquakes beneath the island of Hawaii. *Earthquake Spectra*, 31(3):1763–1788, Aug 2015. doi: 10.1193/012012EQS015M.

G. Woo. Seismic ground motions in Great Britain. In *Earthquake Engineering in Britain*. Institution of Civil Engineers, 1985. ISBN 0 7277 0246 7. Proceedings of a conference organized by the Institution of Civil Engineers and the Society of Earthquake and Civil Engineering Dynamics, University of East Anglia, 18–19 April 1985.

Y.-M. Wu, T.-C. Shin, and C.-H. Chang. Near real-time mapping of peak ground acceleration and peak ground velocity following a strong earthquake. *Bulletin of the Seismological Society of America*, 91(5):1218–1228, Oct 2001.

J. Xiang and D. Gao. The attenuation law of horizontal peak acceleration on the rock site in Yunnan area. *Earthquake Research in China*, 8(4):509–516, 1994.

Y. Xu, J. P. Wang, Y.-M. Wu, and K.-C. Hao. Prediction models and seismic hazard assessment: A case study from Taiwan. *Soil Dynamics and Earthquake Engineering*, 122:94–106, 2019. doi: 10.1016/j.soildyn.2019.03.038.

Z. Xu, X. Shen, and J. Hong. Attenuation relation of ground motion in northern China. In *Proceedings of Eighth World Conference on Earthquake Engineering*, volume II, pages 335–342, 1984.

S. Yaghmaei-Sabegh. New models for frequency content prediction of earthquake records based on Iranian ground-motion data. *Journal of Seismology*, 19(4):831–848, Oct 2015. doi: 10.1007/s10950-015-9497-9.

S. Yaghmaei-Sabegh. Macroseismic intensity attenuation in Iran. *Earthquake Engineering and Engineering Vibration*, 17(1):139–148, Jan 2018. doi: 10.1007/s11803-018-0430-4.

S. Yaghmaei-Sabegh, Z. Shoghian, and M. N. Sheikh. A new model for the prediction of earthquake ground-motion duration in Iran. *Natural Hazards*, 70(1):69–92, 2014. doi: 10.1007/s11069-011-9990-6.

K. Yamabe and K. Kanai. An empirical formula on the attenuation of the maximum acceleration of earthquake motions. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 337–342, 1988.

F. Yamazaki, K. Wakamatsu, J. Onishi, and K. T. Shabestari. Relationship between geomorphological land classification and site amplification ratio based on JMA strong motion records. *Soil Dynamics and Earthquake Engineering*, 19(1):41–53, Jan 2000.

X. Yao, S. Qi, C. Liu, S. Guo, X. Huang, C. Xu, B. Zheng, Z. Zhan, and Y. Zou. An empirical attenuation model of the peak ground acceleration (PGA) in the near field of a strong earthquake. *Natural Hazards*, 105: 691–715, 2021. doi: 10.1007/s11069-020-04332-x.

A. Yazdani and M. Kowsari. Earthquake ground-motion prediction equations for northern Iran. *Natural Hazards*, 69(3):1877–1894, 2013. doi: 10.1007/s11069-013-0778-8.

A. Yazdani, M. Kowsari, and S. Amani. Development of a regional attenuation relationship for Alborz, Iran. *Journal of the Earth and Space Physics*, 41(4):39–50, 2016.

E. Yenier. *Regionally-adjustable generic ground-motion prediction equation*. PhD thesis, University of Western Ontario, Canada, Feb 2015. Paper 2684.

E. Yenier and G. M. Atkinson. Equivalent point-source modeling of moderate-to-large magnitude earthquakes and associated ground-motion saturation effects. *Bulletin of the Seismological Society of America*, 104(3): 1458–1478, 2014. doi: 10.1785/0120130147.

E. Yenier and G. M. Atkinson. An equivalent point-source model for stochastic simulation of earthquake ground motions in California. *Bulletin of the Seismological Society of America*, 105(3):1435–1455, Jun 2015a. doi: 10.1785/0120140254.

