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Further errata of and additions to ‘Ground motion estimation equations 1964-2003’

Final Report

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J. Douglas

Checked by:	**Approved by:**
Name: Julien Rey	Name: Hormoz Modaressi
Date: 13th February 2009	Date: 26th February 2009
Signature:	Signature:

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Synopsis

This report provides a summary of all empirical ground-motion models for the estimation of earthquake peak ground acceleration and elastic response spectral ordinates published between 2007 and 2008 (inclusive) (some earlier studies are also included). This report updates the Imperial College London report of Douglas (2004a) (available at: http://www3.imperial.ac.uk/civilengineering/research/researchnewsandreports/researchreports), which provided a summary of all published models from 1964 until the end of 2003, and the BRGM report of Douglas (2006) (available at: http://www.brgm.fr/publication/pubDetailRapportSP.jsp?id=RSP-BRGM/RP-54603-FR), which provided a summary of all published models from 2004 to 2006. Brief details of the functional form adopted, data used and analysis method followed are given for each study in these reports.

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. The ground-motion models are reported in the form given in the original references except sometimes the equation is simplified if this can be easily done.

This report provides a comprehensive summary of strong-motion attenuation studies, which can be used for finding references to useful works (for seismic hazard assessments in different regions of the world, for example) and for use as a basis for reviews of previously published equations. Note, however, that the size of this report means that it may contain some errors or omissions.

Equations for single earthquakes or for earthquakes of approximately the same size are excluded due to their limited usefulness. Also excluded are those relations based on intensity measurements, those based on theoretical ground motions (stochastic source models etc.) or those originally developed to yield the magnitude of an earthquake, i.e. the regression is performed the other way round, which should not be used for the prediction of ground motion at a site. Studies which derive graphs to give predictions are not considered in this report nor are those nonparametric formulations that provide predictions for different combinations of distance and magnitude, both of which are more difficult to use for seismic hazard analysis than those which give a single formula.

The reports of Douglas (2004a, 2006) and this report summarise, in total, the characteristics of 248 ground motion models [165 studies in Douglas (2004a), 42 in Douglas (2006) and 41 in this report] for the prediction of peak ground acceleration and 155 models [100 studies in Douglas (2004a), 28 in Douglas (2006) and 27 in this report] for the prediction of elastic response spectral ordinates.

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1. Preface

ESEE Report 01-1 ‘A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)’ (Douglas, 2001) was completed and released in January 2001. A report detailing errata of the first 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. 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 a new report listing errata and additions it was decided to produce a new report that includes details on all the studies listed in the first two reports (with the corrections made) and also includes 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.

In the two years since Douglas (2006) was released a number of empirical ground-motion prediction equations have been published, in particular those models developed within the PEER Lifelines Next Generation Attenuation project (Power et al., 2008). Therefore, it was decided to publish this report summarising studies from 2007 and 2008 plus some equations from earlier years that were discovered since the publication of Douglas (2006). One minor error in the summary of Zonno & Montaldo (2002) in Douglas (2006) is that the values of Γ for soil and rock are the wrong way around on p. 129 (the text should read $\Gamma = 0$ for rock and $\Gamma = 1$ for soil). In addition, a minor erratum (Beyer & Bommer, 2007) was published for the article of Beyer & Bommer (2006). The models of Stamatovska (2002) were published in a journal article (Stamatovska, 2006). The model of K.W. Campbell (1988) presented in Joyner & Boore (1988) and summarised in Douglas (2004a) was originally published in Campbell (1987). The model of Zaré et al. (1999) was also published by Zaré (1999), including coefficients for spectral ordinates. Finally, the model of Bragato & Slejko (2005) was also described in Slejko & Bragato (2008).

The reports of Douglas (2004a), Douglas (2006) and this report summarise, in total, the characteristics of 248 ground-motion models [165 studies in Douglas (2004a), 42 in Douglas (2006) and 41 in this report] for the prediction of peak ground acceleration and 155 models [100 studies in Douglas (2004a), 28 in Douglas (2006) and 27 in this report] for the prediction of elastic response spectral ordinates. With this many ground-motion prediction equations available it is important to have criteria available for the selection of appropriate models for seismic hazard assessment in a given region — Cotton et al. (2006) suggest selection requirements for the choice of models.

Summaries and reviews of published ground-motion models for the estimation of strong-motion parameters other than peak ground acceleration and elastic response spectral ordinates are available. For example: Bommer & Martínez-Pereira (1999) review predictive equations for strong-motion duration, Tromans (2004) summarises equations for the prediction of peak ground velocity and displacement, Hancock & Bommer (2005) discuss available equations for estimating number of effective cycles, Bommer & Alarcón (2006) review published equations for predicting peak ground velocity and Alarcón (2007) reviews predictive models for strong-motion duration.

In this and earlier reports the name ‘attenuation relation(ships)’ is used for the models reported. Current best-practice is to refer to such models as ‘ground-motion prediction equations’ (GMPEs). However, ‘attenuation relation(ships)’ is retained here for consistency with the earlier reports.

2. Introduction

A number of reviews of attenuation studies 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 & Brady (1975, 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 upto 1980. Boore & 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 & Boore (1988) give an excellent analysis of ground motion prediction methodology in general, and attenuation relations in particular; Joyner & Boore (1996) update this by including more recent studies. Ambraseys & 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 are Campbell (2003c, a) and Bozorgnia & Campbell (2004), 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.

A summary of the methods used to derive the equations is presented here. This report contains details of all studies for peak ground acceleration and response spectra that could be found in the literature (journals, conference proceedings and technical reports) although some may have been inadvertently missed. 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.

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., 1978) are excluded due to their limited usefulness. Also excluded are those relations based on intensity measurements (e.g. Battis, 1981), those based on simulated ground motions from stochastic source models (e.g. Atkinson & Boore, 1990) [Douglas (2007) lists about twenty stochastic models that can be used for ground-motion prediction in different regions] or 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) or 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. Studies which provide graphs to give predictions (e.g. Schnabel & Seed, 1973) are not considered in this report nor are those nonparametric formulations that give predictions for different combinations of distance and magnitude (e.g. Anderson, 1997; Fajfar & Peruš, 1997), both of which are 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 & Erçelebi, 2007) are also excluded. Models such as that by Olszewska (2006), who uses ’source energy logarithms’ to characterise mining-induced events, have been excluded because such a characterisation of event size is rare in standard seismic hazard assessments. Similarly equations derived using data from nuclear tests, such as those reported by Hays (1980), are not included.

All the studies that present the same attenuation relationship are mentioned at the top of the section and in the tables of general characteristics (Tables 4.1 & 6.1). The information contained within each section, and within the table, is the sum of information contained within each of the publications, i.e. not all the information may be in one study.

To make it easier to understand the functional form of attenuation equation adopted in each study the equations are given with variable names replacing actual coefficients and the derived coefficients and the standard deviation, σ, are given separately (for peak ground acceleration 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 given 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 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.

In the equations unless otherwise stated, D, d, R, r, Δ 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. ‘w.r.t.’ is used as an abbreviation of ‘with respect to’.

In Illustration 1 & Illustration 2 the gross characteristics of the data used and equation obtained is only given for the main equation in the study. The reader should refer to the section on a particular publication for information on other equations derived in the study.

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. The ground-motion models are reported in the form given in the original references except sometimes the equation is simplified if this can be easily done.

This report provides a comprehensive summary of strong motion attenuation studies that can be used for finding references to useful works and for use as a basis for reviews of previously published equations. Note, however, that the size of this report means that it may contain some errors or omissions.

3. Summary of published attenuation relations for peak ground acceleration

3.1. 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).

3.2. 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 $c = -0.00443$ (σ not reported).

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

3.3. BAAG ET AL. (1998)

- Ground-motion model is:

$$\ln \mathrm{PGA} = a_1 + a_2 M + a_3 \ln R + a_4 R$$

$$\text{where} \quad R = \sqrt{R_{\mathrm{epi}}^2 + a_5^2}$$

where PGA is in cms^{-2}, $a_1 = 0.4$, $a_2 = 1.2$, $a_3 = -0.76$, $a_4 = -0.0094$ and $a_5 = 10$ (σ not given).

- This article has not been seen. The model presented may not be a fully empirical model.

3.4. SANCHEZ & JARA (2001)

- Ground-motion model is:

$$\log(A_{\max}) = aM_s + b\log R + c$$

where the units of $A_{\max}$ are not given[1], $a = 0.444$, $b = -2.254$ and $c = 4.059$ (σ is not given).

- Use one site category: firm ground.

3.5. WU ET AL. (2001)

- Ground-motion model is:

$$\log_{10}(Y) = C_1 + C_2M_w - \log_{10}(r_{\text{rup}} + h) + C_3r_{\text{rup}}$$

where Y is in cms^{-2}, $C_1 = 0.00215$, $C_2 = 0.581$, $C_3 = -0.00414$, $h = 0.00871\times10^{0.5M_w}$ 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 $< 35\text{km}$ to restrict interest to large shallow earthquakes, which cause most damage.
- Focal depths between 1.40 and 34.22km.
- 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 $r_{\text{rup}} < 30\text{km}$ so as not to bias the results at larger distances by untriggered instruments.
- Most data from $50 \le d_r \le 200\text{km}$ and $5 \le M_w \le 6$.

[1]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.

- 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 σ of 0.66.
- Display inter-event residuals w.r.t. M_w before and after site correction.

3.6. SHI & 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 cms^{-2}, $a_1 = 1.3012$, $a_2 = 0.6057$, $a_3 = -1.7216$, $a_4 = 1.126$ and $a_5 = 0.482$ (σ not reported).

3.7. BEAUDUCEL ET AL. (2004)

- Ground-motion model is:

$$\log(\mathrm{PGA}) = aM + bR - \log(R) + c$$

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 $20 < d < 100\mathrm{km}$.
- 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 ± 1.5.

- Apply model to other earthquakes from the region and find good match to observations.

3.8. NOWROOZI (2005)

- Ground-motion model is:

$$\ln(A) = c_1 + c_2(M-6) + c_3 \ln(\sqrt{\mathrm{EPD}^2 + h^2}) + c_4 S$$

where A is in cms^{-2}, $c_1 = 7.969$, $c_2 = 1.220$, $c_3 = -1.131$, $c_4 = 0.212$, $h = 10\mathrm{km}$ (fixed after tests) and $\sigma = 0.825$ for horizontal PGA and $c_1 = 7.262$, $c_2 = 1.214$, $c_3 = -1.094$[2], $c_4 = 0.103$, $h = 10\mathrm{km}$ (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 $73\mathrm{km}$. Most depths are shallow (depths fixed at $33\mathrm{km}$) and majority are about $10\mathrm{km}$. 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 d_e 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

[2] There is a typographical error in Equation 12 of Nowroozi (2005) since this coefficient is reported as -1094.

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 $M_w \leq 5$.
- Originally includes terms $c_5(M-6)^2$ and $c_6\mathrm{EPD}$ 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.

3.9. RUIZ & SARAGONI (2005)

- Ground-motion model is:

$$x = \frac{A\mathrm{e}^{BM}}{(R+C)^D}$$

where x is in cms^{-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 $V_s > 1500\mathrm{ms}^{-1}$. 8 records.
    - Rock and hard soil $360 < V_s < 1500\mathrm{ms}^{-1}$. 41 records.

- Focal depths between 28.8 and $50.0\mathrm{km}$.
- Develop separate equations for interface and intraslab (intermediate-depth) events.
- Baseline correct and bandpass filter (fourth-order Butterworth) with cut-offs 0.167 and $25\mathrm{Hz}$.
- 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.

3.10. WALD ET AL. (2005)

- Ground-motion model is:

$$\log_{10}(Y) = B_1 + B_2(M-6) - B_5 \log_{10} R$$

$$where \quad R = \sqrt{R_{jb}^2 + 6^2}$$

where Y is in cms^{-2}, $B_1 = 4.037$, $B_2 = 0.572$, $B_5 = -1.757$ and $\sigma = 0.836$.

