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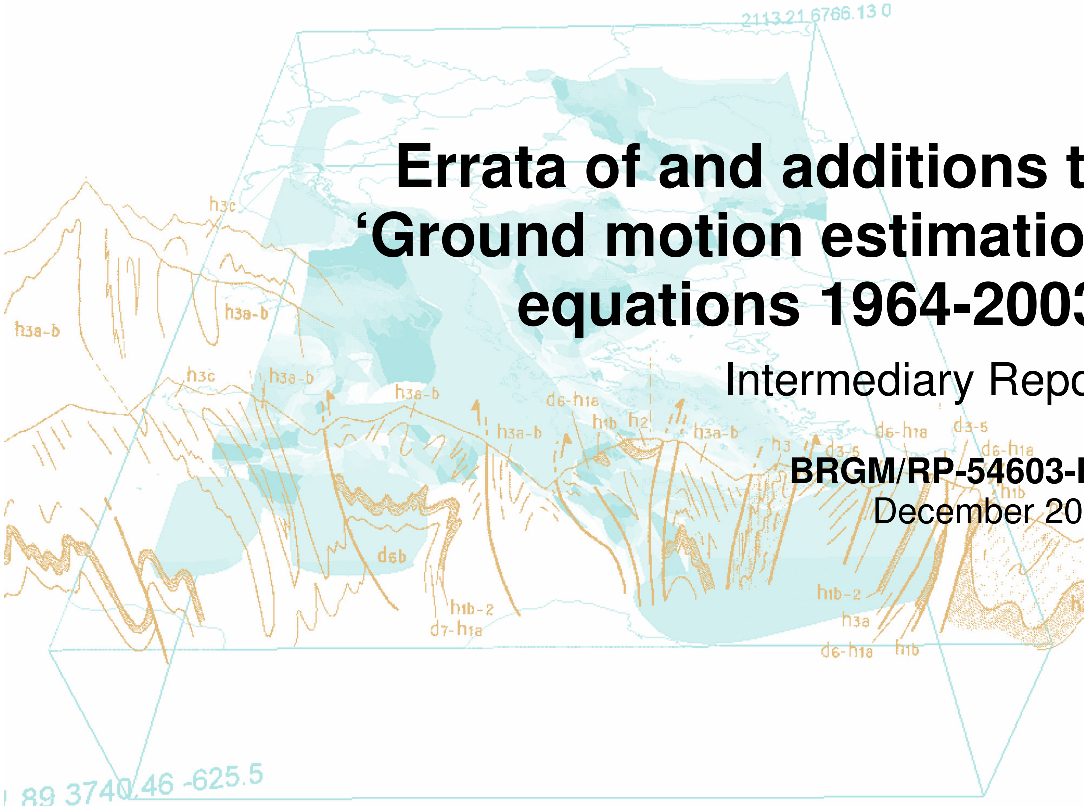

Errata of and additions to ‘Ground motion estimation equations 1964-2003’

Intermediary Report

BRGM/RP-54603-FR

December 2006

Geoscience for a sustainable Earth

brgm

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Study carried out as part of
Research activities - BRGM 2006 PDR06ARN40

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Keywords:
Attenuation relation, ground-motion estimation equation, ground-motion model, strong-motion, accelerograms, summary, earthquakes, seismic hazard

In bibliography, this report should be cited as follows:
Douglas, J. (2006) – Errata of and additions to 'Ground motion estimation equations 1964-2003', BRGM/RP-54603-FR, 103 pages, 2 tables.

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 2004 and 2006 (some earlier studies are also included). This report updates the Imperial College London report of Douglas (2004) (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. 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 wrong 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 which 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 report of Douglas (2004) and this report summarise, in total, the characteristics of 207 ground-motion models [165 studies in Douglas (2004) and 42 in this report] for the prediction of peak ground acceleration and 128 models [100 studies in Douglas (2004) and 28 in this report] for the prediction of elastic response spectral ordinates.

Contents

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 equations. Since these two reports were released some further minor errors were found in 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, 2004).

Since the last version of the report was published at the beginning of 2004, errata have been published for Boore *et al.* (1994) (1997) (Boore, 2005), Spudich *et al.* (1999) (Spudich & Boore, 2005) and Campbell & Bozorgnia (2003d) (Campbell & Bozorgnia, 2003c). Only the errata for these studies are given below. In addition, the articles of Bozorgnia & Campbell (2004b) and Sigbjörnsson & Ambraseys (2003) [summarised in Douglas (2004)] have now been published. It was discovered that the study of Aydan *et al.* (1996) was also reported in Aydan (1997) [a modified version of this equation is reported in Aydan (2001)]. Also numerous new articles were published in 2004-2006 and a few earlier studies that had not been included in the earlier reports were discovered. This report, therefore, summarises these new studies in the style of the earlier reports in the format of a BRGM report. The provisional reports on the models developed within the PEER Lifelines Next Generation Attenuation project are not summarised here because these models have not yet been completely finalised. The report of Douglas (2004) and this report summarise, in total, the characteristics of 207 ground-motion models [165 studies in Douglas (2004) and 42 in this report] for the prediction of peak ground acceleration and 128 models [100 studies in Douglas (2004) and 28 in this report] for the prediction of elastic response spectral ordinates. With this many ground-motion estimation 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) suggests selection requirements to choose 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 & Martinez-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 and Bommer & Alarcon (2006) review published equations for predicting peak ground velocity.

2. Introduction

A number of reviews of attenuation studies have been made in the past which 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. Boore & Joyner (1982) provide a review of attenuation studies published in 1981 and 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 which are used for seismic design in Europe although they do not provide details about methods used. Recent reviews are Campbell (2003b) (2003a) and Bozorgnia & Campbell (2004a), which provide the coefficients for a number of commonly-used equations for peak ground acceleration and spectral ordinates.

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 which 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. 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 theoretical ground motions (stochastic source models etc.) (e.g. Atkinson & Boore, 1990) or those originally developed to yield the magnitude of an earthquake (e.g. Espinosa, 1980), i.e. the regression is performed the wrong way round, which should not be used for the prediction of ground motion at a site. Studies which derive graphs to give predictions (e.g. Schnabel & Seed, 1973) are not considered in this report nor are those nonparametric formulations which provide predictions for different combinations of distance and magnitude (e.g. Anderson, 1997), both of which are more difficult to use for seismic hazard analysis than those which give a single formula.

All the studies which 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.

In Tables 4.1 & 6.1 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, which 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. LOH ET AL. (1991)

- Ground motion model is:

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

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

- Use only data from rock sites.
- Focal depths, h, between 0.2 and 97.4 km. Most records from h<30 km.
- Also derive equations for PGA using $\log_{10}(a)=b_1+b_2+b_3\log\sqrt{(R^2+b_5^2)}$ and $a=b_1 e^{b_2 M}(R+b_4 e^{b_5 M})^{-b_3}$ in order to have diversity in the characterisation of ground motion.
- Use d_h because no clear fault ruptures identified for Taiwanese earthquakes.
- All data from SMA-1s.
- PGAs between 7.3 and 360.2 cms^{-2}.

3.2. BOORE *ET AL.* (1994), BOORE *ET AL.* (1997) AND BOORE (2005)

- See Sections 3.90 and 5.48 of Douglas (2004).
- Due to an error in Equation (3) of Boore *et al.* (1994) and Equation (6) of Boore *et al.* (1997) σ_c reported in Boore *et al.* (1994) (1997) are too large by a factor of $\sqrt{2}$. Therefore correct values of standard deviations are: σ_f=0.431, σ_c=0.160, σ_r=0.460, σ_s=0.184 and $\sigma \ln_Y$=0.495.

3.3. AMAN *ET AL.* (1995)

- Ground motion model is:

$$\log(a^{1/M}) = b_1 - b_3 \log(R)$$

where a is in cms^{-2}, b_1=0.433, b_3=0.073 and σ=0.037.

- Data from three earthquakes with M_B of 5.7, one of M_B of 5.8 and the other M_B of 7.2.
- Compare predicted and observed ground motions for 20/10/1991 Uttarkashi earthquake (M6.1) and find good fit.

3.4. INAN *ET AL.* (1996)

- Ground motion model is:

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

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

3.5. REYES (1998)

- Ground motion model is:

$$\ln \mathrm{Sa} = \alpha_1 + \alpha_2(M-6) + \alpha_3(M-6)^2 + \alpha_4 \ln R + \alpha_5 R$$

where *Sa* is in cms^{-2}, α_1=5.8929, α_2=1.2457, α_3=-9.7565×10^{-2}, α_4=-0.50, α_5=-6.3159×10^{-3} and σ=0.420.

- Use data from one station, University City (CU) in Mexico City, a relatively firm site.

3.6. SPUDICH *ET AL.* (1999) AND SPUDICH & BOORE (2005)

- See Sections 3.134 and 5.77 of Douglas (2004).
- Values of σ_3 (used to compute standard deviation for a randomly orientated component) reported in Spudich *et al.* (1999) are too large by a factor of √2.

3.7. FIELD (2000)

- Ground motion model is:

$$\mu(M, r_{\mathrm{jb}}, V_s) = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln[(r_{\mathrm{jb}}^2 + h^2)^{0.5}] + b_v \ln(V_s/V_a)$$

where $\mu(M,r_{jb},V_S)$ is natural logarithm of ground-motion parameter (e.g. ln(*PGA*) where *PGA* is in g), $b_{1,SS}$=0.853±0.28, $b_{1,rv}$=0.872±0.27, b_2=0.442±0.15, b_3=-0.067±0.16, b_5=-0.960±0.07, b_V=-0.154±0.14, h=8.90 km, V_a=760 ms^{-1}, σ=0.47±0.02 (intra-event) and τ=0.23 (inter-event). Also gives overall $\sigma=(0.93-0.10M_W)^{0.5}$ for $M_W \leq 7.0$ and overall σ=0.48 for M_W>7.0.

- Uses six site classes (from Wills *et al.* (2000)):

  B 760≤V_S≤1500 ms^{-1}. Uses V_S=1000 ms^{-1} in regression. 12 records.

  BC Boundary between B and C. Uses V_S=760 ms^{-1} in regression. 36 records.

  C 360≤V_S≤760 ms^{-1}. Uses V_S=560 ms^{-1} in regression. 16 records.

CD Boundary between C and D. Uses V_S=360 ms^{-1} in regression. 166 records.

D 180≤V_S≤360 ms^{-1}. Uses V_S=270 ms^{-1} in regression. 215 records.

DE Boundary between D and E. Uses V_S=180 ms^{-1} in regression. 2 records.

- Uses data from the SCEC Phase III strong-motion database.
- Uses three faulting mechanism classes:

  Use $b_{1,ss}$ Strike-slip. 14 earthquakes, 103 records.

  Use $b_{1,rv}$ Reverse. 6 earthquakes, 300 records.

  Use $0.5(b_{1,ss}+b_{1,rv})$ Oblique. 8 earthquakes, 46 records.

- Notes that data is unbalanced in that each earthquake has a different number of records for each site type hence it is important to correct observations for the inter-event terms before examining residuals for site effects.
- Plots average site class residuals w.r.t. BC category and the residuals predicted by equation and finds good match.
- Uses 197 records with basin-depth estimates (depth defined to the 2.5 kms^{-1} shear-wave velocity isosurface) to examine dependence of inter-event corrected residuals w.r.t. basin depth. Plots residuals against basin depth and fits linear function. Finds that all slopes are significantly different than zero by more than two sigmas. Finds a significant trend in subset of residuals where basin-depths are known w.r.t. magnitude hence needs to test whether basin-depth effect found is an artifact of something else. Hence derives ground-motion models (coefficients not reported) using only subset of data for which basin-depth estimates are known and examines residuals w.r.t. basin-depth for this subset. Finds similar trends as before hence concludes found basin effect is truly an effect of the basin. Notes that basin-depth coefficients should be derived simultaneously with other coefficients but because only a subset of sites have a value this could not be done.
- Tests for nonlinearity by plotting residuals for site class D w.r.t. predicted ground motion for BC boundary. Fits linear equation. Finds slope for PGA is significantly different than zero.
- Notes that due to large number of class D sites site nonlinearity could have affected other coefficients in equation leading to less of a trend in residuals. Tests for this by plotting residuals for site classes B and BC combined w.r.t. predicted ground motion for BC boundary. Fits linear equation. Finds non-significant slopes. Notes that nonlinearity may lead to rock ground motions being underestimated by model but not enough data to conclude.
- Investigates inter-event variability estimate through Monte Carlo simulations using 250 synthetic databases because uncertainty estimate of τ was considered unreliable possibly due to limited number of events. Find that there could be a problem with the regression methodology adopted w.r.t. the estimation of τ.

- Plots squared residuals w.r.t. magnitude and fits linear equations. Finds significant trends. Notes that method could be not statistically correct because squared residuals are not Gaussian distributed.
- Plots squared residuals w.r.t. V_S and does not find a significant trend.
- Provides magnitude-dependent estimates of overall σ up to M_W7.0 and constant overall σ for larger magnitudes.
- Tests normality of residuals using Kolmogorov-Smirnov test and finds that the null hypothesis cannot be rejected. Also examines theoretical quantile-quantile plots and finds nothing notable.

3.8. HERAK *ET AL.* (2001)

- Ground motion model is:

$$\log a_{\max} = c_1 + c_2 M_L + c_3 \log \sqrt{c_4^2 + D^2}$$

where a_{max} is in g, for horizontal PGA c_1=-1.300±0.192, c_2=0.331±0.040, c_3=-1.152±0.099, c_4=11.8±4.8 km and σ=0.311 and for vertical PGA c_1=-1.518±0.293, c_2=0.302±0.035, c_3=-1.061±0.096, c_4=11.0±5.5 and σ=0.313.

- Records from 39 sites. Records from instruments on ground floor or in basements of relatively small structures.
- Site information only available for a small portion of the recording sites and therefore is not considered. Believe that most sites are ‘rock’ or ‘stiff soil’.
- All records from Kinemetrics SMA-1s.
- Select records with M_L≥4.5 and D≤200 km because of poor reliability of SMA-1 records for small earthquakes and to avoid problems related to a possible change of geometrical spreading when surface waves start to dominate over body waves at large distances.
- Bandpass filter with passbands selected for which signal-to-noise ratio is >1. Widest passband is 0.07–25 Hz.
- Do not use d_f because do not accurately know causative fault geometry for majority of events.
- Do not include an anelastic decay term because data is inadequate to independently determine geometric and anelastic coefficients.
- Note correlation between magnitude and distance in data distribution therefore use two-stage regression. Because many earthquakes have only a few records data is divided into classes based on magnitude (details not given).
- Most data from M_L<5.5, particularly data from D<20 km.
- Find all coefficients significantly different than 0 at levels exceeding 0.999.
- Also regress using one-stage method and find practically equal coefficients and larger standard errors.

- Find residuals are approximately lognormally distributed with slight asymmetry showing longer tail on positive side. Relate this to site amplification at some stations balanced by larger than expected number of slightly negative residuals.
- Find no distance or magnitude dependence of residuals.
- Compute ratio between larger and average horizontal component as 1.15.
- Believe that higher than normal σ is due to lack of consideration of site effects and due to the use of d_e rather than d_f.

3.9. CAMPBELL & BOZORGNIA (2003D) (2003A) (2003B) (2003C)

- See Sections 3.164 and 5.99 of Douglas (2004).
- Corrected $f_5(HW,F,M_w,r_{seis})$ is:

$$f_5(\mathrm{HW}, F, M_w, r_{\mathrm{seis}}) = \mathrm{HW} f_{\mathrm{HW}}(M_w) f_{\mathrm{HW}}(r_{\mathrm{seis}})(F_{\mathrm{RV}} + F_{\mathrm{TH}})$$

3.10. SKARLATOUDIS *ET AL.* (2003)

- Ground motion model is:

$$\log Y = c_0 + c_1 M + c_2 \log(R^2 + h^2)^{1/2} + c_3 F + c_5 S$$

where Y is in cms^{-2}, c_0=0.86, c_1=0.45, c_2=-1.27, c_3=0.10, c_5=0.06 and σ=0.286.

- Use three site classes (from NEHRP):

  S=0 B: 19 stations plus 6 stations between A and B

  S=1 C: 68 stations

  S=2 D: 25 stations

No stations in NEHRP class A or E. Use geotechnical information where available and geological maps for the other stations.

- Focal depths, *h*, between 0.0 and 30.1 km.
- Classify earthquakes into three faulting mechanism classes:

  F=0 Normal, 101 earthquakes

  F=1 Strike-slip, 89 earthquakes

  F=1 Thrust, 35 earthquakes

but only retain two categories: normal and strike-slip/thrust. Classify using plunges of P and T axes and also knowledge of the geotectonic environment. Have fault-plane solutions for 67 earthquakes.

- Choose data that satisfies at least one of these criteria:
  - from earthquake with M_w≥4.5;
  - record has PGA ≥0.05 g, independent of magnitude;
  - record has PGA <0.05 g but at least one record from earthquake has PGA ≥0.05 g.

- Relocate all earthquakes.
- Redigitise all records using a standard procedure and bandpass filter using cut-offs chosen by a comparison of the Fourier amplitude spectrum (FAS) of the record to the FAS of the digitised fixed trace. Find that PGAs from uncorrected and filtered accelerograms are almost identical.
- Convert M_L to M_w, for earthquakes with no M_w, using a locally derived linear equation.
- Most data from earthquakes with M_w<6 and d_h<60 km.
- Note correlation in data between M_w and d_h.
- Note lack of near-field data (R<20 km) for M_w>6.0.
- Plot estimated distance at which instruments would not be expected to trigger and find that all data lie within the acceptable distance range for mean trigger level and only 14 records fall outside the distance range for trigger level plus one σ. Try excluding these records and find no effect. Hence conclude that record truncation would not affect results.
- Use an optimization procedure based on the least-squares technique using singular value decomposition because two-step methods always give less precise results than one-step techniques. Adopted method allows the controlling of stability of optimization and accurate determination and analysis of errors in solution. Also method expected to overcome and quantify problems arising from correlation between magnitude and distance.
- Test assumption that site coefficient for site class D is twice that for C by deriving equations with two site terms: one for C and one for D. Find that the site coefficient for D is roughly twice that of site coefficient for C.
- Test effect of focal mechanism by including two coefficients to model difference between normal, strike-slip and thrust motions. Find that the coefficients for difference between strike-slip and normal and between thrust and normal are almost equal. Hence combine strike-slip and thrust categories.
- Try including quadratic M term but find inadmissible (positive) value due to lack of data from large magnitude events.
- Also derive equations using this functional form: $\log Y=c_0+c_1M+c_2\log(R+c_4)+c_3F+c_5S$ where c_4 was constrained to 6 km from an earlier study due to problems in deriving reliable values of c_2 and c_4 directly by regression.
- Plot observed data scaled to M_w6.5 against predictions and find good fit.
- Find no systematic variations in residuals w.r.t. remaining variables.
- Find reduction in σ w.r.t. earlier studies. Relate this to better locations and site classifications.

3.11. BRAGATO (2004)

- Ground motion model is:

$$\log_{10}(y) = a + (b + cm)m + (d + em)\log_{10}(\sqrt{r^2 + h^2})$$

where y is in g, a=0.46, b=0.35, c=0.07, d=-4.79, e=0.60, h=8.9 km and σ=0.33.

- Investigates effect of nontriggering stations on derivation of empirical ground-motion model based on the assumption that the triggering level is known (or can be estimated from data) but do not know which stations triggered (called left truncated data).
- Develops mathematical theory and computational method (after trying various alternative methods) for truncated regression analysis (TRA) and randomly truncated regression analysis (RTRA) (where triggering level changes with time).
- Tests developed methods on 1000 lognormally-distributed synthetic data points simulated using the equation of Ambraseys *et al.* (1996) for $4 \leq M_S \leq 7$ and $1 \leq d_f \leq 100$ km. A fixed triggering threshold of 0.02 g is imposed. Regresses remaining 908 samples using TRA and RTRA. Finds a very similar equation using TRA but large differences for $d_f>20$ km by using standard regression analysis (SRA) due to slower attenuation. Also apply TRA to randomly truncated synthetic data and find a close match to original curve, which is not found using SRA.
- Applies method to 189 records from rock sites downloaded from ISESD with M>4.5 (scale not specified) and d<80 km (scale not specified) using functional form: $\log_{10}(y)=a+bm+c\log_{10}(\sqrt{(r^2+h^2)})$. Uses these selection criteria to allow use of simple functional form and to avoid complications due to crustal reflections that reduce attenuation. Discards the five points with PGA <0.01 g (assumed threshold of SMA-1s). Applies TRA and SRA. Finds both M-scaling and distance attenuation are larger with TRA than with SRA because TRA accounts for larger spread in original (not truncated) data. Differences are relevant for M<6 and d>20 km.
- Applies method to dataset including, in addition, non-rock records (456 in total). Finds no differences between TRA and SRA results. Believes that this is due to lack of data in range possibly affected by truncation (small M and large d). Finds similar results to Ambraseys *et al.* (1996).
- Applies method to NE Italian data from seven seismometric and ten accelerometric digital stations assuming: $\log_{10}(y)=a+bm+c\log_{10}(\sqrt{(r^2+h^2)})$. Accelerometric stations used usually trigger at 0.001 g. Seismometric stations used trigger based on ratio of short-term and long-term averages (STA/LTA), which varies from station to station and acts like a random threshold. Firstly neglects randomness and assumes trigger level of each station equals lowest recorded PGA and applies TRA and SRA. Finds small differences for d<8 km and d>30 km.
- Applies method using functional form above, which believes is more physically justified. SRA does not converge. Studies reason for this by regressing on data from M intervals of 0.3 units wide. Finds behaviour of PGAs inverts for M<3.

Finds increasing σ with decreasing M for M>3. TRA does converge and shows stronger magnitude saturation than SRA.

- Notes that application of RTRA to model effect of STA/LTA for used data is not realistic since probably not enough data to constrain all 23 parameters and to computational expensive using adopted maximization technique for RTRA.
- Estimates the random truncation parameters for one station (Zoufplan) and finds that the fixed threshold assumption made is acceptable since estimated random truncation parameters predict that only 14% of observations are lost at the earlier assumed fixed threshold level (the lowest PGA recorded).

3.12. GUPTA & GUPTA (2004)

- Ground motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln R_h + C_4 R_h + C_5 v$$

where PGA is in g, C_1=-7.515, C_2=1.049, C_3=-0.105, C_4=-0.0211, C_5=-0.287 and σ=0.511. v=0 for horizontal PGA and 1 for vertical PGA.

- Data from basalt sites (7 stations), thick hard lateritic soil underlain by basalt (1 station) and dam galleries (4 stations).
- Data from 13-station strong-motion network (AR-240 and RFT-250 instrument types) close to Koyna Dam. Exclude data from dam top. Use data from foundation gallery because believe they can be considered as ground acceleration data. Select set of 31 significant records after scrutinizing all data.
- Correct for instrument response and filter using cut-off frequencies based on a signal-to-noise ratio >1.
- Use a 2-stage regression method. Firstly, find C_1, C_2 and C_5 (magnitude and component dependencies) and then find updated C_1, C_3 and C_4 (distance dependence) using residuals from first stage.
- Find that equation matches the observed data quite well.

3.13. KALKAN & GÜLKAN (2004A)

- Ground motion model is:

$$\begin{aligned} \ln Y_V &= C_1 + C_2(M-6) + C_3(M-6)^2 + C_4(M-6)^3 + C_5 \ln r + C_6\Gamma_1 + C_7\Gamma_2 \\ r &= (r_{cl}^2 + h^2)^{1/2} \end{aligned}$$

where Y is in g, C_1=0.055, C_2=0.387, C_3=-0.006, C_4=0.041, C_5=-0.944, C_6=0.277, C_7=0.030, h=7.72 km, σ_{rock}=0.629, σ_{soil}=0.607 and $\sigma_{softsoil}$=0.575.

