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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

John Douglas

Research report number: 04-001-SM

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1. PREFACE

ESEE Report 01-1 ‘A comprehensive worldwide summary of strong-motion attenuation relationships for peak ground acceleration and spectral ordinates (1969 to 2000)’ (Douglas, 2001a) 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 report were released some further minor errors have been found in the text and tables of the original two reports, and additional studies have been found in the literature which were not included in ESEE 01-1 or the follow-on report. Also some new studies have been published. Rather than produce a new report listing errata and additions it was decided to produce a new report which includes details on all the studies listed in the first two reports (with the corrections made) and also includes information on the additional studies.

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. 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,a) and Bozorgnia & Campbell (2004a), which provide the coefficients for a number of commonly-used equations for peak ground accleration 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 using 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 *Esteva & Rosenblueth (1964)*

- Ground motion model is:

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

  where a is in cms^{-2}, $c = 2000$, $\alpha = 0.8$ and $\beta = 2$ (σ is not given).

3.2 *Kanai (1966)*

- Ground motion model is:

  $$\begin{aligned} a &= \frac{a_1}{\sqrt{T_G}}10^{a_2M-P\log_{10}R+Q} \\ P &= a_3 + a_4/R \\ Q &= a_5 + a_6/R \end{aligned}$$

  where a is in cms^{-2}, $a_1 = 5$, $a_2 = 0.61$, $a_3 = 1.66$, $a_4 = 3.60$, $a_5 = 0.167$ and $a_6 = -1.83$ (σ is not given).
- T_G is the fundamental period of the site.

3.3 *Milne & Davenport (1969)*

- Ground motion model is:

  $$A = \frac{a_1\mathrm{e}^{a_2M}}{a_3\mathrm{e}^{a_4M} + \Delta^2}$$

  where A is in percentage of g, $a_1 = 0.69$, $a_2 = 1.64$, $a_3 = 1.1$ and $a_4 = 1.10$ (σ not given).
- Use data from Esteva & Rosenblueth (1964).

3.4 *Esteva (1970)*

- Ground motion model is:

  $$a = c_1\mathrm{e}^{c_2M}(R + c_3)^{-c_4}$$

  where a is in cms^{-2}, $c_1 = 1230$, $c_2 = 0.8$, $c_3 = 25$, $c_4 = 2$ and $\sigma = 1.02$ (in terms of natural logarithm).

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

3.5 Denham & Small (1971)

- Ground motion model is:

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

  where Y is in g, $b_1 = -0.2$, $b_2 = 0.2$ and $b_3 = -1.1$ (σ not given).
- Records from near dam on recent unconsolidated lake sediments which are $\geq 50\,\mathrm{m}$ thick.
- Note need for more points and large uncertainty in b_1, b_2 and b_3.

3.6 Donovan (1973)

- Ground motion model is:

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

  where y is in gal, $b_1 = 1080$, $b_2 = 0.5$, $b_3 = 1.32$ and $\sigma = 0.71$. 25 adopted from Esteva (1970).
- 214 (32%) records from San Fernando (9/2/1971) earthquake and 53% of records with PGA less than $0.5\,\mathrm{ms}^{-2}$.
- Considers portions of data and finds magnitude dependence increases with increasing distance from source and more small accelerations increase magnitude dependence. Thus magnitude and distance cannot be considered independent variables.

3.7 Denham et al. (1973)

- Ground motion model is:

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

  where Y_a is in cms^{-2}, $a_1 = 2.91$, $a_2 = 0.32$ and $a_3 = -1.45$ (σ is not given).
- Use records from Yonki station (20 records) which is on $50\,\mathrm{m}$ of recent alluvium and from Paguna station (5 records) which is on unconsolidated volcanic rock.
- Question validity of combining data at the two sites because of differences in geological foundations.
- Note large standard errors associated with coefficients preclude accurate predictions of ground motions.
- Also derive equation for Yonki station separately.

3.8 Esteva & Villaverde (1973) & Esteva (1974)

- Ground motion model is:

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

  where Y_c is in cms^{-2}, $b_1 = 5600$, $b_2 = 0.8$, $b_3 = 2$, $b_4 = 40$ and $\sigma = 0.64$ (in terms of natural logarithm).

3.9 Orphal & Lahoud (1974)

- Ground motion model is:

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

  where A is in g, $\lambda = 6.6 \times 10^{-2}$, $\alpha = 0.40$, $\beta = -1.39$ and $\sigma = 1.99$ (this is multiplication factor).
- Use 113 records with distances between 15 to $350\,\mathrm{km}$ from San Fernando earthquake to find distance dependence, β.
- Use 27 records of Wiggins Jr. (1964) from El Centro and Ferndale areas, with magnitudes between 4.1 and 7.0 and distances between 17 and $94\,\mathrm{km}$ (assuming focal depth of $15\,\mathrm{km}$), to compute magnitude dependent terms assuming distance dependence is same as for San Fernando.

3.10 Ambraseys (1975b), Ambraseys (1975a) & Ambraseys (1978a)

- Ground motion model is:

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

  where Y is in cms^{-2}, $b_1 = 0.46$, $b_2 = 0.63$, $b_3 = -1.10$ and $\sigma = 0.32$[1]
- Ambraseys & Bommer (1995) state that uses earthquakes with maximum focal depth of $15\,\mathrm{km}$.

3.11 Trifunac & Brady (1975), Trifunac (1976) & Trifunac & Brady (1976)

- Ground motion model is:

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

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[1] From Ambraseys & Bommer (1995).

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

- Use three site categories:

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

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

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

- Exclude records from tall buildings.
- Do not use data from other regions because attenuation varies with geological province and magnitude determination is different in other countries.
- Records baseline and instrument corrected. Accelerations thought to be accurate between 0.07 and $25\,\mathrm{Hz}$ or between 0.125 and $25\,\mathrm{Hz}$ for San Fernando records.
- Most records (71%) from earthquakes with magnitudes between 6.0–6.9, 22% are from 5.0–5.9, 3% are from 4.0–4.9 and 3% are from 7.0–7.7 (note barely adequate data from these two magnitude ranges). 63% of data from San Fernando earthquake.
- Note that for large earthquakes, i.e. long faults, $\log_{10} A_0(R)$ would have a tendency to flatten out for small epicentral distances and for low magnitude shocks curve would probably have a large negative slope. Due to lack of data $\lesssim 20\,\mathrm{km}$ this is impossible to check.
- Note difficulty in incorporating anelastic attenuation because representative frequency content of peak amplitudes change with distance and because relative contribution of digitization noise varies with frequency and distance.
- Note that $\log_{10} A_0(R)$ may be unreliable for epicentral distances less than $10\,\mathrm{km}$ because of lack of data.
- Change of slope in $\log_{10} A_0(R)$ at $R = 75\,\mathrm{km}$ because for greater distances main contribution to strong shaking from surface waves, which are attenuated less rapidly ($\sim 1/R^{1/2}$) than near-field and intermediate-field ($\sim 1/R^{2-4}$), or far-field body waves ($\sim 1/R$).
- Note lack of data to reliably characterise $\log_{10} a_0(M, p, s, v)$ over a sufficiently broad range of their arguments. Also note high proportion of San Fernando data may bias results.
- Firstly partition data into four magnitude dependent groups: 4.0–4.9, 5.0–5.9, 6.0–6.9 and 7.0–7.9. Subdivide each group into three site condition subgroups (for $s = 0$, 1 and 2). Divide each subgroup into two component categories (for $v = 0$ and 1). Calculate $\log_{10} a_0(M, p, s, v) = M + \log_{10} A_0(R) - \log_{10} a_{\max}$ within each of the 24 parts. Arrange each set of n $\log_{10} a_0$ values into decreasing order with increasing n. Then mth data point (where m equals integer part of pn) is estimate for upper bound of $\log_{10} a_0$ for $p\%$ confidence level. Then fit results using least squares to find $a, \ldots f$.

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

3.12 Blume (1977)

- Ground motion model is:

$$a = b_1 e^{b_2 M_L} (R + 25)^{-b_3}$$

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

- Assumes all earthquakes have focal depth of $8\,\mathrm{km}$.
- Makes no distinction for site conditions in first stage where uses only earthquake records.
- Studies effects of PGA cutoff (no cutoff, 0.01, 0.02 and $0.05\,\mathrm{ms^{-2}}$), distance cutoff (no cutoff and $< 150\,\mathrm{km}$) and magnitude cutoff (all, $\geq 5\frac{1}{2}$, ≥ 6, $\geq 6\frac{1}{2}$, $\geq 6\frac{3}{4}$ and $\leq 6\frac{1}{2}$).
- Selects $6\frac{1}{2}$ as optimum magnitude cutoff but uses all data to derive equation for $M_L \leq 6\frac{1}{2}$ because not much difference and dispersion is slightly lower (in terms of ± 1 standard deviation have 2.53 and 2.61).
- In second stage uses only records from underground nuclear explosions, consistent with natural earthquake records, to derive site factor.
- Uses 1911 alluvium and 802 rock records and derive PGA ratio of alluvium to rock assuming their PGAs equal at $4\,\mathrm{km}$.
- Finds site impedance ρV_s, where ρ is density and V_s is shear-wave velocity under site, is best measure of site condition. Use $2000\,\mathrm{fps}$ ($600\,\mathrm{ms^{-1}}$) as shear-wave velocity of alluvium stations.
- Multiplies equation (after taking logarithms) by $\bar{b} = \frac{1}{2}\log_{10}(\rho V_s)$ and normalise to $4\,\mathrm{km}$.
- Notes may not be a good model for other regions.

3.13 McGuire (1977)

- Ground motion model is:

$$E[v] = a 10^{bM} (R + 25)^{-c}$$

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

- Excludes records for which significant soil amplification established but makes no distinction between rock and soil sites.

- Focal depths between 9 and $70\,\mathrm{km}$ with most about $10\,\mathrm{km}$. Most records from earthquakes with magnitudes about 6.5 and most distances less than $50\,\mathrm{km}$. Uses records from 21 different sites.
- Notes that physical laws governing ground motion near the source are different than those governing motion at greater distances therefore excludes records with epicentral distance or distance to fault rupture smaller than one-half of estimated length of rupture.
- Examines correlation among the records but find negligible effect.

3.14 Milne (1977)

- Ground motion model is:

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

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

3.15 Ambraseys (1978b)

- Ground motion model is:

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

  where $\bar{a}$ is in cms^{-2}, $a_1 = 1.31$, $a_2 = -0.92$ and $a_3 = 1.455$ (σ is not given).
- Uses data from former USSR, former Yugoslavia, Portugal, Italy, Iran, Greece and Pakistan.
- Peak ground accelerations have either been taken from true-to-scale accelerograms or have been supplied by local networks. Records have not been high- or low-pass filtered because it was found not to work with short records.
- Believes body-wave or local magnitude are the appropriate magnitude scales because interested in the high-frequency range of spectra, which are seen and sampled by strong-motion instruments, and most engineering structures have high natural frequencies.
- Most of the magnitudes were recalculated using P-waves of periods of not more than $1.2\,\mathrm{s}$ because it was found that the magnitude was dependent on the period of the P-waves used for its determination.
- Groups data into intervals of 0.5 magnitude units by $10\,\mathrm{km}$ in which the mean and standard deviations of the PGAs is calculated. This grouping minimises distance and magnitude-dependent effects. Notes that the number of observations is barely sufficient to allow a statistical treatment of the data and hence only test general trend. Notes that scatter is significant and decreases with increasing magnitude.

3.16 Donovan & Bornstein (1978)

- Ground motion model is:

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

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

  Use 25 because assume energy centre of Californian earthquakes to be at depth $5\,\mathrm{km}$.

- Consider two site conditions but do not model:
  1. Rock: (21 records)
  2. Stiff soil: (38 records)
- 32% of records from San Fernando (9/2/1971) but verifies that relationship is not significantly biased by this data.
- Most records within $50\,\mathrm{km}$ and most from earthquakes with magnitudes of about 6.5.
- Recognises that magnitude and distance are not independent variables.
- Find b_1, b_2 and b_3 by dividing data according to distance and computing b parameters for each set using least squares. Find a distinct trend with little scatter.

3.17 Faccioli (1978)

- Ground motion model is:

$$y = a 10^{bM}(R+25)^{-c}$$

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

- Records from sites underlain by cohesive or cohesionless soils with shear-wave velocities less than about $100\,\mathrm{ms}^{-1}$ and/or standard penetration resistance $N \leq 10$ in uppermost $10\,\mathrm{m}$ with layers of considerably stiffer materials either immediately below or at depths not exceeding a few tens of metres.
- Focal depths between 9 and $100\,\mathrm{km}$.
- free-field accelerograms, to minimize soil-structure interaction.
- Excludes records with $\mathrm{PGA} < 0.4\,\mathrm{ms}^{-2}$.

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

3.18 McGuire (1978)

- Ground motion model is:

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

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

- Uses two site categories:

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

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

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

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

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

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

- Ground motion model is:

$$\ln y = \ln A + B M_s + E \ln[R + d \exp(f M_s)]$$

  where y is in cms^{-2}, $d = 0.864$ and $f = 0.463$ and for path A (rock): $A = 157$ (for median), $A = 186$ (for mean), $B = 1.04$ and $E = -1.90$, for path A (stiff soil): $A = 191$ (for median), $A = 224$ (for mean), $B = 0.823$ and $E = -1.56$ and for path B (stiff soil): $A = 284$ (for median), $A = 363$ (for mean), $B = 0.587$ and $E = -1.05$ (σ not given).

- Separate equations for two types of path:

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

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

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

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

  Use only stiff soil records for deriving subduction zone equation.

- Most earthquakes for path A have $5 \leq M_s \leq 6.7$.
- All data corrected. PGA for corrected Japanese and South American records much higher than uncorrected PGA.

3.20 Cornell et al. (1979)

- Ground motion model is:

$$\ln A_p = a + bM_L + c\ln(R + 25)$$

  where A_p is in cms^{-2}, $a = 6.74$, $b = 0.859$, $c = -1.80$ and $\sigma = 0.57$.

- No more than 7 records from one earthquake to avoid biasing results.
- Records from basements of buildings or free-field.

3.21 Aptikaev & Kopnichev (1980)

- Ground motion model is:

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

  where A_e is in cms^{-2}, for $A_e \geq 160\,\mathrm{cms}^{-2}$ $a_1 = 0.28$, $a_2 = -0.8$ and $a_3 = 1.70$ and for $A_e < 160\,\mathrm{cms}^{-2}$ $a_1 = 0.80$, $a_2 = -2.3$ and $a_3 = 0.80$ (σ not given).

- As a rule, PGA corresponds to S-wave.
- Use five source mechanism categories (about 70 records, 59 earthquakes from W. N. America including Hawaii, Guatemala, Nicaragua, Chile, Peru, Argentina, Italy, Greece, Romania, central Asia, India and Japan):
  1. Contraction faulting (uplift and thrust), about 16 earthquakes.
  2. Contraction faulting with strike-slip component, about 6 earthquakes.
  3. Strike-slip, about 17 earthquakes.
  4. Strike-slip with dip-slip component, about 6 earthquakes.
  5. Dip-slip, about 9 earthquakes.
- Use these approximately 70 records to derive ratios of mean measured, A_0, to predicted PGA, A_e, $\log(A_0/A_e)$, and for ratios of mean horizontal to vertical PGA, $\log A_h/A_v$, for each type of faulting. Use every earthquake with equal weight independent of number of records for each earthquake.

- Results are:

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

  where ± gives 0.7 confidence intervals and number in brackets is number of earthquakes used.

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

3.22 Blume (1980)

- Ground motion model is:

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

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

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

- Mean magnitude is 5.4 and mean distance is $84.4\,\mathrm{km}$.

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

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

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

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

3.23 Iwasaki et al. (1980)

- Ground motion model is:

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

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

- Use four site categories:

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

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

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

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

- Select earthquakes with Richter magnitude ≥ 5.0, hypocentral depth $\leq 60\,\mathrm{km}$ and which include at least one record with PGA $\geq 50\,\mathrm{gals}$ $(0.5\,\mathrm{ms}^{-2})$. Exclude records with PGA $< 10\,\mathrm{gals}$ $(0.1\,\mathrm{ms}^{-2})$.
- All records for $M \geq 7.0$ are from distance $> 60\,\mathrm{km}$.
- Do regression separately for each soil category and also for combined data.

3.24 *Ohsaki* et al. *(1980a)*

- Ground motion model is:

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

  where A is in cms^{-2}, for horizontal PGA $a_1 = 0.440$, $a_2 = 1.381$ and $a_3 = 1.04$ and for vertical PGA $a_1 = 0.485$, $a_2 = 1.85$ and $a_3 = 1.38$ (σ not given).
- All records from free-field bedrock sites.

3.25 *Campbell (1981)*

- Ground motion model is:

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

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

  Uses this functional form because capable of modelling possible nonlinear distance scaling in near field and because distance at which transition from near field to far field occurs probably proportional to fault rupture zone size.
- Considers six site classifications but does not model:

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

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

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

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

- E Shallow soil deposits: Holocene or Pleistocene Age soil $< 10\,\mathrm{m}$ deep overlying soft or hard rock, 17 records. Not used in analysis.
- F Soft soil deposits: extremely soft or loose Holocene Age soils, e.g. beach sand or recent floodplain, lake, swamp, estuarine, and delta deposits, 1 record. Not used in analysis.

- Notes that data from areas outside western USA may be substantially different than those from western USA due to tectonics and recording practices but far outweighed by important contribution these data can make to understanding of near-source ground motion.
- Notes use of only near-source data has made differences in anelastic attenuation negligible to inherent scatter from other factors.
- Selects data from shallow tectonic plate boundaries generally similar to western N. America, deep subduction events excluded because of differences in travel paths and stress conditions.
- Selects data from instruments with similar dynamic characteristics as those used in USA to avoid bias, therefore excludes data from SMAC accelerographs in Japan.
- Selects data which meet these criteria:
  1. Epicentres known with an accuracy of $5\,\mathrm{km}$ or less, or accurate estimate of closest distance to fault rupture surface known.
  2. Magnitudes accurate to within 0.3 units.
  3. Distances were within 20, 30, and $50\,\mathrm{km}$ for magnitudes less than 4.75 between 4.75 and 6.25 and greater than 6.25 respectively. Only uses data from earthquakes with magnitude ≥ 5.0 because of greatest concern for most design applications.
  4. Hypocentres or rupture zones within $25\,\mathrm{km}$ of ground surface.
  5. PGA$\geq 0.2\,\mathrm{ms}^{-2}$ for one component, accelerographs triggered early enough to capture strong phase of shaking.
  6. Accelerograms either free-field, on abutments of dams or bridges, in lowest basement of buildings, or on ground level of structures without basements. Excluded Pacoima Dam record, from San Fernando (9/2/1971) earthquake due to topographic, high-frequency resonance due to large gradation in wave propagation velocities and amplification due to E-W response of dam.
- Well distributed data, correlation between magnitude and distance only 6%.
- Uses PGA from digitised, unprocessed accelerograms or from original accelerograms because fully processed PGAs are generally smaller due to the $0.02\,\mathrm{s}$ decimation and frequency band-limited filtering of records.
- Uses mean of two horizontal components because more stable peak acceleration parameter than either single components taken separately or both components taken together.
- Magnitude scale chosen to be generally consistent with M_w. Division point between using M_L and M_s varied between 5.5 and 6.5; finds magnitudes quite insensitive to choice.

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

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[2] Not shown in paper.

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

3.26 Chiaruttini & Siro (1981)

- Ground motion model is:

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

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

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

  ThA Alluvium with depth $> 20\,\mathrm{m}$, 36 records.

  Rl Rock-like: hard rock or stiff soil, 24[3] records.

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

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

- Use data from free-field instruments or from instruments in basements of small structures and divide data into three regions: those from 1976 Friuli shocks (120 records) $\Rightarrow X_{AN} = X_{AB} = 0$, those from 1972 Ancona swarm (40 records) $\Rightarrow X_{AN} = 1$ & $X_{AB} = 0$ and those from Alpide Belt (Azores to Pakistan excluding those from Friuli and Ancona) (64 records) $\Rightarrow X_{AN} = 0$ & $X_{AB} = 1$. Exclude records with PGA $< 0.15\,\mathrm{ms}^{-2}$ to avoid possible bias at low acceleration values.
- Assume average focal depth of $6\,\mathrm{km}$.
- Note some PGA values derived from velocity records which are retained because compatible with other data. No instrument corrections applied to Friuli records because correction does not substantially alter PGA.

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

- Use M_L because determined at short distances and allows homogenous determination from lowest values up to saturation at $M_L = 7.0$ and it is determined at frequencies of nearly $1\,\mathrm{Hz}$, close to accelerographic band.
- Perform regression on PGAs from each of the three regions and each soil types considered within that region.
- Group rock-like (R) and thick alluvium (ThA) records together for Friuli. Find b_d for Friuli equations derived for thin alluvium-like and rock and thick alluvium not significantly different but b_M is significantly different, at 95% level. Repeat analysis using only Tolmezzo records because of large scatter in residuals but decide it is in thA category.
- For Alpide belt equations find b_M is almost the same for Rl and Al records and the difference in b_d is less than standard error, thus repeat analysis using a dummy variable X_{Al} which equals 0 for Rl and 1 for Al records.

3.27 Joyner & Boore (1981)

- Ground motion model is:

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

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

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

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

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

- Restrict data to western North American shallow earthquakes, depth less than $20\,\mathrm{km}$, with $\mathbf{M} > 5.0$. Most records from earthquakes with magnitudes less than 6.6.
- Exclude records from base of buildings three or more storeys high and from abutments of dams.
- Exclude records associated with distances which had an uncertainty greater than $5\,\mathrm{km}$.
- Exclude records from distances greater than or equal to the shortest distance to an instrument which did not trigger.
- Six earthquakes recorded at only one station so not included in second stage regression.
- Include quadratic dependence term, $\gamma\mathbf{M}^2$, but not significant at 90% level so omitted.
- Include site term, cS, but not significant so omitted.

- Examine residuals against distance for difference magnitude ranges, no obvious differences in trends are apparent among the different magnitude classes.
- Consider a magnitude dependent $h = h_1 \exp(h_2[\mathbf{M} - 6.0])$ but reduction in variance not significant. Also prefer magnitude independent h because requires fewer parameters.
- Examine effect of removing records from different earthquakes from data.
- Examine effect of different h on residuals and b. Note coupling between h and b.
- Note coincidence of anelastic coefficient, b, and measured Q values. Also note similarity between h and proportions of depth of seismogenic zone in California.

3.28 Bolt & Abrahamson (1982)

- Ground motion model is:

  $$y = a\{(x + d)^2 + 1\}^c \mathrm{e}^{-b(x+d)}$$

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

3.29 PML (1982)

- Ground motion model is:

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

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

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

- Develop for use in UK.

3.30 Schenk (1982)

- Ground motion model is:

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

  where A_{mean} is in cms^{-2}, $a = 1.1143$, $b = 1.576$ and $c = 2.371$ (σ not given).

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

3.31 Brillinger & Preisler (1984)

- Ground motion model is:

$$A^{1/3} = a_1 + a_2 M + a_3 \ln(d^2 + a_4^2)$$

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

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

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

- Use ACE procedure to find model. For set of data, with response y_i and predictors w_i and x_i find functions to minimize: $\sum_{i=1}^{n} [\theta(y_i) - \phi(w_i) - \psi(x_i)]^2$ subject to $\sum \phi(w_i) = 0$, $\sum \psi(x_i) = 0$, $\sum \theta(y_i) = 0$ and $\sum \theta(y_i)^2 = n$. Search amongst unrestricted curves or unrestricted monotonic curves. Use EDA to select specific functional forms from the estimates of θ, ϕ and ψ at each data point.

- Do not use weighting because does not seem reasonable from statistical or seismological points of view.
- Do not want any individual earthquake, e.g. one with many records, overly influencing results.
- Note that because each earthquake has its own source characteristics its records are intercorrelated. Therefore use 'random effects model' which accounts for perculiarities of individual earthquakes and correlation between records from same event.
- On physical grounds, restrict θ, ϕ and ψ to be monotonic and find optimal transformation of magnitude is approximately linear, optimal transformation of distance is logarithmic and cube root is optimal for acceleration transformation.
- Note that need correlations between coefficients, which are provided, to attach uncertainties to estimated PGAs.
- Provide method of linearization to give 95% confidence interval for acceleration estimates.
- Also provide a graphical procedure for estimating accelerations that does not rely on an assumed functional form.
- Examine residual plots (not shown) and found a candidate for an outlying observation (the record from the Hollister 1974 earthquake of $0.011\,\mathrm{g}$ at $17.0\,\mathrm{km}$).
- Find that assumption of normality after transformation seems reasonable.

3.32 Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)

- Ground motion model is:

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

  where y is in g, coefficients c_0 to c_4, h and σ are from Joyner & Boore (1981) and c_6 and V_0 are not significant at 90% level so do not report them.
- Use data of Joyner & Boore (1981).
- Continuous site classification for soil sites in terms of shear-wave velocity, V, to depth of one quarter wavelength of waves of period of concern. V measured down to depths of at least $30\,\mathrm{m}$ and then extrapolated using geological data. V known for 33 stations.
- Soil amplification factor based on energy conservation along ray tubes, which is a body wave argument and may not hold for long periods for which surface waves could be important. Does not predict resonance effects.

- Regress residuals, R_{ij}, w.r.t. motion predicted for rock sites on $\log R_{ij} = P_i + c_6 V_j$, where j corresponds to jth station and i to ith earthquake. Decouples site effects variation from earthquake-to-earthquake variation. Find unique intercept by requiring average site effect term calculated using shear-wave velocity to be same as that calculated using rock/soil classification.
- No significant, at 90%, correlation between residuals and V for PGA.
- Repeat regression on residuals using V and depth to underlying rock (defined as either shear-wave velocity $> 750\,\mathrm{ms}^{-1}$ or $> 1500\,\mathrm{ms}^{-1}$). Find no correlation.

3.33 *Kawashima* et al. *(1984) & Kawashima* et al. *(1986)*

- Ground motion model is:

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

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

- Use three site categories:

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

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

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

- Only includes free-field records with $M_{\mathrm{JMA}} \geq 5.0$ and focal depths $D_p < 60\,\mathrm{km}$. Excludes records from structures with first floor or basement.
- Records instrument corrected, because Japanese instruments substantially suppress high frequencies, considering accuracy of digitization for frequencies between $\frac{1}{3}$ and $12\,\mathrm{Hz}$.
- Note that M_{JMA} and Δ not necessarily most suitable parameters to represent magnitude and distance but only ones for all records in set.
- Note lack of near-field data for large magnitude earthquakes, approximately $\frac{3}{4}$ of records from $M_{\mathrm{JMA}} < 7.0$.
- Use $30\,\mathrm{km}$ in distance dependence term because focal depth of earthquakes with magnitudes between 7.5 and 8.0 are between 30 and $100\,\mathrm{km}$ so 30 is approximately half the fault length.
- Try equation: $\log X = f_1 + f_2 M + f_3 \log(\Delta + 30) + f_4 D_p + f_5 M \log(\Delta + 30) + f_6 M D_p + f_7 D_p \log(\Delta + 30) + f_8 M^2 + f_9 \{\log(\Delta + 30)\}^2 + f_{10} D_p^2$ where f_i are coefficients to be found considering each soil category separately. Apply multiple regression analysis to 36 combinations of retained coefficients, f_i, and compute multiple correlation coefficient, R, and adjusted

multiple correlation coefficient, R^*. Find that inclusion of more than three coefficients does not give significant increase in R^*, and can lead to unrealistic results. Conclude due to insufficient data.

- Consider a, b and c dependent and independent of soil type and examine correlation coefficient, R, and adjusted correlation coefficient, R^*. Find that c is not strongly dependent on soil type.
- Find match between normal distribution and histograms of residuals.

3.34 McCann Jr. & Echezwia (1984)

- Four ground motion models:

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

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

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

3.35 Schenk (1984)

- Ground motion model is:

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

where A_{mean} is in cms^{-2}, $a = 0.37$, $b = 1.58$ and $c = 2.35$ (σ not given).