3.11. MOSS & 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 ~ 0.30, based on analysis of recorded motions) and magnitudes (coefficient of variation of ~ 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 $V_{s,30} = 750\mathrm{ms}^{-1}$. Find

slightly different coefficients than Boore et al. (1997) but reduced model standard deviations.

3.12. 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 $a_{\mathrm{PGA}} = 0.4346$, $b_{\mathrm{PGA}} = -0.002459$, $S_{\mathrm{PGA},1} = 0.9259$, $S_{\mathrm{PGA},2} = 0.9338$, $S_{\mathrm{PGA},3} = 0.9929$, $S_{\mathrm{PGA},4} = 0.9656$, $S_{\mathrm{PGA},5} = 0.9336$ and $\sigma = 0.2966$.

- Use five site categories (from Eurocode 8):

  A. $V_{s,30} > 800\mathrm{ms}^{-1}$. Use $S_{\mathrm{PGA},1}$. 43 stations, 396 records.

  B. $360 < V_{s,30} < 800\mathrm{ms}^{-1}$. Use $S_{\mathrm{PGA},2}$. 399 stations, 4190 records.

  C. $180 < V_{s,30} < 360\mathrm{ms}^{-1}$. Use $S_{\mathrm{PGA},3}$. 383 stations, 4108 records.

  D. $V_{s,30} < 180\mathrm{ms}^{-1}$. Use $S_{\mathrm{PGA},4}$. 65 stations, 644 records.

  E. Site D or C underlain in first $20\mathrm{m}$ with a stiffer layer of $V_s > 800\mathrm{ms}^{-1}$. 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 $30\mathrm{m}$ depth.

- Records from K-Net network whose digital stations have detailed geotechnical characterisation down to $20\mathrm{m}$ depth.

- Retain only records from events whose focal depths $< 25\mathrm{km}$.

- Convert M_{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 $25\mathrm{Hz}$. 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.

3.13. AKKAR & 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 cms^{-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 & Bommer (2007a), which is similar to that used by Ambraseys et al. (2005).
- Individually process records using well-defined correction procedure to select the cut-off frequencies (Akkar & Bommer, 2006).

- Use pure error analysis to determine magnitude dependence of inter- and intra-event variabilities before regression analysis.

3.14. 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 cms^{-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 σ s are higher.

- Use two site categories (derive individual equations for each):
    - Rock Roughly $V_s \geq 375\mathrm{ms}^{-1}$.
    - Soil Roughly $V_s < 375\mathrm{ms}^{-1}$.
- 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 d_h 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 $d_h > 50\mathrm{km}$.
- 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: $0.15-0.2\mathrm{Hz}$ and $30-33\mathrm{Hz}$ for rock records and $0.07-0.2\mathrm{Hz}$ and $30-33\mathrm{Hz}$ for soil records. For SMA-1 recommend: $0.15-0.25\mathrm{Hz}$ and $20-23\mathrm{Hz}$ for rock records and $0.15-0.2\mathrm{Hz}$ and $20-23\mathrm{Hz}$ 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 $d_h > 100\mathrm{km}$ 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.

3.15. 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, θ.

3.16. BINDI ET AL. (2007)

- Ground-motion models are:

$$\log_{10} Y = a + bM + (c + dM)\log_{10} R_{\mathrm{hypo}} + s_{1,2}$$

where Y is in ms^{-2}, $a = -1.4580$, $b = 0.4982$, $c = -2.3639$, $d = 0.1901$, $s_2 = 0.4683$, $\sigma_{\mathrm{eve}} = 0.0683$ (inter-event), $\sigma_{\mathrm{sta}} = 0.0694$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2949$ (record-to-record) for horizontal PGA; and $a = -1.3327$, $b = 0.4610$, $c = -2.4148$, $d = 0.1749$, $s_2 = 0.3094$, $\sigma_{\mathrm{eve}} = 0.1212$ (inter-event), $\sigma_{\mathrm{sta}} = 0.1217$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2656$ (record-to-record) for vertical PGA.

$$\log_{10} Y = a + bM + (c + dM)\log_{10}(R_{\mathrm{epi}}^2 + h^2)^{0.5} + s_{1,2}$$

where Y is in ms^{-2}, $a = -2.0924$, $b = 0.5880$, $c = -1.9887$, $d = 0.1306$, $h = 3.8653$, $s_2 = 0.4623$, $\sigma_{\mathrm{eve}} = 0.0670$ (inter-event), $\sigma_{\mathrm{sta}} = 0.0681$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2839$ (record-to-record) for horizontal PGA; and $a = -1.8883$, $b = 0.5358$, $c = -2.0869$, $d = 0.1247$, $h = 4.8954$, $s_2 = 0.3046$, $\sigma_{\mathrm{eve}} = 0.1196$ (inter-event), $\sigma_{\mathrm{sta}} = 0.0696$ (inter-station) and $\sigma_{\mathrm{rec}} = 0.2762$ (record-to-record). Coefficients not reported in article but in electronic supplement.

- Use two site categories:
  - Rock. Maximum amplification less than 2.5 (for accelerometric stations) or than 4.5 (for geophone stations). Amplification thresholds defined after some trials.
  - Soil. Maximum amplification greater than thresholds defined above.

Classify stations using generalized inversion technique.

- Focal depths between 5 and $15\mathrm{km}$.
- Use aftershocks from the 1999 Kocaeli ($M_w 7.4$) earthquake.
- Use data from 31 $1\mathrm{Hz}$ 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 $25\mathrm{Hz}$ for $M_L \leq 4.5$ and 0.1 and $25\mathrm{Hz}$ 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 $10 \leq d_e \leq 140\mathrm{km}$.
- Geophone records from free-field stations and accelerometric data from ground floors of small buildings.
- Use d_h and d_e 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 σ when using M_L or M_w, which relate to frequency band used to compute M_L (about $1\text{-}10\mathrm{Hz}$) compared to M_w (low frequencies), but find similar intra-event σ s using the two different magnitudes, which expected since this σ not source-related.

- Investigate influence of stress drop on inter-event σ for horizontal PGA relations using d_e 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 velocimetric stations but inter-station errors for accelerometric stations less affected.

3.17. BOMMER ET AL. (2007)

- Ground-motion model is:

$$\log_{10}[\mathrm{PSA}(T)] = b_1 + b_2 M_w + b_3 M_w^2 + (b_4 + b_5 M_w)\log_{10}\sqrt{R_{jb}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

where $\mathrm{PSA}(T)$ is in cms^{-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 $V_{s,30} < 360\mathrm{ms}^{-1}$. $S_S = 1$, $S_A = 1$. 75 records from $3 \le M_w < 5$.
  - Sitff soil $360 < V_{s,30} < 750\mathrm{ms}^{-1}$. $S_A = 1$, $S_S = 0$. 173 records from $3 \le M_w < 5$.
  - Rock $V_{s,30} \ge 750\mathrm{ms}^{-1}$. $S_S = 0$, $S_A = 0$. 217 records from $3 \le M_w < 5$.
- Use three faulting mechanism categories:
  - Normal $F_N = 1$, $F_R = 0$. 291 records from $3 \le M_w < 5$.
  - Strike-slip $F_N = 0$, $F_R = 0$. 140 records from $3 \le M_w < 5$.
  - Reverse $F_R = 1$, $F_N = 0$. 24 records from $3 \le M_w < 5$. 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 & 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 $> 40\mathrm{km}$.

- Additional data has been uniformly processed with cut-offs at 0.25 and $25\mathrm{Hz}$.

- Use same regression technique as Akkar & 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 & 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 & Smit, 2001). Derive weighting functions for published equations using bins of $2\mathrm{km} \times 0.2$ magnitude units and require three records per bin before computing σ. Repeat using $1\mathrm{km} \times 0.1$ unit bins. Find less bins allow computation of σ. Also repeat original analysis but require four or five records per bin. Find more robust estimates of σ 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 σ. Find predictions with this model are very similar to those assuming a magnitude-dependent σ.

- Find that compared to σs of Akkar & Bommer (2007b) that inter-event σs has greatly increased but that intra-event σs 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.

3.18. BOORE & ATKINSON (2007) & BOORE & ATKINSON (2008)

- Ground-motion model is:

$$\ln Y = F_M(M) + F_D(R_{JB}, M) + F_S(V_{S30}, R_{JB}, M)$$

$$\textit{where} \quad F_D(R_{JB}, M) = [c_1 + c_2(M - M_{ref})]\ln(R/R_{ref}) + c_3(R - R_{ref})$$

$$R = \sqrt{R_{JB}^2 + h^2}$$

$$F_M(M) = \begin{cases} e_1\mathrm{U} + e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_5(M - M_h) + \\ \quad e_6(M - M_h)^2 \quad \textit{for} \quad M \le M_h \\ e_1\mathrm{U} + e_2\mathrm{SS} + e_3\mathrm{NS} + e_4\mathrm{RS} + e_7(M - M_h) \quad \textit{for} \quad M > M_h \end{cases}$$

$$F_S = F_{LIN} + F_{NL}$$

$$F_{LIN} = b_{lin}\ln(V_{S30}/V_{ref})$$

$$F_{NL} = \begin{cases} b_{nl}\ln(\mathrm{pga\_low}/0.1) \quad \textit{for} \quad \mathrm{pga4nl} \le a_1 \\ b_{nl}\ln(\mathrm{pga\_low}/0.1) + c[\ln(\mathrm{pga4nl}/a_1)]^2 + \\ \quad d[\ln(\mathrm{pga4nl}/a_1)]^3 \quad \textit{for} \quad a_1 < \mathrm{pga4nl} \le a_2 \\ b_{nl}\ln(\mathrm{pga4nl}/0.1) \quad \textit{for} \quad a_2 < \mathrm{pga4nl} \end{cases}$$

$$c = (3\Delta y - b_{nl}\Delta x)/\Delta x^2$$

$$d = -(2\Delta y - b_{nl}\Delta x)/\Delta x^3$$

$$\Delta x = \ln(a_2/a_1)$$

$$\Delta y = b_{nl}\ln(a_2/\text{pga\_low})$$

$$b_{nl} = \begin{cases} b_1 \quad for \quad V_{S30} \leq V_1 \\ (b_1 - b_2)\ln(V_{S30}/V_2)/\ln(V_1/V_2) + b_2 \quad for \quad V_1 < V_{S30} \leq V_2 \\ b_2 \ln(V_{S30}/V_{ref})/\ln(V_2/V_{ref}) \quad for \quad V_2 < V_{S30} < V_{ref} \\ 0.0 \quad for \quad V_{ref} \leq V_{S30} \end{cases}$$

where Y is in g, $M_h = 6.75$ (hinge magnitude), $V_{ref} = 760\mathrm{ms}^{-1}$ (specified reference velocity corresponding to the NEHRP B/C boundary), $a_1 = 0.03\mathrm{g}$ (threshold for linear amplifcation), $a_2 = 0.09\mathrm{g}$ (threshold for nonlinear amplification), $\text{pga\_low} = 0.06\mathrm{g}$ (for transition between linear and nonlinear behaviour), pga4nl is predicted PGA in g for V_{ref} with $F_S = 0$, $V_1 = 180\mathrm{ms}^{-1}$, $V_2 = 300\mathrm{ms}^{-1}$, $b_{lin} = -0.360$, $b_1 = -0.640$, $b_2 = -0.14$, $M_{ref} = 4.5$, $R_{ref} = 1\mathrm{km}$, $c_1 = -0.66050$, $c_2 = 0.11970$, $c_3 = -0.01151$, $h = 1.35$, $e_1 = -0.53804$, $e_2 = -0.50350$, $e_3 = -0.75472$, $e_4 = -0.50970$, $e_5 = 0.28805$, $e_6 = -0.10164$, $e_7 = 0.0$; $\sigma = 0.502$ (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 $180 \leq V_{S30} \leq 1300\mathrm{ms}^{-1}$ (state that equations should not be applied for very hard rock sites, $V_{S30} \geq 1500\mathrm{ms}^{-1}$). 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 & 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 $31\mathrm{km}$ with most $< 20\mathrm{km}$.