- Use three site classes:

  Γ_1=0, Γ_2=0   Rock: average V_s=700 ms^{-1}, 27 records

  Γ_1=1, Γ_2=0   Soil: average V_s=400 ms^{-1}, 26 records

Γ_1=0, Γ_2=1 Soft soil: average V_s=200 ms^{-1}, 47 records

Classify using approximate methods due to lack of available information. Note that correspondence between average V_s values for each site class and more widely accepted soil categories is tenuous.

- Focal depths from 0 to 111.0 km. State that all earthquakes were shallow crustal events. Only 4 records come from earthquakes with reported focal depths >33 km.
- Expand with data from after 1999 and update database of Gülkan & Kalkan (2002).
- Faulting mechanism distribution is: normal (12 earthquakes, 14 records), strike-slip (33 earthquakes, 81 records) and reverse (2 earthquakes, 5 records). Note that poor distribution w.r.t. mechanism does not allow its effect to be modelled.
- Use only records from earthquakes with M_w≥4.5 to emphasize motions having greatest engineering interest and to include only more reliably recorded events. Include data from one M_w4.2 earthquake because of high vertical acceleration (31 *mg*) recorded.
- Data reasonably well distribution w.r.t. *M* and *d* for *d*<100 *km*.
- Data mainly recorded in small and medium-sized buildings ≤3 storeys. Note that these buildings modify recorded motions and this is an unavoidable uncertainty of the study.
- Data from main shocks. Exclude data from aftershocks, in particular that from the 1999 Kocaeli and Düzce aftershocks because these records are from free-field stations, which do not want to commingle with non-free-field data.
- Exclude a few records for which PGA caused by main shock is <10 mg. Exclude data from aftershocks from the same stations.
- Note that data used is of varying quality and could be affected by errors.
- Include cubic term for *M* dependence to compensate for the controversial effects of sparsity of Turkish data. Find that it gives a better fit.
- Use two-step method of Ambraseys *et al.* (1996) to find site coefficients C_6 and C_7 after exploratory analysis to find regression method that gives the best estimates and the lowest σ.
- State equations can be used for 4.5≤M_w≤7.4 and d_f≤200 km.
- Find no significant trends in residuals w.r.t. *M* or *d* for all data and for each site category except for a few high residuals for soil and soft soil records at d_f>100 *km*.
- Compute individual σs for each site class.
- Find that observed ground motions for the Kocaeli earthquake are well predicted.

3.14. KALKAN & GÜLKAN (2004B) AND KALKAN & GÜLKAN (2005)

- Ground motion model is:

$$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln(V_S/V_A)$$
$$r = (r_{cl}^2 + h^2)^{1/2}$$

where Y is in g, b_1=0.393, b_2=0.576, b_3=-0.107, b_5=-0.899, b_V=-0.200, V_A=1112 ms^{-1}, h=6.91 km and σ=0.612.

- Use three site classes:

Rock	Average V_S=700 ms^{-1}, 23 records
Soil	Average V_S=400 ms^{-1}, 41 records
Soft soil	Average V_S=200 ms^{-1}, 48 records

  Use V_S measurements where available (10 stations, 22 records) but mainly classify using approximate methods. Note that correspondence between average V_S values for each site class and more widely accepted soil categories is tenuous.
- Focal depths from 0 to 111.0 km. State that all earthquakes were shallow crustal events. Only 4 records come from earthquakes with reported focal depths >33 km.
- Expand with data from after 1999 and update database of Gülkan & Kalkan (2002).
- Faulting mechanism distribution is: normal (12 earthquakes, 14 records), strike-slip (34 earthquakes, 82 records), reverse (2 earthquakes, 5 records), unknown (9 earthquakes, 11 records). Note that poor distribution w.r.t. mechanism does not allow its effect to be modelled.
- Use only records from earthquakes with $M_W \geq 4.0$ to include only more reliably recorded events.
- Data reasonably well distribution w.r.t. M and d for d<100 km.
- Data from main shocks. Exclude data from aftershocks, in particular that from the 1999 Kocaeli and Düzce aftershocks because of high nonlinear soil behaviour observed during the mainshocks near the recording stations.
- Data mainly recorded in small and medium-sized buildings ≤3 storeys. Note that these buildings modify recorded motions and this is an unavoidable uncertainty of the study.
- State equations can be used for $4.0 \leq M_W \leq 7.5$ and $d_f \leq 250$ km.
- Find no significant trends in residuals w.r.t. M or d for all data and for each site category.
- Find that observed ground motions for the Kocaeli earthquake are well predicted.

3.15. LUBKOWSKI *ET AL.* (2004)

- Ground motion model is not reported. Use six functional forms.

- Use four site categories:

  Very soft soil $V_{s,30}$<180 ms^{-1}. 0 records.

  Soft soil 180≤$V_{s,30}$<360 ms^{-1}. 1 record.

  Stiff soil 360≤$V_{s,30}$<750 ms^{-1}. 34 records.

  Rock $V_{s,30}$≥750 ms^{-1}. 93 records.

Site conditions are unknown for 35 records. Classify mainly using description of local site conditions owing to unavailability of V_s measurements.

- Exclude data from M_w<3.0 to exclude data from earthquakes that are likely to be associated with large uncertainties in their size and location and because ground motions from smaller earthquakes are likely to be of no engineering significance.
- Exclude data from multi-storey buildings, on or in dams or on bridges.
- Most data from M_w<5.5 so believe use of d_e is justified.
- Records from: eastern N America (78 records), NW Europe (61 including 6 from UK) and Australia (24).
- Locations from special studies, ISC/NEIC or local network determinations.
- Note distinct lack of data from <10 km for M_w>5.
- Only retain good quality strong-motion data. No instrument correction applied because of the lack of instrument characteristics for some records. Individually bandpass filter each record with a Butterworth filter with cut-offs at 25 Hz and cut-off frequencies chosen by examination of signal-to-noise ratio and integrated velocity and displacement traces.
- Find use of different functional forms has significant influence on predicted PGA.
- Regression on only rock data generally reduced PGA.
- Predictions using the functional forms with quadratic M-dependence were unreliable for M_w>5.5 because they predict decrease PGA with increasing M since there was insufficient data from large magnitude earthquakes to constrain the predictions.
- Find different regression methods predict similar PGAs with differences of <5% for a M_w5 event at 5 km when all records were used but differences up to 63% when using only rock data. Prefer the one-stage maximum-likelihood method since allows for correlation between M and d in dataset and does not ignore earthquakes recorded by only a single station (25% of data).
- Find, from analysis of residuals, that equation generally underpredicts PGA of data from eastern N America and Australia but overpredicts motions from Europe and UK.
- Find no trends in residuals w.r.t. amplitude, distance, magnitude or fault mechanism.

- Believe that large σs found are due to: lack of data from close to large magnitude earthquakes, use of data from different regions with varying source and path characteristics and use of much data from small earthquakes that are probably associated with higher uncertainty w.r.t. magnitude and location since such earthquakes have not been as well studied as large earthquakes and there is a lack of data with high signal-to-noise ratio from which relocations can be made.
- Do not recommend equations for practical use due to large uncertainties.

3.16. MARIN *ET AL.* (2004)

- Ground motion model is:

$$\log_{10} \mathrm{PGA} = a_1 + a_2 M_L + a_3 \log_{10} R$$

where *PGA* is in *g*, a_1=-3.93, a_2=0.78, a_3=-1.5 and σ=0.55.

- All records from stiff bedrock. Shear-wave velocities estimated from geology gives: 1200–2000 ms^{-1} for carbonated formations and >2500 ms^{-1} for eruptive formations (majority of data).
- Derive equation since find previous equations are not consistent with recent data recorded in France and because of differences between M_L of LDG and other M_L scales.
- Use data from the Alps, the Pyrenees and Armorican Massif recorded by LDG network of vertical seismometers between 1995 and 1996. Convert vertical PGAs to horizontal PGAs using empirical relation of Smit (1998).
- Focal depths between 2 and 12 km.
- 11 records from $3 \leq d_e \leq 50$ km, 34 from $50 < d_e \leq 200$ km and 18 from $d_e > 200$ km (all from two largest earthquakes with M_L5.3 and M_L5.6).
- Plot predictions and data from rock sites of all French earthquakes with $M_L \geq 4$ recorded by RAP network (largest three earthquakes have M_L5.5, M_L5.7 and M_L5.9) and find good agreement. State that this agreement shows that equation can be extrapolated to strongest earthquakes considered for France.
- Note that it will be possible to establish a more robust equation using increasing number of data from RAP, especially from near field and large magnitudes.

3.17. MIDORIKAWA & OHTAKE (2004)

- Ground motion models are:

$$\log A = b - \log(X + c) - kX \quad \text{for } D \leq 30\,\text{km}$$
$$\log A = b + 0.6\log(1.7D + c) - 1.6\log(X + c) - kX \quad \text{for } D > 30\,\text{km}$$
$$\text{where} \quad b = aM_w + hD + d_iS_i + e$$

where A is in gal, a=0.59, c=0.0060×$10^{0.5M_w}$ [adopted from Si & Midorikawa (2000)], d_1=0.00 (for crustal earthquakes), d_2=0.08 (for inter-plate earthquakes), d_3=0.30 (for intra-plate earthquakes), e=0.02, h=0.0023, k=0.003 [adopted from Si & Midorikawa (2000)], $\sigma_{intra\text{-}event}$=0.27 and $\sigma_{inter\text{-}event}$=0.16.

- Use two site categories [definitions of Joyner & Boore (1981)]:
  - Rock
  - Soil

Use $V_{s,30}$ where available. Multiply PGA values from rock sites by 1.4 to normalise them w.r.t. PGA at soil sites.

- All records from the free-field or small buildings where soil-structure interaction is negligible.
- Data from different types of instruments hence instrument correct and bandpass filter.
- Classify earthquakes into these three types:
  - S_1=1, S_2=S_3=0 Crustal. 12 earthquakes, 1255 records. Focal depths, D, between 3 and 30 km.
  - S_2=1, S_1=S_3=0 Inter-plate. 10 earthquakes, 640 records. 6≤D≤49 km.
  - S_3=1, S_1=S_2=0 Intra-plate, 11 earthquakes, 1440 records. 30≤D≤120 km.
- Most data from M_w<7. No data between 6.9 and 7.6.
- Use separate functional forms for D≤30 km and D>30 km because of significantly faster decay for deeper earthquakes.
- Plot histograms of residuals and conclude that they are lognormally distributed.
- Compute σ for 4 M ranges: 5.5–5.9, 6.0–6.5, 6.6–6.9 and 7.6–8.3. Find slight decrease in σ w.r.t. M.
- Compute σ for ranges of 20 km. Find significantly smaller σs for distances <50 km and almost constant σs for longer distances.
- Compute σ for ranges of PGA of roughly 50 km. Find much larger σs for small PGA than for large PGA.
- Believe that main cause of M-dependent σ is that stress-drop is M-dependent and that radiation pattern and directivity are not likely to be significant causes.
- Believe that distance-dependent σ is likely to be due to randomness of propagation path (velocity and Q-structure).
- Believe site effects do not contribute greatly to the variance.
- Plot PGA versus distance and observe a saturation at several hundred cms^{-2}, which suggest may be due to nonlinear soil behaviour.

- Plot σ w.r.t. PGA for three site categories: $100 \leq V_{s,30} \leq 300$ ms^{-1}, $300 \leq V_{s,30} \leq 600$ ms^{-1} and $600 \leq V_{s,30} \leq 2600$ ms^{-1}. Find σ lower for soft soils than for stiff soils, which believe may demonstrate that nonlinear soil response is a cause of PGA-dependent σ.
- Note that because inter-event σ is significantly smaller than intra-event σ, source effects are unlikely to be the main cause for observed σ dependencies.

3.18. ÖZBEY *ET AL.* (2004)

- Ground motion model is:

$$\log(Y) = a + b(M-6) + c(M-6)^2 + d \log \sqrt{R^2 + h^2} + eG_1 + fG_2$$

where Y is in cms^{-2}, a=3.287, b=0.503, c=-0.079, d=-1.1177, e=0.141, f=0.331, h=14.82 km and σ=0.260.

- Use three site classes:

  G_1=0, G_2=0 A: shear-wave velocity >750 ms^{-1}, 4 records, and B: shear-wave velocity 360–750 ms^{-1}, 20 records.

  G_1=1, G_2=0 C: shear-wave velocity 180–360 ms^{-1}, 35 records.

  G_1=0, G_2=1 D: shear-wave velocity <180 ms^{-1}, 136 records.

Originally A and B were separate but combine due to lack of data for site class A.

- Focal depths between 5.4 and 25.0 km.
- Use M_w for M>6 to avoid saturation effects.
- Assume $M_L = M_w$ for $M \leq 6$.
- Select records from earthquakes with $M \geq 5.0$.
- Most (15 earthquakes, 146 records) data from earthquakes with $M \leq 5.8$.
- Only use data from the Earthquake Research Department of General Directorate of Disaster Affairs from $d_f \leq 100$ km.
- Exclude record from Bolu because of possible instrument error.
- Use mixed effects model to account for both inter-event and intra-event variability.
- Find that the mixed effects model yields σs lower than fixed effects model.
- Compare predictions with observed data from the Kocaeli and Düzce earthquakes and find reasonable fit.
- Plot coefficients and σs against frequency and find dependence on frequency.
- Plot inter-event and intra-event residuals against distance and magnitude and find not systematic trends.

- Find intra-event residuals are significantly larger than inter-event residuals. Suggest that this is because any individual event's recordings used to develop model follow similar trends with associated parameters.
- Recommend that equations are only used for ground-motion estimation in NW Turkey.

3.19. PANKOW & PECHMANN (2004) AND PANKOW & PECHMANN (2006)

- Ground motion model is:

$$\begin{aligned}\log_{10}(Z) &= b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \log_{10} D + b_6\Gamma \\ D &= (r_{jb}^2 + h^2)^{1/2}\end{aligned}$$

where Z is in g, b_1=0.237, b_2=0.229, b_3=0, b_5=-1.052, b_6=0.174, h=7.27 km and $\sigma\log_Z$=0.203 (see Spudich & Boore (2005) for correct value of σ_3 for use in calculating σ for randomly-orientated component).

- Use two site classes:

  Γ=0 Rock: sites with soil depths of <5 m.

  Γ=1 Soil

- Use data of Spudich *et al.* (1999).
- Correct equations of Spudich *et al.* (1999) for 20% overprediction of motions for rock sites, which was due either to underestimation of shear-wave velocities for rock sites for extensional regimes (believed to be more likely) or an overestimation of shear-wave velocities at soil sites. Correction based on adjusting b_1 and b_6 to eliminate bias in rock estimates but leave soil estimates unchanged.
- Verify that adjustment reduces bias in rock estimates.
- Do not change $\sigma\log_Z$ because changes to b_1 and b_6 have a negligible influence on $\sigma\log_Z$ w.r.t. errors in determining $\sigma\log_Z$.

3.20. SUNUWAR *ET AL.* (2004)

- Ground motion model is:

$$\log Y(T) = b_1(T) + b_2(T)M_J - b_3(T)D - b_4(T)\log(R)$$

where $Y(T)$ is in cms^{-2}, $b_1(0)$=1.1064, $b_2(0)$=0.2830, $b_3(0)$=0.0076, $b_4(0)$=0.6322 and σ=0.303 for horizontal PGA and $b_1(0)$=0.7134, $b_2(0)$=0.3091, $b_3(0)$=0.0069, $b_4(0)$=0.7421 and σ=0.301 for vertical PGA.

- Records from 225 stations of K-Net network with $39.29 \le V_{s,30} \le 760.25$ ms^{-1} (mean $V_{s,30}$=330.80 ms^{-1}).
- Select earthquakes that occurred within the region of the boundary of the Okhotsk-Amur plates (NE Japan bordering Sea of Japan) defined by its

horizontal location and vertically, to exclude earthquakes occurring in other plates or along other boundaries.

- Focal depths, D, between 8 and 43 km with mean depth of 20.8 km.
- Mean value of M is 4.72.
- Mean d_e is 84.67 km.
- State that exclude records with PGA <5 cms^{-2} (although ranges of PGAs given include records with PGA <5 cms^{-2}).
- Horizontal PGA range: 4.15–411.56 cms^{-2}. Vertical PGA range: 0.50–163.11 cms^{-2}.
- Originally use this form: $\log Y(T)=b_1(T)+b_2(T)M-b_3(T)D-\log(R)+b_5(T)R$ but find $b_5(T)>0$. Regress using the 379 records from sites with $V_{s,30}>300$ ms^{-1} and still find $b_5(T)>0$ but report results for investigating site effects.
- Plot residuals w.r.t. d_h and find mean of residuals is zero but find some high residuals.
- Note that need to refine model to consider site effects.

3.21. SKARLATOUDIS *ET AL.* (2004)

- Ground motion model is:

$$\log Y = c_0 + c_1 M + c_2 \log(R^2 + h^2)^{1/2}$$

where Y is in cms^{-2}, c_0=1.03, c_1=0.32, c_2=-1.11, h=7 km and σ=0.34.

- Classify stations into four NEHRP categories: A, B, C and D (through a site coefficient, c_4) but find practically no effect so neglect.
- Aim to investigate scaling of ground motions for small magnitude earthquakes.
- Most earthquakes have normal mechanisms from aftershock sequences.
- Records from permanent and temporary stations of ITSAK network. Many from EuroSeisTest array.
- Records from ETNA, K2, SSA-1 and SSA-2 plus very few SMA-1 instruments.
- Filter records based on a consideration of signal-to-noise ratio. For digital records use these roll-off and cut-off frequencies based on magnitude (after studying frequency content of records and applying different bandpass filters): for $2\leq M_W<3$ f_r=0.95 Hz and f_c=1.0 Hz, for $3\leq M_W<4$ f_r=0.65 Hz and f_c=0.7 Hz and for $4\leq M_W<5$ f_r=0.35 and f_c=0.4 Hz. Find that this method adequately removes the noise from the accelerograms used.
- Use source parameters computed from high-quality data from local networks. Note that because focal parameters are from different institutes who use different location techniques may mean data set is inhomogeneous.

- Note that errors in phase picking in routine location procedures may lead to less accurate locations (especially focal depths) for small earthquakes as opposed to large earthquakes due to indistinct first arrivals.
- To minimize effects of focal parameter uncertainties, fix h as 7 km, which corresponds to average focal depth in Greece and also within dataset used.
- Exclude data from d_e>40 km because only a few (3% of total) records exist for these distances and also to exclude far-field records that are not of interest.
- Most records from d_e<20 km and $2.5 \le M_w \le 4.5$.
- Also derive equations using this functional form: $\log Y = c_0 + c_1 M + c_2 \log(R + c_3)$ where c_3 was constrained to 6 km from an earlier study due to problems in deriving reliable values of c_2 and c_3 directly by regression.
- Use singular value decomposition for regression following Skarlatoudis *et al.* (2003).
- Combined dataset with dataset of Skarlatoudis *et al.* (2003) and regress. Find significant number of data outside the $\pm 1\sigma$ curves. Also plot average residual at each M w.r.t. M and find systematically underestimation of PGA for $M_w \ge 5$. Conclude that this shows the insufficiency of a common relation to describe both datasets.
- Find no trends in the residuals w.r.t. magnitude or distance.
- Find that the predominant frequencies of PGAs are <15 Hz so believe results not affected by low-pass filtering at 25–27 Hz.

3.22. ULUSAY *ET AL.* (2004)

- Ground motion model is:

$$\mathrm{PGA} = a_1 e^{a_2(a_3 M_w - R_e + a_4 S_A + a_5 S_B)}$$

where PGA is in gal, a_1=2.18, a_2=0.0218, a_3=33.3, a_4=7.8427, a_5=18.9282 and σ=86.4 (note that this σ is additive).

- Use three site categories:

S_A=0, S_B=0	Rock, 55 records.
S_A=1, S_B=0	Soil, 94 records.
S_A=0, S_B=1	Soft soil, 72 records.

Classify by adopting those given by other authors, selecting the class reported by more than one source.

- Most data from instruments in small buildings.
- Use records with PGA >20 gal to avoid bias due to triggering.
- PGAs of records between 20 and 806 gal.
- Use records from earthquakes with $M_w \ge 4$ because smaller earthquakes are generally not of engineering significance.

- Derive linear conversion formulae (correlation coefficients >0.9) to transform M_s (39), m_b (18), M_d (10) and M_L (6) to M_w (73 events in total).
- Note that rupture surfaces have not been accurately defined for most events therefore use d_e.
- Note that accurate focal depths are often difficult to obtain and different data sources provide different estimates therefore do not use d_h.
- Use records from ≥5 km because of assumed average error in epicentral locations.
- Use records from ≤100 km because this is the distance range where engineering significant ground motions occur.
- Most data from $M_w \leq 6$ and $d_e \leq 50$ km.
- Do not consider faulting mechanism because focal mechanism solutions for most earthquakes not available.
- Plot observed versus predicted PGA and find that a few points fall above and below the lines with slopes 1:0.5 and 1:2 but most are between these lines.
- Note that to improve precision of equation site characterisation based on V_s measurements should be included. Also note that directivity, fault type and hanging wall effects should be considered when sufficient data is available.

3.23. AMBRASEYS *ET AL.* (2005A)

- Ground motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 M_w) \log \sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

where y is in ms^{-2}, a_1=2.522, a_2=-0.142, a_3=-3.184, a_4=0.314, a_5=7.6, a_6=0.137, a_7=0.050, a_8=-0.084, a_9=0.062, a_{10}=-0.044, σ_1=0.665-0.065M_w (intra-event) and σ_2=0.222-0.022M_w (inter-event).

- Use three site categories:

S_S=1, S_A=0	Soft soil (S), 180<$V_{s,30}$≤360 ms^{-1}. 143 records.
S_S=0, S_A=1	Stiff soil (A), 360<$V_{s,30}$≤750 ms^{-1}. 238 records.
S_S=0, S_A=0	Rock (R), $V_{s,30}$>750 ms^{-1}. 203 records.

Originally include a fourth category, very soft soil ($V_{s,30}$≤180 ms^{-1}), but only included 11 records so combined with soft soil records. Note that measured $V_{s,30}$ only exist for 89 of 338 stations contributing 161 records so use descriptions of local site conditions to classify stations. Exclude records from stations with unknown site conditions because could not be handled by chosen regression method.

- Use only data from Europe and Middle East because believe their databank is reasonably complete for moderate and large earthquakes that occurred in region. Also these data have been carefully reviewed in previous studies. Finally based on a previous study believe motions in California could be significantly higher than those in Europe. Note that including these data would increase the quantity of high-quality near-source data available.
- Combine data from all seismically active parts of Europe and the Middle East into a common dataset because a previous study shows little evidence for regional differences between ground motions in different regions of Europe.
- Only use earthquakes with a M_0 estimate for which to calculate M_w. Do not convert magnitudes from other scales because this increases the uncertainty in the magnitude estimates. Exclude records from earthquakes with M_w<5 in order to have a good distribution of records at all magnitudes. Note that this also excludes records from small earthquakes that are unlikely to be of engineering significance.
- Use d_f because does not require a depth estimate, which can be associated with a large error.
- Exclude records from >100 km because: excludes records likely to be of low engineering significance, reduces possible bias due to non-triggering instruments, reduces effect of differences in anelastic decay in different regions and it gives a reasonably uniform distribution w.r.t. magnitude and distance, which reduces likelihood of problems in regression analysis.
- Use only earthquakes with published focal mechanism in terms of trends and plunges of T, B and P axes because estimating faulting type based on regional tectonics or to be the same as the associated mainshock can lead to incorrect classification. Classify earthquakes using method of Frohlich & Apperson (1992):

  Thrust Plunge of T axis >50°. 26 earthquakes, 91 records, F_T=1, F_N=0, F_O=0.