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

3.36 *Xu* et al. *(1984)*

- Ground motion model is:

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

  where PGA is in g, $a_1 = 0.1548$, $a_2 = 0.5442$, $a_3 = 8$ and $a_4 = 1.002$ (σ not given).
- All records from aftershocks of 1975 Haicheng earthquake and from 1976 Tangshan earthquake and aftershocks.
- Most records from earthquakes with magnitude less than 5.8 and from distances $< 30\,\text{km}$.
- Exclude records with PGA $< 0.5\,\text{ms}^{-2}$ to avoid too much contribution from far field.
- Due to small number of records simple regression technique justified.
- States valid for $4 \leq M \leq 6.5$ and $R \leq 100\,\text{km}$.
- Also use 158 records from western N. America to see whether significantly different than N. Chinese data. Derive equations using both western N. American and N. Chinese data and just western N. American data and find that predicted PGAs are similar, within uncertainty.
- Insufficient data to find physically realistic anelastic term.

3.37 *Brillinger & Preisler (1985)*

- Ground motion model is:

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

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

- Provide algorithm for random effects regression.
- Note that the functional form adopted in Brillinger & Preisler (1984) is strictly empirical and hence repeat analysis using functional form of Joyner & Boore (1981), which is based on physical reasoning.
- Note that need correlations between coefficients, which are provided, to attach uncertainties to estimated PGAs.

3.38 Kawashima et al. (1985)

- Use very similar data to Kawashima *et al.* (1984); do not use some records because missing due to recording and digitising processes. Use equation and method (although do not check all 36 combinations of forms of equation) used by Kawashima *et al.* (1984), see section 3.33.
- $X(M, \Delta, \mathrm{GC}_i)$ is in gal. Coefficients are: $c = -1.190$ and for ground group 1 $a = 117.0$ and $b = 0.268$ and for ground group 2 $a = 88.19$ and $b = 0.297$ and for group ground 3 $a = 13.49$ and $b = 0.402$ with $\sigma = 0.253$.

3.39 Peng et al. (1985b)

- Ground motion model is:

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

  where a is in cms^{-2}, for N.E. China $A = -0.474$, $B = 0.613$, $C = -0.873$ and $D = -0.00206$ (σ not given) and for S.W. China $A = 0.437$, $B = 0.454$, $C = -0.739$ and $D = -0.00279$ (σ not given).
- Consider two site conditions for NE records but do not model:
  1. Rock: 28 records.
  2. Soil: 45 records.
- Consider all records to be free-field.
- Note that Chinese surface-wave magnitude, M, is different than M_s and may differ by 0.5 or more. Use m_b or M_s and find larger residuals.
- Most records from $M \leq 5.8$.
- Note isoseismals are not elongated for these earthquakes so use of another distance measure will not change results by much.
- Also derives equation for SW China ($3.7 \leq M \leq 7.2$, $6.0 \leq R \leq 428.0\,\mathrm{km}$ all but one record $\leq 106.0\,\mathrm{km}$, 36 records from 23 earthquakes) and note difference between results from NE China although use less data.

- Note that some scatter may be due to radiation pattern.
- Note that data is from limited distance range so need more data to confirm results.

3.40 Peng et al. (1985a)

- Ground motion model is:

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

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

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

3.41 PML (1985)

- Ground motion model is:

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

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

- Use data from Italy (47 records, 9 earthquakes), USA (128 records, 18 earthquakes), Greece (11 records, 8 earthquakes), Iran (2 records, 2 earthquakes), Yugoslavia (7 records, 2 earthquake), Nicaragua (1 record, 1 earthquake), New Zealand (3 records, 3 earthquakes), China (2 records, 2 earthquakes) and Canada (2 records, 1 earthquake).
- Develop for use in UK.
- Select earthquakes with $M_s < 7$ and $R \leq 40\,\mathrm{km}$.
- Focal depths $< 40\,\mathrm{km}$.

- Use two source mechanism categories (40 records have no source mechanism given):

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

$F = 1$ Thrust, 78 records.

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

3.42 McCue (1986)

- Ground motion model is:

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

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

3.43 C.B. Crouse (1987) reported in Joyner & Boore (1988)

- Ground motion model is:

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

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

- Records from deep soil sites (generally greater than $60\,\mathrm{m}$ in thickness).
- Data from shallow crustal earthquakes.

3.44 Krinitzsky et al. (1987) & Krinitzsky et al. (1988)

- Ground motion model is (for shallow earthquakes):

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

where A is in cms^{-2}, $a_1 = 1.23$ (for hard sites), $a_1 = 1.41$ (for soft sites), $a_2 = 0.385$ and $a_3 = -0.00255$ (σ is not given).

Ground motion model is (for subduction zone earthquakes):

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

where A is in cms^{-2}, $b_1 = 2.08$ (for hard sites), $b_1 = 2.32$ (for soft sites), $b_2 = 0.35$ and $b_3 = -0.0025$ (σ is not given).

- Use four site categories:

  1 Rock

  2 Stiff soil

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

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

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

- Use data from ground floors and basements of small or low structures (under 3 stories) because believe that small structures have little effect on recorded ground motions.
- Separate earthquakes into shallow ($h \leq 19\,\mathrm{km}$) and subduction ($h \geq 20\,\mathrm{km}$) because noted that ground motions have different characteristics.
- Use epicentral distance for Japanese data because practical means of representing deep subduction earthquakes with distant and imprecise fault locations.
- Do not use rupture distance or distance to surface projection of rupture because believe unlikely that stress drop and peak motions will occur with equal strength along the fault length and also because for most records fault locations are not reliably determinable.
- Note that there is a paucity of data but believe that the few high peak values observed (e.g. Pacoima Dam and Morgan Hill) cannot be dismissed without the possibility that interpretations will be affected dangerously.
- For subduction equations, use records from Japanese SMAC instruments that have not been instrument corrected, even though SMAC instruments show reduced sensitivity above $10\,\mathrm{Hz}$, because ground motions $> 10\,\mathrm{Hz}$ are not significant in subduction earthquakes. Do not use records from SMAC instruments for shallow earthquakes because high frequency motions may be significant.
- Examine differences between ground motions in extensional (strike-slip and normal faulting) and compressional (reverse) regimes for shallow earthquakes but do not model. Find that the extensional ground motions seem to be higher than compressional motions, which suggest is because rupture propagation comes closer to ground surface in extensional faults than in compressional faults.
- Group records into $1\,M$ unit intervals and plot ground motions against distance. When data is numerous enough the data points are encompassed in boxes (either one, two or three) that have a range equal to the distribution of data. The positions of the calculated values within the boxes were used as guides for shaping appropriate curves. Initially curves developed for $M = 6.5$ were there is most data and then these were extended to smaller and larger magnitudes.

3.45 Sabetta & Pugliese (1987)

- Ground motion model is:

$$\log y = \boldsymbol{a} + \boldsymbol{b}M - \log(R^2 + \boldsymbol{h}^2)^{1/2} + \boldsymbol{e}S$$

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

- Use two site categories:

$S = 0$ Stiff and deep soil: limestone, sandstone, siltstone, marl, shale and conglomerates ($V_s > 800\,\mathrm{ms}^{-1}$) or depth of soil, H, $> 20\,\mathrm{m}$, 74 records.

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

- Select records which satisfy these criteria:
  1. Reliable identification of the triggering earthquake.
  2. Magnitude greater than 4.5 recorded by at least two stations.
  3. Epicentres determined with accuracy of $5\,\mathrm{km}$ or less.
  4. Magnitudes accurate to within 0.3 units.
  5. Accelerograms from free-field. Most are from small electric transformer cabins, 4 from one- or two-storey buildings with basements and 5 from near abutments of dams.
- Depths between 5.0 and $16.0\,\mathrm{km}$ with mean $8.5\,\mathrm{km}$.
- Focal mechanisms are: normal and oblique (7 earthquakes, 48 records), thrust (9 earthquakes, 43 records) and strike-slip (1 earthquake, 4 records).
- Notes lack of records at short distances from large earthquakes.
- Records baseline-, instrument-corrected and filtered with cutoff frequencies determined by visual inspection in order to maximise signal to noise ratio within band. Cutoff frequencies ranged from 0.2 to $0.4\,\mathrm{Hz}$ and from 25 to $35\,\mathrm{Hz}$. This correction routine thought to provide reliable estimates of PGA so uncorrected PGA do not need to be used.
- For well separated multiple shocks, to which magnitude and focal parameters refer, use only first shock.
- Magnitude scale assures a linear relationship between logarithm of PGA and magnitude and avoids saturation effects of M_L.
- Distance to surface projection of fault rupture thought to be a more physically consistent definition of distance for earthquakes having extensive rupture zones and is easier to predict for future earthquakes. Also reduces correlation between magnitude and distance.
- Use Exploratory Data Analysis using the ACE procedure to find transformation functions of distance, magnitude and PGA.
- Include anelastic attenuation term but it is positive and not significant.
- Include magnitude dependent $\boldsymbol{h}$ equal to $\boldsymbol{h_1} \exp(\boldsymbol{h_2} M)$ but find $\boldsymbol{h_2}$ not significantly different than zero. Note distribution of data makes test not definitive.

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

3.46 *K. Sadigh (1987) reported in Joyner & Boore (1988)*

- Ground motion model is:

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

  where y is in g. For strike-slip earthquakes: $b = 1.1$, $c_1 = 0$, $c_2 = 2.5$, for PGA at soil sites $a = -2.611$ and $d = -1.75$, for $\mathbf{M} < 6.5$ $h_1 = 0.8217$, $h_2 = 0.4814$ and for $\mathbf{M} \geq 6.5$ $h_1 = 0.3157$ and $h_2 = 0.6286$, for PGA at rock sites $a = -1.406$ and $d = -2.05$, for $\mathbf{M} < 6.5$ $h_1 = 1.353$ and $h_2 = 0.406$ and for $\mathbf{M} \geq 6.5$ $h_1 = 0.579$ and $h_2 = 0.537$. For reverse-slip increase predicted values by 20%. For $\mathbf{M} < 6.5$ $\sigma = 1.26 - 0.14\mathbf{M}$ and for $\mathbf{M} \geq 6.5$ $\sigma = 0.35$.
- Uses two site categories:
  1. Soil
  2. Rock
- Use two source mechanism categories:
  1. Strike-slip
  2. Reverse-slip
- Supplement data with significant recordings of earthquakes with focal depths $< 20\,\mathrm{km}$ from other parts of world.
- Different equations for $\mathbf{M} < 6.5$ and $\mathbf{M} \geq 6.5$.

3.47 Singh et al. (1987)

- Ground motion model is:

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

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

  More complicated functional form unwarranted due to limited distance range.

- Depths between 15 and $20\,\mathrm{km}$.
- Only use data from a single firm site (Ciudad Universitaria), on a surface layer of lava flow or volcanic tuff.
- Only records from coastal earthquakes.
- Residuals plotted against distance, no trends seen.
- Give amplification factor for lake bed sites (25 to $80\,\mathrm{m}$ deposit of highly compressible, high water content clay underlain by resistant sands), but note based on only a few sites so not likely to be representative of entire lake bed.

3.48 Algermissen et al. (1988)

- Ground motion model is:

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

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

3.49 Annaka & Nozawa (1988)

- Ground motion model is:

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

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

- Focal depths $< 100\,\mathrm{km}$.
- Convert records from sites with $V_s < 300\,\mathrm{ms}^{-1}$ into records from sites with $V_s > 300\,\mathrm{ms}^{-1}$ using 1-D wave propagation theory.
- Introduce term $C_h H$ because it raises multiple correlation coefficient for PGA.
- Note equations apply for site where $300 \leq V_s \leq 600\,\mathrm{ms}^{-1}$.

3.50 K.W. Campbell (1988) reported in Joyner & Boore (1988)

- Ground motion model is:

$$\begin{aligned}\ln y &= a + bM + d\ln[r + h_1\exp(h_2M)] + s \\ \text{where } s &= e_1K_1 + e_2K_2 + e_3K_3 + e_4K_4 + e_5K_5 + e_6(K_4 + K_5)\tanh(e_7r)\end{aligned}$$

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

- Uses two site categories:

$K_3 = 1$ Soils $\leq 10\,\mathrm{m}$ deep.

$K_3 = 0$ Other.

- Uses three embedment categories:

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

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

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

- Selects data using these criteria:

  1. Largest horizontal component of peak acceleration was $\geq 0.02\,\mathrm{g}$ [$\geq 0.2\,\mathrm{ms}^{-2}$].
  2. Accelerograph triggered early enough to record strongest phase of shaking.
  3. Magnitude of earthquake was ≥ 5.0.
  4. Closest distance to seismogenic rupture was < 30 or $< 50\,\mathrm{km}$, depending on whether magnitude of earthquake was < 6.25 or > 6.25.
  5. Shallowest extent of seismogenic rupture was $\leq 25\,\mathrm{km}$.
  6. Recording site located on unconsolidated deposits.

- Excludes records from abutments or toes of dams.

- Derives two equations: unconstrained (coefficients given above) and constrained which includes a anelastic decay term kr which allows equation to be used for predictions outside near-source zone (assumes $k = -0.0059$ for regression, a value appropriate for region of interest should be chosen).

- Uses two source mechanism categories:

$K_1 = 0$ Strike-slip.

$K_1 = 1$ Reverse.

- Uses two directivity categories:

$K_2 = 1$ Rupture toward site.

$K_2 = 0$ Other.

3.51 Fukushima et al. (1988) & Fukushima & Tanaka (1990)

- Ground motion model is:

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

  where A is in cms^{-2}, $a = 0.41$, $b = 0.0034$, $c = 0.032$, $d = 1.30$ and $\sigma = 0.21$.

- Use four site categories for some Japanese stations (302 Japanese records not classified):

  1. Rock: 41 records
  2. Hard: ground above Tertiary period or thickness of diluvial deposit above bedrock $< 10\,\mathrm{m}$, 44 records.
  3. Medium: thickness of diluvial deposit above bedrock $> 10\,\mathrm{m}$, or thickness of alluvial deposit above bedrock $< 10\,\mathrm{m}$, or thickness of alluvial deposit $< 25\,\mathrm{m}$ and thickness of soft deposit is $< 5\,\mathrm{m}$, 66 records.
  4. Soft soil: other soft ground such as reclaimed land, 33 records.

- Use 1100 mean PGA values from 43 Japanese earthquakes ($6.0 \leq M_{\mathrm{JMA}} \leq 7.9$, focal depths $\leq 30\,\mathrm{km}$) recorded at many stations to investigate one and two-stage methods. Fits $\log A = c - b \log X$ (where X is hypocentral distance) for each earthquake and computes mean of b, $\bar{b}$. Also fits $\log A = aM - b^* \log X + c$ using one-stage method. Find that $\bar{b} > b^*$ and shows that this is because magnitude and distance are strongly correlated (0.53) in data set. Find two-stage method of Joyner & Boore (1981) very effective to overcome this correlation and use it to find similar distance coefficient to $\bar{b}$. Find similar effect of correlation on distance coefficient for two other models: $\log A = aM - b\log(\Delta + 30) + c$ and $\log A = aM - \log X - bX + c$, where Δ is epicentral distance.

- Japanese data selection criteria: focal depth $< 30\,\mathrm{km}$, $M_{\mathrm{JMA}} > 5.0$ and predicted PGA $\geq 0.1\,\mathrm{ms}^{-2}$. US data selection criteria: $d_r \leq 50\,\mathrm{km}$, use data from Campbell (1981).

- Because a affects distance and magnitude dependence, which are calculated during first and second steps respectively use an iterative technique to find coefficients. Allow different magnitude scaling for US and Japanese data.

- For Japanese data apply station corrections before last step in iteration to convert PGAs from different soil conditions to standard soil condition using residuals from analysis.

- Two simple numerical experiments performed. Firstly a two sets of artificial acceleration data was generated using random numbers based on attenuation relations, one with high distance decay and which contains data for short distance and one with lower distance decay, higher constant and no short distance data. Find that the overall equation from regression analysis has a smaller distance decay coefficient than individual coefficients for each line. Secondly find the same result for the magnitude dependent coefficient based on similar artificial data.

- Exclude Japanese data observed at long distances where average acceleration level was predicted (by using an attenuation relation derived for the Japanese data) to be less than the trigger level (assume to be about $0.05\,\mathrm{ms}^{-2}$) plus one standard deviation (assume to be 0.3), i.e. $0.1\,\mathrm{ms}^{-2}$, to avoid biasing results and giving a lower attenuation rate.
- Use the Japanese data and same functional form and method of Joyner & Boore (1981) to find an attenuation relation; find the anelastic coefficient is similar so conclude attenuation rate for Japan is almost equal to W. USA.
- Find difference in constant, d, between Japanese and W. USA PGA values.
- Plot residuals against distance and magnitude and find no bias or singularity.

3.52 Gaull (1988)

- Ground motion model is:

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

  where PGA is in ms^{-2}, $a_1 = 5$, $a_2 = 3$, $a_3 = 20$, $a_4 = 6$, $a_5 = 0.77$, $a_6 = 0.0045$ and $a_7 = 1.2$ (σ not given).

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

3.53 Joyner & Boore (1988)

- Use same data and very similar method to Joyner & Boore (1981), see Section 3.27, and find: $\beta = 0.23$, $b = -0.0027$, $h = 8.0$ and $\sigma = 0.28$, for randomly oriented component $\alpha = 0.43$ and for larger component $\alpha = 0.49$.

3.54 McCue et al. (1988)

- Ground motion model is:

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

  where A is in g, $\ln a = -5.75$, $b = 1.72$, $c = 0$, $d = 1.69$ and $R_0 = 1$ (σ not given).

- Few records from free-field, most are in dams or special structures.,
- Because only 62 records, set $R_0 = 1$ and $c = 0$.
- Most records from earthquakes with M_L between 1.5 and 2.0.
- Maximum PGA in set $3.05\,\mathrm{ms}^{-2}$.
- Nonuniform distribution of focal distances. One quarter of records from same hypocentral distance. Therefore plot PGA of these records against magnitude ($1.2 \lesssim M_L \lesssim 4.3$ most less than 2.1) to find b. Then plot $bM - \ln A$ against $\ln(R/R_0)$ for all records to find a and d.
- Notes limited data.

3.55 Petrovski & Marcellini (1988)

- Ground motion model is:

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

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

- Data from 'moderate' soil conditions.
- Data mainly from SMA-1s but 17 from RFT-250s.
- Data from northern Greece (5 records, 4 stations, 3 earthquakes), northern Italy (45 records, 18 stations, 20 earthquakes) and former Yugoslavia (70 records, 42 stations, 23 earthquakes).
- Data from free-field or in basements of structures.
- Select records from earthquakes with $3 \leq M \leq 7$. Most earthquakes with $M \leq 5.5$. 4 earthquakes (4 records) with $M \leq 3.5$, 20 (27 records) with $3.5 < M \leq 4.5$, 13 (25 records) with $4.5 < M \leq 5.5$, 8 (50 records) with $5.5 < M \leq 6.5$ and 1 (14 records) with $M > 6.5$.

- Select records from earthquakes with $h \leq 40\,\mathrm{km}$. Most earthquakes with $h \leq 10\,\mathrm{km}$. 6 earthquakes with $h \leq 5\,\mathrm{km}$, 30 with $5 < h \leq 10\,\mathrm{km}$, 5 with $10 < h \leq 20\,\mathrm{km}$, 4 with $20 < h \leq 30\,\mathrm{km}$ and 1 with $h > 30$.
- Select records that satisfied predetermined processing criteria so that their amplitude would be such as to give negligible errors after processing.
- Select records to avoid concentration of records w.r.t. certain sites, magnitudes, hypocentral distances or earthquakes. Most well-recorded earthquakes is 15/4/1979 Montenegro earthquake with 14 records.
- Try values of c between 0 and $40\,\mathrm{km}$. Find standard deviation does not vary much for different choices.
- Test assumption of the log-normal probability distribution of data using graph in a coordinate system for log-normal distribution of probability, by χ^2 test and by the Kolmogorov-Smirnov test (not shown). Find assumption is acceptable.

3.56 Tong & Katayama (1988)

- Ground motion model is:

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

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

- Omit T from regression and find little effect in estimation.

3.57 Yamabe & Kanai (1988)

- Ground motion model is:

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

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

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

3.58 Youngs et al. (1988)

- Ground motion model is:

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

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

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

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

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

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

- Plots PGA from different magnitude earthquakes against distance; find near-field distance saturation.
- Originally include anelastic decay term $-C_6 R$ but C_6 was negative (and hence nonphysical) so remove.
- Plot residuals from original PGA equation (using rock and soil data) against M_w and R; find no trend with distance but reduction in variance with increasing M_w. Assume standard deviation is a linear function of M_w and find coefficients using combined rock and soil data (because differences in variance estimation from rock and soil are not significant).
- Use derived equation connecting standard deviation and M_w for weighted (weights inversely proportional to variance defined by equation) nonlinear regression in all analyses.
- Plot residuals from original PGA equation; find that hypothesis that coefficients of equations for interface and intraslab earthquakes are the same can be rejected (using likelihood ratio test for nonlinear regression models) at 0.05 percentile level for both soil and rock. Try including a term proportional to depth of rupture into equation (because intraslab deeper than interface events) but find no significant reduction in standard error. Introduce BZ_t term into equation; find B is significant at 0.05 percentile level. Try including rupture type dependence into other coefficients but produces no further decrease in variance so reject.
- Use only data from sites with multiple recordings of both interface and intraslab earthquakes and include dummy variables, one for each site, to remove differences due to systematic site effects. Fix C_1 to C_5 to values from entire set and find individual site terms and B; find B is very similar to that from unconstrained regression.
- Examine residuals for evidence of systematic differences between ground motion from different subduction zones; find no statistically significant differences in PGA among different subduction zones.
- Use geometric mean of two horizontal components to remove effect of component-to-component correlations that affect validity of statistical tests assuming individual components of motion represent independent measurements of ground motion. Results indicate no significant difference between estimates of variance about median relationships obtained using geometric mean and using both components as independent data points.
- Extend to $M_w > 8$ using finite difference simulations of faulting and wave propagation modelled using ray theory. Method and results not reported here.

3.59 Abrahamson & Litehiser (1989)

- Ground motion model is:

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

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

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

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

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

- Data based on Campbell (1981).

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

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

- Depths less than $25\,\mathrm{km}$.

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

- Most records from distances less than $100\,\mathrm{km}$ and magnitude distribution is reasonably uniform but correlation between magnitude and distance of 0.52.

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

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

- Form of h chosen using nonparametric function, $H(M)$, which partitions earthquakes into 0.5 unit bins. Plot $H(M)$ against magnitude. Find that $H(M) = h_1 \exp(h_2 M)$ is controlled by Mexico (19/9/1985) earthquake and h_1 and h_2 are highly correlated, 0.99, although does given lower total variance. Choose $H(M) = \exp(h_2 M)$ because Mexico earthquake does not control fit and all parameters are well-determined, magnitude dependent h significant at 90%.
- Try removing records from single-recorded earthquakes and from shallow or soft soil but effect on predictions and variance small ($< 10\%$).
- Plot weighted residuals within $10\,\mathrm{km}$ no significant, at 90%, trends are present.
- Find no significant effects on vertical PGA due to site classification.

3.60 Campbell (1989)

- Ground motion model is:

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

  where PHA is in g, $a = -2.501$, $b = 0.623$, $c_1 = 7.28$ and $\sigma = 0.506$.
- Selects records from deep soil ($> 10\,\mathrm{m}$). Excludes data from shallow soil ($\leq 10\,\mathrm{m}$) and rock sites and those in basements of buildings or associated with large structures, such as dams and buildings taller than two storeys. Selects records with epicentral distances $\leq 20\,\mathrm{km}$ for $M_L < 4.75$ and distances $\leq 30\,\mathrm{km}$ for $M_L \geq 4.75$ to minimize regional differences in anelastic attenuation and potential biases associated with nontriggering instruments and unreported PGAs.
- Focal depths, H, between 1.8 and $24.3\,\mathrm{km}$ with mean of $8.5\,\mathrm{km}$.
- PGAs scaled from either actual or uncorrected accelerograms in order to avoid potential bias due to correction.
- Uses weighted nonlinear least squares technique of Campbell (1981).
- Tries two other forms of equation: $\ln \mathrm{PHA} = a + bM_L - 1.0 \ln[R + c_1] + e_1 H$ and $\ln \mathrm{PHA} = a + bM_L - 1.0 \ln[R + c_1] + e_2 \ln H$ for epicentral and hypocentral distance. Allows saturation of PGA for short distances but finds nonsignificant coefficients, at 90%. Also tries distance decay coefficient other than -1.0 but finds instability in analysis.
- Examines normalised weighted residuals against focal depth, M_L and distance. Finds that although residuals seem to be dependent on focal depth there are probably errors in focal depth estimation for deep earthquakes in the study so the dependence may not be real. Finds residuals not dependent on magnitude or distance.
- Uses 171 records ($0.9 \leq R \leq 28.1\,\mathrm{km}$) from 75 earthquakes ($2.5 \leq M_L \leq 5.0$, $0.7 \leq H \leq 24.3\,\mathrm{km}$) excluded from original analysis because they were on shallow soil, rock and/or not

free-field, to examine importance of site geology and building size. Considers difference between PGA from records grouped according to instrument location, building size, embedment, and site geology and the predicted PGA using the attenuation equation to find site factors, S. Groups with nonsignificant, at 90%, values of S are grouped together. Finds two categories: embedded alluvial sites from all building sizes (38 records) and shallow-soil (depth of soil $\leq 10\,\mathrm{m}$) sites (35 records) to have statistically significant site factors.

- Performs regression analysis on all records (irrespective of site geology or building size) from Oroville (172 records from 32 earthquakes) and Imperial Valley (71 records from 42 earthquakes) to find individual sites that have significant influence on prediction of PGA (by using individual site coefficients for each station). Finds equations predict similar PGA to those predicted by original equation. Finds significant differences between PGA recorded at different stations in the two regions some related to surface geology but for some finds no reason.
- Uses 27 records ($0.2 \leq R \leq 25.0\,\mathrm{km}$) from 19 earthquakes ($2.5 \leq M_{bLG} \leq 4.8$, $0.1 \leq H \leq 9\,\mathrm{km}$) from E. N. America to examine whether they are significantly different than those from W. N. America. Finds residuals significantly, at 99% level, higher than zero and concludes that it is mainly due to site effects because most are on shallow soils or other site factors influence ground motion. Correcting the recorded PGAs using site factors the difference in PGA between E. N. America and W. N. America is no longer significant although notes may not hold for all of E. N. America.

3.61 Alfaro et al. (1990)

- Ground motion model for near field is:

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

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

  Ground motion model for far field is:

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

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

- Separate crustal and subduction data because of differences in travel path and stress conditions:
  1. Near field
  2. Far field, 20 records from San Salvador, 20 earthquakes, $4.2 \leq M_s \leq 7.2$, depths between 36 and $94\,\mathrm{km}$, $31 \leq r \leq 298\,\mathrm{km}$.

3.62 Ambraseys (1990)

- Ground motion model is:

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

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

- Uses data and method of Joyner & Boore (1981) but re-evaluates M_w for all earthquakes. Finds some large changes, e.g. Santa Barbara changes from $M_w = 5.1$ to $M_w = 5.85$. Uses M_L for 2 earthquakes ($M_L = 5.2$, 6.2).
- Find effect of uncertainty in M_w causes less than 10% change in σ.
- Also calculates equation using M_s instead of M_w.
- Finds assumption $M_s = M_w$ introduces bias, particularly for small magnitude shocks, on unsafe side, and this can be significant in cases where there is a preponderance of small earthquakes in set.