- 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 $< 40^\circ$. 35 earthquakes. Dips between 55 and 90°. $4.3 \leq M \leq 7.9$. $\mathrm{SS}=1$, $\mathrm{U}=0$, $\mathrm{NS}=0$, $\mathrm{RS}=0$.

  - RS Reverse. Plunge of T axis $> 40^\circ$. 12 earthquakes. Dips between 12 and 70°. $5.6 \leq M \leq 7.6$. $\mathrm{RS}=1$, $\mathrm{U}=0$, $\mathrm{SS}=0$, $\mathrm{NS}=0$.

  - NS Normal. Plunge of P axis $> 40^\circ$. 11 earthquakes. Dips between 30 and 70°. $5.3 \leq M \leq 6.9$. $\mathrm{NS}=1$, $\mathrm{U}=0$, $\mathrm{SS}=0$, $\mathrm{RS}=0$.

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 ($\mathrm{U}=1$, $\mathrm{SS}=0$, $\mathrm{NS}=0$, $\mathrm{RS}=0$) mechanism (use σ s and τ s with subscript U otherwise use σ s and τ 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 $> 80\mathrm{km}$ 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 $400\mathrm{km}$.

- 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 $760\mathrm{ms}^{-1}$ using site amplification equations using only data with $R_{JB} \leq 80\mathrm{km}$ and $V_{S30} > 360\mathrm{ms}^{-1}$. 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 $R_{JB} > 80\mathrm{km}$, 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_3s 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 oversaturation. 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 hs.

3.19. CAMPBELL & BOZORGNIA (2007), CAMPBELL & BOZORGNIA (2008B) & CAMPBELL & BOZORGNIA (2008A)

- Ground-motion model is:

$$\ln \hat{Y} = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed}$$

$$\text{where} \quad f_{mag} = \begin{cases} c_0 + c_1 & for \quad M \leq 5.5 \\ c_0 + c_1 M + c_2(M - 5.5) & for \quad 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M - 5.5) + c_3(M - 6.5) & for \quad M > 6.5 \end{cases}$$

$$f_{dis} = (c_4 + c_5 M)\ln(\sqrt{R_{RUP}^2 + c_6^2})$$

$$f_{flt} = c_7 F_{RV} f_{flt,Z} + c_8 F_{NM}$$

$$f_{flt,Z} = \begin{cases} Z_{TOR} & for \quad Z_{TOR} < 1 \\ 1 & for \quad Z_{TOR} \geq 1 \end{cases}$$

$$f_{hng} = c_9 f_{hng,R} f_{hng,M} f_{hng,Z} f_{hng,\delta}$$

$$f_{hng,R} = \begin{cases} 1 & for \quad R_{JB} = 0 \\ \{\max(R_{RUP}, \sqrt{R_{JB}^2 + 1}) - R_{JB}\}/ & \\ \quad \max(R_{RUP}, \sqrt{R_{JB}^2 + 1}) & for \quad R_{JB} > 0, Z_{TOR} < 1 \\ (R_{RUP} - R_{JB})/R_{RUP} & for \quad R_{JB} > 0, Z_{TOR} \geq 1 \end{cases}$$

$$f_{hng,M} = \begin{cases} 0 & for \quad M \leq 6.0 \\ 2(M - 6.0) & for \quad 6.0 < M < 6.5 \\ 1 & for \quad M \geq 6.5 \end{cases}$$

$$f_{hng,Z} = \begin{cases} 0 & for \quad Z_{TOR} \geq 20 \\ (20 - Z_{TOR})/20 & for \quad 0 \leq Z_{TOR} < 20 \end{cases}$$

$$f_{hng,\delta} = \begin{cases} 1 & for \quad \delta \leq 70 \\ (90-\delta)/20 & for \quad \delta > 70 \end{cases}$$

$$f_{site} = \begin{cases} c_{10} \ln\left(\frac{V_{S30}}{k_1}\right) + k_2 \left\{ \ln\left[A_{1100} + c\left(\frac{V_{S30}}{k_1}\right)^n \right] - \ln(A_{1100}+c) \right\} & for \quad V_{S30} < k_1 \\ (c_{10}+k_2 n)\ln\left(\frac{V_{S30}}{k_1}\right) & for \quad k_1 \leq V_{S30} < 1100 \\ (c_{10}+k_2 n)\ln\left(\frac{1100}{k_1}\right) & for \quad V_{S30} \geq 1100 \end{cases}$$

$$f_{sed} = \begin{cases} c_{11}(Z_{2.5}-1) & for \quad Z_{2.5} < 1 \\ 0 & for \quad 1 \leq Z_{2.5} \leq 3 \\ c_{12} k_3 \mathrm{e}^{-0.75}[1-\mathrm{e}^{-0.25(Z_{2.5}-3)}] & for \quad Z_{2.5} > 3 \end{cases}$$

$$\sigma = \sqrt{\sigma_{\ln Y}^2 + \sigma_{\ln AF}^2 + \alpha^2 \sigma_{\ln A_B}^2 + 2\alpha\rho\sigma_{\ln Y_B}\sigma_{\ln A_B}}$$

$$\alpha = \begin{cases} k_2 A_{1100}\{[A_{1100} + c(V_{S30}/k_1)^n]^{-1} - (A_{1100}+c)^{-1}\} & for \quad V_{S30} < k_1 \\ 0 & for \quad V_{S30} \geq k_1 \end{cases}$$

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 ($V_{S30} = 1100\mathrm{ms}^{-1}$) in g. Linear part of f_{site} is consistent with previous studies but with constraint for constant site term for $V_{S30} > 1100\mathrm{ms}^{-1}$ (based on residual analysis) even though limited data for $V_{S30} > 1100\mathrm{ms}^{-1}$. 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 $V_{S30} = 150\text{-}1500\text{ms}^{-1}$.

- Also use depth to 2.5kms^{-1} 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 $Z_{2.5} = 0\text{-}10\text{km}$.
- Use three faulting mechanism categories based on rake angle, λ:
  - Reverse and reverse-oblique. $30 < \lambda < 150^\circ$. 17 earthquakes. $F_{RV} = 1$ and $F_{NM} = 0$.
  - Normal and normal-oblique. $-150 < \lambda < -30^\circ$. 11 earthquakes. $F_{NM} = 1$ and $F_{RV} = 0$.
  - 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) $5.0 \le M < 6.0$ and $N < 3$, c) $6.0 \le M < 7.0$, $R_{RUP} > 60\mathrm{km}$ and $N < 2$ (retain singly-recorded earthquakes with $M \ge 7.0$ and $R_{RUP} \le 60\mathrm{km}$ 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 $Z_{TOR} = 0\text{-}15\mathrm{km}$.

- Include dip of rupture plane, δ. Believe model applicable for $\delta = 15\text{-}90^\circ$.

- Assume that τ 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 τ was subject to soil nonlinearity effects it would have only a relatively small effect on σ_T because intra-event σ dominates. σ 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 100km 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.

3.20. DANCIU & TSELENTIS (2007A) & DANCIU & TSELENTIS (2007B)

- Ground-motion model is:

$$\log_{10} Y = a + bM - c\log_{10}\sqrt{R^2 + h^2} + eS + fF$$

where $a = 0.883$, $b = 0.458$, $c = -1.278$, $h = 11.515$, $e = 0.038$, $f = 0.116$, $\tau = 0.109$ (intra-event) and $\sigma = 0.270$ (inter-event).

- Use three site classes:
  - B Rock, $V_{s,30} > 800\text{ms}^{-1}$. $S = 0$. 75 records.
  - C Stiff soil, $360 \le V_s \le 665\text{ms}^{-1}$. $S = 1$. 197 records.
  - D Soft soil, $200 \le V_s \le 360\text{ms}^{-1}$. $S = 2$. 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 30km with mean of 10.66km.

- 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 25Hz).
- 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 1s 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 1s.
- Also derive equations for various other strong-motion parameters.

3.21. 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 & Boore (1981), Boore et al. (1993, 1997), Ambraseys et al. (1996), Ambraseys et al. (2005a), Ulusay et al. (2004), Kalkan & Gülkan (2004) and Sabetta & 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 $5\mathrm{km}$ (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 $200\mathrm{km}$ 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 & Gülkan, 2004; Sabetta & Pugliese, 1987)are wider than models derived using large well-distributed datasets (Joyner & Boore, 1981; Boore et al. , 1993, 1997; Ambraseys et al., 1996, 2005a). Notes that for $5.5 < M_w < 7$ and $10 \le d_f \le 60\mathrm{km}$ 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 & 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).

3.22. HONG & GODA (2007) & GODA & HONG (2008)

- Ground-motion model is:

$$\ln Y = b_1 + b_2(M-7) + b_3(M-7)^2 + [b_4 + b_5(M-4.5)]\ln[(r_{\mathrm{jb}}^2 + h^2)^{0.5}] + \mathrm{AF}_s$$

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 $\sigma_\varepsilon = 0.464$ (intra-event) for geometric mean.

- AF_s is the amplification factor due to linear and nonlinear soil behaviour used by Atkinson & Boore (2006), which is a function of $V_{s,30}$ and expected PGA at site with $V_{s,30} = 760\mathrm{ms}^{-1}$, $\mathrm{PGA}_{\mathrm{ref}}$. 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 (σ 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 ± 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 $V_{s,30}$.

3.23. GRAIZER & KALKAN (2007) & GRAIZER & KALKAN (2008)

- Ground-motion model is:

$$\ln(Y) = \ln(A) - 0.5\ln\left[\left(1-\frac{R}{R_0}\right)^2 + 4D_0^2\frac{R}{R_0}\right] - 0.5\ln\left[\left(1-\sqrt{\frac{R}{R_1}}\right)^2 + 4D_1^2\sqrt{\frac{R}{R_1}}\right] + b_v\ln\left(\frac{V_{s,30}}{V_A}\right)$$

$$A = [c_1\arctan(M + c_2) + c_3]F$$

$$R_0 = c_4M + c_5$$

$$D_0 = c_6\cos[c_7(M + c_8)] + c_9$$

where Y is in g, $c_1 = 0.14$, $c_2 = -6.25$, $c_3 = 0.37$, $c_4 = 2.237$, $c_5 = -7.542$, $c_6 = -0.125$, $c_7 = 1.19$, $c_8 = -6.15$, $c_9 = 0.525$, $b_v = -0.25$, $V_A = 484.5$, $R_1 = 100\mathrm{km}$ and $\sigma = 0.552$.

- Characterise sites by $V_{s,30}$ (average shear-wave velocity in upper $30\mathrm{m}$). Note that approximately half the stations have measured shear-wave velocity profiles.
- Include basin effects through modification of D_1. For sediment depth ($Z \geq 1\mathrm{km}$ $D_1 = 0.35$; otherwise $D_1 = 0.65$.
- Use three faulting mechanism classes:
    - o Normal 13 records
    - o Strike-slip 1120 records. $F = 1.00$.

  - o 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 $< 20\text{km}$. Focal depths between 4.6 and 19km.

- 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 $>10\text{km}$ and $R^{-1.5}$ at greater distances ($>100\text{km}$) and observation (and theoretical results) that highest amplitude ground motions do not always occur nearest the fault but at distances of $3\text{-}10\text{km}$.

- 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.

3.24. MASSA ET AL. (2007)

- Ground-motion model is:

$$\log_{10}(Y) = a + bM_L + c\log(R) + dS_{\text{soil}}$$

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, $V_{s,30} > 800\mathrm{ms}^{-1}$. Marine clay or other rocks (Lower Pleistocene and Pliocene), volcanic rock and deposits. 11 stations. 833 records.