E. Yenier and G. M. Atkinson. Regionally adjustable generic ground-motion prediction equation based on equivalent point-source simulations: Application to central and eastern North America. *Bulletin of the Seismological Society of America*, 105(4):1989–2009, Aug 2015b. doi: 10.1785/0120140332.

F Yerlikaya-Özkurt, A. Askan, and G.-W. Weber. An alternative approach to the ground motion prediction problem by a non-parametric adaptive regression method. *Engineering Optimization*, 46(12):1651–1668, 2014. doi: 10.1080/0305215X.2013.858141.

S. Yilmaz. Ground motion predictive modelling based on genetic algorithms. *Natural Hazards and Earth System Sciences*, 11, 2011. doi: 10.5194/nhess-11-2781-2011.

H. Yokota, K. Shiba, and K. Okada. The characteristics of underground earthquake motions observed in the mud stone layer in Tokyo. In *Proceedings of Ninth World Conference on Earthquake Engineering*, volume II, pages 429–434, 1988.

R. R. Youngs, S. M. Day, and J. L. Stevens. Near field ground motions on rock for large subduction earthquakes. In *Proceedings of Earthquake Engineering & Soil Dynamics II*, pages 445–462. Geotechnical Division, ASCE, Jun 1988.

R. R. Youngs, N. Abrahamson, F. I. Makdisi, and K. Sadigh. Magnitude-dependent variance of peak ground acceleration. *Bulletin of the Seismological Society of America*, 85(4):1161–1176, Aug 1995.

R. R. Youngs, S.-J. Chiou, W. J. Silva, and J. R. Humphrey. Strong ground motion attenuation relationships for subduction zone earthquakes. *Seismological Research Letters*, 68(1):58–73, Jan/Feb 1997.

Y. Yu and Y. Hu. Empirical long-period response spectral attenuation relations based on southern California digital broad-band recordings. In *Proceedings of Thirteenth World Conference on Earthquake Engineering*, 2004. Paper no. 0344.

Y.-X. Yu and S.-Y. Wang. Attenuation relations for horizontal peak ground acceleration and response spectrum in northeastern Tibetan Plateau region. *Acta Seismologica Sinica*, 17(6):651–661, Nov 2004.

K.-V. Yuen and H.-Q. Mu. Peak ground acceleration estimation by linear and nonlinear models with reduced order Monte Carlo simulation. *Computer-Aided Civil and Infrastructure Engineering*, 26:30–47, 2011. doi: 10.1111/j.1467-8667.2009.00648.x.

K.-H. Yun. Recent advances in developing site-specific ground motion attenuation relations for the nuclear plant sites in Korea. In *OECD NEA Specialists Meeting on the Seismic PSA of Nuclear Facilities*, Jeju, Korea, 2006. Not seen. Cited in Choi et al. (2009).

K.-H. Yun and D.-H. Park. Development of site-specific ground-motion attenuation relations in Korea —– examples for the nuclear power plant sites. In *The 5th International Workshop on the Fundamental Research for Mitigating Earthquake Hazards*, 2005. Not seen. Cited in Choi et al. (2009).

Y. Yuzawa and K. Kudo. Empirical estimation of long-period (1–10 sec.) earthquake ground motion on hard rocks. In *Proceedings of Fourteenth World Conference on Earthquake Engineering*, 2008. Paper no. S10-057.

H. Zafarani and M. Soghrat. Simulation of ground motion in the Zagros region of Iran using the specific barrier model and the stochastic method. *Bulletin of the Seismological Society of America*, 102(5):2031–2045, Oct 2012. doi: 10.1785/0120110315.

H. Zafarani and M. R. Soghrat. Ground motion models for non-spectral intensity measures based on the Iranian database. *Journal of Earthquake Engineering*, 27(13):3786–3806, 2023. doi: 10.1080/13632469.2022.2150334.