3.63 Campbell (1990)

- Ground motion model is:

$$\begin{aligned}\ln(Y) &= a + bM + d\ln[R + c_1\exp(c_2M)] + eF + f_1\tanh[f_2(M + f_3)] + g_1\tanh(g_2D) + h_1K_1 \\ &\quad + h_2K_2 + h_3K_3\end{aligned}$$

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

- Records from firm soil and soft rock sites. Characterises site conditions by depth to basement rock (sediment depth) in km, D.
- Records from different size buildings. $K_1 = 1$ for embedded buildings 3–11 storeys, $K_2 = 1$ for embedded buildings with $>$11 storeys and $K_3 = 1$ for non-embedded buildings $>$2 storeys in height. $K_1 = K_2 = K_3 = 0$ otherwise.
- Uses two fault mechanisms:

$F = 0$ Strike-slip
$F = 1$ Reverse

3.64 Dahle et al. (1990b) & Dahle et al. (1990a)

- Ground motion model is:

$$\begin{aligned}\ln A &= c_1 + c_2M + c_4R + \ln G(R, R_0) \\ \text{where } G(R, R_0) &= R^{-1} \quad \text{for} \quad R \leq R_0 \\ \text{and: } G(R, R_0) &= R_0^{-1}\left(\frac{R_0}{R}\right)^{5/6} \quad \text{for} \quad R > R_0\end{aligned}$$

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

- Use records from rock sites (presumably with hard rock or firm ground conditions).
- Assume intraplate refers to area that are tectonically stable and geologically more uniform than plate boundary areas. Select records from several 'reasonably' intraplate areas (eastern N. America, China, Australia, and some parts of Europe), due to lack of data.
- Select records which are available unprocessed and with sufficient information on natural frequency and damping of instrument.
- Use M_s, when available, because reasonably unbiased with respect to source dimensions and there is globally consistent calculation method.
- Most (72%) records from earthquakes with $M \leq 5.5$. Tangshan and Friuli sequence comprise a large subset. Correlation coefficient between magnitude and distance is 0.31.
- Instrument correct records and elliptical filter with pass band 0.25 to $25.0\,\mathrm{Hz}$.
- If depth unknown assume $15\,\mathrm{km}$.
- Choose $R_0 = 100\,\mathrm{km}$ although depends on crustal structure and focal depth. It is distance at which spherical spreading for S waves overtaken by cylindrical spreading for Lg waves.
- PGA attenuation relation is pseudo-acceleration equation for $0.025\,\mathrm{s}$ period and 5% damping.
- Plot residuals against magnitude and distance.
- Note 'first order' results, because data from several geological regions and use limited data base.

3.65 Jacob et al. *(1990)*

- Ground motion model is:

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

  where A is in g, $a_1 = -1.43$, $a_2 = 0.31$, $a_3 = -0.62$ and $a_4 = -0.0026$ (σ not given).
- Note equation only for hard rock sites.
- Equation from a composite of two separate regressions: one using data from 6 earthquakes, $4.7 \leq M \leq 6.4$ and d primarily between 40 and $820\,\mathrm{km}$ and one using the same data supplemented with data from 2 earthquakes with $M = 1.8$ and $M = 3.2$ and $d \leq 20\,\mathrm{km}$ to extend results to smaller M and d. Give no details of this composite regression.
- Note regressions are preliminary and should be tested against more data.
- Note careful assessment of uncertainties is required.

3.66 Sen (1990)

- Ground motion model is:

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

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

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

3.67 Sigbjörnsson (1990)

- Ground motion model is:

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

  where $P = 1$.

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

- Does not give coefficients, only predictions.

3.68 *Tsai* et al. *(1990)*

- Ground motion model is:

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

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

- All records from rock or rock-like sites.

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

- Use only shallow crustal thrust earthquakes.

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

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

3.69 Ambraseys & Bommer (1991) & Ambraseys & Bommer (1992)

- Ground motion model is:

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

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

- Consider two site classifications (without regard to depths of deposits) but do not model:

  1. Rock
  2. Alluvium

- Select records which have: $M_s \geq 4.0$ and standard deviation of M_s known and reliable estimates of source-site distance and focal depth, $h \leq 25\,\mathrm{km}$, regardless of local soil conditions from free-field and bases of small buildings. No reliable data or outliers excluded. Records from instruments at further distances from the source than the closest non-triggered instrument were non-excluded because of non-homogeneous and irregularly spaced networks and different and unknown trigger levels.

- Most data, about 70%, with distances less than $40\,\mathrm{km}$. Note strong bias towards smaller values of magnitude and PGA.

- PGA read from analogue and digitised data, with different levels of processing. Differences due to different processing usually below 5%, but some may be larger.

- Errors in distances for small shocks may be large.

- Prefer one-stage technique because second step of two-stage method would ignore records from singly-recorded earthquakes which compose over half the events, also find more realistic, b, and h_0 using one-stage method. Do not use weighting because involves assumptions which are difficult to verify.

- Find inadmissable and positive b for vertical PGA so remove and repeat.

- Remove records from distances less than or equal to half their focal depth and also less than or equal to their focal depth, find that h_0 is governed by near-field data.

- Use focal depth explicitly, by replacing $r = (d^2 + h_0^2)^{1/2}$ by $r = (d^2 + h^2)^{1/2}$. Find lower standard deviation and that it is very significant.

- Repeat analysis on subsets of records grouped by focal depth. Find no correlation between h_0 and focal depth of subset. Use h_0 equal to mean focal depth in each subset and find similar results to when focal depth used explicitly.

- Repeat analysis with geometric attenuation coefficient equal to -0.83, corresponding to the Airy phase, as opposed to -1.0.
- Find small dependence of horizontal PGA on site classification, note due to level of information available.

3.70 Crouse (1991)

- Ground motion model is:

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

  where PGA is in gal, using all PGA values $p_1 = 6.36$, $p_2 = 1.76$, $p_4 = -2.73$, $p_5 = 1.58$, $p_6 = 0.608$, $p_7 = 0.00916$ and $\sigma = 0.773$.
- Use data from stiff soil sites (depth of soil $< 25\,\mathrm{m}$).
- Include data from any zones with strong seismic coupling, such as the younger subduction zones (S.W. Japan, Alaska, C. America (Mexico), C. Chile, Peru and northern Honshu and Kuril subduction zones in Japan) unless compelling reasons to exclude data. Do this because lack of data from Cascadia. Most ($> 70\%$) are from Japan.
- Focal depths, h, between 0 and $238\,\mathrm{km}$.
- Compare Japanese and Cascadia PGA values for earthquakes with similar magnitude and depths and find similar.
- Do not exclude data from buildings or which triggered on S-wave. Note could mean some PGAs are underestimated.
- Plot ground motion amplitude (PGA and also some maximum displacements from seismograms) against distance for a number of large magnitude shocks (including some data from rock sites which not included in set for regression). Find that rate of attenuation becomes smaller for shorter distances and process is magnitude dependent. Also plot Japanese PGA data, from earthquakes with $h \leq 50\,\mathrm{km}$, split into three distance groups (between 50 and $75\,\mathrm{km}$, between 100 and $150\,\mathrm{km}$ and between 250 and $300\,\mathrm{km}$) find as distance increases magnitude scaling becomes larger and possible saturation in PGA for large magnitudes. Fit $\ln \mathrm{PGA} = p_1 + p_2 \ln(R + C)$ to some PGA values from large magnitude shocks for $C = 0$ and $C > 0$, find lower standard deviation for $C > 0$.
- Fit $\ln \mathrm{PGA} = a + bM$ and $\ln \mathrm{PGA} = a + bM + cM^2$ to Japanese data split into the three distance groups (mentioned above); find b increases with increasing distance range but both equations fit data equally well.
- Constrain p_4 to negative value and p_5 and p_6 to positive values.
- Include quadratic magnitude term, $p_3 M^2$, but find equal to zero.

- Plot residuals against M; find uniformly distributed and evidence for smaller residuals for larger M.
- Plot residuals against R[4] and find decreasing residuals for increasing R.
- Give equation using only those records available in digital form (235 records).

3.71 Garcìa-Fernàndez & Canas (1991) & Garcia-Fernandez & Canas (1995)

- Ground motion model is:

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

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

- Derive equations for two regions:

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

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

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

3.72 Huo & Hu (1991)

- Ground motion model is (case II):

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

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[4] Not shown in paper.

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

- Use two site categories:

  1. Rock
  2. Soil

- Supplement western USA data in large magnitude range with 25 records from 2 foreign earthquakes with magnitudes 7.2 and 7.3.

- Note that there are uncertainties associated with magnitude and distance and these should be considered in derivation of attenuation relations.

- Develop method, based on weighted consistent least-square regression, which minimizes residual error of all random variables not just residuals between predicted and measured ground motion. Method considers ground motion, magnitude and distance to be random variables and also enables inverse of attenuation equation to be used directly.

- Note prediction for $R > 100\,\mathrm{km}$ may be incorrect due to lack of anelastic attenuation term.

- Use both horizontal components to maintain their actual randomness.

- Note most data from moderate magnitude earthquakes and from intermediate distances therefore result possibly unreliable outside this range.

- Use weighted analysis so region of data space with many records are not overemphasized. Use M-R subdivisions of data space: for magnitude $M < 5.5$, $5.5 \leq M \leq 5.9$, $6.0 \leq M \leq 6.4$, $6.5 \leq M \leq 6.9$, $7.0 \leq M \leq 7.5$ and $M > 7.5$ and for distance $R < 3$, $3 \leq R \leq 9.9$, $10 \leq R \leq 29.9$, $30 \leq R \leq 59.9$, $60 \leq R \leq 99.9$, $100 \leq R \leq 300$ and $R > 300\,\mathrm{km}$. Assign equal weight to each subdivision, and any data point in subdivision i containing n_i data has weight $1/n_i$ and then normalise.

- To find C_5 and C_6 use 316 records from 7 earthquakes ($5.6 \leq M \leq 7.2$) to fit $\log Y = \sum_{i=1}^{m} C_{2,i}E_i - C_4 \log[r + \sum_{i=1}^{m} R_{0,i}E_i]$, where $E_i = 1$ for ith earthquake and 0 otherwise. Then fit $R_0 = C_5 \exp(C_6 M)$ to results.

- Also try equations: $\log y = C_1 + C_2 M - C_4 \log[R + C_5]$ (case I) and $\log y = C_1 + C_2 M - C_3 M^2 - C_4 \log[R + C_5 \exp(C_6 M)]$ (case III) for $M \leq M_c$, where impose condition $C_3 = (C_2 - C_4 C_6 / \ln 10)/(2M_c)$ so ground motion is completely saturated at $M = M_c$ (assume $M_c = 8.0$).

- Find equations for rock and soil separately and for both combined.

3.73 I.M. Idriss (1991) reported in Idriss (1993)

- Ground motion model is:

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

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

- Records from rock sites.

- Uses three fault mechanisms:

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

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

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

- Finds standard deviation to be linear function of magnitude.

3.74 Niazi & Bozorgnia (1991)

- Ground motion model is:

$$\ln Y = a + bM + d \ln[R + c_1 \mathrm{e}^{c_2 M}]$$

  where Y is in g, for horizontal PGA $a = -5.503$, $b = 0.936$, $c_1 = 0.407$, $c_2 = 0.455$, $d = -0.816$ and $\sigma = 0.461$ and for vertical PGA $a = -5.960$, $b = 0.989$, $c_1 = 0.013$, $c_2 = 0.741$, $d = -1.005$ and $\sigma = 0.551$.

- All records from SMART-1 array so essentially identical site conditions and travel paths.

- All records from free-field instruments mounted on $4\mathrm{inch}$ $(10\,\mathrm{cm})$ thick concrete base mats, approximately 2 by $3\,\mathrm{feet}$ $(60$ by $90\,\mathrm{cm})$ across.

- Select earthquakes to cover a broad range of magnitude, distance and azimuth and ensuring thorough coverage of the array. Criteria for selection is: at least 25 stations recorded shock, focal depth $< 30\,\mathrm{km}$, hypocentral distance $< 50\,\mathrm{km}$ except for two large earthquakes from beyond $50\,\mathrm{km}$ to constrain distance dependence.

- Focal depths between 0.2 and $27.2\,\mathrm{km}$ with all but one $\leq 13.9\,\mathrm{km}$.
- Azimuths between 60° and 230°.
- Most records (78%) have magnitudes between 5.9 and 6.5. Note magnitude and distance are not independent (correlation coefficient is 0.6).
- Records have sampling interval of $0.01\,\mathrm{s}$. Processed using trapezoidal band passed filter with corner frequencies 0.07, 0.10, 25.0 and $30.6\,\mathrm{Hz}$.
- Not enough information to use distance to rupture zone.
- Source mechanisms of earthquakes are: 4 normal, 2 reverse, 1 reverse oblique and 1 normal oblique with 4 unknown. Do not model source mechanism dependence because of 4 unknown mechanisms.
- Use weighted regression, give equal weight to recordings from each earthquake within each of 10 distance bins (< 2.5, 2.5–5.0, 5.0–7.5, 7.5–10.0, 10.0–14.1, 14.1–20.0, 20–28.3, 28.3–40.0, 40.0–56.6 and 56.6–$130\,\mathrm{km}$). Do this so earthquakes with smaller number of recordings are not overwhelmed by those with a larger coverage and also to give additional weight to shocks recorded over multiple distance bins. Apply two-stage regression, because of high correlation between magnitude and distance, excluding 3 earthquakes ($M = 3.6, 5.0, 7.8$) with 162 records from first stage to reduce correlation between M and R to 0.1. Also do one-stage regression although do not give coefficients.
- Use mean horizontal component because reduces uncertainty in prediction.
- Examine coefficient of variation for each earthquake using median and normalized standard deviation of recordings in inner ring of array. Find evidence for magnitude dependent uncertainty (large magnitude shocks show less uncertainty). Find that main contribution to scatter is inter-event variations again by examining coefficient of variation; although note may be because using dense array data.
- Examine mean residuals of observations from each earthquake. Find evidence for higher than predicted vertical PGA from reverse faulting earthquakes and lower than predicted vertical PGA from normal faulting earthquakes, although due to lack of information for 4 earthquakes note that difficult to draw any conclusions.
- Examine mean residuals of observations from each station in inner ring. Find mean residuals are relatively small compared with standard deviation of regression so variation between stations is less than variation between earthquakes. Find for some stations some large residuals.

3.75 Rogers et al. (1991)

- Ground motion model is:

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

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

- Use six local site classifications:

  S_1 Holocene
  S_2 Pleistocene soil
  S_3 Soft rock
  S_4 Hard rock
  S_5 Shallow ($< 10\,\mathrm{m}$ depth) soil
  S_6 Soft soil (e.g. bay mud)

- Data from about 800 different stations.
- Note that inclusion of subduction-zone events in analysis may affect results with unmodelled behaviour, particularly with regard to distance scaling although believe use of d_r partially mitigates this problem.
- Firstly compute an equation does not include site coefficients. Conduct regression analysis on site-condition subsets of the residuals using M or $\log R$ as dependent variable. Find several regressions are not statistically significant at the 5% level and/or the predicted effects are small at the independent variable extremes. Find strongest effects and most significant results are for shallow soil sites and soft soil sites although because of the high correlation between M and $\log R$ in the set used it is difficult to construct unbiased models.
- Use a stochastic random-vibration approach to find theoretical equations for estimating PGA that include the effect of local site conditions as distance-dependent terms. Using the results from this analysis construct equation based on the observed PGAs. Try including terms for S_1, S_2, S_5, S_6 and corresponding $\log R$ terms for each site type but iterate to retain only the significant terms.
- Fix magnitude scaling ($0.36M$) and anelastic attenuation ($0.002R$). Do not try to optimise the fit other than using fixed values similar to those given by the stochastic analysis.
- Note that anelastic coefficient may be too low but it produces an acceptable geometric spreading term.
- Note that because Moho critical reflections can increase amplitudes beyond about $50\,\mathrm{km}$ the effects of anelastic or geometric attenuation may be masked.
- Allowing all the coefficients in the equation to be free produces a smaller magnitude scaling coefficient, a smaller geometric spreading coefficient, and a non-significant anelastic attenuation term.
- Note that data from S_5 and S_6 are sparse.

- Compare estimated PGAs with data from within small magnitude ranges. Find that PGAs from Morgan Hill earthquake are overestimated, which believe is due to the unilateral rupture of this earthquake masking the effect of the local site conditions.

3.76 Abrahamson & Youngs (1992)

- Ground motion model is:

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

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

- F is fault type (details not given).

- Develop new algorithm for one-stage maximum-likelihood regression, which is more robust than previous algorithms.

3.77 Ambraseys et al. (1992)

- Ground motion model is:

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

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

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

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

- Investigate effect of different ground motion model, one and two-stage regression technique, record selection technique and recalculation of associated parameters. Find these choice cause large differences in predictions.

- Coefficients given above are for PML (1985) data with recalculated magnitudes and distances and addition of extra records from some earthquakes.

3.78 Kamiyama et al. (1992) & Kamiyama (1995)

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

  $$\begin{aligned} \log_{10} a_{\max} &= -1.64R_0 + b_1R_1 + b_2R_2 + c_a + \sum_{i=1}^{N-1} A_iS_i \\ R_0 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ \log_{10} r - \log_{10} r_c & \text{for} \quad r > r_t \end{cases} \\ R_1 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ 1 & \text{for} \quad r > r_t \end{cases} \\ R_2 &= \begin{cases} 0 & \text{for} \quad r \leq r_t \\ M & \text{for} \quad r > r_t \end{cases} \end{aligned}$$

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

- Instrument correct records and filter with pass band between 0.24 and $11\,\mathrm{Hz}$.

- Model individual soil conditions at each site as amplification factors, AMP_i, as described by Kamiyama & Yanagisawa (1986).

- Most records are from hypocentral distances between 30 and $200\,\mathrm{km}$.

- Focal depths between 0 and $130\,\mathrm{km}$.

- Models peak ground accelerations independent of magnitude and distance in a fault zone, r_t, where $r_t = r_c 10^{(b_1+b_2M)/1.64}$.

- Constrain decay with distance in far field to -1.64 using results from other studies to avoid problems due to correlation between M and $\log_{10} r$.

- Use trial and error method to find r_c so that resulting values of r_t are consistent with empirical estimates of fault length from past studies.

- Also give expression using shortest distance to fault plane (rupture distance), R, by replacing the expression for $r \leq r_c$ and $r > r_c$ by one expression given by replacing r, hypocentral distance, by $R + r_c$ in expression for $r > r_c$. This gives PGA independent of magnitude at distance $R = 0\,\mathrm{km}$.

- Note that use of d_h is not necessarily best choice but use it due to simplicity.

- Check residual plots; find no trends so conclude adequate from statistical point of view.

3.79 Sigbjörnsson & Baldvinsson (1992)

- Ground motion model is:

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

  where A is in g, for average horizontal PGA and $4 < M < 6$ $\alpha = -1.98$, $\beta = 0.365$, $b = -0.0039$ and $\sigma = 0.30$, for larger horizontal PGA and $4 < M < 6$ $\alpha = -1.72$, $\beta = 0.327$, $b = -0.0043$ and $\sigma = 0.30$ and for both horizontal PGAs and $2 < M < 6$ $\alpha = -2.28$, $\beta = 0.386$, $b = 0$ and $\sigma = 0.29$.

- Find that Icelandic data does not fit other published relations.
- Find equation using only records with $M \geq 4.0$, h equal to focal depth and both the horizontal components.
- Find equation using only records with $M \geq 4.0$, h equal to focal depth and larger horizontal component.
- Also repeated with all data. Anelastic coefficient constrained to zero because otherwise positive.
- Also done with h free.
- Note that large earthquakes have $h \approx 10\,\mathrm{km}$ while small events have $h \approx 5\,\mathrm{km}$.

3.80 Taylor Castillo et al. (1992)

- Ground motion model is:

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

  where A is in ms^{-2}, $a_1 = 0.339$, $a_2 = 0.455$, $a_3 = -0.67$, $a_4 = -0.00207$ and $\sigma = 0.61$.

3.81 Tento et al. (1992)

- Ground motion model is:

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

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

- Most records from distances between $10\,\mathrm{km}$ and $40\,\mathrm{km}$.

- Correction technique based on uniform Caltech correction procedure. Most (125) were automatically digitised, rest were manually digitised. Roll-on and cutoff frequencies of Ormsby filter were selected by adopting a record dependent criteria. Cutoff frequencies range between $0.13\,\mathrm{Hz}$ and $1.18\,\mathrm{Hz}$ with a median of $0.38\,\mathrm{Hz}$.

- Records included from analysis were from free-field stations. Excluded those not complete (e.g. started during strong-motion phase). Excluded those with epicentral distances greater than that of first nontriggered station.

- Note relatively small influence of form of equation adopted although two step method seems preferable.

- Note correction procedure plays a relevant role in analysis.

- Note using d instead of R causes greater scatter in data.

- Note moderate underestimation for low magnitude in near field and for high magnitude in far field.

3.82 *Theodulidis & Papazachos (1992)*

- Ground motion model is:

$$\ln Y = C_1 + C_2 M + C_3 \ln(R + R_0) + C_4 S$$

  where Y is in cms^{-2}, $C_1 = 3.88$, $C_2 = 1.12$, $C_3 = -1.65$, $R_0 = 15$, $C_4 = 0.41$ and $\sigma = 0.71$.

- Use two site categories (mean opinion of seven specialists who classified sites into three categories: soft alluvium, crystalline rock and intermediate):

  S=1 Rock: 34+4 records. Japanese sites have diluvium with depth to bedrock $H < 10\,\mathrm{m}$. Alaskan sites have $\mathrm{PGV/PGA} \approx 66 \pm 7\,\mathrm{cms}^{-1}\mathrm{g}^{-1}$.

  S=0 Alluvium: 71+12 records. Japanese sites have diluvium $H > 10\,\mathrm{m}$ or alluvium $H < 10\,\mathrm{m}$, and alluvium with $H < 25\,\mathrm{m}$ as well as soft layers with thickness $< 5\,\mathrm{m}$. Alaskan sites have $\mathrm{PGV/PGA} > 66 \pm 7\,\mathrm{cms}^{-1}\mathrm{g}^{-1}$.

- 70% of records from ground level or basement of buildings with two storeys or less. Rest from buildings with up to eight storeys.

- Some (16) Greek records manually digitized and baseline corrected, some (22) Greek records manually digitized and filtered and rest of the Greek records automatically digitized and filtered.

- Due to lack of data for $7.0 < M_s < 7.5$ include shallow subduction data from other regions with similar seismotectonic environments (Japan and Alaska) using criteria i) depth $< 35\,\mathrm{km}$, ii) M_w or M_{JMA} between 7.0 and 7.5, iii) instruments triggered before S-wave, iv) free-field recording, v) surface geology known at station. Note M_s, M_w and M_{JMA} are equivalent between 6.0 and 8.0.

- Focal depths between $0\,\mathrm{km}$ $(13\,\mathrm{km})$ and $18\,\mathrm{km}$ $(31\,\mathrm{km})$.
- Most data from $M_s < 5.5$ and from $R < 50\,\mathrm{km}$.
- Use four step regression procedure. First step use only Greek data from $M_s > 6.0$ $(9 \leq R \leq 128\,\mathrm{km}$, 14 records) for which distances are more reliable (use both hypocentral and epicentral distance find epicentral distance gives smaller standard deviation) to find geometrical coefficient C_{31} and R_0 ignoring soil conditions. Next find constant (C_{12}), magnitude (C_{22}) and soil (C_{42}) coefficients using all data. Next recalculate geometrical (C_{33}) coefficient using only Greek data with $M_s > 6.0$. Finally find constant (C_{14}), magnitude (C_{24}) and soil (C_{44}) coefficients using all the data; final coefficients are C_{14}, C_{24}, C_{33} and C_{44}.
- Plot residuals against M_s and R and find no apparent trends. Find residuals (binned into 0.2 intervals) fit normal distribution.

3.83 *Boore* et al. *(1993) & Boore* et al. *(1997)*

- Ground motion model is:

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

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

- Use three site categories:

Class A $V_{s,30} > 750\,\mathrm{ms}^{-1}$, some categorised using measured shear-wave velocity, most estimated $\Rightarrow G_B = 0, G_C = 0$, 48 records

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

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

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

- Define shallow earthquakes as those for which fault rupture lies mainly above a depth of $20\,\mathrm{km}$.
- Peak acceleration scaled directly from accelerograms, in order to avoid bias from sparsely sampled older data.
- Do not use data from structures three storeys or higher, from dam abutments or from base of bridge columns. Do not use data from more than one station with the same site condition within a circle of radius $1\,\mathrm{km}$ (note that this is a somewhat arbitrary choice).

- Exclude records triggered by S wave.
- Do not use data beyond cutoff distance which is defined as equal to lesser of distance to the first record triggered by S wave and closest distance to an operational nontriggered instrument.
- Note that little data beyond $80\,\mathrm{km}$.
- Due to positive values of b_4 when $b_5 = -1$, set b_4 to zero and let b_5 vary.

3.84 *Campbell (1993)*

- Ground motion model is:

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

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

- Uses two site categories:

  S=0 Quaternary deposits (soil).

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

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

- Uses two fault mechanisms:

  F=0 Strike-slip.

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

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

- Gives estimates of average minimum depths to top of seismogenic rupture zone.
- Uses stochastic simulation model to find anelastic coefficients β_4 and β_5 because uses only near-source records.
- Uses weighted nonlinear regression method based on Campbell (1981) to control dominance of well-recorded earthquakes.

3.85 *McVerry* et al. *(1993) & McVerry* et al. *(1995)*

- Ground motion model is (Type A):

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

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

- Find that ground motions in previous earthquakes were significantly higher than the motions predicted by equations derived from W. N. America data.
- Only include records from earthquakes for which M_w is known because of poor correlation between M_L and M_w in New Zealand.
- Focal depths, $h_e \leq 122\,\mathrm{km}$.
- 140 records from reverse faulting earthquakes.
- Divide records into crustal and deep earthquakes.
- Only use records for which reliable event information is available, regardless of their distances with respect to untriggered instruments.
- Only use records which triggered on the P-wave.
- Also derive separate equations for shallow, upper crustal earthquakes ($h_e \leq 20\,\mathrm{km}$, 102 records, $5.1 \leq M_w \leq 7.3$, $13 \leq r \leq 274\,\mathrm{km}$) and crustal earthquakes ($h_e \leq 50\,\mathrm{km}$, 169 records, $5.1 \leq M_w \leq 7.3$, $13 \leq r \leq 274\,\mathrm{km}$).
- Also try equations of form: $\log_{10} \mathrm{PGA} = a + bM_w - d \log_{10} r$ (Type B) and $\log_{10} \mathrm{PGA} = a + bM_w - cr - \log_{10} r$ (Type C) because of large standard errors and highly correlated estimates for some of the coefficients (particularly c and d). Find Type B usually gives much reduced standard errors for d than Type A model and have lowest correlation between coefficients, but are sceptical of extrapolating to distance ranges shorter and longer than the range of data. Type C usually has similar standard deviations to Type A. Find that usually all three models give similar predictions over distance range of most of the data, but sometimes considerably different values at other distances.
- Derive separate equations for reverse faulting earthquakes only and usually find similar results to the combined equations.
- Find deep earthquakes produce significantly higher PGAs than shallow earthquakes for similar r.

3.86 Sadigh et al. (1993) & Sadigh et al. (1997)

- Ground motion model is:

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

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

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

- Use two site categories (for horizontal motion):
  1. Rock: bedrock within about a metre of surface. Note that many such sites are soft rock with $V_s \leq 750\,\mathrm{ms}^{-1}$ and a strong velocity gradient because of near-surface weathering and fracturing, 274 records.
  2. Deep soil: greater than $20\,\mathrm{m}$ of soil over bedrock. Exclude data from very soft soil sites such as those from San Francisco bay mud, 690 records.

  Vertical equations only for rock sites.
- Crustal earthquakes defined as those that occur on faults within upper 20 to $25\,\mathrm{km}$ of continental crust.
- Use source mechanism: RV=reverse (26+2) $\Rightarrow Z_T = 1$ and SS=strike-slip (and some normal) (89+0) $\Rightarrow Z_T = 0$. Classified as RV if rake> 45° and SS if rake< 45°. Find peak motions from small number of normal faulting earthquakes not to be significantly different than peak motions from strike-slip events so were including in SS category.
- Records from instruments in instrument shelters near ground surface or in ground floor of small, light structures.
- 4 foreign records (1 from Gazli and 3 from Tabas) supplement Californian records.
- Separate equations for $M_w < 6.5$ and $M_w \geq 6.5$ to account for near-field saturation effects and for rock and deep soil sites.