  - B Stiff soil, $360 < V_{s,30} < 800\mathrm{ms}^{-1}$. 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, $V_{s,30} < 360\mathrm{ms}^{-1}$. 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 ($> 1000\mathrm{m}$) 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 $62.5\mathrm{samples/s}$.

- Relocate events and calculate M_L.

- Exclude data from $M_L < 2.5$ and $d_h > 300\mathrm{km}$.

- Few near-source records ($d_h < 150\mathrm{km}$) from $M_L > 4$ but for $M_L < 4$ distances from 0 to $300\mathrm{km}$ well represented.

- Exclude records with signal-to-noise ratios $< 10\mathrm{dB}$.

- Correct for instrument response and bandpass filter between 0.5 and $25\mathrm{Hz}$ 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 $<50\mathrm{km}$ 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 $d_h<10\mathrm{km}$ where ground motions overpredicted, which relate to lack of near-source data.

3.25. 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 $a_1 = -0.703$, $a_2 = 0.392$, $a_3 = -0.598$, $a_4 = -0.100$, $a_5 = -7.063$, $a_6 = 0.186$, $a_7 = 0.125$, $a_8 = 0.082$, $a_9 = 0.012$ and $a_{10} = -0.038$ (do not report σ 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 σ 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.

3.26. TAVAKOLI & 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 cms^{-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 & Tsai (2002) to demonstrate method.
- Compare results with those obtained using methods of Brillinger & Preisler (1985), Joyner & Boore (1993) and Chen & 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 $100\mathrm{km}$ 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.

3.27. TEJEDA-JACOME & CHAVEZ-GARCIA (2007)

- Ground-motion model is:

$$\ln A = c_1 + c_2 M - c_3 \ln h - c_4 \ln R$$

where A is in cms^{-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 $76.0\mathrm{km}$ (most $< 40\mathrm{km}$). No correlation between h and d_e.
- 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.

3.28. ABRAHAMSON & SILVA (2008)

- Ground-motion model is:

$$\ln \mathrm{Sa(g)} = f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + f_5(\hat{\mathrm{PGA}}_{1100}, V_{S30})$$
$$+ F_{HW} f_4(R_{jb}, R_{rup}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M)$$
$$+ f_{10}(Z_{1.0}, V_{S30})$$

$$f_1(M, R_{rup}) = \begin{cases} a_1 + a_4(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for} \quad M \le c_1 \\ a_1 + a_5(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for} \quad M > c_1 \end{cases}$$
$$R = \sqrt{R_{rup}^2 + c_4^2}$$

$$f_5(\hat{\mathrm{PGA}}_{1100}, V_{S30}) = \begin{cases} a_{10}\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) - b\ln(\hat{\mathrm{PGA}}_{1100} + c) & \\ + b\ln\left(\hat{\mathrm{PGA}}_{1100} + c\left(\frac{V_{S30}^*}{V_{LIN}}\right)^n\right) & \text{for} \quad V_{S30} < V_{LIN} \\ (a_{10} + bn)\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) & \text{for} \quad V_{S30} \ge V_{LIN} \end{cases}$$

$$\text{where} \quad V_{S30}^* = \begin{cases} V_{S30} & \text{for} \quad V_{S30} < V_1 \\ V_1 & \text{for} \quad V_{S30} \ge V_1 \end{cases}$$

$$\text{and} \quad V_1 = \begin{cases} 1500 & \text{for} \quad T \le 0.50\mathrm{s} \\ \exp[8.0 - 0.795\ln(T/0.21)] & \text{for} \quad 0.50 < T \le 1\mathrm{s} \\ \exp[6.76 - 0.297\ln(T)] & \text{for} \quad 1 < T < 2\mathrm{s} \\ 700 & \text{for} \quad T \ge 2\mathrm{s} \end{cases}$$

$$f_4(R_{jb}, R_{rup}, \delta, Z_{TOR}, M, W) = a_{14}T_1(R_{jb})T_2(R_x, W, \delta)T_3(R_x, Z_{TOR})T_4(M)T_5(\delta)$$

$$\text{where} \quad T_1(R_{jb}) = \begin{cases} 1 - \frac{R_{jb}}{30} & \text{for} \quad R_{jb} < 30\mathrm{km} \\ 0 & \text{for} \quad R_{jb} \ge 30\mathrm{km} \end{cases}$$

$$T_2(R_x, W, \delta) = \begin{cases} 0.5 + \dfrac{R_x}{2W\cos(\delta)} & for \quad R_x \leq W\cos(\delta) \\ 1 \quad for \quad R_x > W\cos(\delta) \quad or \quad \delta = 90^\circ \end{cases}$$

$$T_3(R_x, Z_{TOR}) = \begin{cases} 1 \quad for \quad R_x \geq Z_{TOR} \\ \dfrac{R_x}{Z_{TOR}} \quad for \quad R_x < Z_{TOR} \end{cases}$$

$$T_4(M) = \begin{cases} 0 \quad for \quad M \leq 6 \\ M - 6 \quad for \quad 6 < M < 7 \\ 1 \quad for \quad M \geq 7 \end{cases}$$

$$T_5(\delta) = \begin{cases} 1 - \dfrac{\delta - 70}{20} \quad for \quad \delta \geq 70 \\ 1 \quad for \quad \delta < 70 \end{cases}$$

$$f_6(Z_{TOR}) = \begin{cases} \dfrac{a_{16} Z_{TOR}}{10} \quad for \quad Z_{TOR} < 10\text{km} \\ a_{16} \quad for \quad Z_{TOR} \geq 10\text{km} \end{cases}$$

$$f_8(R_{rup}, M) = \begin{cases} 0 \quad for \quad R_{rup} < 100\text{km} \\ a_{18}(R_{rup} - 100)T_6(M) \quad for \quad R_{rup} \geq 100\text{km} \end{cases}$$

$$where \quad T_6(M) = \begin{cases} 1 \quad for \quad M < 5.5 \\ 0.5(6.5 - M) + 0.5 \quad for \quad 5.5 \leq M \leq 6.5 \\ 0.5 \quad for \quad M > 6.5 \end{cases}$$

$$f_{10}(Z_{1.0}, V_{S30}) = a_{21}\ln\left(\frac{Z_{1.0} + c_2}{\hat{Z}_{1.0}(V_{S30}) + c_2}\right) + \begin{cases} a_{22}\ln\left(\dfrac{Z_{1.0}}{200}\right) \quad for \quad Z_{1.0} \geq 200 \\ 0 \quad for \quad Z_{1.0} < 200 \end{cases}$$

$$where \quad \ln[\hat{Z}_{1.0}(V_{S30})] = \begin{cases} 6.745 \quad for \quad V_{S30} < 180\text{ms}^{-1} \\ 6.745 - 1.35\ln\left(\dfrac{V_{S30}}{180}\right) \quad for \quad 180 \leq V_{S30} \leq 500\text{ms}^{-1} \\ 5.394 - 4.48\ln\left(\dfrac{V_{S30}}{500}\right) \quad for \quad V_{S30} > 500\text{ms}^{-1} \end{cases}$$

$$a_{21} = \begin{cases} 0 & \text{for} \quad V_{S30} \geq 1000 \\ \dfrac{-(a_{10}+bn)\ln\left(\dfrac{V_{S30}^{*}}{\min(V_1,1000)}\right)}{\ln\left(\dfrac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right)} & \text{for} \quad (a_{10}+bn)\ln\left(\dfrac{V_{S30}^{*}}{\min(V_1,1000)}\right)+e_2\ln\left(\dfrac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right)<0 \\ e_2 & \text{otherwise} \end{cases}$$

$$e_2 = \begin{cases} 0 & \text{for} \quad T<0.35\text{s} \quad \text{or} \quad V_{S30}>1000 \\ -0.25\ln\left(\dfrac{V_{S30}}{1000}\right)\ln\left(\dfrac{T}{0.35}\right) & \text{for} \quad 0.35 \leq T \leq 2\text{s} \\ -0.25\ln\left(\dfrac{V_{S30}}{1000}\right)\ln\left(\dfrac{2}{0.35}\right) & \text{for} \quad T>2\text{s} \end{cases}$$

$$a_{22} = \begin{cases} 0 & \text{for} \quad T<2\text{s} \\ 0.0625(T-2) & \text{for} \quad T \geq 2\text{s} \end{cases}$$

The model for the standard deviation is:

$$\sigma_B(M,T) = \sqrt{\sigma_0^2(M,T) - \sigma_{Amp}^2(T)}$$

$$\sigma(T,M,\hat{\text{PGA}}_{1100},V_{S30}) = \left[\begin{array}{l} \sigma_0^2(M,T)+\sigma_{Amp}^2(T) \\ +\left(\dfrac{\partial \ln \text{Amp}(T,\hat{\text{PGA}}_{1100},V_{S30})}{\partial \ln \text{PGA}_{1100}}\right)^2 \sigma_B^2(M,\text{PGA}) \\ +2\left(\dfrac{\partial \ln \text{Amp}(T,\hat{\text{PGA}}_{1100},V_{S30})}{\partial \ln \text{PGA}_{1100}}\right) \\ \times \sigma_B(M,T)\sigma_B(M,\text{PGA})\rho_{\varepsilon/\sigma}(T,\text{PGA}) \end{array} \right]^{1/2}$$

$$\text{where} \quad \frac{\partial \ln \text{Amp}(T,\hat{\text{PGA}}_{1100},V_{S30})}{\partial \ln \text{PGA}_{1100}} = \begin{cases} 0 & \text{for} \quad V_{S30} \geq V_{LIN} \\ \dfrac{-b(T)\hat{\text{PGA}}_{1100}}{\hat{\text{PGA}}_{1100}+c} + \dfrac{1}{\hat{\text{PGA}}_{1100}+c\left(\dfrac{V_{S30}}{V_{LIN}}\right)^n} & \text{for} \quad V_{S30}<V_{LIN} \end{cases}$$

$$\sigma_0(M) = \begin{cases} s_1 & for \quad M < 5 \\ s_1 + \left(\frac{s_2 - s_1}{2}\right)(M-5) & for \quad 5 \le M \le 7 \\ s_2 & for \quad M > 7 \end{cases}$$

$$\tau_0(M) = \begin{cases} s_3 & for \quad M < 5 \\ s_3 + \left(\frac{s_4 - s_3}{2}\right)(M-5) & for \quad 5 \le M \le 7 \\ s_4 & for \quad M > 7 \end{cases}$$

where Sa is in g, $\hat{\mathrm{P}}\mathrm{GA}_{1100}$ is median peak acceleration for $V_{S30} = 1100\mathrm{ms}^{-1}$, σ_B and τ_B $(= \tau_0(M,T))$ are intra-event and inter-event standard deviations, σ_0 and τ_0 are intra-event and inter-event standard deviations of the observed ground motions for low levels of outcrop rock motions (directly from regression), σ_{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 ($V_s = 1000\mathrm{ms}^{-1}$), $Z_{1.0}$. 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 $30\mathrm{m}$ 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, reverse/oblique Earthquakes defined by rake angles between 30 and 150°. $F_{RV} = 1$, $F_{NM} = 0$.
  - Normal Earthquakes defined by rake angles between -60 and -120°. $F_{RV} = 0$, $F_{NM} = 1$.
  - Strike-slip All other earthquakes. $F_{RV} = 0$, $F_{NM} = 0$.

- 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 $0 \leq d_r \leq 200\text{km}$.
- 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 $d_r < 100\text{km}$ 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 $d_r > 100\text{km}$ 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 $d_r > 200\text{km}$.
- 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, δ and down-dip rupture width, W.
- Use d_f 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.
- Records well distributed w.r.t. M_w and d_r.