  Normal Plunge of P axis >60°. 38 earthquakes, 191 records, F_T=0, F_N=1, F_O=0.

  Strike-slip Plunge of B axis >60°. 37 earthquakes, 160 records, F_T=0, F_N=0, F_O=0.

  Odd All other earthquakes. 34 earthquakes, 153 records, F_T=0, F_N=0, F_O=1.

Use this method because does not require knowledge of which plane is the main plane and which the auxiliary.

- Do not exclude records from ground floors or basements of large buildings because of limited data.
- Exclude records from instruments that triggered late and those that were poorly digitised.

- Instrument correct records and then apply a low-pass filter with roll-off and cut-off frequencies of 23 and 25 Hz for records from analogue instruments and 50 and 100 Hz for records from digital instruments. Select cut-off frequencies for high-pass bidirectional Butterworth filtering based on estimated signal-to-noise ratio and also by examining displacement trace. For records from digital instruments use pre-event portion of records as noise estimate. For those records from analogue instruments with an associated digitised fixed trace these were used to estimate the cut-offs. For records from analogue instruments without a fixed trace examine Fourier amplitude spectrum and choose the cut-offs based on where the spectral amplitudes do not tend to zero at low frequencies. Note that there is still some subjective in the process. Next choose a common cut-off frequency for all three components. Use a few records from former Yugoslavia that were only available in corrected form.
- Only use records with three usable components in order that ground-motion estimates are unbiased and that mutually consistent horizontal and vertical equations could be derived.
- Note lack of data from large (M_w>6.5) earthquakes particularly from normal and strike-slip earthquakes.
- Data from: Italy (174 records), Turkey (128), Greece (112), Iceland (69), Albania (1), Algeria (3), Armenia (7), Bosnia & Herzegovina (4), Croatia (1), Cyprus (4), Georgia (14), Iran (17), Israel (5), Macedonia (1), Portugal (4), Serbia & Montenegro (24), Slovenia (15), Spain (6), Syria (5) and Uzbekistan (1).
- Note that much strong-motion data could not be used due to lack of local site information.
- Select one-stage maximum-likelihood regression method because accounts for correlation between ground motion from same earthquake whereas ordinary one-stage method does not. Note that because there is little correlation between M_w and distance in the data used (correlation coefficient of 0.23) ordinary one-stage and one-stage maximum-likelihood methods give similar coefficients. Do not use two-stage maximum-likelihood method because underestimates σ for sets with many singly-recorded earthquakes (35 earthquakes were only recorded by one station). Do not use method that accounts for correlation between records from same site because records are used from too many different stations and consequently method is unlikely to lead to an accurate estimate of the site-to-site variability (196 stations contribute a single record). Do not use methods that account for uncertainty in magnitude determination because assume all magnitude estimates are associated with the same uncertainty since all M_w are derived from published M_0 values.
- Apply pure error analysis of Douglas & Smit (2001). Divide dataspace into $0.2M_w$ units by 2 km intervals and compute mean and unbiased standard deviation of untransformed ground motion in each bin. Fit a linear equation to graphs of coefficient of variation against ground motion and test if slope of line is significantly different (at 5% significance level) than zero. If it is not then the

logarithmic transformation is justified. Find that slope of line is not significantly different than zero so adopt logarithmic transformation of ground motion.

- Use pure error analysis to compute mean and unbiased standard deviation of logarithmically transformed ground motion in each $0.2M_W \times 2$ km bin. Plot the standard deviations against M_W and fit linear equation. Test significance (5% level) of slope. Find that it is significantly different than zero and hence magnitude-independent standard deviation is not justified. Use the reciprocals of fitted linear equations as weighting functions for regression analysis.
- Using the standard deviations computed by pure error analysis for each bin estimate lowest possible σ for derived equations.
- Investigate possible magnitude-dependence of decay rate of ground motions using ten best-recorded earthquakes (total number of records between 13 and 26). Fit PGAs for each earthquake with equation of form: $\log y = a_1 + a_2 \log\sqrt{(d^2 + a_3^2)}$. Plot decay rates ($a_2$) against M_W and fit a linear equation. Find that the fitted line has a significant slope and hence conclude that data supports a magnitude-dependent decay rate. Assume a linear dependence between decay rate and M_W due to limited data.
- Try including a quadratic magnitude term in order to model possible differences in scaling of ground motions for earthquakes that rupture entire seismogenic zone. Find that term is not significant at 5% level so drop.
- Could not simultaneously find negative geometric and anelastic decay coefficients so assume decay attributable to anelastic decay is incorporated into geometric decay coefficient.
- Test significance of all coefficients at 5% level. Retain coefficients even if not significant.
- Note that there is not enough data to model possible distance dependence in effect of faulting mechanism or nonlinear soil effects.
- Compute median amplification factor (anti-logarithm of mean residual) for the 16 stations that have recorded more than five earthquakes. Find that some stations show large amplifications or large deamplifications due to strong site effects.
- Compute median amplification factor for the ten best recorded earthquakes. Find that most earthquakes do not show significant overall differences but that a few earthquakes do display consistently lower or higher ground motions.
- Plot residual plots w.r.t. weighted M_W and weighted distance and find no obvious dependence of scatter on magnitude or distance.
- Plot histograms of binned residuals.
- Compare predicted and observed PGAs from the 2004 Parkfield earthquake and find a close match. Note that this may mean that the exclusion of data from California based on possible differences in ground motions was not justified.

3.24. AMBRASEYS *ET AL.* (2005B)

- Ground motion model is:

$$\log y = a_1 + a_2 M_w + (a_3 + a_4 M_w)\log\sqrt{d^2 + a_5^2} + a_6 S_S + a_7 S_A + a_8 F_N + a_9 F_T + a_{10} F_O$$

where y is in ms^{-2}, a_1=0.835, a_2=0.083, a_3=-2.489, a_4=0.206, a_5=5.6, a_6=0.078, a_7=0.046, a_8=-0.126, a_9=0.005, a_{10}=-0.082, σ_1=0.262 (intra-event) and σ_2=0.100 (inter-event).

- Based on Ambraseys *et al.* (2005a). See Section 3.23.

3.25. BRAGATO (2005)

- Ground motion model is:

$$\log_{10}(\mathrm{PGA}) = c_1 + c_2 M_s + c_3 r$$

where *PGA* is in ms^{-2}, c_1=-2.09, c_2=0.47, c_3=-0.039 and σ=0.3 (note that the method given in the article must be followed in order to predict the correct accelerations using this equation).

- Uses data (186 records) of Ambraseys & Douglas (2000, 2003) for $M_S \geq 5.8$. Add 57 records from ISESD (Ambraseys *et al.*, 2004) for $5.0 \leq M_S \leq 5.7$.
- Investigates whether ‘magnitude-dependent attenuation’, i.e. PGA saturation in response to increasing magnitude, can be explained by PGA approaching an upper physical limit through an accumulation of data points under an upper limit.
- Proposes model with: a magnitude-independent attenuation model and a physical mechanism that prevents PGA from exceeding a given threshold. Considers a fixed threshold and a threshold with random characteristics.
- Develops the mathematical models and regression techniques for the truncated and the randomly clipped normal distribution.
- Reduces number of parameters by not considering site conditions or rupture mechanism. Believes following results of Ambraseys & Douglas (2000, 2003) that neglecting site effects is justified in the near-field because they have little effect. Believes that the distribution of data w.r.t. mechanism is too poor to consider mechanism.
- Performs a standard one-stage, unweighted regression with adopted functional form and also with form: $\log_{10}(PGA)=c_1+c_2M+c_3r+c_4Mr+c_5M^2+c_6r^2$ and finds magnitude saturation and also decreasing standard deviation with magnitude.
- Performs regression with the truncation model for a fixed threshold with adopted functional form. Finds almost identical result to that from standard one-stage, unweighted regression.

- Performs regression with the random clipping model. Finds that it predicts magnitude-dependent attenuation and decreasing standard deviation for increasing magnitude.
- Investigates the effect of the removal of high-amplitude (PGA=17.45 ms^{-2}) record from Tarzana of the 1994 Northridge earthquake. Finds that it has little effect.

3.26. BRAGATO & SLEJKO (2005)

- Ground motion model is:

$$\begin{aligned} \log_{10}(Y) &= a + (b + cM)M + (d + eM^3)\log_{10}(r) \\ r &= \sqrt{d^2 + h^2} \end{aligned}$$

where Y is in g, a=-3.27, b=1.95, c=-0.202, d=-3.11, e=0.00751, h=8.9 km and σ=0.399 for horizontal PGA and d_e, a=-3.37, b=1.93, c=-0.203, d=-3.02, e=0.00744, h=7.3 km and σ=0.358 for horizontal PGA and d_f, a=-2.96, b=1.79, c=-0.184, d=-3.26, e=0.00708, h=11.3 km and σ=0.354 for vertical PGA and d_e and a=-3.18, b=1.80, c=-0.188, d=-3.13, e=0.00706, h=9.1 km and σ=0.313 for vertical PGA and d_f.

- Believe relation valid for rather rigid soil.
- Use data from the Seismometric Network of Friuli-Venezia Giulia (SENF) (converted to acceleration), the Friuli Accelerometric Network (RAF), data from the 1976 Friuli sequence and data from temporary seismometric (converted to acceleration) and accelerometric stations of Uprava RS za Geofiziko (URSG) of the 1998 Bovec sequence.
- Data from 1976 Friuli sequence is taken from ISESD. Records have been bandpass filtered with cut-offs of 0.25 and 25 Hz. No instrument correction has been applied. Data from other networks has been instrument corrected and high-pass filtered at 0.4 Hz.
- Hypocentral locations and M_L values adopted from local bulletins and studies.
- Use running vectorial composition of horizontal time series because horizontal vector is the actual motion that intersects seismic hazard. Find that on average running vectorial composition is 8% larger than the larger horizontal peak and 27% larger than the geometric mean. Find that using other methods to combine horizontal components simply changes a by about 0.1 downwards and does not change the other coefficients.
- Use data from 19 earthquakes with $M_L \geq 4.5$ (161 vertical records, 130 horizontal records).
- Note that distribution w.r.t. magnitude of earthquakes used roughly follows log-linear Gutenberg-Richter distribution up to about $M_L \geq 4.5$.
- Few records available for d<10 km and M_L>3.

- Focal depths between 1.0 and 21.6 km. Average depth is 11.4±3.6 km.
- Apply multi-linear multi-threshold truncated regression analysis (TRA) of Bragato (2004) to handle the effect of nontriggering stations using the simplification that for SENF and URSG data the random truncation level can be approximated by the lowest value available in the data set for that station. For data from the 1976 Friuli sequence use a unique truncation level equal to the minimum ground motion for that entire network in the dataset. Use same technique for RAF data.
- Develop separate equations for d_e and d_f (available for 48 records in total including all from M_L>5.8). Note that physically d_f is a better choice but that d_e is more similar to geometric distance used for seismic hazard assessment.
- Use M_L because available for regional earthquakes eastern Alps since 1972.
- Conduct preliminary tests and find that weak-motion data shows higher attenuation than strong-motion data. Investigate horizontal PGA using entire data set and data for 0.5-wide magnitude classes. Find that attenuation is dependent on magnitude and it is not useful to include a coefficient to model anelastic attenuation.
- Since data is not uniformly distributed with magnitude, inversely weight data by number of records within intervals of 0.1 magnitude units wide.
- Because correlation between magnitude and distance is very low (0.03 and 0.02 for vertical and horizontal components, respectively) apply one-stage method.
- Note that large differences between results for d_e and d_f are due to magnitude-dependent weighting scheme used.
- Plot predicted and observed ground motions binned into 0.3 magnitude intervals and find close match.
- Plot residuals w.r.t. focal depth, d_f and M_L. Find that it appears equation over-estimates horizontal PGA for d_f>80 km, M_L<3 and focal depths >15 km but note that this is due to the truncation of low amplitude data. Check apparent trend using TRA and find no significant trend.
- Note that difficult to investigate importance of focal depth on attenuation due to unreliability of depths particularly for small earthquakes. Find that focal depths seem to be correlated to magnitude but believe that this is an artefact due to poor location of small earthquakes. Try regression using d_h and find larger σ hence conclude that depth estimates are not accurate enough to investigate effect of depth on ground motions.
- Investigate methods for incorporation of site effect information using their ability to reduce σ as a criteria.
- Note that largest possible reduction is obtained using individual average station residuals for each site but that this is not practical because this method cannot be used to predict ground motions at arbitrary site and that it requires sufficient number of observations for each station. Using just those stations that recorded

at least five earthquakes obtain estimate of lowest possible σ by adopting this method.

- Try using a classification of stations into three site categories: rock (16 stations, 1020 records), stiff soil (9 stations, 117 records) and soft soil (4 stations, 27 records) and find no reduction in σ, which believe is due to the uneven distribution w.r.t. site class. Find that the strong site effects at Tolmezzo has a significant effect on the obtained site coefficients.
- Use Nakamura (H/V) ratios from ambient noise for a selection of stations by including a term $g(S)=c_{HV}N(S)$, where $N(S)$ is the Nakamura ratio at the period of interest (0.125–1 *s* for PGA), in the equation. Find large reductions in σ and high correlations between Nakamura ratios and station residuals.
- Use receiver functions from earthquake recordings in a similar way to Nakamura ratios. Find that it is reduces σ more than site classification technique but less than using the Nakamura ratios, which note could be because the geometry of the source affects the computed receiver functions so that they are not representative of the average site effects.
- Believe equation is more appropriate than previous equations for $M_L<5.8$ and equivalent to the others up to $M_L 6.3$. Discourage extrapolation for $M_L>6.3$ because it overestimates PGA in the far-field from about $M_L 6.5$.

3.27. FRISENDA *ET AL.* (2005)

- Ground motion model is:

$$\log(Y) = a + bM + cM^2 + d\log(R) + eS$$

where Y is in g, a=-3.19±0.02, b=0.87±0.01, c=-0.042±0.002, d=-1.92±0.01, e=0.249±0.005 and σ=0.316.

- Use two site classes, because lack local geological information (e.g. average V_s):

  S=0 Rock, eight stations, 3790 records.

  S=1 Soil, seven stations, 3109 records.

Classify station using geological reports, M_L station corrections and H/V spectral ratios computed over a 30 s wide time window of S waves for entire waveform data set.

- Data from Regional Seismic Network of Northwestern Italy and Regional Seismic Network of Lunigiana-Garfagnana (ten Lennartz LE3D-5s and five Guralp CMG-40 sensors with Lennartz Mars88/MC recording systems). Sampling rate either 62.5 or 125 samples/s. Records from broadband and enlarged band seismometers converted to acceleration by: correcting for instrument response, bandpass filtering between 1 and 20 Hz and then differentiating. Accuracy of conversion verified by comparing observed and derived PGA values at one station (STV2), which was equipped with both a Kinemetrics K2 accelerometer and a Guralp CMG-40 broadband sensor.

- Find strong attenuation for short distances (<50 km) and small magnitudes (M_L<3.0).
- M_L calculated using a calibration formula derived for northwestern Italy using a similar dataset.
- Compute signal-to-noise (S/N) ratio for the S phase using windows of 3 s wide and find that data is good quality (85% of windows have S/N ratio greater than 10 dB. Only use records with S/N ratio >20 dB.
- Most earthquakes are from SW Alps and NW Apennines.
- Most records from earthquakes with $1 \leq M_L \leq 3$, small number from larger earthquakes particularly those with M_L>4. M_L<1: 1285 records, $1 \leq M_L < 2$: 2902 records, $2 \leq M_L < 3$: 1737 records, $3 \leq M_L < 4$: 693 records and $M_L \geq 4$: 282 records.
- Data shows strong magnitude-distance correlation, e.g. records from earthquakes with M_L<1 are from $0 \leq R \leq 100$ km and those from earthquakes with M_L>4 are mainly from R>50 km. Distribution is uniform for $2 \leq M_L \leq 4$ and $0 \leq R \leq 200$ km.
- Originally include an anelastic decay term ($d_1 R$) in addition but the value of d_1 was positive and not statistically significantly different than zero so it was removed.
- Regression in two-steps: firstly without site effect coefficient (e) and then with e added.
- Compare data to estimated decay within one magnitude unit intervals and find predictions are good up to M_L=4.0.
- Find no systematic trends in the residuals.

3.28. GARCIA *ET AL.* (2005)

- Ground motion model is:

$$
\begin{aligned}
\log Y &= c_1 + c_2 M_w + c_3 R - c_4 \log R + c_5 H \\
R &= \sqrt{R_{\text{cld}}^2 + \Delta^2} \\
\Delta &= 0.00750 \times 10^{0.507 M_w}
\end{aligned}
$$

where Y is in cms^{-2}, for horizontal PGA: c_1=-0.2, c_2=0.59, c_3=-0.0039, c_4=1, c_5=0.008, σ_r=0.27, σ_e=0.10 and for vertical PGA: c_1=-0.4, c_2=0.60, c_3=-0.0036, c_4=1, c_5=0.006, σ_r=0.25 and σ_e=0.11 where σ_r is the intra-event standard deviation and σ_e is the inter-event standard deviation.

- All data from 51 hard (NEHRP B) sites.
- All stations in the Valley of Mexico omitted.
- All data from free-field stations: small shelters, isolated from any building, dam abutment, bridge, or structure with more than one storey.

- Focal depths: $35 \leq H \leq 138$ km, most records (13 earthquakes, 249 records) from $35 \leq H \leq 75$ km.
- Exclude data from $M_W < 5.0$ and $R > 400$ km.
- Exclude data from deep earthquakes where wave paths cross the mantle edge.
- All data from normal-faulting earthquakes.
- Use about 27 records from velocity records from broadband seismograph network that were differentiated to acceleration.
- Adopt Δ from Atkinson & Boore (2003).
- Investigate a number of functional forms. Inclusion of Δ substantially improves fit, leading to a decrease in random variability at close distances, and an increase in c_2 and c_3 coefficients. Find worse correlation when add a quadratic magnitude term. A magnitude-dependent c_4 leads to higher σs. Find unrealistically high ground motions at close distances using the form of c_4 used by Atkinson & Boore (2003).
- If exclude three deep earthquakes then little dependence on H.
- Do not find any noticeable bias in residuals w.r.t. distance, magnitude or depth (not shown).
- Note that decrease in variability w.r.t. magnitude is only apparent for frequencies <1 Hz.
- Discuss observed dependence of, particularly high-frequency, ground motions on focal depth.

3.29. LIU & TSAI (2005)

- Ground motion model is:

$$\ln Y = a \ln(X + h) + bX + cM_w + d$$

where Y is in cms^{-2} for horizontal PGA (for whole Taiwan) a=-0.852, b=-0.0071, c=1.027, d=1.062, h=1.24 km and σ=0.719 and for vertical PGA (for whole Taiwan) a=-1.340, b=-0.0036, c=1.101, d=1.697, h=1.62 km and σ=0.687. Also report coefficients for equations derived for three different sub-regions.

- Do not differentiate site conditions.
- Focal depths, h, between 2.72 and 29.98 km.
- Data from high-quality digital strong-motion networks of Taiwan Strong Motion Instrumentation Program (TSMIP) and Central Mountain Strong Motion Array (CMSMA).
- Select data from earthquakes with $h \leq 30$ km and with records from ≥ 6 stations at $d_e \leq 20$ km.
- Select events following the 1999 Chi-Chi earthquake (M_W7.7) with M_L>6.
- Do not use data from the Chi-Chi earthquake because: a) earlier analysis of Chi-Chi data showed short-period ground motion was significantly lower than

expected and b) the Chi-Chi rupture triggered two M6 events on other faults thereby contaminating the ground motions recorded at some stations.

- Data uniformly distributed for $M_w \leq 6.5$ and $20 \leq d_h \leq 100$ km. Significant number of records for $d_h > 100$ km.
- Use data from the Chi-Chi earthquake and the 2003 Cheng-Kung earthquake (M_w6.8) for testing applicability of developed equations.
- For 32 earthquakes (mainly with $M_w < 5.3$) convert M_L to M_w using empirical equation developed for Taiwan.
- Develop regional equations for three regions: CHY in SW Taiwan (16 earthquakes, 1382 records), IWA in NE Taiwan (14 earthquakes, 2105 records) and NTO in central Taiwan (13 earthquakes, 3671 records) and for whole Taiwan to compare regional differences of source clustering in ground-motion characteristics.
- Use M_w since corresponds to well-defined physical properties of the source, also it can be related directly to slip rate on faults and avoids saturation problems of other M-scales.
- Use relocated focal depths and epicentral locations.
- Do not use d_f or d_r because insufficient information on rupture geometries, particularly those of small earthquakes, even though believe such distance metrics are justified. However, for small earthquakes do not think using d_h rather than d_r will introduce significant bias into the equations. Also use d_h because it is quickly determined after an earthquake hence early ground-motion maps can be produced.
- From equations derived for different sub-regions and from site residual contour maps that ground motions in CHY are about four times higher than elsewhere due to thick, recent alluvial deposits.
- Find predictions for Chi-Chi and Cheng-Kung PGAs are close to observations.
- Plot contour maps of residuals for different sites and relate the results to local geology (alluvial plains and valleys and high-density schist).
- Divide site residuals into three classes: $>0.2\sigma$, -0.2–0.2σ and $<-0.2\sigma$ for four NEHRP-like site classes. Find the distribution of residuals is related to the site class particularly for the softest class. Find residuals for C (very dense soil and soft rock) and D (stiff soil) are similar so suggest combining them. Believe geomorphology may also play an important role in site classification because a geomorphologic unit is often closely related to a geologic unit.

3.30. MCGARR & FLETCHER (2005)

- Ground motion model is:

$$\log(y) = a + bM + d\log(R) + kR + s_1 + s_2$$

where y is in cms^{-2}, a=-0.9892, b=0.8824, d=-1.355, k=-0.1363, s_1=0.337 (for stations on surface), s_2=0 (for station at depth) and σ=0.483.

- Use data from seven stations, one of which (TU1) is located underground within the mine. Determine site factors (constrained to be between 0 and 1) from PGV data. Originally group into three site categories: one for stations with close to horizontal straight-line ray paths, one for stations with steeper ray paths and one for underground station. Find site factors for first two categories similar so combine, partly because there is no precedent for topographic site factors in empirical ground-motion estimation equations. Believe that low site factors found are because stations are on solid rock V_S>1.5 kms^{-1}.
- Most data from Trail Mountain coal mine from between 12/2000 and 03/2001 (maximum M_{CL}2.17). Supplement with data (2 records) from a M4.2 earthquake at Willow Creek mine to provide data at much higher magnitude.
- Most data from M_W<1.7.
- Lower magnitude limit dictated by need for adequate signal-to-noise ratio.
- Focal depths between 50 and 720 m (relative to the ground surface).
- Note that although data may be poorly suited to determine both d and k simultaneously they are retained because both attenuation mechanisms must be operative. State that d and k should be solely considered as empirical parameters due to trade-offs during fitting.
- Do not include a quadratic M term because it is generally of little consequence.
- Use d_h because earthquakes are small compared to distances so can be considered as point sources.
- Selected events using these criteria:
  - event was recorded by ≥6 stations;
  - data had high signal-to-noise ratio;
  - to obtain the broadest M-range as possible; and
  - to have a broad distribution of epicentral locations.
- Find that M_W (estimated for 6 events) does not significantly differ from M_{CL}.
- Find that constrains must be applied to coefficients. Constrain k to range -2–0 because otherwise find small positive values. Believe that this is because data inadequate for independently determining d and k.