3.87 Singh et al. (1993)

- Ground motion model is:

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

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

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

3.88 Sun & Peng (1993)

- Ground motion model is:

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

  where A is in cms^{-2}, $a = 7.7$, $b = 0.49$, $c = 1.45$, $d = 0.19$, $h = 25.0$ and $\sigma = 0.46$.

- Model soil using its fundamental period of the overburden soil, T_s. Thickness of deposit defined as depth to rock base, defined either as $V_s > 800\,\mathrm{ms}^{-1}$ or when ratio of shear-wave velocity in ith layer to shear-wave velocity in $i-1$th layer is greater than 2 (only calculate period to $100\,\mathrm{m}$ because only have important effect on structure). For outcropping rock, $T_s = 0.05\,\mathrm{s}$.
- Eight distance intervals used for weighting, five $10\,\mathrm{km}$ wide up to $50\,\mathrm{km}$, 50–$69.9\,\mathrm{km}$, 70–$99.9\,\mathrm{km}$ and 100–$200\,\mathrm{km}$. Within each interval each earthquake received equal weight, inversely proportional to number of records from that earthquake in interval.
- Use resolve accelerations in direction, θ, which gives largest value. Find scatter is lower than for larger horizontal component.
- Many (27) earthquakes only have one record associated with them and 60 records are from San Fernando.

3.89 Ambraseys & Srbulov (1994)

- Ground motion model is:

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

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

- Do not consider effect of site geology but expect it to be statistically insignificant for PGA.
- Focal depths, $h < 25\,\mathrm{km}$. Mean focal depth is $10 \pm 4\,\mathrm{km}$.
- Mean magnitude of earthquakes considered is 6.0 ± 0.7.
- Most records from $d < 100\,\mathrm{km}$.
- Only use records with $\mathrm{PGA} > 0.01\,\mathrm{g}$.

- Records mainly from SMA-1s located at ground floor or in basements of buildings and structures and free-field sites regardless of topography.
- Records from thrust earthquakes (46% of total), normal earthquakes (26%) and strike-slip earthquakes (28%).
- Baseline correct and low-pass filter records. Select cut-offs from visual examination of Fourier amplitude spectrum of uncorrected time-histories and choose cut-off below which the Fourier amplitude spectrum showed an unrealistic energy increase due to digitization noise and instrument distortions.
- Find (from reprocessing about 300 records) that with very few exceptions differences in PGAs arising from different methods of processing are not significant, remaining below 3%.
- Also derive equation which includes focal depth explicitly.

3.90 *Boore* et al. *(1994a) & Boore* et al. *(1997)*

- Based on Boore *et al.* (1993) see Section 3.83
- Ground motion model is:

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

  where Y is in g, b_1 to b_5, h and σ are same as for Boore *et al.* (1993) (see Section 3.83) and for randomly oriented component $b_V = -0.371$ and $V_A = 1400$ and for larger horizontal component $b_V = -0.364$ and $V_A = 1390$.

- Model site effect as a continuous function of average shear-wave velocity to $30\,\mathrm{m}$ deep, V_S.
- Coefficients b_1, b_2, b_3,b_4 and b_5 from Boore *et al.* (1993).
- Find no basis for different magnitude scaling at different distances.
- Find evidence for magnitude dependent uncertainty.
- Find evidence for amplitude dependent uncertainty.
- Find marginal statistical significance for a difference between strike-slip (defined as those with a rake angle within 30° of horizontal) and reverse-slip motions but do not model it. Modelled in Boore *et al.* (1994b) (by replacing b_1 by $b_{SS}G_{SS}+b_{RS}G_{RS}$ where $G_{SS}=1$ for strike-slip shocks and 0 otherwise and $G_{RS}=1$ for reverse-slip shocks and 0 otherwise) and reported in Boore *et al.* (1997). Coefficients for randomly oriented horizontal component are: $b_{SS}=-0.136$ and $b_{RS}=-0.051$[5].

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

- Analysis done using one and two-stage maximum likelihood methods; note that results are very similar.
- Earthquakes with magnitudes below 6.0 are poorly represented.
- Note that few Class A records.
- Note that V_S does not model all the effects of site because it does not model effect of the thickness of attenuating material on motion.
- Note that ideally would like to model site in terms of average shear-wave velocity to one-quarter wavelength.
- Note lack measurements from distances greater than $100\,\mathrm{km}$ so that weak-motion data from seismographic stations maybe should be used.
- Note that use of cutoff distances independent of geology or azimuth may be over strict but it is simple and objective. Note that methods based on data from nontriggered stations or using seismogram data may be better.

3.91 *Fukushima* et al. *(1994) & Fukushima* et al. *(1995)*

- Ground motion model is:

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

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

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

3.92 Lawson & Krawinkler (1994)

- Ground motion model is:

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

- Use three site categories:

  A Firm to hard rock: granite, igneous rocks, sandstones and shales with close to widely spaced fractures, $750 \leq V_{s,30} \leq 1400\,\mathrm{ms}^{-1} \Rightarrow S_B = 0$, $S_C = 0$.

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

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

- For shallow (fault rupture within $20\,\mathrm{km}$ of earth surface) crustal earthquakes.

- Use free-field records. Records not significantly contaminated by structural feedback, excludes records from structures with $>$2 stories.

- Chooses ground motion model because of simplicity. Note that other possible forms of equation may have significant effect on results, but including more terms complicates relationships without reducing variability.

- Do not give coefficients only predictions.

3.93 Lungu et al. (1994)

- Ground motion model is:

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

  where PGA is in g, $c_1 = -2.122$, $c_2 = 1.885$, $c_3 = -1.011$, $c_4 = -0.012$ and $\sigma = 0.502$.

- Focal depth, h, between 79 and $131\,\mathrm{km}$.

- Consider to separate areas of $90°$ to investigate variation with respect to azimuth; find azimuthal dependence.

- Find individual attenuation equations for three earthquakes. Note faster attenuation for smaller magnitude and faster attenuation for deeper events.

3.94 Musson et al. (1994)

- Ground motion model is (model 1):

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

  where A is in cms^{-2}, $a = 2.11$, $b = 1.23$ and $d = -0.014$.

  Ground motion model is (model 2):

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

  where A is in ms^{-2}, c_1 and c_2 are from Dahle *et al.* (1990b), $c_4 = -0.0148$ and σ is recommended as 0.65 (although this is from an earlier study and is not calculated in regression).
- Use data from Canada (Saguenay earthquake and Nahanni sequence) and Belgium (Roermond earthquake).
- Focal depths, h, between 1 and $30\,\mathrm{km}$ with average $14.4\,\mathrm{km}$.
- Assume peak ground acceleration equals pseudo-acceleration at $30\,\mathrm{Hz}$ due to few unclipped horizontal UK records and because instrument response of UK instruments means records unreliable above $30\,\mathrm{Hz}$. Use only digital VME records for $30\,\mathrm{Hz}$ model.
- Note poorness of data due to UK data and other data being widely separated thus preventing a comparison between the two sets. Also means straightforward regression methods would be inadequate as there would be little control on shape of curves derived.
- Note earlier models over predict UK data.
- Use two-stage least squares method to give model 1. First stage fit only UK/Belgian data to find b, in second stage use this value of b and use all data to find a and d.
- Do not recommend model 1 for general use because too influenced by limitations of data to be considered reliable. Canadian data probably insufficient to anchor curves at small R/large M and extremely high Saguenay earthquake records carry undue weight.
- Use model of Dahle *et al.* (1990b) to get model 2. Fix c_1 and c_2 to those of Dahle *et al.* (1990b) and find c_4. Prefer this model.

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

- Ground motion model is:

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

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

- Sites have different soil conditions, some medium and stiff sites and some very soft soil sites.
- Use some records from Moldova and Bulgaria.
- Focal depths, h, between 91 and $133\,\mathrm{km}$.
- Records from free-field or from basements of buildings.
- Originally include data from a shallower (focal depth $79\,\mathrm{km}$), smaller magnitude ($M_L = 6.1$, $M_w = 6.3$) earthquake with shorter return period than other three earthquakes, but exclude in final analysis.
- Originally do attenuation analysis for two orthogonal directions N45E (which is in direction of fault plane) and N35E (which is normal to fault plane). From this define 3 90° circular sectors based roughly on tectonic regions, and calculate attenuation relations for each of these sectors as well as for all data. Find azimuthal dependence.
- Remove 1 to 3 anomalous records per sector.
- Remove the only record from the 4/3/1977 earthquake, because it has a strong influence on results, and repeat analysis using model $\ln \mathrm{PGA} = b_1 + b_2 M + b_3 \ln R$, find lower predicted PGA.
- Find slower attenuation in direction of fault plane compared with normal to fault plane.
- Find faster attenuation and larger standard deviation (by finding attenuation equations for two different earthquakes) for deeper focus and larger magnitude shocks.

3.96 Ramazi & Schenk (1994)

- Ground motion model is:

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

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

- Use two site categories (from original of four) for which derive two separate equations:

  1. Rock: mainly category (2) a) loose igneous rocks (tuffs), friable sedimentary rocks, foliated metamorphic rock and rocks which have been loosened by weathering, b) conglomerate beds, compacted sand and gravel and stiff clay (argillite) beds where soil thickness $> 60\,\mathrm{m}$ from bed rock. 29 records.

   2. Soil: mainly category (4) a) soft and wet deposits resulting from high level of water table, b) gravel and sand beds with weak cementation and/or uncementated unindurated clay (clay stone) where soil thickness $> 10\,\mathrm{m}$ from bed rock. 54 records.

- Focal depths between 10 and $69\,\mathrm{km}$.
- Find equations using hypocentral distance but find that poor fit for Rudbar (Manjil) earthquake ($M_s = 7.7$) which conclude due to use of hypocentral rather than rupture distance.
- Find equations using rupture distance[6] for Rudbar (Manjil) earthquake and hypocentral distances for other earthquakes. Coefficients given above. They conclude that it is important that equations are derived using rupture distance rather than hypocentral distance because most destructive earthquakes rupture surface in Iran.
- Do not know physical meaning of H term but find that it causes curves to fit data better.

3.97 Xiang & Gao (1994)

- Ground motion model is:

$$A_p = a\mathrm{e}^{bM_s}(R + \Delta)^c$$

  where A_p is in cms^{-2} and for combined Yunnan and W. N. American data $a = 1291.07$, $b = 0.5275$, $c = -1.5785$, $\Delta = 15$ and $\sigma = 0.5203$ (in terms of natural logarithm).

- All records from basement rock.
- Most Yunnan data from main and aftershocks of Luquan and Luncang-Gengma earthquakes.
- Records from Lancang-Gengma sequence corrected.
- Most Yunnan records with $3 \leq M_s \leq 5$ and $10 \leq R \leq 40\,\mathrm{km}$.
- To overcome difficulty due to shortage of large magnitude records and sample heterogeneous distribution in near and far fields use W. N. America data, because intensity attenuation is similar.
- Fit curves to Yunnan and Yunnan with W. N. American data. Find curve for combined data has lower variance and fit to observation data for large magnitudes is better (by plotting predicted and observed PGA).

3.98 Ambraseys (1995)

- Ground motion model is:

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

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

where a is in g, for $4.0 \leq M \leq 7.4$: for horizontal PGA not including focal depth $A = -1.09$, $B = 0.238$, $C = -0.00050$, $D = -1$, $h_0 = 6.0$ and $\sigma = 0.28$, for vertical PGA not including focal depth $A = -1.34$, $B = 0.230$, $C = 0$, $D = -1$, $h_0 = 6.0$ and $\sigma = 0.27$, for horizontal PGA including focal depth $A = -0.87$, $B = 0.217$, $C = -0.00117$, $D = -1$, $h_0 = h$ and $\sigma = 0.26$ and for vertical PGA including focal depth $A = -1.10$, $B = 0.200$, $C = -0.00015$, $D = -1$, $h_0 = h$ and $\sigma = 0.26$.

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

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

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

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

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

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

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

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

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

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

- Splits data into five magnitude dependent subsets: $2.0 \leq M_s \leq 7.3$ (1260 records from 619 shocks), $3.0 \leq M_s \leq 7.3$ (1189 records from 561 shocks), $4.0 \leq M_s \leq 7.3$ (830 records from 334 shocks), , $5.0 \leq M_s \leq 7.3$ (434 records from 107 shocks), and $3.0 \leq M_s \leq 6.0$ (976 records from 524 shocks). Calculates coefficients for each subset. Finds only small differences $\pm 15\%$ over distance range 1–$200\,\mathrm{km}$ between predictions and uncertainties. Concludes results stable. Prefers results from subset with $4.0 \leq M_s \leq 7.3$.
- Finds it difficult to obtain some vertical accelerations due to low ground motion so ignores data from $> 100\,\mathrm{km}$ with PGA $< 1\%\mathrm{g}$ $(0.1\,\mathrm{ms}^{-2})$.
- Repeats regression using $r^2 = d^2 + h^2$. Finds depth important.
- Calculates using one-stage method; finds very similar results for $10 < d < 100\,\mathrm{km}$.
- Considers magnitude dependent function: $\log a = b_1 + b_2 M_s + b_3 r + b_4[r + b_5 \exp(b_6 M_s)]$. Finds b_5 is zero so drops b_3 and repeats. Finds b_5 close to zero so magnitude dependent function not valid for this dataset.
- Local shear-wave velocity, V_s, profiles known for 44 stations (268 records from 132 earthquakes between 2.5 and 7.2) although only 14 from $> 40\,\mathrm{km}$ so barely sufficient to derive equation. Use 145 records from 50 earthquakes with $M_s > 4.0$ to fit $\log a = A + BM_s + Cr + D\log r + E\log V_{s30}$, where V_{s30} is average shear-wave velocity to reference depth of $30\,\mathrm{m}$. Finds C positive so constrain to zero. Find no reduction in standard deviation.
- Uses residuals from main equation to find E. Notes that should not be used because of small number of records. Considers different choices of reference depth; finds using between 5 and $10\,\mathrm{m}$ leads to higher predicted amplifications. Notes better to use V_{s30} because no need for subjective selection of categories.

3.99 Dahle et al. (1995)

- Ground motion model is:

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

  where A is in ms^{-2}, $c_1 = -1.579$, $c_2 = 0.554$, $c_3 = -0.560$, $c_4 = -0.0032$, $c_5 = 0.326$, $r_h = 6$ and $\sigma = 0.3535$
- Use records from Costa Rica, Mexico, Nicaragua and El Salvador. Only Mexican earthquakes with $M_w \geq 6.5$ were used.
- Use two site categories:

$S = 0$ Rock: 92 records

$S = 1$ Soil: 88 records

- Use a Bayesian one-stage regression method (Ordaz *et al.*, 1994) to yield physically possible coefficients.
- Consider tectonic type: subduction or shallow crustal but do not model.
- Find no significant difference between Guerrero (Mexico) and other data.
- Find no significant difference between subduction and shallow crustal data.

3.100 Lee et al. (1995)

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

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

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

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

  where:

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

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

- Use four types of site parameter:
  - Local geological site classification (defined for all records):

    $s = 0$ Sites on sediments.
    $s = 1$ Intermediate sites.
    $s = 2$ Sites on basement rock.
  - Depth of sediments from surface to geological basement rock beneath site, h (defined for 1675 records out of 1926).

  - Local soil type parameter describes average soil stiffness in top $100\text{–}200\,\mathrm{m}$ (defined for 1456 records out of 1926):

$s_L = 0$ 'Rock' soil sites $\Rightarrow S_L^1 = 1$, $S_L^2 = 0$ and $S_L^3 = 0$. Characterises soil up to depth of less than $10\,\mathrm{m}$.

$s_L = 1$ Stiff soil sites $\Rightarrow S_L^1 = 1$, $S_L^2 = 0$ and $S_L^3 = 0$ (shear-wave velocities $< 800\,\mathrm{ms}^{-1}$ up to depth of $75\text{–}100\,\mathrm{m}$).

$s_L = 2$ Deep soil sites $\Rightarrow S_L^2 = 1$, $S_L^1 = 0$ and $S_L^3 = 0$. (shear-wave velocities $< 800\,\mathrm{ms}^{-1}$ up to depth of $150\text{–}200\,\mathrm{m}$).

$s_L = 3$ Deep cohesionless soil sites $\Rightarrow S_L^3 = 1$, $S_L^1 = 0$ and $S_L^2 = 0$ (only use for one site with 10 records).

  - Average soil velocity in top $30\,\mathrm{m}$, v_L (if unavailable then use soil velocity parameter, s_T) (defined for 1572 records out of 1926):

Soil type A $v_L > 750\,\mathrm{ms}^{-1}$.
Soil type B $360\,\mathrm{ms}^{-1} < v_L \leq 750\,\mathrm{ms}^{-1}$.
Soil type C $180\,\mathrm{ms}^{-1} < v_L \leq 360\,\mathrm{ms}^{-1}$.
Soil type D $v_L \leq 180\,\mathrm{ms}^{-1}$.

- Only include records for which significant subset of site parameters (s, h, s_L, v_L) exist.
- Almost all earthquakes have focal depths $H \leq 15\,\mathrm{km}$; all focal depths $H \leq 43\,\mathrm{km}$.
- Use records from 138 aftershocks of Imperial Valley earthquake (15/10/1979), which contribute most of $M \leq 3$ records.
- Use records from 109 earthquakes with $M \leq 3$.
- Use free-field records.
- Characterise path by two methods:
  - Fraction of wave path travelled through geological basement rock measured at surface, from epicentre to station, $0 \leq r \leq 1$.
  - Generalised path type classification:
    1. Sediments to sediments.
    2. Rock-to-sediments, vertically.
    3. Rock-to-sediments, horizontally.
    4. Rock-to-rock.
    5. Rock-to-rock through sediments, vertically.
    6. Rock-to-sediments through rock and sediments, vertically.
    7. Rock-to-sediments though rock and sediments, horizontally.
    8. Rock-to-rock through sediments, horizontally.

  Due to lack of data combine path types 2 and 6 in new category 2', combine path types 3 and 7 in new category 3', combine path types 4, 5 and 8 in new category 4' (when $r \neq 1$) and combine 4, 5 and 8 in new category 5' (when $r = 1$).

- Plot PGA against magnitude and distance to get surface by interpolation. Plot without smoothing and with light and intense smoothing. Find for small magnitude ($M \approx 3$–4) earthquakes attenuation is faster than for large magnitude ($M \approx 6$–7) earthquakes.
- Use a multi-step residue regression method. First fit $\log a_{\max} = M + \mathrm{Att}(\Delta, M, T) + b_1 M + b_2 s + b_3 v + b_4 + b_5 M^2$ (or $\log a_{\max} = M + \mathrm{Att}(\Delta, M, T) + b_1 M + b_2 h + b_3 v + b_4 + b_5 M^2$) and calculate residuals $\epsilon = \log a_{\max} - \log \hat{a}_{\max}$ where $a_{\max}$ is estimated PGA and $\hat{a}_{\max}$ is recorded PGA. Fit $\epsilon = b_7^{(-1)} S_L^{(-1)} + b_7^{(0)} S_L^{(0)} + b_7^{(1)} S_L^{(1)} + b_7^{(2)} S_L^{(2)} + b_7^{(3)} S_L^{(3)}$ where $S_L^{(i)} = 1$ if $s_L = i$ and $S_L^{(i)} = 0$ otherwise. Find significant dependence. Try including v_L both as a continuous and discrete parameter in model but not significant at 5% significance level. Next calculate residuals from last stage and fit $\epsilon = b_0' \log_{10}(\Delta/L) + b_4' + b_{60} r R + b_{61}(1 - r) R$ for each of the five path type groups (1' to 5'). Lastly combine all the individual results together into final equation.
- Note that b_{70} and b_{71} can only be applied for $R \lesssim 100\,\mathrm{km}$ where data is currently available. For $R \gtrsim 100\,\mathrm{km}$ the predominant wave type changes to surface waves and so b_{70} and b_{71} do not apply.

3.101 *Lungu* et al. *(1995b)*

- Study almost identical to Radu *et al.* (1994), see Section 3.95, but different coefficients given: $c_1 = 3.672$, $c_2 = 1.318$, $c_3 = -1.349$, $c_4 = -0.0093$ and $\sigma = 0.395$.

3.102 *Molas & Yamazaki (1995)*

- Ground motion model is:

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

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

- Records from accelerometers on small foundations detached from structures; thus consider as free-field.
- Exclude records with one horizontal component with $\mathrm{PGA} < 1\,\mathrm{cms}^{-2}[0.01\,\mathrm{ms}^{-2}]$ because weaker records not reliable due to resolution ($\pm 0.03\,\mathrm{cms}^{-2}[0.0003\,\mathrm{ms}^{-2}]$) of instruments.
- Exclude earthquakes with focal depths equal to $0\,\mathrm{km}$ or greater than $200\,\mathrm{km}$, due to lack of such data. Depths (depth of point on fault plane closest to site), h, between about $1\,\mathrm{km}$ to $200\,\mathrm{km}$.
- Apply a low-cut filter with cosine-shaped transition from 0.01 to $0.05\,\mathrm{Hz}$.
- Positive correlation between magnitude and distance so use two-stage method.

- Note different definition for M_{JMA} for focal depths $> 60\,\mathrm{km}$.
- Firstly do preliminary analysis with $b_4 = 0$ and no site coefficients; find b_2 is positive so constrain to 0 but find $b_3 < -1.0$ so constrain b_3 to -1.0 and unconstrain b_2. Find linear dependence in residuals on h especially for $h < 100\,\mathrm{km}$. Find significant improvement in coefficient of determination, R^2, using terms $b_4 h$ and c.
- Find singularity in matrices if apply two-stage method, due to number of coefficients, so propose a iterative partial regression method.
- Also separate data into five depth ranges (A: $h = 0.1$ to $30\,\mathrm{km}$, 553 records from 111 earthquakes; B: $h = 30$ to $60\,\mathrm{km}$, 778 records from 136 earthquakes; C: $h = 60$ to $90\,\mathrm{km}$, 526 records from 94 earthquakes; D: $h = 90$ to $120\,\mathrm{km}$, 229 records from 31 earthquakes; E: $h = 120$ to $200\,\mathrm{km}$, 112 records from 19 earthquakes) and find attenuation equations for each range. Note results from D & E may not be reliable due to small number of records. Find similar results from each group and all data together.
- Find weak correlation in station coefficients with soil categories, as defined in Iwasaki *et al.* (1980), but note large scatter.

3.103 Sarma & Free (1995)

- Ground motion model is:

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

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

- Use two site categories:

$S = 0$ Rock

$S = 1$ Soil

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

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

3.104 Ambraseys et al. (1996) & Simpson (1996)

- Ground motion model is:

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

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

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

  R Rock: $V_s > 750\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 0, S_S = 0$, 106 records.
  A Stiff soil: $360 < V_s \leq 750\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 1, S_S = 0$, 226 records.
  S Soft soil: $180 < V_s \leq 360\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 0, S_S = 1$, 81 records.
  L Very soft soil: $V_s \leq 180\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 0, S_S = 1$, 3 records.

- Lower limit of $M_s = 4.0$ because smaller earthquakes are generally not of engineering significance.
- Focal depths less than $30\,\mathrm{km}$, 81% between 5 and $15\,\mathrm{km}$.
- Note for some records distances have uncertainty of about $10\,\mathrm{km}$.
- Most records from distances less than about $40\,\mathrm{km}$.
- For some small events need to estimate M_s from other magnitude scales.

- Most records from free-field stations although some from basements or ground floors of relatively small structures, and tunnel portals. Do not exclude records from instruments beyond cutoff distance because of limited knowledge about triggered level.
- All uncorrected records plotted, checked and corrected for spurious points and baseline shifts.
- Uniform correction procedure was applied for all records. For short records ($< 5\,\mathrm{s}$) a parabolic adjustment was made, for long records ($> 10\,\mathrm{s}$) filtering was performed with pass band 0.20 to $25\,\mathrm{Hz}$ and for intermediate records both parabolic and filtering performed and the most realistic record was chosen. Instrument correction not applied due to limited knowledge of instrument characteristics.
- Also analyze using one-stage method, note results comparable.

3.105 Ambraseys & Simpson (1996) & Simpson (1996)

- Based on Ambraseys *et al.* (1996), see Section 3.104.
- Coefficients are: $C_1' = -1.74$, $C_2 = 0.273$, $C_4 = -0.954$, $C_A = 0.076$, $C_S = 0.058$, $h_0 = 4.7$ and $\sigma = 0.26$.

3.106 Aydan et al. (1996)

- Ground motion model is:

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

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

3.107 Bommer et al. (1996)

- Ground motion model is:

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

  where h is focal depth, A is in g, $a = -1.47$, $b = 0.608$, $d = -1.181$, $q = 0.0089$ and $\sigma = 0.54$.
- Only use subduction earthquakes.

- Do not recommend equation used for hazard analysis, since derive it only for investigating equations of Climent *et al.* (1994).

3.108 Crouse & McGuire (1996)

- Ground motion model is:

  $$\ln Y = a + bM + d\ln(R + c_1\exp\{c_2M\}) + eF$$

  where Y is in g, for site category B: $a = -2.342699$, $b = 1.091713$, $c_1 = 0.413033$, $c_2 = 0.623255$, $d = -1.751631$, $e = 0.087940$ and $\sigma = 0.427787$ and for site category C: $a = -2.353903$, $b = 0.838847$, $c_1 = 0.305134$, $c_2 = 0.640249$, $d = -1.310188$, $e = -0.051707$ and $\sigma = 0.416739$.

- Use four site categories, $\bar{V}_s$ is shear-wave velocity in upper $100\,\mathrm{ft}$ $(30\,\mathrm{m})$:

  A Rock: $\bar{V}_s \geq 2500\,\mathrm{fps}$ $(\bar{V}_s \geq 750\,\mathrm{ms}^{-1})$, 33 records

  B Soft rock or stiff soil: $1200 \leq \bar{V}_s \leq 2500\,\mathrm{fps}$ $(360 \leq \bar{V}_s < 750\,\mathrm{ms}^{-1})$, 88 records

  C Medium stiff soil: $600 \leq \bar{V}_s < 1200\,\mathrm{fps}$ $(180 \leq \bar{V}_s < 360\,\mathrm{ms}^{-1})$, 101 records

  D Soft clay: $\bar{V}_s < 600\,\mathrm{fps}$ $(\bar{V}_s < 180\,\mathrm{ms}^{-1})$, 16 records

- Use two source mechanisms: reverse (R): $\Rightarrow F = 1$, 81 records and strike-slip (S) $\Rightarrow F = 0$, 157 records. Most (77) reverse records from $M_s \leq 6.7$.

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

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

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

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

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

- So that Y is increasing function of M and decreasing function of R for all positive M and R apply constraints. Define $g = b/d$ and $h = -(g + c_2)$, then rewrite equation $\ln Y =$

$a + d\{gM + \ln[R + c_1 \exp(c_2 M)]\} + eF$ and apply constraints $g \le 0$, $d \le 0$, $c \ge 0$, $c_2 \ge 0$ and $h \ge 0$.

- Check plots of residuals (not shown in paper), find uniform distribution.
- Find e not significantly different than 0 and inconsistency in results between different soil classes make it difficult to attach any significance to fault type.
- Lack of records for A and D site categories. Find scale factors $k_1 = 0.998638$ and $k_2 = 1.200678$ so that $Y_A = k_1 Y_B$ and $Y_D = k_2 Y_C$, where Y_S is predicted ground motion for site class S. Find no obvious dependence of k_1 or k_2 on acceleration from examining residuals. Find k_1 and k_2 not significantly different than 1.
- Note limited data for $R < 10\,\mathrm{km}$, advise caution for this range.
- Note equation developed to estimate site-amplification factors not for seismic hazard analysis.