- 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 $5 \le M \le 6$ 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 ($R_{rup} > 100\mathrm{km}$) attenuation for small and moderate earthquakes ($4 \le M \le 5$) 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 $Z_{1.0} < 200\mathrm{m}$) and 3D (for $Z_{1.0} > 200\mathrm{m}$) site response simulations. Motion for shallow soil sites do not fall below motion for $V_{S30} = 1000\mathrm{ms}^{-1}$.

- T_D denotes period at which rock ($V_{S30} = 1100\mathrm{ms}^{-1}$) 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. $\mathrm{Sa}(T_D, V_{S30} = 1100)\dfrac{T_D^2}{T^2} + f_5(\hat{\mathrm{P}}\mathrm{GA}_{1100}, V_{S30}, T) + f_{10}(Z_{1.0}, V_{S30}, T)$.

- 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.

- 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 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.

3.29. AGHABARATI & TEHRANIZADEH (2008)

- Ground-motion model is:

$$\ln y = c_1 + f_1(M_w) + f_2(M_w) f_3(R) + f_4(F) + \mathrm{FR} f_5(Z_{FR}) +$$

$$\mathrm{FS} f_6(Z_{FR}) + f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) +$$

$$f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) + f_9(V_{s,30}, Z_{1.5})$$

$$where\ \ for\quad M_w \leq c_0$$

$$f_1(M_w) = c_3(M_w - c_0) + c_8(T)(8.5 - M_w)^n$$

$$f_2(M_w) = c_2(T) + c_4(M_w - c_0)$$

$$and\ \ for\quad M_w > c_0$$

$$f_1(M_w) = c_5(M_w - c_0) + c_8(T)(8.5 - M_w)^n$$

$$f_2(M_w) = c_2(T) + c_6(M_w - c_0)$$

$$f_3(R) = \ln\sqrt{R_{rup}^2 + c_7(T)^2}$$

$$f_4(F) = c_9(T)\mathrm{FR} + c_{10}(T)\mathrm{FS} + c_{11}(T)\mathrm{FN}$$

$$f_5(Z_{\mathrm{FR}}) = \begin{cases} 0 & Z_{top} \leq 2\mathrm{km} \\ c_{12}(T)(Z_{top}-2)/3 & 2 < Z_{top} \leq 5\mathrm{km} \\ c_{12}(T) & 5 < Z_{top} \leq 10\mathrm{km} \\ c_{12}(T)[1-(Z_{top}-10)/5] & 5 < Z_{top} \leq 10\mathrm{km}(sic) \\ 0 & Z_{top} > 10\mathrm{km} \end{cases}$$

$$f_6(Z_{\mathrm{FS}}) = \begin{cases} c_{13}(T)Z_{top}/2 & 0 < Z_{top} \leq 2\mathrm{km} \\ c_{13}(T) & 2 < Z_{top} \leq 4\mathrm{km} \\ c_{13}(T)[1-(Z_{top}-4)/2] & 4 < Z_{top} \leq 6\mathrm{km} \\ 0 & Z_{top} > 6\mathrm{km} \end{cases}$$

$$g_1(R_{JB}) = \begin{cases} 1-R_{JB}/45 & 0 \leq R_{JB} < 15\mathrm{km} \\ \frac{2}{3}(2-R_{JB}/15) & 15 \leq R_{JB} < 30\mathrm{km} \\ 0 & R_{JB} \geq 30\mathrm{km} \end{cases}$$

$$g_2(M_w) = \begin{cases} 0 & M_w < 6.0 \\ 2(M_w-6) & 6.0 \leq M_w < 6.5 \\ 1 & M_w \geq 6.5 \end{cases}$$

$$g_3(\mathrm{DIP}) = \begin{cases} 1-(\mathrm{DIP}-70)/20 & \mathrm{DIP} \geq 70 \\ 1 & \mathrm{DIP} < 70 \end{cases}$$

$$f_7(\mathrm{HW}, R_{JB}, M_w, \mathrm{DIP}) = c_{14}(T)\mathrm{HW}g_1(R_{JB})g_2(M_w)g_3(\mathrm{DIP})$$

$$f_8(V_{s,30}, V_{lin}, \mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock}) = g_4(V_{s,30}, V_{lin}) + g_5(\mathrm{PGA}_{non-lin}, \mathrm{PGA}_{rock})$$

$$g_4(V_{s,30}, V_{lin}) = c_{15}(T)\ln(V_{s,30}/V_{lin})$$

$$g_5(\mathrm{PGA}_{non-lin},\mathrm{PGA}_{rock}) = \begin{cases} c_{16}(T)\ln(\mathrm{PGA}_{min}/0.1) & \mathrm{PGA}_{non-lin} < a_1 \\ c_{16}(T)[\ln(\mathrm{PGA}_{min}/0.1) & \\ +a\ln(\mathrm{PGA}_{non-lin}/a_1) & \\ +b(\ln(\mathrm{PGA}_{non-lin}/a_1))^2] & a_1 \leq \mathrm{PGA}_{non-lin} \leq a_2 \\ c_{16}(T)\ln(\mathrm{PGA}_{non-lin}/0.1) & \mathrm{PGA}_{non-lin} \geq a_2 \end{cases}$$

$$f_9(V_{s,30},Z_{1.5}) = g_6(V_{s,30},Z_{1.5},\hat{Z}) + g_7(Z_D,Z_{1.5})$$

$$g_6(V_{s,30},Z_{1.5},\hat{Z}) = c_{17}(T)(1/\hat{Z})\ln(V_{s,30}/1500)\ln(Z_{1.5})$$

$$g_7(Z_{1.5},Z_D) = Z_D c_{18}(T)K_1(1-\exp(-(Z_{1.5}-200)/300)) +$$

$$Z_D c_{19}(T)K_2(1-\exp(-(Z_{1.5}-200)/4000))$$

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 $V_s = 1500\mathrm{ms}^{-1}$, $Z_{1.5}$, since more likely to be obtained for engineering projects.
- Use three mechanism classes:
    1. Normal. 34 records. $\mathrm{FN} = 1$, $\mathrm{FS} = \mathrm{FR} = 0$.
    2. Strike-slip. 184 records. $\mathrm{FS} = 1$, $\mathrm{FN} = \mathrm{FR} = 0$.
    3. Reverse. Originally classify as thrust, reverse and reverse oblique but combine. 423 records. $\mathrm{FR} = 1$, $\mathrm{FN} = \mathrm{FS} = 0$.

Note lack of records from normal earthquakes.

- Use data from earthquakes with focal depths $\leq 15\mathrm{km}$.

- 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 $> 60\mathrm{km}$ 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_{FR} and Z_{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 ($\mathrm{HW} = 1$).

- 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 $a_1 = 0.04\mathrm{g}$, $a_2 = 0.1\mathrm{g}$ and $\mathrm{PGA}_{min} = 0.06\mathrm{g}$. $\mathrm{PGA}_{non-lin}$ is expected PGA on rock ($V_{s,30} = 760\mathrm{ms}^{-1}$). $c_{15}(T)$, $c_{16}(T)$ and V_{lin} taken from Choi & 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).

3.30. CAUZZI & 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 $\mathrm{ms^{-2}}$, $a_1 = -1.296$, $a_2 = 0.556$, $a_3 = -1.582$, $a_B = 0.22$, $a_C = 0.304$, $a_D = 0.332$ and $\sigma = 0.344$ for horizontal PGA.

- Use four site categories based on Eurocode 8:

  A. Rock-like. $V_{s,30} \geq 800\mathrm{ms^{-1}}$. $S_B = S_C = S_D = 0$.

  B. Stiff ground. $360 \leq V_{s,30} < 800\mathrm{ms^{-1}}$. $S_B = 1$, $S_C = S_D = 0$.

  C. (c) $180 \leq V_{s,30} < 360\mathrm{ms^{-1}}$. $S_C = 1$, $S_B = S_D = 0$.

  D. Very soft ground. $V_{s,30} < 180\mathrm{ms^{-1}}$. $S_D = 1$, $S_B = S_C = 0$.

  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 $20\mathrm{m}$ profiles of K-Net down to $30\mathrm{m}$. Vast majority of data with $V_{s,30} \leq 500\mathrm{ms^{-1}}$.

- Use mechanism classification scheme of Boore & 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 $10\mathrm{s}$ 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 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 $0.05\mathrm{Hz}$ after zero padding and cosine tapering. After this step records pass criterion of prfcfvdac. Note that filtering of 43% of records may affect reliability beyond $15\mathrm{s}$.

- 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 $22\mathrm{km}$. Exclude earthquakes with focal depth $> 22\mathrm{km}$ to be in agreement with focal depths of most Italian earthquakes.

- Use d_h for greater flexibility in seismic hazard analyses where source zones have variable depth. Exclude data from $d_h > 150\mathrm{km}$ based on deaggregation results.

- Test regional dependence of ground motions using analysis of variance. Divide dataset into intervals of $10\mathrm{km} \times 0.3 M_w$ units and consider only bins with ≥ 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 d_h. Divide dataset into bins of $2\mathrm{km} \times 0.2 M_w$ units and consider only bins with ≥ 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 d_h.

- 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 & 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 $800\mathrm{ms}^{-1}$. Find b_V closely matches theoretical values 1 close to resonance period and 0.5 at long periods.

- Examine residuals w.r.t. d_h and M_w. Find no trends.

3.31. CHIOU & YOUNGS (2008)

- Ground-motion model is:

$$\ln(y) = \ln(y_{ref}) + \phi_1 \min\left[\ln\left(\frac{V_{S30}}{1130}\right), 0\right]$$

$$+ \phi_2 \{ e^{\phi_3[\min(V_{S30},1130)-360]} - e^{\phi_3(1130-360)} \} \ln\left(\frac{y_{ref} e^{\eta} + \phi_4}{\phi_4}\right)$$

$$+ \phi_5 \left\{1 - \frac{1}{\cosh[\phi_6 \max(0, Z_{1.0} - \phi_7)]}\right\} + \frac{\phi_8}{\cosh[0.15 \max(0, Z_{1.0} - 15)]}$$

$$\textit{where} \quad \ln(y_{ref}) = c_1 + [c_{1a}F_{RV} + c_{1b}F_{NM} + c_7(Z_{TOR} - 4)](1 - \mathrm{AS}) + [c_{10} + c_{7a}(Z_{TOR} - 4)]\mathrm{AS}$$

$$+ c_2(M - 6) + \frac{c_2 - c_3}{c_n} \ln[1 + e^{c_n(c_M - M)}]$$

$$+ c_4 \ln\{R_{RUP} + c_5 \cosh[c_6 \max(M - c_{HM}, 0)]\}$$

$$+ (c_{4a} - c_4) \ln(\sqrt{R_{RUP}^2 + c_{RB}^2})$$

$$+ \left\{c_{\gamma 1} + \frac{1}{\cosh[\max(M - c_{\gamma 3}, 0)]}\right\} R_{RUP}$$

$$+ c_9 F_{HW} \tanh\left(\frac{R_X \cos^2\delta}{c_{9a}}\right)\left(1 - \frac{\sqrt{R_{JB}^2 + Z_{TOR}^2}}{R_{RUP} + 0.001}\right)$$

$$\tau = \tau_1 + \frac{\tau_2 - \tau_1}{2} \times [\min\{\max(M, 5), 7\} - 5]$$

$$\sigma = \left\{\sigma_1 + \frac{\sigma_2 - \sigma_1}{2}[\min(\max(M, 5), 7) - 5] + \sigma_4 \times \mathrm{AS}\right\}$$

$$\times \sqrt{(\sigma_3 F_{Inferred} + 0.7 F_{Measured}) + (1 + \mathrm{NL})^2}$$

$$\textit{where} \quad \mathrm{NL} = \left(b \frac{y_{ref} e^{\eta}}{y_{ref} e^{\eta} + c}\right)$$

$$\sigma_T^2 = (1 + \mathrm{NL}_0)^2 \tau^2 + \sigma_{\mathrm{NL}_0}^2$$

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 $\sigma_4 = 0.0663$ (η is the inter-event residual). σ_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. σ_{NL_0} is the equation for σ 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 $150 \leq V_{S30} \leq 1500\mathrm{ms}^{-1}$.