3.31. ATKINSON (2006)

- Ground motion model is:

$$\begin{aligned}\log Y &= c0 + c1(\mathrm{M}-5) + c2(\mathrm{M}-5)^2 + c3\log R + c4R + S_i\\ R &= \sqrt{d^2+h^2}\end{aligned}$$

where $c0$=2.007, $c1$=0.567, $c2$=0.0311, $c3$=-1.472, $c4$=0.00000, h=5 km [from Boore *et al.* (1997)], $\sigma(BJF)$=0.309, $\sigma(emp\text{-}amp)$=0.307 and $\sigma(NoSiteCorr)$=0.305.

Individual station: with empirical-corrected amplitudes σ=0.269 and with BJF-corrected amplitudes σ=0.268.

- Uses data from 21 TriNet stations with known $V_{s,30}$ values. $190 \leq V_{s,30} \leq 958$ ms^{-1}. Uses two approaches for site term S_i. In first method (denoted ‘empirically-corrected amplitudes’, *emp-amp*) uses empirical site amplification factors from previous study of TriNet stations (for PGA uses site factor for PSA at 0.3 *s* because correction for PGA is unavailable). In second method [denoted ‘Boore-Joyner-Fumal (BJF)-corrected amplitudes’, *BJF*] uses amplification factors based on $V_{s,30}$ from Boore *et al.* (1997) to correct observations to reference (arbitrarily selected) $V_{s,30}$=760 ms^{-1}.
- Uses only data with amplitudes >0.01% g (100 times greater than resolution of data, 0.0001% g).
- States that developed relations not intended for engineering applications due to lack of data from large events and from short distances. Equations developed for investigation of variability issues for which database limitations are not crucial.
- Many records from Landers mainshock and aftershocks.
- Uses standard linear regression since facilitates comparisons using regressions of different types of datasets, including single-station datasets.
- Notes possible complications to functional form due to effects such as magnitude-dependent shape are not important due to small source size of most events.
- Truncates data at 300 km to get dataset that is well distributed in distance-amplitude space.
- Notes that small differences between σs when no site correction is applied and when site correction is applied could be due to complex site response in Los Angeles basin.
- Fits trend-lines to residuals versus distance for each station and finds slope not significantly different from zero at most stations except for Osito Audit (OSI) (lying in mountains outside the geographical area defined by other stations), which has a significant positive trend.
- Finds empirical-amplification factors give better estimate of average site response (average residuals per station closer to zero) than $V_{s,30}$-based factors at short periods but the reverse for long periods. Notes $V_{s,30}$ gives more stable site-response estimates, with residuals for individual stations less than factor of 1.6 for most stations.
- Finds standard deviations of station residuals not unusually large at sites with large mean residual, indicating that average site response estimates could be improved.
- Plots standard deviation of station residuals using $V_{s,30}$-based factors and the average of these weighted by number of observations per station. Compares with standard deviation from entire databank. Finds that generally standard

deviations of station residuals slightly lower (about 10%) than for entire databank.

- Examines standard deviations of residuals averaged over 0.5-unit magnitude bins and finds no apparent trend for **M**3.5 to **M**7.0 but notes lack of large magnitude data.
- Restricts data by magnitude range (e.g. 4≤**M**≤6) and/or distance (e.g. ≤80 km) and find no reduction in standard deviation.
- Finds no reduction in standard deviation using one component rather than both.
- Performs separate analysis of residuals for Landers events (10 stations having ≥20 observations) recorded at >100 km. Notes that due to similarity of source and path effects for a station this should represent a minimum in single-station σ. Finds σ of 0.18±0.06.

3.32. BEYER & BOMMER (2006)

- Exact functional form of ground-motion model is not given but note includes linear and quadratic terms of magnitude and a geometric spreading term. Coefficients not given but report ratios of σ using different definitions w.r.t. σ using geometric mean.
- Distribution w.r.t. NEHRP site classes is:

  A 8 records

  B 37 records

  C 358 records

  D 534 records

  E 11 records

  Unspecified 1 record
- Use data from Next Generation Attenuation (NGA) database.
- Distribution w.r.t. mechanism is:

  Strike-slip 333 records, 51 earthquakes

  Normal 36 records, 12 earthquakes

  Reverse 329 records, 21 earthquakes

  Reverse-oblique 223 records, 9 earthquakes

  Normal-oblique 25 records, 7 earthquakes

  Undefined 3 records, 3 earthquakes
- Exclude records from Chi-Chi 1999 earthquake and its aftershocks to avoid bias due to over-representation of these data (>50% of 3551 records of NGA databank).
- Exclude records with PGA (defined using geometric mean) <0.05 g to focus on motions of engineering significance and to avoid problems with resolution of analogue records.
- Exclude records with maximum usable period <0.5 s.
- Exclude records without hypocentral depth estimate since use depth in regression analysis.

- Earthquakes contribute between 1 and 138 accelerograms.
- Note data is from wide range of *M*, *d*, mechanism, site class and instrument type.
- State aim was not to derive state-of-the-art ground-motion models but to derive models with the same data and regression method for different component definitions.
- Assume ratios of σs from different models fairly insensitive to assumptions made during regression but that these assumptions affect σ values themselves.
- Find ratios of σs from using different definitions close to 1.
- Note that results should be applied with caution to subduction and stable continental regions since have not been checked against these data.

3.33. BINDI *ET AL.* (2006)

- Ground motion model is for d_e:

$$\log(y) = a + bM + c\log\sqrt{(R^2 + h^2)} + e_1S_1 + e_2S_2 + e_3S_3 + e_4S_4$$

where y is in g, a=-2.487, b=0.534, c=-1.280, h=3.94, e_1=0, e_2=0.365, e_3=0.065, e_4=0.053, σ_{event}=0.117 and σ_{record}=0.241 (or alternatively $\sigma_{station}$=0.145 and σ_{record}=0.232). For d_h:

$$\log(y) = a + bM + c\log R_h + e_1S_1 + e_2S_2 + e_3S_3 + e_4S_4$$

where y is in g, a=-2.500, b=0.544, c=-1.284 and σ=0.292 (do not report site coefficients for d_h).

- Use four site classes:

  A_C Lacustrine and alluvial deposits with thickness >30 *m* (180≤$V_{s,30}$<360 ms^{-1}). Sites in largest lacustrine plains in Umbria region. S_4=1 and others are zero.

  B_C Lacustrine and alluvial deposits with thickness 10–30 *m* (180≤$V_{s,30}$<360 ms^{-1}). Sites in narrow alluvial plains or shallow basins. S_3=1 and others are zero.

  C_E Shallow debris or colluvial deposits (3–10 m) overlaying rock (surface layer with V_s<360 ms^{-1}). Sites located on shallow colluvial covers or slope debris (maximum depth 10 m) on gentle slopes. S_2=1 and others are zero.

  D_A Rock ($V_{s,30}$>800 ms^{-1}). Sites on outcropping rock, or related morphologic features, such as rock crests and cliffs. S_1=1 and others are zero.

Base classifications on recently collected detailed site information from site investigations, census data, topographic maps, data from previous reports on depth of bedrock, and data from public and private companies. Subscripts correspond to classification in Eurocode 8.

- Focal depths between 1.1 and 8.7 km except for one earthquake with depth 47.7 km.
- Nearly all earthquakes have normal mechanism, with a few strike-slip earthquakes.
- Select earthquakes with $M_L \geq 4.0$ and $d < 100$ km.
- Use M_L since available for all events.
- Fault geometries only available for three events so use d_e and d_h rather than d_f. Note that except for a few records differences between d_e and d_f are small.
- Correct for baseline and instrument response and filter analogue records to remove high- and low-frequency noise by visually selecting a suitable frequency interval: average range was 0.5–25 Hz. Filter digital records with bandpass of, on average, 0.3–40 Hz.
- For $M_L<5$ no records from $d_e>50$ km.
- Use maximum-likelihood regression with event and record σs and also one with station and record σs. Perform each regression twice: once including site coefficients and once without to investigate reduction in σs when site information is included.
- Investigate difference in residuals for different stations when site coefficients are included or not. Find significant reductions in residuals for some sites, particularly for class C_E.
- Note that some stations seem to display site-specific amplifications different than the general trend of sites within one site class. For these sites the residuals increase when site coefficients are introduced.
- Find large negative residuals for records from the deep earthquake.
- Find similar residuals for the four earthquakes not from the 1997–1998 Umbria-Marche sequence.

3.34. CAMPBELL & BOZORGNIA (2006A) AND CAMPBELL & BOZORGNIA (2006B)

- Ground motion model is:

$$
\begin{aligned}
\ln Y &= f_1(M) + f_2(R) + f_3(F) + f_4(\mathrm{HW}) + f_5(S) + f_6(D) \\
f_1(M) &= \begin{cases} c_0 + c_1 M & M \leq 5.5 \\ c_0 + c_1 M + c_2(M-5.5) & 5.5 < M \leq 6.5 \\ c_0 + c_1 M + c_2(M-5.5) + c_3(M-6.5) & M > 6.5 \end{cases} \\
f_2(R) &= (c_4 + c_5 M)\ln(\sqrt{r_{\mathrm{rup}}^2 + c_6^2}) \\
f_3(F) &= c_7 F_{\mathrm{RV}} f_F(H) + c_8 F_N \\
f_F(H) &= \begin{cases} H & H < 1\,\mathrm{km} \\ 1 & H \geq 1\,\mathrm{km} \end{cases} \\
f_4(\mathrm{HW}) &= c_9 F_{\mathrm{RV}} f_{\mathrm{HW}}(M) f_{\mathrm{HW}}(H) \\
f_{\mathrm{HW}}(R) &= \begin{cases} 1 & r_{\mathrm{jb}} = 0\,\mathrm{km} \\ 1 - (r_{\mathrm{jb}}/r_{\mathrm{rup}}) & r_{jb} > 0\,\mathrm{km} \end{cases} \\
f_{\mathrm{HW}}(M) &= \begin{cases} 0 & M \leq 6.0 \\ 2(M-6.0) & 6.0 < M < 6.5 \\ 1 & M \geq 6.5 \end{cases} \\
f_{\mathrm{HW}}(H) &= \begin{cases} 0 & H \geq 20\,\mathrm{km} \\ 1 - (H/20) & H < 20\,\mathrm{km} \end{cases} \\
f_5(S) &= \begin{cases} c_{10}\ln\left(\frac{V_{s30}}{k_1}\right) + k_2\left\{\ln\left[\mathrm{PGA}_r + c\left(\frac{V_{s30}}{k_1}\right)^n\right] - \ln[\mathrm{PGA}_r + c]\right\} & V_{s30} < k_1 \\ (c_{10} + k_2 n)\ln\left(\frac{V_{s30}}{k_1}\right) & V_{s30} \geq k_1 \end{cases} \\
f_6(D) &= \begin{cases} c_{11}(D-1) & D < 1\,\mathrm{km} \\ 0 & 1 \leq D \leq 3\,\mathrm{km} \\ c_{12}\{k_3[0.0000454 - \exp(-3.33D)] + k_4[0.472 - \exp(-0.25D)]\} & D > 3\,\mathrm{km} \end{cases}
\end{aligned}
$$

Do not report coefficients, only display predicted ground motions. H is the depth to top of coseismic rupture in km, PGA_r is the reference value of PGA on rock with V_{s30}=1100 ms^{-1}, D is depth to 2.5 kms^{-1} shear-wave velocity horizon (so-called sediment or basin depth) in km.

- Use V_{s30} (average shear-wave velocity in top 30 m in ms^{-1}) to characterise site conditions.
- Model developed as part of PEER Next Generation Attenuation (NGA) project.
- State that model is not final and articles should be considered as progress reports.
- NGA database only includes records that represent free-field conditions (i.e. records from large buildings are excluded).
- Include earthquake if: 1) it occurred within the shallow continental lithosphere, 2) it was in a region considered to be tectonically active, 3) it had enough records to establish a reasonable source term and 4) it had generally reliable source parameters.
- Exclude records from earthquakes classified as poorly recorded defined by: M<5.0 and N<5, 5.0≤M<6.0 and N<3 and 6.0≤M<7.0, r_{rup}>60 km and N<2 where N is number of records. Include singly-recorded earthquakes with M≥7.0 and r_{rup}≤60 km because of importance in constraining near-source estimates.

- Include records if: 1) it was from or near ground level, 2) it had negligible structural interaction effects and 3) it had generally reliable site parameters.
- Find two-step regression technique was much more stable than one-step method and allows the independent evaluation and modelling of ground-motion scaling effects at large magnitudes. Find random effects regression analysis gives very similar results to two-step method.
- Use classical data exploration techniques including analysis of residuals to develop functional forms. Develop forms using numerous iterations to capture observed trends. Select final forms based on: 1) their simplicity, although not an overriding factor, 2) their seismological bases, 3) their unbiased residuals and 4) their ability to be extrapolated to parameter values important for engineering applications (especially probabilistic seismic hazard analysis). Find that data did not always allow fully empirical development of functional form therefore apply theoretical constraints [coefficients n and c (period-independent) and k_i (period-dependent)].
- Use three faulting mechanisms:

  F_{RV}=1, F_N=0 Reverse and reverse-oblique faulting, $30^\circ<\lambda<150^\circ$, where λ is the average rake angle.

  F_N=1, F_{RV}=1 Normal and normal-oblique faulting, $-150^\circ<\lambda<-30^\circ$.

  F_{RV}=0, F_{RV}=0 Strike-slip, other λs.
- Find slight tendency for over-saturation of short-period ground motions at large magnitudes and short distances. Find other functional forms for magnitude dependence too difficult to constrain empirically or could not be reliably extrapolated to large magnitudes.
- Note transition depth for buried rupture (1 km) is somewhat arbitrary.
- Find weak but significant trend of increasing ground motion with dip for both reverse and strike-slip faults. Do not believe that seismological justified therefore do not include such a term.
- Nonlinear site model constrained by theoretical studies since empirical data insufficient to constrain complex nonlinear behaviour.
- Use depth to 2.5 kms^{-1} horizon because it showed strongest correlation with shallow and deep sediment-depth residuals.
- Believe that aspect ratio (ratio of rupture length to rupture width) has promise as a source parameter since it shows high correlation with residuals and could model change in ground-motion scaling at large magnitudes.
- Do not find standard deviations are magnitude-dependent. Believe difference with earlier conclusions due to larger number of high-quality intra-event recordings for both small and large earthquakes.
- Find standard deviation is dependent on level of ground shaking at soft sites.

3.35. COSTA *ET AL.* (2006)

- Ground motion model is:

$$\log_{10}(\mathrm{PGA}) = c_0 + c_1 M + c_2 M^2 + (c_3 + c_4 M)\log(\sqrt{d^2 + h^2}) + c_S S$$

where *PGA* is in g, c_0=-3.879, c_1=1.178, c_2=-0.068, c_3=-2.063, c_4=0.102, c_S=0.411, h=7.8 and σ=0.3448 (for larger horizontal component), c_0=-3.401, c_1=1.140, c_2=-0.070, c_3=-2.356, c_4=0.150, c_S=0.415, h=8.2 and σ=0.3415 (for horizontal component using vectorial addition), c_0=-3.464, c_1=0.958, c_2=-0.053, c_3=-2.224, c_4=0.147, c_S=0.330, h=6.1 and σ=0.3137 (for vertical).

- Use two site classes (since do not have detailed information on geology at all considered stations):

  S=0 Rock

  S=1 Soil

- Use selection criteria: $3.0 \leq M \leq 6.5$ and $1 \leq d_e \leq 100$ km.
- Bandpass filter with cut-offs between 0.1 and 0.25 *Hz* and between 25 and 30 Hz.
- Compute mean ratio between recorded and predicted motions at some stations of the RAF network. Find large ratios for some stations on soil and for some on rock.

3.36. GOMEZ-SOBERON *ET AL.* (2006)

- Ground motion model is:

$$\ln a = \alpha_0 + \alpha_1 M + \alpha_2 M^2 + \alpha_3 \ln R + \alpha_5 R$$

where a is in cms^{-2}, α_0=1.237, α_1=1.519, α_2=-0.0313, α_3=-0.844, α_5=-0.004 and σ=0.780.

- Exclude records from soft soil sites or with previously known site effects (amplification or deamplification).
- Focal depths between 5 and 80 km.
- Also derive equation using functional form $\ln a = \alpha_0 + \alpha_1 M + \alpha_2 \ln R + \alpha_4 R$.
- Select records from stations located along the seismically active Mexican Pacific coast.
- Only use records from earthquakes with M>4.5.
- Exclude data from normal faulting earthquakes using focal mechanisms, focal depths, location of epicentre and characteristics of records because subduction zone events are the most dominant and frequent type of earthquakes.
- Use M_w because consider best representation of energy release.
- Visually inspect records to exclude poor quality records.
- Exclude records from dams and buildings.
- Exclude records from ‘slow’ earthquakes, which produce smaller short-period ground motions.

- Correct accelerations by finding quadratic baseline to minimize the final velocity then filter using most appropriate bandpass filter (low cut-off frequencies between 0.05 and 0.4 Hz and high cut-off frequency of 30 Hz).
- Use data from 105 stations: 7 in Chiapas, 6 in Oaxaca, 6 in Colima, 19 in Jalisco, 49 in Guerrero, 14 in Michoacбn and 6 near the Michoacбn-Guerrero border.

3.37. HERNANDEZ *ET AL.* (2006)

- Ground motion model is:

$$\log(y) = aM_L - \log(X) + bX + c_j$$

where y is in cms^{-2}, a=0.41296, b=0.0003, c_1=0.5120, c_2=0.3983, c_3=0.2576, c_4=0.1962, c_5=0.1129 and σ=0.2331.

- Data from ARM1 and ARM2 vertical borehole arrays of the Hualien LSST array at: surface (use c_1), 5.3 m (use c_2), 15.8 m (use c_3), 26.3 m (use c_4) and 52.6 m (use c_5). Surface geology at site is massive unconsolidated poorly bedded Pleistocene conglomerate composed of pebbles varying in diameter from 5 to 20 cm, following 5 m is mainly composed of fine and medium sand followed by a gravel layer of 35 m.
- Apply these criteria to achieve uniform data: M_L>5, focal depth <30 km and 0.42M_L-log(X+0.02510$^{0.42M_L}$-0.0033X+1.22>log10 from a previous study.
- Most records from M_L<6.
- Bandpass filter records with cut-offs at 0.08 and 40 Hz.
- Propose M_S=1.154M_L-1.34.
- Some comparisons between records and predicted spectra are show for four groups of records and find a good match although for the group M_L6.75 and X=62 km find a slight overestimation, which believe is due to not modelling nonlinear magnitude dependence.
- Coefficients for vertical equations not reported.

3.38. KANNO *ET AL.* (2006)

- Ground motion model is for D≤30 km:

$$\log \mathrm{pre} = a_1 M_w + b_1 X - \log(X + d_1 10^{0.5M_w}) + c_1$$

and for D>30 km:

$$\log \mathrm{pre} = a_2 M_w + b_2 X - \log(X) + c_2$$

where *pre* is in cms^{-2}, a_1=0.56, b_1=-0.0031, c_1=0.26, d_1=0.0055, a_2=0.41, b_2=-0.0039, c_2=1.56, σ_1=0.37 and σ_2=0.40.

- Use $V_{s,30}$ to characterise site effects using correction formula: $G=\log(obs/pre)=p\log V_{s,30}+q$. Derive p and q by regression analysis on residuals averaged at intervals of every 100 ms^{-1} in $V_{s,30}$. p=-0.55 and q=1.35 for PGA. Note that the equation without site correction predicts ground motions at sites with $V_{s,30}\approx$300 ms^{-1}.
- Focal depths, D, for shallow events between 0 km and 30 km and for deep events between 30 km and about 180 km.
- Note that it is difficult to determine a suitable model form due to large variability of strong-motion data, correlation among model variables and because of coupling of variables in the model. Therefore choose a simple model to predict average characteristics with minimum parameters.
- Introduce correction terms for site effects and regional anomalies.
- Originally collect 91731 records from 4967 Japanese earthquakes.
- Include foreign near-source data (from California and Turkey, which are compressional regimes similar to Japan) because insufficient from Japan.
- High-pass filter records with cut-off of 0.1 Hz. Low-pass filter analogue records using cut-offs selected by visual inspection.
- Choose records where: 1) $M_W\geq$5.5, 2) data from ground surface, 3) two orthogonal horizontal components available, 4) at least five stations triggered and 5) the record passed this M_W-dependent source distance criterion: $f(M_W,X)\geq\log 10$ (for data from mechanical seismometer networks) or $f(M_W,X)\geq\log 2$ (for data from other networks) where $f(M_W,X)=0.42M_W-0.0033X-\log(X+0.025 10^{0.43M_W})+1.22$ (from a consideration of triggering of instruments).
- Examine data distributions w.r.t. amplitude and distance for each magnitude. Exclude events with irregular distributions that could be associated with a particular geological/tectonic feature (such as volcanic earthquakes).
- Do not include data from Chi-Chi 1999 earthquake because have remarkably low amplitudes, which could be due to a much-fractured continental margin causing different seismic wave propagation than normal.
- Data from 2236 different sites in Japan and 305 in other countries.
- Note relatively few records from large and deep events.
- Note that maybe best to use stress drop to account for different source types (shallow, interface or intraslab) but cannot use since not available for all earthquakes in dataset.
- Investigate effect of depth on ground motions and find that ground-motions amplitudes from earthquakes with D>30 km are considerably different than from shallower events hence derive separate equations for shallow and deep events.
- Select 0.5 within function from earlier study.

- Weight regression for shallow events to give more weight to near-source data. Use weighting of 6.0 for $X \leq 25$ km, 3.0 for $25 < X \leq 50$ km, 1.5 for $50 < X \leq 75$ km and 1.0 for $X > 75$ km. Note that weighting scheme has no physical meaning.
- Note that amplitude saturation at short distances for shallow model is controlled by crustal events hence region within several tens of kms of large ($M_w > 8.0$) interface events falls outside range of data.
- Note standard deviation decreases after site correction term is introduced.
- Introduce correction to model anomalous ground motions in NE Japan from intermediate and deep earthquakes occurring in the Pacific plate due to unique Q structure beneath the island arc. Correction is: $\log(obs/pre) = (\alpha R_{tr} + \beta)(D - 30)$ where R_{tr} is shortest distance from site to Kuril and Izu-Bonin trenches. α and β are derived by regression on subset fulfilling criteria: hypocentre in Pacific plate, station E of 137° E and station has $V_{s,30}$ measurement. For PGA $\alpha = -6.73 \times 10^{-5}$ and $\beta = 2.09 \times 10^{-2}$. Find considerable reduction in standard deviation after correction. Note that R_{tr} may not be the best parameter due to observed bias in residuals for deep events.
- Examine normalised observed ground motions w.r.t. predicted values and find good match.
- Examine residuals w.r.t. distance and predicted values. Find residuals decrease with increasing predicted amplitude and with decreasing distance. Note that this is desirable from engineering point of view, however, note that it may be due to insufficient data with large amplitudes and from short distances.
- Examine total, intra-event and inter-event residuals w.r.t. D for $D > 30$ km. When no correction terms are used, intra-event residuals are not biased but inter-event residuals are. Find mean values of total error increase up to $D = 70$ km and then are constant. Find depth correction term reduces intra-event residuals considerably but increases inter-event error slightly. Overall bias improves for $D < 140$ km. Find site corrections have marginal effect on residuals.
- Find no bias in residuals w.r.t. magnitude.

3.39. LAOUAMI *ET AL.* (2006)

- Ground motion model is:

$$y = c \exp(\alpha M_s)[D^k + a]^{-\beta - \gamma R}$$

where D is d_h and R is d_e, y is in ms^{-2}, $c = 0.38778$, $\alpha = 0.32927$, $k = 0.29202$, $a = 1.557574$, $\beta = 1.537231$, $\gamma = 0.027024$ and $\sigma = 0.03$ (note that this σ is additive).