3.109 Free (1996) & Free et al. (1998)

- Ground motion model is:

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

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

- Use two site categories:

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

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

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

- Select data using these criteria:
  1. Epicentre and recording station must be within the stable continental region boundaries defined by Johnston *et al.* (1994) because a) such regions form end of spectrum of regions described by 'intraplate' and hence allows differences with interplate regions to be seen, b) they are clearly delineated regions and c) intraplate oceanic crust is excluded.
  2. Minimum magnitude level $\mathbf{M} = 1.5$.
  3. Use records from dam abutments and downstream free-field sites but excludes records from crests, slopes, toes, galleries, or basements.

4. Use records from acceleration and velocity instruments.
5. Specify no minimum PGA.
6. Specify no maximum source distance. Do not exclude records from distances greater than shortest distance to a non-triggered station.

- Data from Australia, N.W. Europe, Peninsular India and E. N. America.
- Focal depths, $2 \leq h \leq 28\,\mathrm{km}$.
- Most records from $\mathbf{M} < 4.0$.
- Visually inspect all records including integrated velocities and displacements, identify and remove traces dominated by noise, identify and correct transient errors (spikes, ramps, linear sections, back time steps and clipped peaks), identify scaling errors, identify and remove multiple event records. Linear baseline correct and elliptically filter with cut-off 0.25 to $0.5\,\mathrm{Hz}$ (determine frequency by visual inspection of adjusted record) and 33 to $100\,\mathrm{Hz}$ (generally pre-determined by Nyquist frequency).
- Large proportion of records from velocity time histories which differentiate to acceleration. Test time domain method (central difference technique) and frequency domain method; find very similar results. Use time domain method.
- Distribution with respect to magnitude did not allow two-stage regression technique.
- In many analyses distribution of data with respect to distance did not allow simultaneous determination of coefficients C_4 and C_5, for these cases constrain C_4 to -1.
- Test effect of minimum magnitude cut-off for two cut-offs $\mathbf{M} = 1.5$ and $\mathbf{M} = 3.5$. Find if include data from $\mathbf{M} < 3.5$ then there is substantial over prediction of amplitudes for $d < 10\,\mathrm{km}$ for large magnitudes unless include C_3 term. C_3 effectively accounts for large number of records from small magnitudes and so predictions using the different magnitude cut-offs are very similar over broad range of $\mathbf{M}$ and d.
- Try including focal depth, h, explicitly by replacing h_0 with h because h_0 determined for whole set (which is dominated by small shocks at shallow depths) may not be appropriate for large earthquakes. Find improved fit at small distances but it does not result in overall improvement in fit (σ increases); this increase thought due to large errors in focal depth determination.
- Find larger standard deviations than those found in previous studies which note may be due to intrinsic differences between regional subsets within whole set. Repeat analysis separately for Australia (for horizontal and vertical), N. America (for horizontal and vertical) and N.W. Europe (horizontal); find reduced standard deviations (although still large), C_5 varies significantly between 3 regions.
- Repeat analysis excluding velocity records.
- Also repeat analysis using only rock records.

3.110 Ohno et al. (1996)

- Ground motion model is:

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

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

- Use two site conditions:

$q = 0$ Pre-Quaternary: Rock (sandstone, siltstone, shale, granite, mudstone, etc.); thickness of surface soil overlying rock is less than $10\,\mathrm{m}$; shallow soil or thin alluvium, 160 records. S-wave velocities $> 600\,\mathrm{ms}^{-1}$.

$q = 1$ Quaternary: Soil (alluvium, clay, sand, silt, loam, gravel, etc.), 336 records. S-wave velocities $\leq 600\,\mathrm{ms}^{-1}$.

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

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

3.111 Romeo et al. (1996)

- Ground motion model is:

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

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

- Use two site categories:

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

$S = 1$ All other sites.

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

3.112 Sarma & Srbulov (1996)

- Ground motion model is:

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

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

- Consider two soil categories but do not model:

  1. Rock
  2. Soil

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

- Most records from W. USA but many from Europe and Middle East.
- Focal depths between 2 and $29\,\mathrm{km}$.
- Records from instruments on ground floor or in basements of buildings and structures up to 3 storeys and at free-field sites, regardless of topography.
- Records baseline corrected and low-pass filtered using elliptic filter.

3.113 Singh et al. (1996)

- Ground motion model is:

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

  where AGM is in cms^{-2}, $b_1 = 1.14$ and $b_3 = -0.615$ (σ is not given). Note there are typographical errors in the abstract.

- Data from three earthquakes with $m_b = 5.7$, one with $m_b = 5.8$ and one with $m_b = 7.2$.
- Adopt magnitude scaling coefficient (0.31) from Boore (1983).

3.114 Spudich et al. (1996) & Spudich et al. (1997)

- Ground motion model is:

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

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

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

  $\Gamma = 0$ Rock: 35 records

  $\Gamma = 1$ Soil: 93 records

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

3.115 Stamatovska & Petrovski (1996)

- Ground motion model is:

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

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

- Correct PGAs for local site effects so that PGAs used correspond to a site with a shear-wave velocity of $700\,\mathrm{ms}^{-1}$. Do not state how this is performed.
- Most records from SMA-1s.
- Not all records from free-field.
- Records from strong intermediate depth earthquakes in Vrancea region.
- Focal depths, $89.1 \leq h \leq 131\,\mathrm{km}$.
- For each of the four earthquakes, calculate coefficents in equation $\ln \mathrm{Acc} = b_0 + b_1 \ln(R_e/\rho)$, the main direction of energy propagation and the relation between the semi-axes of the ellipse in two orthogonal directions ($a : b$).

- Also calculate coefficents in equation $\ln \mathrm{Acc} = b + b_M M + b_R \ln(R_h + C)$ for different azimuth by normalising the values of R_e/ρ by the azimuth. Give coefficients for Bucharest, Valeni and Cerna Voda.
- Note that uncertainty is high and suggest this is because of distribution of data with respect to M, R_e and h, the use of data processed in different ways, soil-structure interaction and the use of an approximate correction method for local site effects.

3.116 Campbell (1997), Campbell (2000), Campbell (2001) & Campbell & Bozorgnia (1994)

- Ground motion model (horizontal component) is:

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

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

Ground motion model (vertical component) is:

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

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

- Uses three site categories:

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

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

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

Also includes sediment depth (D) as a variable.

- Restricts to near-source distances to minimize influence of regional differences in crustal attenuation and to avoid complex propagation effects that have been observed at longer distances.
- Excludes recordings from basement of buildings greater than two storeys on soil and soft rock, greater than five storeys on hard rock, toe and base of dams and base of bridge columns. Excludes recordings from shallow and soft soil because previous analyses showed such sites have accelerations significantly higher than those on deep, firm alluvium. Include records from dam abutments because comprise a significant number of rock recordings and due to stiff foundations are expected to be only minimally affected by dam. Some of these could be strongly affected by local topography.
- Includes earthquakes only if they had seismogenic rupture within shallow crust (depths less than about $25\,\mathrm{km}$). Includes several large, shallow subduction interface earthquakes because previous studies found similar near-source ground motions to shallow crustal earthquakes.
- Includes only earthquakes with M about 5 or larger to emphasize those ground motions of greatest engineering interest and limit analysis to more reliable, well-studied earthquakes.
- Notes that distance to seismogenic rupture is a better measure than distance to rupture or distance to surface projection because top layer of crust is non-seismogenic and will not contribute to ground motion. Give estimates for average depth to top of seismogenic rupture for hypothetical earthquakes.
- Considers different focal mechanisms: reverse (H:6, V:5), thrust (H:9, V:6), reverse-oblique (H:4, V:2) and thrust-oblique (0), total (H:19, V:13) $\Rightarrow F = 1$ (H:278 records, V:116 records) (reverse have a dip angle greater than or equal to $45°$), strike-slip (H:27, V:13) $\Rightarrow F = 0$ (H:367 records, V:109 records) (strike-slip have an absolute value of rake less than or equal to $22.5°$ from the horizontal as measured along fault plane). There is only one normal faulting earthquakes in set of records (contributing four horizontal records) so difference is not modelled although $F = 0.5$ given as first approximation (later revised to $F = 0$).
- Mostly W. USA with 20 records from Nicaragua(1) Mexico (5), Iran (8), Uzbekistan (1), Chile (3), Armenia (1) and Turkey (1).
- Does regression firstly with all data. Selects distance threshold for each value of magnitude, style of faulting and local site condition such that the 16th percentile estimate of A_H was equal to $0.02\,\mathrm{g}$ (which corresponds to a vertical trigger of about $0.01\,\mathrm{g}$). Repeats regression repeated only with those records within these distance thresholds. Avoids bias due to non-triggering instruments.
- Finds dispersion (uncertainty) to be dependent on magnitude and PGA, models as linear functions. Finds better fit for PGA dependency.

3.117 Munson & Thurber (1997)

- Ground motion model is:

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

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

- Use two site categories:

$S = 0$ Lava: 38 records

$S = 1$ Ash: $60 \lesssim V_s \lesssim 200\,\mathrm{ms}^{-1}$, 13 records

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

3.118 Rhoades (1997)

- Ground motion model is:

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

  where $\alpha = -1.237 \pm 0.254$, $\beta = 0.278 \pm 0.043$, $\gamma = -0.00220 \pm 0.00042$, $h = 6.565 \pm 0.547$, $\tau^2 = 0.00645 \pm 0.00382$ and $\sigma^2 = 0.0527 \pm 0.00525$ (where τ^2 is the inter-earthquake variance and σ^2 is the intra-earthquake variance and $\pm$ signifies the standard error of the estimate.

- Notes that errors in magnitude determination are one element that contributes to the between-earthquake component of variance and could thus cause apparent differences between earthquakes, even if none existed.
- Develops a method to explicitly include consideration of magnitude uncertainties in a random earthquake effects model so that the between-earthquake component of variance can be split into the part that is due only to magnitude uncertainty (and is therefore of no physical consequence) and the part for which a physical explanation may be sought.

- Applies method to data of Joyner & Boore (1981). Assume two classes of magnitude estimates: those with estimates of M_w, which assumes to be associated with a standard error of 0.1, and those for which M_L was used as a surrogate for M_w, which assumes to be associated with a standard error of 0.3. Find that the inter-earthquake variance is much lower than that computed assuming that the magnitudes are exact but that other coefficients are similar. Believes that the high inter-earthquake variance derived using the exact magnitudes model is largely explained by the large uncertainties in the magnitude estimates using M_L.

3.119 Schmidt et al. (1997)

- Ground motion model is:

$$\begin{aligned} \ln A &= c_1 + c_2 M + c_3 \ln r + c_4 r + c_5 S_1 + c_6 S_2 \\ \text{where } r &= \sqrt{R^2 + 6^2} \end{aligned}$$

  where A is in ms^{-2}, $c_1 = -1.589$, $c_2 = 0.561$, $c_3 = -0.569$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.80$ (for all earthquakes), $c_1 = -1.725$, $c_2 = 0.687$, $c_3 = -0.742$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.83$ (for shallow crustal earthquakes) and $c_1 = -0.915$, $c_2 = 0.543$, $c_3 = -0.692$, $c_4 = -0.003$, $c_5 = 0.173$, $c_6 = 0.279$ and $\sigma = 0.74$ (for subduction zone earthquakes).

- Use three site categories:

$S_1 = 0, S_2 = 0$ Rock, 54 records.
$S_1 = 1, S_2 = 0$ Hard soil, 63 records.
$S_1 = 0, S_2 = 1$ Soft soil, 83 records.

- Most records from SMA-1s with 6 records from SSA-2.
- Use PSA at $40\,\mathrm{Hz}$ $(0.025\,\mathrm{s})$ as peak ground acceleration.
- Records instrument corrected and bandpass filtered with cut-offs of 0.2 and $20\,\mathrm{Hz}$.
- Use data from shallow crustal earthquakes (133 records) and subduction zone earthquakes (67 records).
- Perform regression on combined shallow crustal and subduction zone records, on just the shallow crustal records using d_h and using d_e and on just subduction zone records.
- Note that distribution w.r.t. distance improves in the near field when epicentral distance is used but only possible to use d_e for shallow crustal earthquakes because for subduction zone earthquakes hypocentral distance is much greater than epicentral distance so should use d_h instead.
- For $4 \leq M \leq 6$ distribution w.r.t. epicentral distance is quite good but for $M > 6$ no records from $d_e < 40\,\mathrm{km}$.

- Use a two step procedure. Firstly use entire set and both horizontal components and compute two soil terms (one for hard and one for soft soil). In second step use soil terms to correct motions for rock conditions and then repeat regression.
- Use Bayesian analysis (Ordaz *et al.*, 1994) so that derived coefficients comply with physics of wave propagation because include *a priori* information on the coefficients to avoid physically unrealistic values. Choose initial values of coefficients based on theory and previous results
- Cannot find coefficient in r by regression so adopt $6\,\mathrm{km}$ from previous study.
- Examine residuals w.r.t. distance and magnitude and find no trends.

3.120 Youngs et al. (1997)

- Ground motion model for soil is:

$$\begin{aligned}
\ln \mathrm{PGA} &= C_1^* + C_2\mathbf{M} + C_3^* \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{C_4^* - \frac{C_2}{C_3^*}\mathbf{M}}\right] + C_5 Z_t + C_9 H + C_{10} Z_{ss} \\
\text{with: } C_1^* &= C_1 + C_6 Z_r \\
C_3^* &= C_3 + C_7 Z_r \\
C_4^* &= C_4 + C_8 Z_r
\end{aligned}$$

where PGA is in g, $C_1 = -0.6687$, $C_2 = 1.438$, $C_3 = -2.329$, $C_4 = \ln(1.097)$, $C_5 = 0.3643$, $C_9 = 0.00648$ and $\sigma = 1.45 - 0.1\mathbf{M}$ (other coefficients in equation not needed for prediction on deep soil and are not given in paper).

Ground motion model for rock is:

$$\begin{aligned}
\ln \mathrm{PGA} &= C_1^* + C_2\mathbf{M} + C_3^* \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{C_4^* - \frac{C_2}{C_3^*}\mathbf{M}}\right] + C_5 Z_{ss} + C_8 Z_t + C_9 H \\
\text{with: } C_1^* &= C_1 + C_3 C_4 - C_3^* C_4^* \\
C_3^* &= C_3 + C_6 Z_{ss} \\
C_4^* &= C_4 + C_7 Z_{ss}
\end{aligned}$$

where PGA is in g, $C_1 = 0.2418$, $C_2 = 1.414$, $C_3 = -2.552$, $C_4 = \ln(1.7818)$, $C_8 = 0.3846$, $C_9 = 0.00607$ and $\sigma = 1.45 - 0.1\mathbf{M}$ (other coefficients in equation not needed for prediction on rock and are not given in paper).

Use different models to force rock and soil accelerations to same level in near field.

- Use three site categories to do regression but only report results for rock and deep soil:

$Z_r = 1, Z_{ds} = 0, Z_{ss} = 0$ Rock: Consists of at most about a metre of soil over weathered rock, 96 records.

$Z_{ds} = 1, Z_r = 0, Z_{ss} = 0$ Deep soil: Depth to bedrock is greater than $20\,\mathrm{m}$, 284 records.

$Z_{ss} = 1, Z_{ds} = 0, Z_r = 0$ Shallow soil: Depth to bedrock is less than $20\,\mathrm{m}$ and a significant velocity contrast may exist within $30\,\mathrm{m}$ of surface, 96 records.

- Use free-field recordings, i.e. instruments in basement or ground-floor of buildings less than four storeys in height. Data excluded if quality of time history poor or if portion of main shaking not recorded.
- Consider tectonic type: interface (assumed to be thrust) (98 records) $\Rightarrow Z_t = 0$, intraslab (assumed to be normal) (66 records) $\Rightarrow Z_t = 1$
- Focal depths, H, between 10 and $229\,\mathrm{km}$
- Not enough data to perform individual regression on each subset so do joint regression analysis.
- Both effect of depth and tectonic type significant.
- Large differences between rock and deep soil.
- Note differences between shallow crustal and interface earthquake primarily for very large earthquakes.
- Assume uncertainty to be linear function of magnitude.

3.121 *Zhao et al. (1997)*

- Ground motion model (Model 1) is:

  $$\log_{10}\mathrm{PGA} = A_1 M_w + A_2 \log_{10}\sqrt{r^2+d^2} + A_3 h_c + A_4 + A_5\delta_R + A_6\delta_A + A_7\delta_I$$

  where PGA is in ms^{-2}, $\delta_R = 1$ for crustal reverse 0 otherwise, $\delta_A = 1$ for rock 0 otherwise, $\delta_I = 1$ for interface 0 otherwise, $A_1 = 0.298$, $A_2 = -1.56$, $A_3 = 0.00619$, $A_4 = -0.365$, $A_5 = 0.107$, $A_6 = -0.186$, $A_7 = -0.124$, $d = 19$ and $\sigma = 0.230$.
- Models also given for soil sites only (Model 2), unspecified site (Model 3), focal mechanism and tectonic type unknown (Model 4) and only magnitude, depth and distance known (Model 5)
- Records from ground or base of buildings. 33 from buildings with more than 3 storeys; find no significant differences.
- Retain two site categories:
  1. Rock: Topographic effects expected, very thin soil layer ($\leq 3\,\mathrm{m}$) overlying rock or rock outcrop.
  2. Soil: everything else
- Use depth to centroid of rupture, h_c, $4 \leq h_c \leq 149$. Only nine are deeper than $50\,\mathrm{km}$. Exclude records from deep events which travelled through mantle.
- Consider tectonic type: C=crustal (24+17 records), I=interface (7+0 records) and S=slab (20+0 records)

- Consider source mechanism: N=normal (15+1 records), R=reverse (22+5 records) and S=strike-slip (12+11 records). Classify mixed mechanisms by ratio of components ≥ 1.0.
- For only five records difference between the distance to rupture surface and the distance to centroid could be more than 10%.
- 66 foreign near-source records ($d_r \leq 10\,\mathrm{km}$) from 17 crustal earthquakes supplement NZ data. Mainly from western North America including 17 from Imperial Valley and 12 from Northridge.
- Exclude one station's records (Atene A) due to possible topographical effects.
- Exclude records which could have been affected by different attenuation properties in the volcanic region.
- Note regional difference between Fiordland and volcanic region and rest of country but do model.
- Retain coefficients if significant at $\alpha = 0.05$.
- Anelastic term not significant.

3.122 *Bouhadad* et al. *(1998)*

- Ground motion model is:
$$A = c\exp(\alpha M)[R^k + a]^{-\beta-\gamma R}$$
- Coefficients not given, only predictions.

3.123 *Costa* et al. *(1998)*

- Ground motion model is:
$$\log(A) = a + bM + c\log(r)$$
where A is in g, $a = -1.879$, $b = 0.431$ and $c = -1.908$ (for vertical components) and $a = -2.114$, $b = 0.480$ and $c = -1.693$ (for horizontal components).
- All records from digital instruments.
- Try including a term $d\log(M)$ but tests show that d is negligible with respect to a, b and c.

3.124 *Manic (1998)*

- Ground motion model is:
$$\begin{aligned}\log(A) &= c_1 + c_2 M + c_3\log(D) + c_4 D + c_5 S\\ D &= (R^2 + d_0^2)^{1/2}\end{aligned}$$
where A is in g, $c_1 = -1.664$, $c_2 = 0.333$, $c_3 = -1.093$, $c_4 = 0$, $c_5 = 0.236$, $d_0 = 6.6$ and $\sigma = 0.254$.

- Uses four site categories (following Ambraseys *et al.* (1996)) but only two have data within them:

$S = 0$ Rock (R): $v_s > 750\,\mathrm{ms}^{-1}$, 92 records.

$S = 1$ Stiff soil (A): $360 < v_s \leq 750\,\mathrm{ms}^{-1}$, 184 records.

where v_s is average shear-wave velocity in upper $30\,\mathrm{m}$.

- Uses both horizontal components to get a more reliable set of data.
- Tries using M_L rather than M_s, epicentral distance rather than hypocentral distance and constraining anelastic decay coefficient, c_4, to zero. Chooses combination which gives minimum σ.

3.125 Rinaldis et al. (1998)

- Ground motion model is:

$$\ln Y = C_{14} + C_{22}M + C_{31}\ln(R + 15) + C_{43}S + C_{54}F$$

where Y is in cms^{-2}, $C_{14} = 5.57$, $C_{22} = 0.82$, $C_{31} = -1.59$, $C_{43} = -0.14$, $C_{54} = -0.18$ and $\sigma = 0.68$. Assume $15\,\mathrm{km}$ inside $\ln(R + \ldots)$ from Theodulidis & Papazachos (1992).

- Use two site categories:

$S = 0$ Rock: includes stiff sites.

$S = 1$ Alluvium: includes both shallow and deep soil sites.

- Use two source mechanism categories:

$F = 0$ Thrust and strike-slip earthquakes.

$F = 1$ Normal earthquakes.

- Use epicentral distance because in Italy and Greece the surface geology does not show any evident faulting, consequently it is impossible to use a fault distance definition.
- Good distribution and coverage of data with respect to site category and source mechanism.
- Consider six strong-motion records (three Italian and three Greek) with different associated distances, magnitudes and record length and apply the different processing techniques of ENEA-ENEL and ITSAK to check if data from two databanks can be merged. Digitise six records using same equipment. ITSAK technique: subtract the reference trace (either fixed trace or trace from clock) from uncorrected accelerogram and select band-pass filter based on either Fourier amplitude spectra of acceleration components or selected using a different technique. ENEA-ENEL technique: subtract the reference trace from uncorrected accelerogram and select band-pass filter by comparing Fourier amplitude spectra of acceleration components with that of fixed trace. Find small differences in PGA, PGV, PGD so can merge Italian and Greek data into one databank.

- Use four step regression procedure, similar to that Theodulidis & Papazachos (1992) use. First step use only data with $M \geq 6.0$ ($7 \leq R \leq 138\,\mathrm{km}$) for which distances are more accurate to find geometrical coefficient C_{31}. Next find constant (C_{12}) and magnitude (C_{22}) coefficients using all data. Next find constant (C_{13}) and soil (C_{43}) coefficients using all data. Finally find constant (C_{14}) and source mechanism (C_{54}) coefficients using data with $M \geq 6.0$ for which focal mechanism is better constrained; final coefficients are C_{14}, C_{22}, C_{31}, C_{43} and C_{54}. Investigate influence of distance on C_{54} by subdividing data in final step into three categories with respect to distance ($7 \leq R \leq 140\,\mathrm{km}$, $7 \leq R \leq 100\,\mathrm{km}$ and $7 \leq R \leq 70\,\mathrm{km}$).
- Equation intended as first attempt to obtain attenuation relations from combined databanks and site characteristics and fault rupture properties could and should be taken into account.

3.126 Sadigh & Egan (1998)

- Based on Sadigh *et al.* (1997), see Section 3.86.
- Ground motion model is:

$$\ln \mathrm{PGA} = C_1 + C_2 M + C_3 \ln[r_{\mathrm{rup}} + \exp(C_4 + C_5 M)]$$

where PGA is in g, for $M < 6.5$ $C_4 = 1.29649$ and $C_5 = 0.25$ and for $M \geq 6.5$ $C_4 = -0.48451$ and $C_5 = 0.524$. For rock sites: $C_3 = -2.100$, for strike-slip mechanism and $M < 6.5$ $C_1 = -0.949$ and $C_2 = 1.05$, for strike-slip mechanism and $M \geq 6.5$ $C_1 = -1.274$ and $C_2 = 1.10$, for reverse-slip and $M < 6.5$ $C_1 = 0.276$ and $C_2 = 0.90$ and for reverse-slip and $M \geq 6.5$ $C_1 = -1.024$ and $C_2 = 1.10$. For soil sites: $C_3 = -1.75$, for strike-slip mechanism and $M < 6.5$ $C_1 = -1.1100$ and $C_2 = 0.875$, for strike-slip mechanism and $M \geq 6.5$ $C_1 = -1.3830$ and $C_2 = 0.917$, for reverse-slip mechanism and $M < 6.5$ $C_1 = -0.0895$ and $C_2 = 0.750$ and for reverse-slip mechanism and $M \geq 6.5$ $C_1 = -1.175$ and $C_2 = 0.917$ (σ not given).

- Use two site categories:
  1. Rock: bedrock within about a metre of surface. Note that many such sites are soft rock with $V_s \leq 750\,\mathrm{ms}^{-1}$ and a strong velocity gradient because of near-surface weathering and fracturing, 274 records.
  2. Deep soil: greater than $20\,\mathrm{m}$ of soil over bedrock. Exclude data from very soft soil sites such as those from San Francisco bay mud, 690 records.
- Define crustal earthquakes as those that occur on faults within upper 20 to $25\,\mathrm{km}$ of continental crust.
- Consider source mechanism: RV=reverse (26+2) and SS=strike-slip (and some normal) (89+0). Classified as RV if rake$> 45°$ and SS if rake$< 45°$. Find peak motions from small number of normal faulting earthquakes not to be significantly different than peak motions from strike-slip events so include in SS category.

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

3.127 Sarma & Srbulov (1998)

- Ground motion model is:

$$\log(a_p/g) = C_1 + C_2 M_s + C_3 d + C_4 \log d$$

  where a_p is in g, for soil sites $C_1 = -1.86$, $C_2 = 0.23$, $C_3 = -0.0062$, $C_4 = -0.230$ and $\sigma = 0.28$ and for rock sites $C_1 = -1.874$, $C_2 = 0.299$, $C_3 = -0.0029$, $C_4 = -0.648$ and $\sigma = 0.33$.

- Use two site categories because of limited available information (based on nature of top layer of site regardless of thickness) for which derive separate equations:
  1. Soil
  2. Rock
- Use record from free-field or in basements of buildings ≤ 3 storeys high.
- Use M_s because better represents size of shallow earthquakes and is determined from teleseismic readings with much smaller standard errors than other magnitude scales and also saturates at higher magnitudes than all other magnitude scales except M_w which is only available for relatively small portion of earthquakes. For some small earthquakes convert to M_s from other magnitude scales.
- For very short records, $\leq 5\,\mathrm{s}$ long, correct using parabolic baseline, for records $> 10\,\mathrm{s}$ long correct using elliptical filter and for records between 5 and $10\,\mathrm{s}$ long both parabolic correction and filtering applied and select best one from appearance of adjusted time histories.
- Equations not any more precise than other attenuation relations but are simply included for completeness and for a comparison of effects of dataset used with other dataset. Data did not allow distinction between different source mechanisms.

3.128 Sharma (1998)

- Ground motion model is:

$$\log A = c_1 + c_2 M - b \log(X + \mathrm{e}^{c_3 M})$$

  where A is in g, $c_1 = -1.072$, $c_2 = 0.3903$, $b = -1.21$, $c_3 = 0.5873$ and $\sigma = 0.14$.

- Considers two site categories but does not model:

  R Rock: generally granite/quartzite/sandstone, 41 records.

  S Soil: exposed soil covers on basement, 25 records.

- Focal depths between 7.0 and $50.0\,\mathrm{km}$.

- Most records from distances $> 50\,\mathrm{km}$. Correlation coefficient between M and X is 0.63.

- Does not include source mechanism as parameter because not well defined and including many terms may lead to errors. Also neglects tectonic type because set is small and small differences are expected.

- Fit $\log A = -b \log X + c$ to data from each earthquake separately and find average b equal to 1.292. Then fit $\log A = aM - b \log X + c$ to data from all earthquakes and find $b = 0.6884$. Fit $\log A = -b \log X + \sum d_i l_i$ to all data, where $l_i = 1$ for ith earthquake and 0 otherwise and find $b = 1.21$, use this for rest of analysis.

- Use weighted regression, due to nonuniform sampling over all M and X. Divide data into distance bins $2.5\,\mathrm{km}$ wide up to $10\,\mathrm{km}$ and logarithmically dependent for larger distances. Within each bin each earthquake is given equal weight by assigning a relative weight of $1/n_{j,l}$, where $n_{j,l}$ is the number of recordings for jth earthquake in lth distance bin, then normalise so that sum to total number of recordings.

- Original data included two earthquakes with focal depths $91.0\,\mathrm{km}$ and $119.0\,\mathrm{km}$ and $M = 6.8$ and 6.1 which caused large errors in regression parameters due to large depths so excluded them.