- Use depth to shear-wave velocity of $1.0\mathrm{kms}^{-1}$, $Z_{1.0}$, to model effect of near-surface sediments since $1\mathrm{kms}^{-1}$ 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 $20\mathrm{km}$ and $Z_{TOR} \leq 15\mathrm{km}$. Therefore note that application to regions with very thick crusts (e.g. ?$20\mathrm{km}$) 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 ($\geq 20\mathrm{km}$) 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. $\mathrm{AS}=1$ 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 $70\mathrm{km}$ (selected by visual inspection) to remove effects of bias in sample.

- To complete missing information in the NGA database estimate strike, dip (δ) and rake (λ) 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 δ 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 λ 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 $< 10\mathrm{km}$. 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, $M 4.92$; 2002 Yorba Linda, $M 4.27$; 2003 Big Bear City, $M 4.92$) 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 $60\mathrm{km}$. 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, γ, 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 γ 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 $1130\mathrm{ms}^{-1}$ because expected that no significant nonlinear site response at that velocity and very few records with $V_{S30} > 1100\mathrm{ms}^{-1}$ 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 η_i (inter-event) and ε_{ij} (intra-event). Assume inter-event residuals independent and normally distributed with variance τ^2. Assume intra-event error components independent and normally distributed with variances σ_P^2 (path), σ_S^2 (site) and σ_X^2 (remaining). Assume total intra-event variance to be normally distributed with variance σ^2. Show that σ^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 2τ 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 $V_{S30} > 1130\text{ms}^{-1}$, 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 $> 50\text{km}$ are major contribution to hazard adjustments to $c_{\gamma 1}$ and $c_{\gamma 2}$ may be warranted.

3.32. COTTON ET AL. (2008)

- Ground-motion model is:

$$\log[\text{PSA}(f)] = a(f) + b(f)M_w + c(f)M^2 + d(f)R - \log_{10}[R + e(f) \times 10^{0.42M_w}] + S_i(f)$$

where $\text{PSA}(f)$ is in ms^{-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 200m) 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 σ 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 $V_{s,30} > 800\mathrm{ms}^{-1}$.
    - Class B $360 < V_{s,30} < 800\mathrm{ms}^{-1}$. Use coefficient S_B.
    - Class C $180 < V_{s,30} < 360\mathrm{ms}^{-1}$. Use coefficient S_C.
    - Class D $V_{s,30} < 180\mathrm{ms}^{-1}$. 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 $< 100\mathrm{km}$.
- Only retain events with depth $< 25\mathrm{km}$ 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 $25\mathrm{Hz}$. Longest usable period of model is less than $3\mathrm{s}$ 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 $99\mathrm{km}$. 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 σs 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 σs for surface motions are larger (by about 9%) than those for motions at depth.

3.33. CUA & HEATON (2008)

- Ground-motion model is:

$$\log Y = aM + b[R_1 + C(M)] + d\log[R_1 + C(M)] + e$$

$$R_1 = \sqrt{R^2 + 9}$$

$$C(M) = c_1 \exp[c_2(M-5)][\tan^{-1}(M-5) + \pi/2]$$

where Y is in cms^{-2}, $a = 0.73$, $b = -7.2\times10^{-4}$, $c_1 = 1.16$, $c_2 = 0.96$, $d = -1.48$, $e = -0.42$ and $\sigma = 0.31$ for rock and $a = 0.71$, $b = -2.38\times10^{-3}$, $c_1 = 1.72$, $c_2 = 0.96$, $d = -1.44$, $e = -2.45\times10^{-2}$ 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, $V_{s,30} > 464\text{ms}^{-1}$. 35 SCSN stations with 958 records. 50 records from NGA.
- Soil Class C and below, $V_{s,30} \leq 464\text{ms}^{-1}$. 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 σs.
- 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 σ (to 0.24).

3.34. HUMBERT & VIALLET (2008)

- Ground-motion model is:

$$\log(\text{PGA}) = aM + bR - \log(R) + c$$

where PGA is in cms^{-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 30km.

- Plot d_h, 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 σ than in standard regression.

- Find that epistemic uncertainties increase at edge of magnitude-distance space.

3.35. 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 $\sigma = 1.28 + 0.05\ln(T) - 0.08M$. σ for $M < 5$ equals σ at $M5$ and σ for $M > 7.5$ equals σ at $M7.5$. σ for $T < 0.05$ equals σ for $T = 0.05\mathrm{s}$. Correction factor for $V_{S30} > 900\mathrm{ms}^{-1}$ $\Delta\alpha_1(T) = \ln[(1 + 11T + 0.27T^2)/(1 + 16T + 0.08T^2)]$ for $0.05 \leq T \leq 10\mathrm{s}$ [$\Delta\alpha_1(T)$ for $T < 0.05\mathrm{s}$ equals $\Delta\alpha_1(0.05)$].

- Use two site classes (may derive model for $180 \leq V_{S30} < 450\mathrm{ms}^{-1}$ in future):

  1. $V_{S30} > 900\mathrm{ms}^{-1}$. 45 records. Since not enough records from stations with $V_{S30} > 900\mathrm{ms}^{-1}$ derive correction factor, $\Delta\alpha_1(T)$, to α_1 based on residuals for these 45 records. Find no trends in residuals w.r.t. M, R or V_{S30}.

  2. $450 \leq V_{S30} \leq 900\mathrm{ms}^{-1}$. 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:

- Rake within 30° of horizontal. Includes records from normal events (rake within 30° of vertical downwards) because insufficient data to retain as separate category. $F = 0$.

- 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 ≥ 3 storeys.

- Excludes records from `deep' events, records from distances $> 200\text{km}$ and records from co-located stations.

- Only retains records with $450 \leq V_{S30} \leq 900\text{ms}^{-1}$ 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 $R \leq 5\text{km}$ and 33 from $R \leq 10\text{km}$ (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 0.01s 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 100km 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 α_1 and α_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 $5.2 \le M \le 7.2$ model provides excellent representation of data. Examine residuals for 5 Chi-Chi aftershocks and find that for $R > 15\text{km}$ there is no bias but for shorter distances some negative bias.
- Compares predictions to observations for Hector Mine ($M7.1$), Loma Prieta ($M6.9$), Northridge ($M6.7$) and San Fernando ($M6.6$) 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.

3.36. LIN & 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 50km maximum focal depth for interface events. 12 events from Taiwan (819 records) and 5 from elsewhere (54 records). $Z_t = 0$.

  - o 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 30km (for interface) and 43.39 and 161km (for intraslab).

- Develop separate M_L-M_w conversion formulae for deep ($H > 50\text{km}$) 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 $M_w 6.3$ $H = 6\text{km}$ and intraslab $M_w 5.9$ $H = 39\text{km}$) 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 σ 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.

3.37. 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, $V_{s,30} > 800\text{ms}^{-1}$: 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, $360 < V_{s,30} < 800\text{ms}^{-1}$: 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, $V_s < 360\text{ms}^{-1}$: 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 from 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 $d_e > 100\text{km}$ 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 57.9km. Most less than 15km.

- Bandpass filter using fourth-order acausal Butterworth filter with cut-offs of 0.4 and 25Hz for $M_L \leq 4.5$ and 0.2 and 25Hz 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 d_f since not sufficient information on rupture locations. Do not use d_h 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 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 $d_e < 10\mathrm{km}$ and $M_L > 5.5$ $10\mathrm{km}$ is considered the distance at which distance saturation starts (since little data with $d_e < 10\mathrm{km}$ to constrain curves and predictions for shorter distances unrealistically high).
- Also derive equations for other strong-motion intensity parameters.

3.38. MEZCUA ET AL. (2008)

- Ground-motion model is:

$$\ln Y = C_1 + C_2 M + C_3 \ln R$$

where Y is in cms^{-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 $400 \le V_s \le 750\mathrm{ms}^{-1}$. 23 stations.
    2. Alluvium or firm soil. Quaternary consolidated deposits. Similar to Spanish building code class III with $200 \le V_s \le 400\mathrm{ms}^{-1}$. 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 $5 \le d_e \le 100\mathrm{km}$ and $M \ge 3$.
- Focal depths between 1 and $16\mathrm{km}$.
- Most data from $3 \le M \le 4$ and $d_e \le 50\mathrm{km}$. Only one record with $M > 5$ and $d_e < 20\mathrm{km}$.

- 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 $4.9 \le M_w \le 5.1$. Find reasonable fit.

3.39. 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, $a = -4.417$, $b = 0.770$, $c = -1.097$, $D = 0$, $D_1 = 0.123$, $\sigma_{\mathrm{eve}} = 0.069$ and $\sigma_{\mathrm{rec}} = 0.339$ for horizontal PGA and intra-event sigma; $a = -4.128$, $b = 0.722$, $c = -1.250$, $D = 0$, $D_1 = 0.096$, $\sigma_{\mathrm{eve}} = 0.085$ and $\sigma_{\mathrm{rec}} = 0.338$ for vertical PGA and intra-event sigma; $a = -4.367$, $b = 0.774$, $c = -1.146$, $D = 0$, $D_1 = 0.119$, $\sigma_{\mathrm{sta}} = 0.077$ and $\sigma_{\mathrm{rec}} = 0.337$ for horizontal PGA and intra-station sigma; and $a = -4.066$, $b = 0.729$, $c = -1.322$, $D = 0$, $D_1 = 0.090$, $\sigma_{\mathrm{sta}} = 0.105$ and $\sigma_{\mathrm{rec}} = 0.335$.

- Use two site categories ($s_{1,2}$) because insufficient information to use more[3]:
  - D - Rock. Average $V_s > 800\mathrm{ms}^{-1}$. 10 stations.
  - D_1 - Soil. Average $V_s < 800\mathrm{ms}^{-1}$. Includes all kinds of superficial deposits, from weak rocks to alluvial deposits although they are mainly shallow alluvium and soft rock (600 - $700\mathrm{ms}^{-1}$) 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 $1\mathrm{s}$, 5 stations; Lennartz $5\mathrm{s}$, 13 stations).

[3]Note that the authors use $s_{1,2}$ to significant site effects when the functional form is reported (their equation 2) but the coefficients are labeled D and D_1 in their Tables 3-6.

- Select data with $M > 2.7$.
- Baseline and instrument correct records from analogue accelerometric instruments and filter in average bandpass $0.5 - 20\mathrm{Hz}$ after visual inspection of the Fourier amplitude spectra. Baseline correct records from digital accelerometric instruments and filter in average bandpass $0.2 - 30\mathrm{Hz}$ after visual inspection of the Fourier amplitude spectra. Instrument correct records from digital velocimetric instruments and filter in average bandpass $0.5 - 25\mathrm{Hz}$ after visual inspection of the Fourier amplitude spectra.
- Most data from $d_h < 40\mathrm{km}$ and almost all velocimetric data from $20 - 30\mathrm{km}$.
- Most focal depths between 10 and $30\mathrm{km}$.
- 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 σ_{eve} suggests that the calibrated local magnitudes and relocated hypocentral locations are accurate.
- Note that small value of σ_{sta} suggests that the site classification is correct.
- Note that records from accelerometric and velocimetric instruments are similar.

3.40. SLEJKO ET AL. (2008)

- Ground-motion model is:

$$\log_{10} PGA = a + (b + cM_s)M_s + (d + eM_s)\log_{10} r$$

$$where \quad r^2 = D^2 + h^2$$

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 $d_e < 100\mathrm{km}$ because data from larger distances only available for large earthquakes.
- Only eight records have PGA $< 0.005\mathrm{g}$ (standard trigger level).