- All records except one at 13 km from distances of 20 to 70 km so note that lack information from near field.
- Compare predictions to records from the 2003 Boumerdes (M_w6.8) earthquake and find that it underpredicts the recorded motions, which note maybe due to local site effects.

3.40. LUZI *ET AL.* (2006)

- 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, s_1=0, s_2=0.123, σ_{event}=0.069 and σ_{record}=0.339 (for horizontal PGA assuming intra-event σ), a=-4.367, b=0.774, c=-1.146, s_1=0, s_2=0.119, $\sigma_{station}$=0.077 and σ_{record}=0.337 (for horizontal PGA assuming intra-station σ), a=-4.128, b=0.722 ,c=-1.250, s_1=0, s_2=0.096, σ_{event}=0.085 and σ_{record}=0.338 (for vertical PGA assuming intra-event σ), a=-4.066, b=0.729, c=-1.322, s_1=0, s_2=0.090, $\sigma_{station}$=0.105 and σ_{record}=0.335 (for vertical PGA assuming intra-station σ).

- Use two site classes:

1. Rock, where V_s>800 ms^{-1}. Use s_1.
2. Soil, where V_s<800 ms^{-1}. This includes all kinds of superficial deposits from weak rock to alluvial deposits. Use s_2.

Can only use two classes due to limited information.

- Use 195 accelerometric records from 51 earthquakes (2.5≤M_L≤5.4) from 29 sites. Most records are from rock or stiff sites. Most data from d_h<50 km with few from >100 km. Also use data from velocimeters (Lennartz 1 or 5 s sensors and Guralp CMG-40Ts). In total 2895 records with d_h<50 km from 78 events and 22 stations available, most from 20≤d_h≤30 km.
- For records from analogue instruments, baseline correct, correct for instrument response and bandpass filter with average cut-offs at 0.5 and 20 Hz (after visual inspection of Fourier amplitude spectra). For records from digital instruments, baseline correct and bandpass filter with average cut-offs at 0.2 and 30 Hz. Sampling rate is 200 Hz. For records from velocimeters, correct for instrument response and bandpass filter with average cut-offs at 0.5 and 25 Hz. Sampling rate is 100 Hz.
- Select records from 37 stations with 10≤d_h≤50 km.
- Compare predictions and observations for M_L4.4 and find acceptable agreement. Also find agreement between data from accelerometers and velocimeters.

3.41. MAHDAVIAN (2006)

- Ground motion model is:

$$\log(y) = a + bM + c\log(R) + dR$$

where y is in cms^{-2}. For horizontal PGA: a=1.861, b=0.201, c=-0.554, d=-0.0091 and σ=0.242 (for Zagros, rock sites and $M_s \geq 4.5$ or $m_b \geq 5.0$), a=1.831, b=0.208, c=-0.499, d=-0.0137 and σ=0.242 (for Zagros, rock sites and $3<M_s<4.6$ or $4.0 \leq m_b<5.0$), a=2.058, b=0.243, c=-1.02, d=-0.000875 and σ=0.219 (for central Iran and rock sites), a=2.213, b=0.225, c=-0.847, d=-0.00918 and σ=0.297 (for Zagros and soil sites), a=1.912, b=0.201, c=-0.790, d=-0.00253 and σ=0.204 (for central Iran and soil sites). For vertical PGA: a=2.272, b=0.115, c=-0.853, d=-0.00529 and σ=0.241 (for Zagros, rock sites and $M_s \geq 4.5$ or $m_b \geq 5.0$), a=2.060, b=0.147[1] , c=-0.758, d=-0.00847 and σ=0.270 (for Zagros, rock sites and $M_s \geq 3.0$ or $m_b \geq 4.0$), a=1.864, b=0.232, c=-1.049, d=-0.000372 and σ=0.253 (for central Iran and rock sites), a=2.251, b=0.140[2] , c=-0.822, d=-0.00734 and σ=0.290[3] (for Zagros and soil sites) and a=1.76, b=0.232[4] , c=-1.013, d=-0.000551 and σ=0.229 (for central Iran and soil sites).

- Uses two site classes:

1. Sedimentary. 55 records.
2. Rock. 95 records.

Bases classification on geological maps, station visits, published classifications and shape of response spectra from strong-motion records. Notes that the classification could be incorrect for some stations. Uses only two classes to reduce possible errors.

- Divides Iran into two regions: Zagros and other areas.
- Select data with M_s or m_b where $m_b>3.5$. Notes that only earthquakes with $m_b>5.0$ are of engineering concern for Iran but since not enough data (especially for Zagros) includes smaller earthquakes.
- Use M_s when $m_b \geq 4$.
- Records bandpass filtered using Ormsby filters with cut-offs and roll-offs of 0.1–0.25 Hz and 23–25 Hz.
- Notes that some data from far-field.
- Notes that some records do not feature the main portion of shaking.
- To be consistent, calculates d_h using S-P time difference. For some records P wave arrival time is unknown so use published hypocentral locations. Assumes

[1]Assume that 147 reported in paper is a typographical error.

[2]Assume that 0140 reported in paper is a typographical error.

[3]Assume that 0290 reported in paper is a typographical error.

[4]Assume that 0232 reported in paper is a typographical error.

focal depth of 10 km for small and moderate earthquakes and 15 km for large earthquakes.

- Does not recommend use of relation for Zagros and soil sites due to lack of data (15 records) and large σ.
- Compares recorded and predicted motions for some ranges of magnitudes and concludes that they are similar.

3.42. MCVERRY *ET AL.* (2006)

- Ground motion model for crustal earthquakes is:

$$\begin{aligned}\ln \mathrm{SA}'_{A/B}(T) &= C'_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C'_5(T)r + \\ &[C'_8(T) + C_{6AS}(M-6)]\ln\sqrt{r^2 + C^2_{10AS}(T)} + C'_{46}(T)r_{VOL} + C_{32}\mathrm{CN} + \\ &C_{33AS}(T)\mathrm{CR} + F_{HW}(M,r)\end{aligned}$$

Ground motion model for subduction earthquakes is:

$$\begin{aligned}\ln \mathrm{SA}'_{A/B}(T) &= C'_{11}(T) + \{C_{12Y} + [C'_{15}(T) - C'_{17}(T)]C_{19Y}\}(M-6) + C_{13Y}(T)(10-M)^3 + \\ &C'_{17}(T)\ln[r + C_{18Y}\exp(C_{19Y}M)] + C'_{20}(T)H_c + C'_{24}(T)\mathrm{SI} + C'_{46}(T)r_{VOL}(1-\mathrm{DS})\end{aligned}$$

where $C_{15}'(T)=C_{17Y}(T)$. For both models:

$$\ln \mathrm{SA}'_{C,D}(T) = \ln \mathrm{SA}'_{A/B}(T) + C'_{29}(T)\delta_C + [C_{30AS}(T)\ln(\mathrm{PGA}'_{A/B} + 0.03) + C'_{43}(T)]\delta_D$$

where $PGA'_{A/B}=SA'_{A/B}(T=0)$. Final model given by:

$$\mathrm{SA}_{A/B,C,D}(T) = \mathrm{SA}'_{A/B,C,D}(T)(\mathrm{PGA}_{A/B,C,D}/\mathrm{PGA}'_{A/B,C,D})$$

where r_{VOL} is length in km of source-to-site path in volcanic zone and $F_{HW}(M,r)$ is hanging wall factor of Abrahamson & Silva (1997). Coefficients for *PGA* (larger component) are: C_1=0.28815, C_3=0, C_4=-0.14400, C_5=-0.00967, C_6=0.17000, C_8=-0.70494, C_{10}=5.60000, C_{11}=8.68354, C_{12}=1.41400, C_{13}=0, C_{15}=-2.552000, C_{17}=-2.56727, C_{18}=1.78180, C_{19}=0.55400, C_{20}=0.01550, C_{24}=-0.50962, C_{29}=0.30206, C_{30}=-0.23000, C_{32}=0.20000, C_{33}=0.26000, C_{43}=-0.31769, C_{46}=-0.03279, σ_{M6}=0.4865, σ_{slope}=-0.1261, where $\sigma=\sigma_{M6}+\sigma_{slope}(M_W-6)$ for $5<M_W<7$, $\sigma=\sigma_{M6}-\sigma_{slope}$ for $M_W<5$ and $\sigma=\sigma_{M6}+\sigma_{slope}$ for $M_W>7$ (intra-event), and τ=0.2687 (inter-event). Coefficients for *PGA'* (larger component) are: C_1=0.18130, C_3=0, C_4=-0.14400, C_5=-0.00846, C_6=0.17000, C_8=-0.75519, C_{10}=5.60000, C_{11}=8.10697, C_{12}=1.41400, C_{13}=0, C_{15}=-2.552000, C_{17}=-2.48795, C_{18}=1.78180, C_{19}=0.55400, C_{20}=0.01622, C_{24}=-0.41369, C_{29}=0.44307, C_{30}=-0.23000, C_{32}=0.20000, C_{33}=0.26000, C_{43}=-0.29648, C_{46}=-0.03301, σ_{M6}=0.5035, σ_{slope}=-0.0635 and τ=0.2598.

- Use site classes (combine A and B together and do not use data from E):

A, Strong rock. Strong to extremely-strong rock with: a) unconfined compressive strength >50 MPa, and b) $V_{s,30}$>1500 ms^{-1}, and c) not underlain by materials with compressive strength <18 MPa or V_s<600 ms^{-1}.

B, Rock. Rock with: a) compressive strength between 1 and 50 MPa, and b) $V_{s,30}$>360 ms^{-1}, and c) not underlain by materials having compressive strength <0.8 MPa or V_s<300 ms^{-1}.

C, δ_C=1, δ_D=0 Shallow soil sites. Sites that: a) are not class A, class B or class E sites, and b) have low-amplitude natural period, T, ≤0.6 s, or c) have soil depths ≤ these depths:

Soil type and description		Maximum soil depth (m)
Cohesive soil	Representative undrained shear strengths (kPa)	
Very soft	<12.5	0
Soft	12.5–25	20
Firm	25–50	25
Stiff	50–100	40
Very stiff or hard	100–200	60
Cohesionless soil	Representative SPT N values	
Very loose	<6	0
Loose dry	6–10	40
Medium dense	10–30	45
Dense	30–50	55
Very dense	>50	60
Gravels	>30	100

D, δ_D=1, δ_C=0 Deep or soft soil sites. Sites that: a) are not class A, class B or class E sites, and b) have a low-amplitude T>0.6 s, or c) have soil depths > depths in table above, or c) are underlain by <10 m of soils with an undrained shear-strength <12.5 kPa or soils with SPT N-values <6.

E, Very soft soil sites. Sites with: a) >10 m of very soft soils with undrained shear-strength <12.5 kPa, b) >10 m of soils with SPT N values <6, c) >10 m of soils with V_S<150 ms^{-1}, or d) >10 m combined depth of soils with properties as described in a), b) and c).

Categories based on classes in existing New Zealand Loadings Standard but modified following statistical analysis. Note advantage of using site categories related to those in loading standards. Site classifications based on site periods but generally categories from site descriptions.

- Classify earthquakes in three categories:

  Crustal, Earthquakes occurring in the shallow crust of overlying Australian plate. 24 earthquakes. Classify into:

  Strike-slip $-33\leq\lambda\leq33^\circ$, $147\leq\lambda\leq180^\circ$ or $-180\leq\lambda\leq-147^\circ$ where λ is the rake. 6 earthquakes. Centroid depths, H_C, $4\leq H_C\leq13$ km. $5.20\leq M_W\leq6.31$. CN=0, CR=0.

  Normal $-146\leq\lambda\leq-34^\circ$. 7 earthquakes. $7\leq H_C\leq17$ km. $5.27\leq M_W\leq7.09$. CN=-1, CR=0.

  Oblique-reverse $33\leq\lambda\leq66^\circ$ or $124\leq\lambda\leq146^\circ$. 3 earthquakes. $5\leq H_C\leq19$ km. $5.75\leq M_W\leq6.52$. CR=0.5, CN=0.

  Reverse $67\leq\lambda\leq123^\circ$. 8 earthquakes. $4\leq H_C\leq13$ km. $5.08\leq M_W\leq7.23$. CR=1, CN=0.

  Interface, Earthquake occurring on the interface between Pacific and Australian plates with H_C<50 km. 5 reserve and 1 strike-slip with reverse component. Use data with $15\leq H_C\leq24$ km. Classify using location in 3D space. 6 earthquakes. $5.46\leq M_W\leq6.81$. SI=1, DS=0.

  Slab, Earthquakes occurring in slab source zone within the subducted Pacific plate. Predominant mechanism changes with depth. 19 earthquakes. $26\leq H_C\leq149$ km. Split into shallow slab events with $H_C\leq50$ km (9 normal and 1 strike-slip, $5.17\leq M_W\leq6.23$) and deep slab events with H_C>50 km (6 reverse and 3 strike-slip, $5.30\leq M_W\leq6.69$). SI=0, DS=1 (for deep slab events).

Note seismicity cross sections not sufficient to distinguish between interface and slab events, also require source mechanism.

- Find that mechanism is not a significant extra parameter for motions from subduction earthquakes.
- State that model is not appropriate for source-to-site combinations where the propagation path is through the highly attenuating mantle wedge.

- Note magnitude range of New Zealand is limited with little data for large magnitudes and from short distances. Most data from d>50 *km* and M_W<6.5.
- Only include records from earthquakes with available M_W estimates because correlations between M_L and M_W are poor for New Zealand earthquakes. Include two earthquakes without M_W values (M_S was converted to M_W) since they provide important data for locations within and just outside the Central Volcanic Region.
- Only include data with centroid depth, mechanism type, source-to-site distance and a description of site conditions.
- Only include records with PGA above these limits (dependent on resolution of instrument):

  Acceleroscopes (scratch-plates): 0.02 g

  Mechanical-optical accelerographs: 0.01 g

  Digital 12-bit accelerographs: 0.004 g

  Digital 16-bit accelerographs: 0.0005 g
- Exclude data from two sites: Athene A (topographic effect) and Hanmer Springs (site resonance at 1.5–1.7 Hz) that exhibit excessive amplifications for their site class.
- Exclude data from sites of class E (very soft soil sites with 10 m of material with V_S<150 ms^{-1}) to be consistent with Abrahamson & Silva (1997) and Youngs *et al.* (1997). Not excluded because of large amplifications but because spectra appear to have site-specific characteristics.
- Exclude records from bases of buildings with >4 storeys because may have been influenced by structural response.
- Exclude data from very deep events with travel paths passing through the highly attenuating mantle were excluded.
- Only use response spectral ordinates for periods where they exceed the estimated noise levels of the combined recording and processing systems.
- Lack of data from near-source. Only 11 crustal records from distances <25 km with 7 of these from 3 stations. To constrain model at short distances include overseas PGA data using same criteria as used for New Zealand data. Note that these data were not intended to be comprehensive for 0–10 km range but felt to be representative. Note that it is possible New Zealand earthquakes may produce PGAs at short distances different that those observed elsewhere but feel that it is better to constrain the near-source behaviour rather than predict very high PGAs using an unconstrained model.
- In order to supplement limited data from moderate and high-strength rock and from the volcanic region, data from digital seismographs were added.
- Data corrected for instrument response.
- Derive model from ‘base models’ (other ground-motion models for other regions). Select ‘base model’ using residual analyses of New Zealand data w.r.t. various models. Choose models of Abrahamson & Silva (1997) for crustal

earthquakes and Youngs *et al.* (1997). Link these models together by common site response terms and standard deviations to get more robust coefficients.

- Apply constraints using ‘base models’ to coefficients that are reliant on data from magnitude, distance and other model parameters sparsely represented in the New Zealand data. Coefficients constrained are those affecting estimates in near-source region, source-mechanism terms for crustal earthquakes and hanging-wall terms. Eliminate some terms in ‘base models’ because little effect on measures of fit using Akaike Information Criterion (AIC).
- Apply the following procedure to derive model. Derive models for PGA and SA using only records with response spectra available (models with primed coefficients). Next derive model for PGA including records without response spectra (unprimed coefficients). Finally multiply model for SA by ratio between the PGA model using all data and that using only PGA data with corresponding response spectra. Apply this method since PGA estimates using complete dataset for some situations (notably on rock and deep soil and for near-source region) are higher than PGA estimates using reduced dataset and are more in line with those from models using western US data. This scaling introduces a bias in final model. Do not correct standard deviations of models for this bias.
- Use d_r for 10 earthquakes and d_c for rest. For most records were d_c was used, state that it is unlikely model is sensitive to use d_c rather than d_r. For five records discrepancy likely to be more than 10%.
- Free coefficients are: C_1, C_{11}, C_8, C_{17}, C_5, C_{46}, C_{20}, C_{24}, C_{29} and C_{43}. Other coefficients fixed during regression. Coefficients with subscript AS are from Abrahamson & Silva (1997) and those with subscript Y are from Youngs *et al.* (1997). Try varying some of these fixed coefficients but find little improvement in fits.
- State that models apply for $5.25 \leq M_W \leq 7.5$ and for distances ≤ 400 km, which is roughly range covered by data.
- Note possible problems in applying model for $H_c>150$ km therefore suggest H_c is fixed to 150 km if applying model to deeper earthquakes.
- Note possible problems in applying model for $M_W<5.25$.
- Apply constraints to coefficients to model magnitude- and distance-saturation.
- Try including an anelastic term for subduction earthquakes but find insignificant.
- Investigate possibility of different magnitude-dependence and attenuation rates for interface and slab earthquakes but this required extra parameters that are not justified by AIC.
- Investigate possible different depth dependence for interface and slab earthquakes but extra parameters not justified in terms of AIC.
- Try adding additive deep slab term but not significant according to AIC.
- Cannot statistically justify nonlinear site terms. Believe this could be due to lack of near-source records.

- Find that if a term is not included for volcanic path lengths then residuals for paths crossing the volcanic zone are increasingly negative with distance but this trend is removed when a volcanic path length term is included.
- Compare predictions to observed ground motions in 21/08/2003 Fiordland interface (M_W7.2) earthquake and its aftershocks. Find ground motions, in general, underestimated.

3.43. SOURIAU (2006)

- Ground motion model is:

$$\log_{10}(\mathrm{PGA}) = a + bM + c\log_{10} R$$

where y is in ms^{-2}, a=-2.50±0.18, b=0.99±0.05 and c=-2.22±0.08 when M=M_{LDG} and a=-2.55±0.19, b=1.04±0.05 and c=-2.17±0.08 when M=M_{ReNass} (σ is not given although notes that ‘explained variance is of the order of 84%’).

- Focal depths between 0 and 17 km.
- Most data from R<200 km.
- Uses PGAs from S-waves.
- Finds that introducing an anelastic attenuation term does not significantly improve explained variance because term is poorly constrained by data due to trade offs with geometric term and travel paths are short. When an anelastic term is introduced finds: $\log_{10}(PGA)=-3.19(\pm0.25)+1.09(\pm0.05)M_{ReNass}-1.83(\pm0.12)\log_{10}R-0.0013(\pm0.0004)R$.

3.44. ZARE & SABZALI (2006)

- Ground motion model is:

$$\log \mathrm{Sa}(T) = a_1(T)M + a_2(T)M^2 + b(T)\log(R) + c_i(T)S_i$$

where Sa is in g, a_1=0.5781, a_2=-0.0317, b=-0.4352, c_1=-2.6224, c_2=-2.5154, c_3=-2.4654, c_4=-2.6213 and σ=0.2768 (for horizontal PGA), a_1=0.5593, a_2=-0.0258, b=-0.6119, c_1=-2.6261, c_2=-2.6667, c_3=-2.5633, c_4=-2.7346 and σ=0.2961 (for vertical PGA).

- Use four site classes based on fundamental frequency, f, from receiver functions:

  Class 1 f>15 Hz. Corresponds to rock and stiff sediment sites with $V_{s,30}$>700 ms^{-1}. 22 records. S_1=1 and other S_i=0.

  Class 2 5<f≤15 Hz. Corresponds to stiff sediments and/or soft rocks with 500<$V_{s,30}$≤700 ms^{-1}. 16 records. S_2=1 and other S_i=0.

Class 3 $2<f \leq 5$ Hz. Corresponds to alluvial sites with $300<V \leq 500$ ms^{-1}. 25 records. S_3=1 and other S_i=0.

Class 4 $f \leq 2$ Hz. Corresponds to thick soft alluvium. 26 records. S_4=1 and other S_i=0.

- Separate records into four mechanisms: reverse (14 records), reverse/strike-slip (1 record), strike-slip (26 records) and unknown (48 records).
- Select records that have PGA >0.05 g on at least one component and are of good quality in frequency band of 0.3 Hz or less.
- Find results using one- or two-step regression techniques are similar. Only report results from one-step regression.
- M_W for earthquakes obtained directly from level of acceleration spectra plateau of records used.
- d_h for records obtained from S-P time difference.
- Most data from d_h<60 km.
- Bandpass filter records with cut-offs of between 0.08 and 0.3 Hz and between 16 and 40 Hz.
- Note that the lack of near-field data is a limitation.

3.45. ZHAO *ET AL.* (2006) AND FUKUSHIMA *ET AL.* (2006)

- Ground motion model is:

$$\begin{aligned} \log_e(y) &= aM_w + bx - \log_e(r) + e(h-h_c)\delta_h + F_R + S_I + S_S + S_{SL}\log_e(x) + C_k \\ \text{where} \quad r &= x + c\exp(dM_w) \end{aligned}$$

where y is in cms^{-2}, δ_h=1 when $h \geq h_c$ and 0 otherwise, a=1.101, b=-0.00564, c=0.0055, d=1.080, e=0.01412, S_R=0.251, S_I=0.000, S_S=2.607, S_{SL}=-0.528, C_H=0.293, C_1=1.111, C_2=1.344, C_3=1.355, C_4=1.420, σ=0.604 (intra-event) and τ=0.398 (inter-event). Use h_c=15 km because best depth effect for shallow events.

- Use five site classes (T is natural period of site):

Hard rock NEHRP site class A, $V_{s,30}$>1100 ms^{-1}. 93 records. Use C_H.

SC I Rock, NEHRP site classes A+B, $600<V_{s,30} \leq 1100$ ms^{-1}, T<0.2 s. 1494 records. Use C_1.

SC II Hard soil, NEHRP site class C, $300<V_{s,30} \leq 600$ ms^{-1}, $0.2 \leq T<0.4$ s. 1551 records. Use C_2.

SC III Medium soil, NEHRP site class D, $200<V_{s,30} \leq 300$ ms^{-1}, $0.4 \leq T<0.6$ s. 629 records. Use C_3.

SC IV Soft soil, NEHRP site classes E+F, $V_{s,30} \leq 200$ ms^{-1}, $T \geq 0.6$ s. 989 records. Use C_4.

Site class unknown for 63 records.

- Focal depths, h, between about 0 and 25 km for crustal events, between about 10 and 50 km for interface events, and about 15 and 162 km for intraslab events. For earthquakes with $h>125$ km use $h=125$ km.
- Classify events into three source types:

  Crustal.

  Interface. Use S_I.

  Slab. Use S_S and S_{SL}.

and into four mechanisms using rake angle of $\pm 45^{\circ}$ as limit between dip-slip and strike-slip earthquakes except for a few events where bounds slightly modified:

Reverse. Use F_R if also crustal event.

Strike-slip

Normal

Unknown

Distribution of records by source type, faulting mechanism and region is given in following table.