- Check capability of data to compute coefficients by deleting, in turn, c_1, c_2 and c_3, find higher standard deviation.

- Makes one coefficient at a time equal to values given in Abrahamson & Litehiser (1989), finds sum of squares increases.

- Notes lack of data could make relationship unreliable.

3.129 Smit (1998)

- Ground motion model is:

  $$\log Y = a + bM - \log R + dR$$

  where Y is in $\mathrm{nm/s^2}$, $b = 0.868$, $d = -0.001059$, $\sigma = 0.35$, for horizontal PGA $a = 5.230$ and for vertical PGA $a = 5.054$.

- Most records from rock sites.

- Focal depths between 0 and about $27\,\mathrm{km}$ (most less than $10\,\mathrm{km}$).

- Most records from $M_L < 3.5$.

- Most earthquakes have strike-slip mechanism.
- Uses records from high gain short period seismographs and from strong-motion instruments.
- Records are instrument corrected.
- Eliminates some far-field data from small magnitude earthquakes using signal to noise ratio criterion.
- Records cover entire azimuthal range.
- Notes that need more data in near field.
- Notes that care must be taken when using equations for prediction of ground motion in strong earthquakes ($M \approx 6$) because of lack of data.

3.130 Cabañas et al. (1999), Cabañas et al. (2000) & Benito et al. (2000)

- Ground motion model is:

$$\ln A = C_1 + C_2 M + C_3(R + R_0) + C_4 \ln(R + R_0) + C_5 S$$

  where A is in cms^{-2}, $C_1 = 0$, $C_2 = 0.664$, $C_3 = 0.009$, $C_4 = -2.206$, $R_0 = 20$, $C_5 = 8.365$ (for S1), $C_5 = 8.644$ (for S2), $C_5 = 8.470$ (for S3) and $C_5 = 8.565$ (for S4) for horizontal PGA using d_e and M_s and all Mediterranean data, $C_1 = 0$, $C_2 = 0.658$, $C_3 = 0.008$, $C_4 = -2.174$, $R_0 = 20$, $C_5 = 7.693$ (for S1), $C_5 = 7.915$ (for S2) and $C_5 = 7.813$ (for S4) (C_5 not derived for S3) for vertical PGA using d_e and M_s and all Mediterranean data. σ is not given (R^2 is reported).

- Use four site categories:

  S1 Hard basement rock.

  S2 Sedimentary rock and conglomerates.

  S3 Glacial deposits.

  S4 Alluvium and consolidated sediments.

- Derive separate equations using data from Mediterranean region and also just using data from Spain.
- Equations for Spain derived using m_{bLg}.
- Spanish data all from earthquakes with $2.5 \leq m_{bLg} \leq 6.0$ and $0 \leq d_h \leq 300\,\mathrm{km}$.

3.131 Chapman (1999)

- Ground motion model is:

  $$\log_{10} Y = a + b(M-6) + c(M-6)^2 + d\log(r^2+h^2)^{1/2} + eG_1 + fG_2$$

  where Y is in cms^{-2}, $a = 3.098$, $b = 0.3065$, $c = -0.07570$, $d = -0.8795$, $h = 6.910$, $e = 0.1452$, $f = 0.1893$ and $\sigma = 0.2124$.

- Use three site categories:

  A & B $V_{s,30} > 760\,\mathrm{ms}^{-1}$, 24 records $\Rightarrow G_1 = 0, G_2 = 0$.

  C $360 < V_{s,30} \leq 760\,\mathrm{ms}^{-1}$, 116 records $\Rightarrow G_1 = 1, G_2 = 0$.

  D $180 < V_{s,30} \leq 360\,\mathrm{ms}^{-1}$, 164 records $\Rightarrow G_1 = 0, G_2 = 1$.

- Uses records from ground level or in basements of structures of two stories or less, and excludes records from dam or bridge abutments.

- Selects records which include major motion portion of strong-motion episode, represented by S wavetrain. Excludes records triggered late on S wave or those of short duration terminating early in coda.

- Most records already corrected. Some records instrument corrected and 4-pole causal Butterworth filtered (corner frequencies 0.1 and $25\,\mathrm{Hz}$). Other records instrument corrected and 4-pole or 6-pole causal Butterworth bandpass filtered (corner frequencies 0.2 and $25\,\mathrm{Hz}$). All data filtered using 6-pole causal high-pass Butterworth filter with corner frequency $0.2\,\mathrm{Hz}$ and velocity and displacement curves examined.

- Uses method of Campbell (1997) to reduce bias due to non-triggered instruments, for some recent shocks. Firstly uses all data to determine minimum distances (which are functions of magnitude and site condition) at which 16th percentile values of PGA are $< 0.02\,\mathrm{g}[0.2\,\mathrm{ms}^{-1}]$ (corresponding to $0.01\,\mathrm{g}[0.1\,\mathrm{ms}^{-1}]$ vertical component trigger threshold). Next delete records from larger distances and repeat regression.

- Check residuals against distance and magnitude for each site class; find no obvious non-normal magnitude or distance dependent trends.

3.132 Cousins et al. (1999)

- Based on Zhao *et al.* (1997) see Section 3.121

- Ground motion model is:

  $$\begin{aligned}\log_{10}\mathrm{PGA} &= A_1M_w + A_2\log_{10}R + A_3h_c + A_4 + A_5 + A_6 + A_7R + A_8M_w + A_9 \\ &\quad + A_{10}R_v\end{aligned}$$

where PGA is in ms^{-2}, $R = \sqrt{r^2 + d^2}$ and R_v is distance travelled by direct seismic wave through volcanic region. A_5 only for crustal reverse, A_6 only for interface, A_7 only for strong and weak rock, A_8 only for strong rock, A_9 only for strong rock, $A_1 = 0.2955$, $A_2 = -1.603$, $A_3 = 0.00737$, $A_4 = -0.3004$, $A_5 = 0.1074$, $A_6 = -0.1468$, $A_7 = -0.00150$, $A_8 = 0.3815$, $A_9 = -2.660$, $A_{10} = -0.0135$, $d = 19.0$ and $\sigma = 0.24$.

- Originally considers five site categories but retain three:
  1. Strong rock: $V_s > 700\,\mathrm{ms}^{-1}$
  2. Weak rock: $375 \leq V_s \leq 700\,\mathrm{ms}^{-1}$ and category AV those sites with a very thin layer ($\leq 3\,\mathrm{m}$) overlying rock
  3. Soil: everything else
- Depth to centroid of rupture, h_c, used, $4 \leq h_c \leq 94\,\mathrm{km}$.
- 60% on soil, 40% on rock
- Consider tectonic type: C=Crustal (12+17), I=Interface (5+0) and S=Slab(8+0)
- Consider source mechanism: N=normal (6+1), R=reverse (12+5) and S=strike-slip (7+11). Mixed classified by ratio of components ≥ 1.0.
- Mixture of analogue and digital accelerograms (72%) and seismograms (28%)
- Accelerograms sampled at 100–250 samples/sec. Bandpass frequencies chosen by analysis of Fourier amplitude spectrum compared with noise spectrum. $f_{\min}$ between 0.15 and $0.5\,\mathrm{Hz}$ and $f_{\max}$ equal to $25\,\mathrm{Hz}$. Instrument correction applied to analogue records.
- Seismograms sampled at 50–100 samples/sec. Differentiated once. Instrument corrected and high pass filtered with $f_{\min} = 0.5\,\mathrm{Hz}$. No low pass filter needed.
- Clipped seismograms usually retained.
- Directional effect noticed but not modelled.
- Most records from more than $100\,\mathrm{km}$ away. Note lack of near-source data.
- Records from accelerograms further away than first operational non-triggering digital accelerograph, which had a similar triggering level, were excluded.
- Models difference between high attenuating volcanic and normal regions.

3.133 Ólafsson & Sigbjörnsson (1999)

- Ground motion model is:

$$\log(a_{\max}) = \phi_1 + \phi_2 \log M_0 - \phi_3 \log(R)$$

where $a_{\max}$ is in cms^{-2}, M_0 is in $\mathrm{dyn\,cm}$ and R is in cm, $\phi_1 = 0.0451$, $\phi_2 = 0.3089$, $\phi_3 = 0.9642$ and $\sigma = 0.3148$.

- Instruments in basement of buildings located on rock or very stiff ground.
- Records from 21 different stations.
- Focal depths between 1 and $11\,\mathrm{km}$.
- Most records from digital instruments with $200\,\mathrm{Hz}$ sampling frequency and high dynamic range.
- Seismic moments calculated using the strong-motion data.
- Most data from $M_0 \leq 5 \times 10^{23}\mathrm{dyn\,cm}$ and from $d_e \leq 40\,\mathrm{km}$.

3.134 Spudich et al. (1999)

- Update of Spudich *et al.* (1997) see Section 3.114.
- Ground motion model is:

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

  where Z is in g, $b_1 = 0.299$, $b_2 = 0.229$, $b_3 = 0$, $b_5 = -1.052$, $b_6 = 0.112$, $h = 7.27$ and $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2}$ where $\sigma_1 = 0.172$, $\sigma_2 = 0.108$ and for randomly oriented horizontal component $\sigma_3 = 0.094$ and for larger horizontal component $\sigma_3 = 0$.

- Use two site categories (could not use more or $V_{s,30}$ because not enough data):

$\Gamma = 0$ Rock: includes hard rock (12 records) (plutonic igneous rocks, lava flows, welded tuffs and metamorphic rocks unless severely weathered when they are soft rock), soft rock (16 records) (all sedimentary rocks unless there was some special characteristic noted in description, such as crystalline limestone or massive cliff-forming sandstone when they are hard rock) and unknown rock (8 records). 36 records in total.

$\Gamma = 1$ Soil (alluvium, sand, gravel, clay, silt, mud, fill or glacial outwash of more than $5\,\mathrm{m}$ deep): included shallow soil (8 records) (5 to $20\,\mathrm{m}$ deep), deep soil (77 records) ($> 20\,\mathrm{m}$ deep) and unknown soil (21 records). 106 records in total.

- Applicable for extensional regimes, i.e. those regions where lithosphere is expanding areally. Significantly different ground motion than non-extensional areas.
- Criteria for selection of records is: $M_w \geq 5.0$, $d_f \leq 105\,\mathrm{km}$. Reject records from structures of more than two storeys or from deeply embedded basements or those which triggered on S wave. Also reject those close to dams which may be affected by dam. Also only use records already digitised.
- Include records from those instrument beyond cutoff distance, i.e. beyond first instrument which did not trigger, because of limited records and lack of data on non-triggering.

- Not enough data to be able to find all coefficients so use b_2 and b_3 from Boore *et al.* (1993) and b_6 from Boore *et al.* (1994a).
- One-stage maximum likelihood method used because many events used which only have one record associated with them and the two-stage method underestimates the earthquake-to-earthquake component of variation in that case.
- Correction technique based on uniform correction and processing using upper, f_h, and lower, f_l, frequencies for passband based on a visual inspection of Fourier amplitude spectrum and baseline fitting with a polynomial of degree 5.
- Check to see whether normal and strike-slip earthquakes give significantly different ground motions. No significant difference.

3.135 Wang et al. (1999)

- Ground motion model is:

$$\log A = a + bM_s + c \log R + dR$$

  where A is in cms^{-2}, using just soil records $a = 0.430$, $b = 0.428$, $c = -0.764$, $d = -0.00480$ and $\sigma = 0.271$.
- Use records from aftershocks of Tangshan earthquake.
- Focal depths between 5.7 and $12.9\,\mathrm{km}$.
- Note M_s values used may have some systematic deviation from other regions and errors, which decrease with increasing magnitude, can reach ± 0.5.
- Errors in epicentral locations not less than $2\,\mathrm{km}$. Reject 3 records because have $R < 2\,\mathrm{km}$, if include then find standard deviation increases and c obtained is unreasonable.
- Fit equation to all data (both rock and soil) but note that only for reference. Also fit equation to soil data only ($2.1 \leq R \leq 41.3\,\mathrm{km}$, $3.7 \leq M_s \leq 4.9$, 33 records from 6 earthquakes).
- Remove all four earthquakes with $M_s < 4.0$, for which error in magnitude determination is large, and fit equation to soil data only ($2.8 \leq R \leq 41.1\,\mathrm{km}$, $4.5 \leq M_s \leq 4.9$, 13 records from 2 earthquakes). Find smaller uncertainties.
- Also fit data to $\log A = a + bM_s - c \log(R + R_0)$; find similar results.
- Also use resultant of both horizontal components; find similar results to using larger component.
- Also fit eastern North America data ($3.9 \leq R \leq 61.6\,\mathrm{km}$, $2.3 \leq M_s \leq 3.8$, 7 records from 3 earthquakes); find similar attenuation characteristics.
- All equations pass F-tests.

3.136 Zaré et al. (1999)

- Ground motion model is:

$$\log A = aM - bX - d\log X + c_i S_i$$

  where units of A not given (but probably ms^{-2}), for vertical PGA $a = 0.362$, $b = 0.0002$, $c_1 = -1.124$, $c_2 = -1.150$, $c_3 = -1.139$, $c_4 = -1.064$, $d = 1$ and $\sigma = 0.336$ and for horizontal PGA $a = 0.360$, $b = 0.0003$, $c_1 = -0.916$, $c_2 = -0.862$, $c_3 = -0.900$, $c_4 = -0.859$, $d = 1$ and $\sigma = 0.333$.

- Use four site categories, which were based on H/V receiver function (RF) measurements (use geotechnical measurements at 50 sites and strong-motion accelerograms at other sites):

Site class 1 RF does not exhibit any significant amplification below $15\,\mathrm{Hz}$. Corresponds to rock and stiff sediment sites with average S-wave velocity in top $30\,\mathrm{m}$ ($V_{s,30}$) $> 700\,\mathrm{ms}^{-1}$. Use c_1.

Site class 2 RF exhibits a fundamental peak exceeding 3 at a frequency between 5 and $15\,\mathrm{Hz}$. Corresponds to stiff sediments and/or soft rocks with $500 < V_{s,30} \leq 700\,\mathrm{ms}^{-1}$. Use c_2.

Site class 3 RF exhibits peaks between 2 and $5\,\mathrm{Hz}$. Corresponds to alluvial sites with $300 < V_{s,30} \leq 500\,\mathrm{ms}^{-1}$. Use c_3.

Site class 4 RF exhibits peaks for frequencies $< 2\,\mathrm{Hz}$. Corresponds to thick soft alluvium. Use c_4.

- Only 100 records are associated with earthquakes with known focal mechanisms, 40 correspond to strike-slip/reverse, 31 to pure strike-slip, 24 to pure reverse and 4 to a pure vertical plane. Note that use of equations should be limited to sources with such mechanisms.

- Use only records for which the signal to noise ratio was acceptable.

- Source parameters from teleseismic studies available for 279 records.

- Calculate source parameters directly from the strong-motion records for the remaining 189 digital records using a source model. Hypocentral distance from S-P time and seismic moment from level of acceleration spectra plateau and corner frequency.

- Focal depths from 9 to $133\,\mathrm{km}$ but focal depth determination is very imprecise and majority of earthquakes are shallow.

- Suggest that whenever estimation of depth of earthquake is impossible use distance to surface projection of fault rather than hypocentral distance because differences between hypocentral and epicentral distances are not significant for shallow earthquakes.

- Also derive equations based only on data from the Zagros thrust fault zone (higher seismic activity rate with many earthquakes with $4 \leq M \leq 6$) and based only on data from the Alborz-Central Iran zone (lower seismic activity rate but higher magnitude earthquakes). Find some differences between regions.

- Investigate fixing d to 1 (corresponding to body waves) and to 0.5 (corresponding to surface waves).

- Note that there are very few (only two) near-field (from less than $10\,\mathrm{km}$ from surface fault rupture) records from earthquakes with $M_w > 6.0$ and so results are less certain for such combinations of magnitude and distance.

3.137 Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)

- Ground motion model is:

$$\log y = b_1 + b_2 M_s + b_3 d + b_A S_A + b_S S_S$$

  where y is in ms^{-2}, for horizontal PGA $b_1 = -0.659$, $b_2 = 0.202$, $b_3 = -0.0238$, $b_A = 0.020$, $b_S = 0.029$ and $\sigma = 0.214$ and for vertical PGA $b_1 = -0.959$, $b_2 = 0.226$, $b_3 = -0.0312$, $b_A = 0.024$, $b_S = 0.075$ and $\sigma = 0.270$.

  Assume decay associated with anelastic effects due to large strains and cannot use both $\log d$ and d because highly correlated in near field.

- Use four site categories (often use shear-wave velocity profiles):

  L Very soft soil: approximately $V_{s,30} < 180\,\mathrm{ms}^{-1}$, (combine with category S) $\Rightarrow S_A = 0, S_S = 1$, 4 records.

  S Soft soil: approximately $180 \leq V_{s,30} < 360\,\mathrm{ms}^{-1} \Rightarrow S_A = 0, S_S = 1$, 87 records.

  A Stiff soil: approximately $360 \leq V_{s,30} < 750\,\mathrm{ms}^{-1} \Rightarrow S_A = 1, S_S = 0$, 68 records.

  R Rock: approximately $V_{s,30} > 750\,\mathrm{ms}^{-1} \Rightarrow S_A = 0, S_S = 0$, 23 records.

  where $V_{s,30}$ is average shear-wave velocity to $30\,\mathrm{m}$. Know no site category for 14 records.

- Use only records from 'near field' where importance of vertical acceleration is greatest. Select records with $M_s \geq 5.8$, $d \leq 15\,\mathrm{km}$ and focal depth $h \leq 20\,\mathrm{km}$. Do not use magnitude dependent definition to avoid correlation between magnitude and distance for the records.

- Focal depths, $1 \leq h \leq 19\,\mathrm{km}$.

- Majority (133 records, 72%) of records from W. N. America, 40 records (22%) from Europe and rest from Canada, Nicaragua, Japan and Taiwan.

- Consider three source mechanisms but do not model:

  1. Normal, 8 earthquakes, 16 records.
  2. Strike-slip, 18 earthquakes, 72 records.
  3. Thrust, 16 earthquakes, 98 records.

- Use only free-field records using definition of Joyner & Boore (1981), include a few records from structures which violate this criterion but feel that structure did not affect record in period range of interest.

- Records well distributed in magnitude and distance so equations are well constrained and representative of entire dataspace. Note lack of records from normal earthquakes. Correlation coefficient between magnitude and distance is -0.10.
- Use same correction procedure (elliptical filter with pass band 0.2 to $25\,\mathrm{Hz}$, roll-off frequency $1.001\,\mathrm{Hz}$, sampling interval $0.02\,\mathrm{s}$, ripple in pass-band 0.005 and ripple in stop-band 0.015 with instrument correction) for almost all records. Use 19 records available only in corrected form as well because in large magnitude range. Think different correction procedures will not affect results.
- Try both one-stage and two-stage regression method for horizontal PGA; find large differences in b_2 but very similar b_3. Find that (by examining cumulative frequency distribution graphs for magnitude scaling of one-stage and two-stage methods) that two-stage better represents large magnitude range than one-stage method. Examine plot of amplitude factors from first stage of two-stage method against M_s; find that amplitude factor of the two Kocaeli ($M_s = 7.8$) records is far below least squares line through the amplitude factors. Remove the two Kocaeli records and repeat analysis; find b_2 from two-stage method is changed by a lot but b_2 from one-stage method is not. Conclude two-stage method is too greatly influenced by the two records from Kocaeli and hence use one-stage method.
- Find b_2 and b_3 significantly different than 0 at 5% level but b_A and b_S not significant.

3.138 Bozorgnia et al. (2000)

- Ground motion model is:

$$\begin{aligned}
\ln Y &= c_1 + c_2 M_w + c_3(8.5 - M_w)^2 \\
&\quad + c_4 \ln(\{R_s^2 + [(c_5 S_{HS} + c_6\{S_{PS} + S_{SR}\} + c_7 S_{HR}) \\
&\quad \exp(c_8 M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10} F_{SS} + c_{11} F_{RV} + c_{12} F_{TH} \\
&\quad + c_{13} S_{HS} + c_{14} S_{PS} + c_{15} S_{SR} + c_{16} S_{HR}
\end{aligned}$$

- Use four site categories:

HS Holocene soil: recent alluvium $\Rightarrow S_{HS} = 1, S_{PS} = 0, S_{SR} = 0, S_{HR} = 0$.
PS Pleistocene soil: older alluvium $\Rightarrow S_{PS} = 1, S_{HS} = 0, S_{SR} = 0, S_{HR} = 0$.
SR Soft rock $\Rightarrow S_{SR} = 1, S_{HS} = 0, S_{PS} = 0, S_{HR} = 0$.
HR Hard rock $\Rightarrow S_{HR} = 1, S_{HS} = 0, S_{PS} = 0, S_{SR} = 0$.

- Consider all records to be free-field.
- All earthquakes occurred in shallow crustal tectonic environment.
- Consider three source mechanisms: strike-slip ($F_{SS} = 1, F_{RV} = 0, F_{TH} = 0$) 20+ earthquakes (including 1+ normal faulting shock), reverse ($F_{RV} = 1, F_{SS} = 0, F_{TH} = 0$) 7+ earthquakes and thrust ($F_{TH} = 1, F_{SS} = 0, F_{RV} = 0$) 6+ earthquakes.

- Coefficients not given, only predictions.

3.139 Campbell & Bozorgnia (2000)

- Ground motion model is:

$$\begin{aligned}\ln Y &= c_1 + c_2M_w + c_3(8.5 - M_w)^2 + c_4 \ln(\{R_s^2 + [(c_5 + c_6\{S_{PS} + S_{SR}\} + c_7S_{HR}) \\ &\quad \exp(c_8M_w + c_9\{8.5 - M_w\}^2)]^2\}^{1/2}) + c_{10}F_{SS} + c_{11}F_{RV} + c_{12}F_{TH} \\ &\quad + c_{13}S_{HS} + c_{14}S_{PS} + c_{15}S_{SR} + c_{16}S_{HR}\end{aligned}$$

  where Y is in g, for horizontal uncorrected PGA $c_1 = -2.896$, $c_2 = 0.812$, $c_3 = 0$, $c_4 = -1.318$, $c_5 = 0.187$, $c_6 = -0.029$, $c_7 = -0.064$, $c_8 = 0.616$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.179$, $c_{12} = 0.307$, $c_{13} = 0$, $c_{14} = -0.062$, $c_{15} = -0.195$, $c_{16} = -0.320$ and $\sigma = 0.509$, for horizontal corrected PGA $c_1 = -4.033$, $c_2 = 0.812$, $c_3 = 0.036$, $c_4 = -1.061$, $c_5 = 0.041$, $c_6 = -0.005$, $c_7 = -0.018$, $c_8 = 0.766$, $c_9 = 0.034$, $c_{10} = 0$, $c_{11} = 0.343$, $c_{12} = 0.351$, $c_{13} = 0$, $c_{14} = -0.123$, $c_{15} = -0.138$, $c_{16} = -0.289$ and $\sigma = 0.465$, for vertical uncorrected PGA $c_1 = -2.807$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.391$, $c_5 = 0.191$, $c_6 = 0.044$, $c_7 = -0.014$, $c_8 = 0.544$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.091$, $c_{12} = 0.223$, $c_{13} = 0$, $c_{14} = -0.096$, $c_{15} = -0.212$, $c_{16} = -0.199$ and $\sigma = 0.548$ and for vertical corrected PGA $c_1 = -3.108$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.287$, $c_5 = 0.142$, $c_6 = 0.046$, $c_7 = -0.040$, $c_8 = 0.587$, $c_9 = 0$, $c_{10} = 0$, $c_{11} = 0.253$, $c_{12} = 0.173$, $c_{13} = 0$, $c_{14} = -0.135$, $c_{15} = -0.138$, $c_{16} = -0.256$ and $\sigma = 0.520$.

- Use four site categories:

  HS Holocene soil: soil deposits of Holocene age (11,000 years or less), generally described on geological maps as recent alluvium, approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $290\,\mathrm{ms}^{-1} \Rightarrow S_{HS} = 1, S_{PS} = 0, S_{SR} = 0, S_{HR} = 0$.

  PS Pleistocene soil: soil deposits of Pleistocene age (11,000 to 1.5 million years) , generally described on geological maps as older alluvium or terrace deposits, approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $370\,\mathrm{ms}^{-1} \Rightarrow S_{PS} = 1, S_{HS} = 0, S_{SR} = 0, S_{HR} = 0$.

  SR Soft rock: primarily includes sedimentary rock deposits of Tertiary age (1.5 to 100 million years), approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $420\,\mathrm{ms}^{-1} \Rightarrow S_{SR} = 1, S_{HS} = 0, S_{PS} = 0, S_{HR} = 0$.

  HR Hard rock: primarily includes older sedimentary rock deposits, metamorphic rock and crystalline rock, approximate average shear-wave velocity in top $30\,\mathrm{m}$ is $800\,\mathrm{ms}^{-1} \Rightarrow S_{HR} = 1, S_{HS} = 0, S_{PS} = 0, S_{SR} = 0$.

- Earthquakes from shallow crustal active tectonic regions.

- Most earthquakes with $6 \leq M_w \leq 7$.

- Use three source mechanism categories:

  SS Strike-slip: primarily vertical or near-vertical faults with predominantly lateral slip (includes only normal faulting earthquake in set), $\Rightarrow F_{SS} = 1, F_{RV} = 0, F_{TH} = 0$.

RV Reverse: steeply dipping faults with either reverse or reverse-oblique slip, $\Rightarrow F_{RV} = 1, F_{SS} = 0, F_{TH} = 0$.

TH Thrust: shallow dipping faults with predominantly thrust slip including blind-thrust shocks, $\Rightarrow F_{TH} = 1, F_{SS} = 0, F_{RV} = 0$.

- Consider all records to be free-field. Records from ground level in instrument shelter or a building <3 storeys high (<7 if located on hard rock). Include records from dam abutments to increase number of rock records. Exclude data from basements of buildings of any size or at toe or base of dams.

- Exclude data from $R_s > 60\,\mathrm{km}$ to avoid complicating problems related to arrival of multiple reflections from lower crust. Distance range is believed to include most ground shaking amplitudes of engineering interest, except for possibly long period spectral accelerations on extremely poor soil.

- Equations for uncorrected (Phase 1 standard level of processing) and corrected (Phase 2 standard level of processing).

- Find sediment depth (depth to basement rock) has significant effect on amplitude of ground motion and should be taken into account; it will be included once its mathematical form is better understood.

3.140 Jain et al. *(2000)*

- Ground motion model is:

$$\ln(\mathrm{PGA}) = b_1 + b_2 M + b_3 R + b_4 \ln(R)$$

  where PGA is in g, for central Himalayan earthquakes $b_1 = -4.135$, $b_2 = 0.647$, $b_3 = -0.00142$, $b_4 = -0.753$ and $\sigma = 0.59$ and for non-subduction earthquakes in N.E. India $b_1 = -3.443$, $b_2 = 0.706$, $b_3 = 0$, $b_4 = -0.828$ and $\sigma = 0.44$ (coefficients of other equations not given here because they are for a particular earthquake).

- Data from strong-motion accelerographs (SMA) and converted from structural response recorders (SRR), which consist of six seismoscopes with natural periods 0.40, 0.75 and $1.25\,\mathrm{s}$ and damping levels 5 and 10%. Conversion achieved by deriving spectral amplification factors (ratio of response ordinate and PGA) using SMA recordings close to SRR, checking that these factors were independent of distance. The mean of the six estimates of PGA (from the six spectral ordinates) from each SRR are then used as PGA values. Check quality of such PGA values through statistical comparisons and discard those few which appear inconsistent.