- Use truncated regression analysis (Bragato, 2004) to account for bias due to non-triggering stations.

3.41. 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 cms^{-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 $d_h < 1\mathrm{km}$ 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.

4. General characteristics of attenuation relations for peak ground acceleration

Illustration 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_b Body-wave magnitude

M_C Chinese surface wave magnitude

M_{CL} Coda length magnitude

M_D Duration magnitude

M_{JMA} Japanese Meteorological Agency magnitude

M_L Local magnitude

M_{bLg} Magnitude calculated using Lg amplitudes on short-period vertical seismographs

M_s Surface-wave magnitude

M_w Moment magnitude

d_{min} Shortest source-to-site distance

d_{max} Longest source-to-site distance

d scale Distance measure, where:

d_c Distance to rupture centroid

d_e Epicentral distance

d_E Distance to energy centre

d_f Distance to projection of rupture plane on surface (Joyner & Boore, 1981)

d_h Hypocentral (or focal) distance

d_q Equivalent hypocentral distance (EHD) (Ohno et al. , 1993)

d_r Distance to rupture plane

d_s Distance to seismogenic rupture plane (assumes near-surface rupture in sediments is non-seismogenic) (Campbell, 1997)

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 & Bommer (2006)], where:

1 Principal 1

2 Principal 2

A Arithmetic mean

B Both components

C Randomly chosen component

D50 GMrotD50 (Boore et al., 2006)

G Geometric mean

I50 GMrotI50 (Boore et al., 2006)

L Larger component

M Mean (not stated what type)

N Fault normal

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 & 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

R Regression method used, where:

1 Ordinary one-stage

1B Bayesian one-stage (Ordaz et al., 1994)

1M Maximum likelihood one-stage (Joyner & Boore, 1993)

1W Weighted one-stage

1WM Weighted maximum-likelihood one-stage

2 Two-stage (Joyner & Boore, 1981)

2M Maximum likelihood two-stage (Joyner & Boore, 1993)

2W Two-stage with second staged weighted as described in Joyner & 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

F Interface

HW Hanging wall

I Intraplate

M Mining-induced

N Normal

O Oblique or odd (Frohlich & Apperson, 1992)

R Reverse

S Strike-slip

T Thrust

U Unspecified

`+' 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.

Illustration 1 : Characteristics of published peak ground acceleration relations

Reference	Area	H	V	E	M_{min}	M_{max}	M scale	d_{min}	d_{max}	d scale	S	C	R	M
Davenport (1972)	Unknown	U	-	U	U	U	U	U	U	d_h	1	U	U	A
Gitterman *et al.* (1993)	Israel	U	-	U	3.9	5.1	M_L	U	U	d_e	1	U	U	A
Baag *et al.* (1998)	Korea	U	-	U	U	U	U	U	U	d_e	1	U	U	A
Sanchez & Jara (2001)	Pacific coast of Mexico	U	-	U	U	U	M_s	U	U	d_e	1	U	U	BF
Wu *et al.* (2001)	Taiwan	1941	-	60	4.8	7.6	M_w (M_L)	0.05*	400*	d_r (d_e for some)	1 & I	U	U	A
Shi & Shen (2003)	Shanghai region	U	-	U	U	U	M_s	U	U	d_h	1	U	U	A
Beauducel *et al.* (2004)	Guadeloupe	1430	-	398	1.1	6.3	M_D (m_b, M_w)	1.7	450	d_h	1	R	1	A
Nowroozi (2005)	Iran	279	279	45	3.0*	7.4	M_w (M_s, m_b, M_L)	2	245	d_e	4	V	1	A
Ruiz & Saragoni (2005)[1]	Chile	41	41	8	6.4	7.8	M_s	35.72	315.01	d_h	1	B	1	F
Wald *et al.* (2005)	California	U	-	U	U	5.3*	M_w	U	U	d_f	1	L	U	A
Moss & Der Kiureghian (2006)	W. N. America	271	-	20	5.2	7.7	M_w	0	118.2	d_f	C	G	O	A
Pousse *et al.* (2006)	Japan	9390[2]	-	U	4.1	7.3	(M_w)	5*	250*	d_h (d_r for some)	5	B	2M	A
Akkar & Bommer (2007b)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	d_f	3	G	1WM	A (N, S, R)
Amiri *et al.* (2007a) & Amiri *et al.* (2007b)	Alborz and central Iran[3]	200*	200*	50*	4.5*	7.3*	M_s (m_b)	5*	400*	d_h	2	L	1	A
Aydan (2007)	Turkey	U	-	U	U	U	U	U	U	d_h	C	U	U	A
Bindi *et al.* (2007)	NW Turkey	4047	4047	528	0.5	5.9	M_L[4]	5*	200*	d_h[5]	2	L	1M	A
Bommer *et al.* (2007)	Europe and Middle East	997	-	289	3	7.6	M_w	0	99	d_f (d_e for small events)	3	G	1WM	A (N, S, R)

continued on next page

[1] Also develop equations for hard rock sites and intraslab events.
[2] Does not need to be multiplied by two.
[3] Also develop models for the Zagros region of Iran using about 100 records.
[4] Also derive model using M_w.
[5] Also derive model using d_e.

Reference	Area	H	V	E	M_{min}	M_{max}	M scale	d_{min}	d_{max}	d scale	S	C	R	M
Boore & Atkinson (2007) & Boore & Atkinson (2008)	Worldwide shallow crustal	1574	-	58	4.27[6]	7.90[7]	M_w	0	280[8]	d_f	C	I50	2M	A (N, R, S, U)
Campbell & Bozorgnia (2007), Campbell & Bozorgnia (2008b) & Campbell & Bozorgnia (2008a)	Worldwide shallow crustal	1561	-	64	4.27[9]	7.90[10]	M_w	0.07	199.27	d_r	C	I50	1M	A (N, R, S, HW)
Danciu & Tselentis (2007a) & Danciu & Tselentis (2007b)	Greece	335	-	151	4.5	6.9	M_w	0*	136	d_e	3	A	1M	A (ST, N)
Douglas (2007)			See text				M_w	See text		d_f	See text		1	A
Hong & Goda (2007) & Goda & Hong (2008)	California	592	-	39	5*	7.3*	M_w	0.2*	100*	d_f	C	G, Q, R	1M	A
Graizer & Kalkan (2007) & Graizer & Kalkan (2008)	Worldwide shallow crustal	2583	-	47	4.9[11]	7.9[12]	M_w	0.1	349.6[13]	d_r	C	U	O	A (R,SN)
Massa *et al.* (2007)	Central northern Italy	1063	-	243	2.5	5.2	M_L	0*	300*	d_h	2	L	1	A
Sobhaninejad *et al.* (2007)	Europe & Middle East	589	589	131	5.0	7.6	M_w	0	99	d_f (d_e for small events)	3	L	O	A (N, T, S, O)
Tavakoli & Pezeshk (2007)	Taiwan	424	-	48	4.3*	7.3*	M_L	5*	260*	d_h	1	G	O	A
Tejeda-Jácome & Chávez-García (2007)	Colima, Mexico	162	162	26	3.3	5.2	M_L	5*	175	d_h	1	G	2M	A

continued on next page

[6] Recommend that model is not extrapolated below 5 due to lack of data.
[7] Believe that model can be used to 8.0.
[8] Recommend that model is not used for distances ≥ 200 km.
[9] Believe that model can be extrapolated down to 4.0.
[10] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[11] Graizer & Kalkan (2007) state that valid down to 4.5.
[12] Graizer & Kalkan (2007) state that valid up to 7.6.
[13] Graizer & Kalkan (2007) state that valid up to 200 km.

Reference	Area	H	V	E	M_{min}	M_{max}	M scale	d_{min}	d_{max}	d scale	S	C	R	M
Abrahamson & Silva (2008)	Worldwide shallow crustal	2754	-	135	4.27[14]	7.9[15]	M_w	0.06*	200*	d_r	C	I50	1M	A (N, R, S, HW)
Aghabarati & Tehranizadeh (2008)	Worldwide shallow crustal	646	-	54	5.2	7.9	M_w	0	60	d_r[16]	C	G	1M	A (N, R, S)
Cauzzi & Faccioli (2008), Cauzzi (2008) & Cauzzi *et al.* (2008)	Worldwide shallow crustal	1164	1132	60	5.0	7.2	M_w	6*	150*	d_h	4 & C	G	2M	A (N, R, S)
Chiou & Youngs (2008)	Worldwide shallow crustal	1950	-	125	4.265[17]	7.90[18]	M_w	0.2*[19]	70*[20]	d_r	C	I50	1M	A (N, R, S, HW, AS)
Cotton *et al.* (2008)	Japan	3894	-	337	4	7.3	M_w (M_{JMA})	1	100	d_r (d_h for small)	4[21] & 2[22]	G	2M	A
Cua & Heaton (2008)	Southern California+other shallow crustal	3588+1607	-	70	2 (5)	7.3 (7.9)	M_w	0.8 (0.1)*	200 (200)*	d_f (d_e for $M < 5$)	2	G	1	A
Humbert & Viallet (2008)	Europe & Middle East	960	-	138	4.0	7.4	M_s	U	U	d_h	1	U	O	A
Idriss (2008)	Worldwide shallow crustal	942	-	72	4.5	7.7	M_w	0.3	199.3	d_r	2	I50	1	A (R/RO/NO, S/N)
Lin & Lee (2008)	NE Taiwan+10 foreign	4244+139	-	44+10	4.1 (6.0)	7.3 (8.1)	M_w (M_L)	15	630	d_h	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*	d_e	3	L	1M	A
Mezcua *et al.* (2008)	Spain	250	-	149	3.1	5.3	M_w ($m_b(L_g)$)	5*	100*	d_h	1	U	1	A
Morasca *et al.* (2008)	Molise	3090	3090	100	2.7	5.7	M_L	12*	60*	d_h	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*	d_e	1	U	O	A

continued on next page

[14] Recommend that model is not extrapolated below 5 due to lack of data.
[15] Believe that model can be reliably extrapolated to 8.5.
[16] Not clear from article if the authors mean d_r or d_f.
[17] Believe that model can be extrapolated down to 4.0.
[18] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[19] Believe that model valid to 0 km.
[20] Believe that model valid to 200 km.
[21] For stations on surface.
[22] For borehole stations.

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$d_{\min}$	$d_{\max}$	d scale	S	C	R	M
Srinivasan *et al.* (2008)	Kolar Gold Fields, India	795	-	795	0.5	3.0	M_L	1	4.76	d_h	1	G	1	A

5. Summary of published attenuation relations for spectral ordinates

5.1. DAS ET AL. (2002)

- 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 10 and 100km.
- 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 $T > 1\text{s}$ 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 σ.

5.2. WALD ET AL. (2005)

- See Section 3.10.
- Response parameter is pseudo-acceleration for 5% damping.

5.3. POUSSE ET AL. (2006)

- See Section 3.12.
- Response parameter is pseudo-acceleration for 5% damping.
- Coefficients not reported.

5.4. AKKAR & BOMMER (2007B)

- See Section 3.13.
- 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 1s) than for records from digital instruments (starting around 3s). Due to lack of data for longer periods limit regression to periods $\leq 4\text{s}$.
- 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 $> 3\text{s}$ 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).

5.5. BINDI ET AL. (2007)

- See Section 3.16.
- 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.

5.6. BOMMER ET AL. (2007)

- See Section 3.17.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive equations only up to $0.5\mathrm{s}$ 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 $2\mathrm{s}$ but since study is for exploring influence of lower magnitude limit short-period motions are the most important.