Region	Focal Mechanism	Crustal	Interface	Slab	Total
Japan	Reverse	250	1492	408	2150
	Strike-slip	1011	13	574	1598
	Normal	24	3	735	762
	Unknown			8	8
	Total	1285	1508	1725	4518
Iran and Western USA	Reverse	123	12		135
	Strike-slip	73			73
	Total	196	12		208
All	Total	1481	1520	1725	4726

- Exclude data from distances larger than a magnitude-dependent distance (300 km for intraslab events) to eliminate bias introduced by untriggered instruments.
- Only few records from <30 km and all from <10 km from 1995 Kobe and 2000 Tottori earthquake. Therefore add records from overseas from <40 km to constrain near-source behaviour. Note that could affect inter-event error but since only 20 earthquakes (out of 269 in total) added effect likely to be small.
- Do not include records from Mexico and Chile because Mexico is characterised as a ‘weak’ coupling zone and Chile is characterised as a ‘strong’ coupling zone (the two extremes of subduction zone characteristics), which could be very different than those in Japan.
- Note reasonably good distribution w.r.t. magnitude and depth.
- State that small number of records from normal faulting events does not warrant them between considered as a separate group.
- Note that number of records from each event varies greatly.
- Process all Japanese records in a consistent manner. First correct for instrument response. Next low-pass filter with cut-offs at 24.5 Hz for 50 samples-per-second data and 33 Hz for 100 samples-per-second data. Find that this step does not noticeably affect short period motions. Next determine location of other end of usable period range. Note that this is difficult due to lack of estimates of recording noise. Use the following procedure to select cut-off:
    1. Visually inspect acceleration time-histories to detect faulty recordings, S-wave triggers or multiple events.
    2. If record has relatively large values at beginning (P wave) and end of record, the record was mirrored and tapered for 5 s at each end.
    3. Append 5 s of zeros at both ends and calculate displacement time-history in frequency domain.
    4. Compare displacement amplitude within padded zeros to peak displacement within the record. If displacement in padded zeros was relatively large, apply a high-pass filter.
    5. Repeat using high-pass filters with increasing corner frequencies, f_C, until the displacement within padded zeros was ‘small’ (subjective judgement). Use $1/f_C$ found as maximum usable period.

Verify method by using K-Net data that contains 10 *s* pre-event portions.

- Conduct extensive analysis on inter- and intra-event residuals. Find predictions are reasonably unbiased w.r.t. magnitude and distance for crustal and interface events and not seriously biased for slab events.
- Do not smooth coefficients.
- Do not impose constraints on coefficients. Check whether coefficient is statistically significant.
- Note that the assumption of the same anelastic attenuation coefficient for all types and depths of earthquakes could lead to variation in the anelastic attenuation rate in a manner that is not consistent with physical understanding of anelastic attenuation.

- Derive C_H using intra-event residuals for hard rock sites.
- Residual analyses show that assumption of the same magnitude scaling and near-source characteristics for all source types is reasonable and that residuals not not have a large linear trend w.r.t. magnitude. Find that introducing a magnitude-squared term reveals different magnitude scaling for different source types and a sizable reduction in inter-event error. Note that near-source behaviour mainly controlled by crustal data. Derive correction function from inter-event residuals of each earthquake source type separately to avoid trade-offs. Form of correction is: $\log_e(S_{MSst})=P_{st}(M_W\text{-}M_C)+Q_{st}(M_W\text{-}M_C)^2+W_{st}$. Derive using following three-step process:
  1. Fit inter-event residuals for earthquake type to a quadratic function of M_W-M_C for all periods.
  2. Fit coefficients P_{st} for (M_W-M_C) and Q_{st} for $(M_W\text{-}M_C)^2$ (from step 1) where subscript *st* denotes source types, to a function up to fourth oder of $\log_e(T)$ to get smoothed coefficients.
  3. Calculate mean values of differences between residuals and values of $P_{st}(M_W\text{-}M_C)+Q_{st}(M_W\text{-}M_C)^2$ for each earthquake, W_{st}, and fit mean values W_{st} to a function of $\log_e(T)$.

For PGA Q_C=W_C=Q_I=W_I=0, τ_C=0.303, τ_I=0.308, P_S=0.1392, Q_S=0.1584, W_S=-0.0529 and τ_S=0.321. Since magnitude-square term for crustal and interface is not significant at short periods when coefficient for magnitude-squared term is positive, set all coefficients to zero. Find similar predicted motions if coefficients for magnitude-squared terms derived simultaneously with other coefficients even though the coefficients are different than those found using the adopted two-stage approach.

- Compare predicted and observed motions normalized to M_W7 and find good match for three source types and the different site conditions. Find model overpredicts some near-source ground motions from SC III and SC IV that is believed to be due to nonlinear effects.

4. General characteristics of attenuation relations for peak ground acceleration

Table 4.1 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

Mmin Magnitude of smallest earthquake

Mmax 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

dmin Shortest source-to-site distance in km

dmax Longest source-to-site distance in km

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
- B Both components
- C Randomly chosen component
- D50 *GMrotD*50 (Boore *et al.* , 2006).
- G Geometric mean
- I50 *GMrotI*50 (Boore *et al.* , 2006).
- L Larger component
- M Mean (not stated what type)
- N Fault normal
- O Randomly oriented component
- P Fault parallel
- 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 mechanisms which are separately modelled), where:

- A All (this is assumed if no information is given in the reference)
- B Interslab

C Shallow crustal
F Interface
I Intraplate
M Mining-induced
N Normal
O Oblique or odd (Frohlich & Apperson, 1992)
R Reverse
S Strike-slip
T Thrust

‘+’ 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.

Tab. 4.1: 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
Loh *et al.* (1991)	Taiwan	112	-	63	4.0	7.1	M_L	5.0	178.3	d_h	1	L	U	A
Aman *et al.* (1995)	Himalayan region	84*	-	5	5.7	7.2	M_B	3*	350*	d_e	1	U	U	A
Inan *et al.* (1996)	Turkey	U	-	U	U	U	U	U	U	d_e	1	U	U	A
Reyes (1998)	University City, Mexico City	20+	-	20+	U	U	M_w	U	U	d_r	I	S	U	A
Field (2000)	S California	447	-	28	5.1	7.5	M_w	0	148.9	d_f	C (6)	G	1M	A (R, S, O)
Herak *et al.* (2001)	Dinarides	145	145	46	4.5	6.8	M_L	3*	200*	d_e	1	L	2	A
Skarlatoudis *et al.* (2003)	Greece	1000	-	225	4.5	7.0	M_w (M_L)	1.5*	150*	d_e	2	U	O	A (N, ST)
Bragato (2004)	NE Italy (45–46.5°N & 12–14°E)	814	-	192	2.5	4.5	M_L	U	U	d_e	1	U	O	A
Gupta & Gupta (2004)	Koyna region, India	31	31	U	U	6.5	M_L	3*	25*	d_h	1	L	O	A
Kalkan & Gülkan (2004a)	Turkey	-	100	47	4.2	7.4	M_w (unspecified scales)	1.2	250	d_f, d_e for small events	3	-	1	A
Kalkan & Gülkan (2004b) and Kalkan & Gülkan (2005)	Turkey	112	-	57	4.0	7.4	M_w (unspecified scales)	1.2	250	d_f, d_e for small events	3	L[1]	1	A
Lubkowski *et al.* (2004)	Stable continental regions	163	-	U	3.0	6.8	M_w (M_L)	0	854	d_e (d_f for 1 event)	1	U	1, 1M, 2, 2M	A
Marin *et al.* (2004)	France	63	-	14	2.6	5.6	M_L	5	700	d_h	1	L	1	A
Midorikawa & Ohtake (2004)	Japan	3335	-	33	5.5	8.3	M_w	0*	300*	d_r	2	L	1	A (C, B, F)
Özbey *et al.* (2004)	NW Turkey	195	-	17	5.0	7.4	M_w (M_L)	5*	300*	d_f	3	G	1M	NS
Pankow & Pechmann (2004) and Pankow & Pechmann (2006)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	d_f	2	G, O	1M	NS
Sunuwar *et al.* (2004)	Okhotsk-Amur plate boundary	667	667	42	4.0	5.6	M_{JMA}	>3	>264	d_h	1	L	2M	A
Skarlatoudis *et al.* (2004)	Greece	819	-	423	1.7	5.1	M_w	3	40	d_e	1	U	O	A

continued on next page

[1] The caption of their Table 2 states that reported coefficients are for mean.

Tab. 4.1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$d_{\min}$	$d_{\max}$	d scale	S	C	R	M
Ulusay *et al.* (2004)	Turkey	221	-	122	4.1	7.5	M_w (M_s, m_b, M_d, M_L)	5.1	99.7	d_e	3	L	I	A
Ambraseys *et al.* (2005a)	Europe & Middle East	595	-	135	5.0	7.6	M_w	0	99	d_f (d_e for small events)	3	L	1WM	A (N, T, S, O)
Ambraseys *et al.* (2005b)	Europe & Middle East	-	595	135	5.0	7.6	M_w	0	99	d_f (d_e for small events)	3	-	1WM	A (N, T, S, O)
Bragato (2005)	Worldwide	243	-	60*	5.0	7.8	M_s	0	15	d_f	1	L	O	A
Bragato & Slejko (2005)	E Alps (45.6–46.8°N & 12–14°E)	1402	3168	240	2.5	6.3	M_L	0	130	d_f & d_e	1	R	O	A
Frisenda *et al.* (2005)	NW Italy	6899[2]	-	>1152	0.0*	5.1[3]	M_L	0	300[4]	d_h	2	B	1	A
García *et al.* (2005)	Central Mexico	277	277	16	5.2	7.4	M_w	4*	400*	d_r for $M_w > 6.5$, d_h otherwise	1	G[5]	1M	B
Liu & Tsai (2005)	Taiwan	7907	7907	51	4.05	7.10	M_w (M_L)	5*	300*	d_h	1	M	2M	A
McGarr & Fletcher (2005)	Central Utah coal-mining areas	72	-	12	0.98	4.2	M_w (M_{CL})	0.5*	10*	d_h	2	L	2M	M
Atkinson (2006)	Los Angeles region	4179	-	485+	3.1*	7.1*	M_w	5*	300*	d_e (d_f for some)	I, C	B	1	A

continued on next page

[2] Authors state in text that ‘more than 14 000’ values were used but their Table 1 gives 2×6899.
[3] State equations valid to 4.5.
[4] State equations valid up to 200 km.
[5] Call it ‘quadratic mean’, which is assumed to be geometric mean.

Tab. 4.1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$d_{\min}$	$d_{\max}$	d scale	S	C	R	M
Beyer & Bommer (2006)	Shallow crustal (USA, Taiwan, Turkey and others)	949	-	103	4.3*	7.9*	M_w	6*	200*	d_h	U	1, 2, A, B, C, D50, G, I50, L, N, P, R	1M	A (U)
Bindi *et al.* (2006)	Umbria-Marche	239	-	45	4.0	5.9	M_L	1*	100*	d_e & d_h	4	L	1M	NS
Campbell & Bozorgnia (2006a) and Campbell & Bozorgnia (2006b)	Worldwide	1500+	-	60+	4.2	7.9	M_w	0	200	d_r	C	G	2M	A (R, S, N)
Costa *et al.* (2006)	NE Italy & Slovenia	900*	900*	123	3.0*	6.5*	U	1*	100*	d_e	2	L, V	1	A
Gómez-Soberón *et al.* (2006)	Mexico	1983	-	109	4.5*	8.1*	M_w (M_s if $M > 6$, m_b if $M < 6$)	5*	800*	d_h (d_r for some)	1	U	2	F
Hernandez *et al.* (2006)	Haulien LSTT (Taiwan)	456	456	51	5	7.3	M_L	13.7	134.8	d_h	5	B	1	A
Kanno *et al.* (2006)	Japan+some foreign	3392+377 (shallow) & 8150 (deep)	-	73+10 & 111	5.0* (6.1) & 5.5*	8.2* (7.4) & 8.0*	M_w (M_{JMA})	1* (1.5*) & 30*	450* (350*) & 450*	d_r (d_h for some)	C	R	2M	A
Laouami *et al.* (2006)	Algeria	28	-	4	5.6	6.0	M_s	13	70	d_e & d_h	1	U	1	A
Luzi *et al.* (2006)	Molise (Italy)	886	-	U	2.6*	5.7	M_L	5*	55*	d_h	2	L	1M	A
Mahdavian (2006)	Central Iran[6]	150	150	U	3.1	7.4	M_s (m_b)	4	98	d_h	2	A	1	A
McVerry *et al.* (2006)	New Zealand+66 overseas	535+66	-	49+17	5.08 (5.2)	7.23 (7.4)	M_w	6 (0.1)	400 (10)	d_c (d_r)	3	L, G	1M	C (R, OR, S & N) & F, B
Souriau (2006)	France	175	-	20	3.0	5.4	M_L (ReNass & LDG)	10*	800*	d_h	1	L	1	A

continued on next page

[6] Also develops equations for Zagros using 98 records from an unknown number of earthquakes.

Tab. 4.1: *continued*

Reference	Area	H	V	E	$M_{\min}$	$M_{\max}$	M scale	$d_{\min}$	$d_{\max}$	d scale	S	C	R	M
Zare & Sabzali (2006)	Iran	89	89	55*	2.7	7.4	M_w	4	167	d_h	4	U	1M & 2M	A
Zhao *et al.* (2006) and Fukushima *et al.* (2006)	Japan+208 overseas	4518+208	-	249+20	5.0	8.3	M_w	0*	300*	d_r	5	G	1M	C (R, S/N) & F, B

5. Summary of published attenuation relations for spectral ordinates

5.1. LOH *ET AL.* (1991)

- See Section 3.1.
- Response parameters are acceleration, velocity and displacement for 5% damping.
- Only give coefficients for acceleration for periods ≥0.1 s.

5.2. BOORE *ET AL.* (1994), BOORE *ET AL.* (1997) AND BOORE (2005)

- See Section 3.2.

5.3. REYES (1998)

- See Section 3.5.
- Response parameter is acceleration for 5% damping.

5.4. SPUDICH *ET AL.* (1999) AND SPUDICH & BOORE (2005)

- See Section 3.6.

5.5. 5 FIELD (2000)

- See Section 3.7.
- Distribution w.r.t. site class for 3.0 *s* is: B, 10 records; BC, 27 records; C, 13 records; CD, 119 records; D, 187 records; DE, 1 record.
- Response parameter is acceleration for 5% damping.
- Constrains b_3 for 1.0 and 3.0 *s* to zero because originally finds positive value.
- 151 records have basin-depth estimates.
- Does not find significant slopes for residuals w.r.t. predicted ground motion at BC sites.
- Plots squared residuals w.r.t. V_S and finds small significant trends for 1.0 and 3.0 *s*.

5.6. CAMPBELL & BOZORGNIA (2003D) (2003A) (2003B) (2003C)

- See Section 3.9.

5.7. KALKAN & GÜLKAN (2004A)

- See Section 3.13.
- Response parameter is pseudo-acceleration for 5% damping.

5.8. KALKAN & GÜLKAN (2004B) AND KALKAN & GÜLKAN (2005)

- See Section 3.14.
- Response parameter is pseudo-acceleration for 5% damping.

5.9. MATSUMOTO *ET AL.* (2004)

- Ground-motion model is (for d_r):

$$\log SA(T) = C_m(T)M + C_h(T)H_c - C_d(T)\log[R + 0.334\exp(0.653M)] + C_o(T)$$

Ground-motion model is (for d_q):

$$\log SA(T) = C_m(T)M + C_h(T)H_c - C_d(T)X_{\mathrm{eq}} - \log X_{\mathrm{eq}} + C_o(T)$$

$H_c = h$ for $h<100$ km and $H_c=100$ km for $h>100$ km.

- Response parameter is acceleration for 5% damping.
- Data from 91 dam sites with rock foundations. Most instruments in inspection gallery at lowest elevation (for concrete dams) and in bottom inspection gallery (for embankment dams). Note that $1.8 \le V_p \le 4.5$ kms^{-1} for bedrock of many concrete dams and $1.5 \le V_p \le 3.0$ kms^{-1} for bedrock of embankment dams, which convert to $0.7 \le V_s \le 1.5$ kms^{-1}.
- Select data from $M>5$, $d_e<200$ km and focal depth $h<130$ km.
- Most records from $h<60$ km.
- Most records from $d<100$ km.
- Classify earthquakes into three types:
  - Shallow crustal Epicentres located inland at shallow depths. 175 records[5].
  - Inter-plate Epicentres located in ocean with $h<60$ km. 55 records.
  - Deep intra-slab Epicentres located inland with $h>60$ km. 63 records.
- Know fault source mechanism for 12 earthquakes.
- Adopt $0.334\exp(0.653M)$ from earlier Japanese study.
- Derive coefficients regardless of earthquake type. Then derive correction factors for each earthquake type.
- Do not report coefficients only graphs of coefficients against period.

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[5]The authors also give number of 'sets' as 81 for shallow crustal, 29 for inter-plate and 29 for deep intra-slab

- Find good agreement between predicted spectra and observed spectra for two stations that recorded the magnitude 8.0 Tokati-oki 2003 earthquake.

5.10. ÖZBEY *ET AL.* (2004)

- See Section 3.18.
- Response parameter is acceleration for 5% damping.

5.11. PANKOW & PECHMANN (2004) AND PANKOW & PECHMANN (2006)

- See Section 3.19.
- Response parameter is pseudo-velocity for 5% damping.

5.12. SUNUWAR *ET AL.* (2004)

- See Section 3.20.
- Response parameter is pseudo-acceleration for 5% damping.
- Developed equations up to 5 *s* but do not think results for 4 and 5 *s* are satisfactory.

5.13. TAKAHASHI *ET AL.* (2004)

- Ground-motion model is:

$$\begin{aligned} \log[y(T)] &= aM - bx - \log r + e(h - h_c)\delta_h + S_R + S_I + S_S + S_k \\ r &= x + c\exp(dM) \end{aligned}$$

Use S_R only for crustal reverse events, S_I only for interface events, S_S only for subduction slab events and S_k for each of the site classes (k=1, ..., 4). δ_h=0 for $h<h_c$ and 1 otherwise. For h>125 km use h=125 km.

- Use four site categories:

SC I Rock, natural period T<0.2 s, $V_{s,30}$>600 ms^{-1}, approximately NEHRP classes A and B. 1381 records.

SC II Hard soil, natural period 0.2≤T<0.4 s, 300<$V_{s,30}$≤600 ms^{-1}, approximately NEHRP class C. 1425 records.

SC III Medium soil, natural period 0.4≤T<0.6 s, 200<$V_{s,30}$≤300 ms^{-1}, approximately NEHRP class D. 594 records.

SC IV Soft soil, natural period T≥0.6 s, $V_{s,30}$≤200 ms^{-1}, approximately NEHRP classes E and F. 938 records.

Site classification unknown for 62 records. Prefer using site classes rather than individual coefficients for each station because avoids possibility of source effects being shifted into site terms and can be used when there are only a few records per station.

- Response parameter is acceleration for 5% damping.
- Classify earthquakes into three types:

Crustal	Focal depths ≤25 km. 81 earthquakes, 1497 records.
Interface	88 earthquakes, 1188 records.
Slab	101 earthquakes. 1715 records.

- Classify earthquakes into four mechanisms:

Reverse	160 earthquakes (28 crustal), 1969 records (373 crustal).
Strike-slip	82 earthquakes (39 crustal), 1674 records (1100 crustal).
Normal	26 earthquakes (4 crustal), 749 records (24 crustal).
Unknown	2 earthquakes (0 crustal), 8 records (0 crustal).

Consider differences between reverse and strike-slip motions for crustal earthquakes because enough data but note there is not enough data to consider normal earthquakes as a separate group.

- Focal depths, h, between about 0 and 162 km with most <60 km.
- Exclude data from distances greater than a specified limit for a given magnitude in order to eliminate bias due to untriggered instruments. For subduction slab events, fix maximum distance as 300 km.
- Note that there is little near-source data from Japan from within 30 km. All Japanese data from within 10 km is from two earthquakes (Kobe 1995 and Tottori 2000). Add data from within 40 km from earthquakes in western USA (h<20 km) and from the Tabas 1978 (Iran) earthquake to help constrain near-source behaviour of derived equations. Use data from: Japan (61 crustal earthquakes, 1301 records; 87 interface earthquakes, 1176 records; 101 slab earthquakes, 1715 records) and Iran and western USA (20 crustal earthquakes; 196 records; 1 interface earthquake, 12 records).
- Note that reasonably good distribution of data for all magnitudes and focal depths.
- Note strong correlation between focal depth and distance.
- Use ISC relocations rather than JMA locations because find that they are more reliable.
- Use M_w values from Harvard CMT unless value from special study is available.
- Prefer the one-stage maximum-likelihood method to the two-stage method because when there are many events with only a small number of records and many individual site terms, the coefficients must be determined using an iterative method and hence their reliability is questionable.
- Find that, by residual analysis (not shown), that equations predict unbiased ground motions for crustal and interface events but biased ground motions for slab events with bias that depends on distance. Apply this magnitude-independent path modification factor SF for slab events: $\log(SF)=S_{SL}[\log(\sqrt{(x^2+R_a^2)})-\log(R_c)]$ where R_a=90.0 km and R_c=125.0 km.
- Find that, because of lack of near-source data, it is not possible to find reliable estimates of c and d so use an iterative method to find d by fixing c.

- Estimate site coefficient, S_H, for hard rock sites ($V_{s,30}$=1500 ms^{-1}) from 10 stations with 1020≤$V_{s,30}$≤2200 ms^{-1} with 1436 records, based on residuals.
- Examine residuals w.r.t. magnitude, distance and focal depth for all three source types and find no significant bias. Find that PGAs from two events on east coast of Hokkaido are under-estimated and note that investigation needed to see if it is a regional anomaly. Also find that ground motions from 2003 Miyagi (M_W7.0) event are under-estimated, which note is due to a known regional anomaly.
- Believe model more robust than other models for subduction events due to lower prediction errors.
- Note that predictions for near-source ground motion for subduction events are largely constrained by data from shallow crustal events from western USA hence adding subduction records from <50 *km* could result in improvements.

5.14. YU & HU (2004)

- Ground-motion model is:

$$\log Y = c_1 + c_2 M + c_3 \log(R + c_4 e^{c_5 M})$$

- Response parameter is acceleration for 5% damping.
- Use data from 377 sites with $V_{s,30}$>500 ms^{-1}.
- Use data from the Trinet broadband high and low gain channels (BH and HL). BH are STS-1 and STS-2 instruments and HL are mainly FBA-23 instruments. Use BH data when not clipped and otherwise HL data.
- Eliminate DC offset for each record. Convert ground motions into acceleration while applying a high-pass filter with cut-off of 40 *s*. Display recovered acceleration, velocity and displacement time-histories from a M_L5.1 earthquake from the BH and HL data. Note that they are similar and hence that reliable ground motion can be recovered from these data.
- Display the signal and noise Fourier amplitude spectra for one record and find that the signal-to-noise ratio is higher in the BH channel than in the HL channel. State that the signal-to-noise ratio is still >1 for periods of 20 *s* for both types of data.
- Compute acceleration and relative displacement response spectra for both channels. Find that for periods >0.3 s the response spectra from the two channels are very close. State that the difference for short periods is due to the low sampling rate (20 sps) for the BH channel and the higher (80 or 100 sps) sampling rate for HL channel.
- Conclude that reliable ground motions up to 20 s can be recovered from these data.
- Use a two-stage regression method where first determine c_4 and c_5 and then the other coefficients.

- Most data from digital instruments from $M \leq 5.5$ and $R<300$ km. Most data from analogue instruments from $6.0 \leq M \leq 7.0$ and $10<R<100$ km.
- Use data from analogue instruments for short-period range (0.04–3 s) and data from Trinet instruments for long-period range (1–20 s). Connect the two sets of coefficients at 1.5 s after confirming that the predictions match at this period.
- Do not give coefficients only predictions.