- Data split into four categories for which derive separate equations:

  a Central Himalayan earthquakes (thrust): (32 SMA records, 117 SRR records), 3 earthquakes with $5.5 \leq M \leq 7.0$, focal depths $10 \leq h \leq 33\,\mathrm{km}$ and $2 \leq R \leq 322\,\mathrm{km}$.

  b Non-subduction earthquakes in NE India (thrust): (43 SMA records, 0 SRR records), 3 earthquakes with $5.2 \leq M \leq 5.9$, focal depths $33 \leq h \leq 49\,\mathrm{km}$ and $6 \leq R \leq 243\,\mathrm{km}$.

  c Subduction earthquakes in NE India: (33 SMA records, 104 SRR records), 1 earthquake with $M = 7.3$, focal depth $h = 90\,\mathrm{km}$ and $39 \leq R \leq 772\,\mathrm{km}$.

  d Bihar-Nepal earthquake in Indo-Gangetic plains (strike-slip): (0 SMA records, 38 SRR records), 1 earthquake with $M = 6.8$, focal depth $h = 57\,\mathrm{km}$ and $42 \leq R \leq 337\,\mathrm{km}$.

- Limited details of fault ruptures so use epicentral distance.
- Use epicentral locations which give best correlation between distance and PGA.
- Find PGA not well predicted by earlier equations.
- Simple model and regression method because of limited data.
- Remove one PGA value from category b equation because significantly affecting equation and because epicentral location only approximate.
- Constrain b_3 for category b equation to zero because otherwise positive.
- Category c originally contained another earthquake (14 SMA records, $M = 6.1$, $200 \leq d \leq 320\,\mathrm{km}$) but gave very small b_2 so exclude it.
- Equations for category c and category d have b_2 equal to zero because only one earthquake.
- Find considerable differences between predicted PGA in different regions.
- Note lack of data hence use equations only as first approximation.

3.141 Kobayashi et al. (2000)

- Ground motion model is:

$$\log_{10} y = aM - bx - \log(x + c10^{dM}) + eh + S_k$$

where h is focal depth, y is in cms^{-2}, $a = 0.578$, $b = 0.00355$, $e = 0.00661$, $S = -0.069$, $S_R = -0.210$, $S_H = -0.114$, $S_M = 0.023$, $S_S = 0.237$ and $\sigma_T = \sqrt{\sigma^2 + \tau^2}$ where $\sigma = 0.213$ and $\tau = 0.162$.

- Use four site categories (most data from medium and hard soils):

$S_k = S_R$ Rock
$S_k = S_H$ Hard soil
$S_k = S_M$ Medium soil
$S_k = S_S$ Soft soil

S is the mean site coefficient, i.e. when do not consider site category.

- Records interpolated in frequency domain from 0.02 to $0.005\,\mathrm{s}$ interval and displacement time history calculated using a fast Fourier transform (FFT) method having perpended to beginning and appended to end at least $5\,\mathrm{s}$ of zeros to record. Number of samples in FFT is large enough that duration used in FFT is at least twice that of selected duration for processing window so that numerical errors are small. Bandpass Ormsby filter used, with limits 0.2 and $24.5\,\mathrm{Hz}$, and displacement time history plotted. If displacement in pre- and appended portions is large then increase lower frequency limit in filter until displacements are small, using smoothed Fourier spectral amplitudes from 0.05 to $25\,\mathrm{Hz}$ to make choice.

- Most earthquakes are intra-slab.

- Note lack of near-field data for all magnitudes, most data from $> 100\,\mathrm{km}$, therefore use coefficients, c and d, from an early study.

- Excludes data from distances greater than the distance at which an earlier study predicts $\mathrm{PGA} < 0.02\,\mathrm{ms}^{-2}$.

- Consider residuals of earthquakes in western Japan (a small subset of data) and find small difference in anelastic coefficient and focal depth coefficient but note may be due to small number of records or because type of source not modelled.

- Note model predicts intraslab motions well but significantly over predicts interface motions.

- Plots site correction factors (difference between individual site factor and mean factor for that category) and find rock sites have largest variation, which suggest due to hard and soft rock included.

- Examine residual plots. Find no significant bias.

3.142 Monguilner et al. (2000a)

- Ground motion model is:

$$\log a_m = C_0' + C_1 M + C_2 \Delta + C_3 \log \Delta + C_4' S_r$$

  where $\Delta = \sqrt{\mathrm{DE}^2 + H^2 + S^2}$, DE is epicentral distance, H is focal depth, S is fault area and $C_0' = -1.23$, $C_1 = 0.068$, $C_2 = -0.001$ and $C_3 = -0.043$ (σ is not given). Note that there are typographical inconsistencies in the text, namely S_r maybe should be replaced by S_{al}.

- Use two site categories (based on Argentinean seismic code):

$S_r = 1$ Stiff soil (II$_\mathrm{A}$).

$S_r = 0$ Intermediate stiff soil (II$_\mathrm{B}$).

Since there is no geotechnical data available, classify sites, assuming a uniform surface layer, using the predominant period of ground motions estimated using Fourier spectra to get an equivalent shear-wave velocity (mainly these are between 100 and $400\,\mathrm{ms}^{-1}$).

- Records from instruments located in basements or ground floors of relatively small buildings.
- Records from SMAC and SMA-1 instruments.
- Uniform digitisation and correction procedure applied to all records to reduce noise in high and low frequency range.
- Calculate fault area using $\log S = M_s + 8.13 - 0.6667 \log(\sigma \Delta\sigma/\mu)$ where $\Delta\sigma$ is stress drop, σ is average stress and μ is rigidity.
- Most magnitudes between 5.5 and 6.0.
- Most records from $\mathrm{DE} < 100\,\mathrm{km}$.
- Most focal depths, $H \leq 40\,\mathrm{km}$. One earthquake with $H = 120\,\mathrm{km}$.
- Use weighted regression because of a correlation between magnitude and distance of 0.35. Weight each record by $\omega_i = (\omega_M + \omega_{\mathrm{DH}})/2$ where (note there are typographical errors in formulae in paper):

$$\begin{aligned}
\omega_M &= \frac{n_s(i_s)\Delta M(n_i) n_e(n_i, i_s)\Delta M_T}{n_{\mathrm{cat}}} \\
\omega_{\mathrm{DH}} &= \frac{n_s(i_s)\Delta \log \mathrm{DH}(n_i) n_e(n_i, i_s)\Delta \log \mathrm{DH}_T}{n_{\mathrm{cat}}} \\
\Delta M_T &= \frac{\sum \Delta M(n_i)}{n_{\mathrm{cat}}} \\
\Delta \log \mathrm{DH}_T &= \frac{\sum \Delta \log \mathrm{DH}(n_i)}{n_{\mathrm{cat}}}
\end{aligned}$$

  where $\Delta M(n_i)$ is the width of the n_ith magnitude interval and $\Delta \log \mathrm{DH}(n_i)$ is the width of the n_ith distance interval, n_{cat} is total number of intervals, n_i the index of the interval, $n_e(n_i, i_s)$ is the number of records in interval n_i from site classification i_s and n_s is the number of records from site classification i_s. Use two site classifications, three magnitude intervals and four epicentral distance intervals so $n_{\mathrm{cat}} = 2 \times 3 \times 4 = 24$.
- First do regression on $\log a_i = C_0 + C_1 M + C_2 \Delta + C_3 \log \Delta$ and then regress residuals, ϵ_i, against $C_4 S_r + C_5 S_{al}$ where $S_{al} = 1$ if site is intermediate stiff soil and $S_{al} = 0$ otherwise. Then $C_0' = C_0 + C_5$ and $C_4' = C_4 + C_5$. Similar method to that used by Ambraseys *et al.* (1996).

3.143 Sharma (2000)

- Based on Sharma (1998), see 3.128.
- A is in g and coefficients are: $c_1 = -2.87$, $c_2 = 0.634$, $c_3 = 0.62$, $b = 1.16$ and $\sigma = 0.142$.
- Fit $\log A = -b \log X + c$ to data from each earthquake separately and find average b equal to 1.18. Then fit $\log A = aM - b \log X + c$ to data from all earthquakes and find $b = 0.405$. Fit $\log A = -b \log X + \sum d_i l_i$ to all data, where $l_i = 1$ for ith earthquake and 0 otherwise and find $b = 1.16$, use this for rest of analysis.

3.144 Si & Midorikawa (2000)

- Ground motion model for rupture distance is:

  $$\log A = aM_w + hD + \sum d_i S_i + e - \log(X + c_1 10^{c_2 M_w}) - kX$$

  where A is in cms^{-2}, $a = 0.50$, $h = 0.0036$, $d_1 = 0$, $d_2 = 0.09$, $d_3 = 0.28$, $e = 0.60$, $k = 0.003$ and $\sigma = 0.27$ (c_1 and c_2 are not given).

  Ground motion model for equivalent hypocentral distance (EHD) is:

  $$\log A = aM_w + hD + \sum d_i S_i + e - \log X_{eq} - kX_{eq}$$

  where A is in cms^{-2}, $a = 0.50$, $h = 0.0043$, $d_1 = 0$, $d_2 = 0.01$, $d_3 = 0.22$, $e = 0.61$, $k = 0.003$ and $\sigma = 0.28$.

- Use two site categories for most records following Joyner & Boore (1981):

  1. Rock
  2. Soil

- Records from free-field or small buildings where soil-structure interaction effects are negligible.

- Records from three different type of instrument so instrument correct. Filter with corner frequencies, chosen according to noise level, a) 0.08 & $0.15\,\mathrm{Hz}$, b) 0.10 & $0.20\,\mathrm{Hz}$ or c) 0.15 to $0.33\,\mathrm{Hz}$.

- Exclude records obviously affected by soil liquefaction.

- Focal depth (defined as average depth of fault plane), D, between 6 and $120\,\mathrm{km}$; most less than $40\,\mathrm{km}$.

- Select records satisfying: distances $< 300\,\mathrm{km}$ for $M_w > 7$, distances $< 200\,\mathrm{km}$ for $6.6 \leq M_w \leq 7$, distances $< 150\,\mathrm{km}$ for $6.3 \leq M_w \leq 6.5$ and distances $< 100\,\mathrm{km}$ for $M_w < 6.3$.

- Fix $k = 0.003$.

- Multiply rock PGAs by 1.4 to get soil PGA based on previous studies.

- Use three fault types: crustal (<719 records from 9 earthquakes) $\Rightarrow S_1 = 1, S_2 = 0, S_3 = 0$, inter-plate (<291 records from 7 earthquakes) $\Rightarrow S_2 = 1, S_1 = 0, S_3 = 0$ and intra-plate (<127 records from 5 earthquakes) $\Rightarrow S_3 = 1, S_1 = 0, S_2 = 0$.

- Use weighted regression giving more weight to near-source records (weight factor of 8 for records $< 25\,\mathrm{km}$, 4 for records between 20 and $50\,\mathrm{km}$, 2 for records between 50 and $100\,\mathrm{km}$ and 1 for records $> 100\,\mathrm{km}$). Use only three earthquakes with sufficient near-source data to find c_1 and c_2 then use all earthquakes to find a, h, d_i, e in second stage using weighted regression dependent on number of recordings for each earthquake (weight factor of 3 for >83 records, 2 for between 19 and 83 records, 1 for <19 records.

- Note that M_w and D are positively correlated so a and h may not be correctly determined when using rupture distance. Constrain a for rupture distance model to that obtained for EHD and constrain PGA to be independent of magnitude at $0\,\mathrm{km}$ and repeat regression. Coefficients given above.

3.145 Smit et al. (2000)

- Ground motion model is:

$$\begin{aligned}\log Y &= a + bM - \log R + dR \\ \text{where } T &= \sqrt{D^2 + h^2}\end{aligned}$$

  where Y is in cms^{-2}, $a = 0.72$, $b = 0.44$, $d = -0.00231$, $h = 4.5$ and $\sigma = 0.28$.

- Records from soil or alluvium sites.

- All records corrected.

- Note that scatter can be reduced by increasing number of records used (especially in near field), improving all seismological and local site parameters and increasing number of variables (especially in near field and those modelling local site behaviour) but that this requires much more information than is available.

3.146 Takahashi et al. (2000)

- Ground motion model is:

$$\log_{10}[y] = aM - bx - \log_{10}(x + c10^{dM}) + e(h - h_c)\delta_h + S_k$$

  where y is in cms^{-2}, $a = 0.446$, $b = 0.00350$, $c = 0.012$, $d = 0.446$, $e = 0.00665$, $S = 0.941$, $S_R = 0.751$, $S_H = 0.901$, $S_M = 1.003$, $S_S = 0.995$, $\sigma_T = \sqrt{\sigma^2 + \tau^2}$ where $\sigma = 0.135$ (intra-event) and $\tau = 0.203$ (inter-event), h_c is chosen as $20\,\mathrm{km}$ because gave positive depth term.

- Use four site categories:

$S_k = S_R$ Rock

$S_k = S_H$ Hard soil

$S_k = S_M$ Medium soil

$S_k = S_S$ Soft soil

  Note site conditions for many stations are uncertain. S is the mean site term for all data.

- Note ISC focal depths, h, significant reduce prediction errors compared with JMA depths. $\delta_h = 1$ for $h \geq h_c$ and $\delta_h = 0$ otherwise.

- Most Japanese data from $x > 50\,\mathrm{km}$.
- Use 166 Californian and Chilean (from 2 earthquakes) records to control model in near source.
- Due to lack of multiple records from many sites and because c and d require near-source records use a maximum likelihood regression method of two steps. Firstly, find all coefficients using all data except those from sites with only one record associated with them and unknown site class. Next, use individual site terms for all sites so as to reduce influence of uncertainty because of approximate site classifications and find a, b, e and site terms using c and d from first step.
- Intra-event and inter-event residuals decrease with increasing magnitude.
- Conclude variation in residuals against distance is due to small number of records at short and large distances.
- Individual site factors means prediction error propagates into site terms when number of records per station is very small.
- Note model may not be suitable for seismic hazard studies because model prediction errors are partitioned into σ_T and mean site terms for a given site class. Suitable model can be derived when accurate site classifications are available.

3.147 Wang & Tao (2000)

- Ground motion model is:

$$\log Y = C + (\alpha + \beta M)\log(R + R_0)$$

  where Y is in cms^{-2}, $C = 4.053$, $\alpha = -2.797$, $\beta = 0.251$, $R_0 = 8.84$ and $\sigma = 0.257$.

- Use same data as Joyner & Boore (1981), see Section 3.27.
- Use a two-stage method based on Joyner & Boore (1981). Firstly fit data to $\log Y = C + \sum_{i=1}^{n}(a_i E_i)\log(R_i + R_0)$, where $E_i = 1$ for records from ith earthquake and $E_i = 0$ otherwise, to find C and a_i for each earthquake. Next fit $a = \alpha + \beta M$ to find α and β using a_i from first stage.

3.148 Chang *et al.* (2001)

- Ground motion model for shallow crustal earthquakes is:

$$\ln A = c_1 + c_2 M - c_3 \ln D_p - (c_4 - c_5 D_p)\ln D_e$$

  where A is in cms^{-2}, $c_1 = 2.8096$, $c_2 = 0.8993$, $c_3 = 0.4381$, $c_4 = 1.0954$, $c_5 = 0.0079$ and $\sigma = 0.60$.

  Ground motion model for subduction earthquakes is:

$$\ln A = c_1' + c_2' M - c_3' \ln D_p - c_4' \ln D_h$$

  where A is in cms^{-2}, $c_1' = 4.7141$, $c_2' = 0.8468$, $c_3' = 0.17451$, $c_4' = 1.2972$ and $\sigma = 0.56$.

- Note that there is limited site information available for strong-motion stations in Taiwan so do not consider local site effects.
- Use strong-motion data from Central Weather Bureau from 1994 to 1998 because it is more numerous and of better quality than older data.
- Separate earthquakes into shallow crustal and subduction earthquakes because of different seismic attenuation and seismogenic situation for the two types of earthquake.
- Shallow crustal earthquakes are mostly due to continental deformation, shallow collision or back-arc opening or are the uppermost interface earthquakes. Focal depths depth between 1.1 and $43.7\,\mathrm{km}$ with most shallower than $20\,\mathrm{km}$. Most records from earthquakes with $4.5 \leq M_w \leq 6.0$.
- Subduction earthquakes are located in the Wadati-Benioff zone or the deep lateral collision zone and are principally intraslab. Focal depth between 39.9 and $146.4\,\mathrm{km}$.
- Do not use records from earthquakes associated with coseismic rupture because they have complex near-field source effects.
- To avoid irregularly large amplitudes at great distances reject distant data predicted to be less than trigger level plus 1 standard deviation using this threshold formula: $aM_w - b\ln D + c \geq \ln V$, where V is geometric mean of PGA equal to threshold plus 1 standard deviation. For shallow crustal earthquakes: $a = 0.64$, $b = 0.83$, $c = 2.56$ and $V = 6.93$ and for subduction earthquakes: $a = 0.76$, $b = 1.07$, $c = 3.13$ and $V = 6.79$.
- For shallow crustal earthquakes examine effect of focal depth on seismic attenuation by finding geometric attenuation rate using epicentral distance, D_e, for earthquakes with $5\,\mathrm{km}$ depth intervals. Find that deeper earthquakes have slower attenuation than shallow earthquakes. Therefore assume ground motion, A, is product of f_{source} (source effects) and $f_{\mathrm{geometrical-spreading}}$ (geometrical spreading effects) where $f_{\mathrm{source}} = C_1 \exp(c_2 M)/D_p^{-c_3}$ and $f_{\mathrm{geometrical-spreading}} = D_e^{-(c_4 - c_5 D_p)}$ where D_p is focal depth.
- For subduction earthquakes examine effect of focal depth in the same way as done for shallow crustal earthquakes but find no effect of focal depth on attenuation rate. Therefore use $f_{\mathrm{geometrical-spreading}} = D_h^{-c_4}$.
- Plot residuals of both equations against distance and find no trend.
- Note that it is important to separate subduction and shallow crustal earthquakes because of the different role of focal depth and attenuation characteristics.
- Plot residual maps of ground motion for Taiwan and find significant features showing the important effect of local structures on ground motion.

3.149 Lussou et al. (2001)

- Ground motion model is:

  $$\log \mathrm{PSA}(f) = a(f)M + b(f)R - \log R + c(i, f)$$

  where $\mathrm{PSA}(f)$ is in cms^{-2}, $a(f) = 3.71 \times 10^{-1}$, $b(f) = -2.54 \times 10^{-3}$, $c(A, f) = 0.617$, $c(B, f) = 0.721$, $c(C, f) = 0.845$, $c(D, f) = 0.891$ and $\sigma = 3.13 \times 10^{-1}$.

- Use four site categories, based on $V_{s,30}$ (average shear-wave velocity in top $30\,\mathrm{m}$) as proposed in Eurocode 8:

  A $V_{s,30} > 800\,\mathrm{ms}^{-1}$. Use $c(A, f)$. 14 records.
  B $400 < V_{s,30} \leq 800\,\mathrm{ms}^{-1}$. Use $c(B, f)$. 856 records.
  C $200 < V_{s,30} \leq 400\,\mathrm{ms}^{-1}$. Use $c(C, f)$. 1720 records.
  D $100 < V_{s,30} \leq 200\,\mathrm{ms}^{-1}$. Use $c(D, f)$. 421 records.

- Good determination of site conditions between shear-wave velocities have been measured down to 10 to $20\,\mathrm{m}$ at every site. Extrapolate shear-wave velocity data to $30\,\mathrm{m}$ to find $V_{s,30}$. $V_{s,30}$ at stations is between about $50\,\mathrm{ms}^{-1}$ and about $1150\,\mathrm{ms}^{-1}$.

- Use data from Kyoshin network from 1996, 1997 and 1998.

- All data from free-field sites.

- No instrument correction needed or applied.

- Use data from earthquakes with $M_{\mathrm{JMA}} > 3.5$ and focal depth $< 20\,\mathrm{km}$ because want to compare results with Ambraseys *et al.* (1996) and Boore *et al.* (1997). Also this criteria excludes data from deep subduction earthquakes and data that is not significant for seismic hazard studies.

- Homogeneous determination of JMA magnitude and hypocentral distance.

- Roughly uniform distribution of records with magnitude and distance.

- Assume pseudo-spectral acceleration for 5% damping at $0.02\,\mathrm{s}$ equals PGA.

- Note equation valid for $3.5 \leq M_{\mathrm{JMA}} \leq 6.3$ and $10 \leq d_h \leq 200\,\mathrm{km}$.

- Find inclusion of site classification has reduced standard deviation.

3.150 Chen & Tsai (2002)

- Ground motion model is:

  $$\log_{10} \mathrm{PGA} = \theta_0 + \theta_1 M + \theta_2 M^2 + \theta_3 R + \theta_4 \log_{10}(R + \theta_5 10^{\theta_6 M})$$

where PGA is in cms^{-2}, $\theta_0 = -4.366 \pm 2.020$, $\theta_1 = 2.540 \pm 0.714$, $\theta_2 = -0.172 \pm 0.0611$, $\theta_3 = 0.00173 \pm 0.000822$, $\theta_4 = -1.845 \pm 0.224$, $\theta_5 = 0.0746 \pm 0.411$, $\theta_6 = 0.221 \pm 0.405$, $\sigma_e^2 = 0.0453 \pm 0.0113$ (earthquake-specific variance), $\sigma_s^2 = 0.0259 \pm 0.00699$ (site-specific variance) and $\sigma_r^2 = 0.0297 \pm 0.00235$ (record-specific variance). ± signifies the estimated standard errors.

- Records from 45 stations on rock and firm soil. All sites have more than two records.
- Use a new estimation procedure where the residual variance is decomposed into components due to various source of deviations. Separate variance into earthquake-to-earthquake variance, site-to-site variance and the remainder.
- Proposed method does not require additional regression or searching procedures.
- Perform a simulation study and find proposed procedure yields estimates with smaller biases and take less computation time than do other similar regression techniques.
- Visually examine the equation for various magnitude values before regressing.

3.151 Gregor et al. (2002)

- Ground motion model is (their model D):

$$\ln \mathrm{GM} = \theta_1+\theta_2 M+(\theta_3+\theta_4 M)\ln[D+\exp(\theta_5)]+\theta_6(1-S)+\theta_7(M-6)^2+\theta_8 F+\theta_9/\tanh(D+\theta_{10})$$

where GM is in g, $\theta_1 = 4.31964$, $\theta_2 = -0.00175$, $\theta_3 = -2.40199$, $\theta_4 = 0.19029$, $\theta_5 = 2.14088$, $\theta_6 = 0.09754$, $\theta_7 = -0.21015$, $\theta_8 = 0.38884$, $\theta_9 = -2.29732$, $\theta_{10} = 448.88360$, $\sigma = 0.5099$ (intra-event) and $\tau = 0.4083$ (inter-event) for horizontal PGA using the static dataset without the Chi-Chi data and $\theta_1 = 1.50813$, $\theta_2 = 0.15024$, $\theta_3 = -2.52562$, $\theta_4 = 0.17143$, $\theta_5 = 2.12429$, $\theta_6 = 0.10517$, $\theta_7 = -0.16655$, $\theta_8 = 0.22243$, $\theta_9 = -0.11214$, $\theta_{10} = 19.85830$, $\sigma = 0.5141$ (intra-event) and $\tau = 0.4546$ (inter-event) for vertical PGA using the static dataset without the Chi-Chi data. Coefficients are also given for the three other models and for both the dynamic and the static datasets but are not reported here due to lack of space.

- Use two site categories:

$S = 0$ Soil: includes sites located on deep broad and deep narrow soil deposits.

$S = 1$ Rock: includes sites that are located on shallow stiff soil deposits;

- Use three rupture mechanism categories:

$F = 0$ Strike-slip, 39 earthquakes, 387 records;

$F = 0.5$ Reverse/oblique, 13 earthquakes, 194 records;

$F = 1$ Thrust, 16 earthquakes, 412 records.

- Process records using two procedures as described below.

1. Use the standard PEER procedure with individually chosen filter cut-offs.
2. Fit the original integrated velocity time-history with three different functional forms (linear in velocity; bilinear, piecewise continuous function; and quadratic in velocity). Choose the 'best-fit' result and view it for reasonableness. Differentiate the velocity time-history and then low-pass filter with a causal Butterworth filter with cut-offs about $50\,\mathrm{Hz}$.

- PGA values from the two processing techniques are very similar.
- Investigate using a nonlinear model for site response term but the resulting models did not improve the fit.
- Also try three other functional forms:

$$\begin{aligned}\ln(\mathrm{GM}) &= \theta_1+\theta_2 M+\theta_3\ln[D+\theta_4\exp(\theta_5 M)]+\theta_6(1-S)+\theta_7 F \quad \text{model A}\\ \ln(\mathrm{GM}) &= \theta_1+\theta_2 M+(\theta_3+\theta_4 M)\ln[D+\exp(\theta_5)]+\theta_6(1-S)+\theta_7(M-6)^2+\theta_8 F \quad \text{model B}\\ \ln(\mathrm{GM}) &= \theta_1+\theta_2 M+\theta_3\ln[D+\exp(\theta_5 M)]+\theta_6(1-S)+\theta_7 F+\theta_8/\tanh(D+\theta_9) \quad \text{model C}\end{aligned}$$

  which all give similar standard deviations and predictions but prefer model D.

- Models oversaturate slightly for large magnitudes at close distances. Therefore recommend that the PGA equations are not used because this oversaturation is based on very little data.
- Because the Chi-Chi short period ground motions may be anomalous relative to California they develop equations including and excluding the Chi-Chi data, which only affects predictions for large magnitudes ($M > 7.5$).

3.152 Gülkan & Kalkan (2002)

- Ground motion model is:

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

  where Y is in g, $b_1=-0.682$, $b_2=0.253$, $b_3=0.036$, $b_5=-0.562$, $b_V=-0.297$, $V_A=1381$, $h=4.48$ and $\sigma=0.562$.

- Use three site categories:

Soft soil	Average shear-wave velocity, V_S, is $200\,\mathrm{ms}^{-1}$. 40 records.
Soil	Average shear-wave velocity, V_S, is $400\,\mathrm{ms}^{-1}$. 24 records.
Rock	Average shear-wave velocity, V_S, is $700\,\mathrm{ms}^{-1}$. 29 records.

  Actual shear-wave velocities and detailed site descriptions are not available for most stations in Turkey. Therefore estimate site classification by analogy with information in similar geologic materials. Obtain type of geologic material in number of ways: consultation with geologists at Earthquake Research Division of Ministry of Public Works and Settlement, various geological maps, past earthquake reports and geological references prepared for Turkey.

- Only used records from small earthquakes recorded at closer distances than large earthquakes to minimize the influence of regional differences in attenuation and to avoid the complex propagation effects coming from longer distances.
- Only use records from earthquakes with $M_w \gtrsim 5.0$ to emphasize ground motions of engineering significance and to limit analysis to more reliably recorded earthquakes.
- During regression lock magnitudes within ± 0.25 magnitude unit bands centred at halves or integer magnitudes to eliminate errors coming from magnitude determination.
- Note that use of epicentral distance for small earthquakes does not introduce significant bias because dimensions of rupture area of small earthquakes are usually much smaller than distance to recording stations.
- Examine peak ground motions from the small number of normal- (14 records) and reverse-faulting (6 records) earthquakes in set and find that they were not significantly different from ground motions from strike-slip earthquakes (73 records). Therefore combine all data.
- Records mainly from small buildings built as meteorological stations up to three stories tall. Note that this modifies the recorded accelerations and hence increases the uncertainty.
- Exclude data from aftershocks (mainly of the Kocaeli and Duzce earthquakes) because it was from free-field stations and did not want to mix it with the data from the non-free-field records.
- Exclude a few records for which PGA of mainshock is $\lesssim 0.04\,\mathrm{g}$.
- Note that there is limited data and the data is poorly distributed. Also note that there is near-total lack of knowledge of local geology and that some of the records could be affected by the building in which the instrument was housed.
- More than half the records (49 records, 53% of total) are from two $M_w > 7$ earthquakes (Kocaeli and Duzce) so the results are heavily based on the ground motions recorded in these two earthquakes.

3.153 Khademi (2002)

- Ground motion model is:

  $$Y = C_1 \exp(C_2 M)((R + C_3 \exp(C_4 M))^{C_5}) + C_6 S$$

  where Y is in g, $C_1 = 0.040311$, $C_2 = 0.417342$, $C_3 = 0.001$, $C_4 = 0.65$, $C_5 = -0.351119$ and $C_6 = -0.035852$ for horizontal PGA and $C_1 = 0.0015$, $C_2 = 0.8548$, $C_3 = 0.001$, $C_4 = 0.4$, $C_5 = -0.463$ and $C_6 = 0.0006$ for vertical PGA.
- Uses two site categories:

$S = 0$ Rock, site categories I and II of Iranian building code.