5.7. BOORE & ATKINSON (2007) & BOORE & ATKINSON (2008)

- See Section 3.18.
- 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 $1\mathrm{s}$, slight decrease at $2\mathrm{s}$ and a rapid fall off in number of records for periods $> 2\mathrm{s}$.
- 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 & Stewart (2005) do not provide coefficients for site amplification for periods $> 5\mathrm{s}$ 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_3s from four-event analysis with constraints for short and long periods.
- No data from normal-faulting events for $10\mathrm{s}$ so assume ratio of motions for normal and unspecified faults is same as for $7.5\mathrm{s}$.
- Possible underprediction of long-period motions at large distances in deep basins.
- Chi-Chi data major controlling factor for predictions for periods $> 5\mathrm{s}$ even for small events.

5.8. CAMPBELL & BOZORGNIA (2007), CAMPBELL & BOZORGNIA (2008B) & CAMPBELL & BOZORGNIA (2008A)

- See Section 3.19.
- 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 > 4-5s 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.

5.9. DANCIU & TSELENTIS (2007A) & DANCIU & TSELENTIS (2007B)

- See Section 3.20.
- Response parameter is acceleration for 5% damping.

5.10. FUKUSHIMA ET AL. (2007B) & FUKUSHIMA ET AL. (2007A)

- 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, $V_{s,30} > 600$ms^{-1}, NEHRP classes A+B. 23 sites.
  - SC-2 - Site natural period $0.2 \leq T_G < 0.6$s, $200 \leq V_{s,30} < 600$ms^{-1}, NEHRP classes C+D. 100 sites.
  - SC-3 - Site natural period $T_G \geq 0.6$s, $V_{s,30} \leq 200$ms^{-1}, NEHRP class E. 95 sites.

- o SC-4 - Unknown site natural period, $V_{s,30} > 800\mathrm{ms}^{-1}$, NEHRP classes A+B. 44 sites.
- o SC-5 - Unknown site natural period, $300 \leq V_{s,30} < 800\mathrm{ms}^{-1}$, 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 $25\mathrm{Hz}$ therefore present results up to $3\mathrm{s}$ to avoid filter effects.
- Find roughly 2% reduction in standard deviation using classification scheme compared to rock/soil scheme.

5.11. HONG & GODA (2007) & GODA & HONG (2008)

- See Section 3.22.
- 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 $1.0\mathrm{s}$. 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 $3\mathrm{s}$ in article. Provide coefficients for other periods as electronic supplement.

5.12. MASSA ET AL. (2007)

- See Section 3.24.

- Response parameter is acceleration for 5% damping.

5.13. TEJEDA-JACOME & CHAVEZ-GARCIA (2007)

- See Section 3.27.

- Response parameter is pseudo-acceleration for 5% damping.

- Signal-to-noise ratios mean analysis limited to $1\mathrm{s}$ for horizontal and $0.8\mathrm{s}$ for vertical.

5.14. ABRAHAMSON & SILVA (2008)

- See Section 3.28.

- 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 $2\text{-}4\text{s}$ for $T > 5\text{s}$ because they could not be constrained by data.
- Smooth coefficients in several steps.

5.15. AGHABARATI & TEHRANIZADEH (2008)

- See Section 3.29.
- Response parameter is pseudo-acceleration for 5% damping.

5.16. CAUZZI & FACCIOLI (2008), CAUZZI (2008) & CAUZZI ET AL. (2008)

- See Section 3.30.
- 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.

5.17. CHEN & YU (2008B)

- Ground-motion model is:

$$\log \text{Sa} = C_1 + C_2 M + C_3 M^2 + C_4 \log[R + C_5 \exp(C_6 M)]$$

- Use records from sites with $V_{s,30} \geq 500\text{ms}^{-1}$.
- 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-$2.9\mathrm{km}$, 3.0-$9.9\mathrm{km}$, 10-$29.9\mathrm{km}$, $30-59.9\mathrm{km}$, 60-$99.9\mathrm{km}$, 100-$200\mathrm{km}$ and $>200\mathrm{km}$. 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 ($M5.9$).

5.18. CHEN & YU (2008A)

- Response parameter is acceleration for 0.5, 2, 7, 10 and 20% damping.
- Continuation of Chen & Yu (2008b) (Section 5.17) for other damping levels.

5.19. CHIOU & YOUNGS (2008)

- See Section 3.31.
- 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 $8.0\mathrm{s}$, 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.

5.20. COTTON ET AL. (2008)

- See Section 3.32.
- Response parameter is pseudo-acceleration for 5% damping.

5.21. 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 300km 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 300km 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 126km and for interface[4] earthquakes between 21 and 51km.

- Also derive model using: $\log_{10} Y(T) = c + aM_w + hD - \log_{10} R - bR$. Find lower σs for functional form using R_1 and R_2 for periods $< 1\text{s}$. Examine residuals w.r.t. d_h for 0.1 and 1.0s 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 $< 2\text{s}$.

- Convert computed anelastic coefficients to Q models and find that can relate observations to different Q models for fore-arc and back-arc regions.

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[4] Authors call them `interplate'.

5.22. GHASEMI ET AL. (2008)

- Ground-motion model is:

$$\log_{10} Sa(T) = a_1 + a_2 M + a_3 \log_{10}(R + a_4 10^{a_5 M}) + a_6 S_1 + a_7 S_2$$

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 - $V_{s,30} \geq 760\text{ms}^{-1}$. $S_1 = 1$, $S_2 = 0$.
  - Soil - $V_{s,30} < 760\text{ms}^{-1}$. $S_2 = 1$, $S_1 = 0$.

  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 $R < 100\text{km}$ 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 $> 1\text{s}$ 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 1s) w.r.t. M and R. Find no significant (at 5% level) trends.
- Examine histograms of residuals for 0.1 and 1s and find that expected normal distribution fits the histograms closely.

6. General characteristics of attenuation relations for spectral ordinates

Illustration 2 gives the general characteristics of published attenuation relations for spectral ordinates. The columns are the same as in Illustration 1 with three extra columns:

*T*s Number of periods for which attenuation equations are derived

T_{min} Minimum period for which attenuation equation is derived

T_{max} Maximum period for which attenuation equation is derived

Illustration 2 : Characteristics of published spectral relations

Reference	Area	H	V	E	M_{min}	M_{max}	M scale	d_{min}	d_{max}	d scale	S	Ts	T_{min}	T_{max}	C	R	M
Das *et al.* (2002)	NE India	174	-	6	5.7*	7.2*	U	53.51*	153.91*	d_h	1	20	0.04	1	V	2	A
Wald *et al.* (2005)	California	U	-	U	U	5.3*	M_w	U	U	d_f	1	3	0.3	3	L	U	A
Pousse *et al.* (2006)	Japan	9390[1]	-	U	4.1	7.3	(M_w)	5*	250*	d_h (d_r for some)	5	U	0.01	3	B	2M	A
Akkar & Bommer (2007b)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	d_f	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[2]	5*	200*	d_h[3]	2	8	0.1	1[4]	L	1M	A
Bommer *et al.* (2007)	Europe and Middle East	997	-	289	3	7.6	M_w	0	99	d_f (d_e for small events)	3	10	0.05	0.50	G	1WM	A (N, S, R)
Boore & Atkinson (2007) & Boore & Atkinson (2008)	Worldwide shallow crustal	600*–1574	-	18*–58	4.27–5.00[5]	7.90[6]	M_w	0	280[7]	d_f	C	21	0.01	10	I50	2M	A (N, R, S, U)
Campbell & Bozorgnia (2007), Campbell & Bozorgnia (2008b) & Campbell & Bozorgnia (2008a)	Worldwide shallow crustal	506–1561	-	21–64	4.27[8]	7.90[9]	M_w	0.07	199.27	d_r	C	21	0.01	10	I50	1M	A (N, R, S, HW)
Danciu & Tselentis (2007a) & Danciu & Tselentis (2007b)	Greece	335	-	151	4.5	6.9	M_w	0*	136	d_e	3	31	0.10	4	A	1M	A (N, ST)

continued on next page

[1] Does not need to be multiplied by two.
[2] Also derive model using M_w.
[3] Also derive model using d_e.
[4] Their Figure 2 present σs up to 2 s but the coefficients of the model are not given beyond 1 s.
[5] Recommend that model is not extrapolated below 5 due to lack of data.
[6] Believe that model can be used to 8.0.
[7] Recommend that model is not used for distances $\geq$ 200 km.
[8] Believe that model can be extrapolated down to 4.0.
[9] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$d_{\min}$	$d_{\max}$	d scale	S	Ts	$T_{\min}$	$T_{\max}$	C	R	M
Fukushima *et al.* (2007b) & Fukushima *et al.* (2007a)	Mainly west Eurasia+some US and Japanese	399+339	-	40+10	5.5	7.4	M_w (M_s)	0.5	235	d_h (d_r for 2 earthquakes)	5	U	0.03	3	B	2M	A
Hong & Goda (2007) & Goda & Hong (2008)	California	484–592	-	34–39	5*	7.4*	M_w	0.2*	100*	d_f	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*	d_h	2	8	0.1	1.5	L	1	A
Tejeda-Jácome & Chávez-García (2007)	Colima, Mexico	162	162	26	3.3	5.2	M_L	5*	175	d_h	1	H:10, V:9	0.07	H:0.99, V:0.80	G	2M	A
Abrahamson & Silva (2008)	Worldwide shallow crustal	500*–2754	-	64–135	4.27[10]	7.9[11]	M_w	0.06*	200*	d_r	C	22	0.01	10	I50	1M	A (N, R, S, HW)
Aghabarati & Tehranizadeh (2008)	Worldwide shallow crustal	646	646	54	5.2	7.9	M_w	0	60	d_r	C	26	0.025	10	G	1M	A (N, R, S)
Cauzzi & Faccioli (2008) & Cauzzi (2008)	Worldwide shallow crustal	1164	1132	60	5.0	7.2	M_w	6*	150*	d_h	4 & C	400	0.05	20	G	2M	A (N, S, R)
Chen & Yu (2008b)	Worldwide shallow crustal	130	-	U	5.0*	7.5*	M_w	0*	200*	U	1	U	0.04	10	B	1	A
Chen & Yu (2008a)	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

[10] Recommend that model is not extrapolated below 5 due to lack of data.
[11] Believe that model can be reliably extrapolated to 8.5.

Reference	Area	H	V	E	M_{min}	M_{max}	M scale	d_{min}	d_{max}	d scale	S	Ts	T_{min}	T_{max}	C	R	M
Chiou & Youngs (2008)	Worldwide shallow crustal	$\leq$1950[12]	-	$\leq$125	4.265[13]	7.90[14]	M_w	0.2*[15]	70*[16]	d_r	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_{JMA})	1	100	d_r (d_h for small)	4[17] & 2[18]	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*	d_h	1	16	0.1	5	V	2	B, F
Ghasemi *et al.* (2008)	Iran+West Eurasia	716+177	-	200	5.0	7.4	M_w	0.5	100	d_r (d_h for small events)	2	17	0.05	3	I50	1M	A
Idriss (2008)	Worldwide shallow crustal	942	-	72	4.5	7.7	M_w	0.3	199.3	d_r	2	31	0.01	10	I50	1	A (R/RO/NO, S/N)
Lin & Lee (2008)	NE Taiwan+10 foreign	4244+139	-	44+10	4.1 (6.0)	7.3 (8.1)	M_w (M_L)	15	630	d_h	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*	d_e	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*	d_h	2	12	0.04	2	L	1M	A
Yuzawa & Kudo (2008)	Japan	1988	-	18	5.9, 5.7	8.0, 7.9	M_{JMA}, M_w	U	U	d_q	1	45	1	10	U	2	A

[12] Due to filtering number of records and earthquakes depends on period.
[13] Believe that model can be extrapolated down to 4.0.
[14] Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.
[15] Believe that model valid to 0 km.
[16] Believe that model valid to 200 km.
[17] For stations on surface.
[18] For borehole stations.

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Scientific and Technical Centre
ARN/RIS Division
3, avenue Claude-Guillemin - BP 36009
45060 Orléans Cedex 2 – France – Tel.: +33 (0)2 38 64 34 34