5.15. AMBRASEYS *ET AL.* (2005A)

- See Section 3.23.
- Response parameter is acceleration for 5% damping.
- Only use spectral accelerations within passband of filter ($1.25 f_l$ and f_h) where f_l is the low cut-off frequency and f_h is the high roll-off frequency.
- Note that after 0.8 s the number of records available for regression analysis starts to decrease rapidly and that after 4 s there are few records available. Only conduct regression analysis up to 2.5 s because for longer periods there are too few records to obtain stable results. Note that larger amplitude ground motions are better represented in the set for long-periods (>1 s).
- Find that logarithmic transformation may not be justified for nine periods (0.26, 0.28 and 0.44–0.65 s) by using pure error analysis but use logarithmic transformation since it is justified for neighbouring periods.
- By using pure error analysis, find that for periods >0.95 s the null hypothesis of a magnitude-independent standard deviation cannot be rejected so assume magnitude-independent σ. Note that could be because magnitude-dependent standard deviations are a short-period characteristic of ground motions or because the distribution of data w.r.t. magnitude changes at long periods due to filtering.
- Find that different coefficients are significant at different periods so try changing the functional form to exclude insignificant coefficients and then applying regression again. Find that predicted spectra show considerable variation between neighbouring periods therefore retained all coefficients for all periods even when not significant.
- Note that smoothing could improve the reliability of long-period ground-motion estimates because they were based on less data but that smoothing is not undertaken since the change of weighted to unweighted regression at 0.95 s means a simple function cannot fit both short- and long-period coefficients.

5.16. AMBRASEYS *ET AL.* (2005B)

- See Section 3.24.
- Response parameter is acceleration for 5% damping.
- By using pure error analysis, find that for periods 0.15–0.40, 0.60–0.65, 0.75 and 0.85 s the null hypothesis of a magnitude-independent standard deviation is rejected so use weighted regression for these periods.

5.17. BRAGATO & SLEJKO (2005)

- See Section 3.26.
- Response parameter is acceleration for 5% damping.

5.18. GARCIA *ET AL.* (2005)

- See Section 3.28.
- Response parameter is pseudo-acceleration for 5% damping.
- No coefficient smoothing performed because coefficients w.r.t. frequency show acceptable behaviour.

5.19. MCGARR & FLETCHER (2005)

- See Section 3.30.
- Response parameter is pseudo-velocity for 5% damping.
- Constrain k to 0 for $T \geq 0.5$ *s* because otherwise positive.

5.20. POUSSE *ET AL.* (2005)

- Ground-motion model is:

$$\log_{10}(\mathrm{PSA}(f)) = a(f)M + b(f)X - \log_{10}(X) + S_k$$

  Select this form to compare results with Berge-Thierry *et al.* (2003).
- Use five Eurocode 8 categories:

  A $V_{s,30}>800$ ms^{-1}, use S_1

  B $360<V_{s,30}<800$ ms^{-1}, use S_2

  C $180<V_{s,30}<360$ ms^{-1}, use S_3

  D $V_{s,30}<180$ ms^{-1}, use S_4

  E Soil D or C underlain in first 20 m by a layer of $V_{s,30}>800$ ms^{-1}, use S_5

  where $V_{s,30}$ is average shear-wave velocity in upper 30 m. Since soil profiles only available up to 20 m, use method of Atkinson & Boore (2003) to assign sites to categories using Kik-Net profiles to define probability curves. Generate five redistributions to test stability of results. Find coefficients and σ relative stable (changes less than 10%) except for site class A (changes up to 50%.
- Response parameter is pseudo-acceleration for 5% damping.
- Use data from the K-Net and Kik-Net networks.
- Process records using non-causal 4 pole Butterworth filter with cut-offs of 0.25 and 25 Hz for consistency with earlier studies.
- Select records from events with $M_W>4$ and with focal depth <25 km to exclude records of subduction events and to remain close to tectonic conditions in France.

- Exclude records from distances greater than the distance predicted by a magnitude-dependent equation predicting the location of a PGA threshold of 10 cms^{-2} (corresponding to trigger of older Japanese sensors) to prevent possible underestimation of attenuation rate.
- Visually inspect records to check for glitches and to use only main shock if multiple events present.
- Convert M_{JMA} to M_w to compare results with other studies.
- For 10 large earthquakes for which source dimensions are known use d_r.
- Note good distribution w.r.t. M_w and d_r except between 6.1 and 7.3 where only two events.
- Find that pseudo-acceleration at 0.01 *s* equals PGA.
- Also compute coefficients using geometric mean and find identical coefficients and standard deviations lower by 0.02.
- Find σ lower when use five site classes than when no site information is used.
- Find peak in σ at about 1 s. Peak also present when unfiltered data used. Also present when data from different magnitude ranges (4.0–4.5, 4.0–5.0, 4.0–5.5 and 4.0–6.0) are used.
- Note that results for site class E are uncertain due to limited number of records.
- Examine residuals w.r.t. distance and magnitude and find no significant bias.
- Examine quartile plots of residuals and find that residuals are normally distributed up to 2–4 σs. All pass Kolmogorov-Smirnov test at 5% significance level for normality except at 0.01 s.
- Conducted sensitivity analysis by changing minimum magnitude, geographical area and minimum number of events recorded at each station. Find dependence of σ on period was similar as were site coefficients. *b* shows some variations.
- Coefficients not reported.

5.21. ATKINSON (2006)

- See Section 3.31.
- Response parameter is pseudo-acceleration for 5% damping.
- Compares predictions to observations grouped into 1-unit magnitude bins at 0.3 and 1.0 s and finds equations are reasonable description of data. Also compares predictions to observations from large magnitudes events and from close distances and finds that equations would overestimate short-period motions from large events at close distances.
- Compares overall distribution of residuals for 0.3 s with normal distribution. Finds that residuals generally follow normal distribution but data shows greater number of large-residual observations that predicted by normal distribution, most of which come from a single event (22/02/2000 **M**3.24) recorded at >100 km. Finds no evidence for truncation of residuals up to three standard deviations.

- For analysis of Landers events, regresses 0.3 *s* data for 10 stations with more than 50 records using same functional form without distance terms (since distances are almost constant) to get site-specific equations. Find on average σ=0.19±0.04. Therefore concludes single station-single source standard deviations much lower (60%) than standard σs.
- Notes that decreasing σ with increasing period could be due to dominance of small events for which long-period motions are at the moment end of the spectrum, which should be correlated with **M** and independent of stress drop.

5.22. BEYER & BOMMER (2006)

- See Section 3.32.
- Response parameter is acceleration for 5% damping.
- Use records only up to maximum usable period specified in NGA database.

5.23. BINDI *ET AL.* (2006)

- See Section 3.33.
- Response parameter is pseudo-velocity for 5% damping.
- Only use records from within passband of filter. For T>2 s only use digital records.

5.24. CAMPBELL & BOZORGNIA (2006A) AND CAMPBELL & BOZORGNIA (2006B)

- See Section 3.34.
- Response parameter is pseudo-acceleration for 5% damping.

5.25. HERNANDEZ *ET AL.* (2006)

- See Section 3.37.
- Response parameter is pseudo-acceleration for 5% damping.

5.26. KANNO *ET AL.* (2006)

- See Section 3.38.
- Response parameter is acceleration for 5% damping.
- Note the poorer correlation between residuals and $V_{s,30}$ for short periods could be due to higher modal effects or to nonlinear effects (although note that few records where nonlinear effects are likely).

5.27. MCVERRY *ET AL.* (2006)

- See Section 3.42.
- Response parameter is acceleration for 5% damping.

5.28. SAKAMOTO *ET AL.* (2006)

- Ground motion model is:

$$
\begin{aligned}
\log \mathrm{SA}(T) &= a(T)M_w + b(T)X + g + d(T)D + c(T) \\
\text{where} \quad g &= -\log(X+e) \quad \text{for} \quad D \leq 30\,\mathrm{km} \\
g &= 0.4\log(1.7D+e) - 1.4\log(X+e) \quad \text{for} \quad D > 30\,\mathrm{km} \\
e &= 0.00610^{0.5M_w}
\end{aligned}
$$

- Soil characteristics known to bedrock for 571 (out of 1013) stations. Classify stations using NEHRP classification using $V_{S,30}$ or converted *N*-values:

  A $V_{S,30}$>1500 ms^{-1}, 0 stations

  B 760<$V_{S,30}$≤1500 ms^{-1}, 0 stations

  C1 460<$V_{S,30}$≤760 ms^{-1}, 174 stations

  C2 360<$V_{S,30}$≤460 ms^{-1}, 193 stations

  D1 250<$V_{S,30}$≤360 ms^{-1}, 300 stations

  D2 180<$V_{S,30}$≤250 ms^{-1}, 230 stations

  E $V_{S,30}$≤180 ms^{-1}, 116 stations

Define nonlinear (based on PGA at bedrock) soil amplification model using nonlinear analyses of sampled soil conditions for each class of soils. Use this model to convert observed ground motion to motion at a C1 site.

- Response parameter is acceleration for 5% damping.
- Focal depths, *D*, between 3 and 122 km.
- Distribution with respective to earthquake type (based on mechanism, location and depth) is: crustal (3≤*D*≤25 km), 13; interplate (10≤*D*≤70 km), 23; and intraplate, 16 (30≤*D*≤122 *km*).
- PGA from 2 to 1114 cms^{-2}.
- Try including different constant terms to model effect of earthquake type but find lower statistical confidences of results. Therefore remove these coefficients. Believe that modelling of focal-depth dependency may already include effect of earthquake type due to high correlation between depth and type.
- Fit fourth-degree polynomials (in log(*T*)) through derived coefficients to generate smooth spectra.
- Compare inter- and intra-event residuals to normal distribution using Kolmogorov-Smirnov test and find that the intra-event residuals have a normal distribution and that the inter-event residuals almost have.
- Examine magnitude-dependence of the standard deviations using residuals binned within different magnitude ranges (M_W<6.0, 6.0≤M_W<6.5, 6.5≤M_W<7.0

and $M_w \geq 7.0$) and do not find a clear trend for either inter- or intra-event residuals.

- Examine distance-dependence of the intra-event standard deviations and find that for some periods the standard deviations show some depth-dependence for short and long distances.
- Examine amplitude-dependence of the intra-event standard deviations and find some positive dependence (σ increases for higher amplitude motions) for $T \leq 0.4$ s. Note that this may be due to a lack of small amplitude motions due to nontriggering of instruments.

5.29. SHARMA & BUNGUM (2006)

- Ground motion model is:

$$\ln(A) = c_2 M - b\ln(X + \exp(c_3 M))$$

- Response parameter is acceleration for an unspecified damping (but assumed to be 5%).
- Use two site classes:
  - R Rock. Generally granite/quartzite/sandstone.
  - S Soil. Sites with exposed soil cover with different levels of consolidation.
- Data from three strong-motion (SMA-1) arrays: Kangra, Uttar Pradesh and Shillong, in the Himalayas.
- Instruments generally from ground floors of buildings.
- Rotate components into NS and EW directions.
- Focal depths between 7 and 121 km.
- Note that distribution of records is uneven. Five events have less than 9 records and one earthquake has 43.
- Note that M_w avoids magnitude saturation problems.
- Note that lack of near-field data (all but one record from >20 km) means that results are not stable. Therefore introduce nine European records from seven reverse-faulting earthquakes for $M \geq 6.0$ and $d_e \leq 20$ km.
- Use method of Campbell (1981) to avoid problems due to correlation between magnitude and distance. Divide data into a number of subsets based on distance. For each interval, each earthquake is given equal weight by assigning a relative weight of $1/n_{j,l}$ to the record where $n_{j,l}$ is the total number of records from the jth earthquake within ith distance bin. Normalise weights so that they sum to total number of records. Use distance bins of 5 km wide up to 10 km and then bins of equal width w.r.t. logarithmic distance.
- Use d_h rather than d_r because: a) large depth of some events and b) poorly known fault geometries. Note that d_h has a reasonable seismological basis and can be reliably and easily determined for most significant (including hypothetical design) earthquakes.

- Regress all data using: $\ln(A)=c-b\ln(X)$ and find $b=1.22\pm0.69$. Next regress using: $\ln(A)=aM-b\ln(X)+c$ and find $b=0.515\pm0.081$. Conclude that this is due to correlation between magnitude and distance and hence conduct the first step of a two-step regression with dummy variables for each earthquake. Find a decay rate of -1.20 ± 0.036. Use this fixed decay rate for rest of analysis.
- Try to regress on rock and soil data simultaneously by including a linear site term $c_4 S_{SR}$ but find that there are problems during the regression process. Hence regress separately on rock and soil data.

5.30. ZARE & SABZALI (2006)

- See Section 3.44.
- Response parameter is not given but assumed to be acceleration for 5% damping.

5.31. ZHAO *ET AL.* (2006) AND FUKUSHIMA *ET AL.* (2006)

- See Section 3.45.
- Response parameter is acceleration for 5% damping.

6. General characteristics of attenuation relations for spectral ordinates

Table 6.1 gives the general characteristics of published attenuation relations for spectral ordinates. The columns are the same as in Table 4.1 with three extra columns:

*T*s	Number of periods for which attenuation equations are derived
Tmin	Minimum period in s for which attenuation equation is derived
Tmax	Maximum period in s for which attenuation equation is derived

Tab. 6.1: 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
Loh *et al.* (1991)	Taiwan	112	-	63	4.0	7.1	M_L	5.0	178.3	d_h	1	11	0.04	10	L	U	A
Reyes (1998)	University City, Mexico City	20+	-	20+	U	U	M_w	U	U	d_r	I	2	1.0	3.0	S	U	A
Field (2000)	S California	357–447	-	28	5.1	7.5	M_w	0	148.9	d_f	C (6)	3	0.3	3.0	G	1M	A (R, S, O)
Kalkan & Gülkan (2004a)	Turkey	-	95–100[1]	47	4.2	7.4	M_w (unspecified scales)	1.2	250	d_f, d_e for small events	3	46	0.1	2	-	1	A
Kalkan & Gülkan (2004a)	Turkey	112	-	57	4.0	7.4	M_w (unspecified scales)	1.2	250.0	d_f, d_e for small events	3	46	0.1	2	L[2]	1	A
Matsumoto *et al.* (2004)	Japan	293[3]	-	63	5.0*	7.6*	M_{JMA}	0*	195*	d_r & d_q	1	U	0.02*	4*	M	1M	A (B, C, F)
Özbey *et al.* (2004)	NW Turkey	195	-	17	5.0	7.4	M_w (M_L)	5*	300*	d_f	3	31	0.10	4.0	G	1M	NS
Pankow & Pechmann (2004) and Pankow & Pechmann (2006)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	d_f	2	46	0.1	2.0	G, O	1M	NS
Sunuwar *et al.* (2004)	Okhotsk-Amur plate boundary	667	667	42	4.0	5.6	M_{JMA}	>3	>264	d_h	1	19	0.05	3.0	L	2M	A
Takahashi *et al.* (2004)	Mainly Japan+W USA+Iran	4400	-	270	4.9*	8.3*	M_w	0.3*	300	d_r for some, d_h for rest	4	21	0.02	5.0	G	1M	A (B, F, R, S)
Yu & Hu (2004)	W USA	522+187[4]	-	38+14*	5.0	7.5	M_s	1.5*	575*	d_e	1	U	0.04	20	B	O	A
Ambraseys *et al.* (2005a)	Europe & Middle East	207–595	-	59–135	5.0	7.6	M_w	0	99	d_f (d_e for small events)	3	61	0.05	2.5	L	1M	A (N, T, S, O)

continued on next page

[1] Authors do not state reason for different number of records used for different periods.
[2] The caption of their Table 2 states that reported coefficients are for mean.
[3] The authors also report that they used 139 ‘sets’, which could refer to number of records rather than the 293 ‘components’ that they also report.
[4] Does not need to be multiplied by two.

Tab. 6.1: *continued*

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
Ambraseys *et al.* (2005b)	Europe & Middle East	-	207–595	59–135	5.0	7.6	M_w	0	99	d_f (d_e for small events)	3	61	0.05	2.5	-	1M	A (N, T, S, O)
Bragato & Slejko (2005)	E Alps (45.6–46.8°N & 12–14°E)	1402	3168	240	2.5	6.3	M_L	0	130	d_f & d_e	1	47	0.05	2.0	R	O	A
García *et al.* (2005)	Central Mexico	277	277	16	5.2	7.4	M_w	4*	400*	d_r for $M_w > 6.5$, d_h otherwise	1	15	0.04	5	G[5]	1M	B
McGarr & Fletcher (2005)	Central Utah coal-mining areas	31–72	-	12	0.98	4.2	M_w (M_{CL})	0.5*	10*	d_h	2	5	0.1	2.0	L	2M	M
Pousse *et al.* (2005)	Japan	6812	-	591	4.1	7.3	M_w (M_{JMA})	5.5	303	d_h (d_r for 10 events)	5	U	0.01	4.0	B	2	A
Atkinson (2006)	Los Angeles region	461–4973	-	509+	3.1*	7.1*	M_w	5*	350*	d_e (d_f for some)	3	0.3	3.0	I, C	B	1	A
Beyer & Bommer (2006)	Shallow crustal (USA, Taiwan, Turkey and others)	949	-	103	4.3*	7.9*	M_w	6*	200*	d_h	U	77	0.01	5.0	1, 2, A, B, C, D50, G, I50, L, N, P, R	1M	A (U)
Bindi *et al.* (2006)	Umbria-Marche	144–239	-	≤ 45	4.0	5.9	M_L	1*	100*	d_e & d_h	4	14	0.04	4	L	1M	NS

continued on next page

[5] Call it ‘quadratic mean’, which is assumed to be geometric mean.

Tab. 6.1: *continued*

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
Campbell & Bozorgnia (2006a) and Campbell & Bozorgnia (2006b)	Worldwide	1500+	-	60+	4.2	7.9	M_w	0	200	d_r	C	U	U	10	G	2M	A
Hernandez *et al.* (2006)	Haulien LSTT (Taiwan)	456	456	51	5	7.3	M_L	13.7	134.8	d_h	5	143	0.03	10	B	1	A
Kanno *et al.* (2006)	Japan+some foreign	3205–3392+331–377 (shallow) & 7721–8150 (deep)	-	70–73+10 & 101–111	5.0* (6.1) & 5.5*	8.2* (7.4) & 8.0*	M_w (M_{JMA})	1* (1.5*) & 30*	450* (350*) & 450*	d_r (d_h for some)	C	37	0.05	5	R	2M	A
McVerry *et al.* (2006)	New Zealand	435	-	49	5.08	7.09	M_w	6	400	d_c (d_r)	3	11	0.075	3	L, G	1M	C (R, OR, S & N) & F, B
Sakamoto *et al.* (2006)	Japan	3198	-	52	5.5	8.3	M_w	1	300	d_r	5	U	0.02	5	M	1M	A
Sharma & Bungum (2006)	Indian Himalayas+9 European records	175+9	-	12+7	4.5 (6.0)	7.2 (7.4)	M_w (m_b)	10	200	d_h	2	13	0.04	2.5	G	1W	A
Zare & Sabzali (2006)	Iran	89	89	55*	2.7	7.4	M_w	4	167	d_h	4	21	0.10	4	U	1M & 2M	A
Zhao *et al.* (2006) and Fukushima *et al.* (2006)	Japan+208 overseas	2763–4518+208	-	$<$249+20	5.0	8.3	M_w	0*	300*	d_r	5	20	0.05	5	G	1M	C (R, S/N) & F, B

7. Acknowledgements

The original reports were funded by EPSRC grants no. GR/L87385 and no. GR/52114/01(P) and EC grant no. EVR1-CT-1999-40008; I thank both funding agencies for their support. This new report is funded through internal BRGM research projects. I thank Nicholas Ambraseys, Julian Bommer, Patrick Smit, Anna Baba, Julian Garcia-Mayordomo, Marco Pagani, Jorge Prieto-Salazar, Carlos Rodriguez, Tizi Rossetto, Iain Tromans, Juliet Bird, Jonathan Hancock, Fleur Strasser, Thierry Winter, Guillaume Bertrand and Pascal Dominique for references and their enthusiasm towards the original reports. Also I thank Dr A. Dahle for sending me a copy of Dahle *et al.* (1991), Dr K. W. Campbell for sending me copies of his recent articles and for correcting a number of errors in my presentation of his studies (I am responsible for any remaining errors), Dr G. Costa for giving me a copy of Costa *et al.* (1998), Dr M. Zaré for sending me a copy of Zaré *et al.* (1999), Mr C. Ende for sending me a copy of the poster for Schwarz *et al.* (2002), Ms V. Montaldo for sending me a copy of Zonno & Montaldo (2002), Prof. H. Bungum for giving me copies of Taylor Castillo *et al.* (1992) and Schmidt *et al.* (1997), Dr B. Benito for sending me copies of Benito *et al.* (2000), Cabacas *et al.* (1999) and Cabacas *et al.* (2000), Prof. P. Suhadolc for sending me a copy of Herak *et al.* (2001) and Dr G. McVerry for sending me a copy of McVerry *et al.* (2006). Finally, I thank the developers of LaTeX2RTF for making the conversion of my LaTeX document to a Word document much easier.

8. References

Abrahamson, N. A., & Silva, W. J. 1997. Empirical response spectral attenuation relations for shallow crustal earthquakes. *Seismological Research Letters*, **68**(1), 94–127.

Aman, A., Singh, U. K., & Singh, R. P. 1995. A new empirical relation for strong seismic ground motion for the Himalayan region. *Current Science*, **69**(9), 772–777.

Ambraseys, N., & Douglas, J. 2000 (Aug). *Reappraisal of the effect of vertical ground motions on response*. ESEE Report 00-4. Department of Civil and Environmental Engineering, Imperial College, London.

Ambraseys, N. N., & Bommer, J. J. 1995. Attenuation relations for use in Europe: An overview. *Pages 67–74 of:* Elnashai, A. S. (ed), *Proceedings of Fifth SECED Conference on European Seismic Design Practice*.

Ambraseys, N. N., & Douglas, J. 2003. Near-field horizontal and vertical earthquake ground motions. *Soil Dynamics and Earthquake Engineering*, **23**(1), 1–18.

Ambraseys, N. N., Simpson, K. A., & Bommer, J. J. 1996. Prediction of horizontal response spectra in Europe. *Earthquake Engineering and Structural Dynamics*, **25**(4), 371–400.

Ambraseys, N. N., Smit, P., Douglas, J., Margaris, B., Sigbjцrnsson, R., Уlafsson, S., Suhadolc, P., & Costa, G. 2004. Internet site for European strong-motion data. *Bollettino di Geofisica Teorica ed Applicata*, **45**(3), 113–129.

Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. 2005a. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, **3**(1), 1–53.

Ambraseys, N. N., Douglas, J., Sarma, S. K., & Smit, P. M. 2005b. Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from Europe and the Middle East: Vertical peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering*, **3**(1), 55–73.

Anderson, J. G. 1997. Nonparametric description of peak acceleration above a subduction thrust. *Seismological Research Letters*, **68**(1), 86–93.

Atkinson, G. M. 2006. Single-station sigma. *Bulletin of the Seismological Society of America*, **96**(2), 446–455.

Atkinson, G. M., & Boore, D. M. 1990. Recent trends in ground motion and spectral response relations for North America. *Earthquake Spectra*, **6**(1), 15–35.

Atkinson, G. M., & Boore, D. M. 2003. Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. *Bulletin of the Seismological Society of America*, **93**(4), 1703–1729.