H. Zafarani, M. Mousavi, A. Noorzad, and A. Ansari. Calibration of the specific barrier model to Iranian plateau earthquakes and development of physically based attenuation relationships for Iran. *Soil Dynamics and Earthquake Engineering*, 28(7):550–576, 2008. doi: 10.1016/j.soildyn.2007.08.001.

H. Zafarani, S. Rahpeyma, and M. Mousavi. Regional adjustment factors for three NGA-West2 ground-motion prediction equations to be applicable in northern Iran. *Journal of Seismology*, 21:473–493, 2017. doi: 10.1007/s10950-016-9611-7.

H. Zafarani, L. Luzi, G. Lanzano, and M. R. Soghrat. Empirical equations for the prediction of PGA and pseudo spectral accelerations using Iranian strong-motion data. *Journal of Seismology*, 22:263–285, 2018. doi: 10.1007/s10950-017-9704-y.

G. Zalachoris and E. M. Rathje. Ground motion models for earthquake events in Texas, Oklahoma, and Kansas. In *3rd International Conference on Performance-based Design in Earthquake Geotechnical Engineering*, 2017.

G. Zalachoris and E. M. Rathje. Ground motion model for small-to-moderate earthquakes in Texas, Oklahoma, and Kansas. *Earthquake Spectra*, 35(1):1–20, Feb 2019. doi: 10.1193/022618EQS047M.

A. Zandieh, S. Pezeshk, and K. W. Campbell. An equivalent point-source stochastic simulation of the NGA-West2 ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 108(2): 815–835, Apr 2018. doi: 10.1785/0120170116.

M. Zaré and P.-Y. Bard. Strong motion dataset of Turkey: Data processing and site classification. *Soil Dynamics and Earthquake Engineering*, 22:703–718, 2002.

M. Zaré and H. Memarian. Macroseismic intensity and attenuation laws: A study on the intensities of the Iranian earthquakes of 1975–2000. In *Fourth International Conference of Earthquake Engineering and Seismology*, May 2003.

M. Zare and S. Sabzali. Spectral attenuation of strong motions in Iran. In *Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, volume 1, pages 749–758, 2006. Paper number 146.

M. Zaré, M. Ghafory-Ashtiany, and P.-Y. Bard. Attenuation law for the strong-motions in Iran. In *Proceedings of the Third International Conference on Seismology and Earthquake Engineering, Tehran*, volume 1, pages 345–354, 1999.

J. Zeiß, S. Stange, and A. Brüstle. Regional model of peak ground motion in southwestern Germany. *Journal of Seismology*, 26:1105–1136, 2022. doi: 10.1007/s10950-022-10114-8.

B. Zhang, Y. Yu, X. Li, and Y. Wang. Ground motion prediction equation for the average horizontal component of PGA, PGV, and 5% damped acceleration response spectra at periods ranging from 0.033 to 8.0s in southwest China. *Soil Dynamics and Earthquake Engineering*, 159:107297, 2022. doi: 10.1016/j.soildyn.2022.107297.

P. Zhang, Z.-X. Yang, H. K. Gupta, S. C. Bhatia, and K. M. Shedlock. Global Seismic Hazard Assessment Program (GSHAP) in continental Asia. *Annali di Geofisica*, 42(6):1167–1190, Dec 1999.

J. X. Zhao. Geometric spreading functions and modeling of volcanic zones for strong-motion attenuation models derived from records in Japan. *Bulletin of the Seismological Society of America*, 100(2):712–732, Apr 2010. doi: 10.1785/0120090070.

J. X. Zhao and M. C. Gerstenberger. Ground-motion prediction models for post-earthquake rapid reporting and reliable loss modelling using a sparsely distributed recording network in New Zealand. Consultancy Report 2010/123, GNS Science, New Zealand, Jun 2010.

J. X. Zhao, D. J. Dowrick, and G. H. McVerry. Attenuation of peak ground acceleration in New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 30(2):133–158, Jun 1997.

J. X. Zhao, J. Zhang, A. Asano, Y. Ohno, T. Oouchi, T. Takahashi, H. Ogawa, K. Irikura, H. K. Thio, P. G. Somerville, Y. Fukushima, and Y. Fukushima. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, 96(3): 898–913, 2006. doi: 10.1785/0120050122.

J. X. Zhao, S. Zhou, P. Gao, T. Long, Y. Zhang, H. K. Thio, M. Lu, and D. A. Rhoades. An earthquake classification scheme adapted for Japan determined by the goodness of fit for ground-motion prediction equations. *Bulletin of the Seismological Society of America*, 105(5):2750–2763, Oct 2015. doi: 10.1785/0120150013.

J. X. Zhao, F. Jiang, P. Shi, H. Xing, H. Huang, R. Hou, Y. Zhang, P. Yu, X. Lan, D. A. Rhoades, P. G. Somerville, K. Irikura, and Y. Fukushima. Ground-motion prediction equations for subduction slab earthquakes in Japan using site class and simple geometric attenuation functions. *Bulletin of the Seismological Society of America*, 106(4):1535–1551, Aug 2016a. doi: 10.1785/0120150056.

J. X. Zhao, X. Liang, F. Jiang, H. Xing, M. Zhu, R. Hou, Y. Zhang, X. Lan, D. A. Rhoades, K. Irikura, Y. Fukushima, and P. G. Somerville. Ground-motion prediction equations for subduction interface earthquakes in Japan using site class and simple geometric attenuation functions. *Bulletin of the Seismological Society of America*, 106(4):1518–1534, Aug 2016b. doi: 10.1785/0120150034.

J. X. Zhao, S. Zhou, J. Zhou, C. Zhao, H. Zhang, Y. Zhang, P. Gao, X. Lan, D. A. Rhoades, Y. Fukushima, P. G. Somerville, and K. Irikura. Ground-motion prediction equations for shallow crustal and upper-mantle earthquakes in Japan using site class and simple geometric attenuation functions. *Bulletin of the Seismological Society of America*, 106(4):1552—-1569, Aug 2016c. doi: 10.1785/0120150063.

Y. Zhao et al. An attenuation pattern of surface peak acceleration in Yunnan region. *Journal of Seismological Research*, 26(3), 2003. Not seen. Cited in Li et al. (2009).

S. Zheng and Y. L. Wong. Seismic ground motion relationships in southern China based on stochastic finite-fault model. *Earthquake Engineering and Engineering Vibration*, 3(1):11–21, Jun 2004. doi: 10.1007/BF02668847.

M. L. Zoback. First- and second-order patterns of stress in the lithosphere: The World Stress Map project. *Journal of Geophysical Research*, 97(B8):11703–11728, 1992.

M. R. Zolfaghari and A. Darzi. Ground-motion models for predicting vertical components of PGA, PGV and 5% damped spectral acceleration (0.01—10 s) in Iran. *Bulletin of Earthquake Engineering*, 17(7):3615–3635, Jul 2019a. doi: 10.1007/s10518-019-00623-2.

M. R. Zolfaghari and A. Darzi. A prediction model for vertical-to-horizontal ratios of PGA, PGV, and 5%-damped response spectra (0.01—10 s) for Iran. *Journal of Seismology*, 23(4):819–837, Jul 2019b. doi: 10.1007/s10950-019-09836-z.

G. Zonno and V. Montaldo. Analysis of strong ground motions to evaluate regional attenuation relationships. *Annals of Geophysics*, 45(3–4):439–454, Jun–Aug 2002.

E. Zuccolo, F. Bozzoni, and C. G. Lai. Regional low-magnitude GMPE to estimate spectral accelerations for earthquake early warning applications in southern Italy. *Seismological Research Letters*, 88(1):61–71, Jan/Feb 2017. doi: 10.1785/0220160038.