Aydan, O. 1997. *The seismic characteristics and the occurrence pattern of Turkish earthquakes*. Tech. rept. TDV/TR 97-007. Turkish Earthquake Foundation. Not seen. Reported in Ulusay *et al.* (2004).

Aydan, O. 2001. Comparison of suitability of submerged tunnel and shield tunnel for subsea passage of Bosphorus. *Jeol. mühendis*, **25**(1), 1–17. Not seen. Reported in Ulusay *et al.* (2004).

Aydan, O, Sedaki, M., & Yarar, R. 1996. The seismic characteristics of Turkish earthquakes. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*. Paper no. 1270.

Battis, J. 1981. Regional modification of acceleration attenuation functions. *Bulletin of the Seismological Society of America*, **71**(4), 1309–1321.

Benito, B., Cabanas, L., Jimenez, M. E., Cabanas, C., Lopez, M., Gomez, P., & Alvarez, S. 2000. Caracterizacion del movimiento del suelo en emplazamientos de la peninsula iberica y evaluacion del daco potencial en estructuras. proyecto dacos. *In:* Consejo de Seguridad Nuclear (ed), *Monografia ref. 19.2000*. In Spanish. Not seen.

Berge-Thierry, C., Cotton, F., Scotti, O., Griot-Pommera, D.-A., & Fukushima, Y. 2003. New empirical response spectral attenuation laws for moderate European earthquakes. *Journal of Earthquake Engineering*, **7**(2), 193–222.

Beyer, K., & Bommer, J. J. 2006. Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion. *Bulletin of the Seismological Society of America*, **96**(4A), 1512–1522. doi: 10.1785/0120050210.

Bindi, D., Luzi, L., Pacor, F., Franceshina, G., & Castro, R. R. 2006. Ground-motion predictions from empirical attenuation relationships versus recorded data: The case of the 1997–-1998 Umbria-Marche, central Italy, strong-motion data set. *Bulletin of the Seismological Society of America*, **96**(3), 984–1002.

Bommer, J. J., & Alarcon, J. E. 2006. The prediction and use of peak ground velocity. *Journal of Earthquake Engineering*, **10**(1), 1–31.

Bommer, J. J., & Martнnez-Pereira, A. 1999. The effective duration of earthquake strong motion. *Journal of Earthquake Engineering*, **3**(2), 127–172.

Boore, D. M. 2005. Erratum: Equations for estimating horizontal response spectra and peak acceleration from western north american earthquakes: A summary of recent work. *Seismological Research Letters*, **76**(3), 368–369.

Boore, D. M., & Joyner, W. B. 1982. The empirical prediction of ground motion. *Bulletin of the Seismological Society of America*, **72**(6), S43–S60. Part B.

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1994. *Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report. Part 2*. Open-File Report 94-127. U.S. Geological Survey.

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1997. Equations for estimating horizontal response spectra and peak acceleration from western North

American earthquakes: A summary of recent work. *Seismological Research Letters*, **68**(1), 128–153.

Boore, D. M., Watson-Lamprey, J., & Abrahamson, N. A. 2006. Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America*, **96**(4A), 1502–1511. doi: 10.1785/0120050209.

Bozorgnia, Y., & Campbell, K. W. 2004a. Engineering characterization of ground motion. *Chap. 5 of:* Bozorgnia, Y., & Bertero, V. (eds), *Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering*. Boca Raton, FL: CRC Press.

Bozorgnia, Y., & Campbell, K. W. 2004b. The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and the vertical design spectra. *Journal of Earthquake Engineering*, **8**(2), 175–207.

Bozorgnia, Y., Niazi, M., & Campbell, K. W. 1995. Characteristics of free-field vertical ground motion during the Northridge earthquake. *Earthquake Spectra*, **11**(4), 515–525.

Bragato, P. L. 2004. Regression analysis with truncated samples and its application to ground-motion attenuation studies. *Bulletin of the Seismological Society of America*, **94**(4), 1369–1378.

Bragato, P. L. 2005. Estimating an upper limit probability distribution for peak ground acceleration using the randomly clipped normal distribution. *Bulletin of the Seismological Society of America*, **95**(6), 2058–2065. doi: 10.1785/0120040213.

Bragato, P. L., & Slejko, D. 2005. Empirical ground-motion attenuation relations for the eastern Alps in the magnitude range 2.5–6.3. *Bulletin of the Seismological Society of America*, **95**(1), 252–276. doi: 10.1785/0120030231.

Cabanas, L., Benito, B., Cabanas, C, Lopez, M., Gomez, P., Jimenez, M. E., & Alvarez, S. 1999. Banco de datos de movimiento fuerte del suelo mfs. aplicaciones. *Pages 111–137 of:* Complutense (ed), *Fнsica de la tierra*, vol. 11. In Spanish with English abstract.

Cabanas, L., Lopez, M., Benito, B., & Jimenez, M. E. 2000 (Sep). Estimation of PGA attenuation laws for Spain and Mediterranean region. comparison with other ground motion models. *In: Proceedings of the XXVII General Assembly of the European Seismological Commission (ESC)*.

Campbell, K. W. 1981. Near-source attenuation of peak horizontal acceleration. *Bulletin of the Seismological Society of America*, **71**(6), 2039–2070.

Campbell, K. W. 1985. Strong motion attenuation relations: A ten-year perspective. *Earthquake Spectra*, **1**(4), 759–804.

Campbell, K. W. 1997. Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **68**(1), 154–179.

Campbell, K. W. 2003a. Engineering models of strong ground motion. *Chap. 5 of:* Chen, W. F., & Scawthorn, C. (eds), *Handbook of Earthquake Engineering*. Boca Raton, FL, USA: CRC Press.

Campbell, K. W. 2003b. Strong-motion attenuation relations. *Chap. 60 of:* Lee, W. H. K., Kanamori, H., Jennings, P. C., & Kisslinger, C. (eds), *International Handbook of Earthquake and Engineering Seismology*. London: Academic Press.

Campbell, K. W., & Bozorgnia, Y. 2003a. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **93**(3), 1413.

Campbell, K. W., & Bozorgnia, Y. 2003b. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **93**(4), 1872.

Campbell, K. W., & Bozorgnia, Y. 2003c. Erratum: Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **94**(6), 2417.

Campbell, K. W., & Bozorgnia, Y. 2003d. Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra. *Bulletin of the Seismological Society of America*, **93**(1), 314–331.

Campbell, K. W., & Bozorgnia, Y. 2006a (Apr). Campbell-Bozorgnia Next Generation Attenuation (NGA) relations for PGA, PGV and spectral acceleration: A progress report. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 906.

Campbell, K. W., & Bozorgnia, Y. 2006b (Sep). Next Generation Attenuation (NGA) empirical ground motion models: Can they be used in Europe? *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper no. 458.

Costa, G., Suhadolc, P., & Panza, G. F. 1998. The Friuli (NE Italy) Accelerometric Network: Analysis of low-magnitude high-quality digital accelerometric data for seismological and engineering applications. *In: Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*. Oakland, USA: Earthquake Engineering Research Institute. Seattle, USA. 31 May–4 June.

Costa, G., Suhadolc, P., Delise, A., Moratto, L., Furlanetto, E., & Fitzko, F. 2006. Estimation of site effects at some stations of the Friuli (NE Italy) accelerometric network (RAF). *Pages 729–739 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, vol. 1. Paper number 089.

Cotton, F., Scherbaum, F., Bommer, J. J., & Bungum, H. 2006. Criteria for selecting and adjusting ground-motion models for specific target regions: Application to central Europe and rock sites. *Journal of Seismology*, **10**(2), 137–156. DOI: 10.1007/s10950-005-9006-7.

Dahle, A., Bungum, H., & Kvamme, L. B. 1991. Empirically derived PSV spectral attenuation models for intraplate conditions. *European Earthquake Engineering*, **3**, 42–52.

Douglas, J. 2001 (Jan). *A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)*. ESEE Report 01-1. Department of Civil and Environmental Engineering, Imperial College, London.

Douglas, J. 2002 (Oct). *Errata of and additions to ESEE Report No. 01-1: 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)'*. Dept. report. Department of Civil and Environmental Engineering, Imperial College, London.

Douglas, J. 2003. Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground acceleration and response spectral ordinates. *Earth-Science Reviews*, **61**(1–2), 43–104.

Douglas, J. 2004 (Jan.). *Ground motion estimation equations 1964–2003: Reissue of ESEE Report No. 01-1: 'A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)' with corrections and additions*. Tech. rept. 04-001-SM. Department of Civil and Environmental Engineering; Imperial College of Science, Technology and Medicine; London; U.K. On Internet at: `http://www3.imperial.ac.uk/civilengineering/research/researchnewsandreports/researchreports`.

Douglas, J., & Smit, P. M. 2001. How accurate can strong ground motion attenuation relations be? *Bulletin of the Seismological Society of America*, **91**(6), 1917–1923.

Espinosa, A. F. 1980. Attenuation of strong horizontal ground accelerations in the western United States and their relation to M_L. *Bulletin of the Seismological Society of America*, **70**(2), 583–616.

Field, E. H. 2000. A modified ground-motion attenuation relationship for southern California that accounts for detailed site classification and a basin-depth effect. *Bulletin of the Seismological Society of America*, **90**(6B), S209–S221.

Frisenda, M., Massa, M., Spallarossa, D., Ferretti, G., & Eva, C. 2005. Attenuation relationships for low magnitude earthquakes using standard seismometric records. *Journal of Earthquake Engineering*, **9**(1), 23–40.

Frohlich, C., & Apperson, K. D. 1992. Earthquake focal mechanisms, moment tensors, and the consistency of seismic activity near plate boundaries. *Tectonics*, **11**(2), 279–296.

Fukushima, Y., Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Fukushima, Y., Thio, H. K., & Somerville, P. G. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 683.

Garcia, D., Singh, S. K., Herraiz, M., Ordaz, M., & Pacheco, J. F. 2005. Inslab earthquakes of central Mexico: Peak ground-motion parameters and response spectra. *Bulletin of the Seismological Society of America*, **95**(6), 2272–2282. doi: 10.1785/0120050072.

Gomez-Soberon, C., Tena-Colunga, A., & Ordaz, M. 2006 (Apr). Updated attenuation laws in displacement and acceleration for the Mexican Pacific coast as the first step to improve current design spectra for base-isolated structures in Mexico. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 1010.

Gülkan, P., & Kalkan, E. 2002. Attenuation modeling of recent earthquakes in Turkey. *Journal of Seismology*, **6**(3), 397–409.

Gupta, S., & Gupta, I. D. 2004. The prediction of earthquake peak ground acceleration in Koyna region, India. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1437.

Hancock, J., & Bommer, J. J. 2005. The effective number of cycles of earthquake ground motion. *Earthquake Engineering and Structural Dynamics*, **34**, 637–664. DOI: 10.1002/eqe.437.

Herak, M., Markusic, S., & Ivancic, I. 2001. Attenuation of peak horizontal and vertical acceleration in the Dinarides area. *Studia Geophysica et Geodaetica*, **45**(4), 383–394.

Hernandez, B., Fukushima, Y., Bossu, R., & Albaric, J. 2006. Seismic attenuation relation for Hualien (Taiwan) at the free surface and down to 52.6 *m* deep. *Pages 145–154 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, vol. 1. Paper number 008.

Idriss, I. M. 1978 (Jun). Characteristics of earthquake ground motions. *Pages 1151–1265 of: Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, vol. III.

Inan, E., Colakoglu, Z., Koc, N., Bayülke, N., & Coruh, E. 1996. *Earthquake catalogs with acceleration records from 1976 to 1996*. Tech. rept. General Directorate of Disaster Affairs, Earthquake Research Department, Ankara, Turkey. In Turkish. Not seen. Reported in Ulusay *et al.* (2004).

Joyner, W. B., & Boore, D. M. 1981. Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bulletin of the Seismological Society of America*, **71**(6), 2011–2038.

Joyner, W. B., & Boore, D. M. 1988. Measurement, characterization, and prediction of strong ground motion. *Pages 43–102 of: Proceedings of Earthquake Engineering & Soil Dynamics II*. Geotechnical Division, ASCE.

Joyner, W. B., & Boore, D. M. 1993. Methods for regression analysis of strong-motion data. *Bulletin of the Seismological Society of America*, **83**(2), 469–487.

Joyner, W. B., & Boore, D. M. 1996 (Aug). Recent developments in strong motion attenuation relationships. *Pages 101–116 of: Proceedings of the 28th Joint Meeting of the U.S.-Japan Cooperative Program in Natural Resource Panel on Wind and Seismic Effects*.

Kalkan, E., & Gülkan, P. 2004a. Empirical attenuation equations for vertical ground motion in Turkey. *Earthquake Spectra*, **20**(3), 853–882.

Kalkan, E., & Gülkan, P. 2004b. Site-dependent spectra derived from ground motion records in Turkey. *Earthquake Spectra*, **20**(4), 1111–1138.

Kalkan, E., & Gülkan, P. 2005. Erratum: Site-dependent spectra derived from ground motion records in Turkey. *Earthquake Spectra*, **21**(1), 283.

Kanno, T., Narita, A., Morikawa, N., Fujiwara, H., & Fukushima, Y. 2006. A new attenuation relation for strong ground motion in Japan based on recorded data. *Bulletin of the Seismological Society of America*, **96**(3), 879–897.

Laouami, N., Slimani, A., Bouhadad, Y., Chatelain, J.-L., & Nour, A. 2006. Evidence for fault-related directionality and localized site effects from strong motion recordings of the 2003 Boumerdes (Algeria) earthquake: Consequences on damage distribution and the Algerian seismic code. *Soil Dynamics and Earthquake Engineering*, **26**(11), 991–1003.

Liu, K.-S., & Tsai, Y.-B. 2005. Attenuation relationships of peak ground acceleration and velocity for crustal earthquakes in Taiwan. *Bulletin of the Seismological Society of America*, **95**(3), 1045–1058. doi: 10.1785/0120040162.

Loh, C.-H., Yeh, Y. T., Jean, W.-Y., & Yeh, Y.-H. 1991. Probabilistic seismic risk analysis in the Taiwan area based on PGA and spectral amplitude attenuation formulas. *Engineering Geology*, **30**(3–4), 277–304.

Lubkowski, Z., Bommer, J., Baptie, B., Bird, J., Douglas, J., Free, M., Hancock, J., Sargeant, S., Sartain, N., & Strasser, F. 2004. An evaluation of attenuation relationships for seismic hazard assessment in the UK. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1422.

Luzi, L., Morasca, P., Zolezzi, F., Bindi, D., Pacor, F., Spallarossa, D., & Franceschina, G. 2006. Ground motion models for Molise region (southern Italy). *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 938.

Mahdavian, A. 2006. Empirical evaluation of attenuation relations of peak ground acceleration in the Zagros and central Iran. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 558.

Marin, S., Avouac, J.-P., Nicolas, M., & Schlupp, A. 2004. A probabilistic approach to seismic hazard in metropolitan France. *Bulletin of the Seismological Society of America*, **94**(6), 2137–2163.

Matsumoto, N., Sasaki, T., Inagaki, K., & Annaka, T. 2004. Attenuation relations of acceleration response spectra at dam foundations in Japan. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 689.

McGarr, A., & Fletcher, J. B. 2005. Development of ground-motion prediction equations relevant to shallow mining-induced seismicity in the Trail Mountain area, Emery County, Utah. *Bulletin of the Seismological Society of America*, **95**(1), 31–47. doi: 10.1785/0120040046.

McGuire, R. K. 1976. *FORTRAN computer program for seismic risk analysis*. Open-File Report 76-67. United States Department of the Interior Geological Survey.

McVerry, G. H., Zhao, J. X., Abrahamson, N. A., & Somerville, P. G. 2006. New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes. *Bulletin of the New Zealand Society for Earthquake Engineering*, **39**(4).

Midorikawa, S., & Ohtake, Y. 2004. Variance of peak ground acceleration and velocity in attenuation relationships. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 0325.

Ohno, S., Ohta, T., Ikeura, T., & Takemura, M. 1993. Revision of attenuation formula considering the effect of fault size to evaluate strong motion spectra in near field. *Tectonophysics*, **218**, 69–81.

Ordaz, M., & Reyes, C. 1999. Earthquake hazard in Mexico City: Observations versus computations. *Bulletin of the Seismological Society of America*, **89**(5), 1379–1383.

Ordaz, M., Singh, S. K., & Arciniega, A. 1994. Bayesian attenuation regressions: An application to Mexico City. *Geophysical Journal International*, **117**(2), 335–344.

Ozbey, C., Sari, A., Manuel, L., Erdik, M., & Fahjan, Y. 2004. An empirical attenuation relationship for northwestern Turkey ground motion using a random effects approach. *Soil Dynamics and Earthquake Engineering*, **24**, 115–125.

Pankow, K. L., & Pechmann, J. C. 2004. The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America*, **94**(1), 341–348.

Pankow, K. L., & Pechmann, J. C. 2006. Erratum: The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America*, **96**(1), 364. doi: 10.1785/0120050184.

Pousse, G., Berge-Thierry, C., Bonilla, L. F., & Bard, P.-Y. 2005. Eurocode 8 design response spectra evaluation using the K-Net Japanese database. *Journal of Earthquake Engineering*, **9**(4), 547–574. doi:10.1142/S1363246905002067.

Reyes, C. 1998. *El estado limite de servicio en el diseco sismico de edificios*. Ph.D. thesis, School of Engineering, National Autonomous University of Mexico (UNAM). In Spanish. Not seen, reported in Ordaz & Reyes (1999).

Sadigh, K., Youngs, R. R., & Power, M. S. 1978. A study of attenuation of peak horizontal accelerations for moderately strong earthquakes. *Pages 243–250 of: Proceedings of Sixth European Conference on Earthquake Engineering*, vol. 1.

Sakamoto, S., Uchiyama, Y., & Midorikawa, S. 2006 (Apr). Variance of response spectra in attenuation relationship. *In: Proceedings of the Eighth U.S. National Conference on Earthquake Engineering*. Paper no. 471.

Schmidt, V., Dahle, A., & Bungum, H. 1997 (Nov.). *Costa Rican spectral strong motion attenuation*. Tech. rept. NORSAR, Kjeller, Norway. Reduction of Natural Disasters in central America Earthquake Preparedness and Hazard Mitigation Phase II: 1996–2000, Part 2.

Schnabel, P. B., & Seed, H. B. 1973. Accelerations in rock for earthquakes in the western United States. *Bulletin of the Seismological Society of America*, **63**(2), 501–516.

Schwarz, J., Ende, C., Habenberger, J., Lang, D. H., Baumbach, M., Grosser, H., Milereit, C., Karakisa, S., & Zünbül, S. 2002 (Sep). Horizontal and vertical response spectra on the basis of strong-motion recordings from the 1999 Turkey earthquakes. *In: Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*.

Sharma, M., & Bungum, H. 2006. New strong ground-motion spectral acceleration relations for the Himalayan region. *In: Proceedings of First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*. Paper number 1459.

Si, H., & Midorikawa, S. 2000. New attenuation relations for peak ground acceleration and velocity considering effects of fault type and site condition. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 0532.

Sigbjörnsson, R., & Ambraseys, N. N. 2003. Uncertainty analysis of strong ground motion. *Bulletin of Earthquake Engineering*, **1**(3), 321–347.

Skarlatoudis, A., Theodulidis, N., Papaioannou, C., & Roumelioti, Z. 2004. The dependence of peak horizontal acceleration on magnitude and distance for small magnitude earthquakes in Greece. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1857.

Skarlatoudis, A. A., Papazachos, C. B., Margaris, B. N., Theodulidis, N., Papaioannou, C., Kalogeras, I., Scordilis, E. M., & Karakostas, V. 2003. Empirical peak ground-motion predictive relations for shallow earthquake in Greece. *Bulletin of the Seismological Society of America*, **93**(6), 2591–2603.

Smit, P. 1998 (Sep). Strong motion attenuation model for central Europe. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*. smisma.

Souriau, A. 2006. Quantifying felt events: A joint analysis of intensities, accelerations and dominant frequencies. *Journal of Seismology*, **10**(1), 23–38.

Spudich, P., & Boore, D. M. 2005. Erratum: SEA99: A revised ground-motion prediction relation for use in extensional tectonic regimes. *Bulletin of the Seismological Society of America*, **95**(3), 1209. doi: 10.1785/0120050026.

Spudich, P., Joyner, W. B., Lindh, A. G., Boore, D. M., Margaris, B. M., & Fletcher, J. B. 1999. SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes. *Bulletin of the Seismological Society of America*, **89**(5), 1156–1170.

Sunuwar, L., Cuadra, C., & Karkee, M. B. 2004. Strong ground motion attenuation in the Sea of Japan (Okhotsk-Amur plates boundary) region. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 0197.

Takahashi, T., Asano, A., Saiki, T., Okada, H., Irikura, K., Zhao, J. X., Zhang, J., Thio, H. K., Somerville, P. G., Fukushima, Y., & Fukushima, Y. 2004. Attenuation models for response spectra derived from Japanese strong-motion records accounting for tectonic source types. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 1271.

Taylor Castillo, W., Santos Lopez, P., Dahle, A., & Bungum, H. 1992 (Nov.). *Digitization of strong motion data and estimation of PGA attenuation*. Tech. rept. NORSAR, Kjeller, Norway. Reduction of Natural Disasters in central America Earthquake Preparedness and Hazard Mitigation Seismic Zonation and Earthquake Hazard Assessment.

Trifunac, M. D., & Brady, A. G. 1975. On the correlation of peak acceleration of strong motion with earthquake magnitude, epicentral distance and site conditions. *Pages 43–52 of: Proceedings of the U.S. National Conference on Earthquake Engineering*.

Trifunac, M. D., & Brady, A. G. 1976. Correlations of peak acceleration, velocity and displacement with earthquake magnitude, distance and site conditions. *Earthquake Engineering and Structural Dynamics*, **4**(5), 455–471.

Tromans, I. 2004 (Jan). *Behaviour of buried water supply pipelines in earthquake zones*. Ph.D. thesis, University of London.

Ulusay, R., Tuncay, E., Sonmez, H., & Gokceoglu, C. 2004. An attenuation relationship based on Turkish strong motion data and iso-acceleration map of Turkey. *Engineering Geology*, **74**, 265–291.

Wills, C. J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G. J., Tan, S., Taylor, G., & Treiman, J. 2000. A site-conditions map for California based on geology and shear-wave velocity. *Bulletin of the Seismological Society of America*, **90**(6B), S187–S208.

Youngs, R. R., Chiou, S.-J., Silva, W. J., & Humphrey, J. R. 1997. Strong ground motion attenuation relationships for subduction zone earthquakes. *Seismological Research Letters*, **68**(1), 58–73.

Yu, Y., & Hu, Y. 2004. Empirical long-period response spectral attenuation relations based on southern California digital broad-band recordings. *In: Proceedings of Thirteenth World Conference on Earthquake Engineering*. Paper no. 0344.

Zare, M., & Sabzali, S. 2006. Spectral attenuation of strong motions in Iran. *Pages 749–758 of: Proceedings of Third International Symposium on the Effects of Surface Geology on Seismic Motion*, vol. 1. Paper number 146.

Zarй, M., Ghafory-Ashtiany, M., & Bard, P.-Y. 1999. Attenuation law for the strong-motions in Iran. *Pages 345–354 of: Proceedings of the Third International Conference on Seismology and Earthquake Engineering, Tehran*, vol. 1.

Zhao, J. X., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H. K., Somerville, P. G., Fukushima, Y., & Fukushima, Y. 2006. Attenuation relations of strong ground motion in Japan using site classification based on predominant period. *Bulletin of the Seismological Society of America*, **96**(3), 898–913.

Zonno, G., & Montaldo, V. 2002. Analysis of strong ground motions to evaluate regional attenuation relationships. *Annals of Geophysics*, **45**(3–4), 439–454.

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