$S = 1$ Soil, site categories III and IV of Iranian building code.

- Selection criteria are: i) causative earthquake, earthquake fault (if known) and respective parameters are determined with reasonable accuracy, ii) PGA of at least one component $>$ $50\,\mathrm{gal}$, iii) records from free-field conditions or ground level of low-rise buildings (¡ three stories), iv) some aftershocks have been eliminated to control effect of a few large earthquakes and v) records have been processed with acceptable filter parameters.

- Regresses directly on Y not on logarithm of Y. Therefore does not calculate standard deviation in normal way. Considers the deviation of individual records from predictive equations as being PGA dependent. Finds that a sigmoidal model fits the data well. Therefore $Y = (ab + cx^d)/(b + x^d)$ where Y is the error term and x is the predicted ground motion, $a = 0.038723$, $b = 0.00207$, $c = 0.29094$ and $d = 4.97132$ for horizontal PGA and $a = 0.00561$, $b = 0.0164$, $c = 0.1648$ and $d = 1.9524$ for vertical PGA.

3.154 *Margaris* et al. *(2002a) & Margaris* et al. *(2002b)*

- Ground motion model is:

$$\ln Y = c_0 + c_1 M_w + c_2 \ln(R + R_0) + c_3 S$$

  where Y is in cms^{-2}, $c_0 = 4.16$, $c_1 = 0.69$, $c_2 = -1.24$, $R_0 = 6$, $c_3 = 0.12$ and $\sigma = 0.70$.

- Use three site categories:

$S = 0$ NEHRP and UBC category B. 145 records.

$S = 1$ NEHRP and UBC category C. 378 records.

$S = 2$ NEHRP and UBC category D. 221 records.

- Selection criteria are: a) earthquake has $M_w \geq 4.5$, b) $\mathrm{PGA} \geq 0.05\,\mathrm{g}$ and c) $\mathrm{PGA} < 0.05\,\mathrm{g}$ but another record from same earthquake has $\mathrm{PGA} \geq 0.05\,\mathrm{g}$.

- Records mainly from normal faulting earthquakes.

- Exclude data recorded in buildings with four stories or higher.

- Automatically digitize records and process records homogenously, paying special attention to the filters used.

- Correlation between M_w and R in set of records used. For $4.5 \leq M_w \leq 5.0$ records exist at $R \leq 40\,\mathrm{km}$ and for larger magnitudes records exist at intermediate and long distances. For $M_w > 6.0$ there is a lack of records for $R < 20\,\mathrm{km}$.

- Use a two step regression method. In first step use all records to find c_1. In second step use records from earthquakes with $M_w \geq 5.0$ to find c_0, c_2 and c_3.

- Adopt $R_0 = 6\,\mathrm{km}$ because difficult to find R_0 via regression due to its strong correlation with c_2. This corresponds to average focal depth of earthquakes used.

- Also try ground motion model: $\ln Y = c_0' + c_1' M_w + c_2' \ln(R^2 + h_0^2)^{1/2} + c_3' S$. Coefficients are: $c_0' = 3.52$, $c_1' = 0.70$, $c_2' = -1.14$, $h_0 = 7\,\mathrm{km}$ (adopted), $c_3' = 0.12$ and $\sigma = 0.70$.
- Find no apparent trends in residuals w.r.t. distance.
- Due to distribution of data, equations valid for $5 \leq R \leq 120\,\mathrm{km}$ and $4.5 \leq M_w \leq 7.0$.

3.155 Schwarz et al. *(2002)*

- Ground motion model is:

$$\begin{aligned} \log_{10} a_{H(V)} &= c_1 + c_2 M_L + c_4 \log_{10}(r) + c_R S_R + c_A S_A + c_S S_S \\ \text{where } r &= \sqrt{R_e^2 + h_0^2} \end{aligned}$$

  where $a_{H(V)}$ is in g, $c_1 = -3.0815$, $c_2 = 0.5161$, $c_4 = -0.9501$, $c_R = -0.1620$, $c_A = -0.1078$, $c_S = 0.0355$, $h_0 = 2.0$ and $\sigma = 0.3193$ for horizontal PGA and $c_1 = -2.8053$, $c_2 = 0.4858$, $c_4 = -1.1842$, $c_R = -0.1932$, $c_A = -0.0210$, $c_S = 0.0253$, $h_0 = 2.5$ and $\sigma = 0.3247$ for vertical PGA.

- Use three site categories:

  R Rock, subsoil classes A1, (A2) $V_s > 800\,\mathrm{ms}^{-1}$ (according to E DIN 4149) or subsoil class B (rock) $760 < V_s \leq 1500\,\mathrm{ms}^{-1}$ (according to UBC 97). $S_R = 1$, $S_A = 0$, $S_S = 0$. 59 records.

  A Stiff soil, subsoil classes (A2), B2, C2 $350 \leq V_s \leq 800\,\mathrm{ms}^{-1}$ (according to E DIN 4149) or subsoil class C (very dense soil and soft rock) $360 < V_s \leq 760\,\mathrm{ms}^{-1}$ (according to UBC 97). $S_A = 1$, $S_R = 0$, $S_S = 0$. 88 records.

  S Soft soil, subsoil classes A3, B3, C3 $V_s < 350\,\mathrm{ms}^{-1}$ (according to E DIN 4149) or subsoil class D (stiff clays and sandy soils) $180 < V_s \leq 360\,\mathrm{ms}^{-1}$ (according to UBC 97). $S_S = 1$, $S_R = 0$, $S_A = 0$. 536 records.

  KOERI stations classified using UBC 97 and temporary stations of German TaskForce classified using new German code E DIN 4149. Classify temporary stations of German TaskForce using microtremor H/V spectral ratio measurements by comparing shapes of H/V spectral ratios from microtremors to theoretical H/V spectral ratios as well as with theoretical transfer functions determined for idealized subsoil profiles.

- Use Kocaeli aftershock records from temporary German TaskForce stations (records from earthquakes with $1 \lesssim M_L < 4.9$ and distances $R_e < 70\,\mathrm{km}$, 538 records) and from mainshock and aftershocks records from Kandilli Observatory (KOERI) stations ($4.8 \leq M_L \leq 7.2$ and distances $10 \leq R_e \leq 250\,\mathrm{km}$, 145 records).
- Visually inspect all time-histories and only use those thought to be of sufficiently good quality.
- Baseline correct all records.

- Use technique of Ambraseys *et al.* (1996) to find the site coefficients c_R, c_A and c_S, i.e. use residuals from regression without considering site classification.
- Note that equations may not be reliable for rock and stiff soil sites due to the lack of data and that equations probably only apply for $2 \leq M_L \leq 5$ due to lack of data from large magnitude earthquakes.

3.156 Stamatovska (2002)

- Ground motion model is:

$$\ln \mathrm{PGA} = b' + b_M M + b_R \ln \left\{ \left[\left(\frac{R_e}{\rho} \right)^2 + h^2 \right]^{1/2} + C \right\}$$

  where PGA is in cms^{-2}. For Bucharest azimuth $b' = -0.21056$, $b_M = 1.29099$, $b_R = -0.80404$, $C = 40$ and $\sigma = 0.52385$, for Valeni azimuth $b' = -1.52412$, $b_M = 1.42459$, $b_R = -0.70275$, $C = 40$ and $\sigma = 0.51389$ and for Cherna Voda $b' = 4.16765$, $b_M = 1.11724$, $b_R = -1.44067$, $C = 40$ and $\sigma = 0.47607$.
- Focal depths, h, between 89 and $131\,\mathrm{km}$.
- Incomplete data on local site conditions so not included in study.
- Some strong-motion records are not from free-field locations.
- Uses ρ to characterise the non-homogeneity of region. Includes effect of instrument location w.r.t. the main direction of propagation of seismic energy, as well as the non-homogeneous attenuation in two orthogonal directions. $\rho = \sqrt{(1 + tg^2\alpha)/(a^{-2} + tg^2\alpha)}$ where α is angle between instrument and main direction of seismic energy or direction of fault projection on surface and a is parameter defining the non-homogeneous attenuation in two orthogonal directions, or relation between the semi-axes of the ellipse of seismic field.
- Uses a two step method. In first step derive equations for each earthquake using $\ln \mathrm{PGA} = b'_0 + b_1 \ln(R_e/\rho)$. In the second step the complete ground motion model is found by normalizing separately for each earthquake with a value of ρ defined for that earthquake according to the location for which the equation was defined.
- Notes that there is limited data so coefficients could be unreliable.
- Strong-motion records processed by different institutions.

3.157 Tromans & Bommer (2002)

- Ground motion model is:

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

where y is in cms^{-2}, $C_1 = 2.080$, $C_2 = 0.214$, $h_0 = 7.27$, $C_4 = -1.049$, $C_A = 0.058$, $C_S = 0.085$ and $\sigma = 0.27$.

- Use three site categories:

  S Soft soil, $V_{s,30} \leq 360\,\mathrm{ms}^{-1}$. $S_S = 1$, $S_A = 0$. 25% of records.

  A Stiff soil, $360 < V_{s,30} < 750\,\mathrm{ms}^{-1}$. $S_A = 1$, $S_S = 0$. 50% of records.

  R Rock, $V_{s,30} \geq 750\,\mathrm{ms}^{-1}$. $S_S = 0$, $S_A = 0$. 25% of records.

  If no $V_{s,30}$ measurements at station then use agency classifications.

- Supplement dataset of Bommer *et al.* (1998) with 66 new records using same selection criteria as Bommer *et al.* (1998) with a lower magnitude limit of $M_s = 5.5$. Remove 3 records from Bommer *et al.* (1998) with no site classifications.

- Roughly uniform distribution of records w.r.t. magnitude and distance. New data contributes significantly to large magnitude and near-field ranges.

- Correct records using an elliptical filter selecting an appropriate low-frequency cut-off, f_L, individually for each record using the criterion of Bommer *et al.* (1998).

- Plot PGA against f_L for two pairs of horizontal components of ground motion from the BOL and DZC stations from the Duzce earthquake (12/11/1999). Record from BOL was recorded on a GSR-16 digital accelerograph and that from DZC was recorded on a SMA-1 analogue accelerograph. Find PGA is stable for low-frequency cut-offs up to at least $0.4\,\mathrm{Hz}$ for the selected records.

3.158 Zonno & Montaldo (2002)

- Ground motion model is:

$$\log_{10}(Y) = a + bM + c\log_{10}(R^2 + h^2)^{1/2} + e\Gamma$$

  where Y is in g, $a = -1.632$, $b = 0.304$, $c = -1$, $h = 2.7$, $e = 0$ and $\sigma = 0.275$.

- Use two site categories:

  Soil $V_{s,30} \leq 750\,\mathrm{ms}^{-1}$, $\Gamma = 0$.

  Rock $V_{s,30} > 750\,\mathrm{ms}^{-1}$, $\Gamma = 1$.

- Note that amount of data available for the Umbria-Marche area in central Italy is sufficiently large to perform statistical analysis at regional scale.

- Focal depths between 2 and $8.7\,\mathrm{km}$. Exclude data from an earthquake that occurred at $47\,\mathrm{km}$.

- Select only records from earthquakes with $M_L \geq 4.5$ recorded at less than $100\,\mathrm{km}$.

- Exclude data from Nocera Umbra station because it shows a strong amplification effect due to the presence of a sub-vertical fault and to highly fractured rocks.
- Uniformly process records using BAP (Basic strong-motion Accelerogram Processing software). Instrument correct records and band-pass filter records using a high-cut filter between 23 and $28\,\mathrm{Hz}$ and a bi-directional Butterworth low-cut filter with corner frequency of $0.4\,\mathrm{Hz}$ and rolloff parameter of 2.
- Note that can use M_L because it does not saturate until about 6.5 and largest earthquake in set is $M_L = 5.9$.
- More than half of records are from earthquakes with $M_L \leq 5.5$.
- State that equations should not be used for $M_L > 6$ because of lack of data.
- Use similar regression method as Ambraseys *et al.* (1996) to find site coefficient, e.

3.159 Alarcón (2003)

- Ground motion model is (his model 2):

$$\log(a) = A + BM + Cr + D\log(r)$$

where a is in gal, $A = 5.5766$, $B = 0.06052$, $C = 0.0039232$, $D = -2.524849$ and $\sigma = 0.2597$.

- Due to lack of information classify stations as soil or rock (stations with $\leq 10\,\mathrm{m}$ of soil). Only derives equation for rock.
- Uses data from National Accelerometer Network managed by INGEOMINAS from 1993 to 1999.
- Exclude data from subduction zone, focal depths $h > 60\,\mathrm{km}$.
- Focal depths, $11.4 \leq h \leq 59.8\,\mathrm{km}$.
- Exclude data from earthquakes with $M_L < 4.0$.
- Exclude data with $\mathrm{PGA} < 5\,\mathrm{gal}$. $5 \leq \mathrm{PGA} \leq 100.1\,\mathrm{gal}$.
- Derive equations using four different models:

$$\begin{aligned}
a &= C_1 \mathrm{e}^{C_2 M}(R + C_3)^{-C_4} \\
\log(a) &= A + BM + Cr + D\log(r) \\
\log(y) &= C_0 + C_1(M-6) + C_2(M-6) + C_3\log(r) + C_4 r \\
\ln(a) &= a + bM + d\ln(R) + qh
\end{aligned}$$

3.160 *Alchalbi* et al. *(2003)*

- Ground motion model is:

  $$\log A = b_0 + b_1 M_c + b_r \log r$$

  where A is in g, $b_0 = -1.939$, $b_1 = 0.278$, $b_2 = -0.858$ and $\sigma = 0.259$ for horizontal PGA and $b_0 = -2.367$, $b_1 = 0.244$, $b_2 = -0.752$ and $\sigma = 0.264$ for vertical PGA.

- Use two site categories: bedrock ($S = 0$) and sediments ($S = 1$) but found the coefficient b_3 in the term $+b_3 S$ is close to zero so repeat analysis constraining b_3 to 0.

- Records from SSA-1 instruments.

- Carefully inspect and select records.

- Do not use record from the Aqaba ($M = 7.2$) earthquake because it is very far and was only recorded at one station.

- Do not use records from buildings or dams because they are affected by response of structure.

- Instrument correct records. Apply bandpass filter (0.1 to 25 Hz) to some low-quality records.

- Do regression using only records from earthquakes with $4.8 \leq M \leq 5.8$ and also using only records from earthquakes with $3.5 \leq M \leq 4.5$.

- Most data from $M \leq 5$ and $r \leq 100\,\mathrm{km}$.

- Note that use a small set of records and so difficult to judge reliability of derived equation.

3.161 *Atkinson & Boore (2003)*

- Ground motion model is:

  $$\begin{array}{rcl}
\log Y & = & c_1 + c_2\mathbf{M} + c_3 h + c_4 R - g\log R + c_5\mathrm{sl}S_C + c_6\mathrm{sl}S_D + c_7\mathrm{sl}S_E \\
\text{where } R & = & \sqrt{D_{\mathrm{fault}}^2 + \Delta^2} \\
\text{and } \Delta & = & 0.00724\,10^{0.507\mathbf{M}} \\
\text{and sl} & = & \left\{ \begin{array}{rll}
1 & \text{for} & \mathrm{PGA}_{rx} \leq 100\,\mathrm{cms}^{-1}\mathrm{or} f \leq 1\,\mathrm{Hz} \\
1-(f-1)(\mathrm{PGA}_{rx}-100)/400 & \text{for} & 100 < \mathrm{PGArx} < 500\,\mathrm{cms}^{-1}(1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\
1-(f-1) & \text{for} & \mathrm{PGA}_{rx} \geq 500\,\mathrm{cms}^{-1}(1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\
1-(\mathrm{PGA}_{rx}-100)/400 & \text{for} & 100 < \mathrm{PGArx} < 500\,\mathrm{cms}^{-1}(f \geq 2\,\mathrm{Hz} \\
0 & \text{for} & \mathrm{PGA}_{rx} \geq 500\,\mathrm{cms}^{-1}(f \geq 2\,\mathrm{Hz})
\end{array} \right.
\end{array}$$

  where Y is in cms^{-2}, f is frequency of interest, PGA_{rx} is predicted PGA on NEHRP B sites, $c_1 = 2.991$, $c_2 = 0.03525$, $c_3 = 0.00759$, $c_4 = -0.00206$, $\sigma_1 = 0.20$ (intra-event) and $\sigma_2 = 0.11$ (inter-event) for interface events and $c_1 = -0.04713$, $c_2 = 0.6909$, $c_3 = 0.01130$, $c_4 = -0.00202$, $\sigma_1 = 0.23$ and $\sigma_2 = 0.14$ for in-slab events and $c_5 = 0.19$, $c_6 = 0.24$, $c_7 = 0.29$ for all events. $g = 10^{1.2-0.18\mathbf{M}}$ for interface events and $g = 10^{0.301-0.01\mathbf{M}}$ for in-slab events. Recommended revised c_1 for interface events in Cascadia is 2.79 and in Japan 3.14, recommended revised c_1 for in-slab events in Cascadia is -0.25 and in Japan 0.10.

- Use four site categories:

  B NEHRP site class B, $V_{s,30} > 760\,\mathrm{ms}^{-1}$. $S_C = 0$, $S_D = 0$ and $S_E = 0$.

  C NEHRP site class C, $360 < V_{s,30} \leq 760\,\mathrm{ms}^{-1}$. $S_C = 1$, $S_D = 0$ and $S_E = 0$.

  D NEHRP site class D, $180 \leq V_{s,30} \leq 360\,\mathrm{ms}^{-1}$. $S_D = 1$, $S_C = 0$ and $S_E = 0$.

  E NEHRP site class E, $V_{s,30} < 180\,\mathrm{ms}^{-1}$. $S_E = 1$, $S_C = 0$ and $S_D = 0$.

  Stations in KNET were classified using shear-wave velocity profiles using an statistical method to extrapolate measured shear-wave velocities to depths up to 10–$20\,\mathrm{m}$ to $30\,\mathrm{m}$. Stations in Guerrero array assumed to be on rock, i.e. site class B. Broadband stations in Washington and British Columbia sited on rock ($V_{s,30} \approx 1100\,\mathrm{ms}^{-1}$), i.e. site class B. Strong-motion stations in Washington classified using map of site classes based on correlations between geology and $V_{s,30}$ in Washington, and verified at 8 stations using actual borehole measurements. Converted Youngs *et al.* (1997) Geomatrix classifications by assuming Geomatrix A=NEHRP B, Geomatrix B=NEHRP C, Geomatrix C/D=NEHRP D and Geomatrix E=NEHRP E using shear-wave velocity and descriptions of Geomatrix classification.

- Note that cannot develop equations using only Cascadia data because not enough data. Combine data of Crouse (1991) and Youngs *et al.* (1997) with additional data from Cascadia (strong-motion and broadband seismographic records), Japan (KNET data), Mexico (Guerrero array data) and El Salvador data.

- Classify event by type using focal depth and mechanism as:

  In-slab All earthquakes with normal mechanism. Earthquakes with thrust mechanism at depths $> 50\,\mathrm{km}$ or if occur on steeply dipping planes.

  Interface Earthquakes with thrust mechanism at depths $< 50\,\mathrm{km}$ on shallow dipping planes.

  Exclude events of unknown type.

- Exclude events with focal depth $h > 100\,\mathrm{km}$.

- Exclude events that occurred within crust above subduction zones.

- Use many thousands of extra records to explore various aspects of ground motion scaling with M and D_{fault}.

- Data relatively plentiful in most important M-D_{fault} ranges, defined according to deaggregations of typical hazard results. These are in-slab earthquakes of $6.5 \leq \mathbf{M} \leq 7.5$ for $40 \leq D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ and interface earthquakes of $\mathbf{M} \geq 7.5$ for $20 \leq D_{\mathrm{fault}} \leq 200\,\mathrm{km}$.

- Data from KNET from moderate events at large distances are not reliable at higher frequencies due to instrumentation limitations so exclude KNET data from $\mathbf{M} < 6$ at $D_{\mathrm{fault}} > 100\,\mathrm{km}$ and for $\mathrm{M} \geq 6$ at $D_{\mathrm{fault}} > 200\,\mathrm{km}$. Excluded data may be reliable at low frequencies.

- Estimate D_{fault} for data from Crouse (1991) and for recent data using fault length versus $\mathbf{M}$ relations of Wells & Coppersmith (1994) to estimate size of fault plane and assuming epicentre lies above geometric centre of dipping fault plane. Verified estimates for several large events for which fault geometry is known.

- Perform separate regressions for interface and in-slab events because analyses indicated extensive differences in amplitudes, scaling and attenuation between two types.

- Experiment with a variety of functional forms. Selected functional form allows for magnitude dependence of geometrical spreading coefficient, g; the observed scaling with magnitude and amplitude-dependent soil nonlinearity.

- For $h > 100\,\text{km}$ use $h = 100\,\text{km}$ to prevent prediction of unrealistically large amplitudes for deeper earthquakes.

- R is approximately equal to average distance to fault surface. Δ is defined from basic fault-to-site geometry. For a fault with length and width given by equations of Wells & Coppersmith (1994), the average distance to the fault for a specified D_{fault} is calculated (arithmetically averaged from a number of points distributed around the fault), then used to determine Δ. Magnitude dependence of R arises because large events have a large spatial extent, so that even near-fault observation points are far from most of the fault. Coefficients in Δ were defined analytically, so as to represent average fault distance, not be regression. Although coefficients in Δ were varied over a wide range but did not improve accuracy of model predictions.

- Determine magnitude dependence of g by preliminary regressions of data for both interface and in-slab events. Split data into 1 magnitude unit increments to determine slope of attenuation as a function of magnitude using only 1 and $2\,\text{s}$ data and records with $50 \leq D_{\text{fault}} \leq 300\,\text{km}$ ($50\,\text{km}$ limit chosen to avoid near-source distance saturation effects). Within each bin regression was made to a simple functional form: $\log Y' = a_1 + a_2\mathbf{M} - g \log R + a_3 S$ where $Y' = Y \exp(0.001R)$, i.e. Y corrected for curvature due to anelasticity, and $S = 0$ for NEHRP A or B and 1 otherwise. g is far-field slope determined for each magnitude bin.

- Nonlinear soil effects not strongly apparent in database on upon examination of residuals from preliminary regressions, as most records have $\text{PGA} < 200\,\text{cms}^{-2}$, but may be important for large M and small D_{fault}. To determine linear soil effects perform separate preliminary regressions for each type of event to determine c_5, c_6 and c_7 assuming linear response. Smooth these results (weighted by number of observations in each subset) to fix c_5, c_6 and c_7 (independent of earthquake type) for subsequent regressions. sl was assigned by looking at residual plots and from consideration of NEHRP guidelines. Conclude that there is weak evidence for records with $\text{PGA}_{rx} > 100\,\text{cms}^{-2}$, for NEHRP E sites at periods $< 1\,\text{s}$. Use these observations to fix sl for final regression.

- Final regression needs to be iterated until convergence because of use of PGA_{rx} in definition of dependent variable.

- To optimize fit for M-D_{fault} range of engineering interest limit final regression to data within: $5.5 \leq \mathbf{M} < 6.5$ and $D_{\text{fault}} \leq 80\,\text{km}$, $6.5 \leq \mathbf{M} < 7.5$ and $D_{\text{fault}} \leq 150\,\text{km}$ and $\mathbf{M} \geq 7.5$ and

$D \leq 300\,\mathrm{km}$ for interface events and $6.0 \leq \mathbf{M} < 6.5$ and $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ and $\mathbf{M} \geq 6.5$ and $D_{\mathrm{fault}} \leq 200\,\mathrm{km}$ for in-slab events. These criteria refined by experimentation until achieved an optimal fit for events that are important for seismic hazard analysis. Need to restrict M-D_{fault} for regression because set dominated by records from moderate events and from intermediate distances whereas hazard is from large events and close distances.

- Lightly smooth coefficients (using a weighted 3-point scheme) over frequency to get smooth spectral shape and allows for reliable linear interpolation of coefficients for frequencies not explicitly used in regression.
- In initial regressions, use a $\mathbf{M}^2$ term as well as a $\mathbf{M}$ term leading to a better fit over a linear magnitude scaling but lead to a positive sign of the $\mathbf{M}^2$ rather than negative as expected. Therefore to ensure the best fit in the magnitude range that is important for hazard and constrained by data quadratic source terms refit to linear form. Linear model constrained to provide same results in range $7.0 \leq \mathbf{M} \leq 8.0$ for interface events and $6.5 \leq \mathbf{M} \leq 7.5$ for in-slab events. To ensure that non-decreasing ground motion amplitudes for large magnitudes: for $\mathbf{M} > 8.5$ use $\mathrm{M} = 8.5$ for interface events and for $\mathbf{M} > 8.0$ use $\mathrm{M} = 8.0$ for in-slab events.
- Calculate σ based on records with $\mathbf{M} \geq 7.2$ and $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ for interface events and $\mathbf{M} \geq 6.5$ and $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$ for in-slab events. These magnitude ranges selected to obtain the variability applicable for hazard calculations. Do not use KNET data when computing σ because data appear to have greater high-frequency site response than data from same soil class from other regions, due to prevalence of sites in Japan with shallow soil over rock.
- Determine σ_1 using data for several well-recorded large events and determining average value. Then calculate σ_2 assuming $\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$.
- Examine residuals w.r.t. D_{fault} using all data from $\mathbf{M} \geq 5.5$ and $D_{\mathrm{fault}} \leq 200\,\mathrm{km}$ and $\mathbf{M} \geq 6.5$ and $D_{\mathrm{fault}} \leq 300\,\mathrm{km}$. Find large variability but average residuals near 0 for $D_{\mathrm{fault}} \leq 100\,\mathrm{km}$.
- Find significantly lower variability for $\mathbf{M} \geq 7.2$ events ($\sigma = 0.2$–0.35 for larger events and $\sigma = 0.25$–0.4 for smaller events).
- Examine graphs and statistics of subsets of data broken down by magnitude, soil type and region. Find significant positive residuals for $\mathbf{M} < 6.6$ due to use of linear scaling with magnitude. Accept positive residuals because small magnitudes do not contribute strongly to hazard.
- Find large positive residuals for class C sites for interface events (most records are from Japan) whereas residuals for class C sites for in-slab events (which are from both Japan and Cascadia) do not show trend. No other overwhelming trends. Differences in residuals for Japan and Cascadia class C sites likely due to differences in typical soil profiles in the two regions within the same NEHRP class. Sites in Japan are typically shallow soil over rock, which tend to amplify high frequencies, whereas in Cascadia most soil sites represent relatively deep layers over rock or till. Provide revised c_1 coefficients for Japan and Cascadia to model these differences.

- Note that debate over whether 1992 Cape Mendocino earthquake is a subduction zone or crustal earthquake. Excluding it from regressions has a minor effect on results, reducing predictions for interface events for $\mathbf{M} < 7.5$.

3.162 Boatwright et al. (2003)

- Ground motion model is:

$$\begin{aligned} \log \mathrm{PGA} &= \psi(\mathbf{M}) - \log g(r) - \eta'(\mathbf{M}) r \\ \text{where} & \\ \psi(\mathbf{M}) &= \psi_1 + \psi_2(\mathbf{M} - 5.5) \quad \text{for} \quad \mathbf{M} \leq 5.5 \\ &= \psi_1 + \psi_3(\mathbf{M} - 5.5) \quad \text{for} \quad \mathbf{M} > 5.5 \\ \eta'(\mathbf{M}) &= \eta_1 \quad \text{for} \quad \mathbf{M} \leq 5.5 \\ &= \eta_1 \times 10^{\rho(\mathbf{M}-5.5)} \quad \mathbf{M} > 5.5 \\ g(r) &= r \quad \text{for} \quad r \leq r_0 = 27.5\,\mathrm{km} \\ &= r_0 (r/r_0)^{0.7} \quad \text{for} \quad r > r_0 = 27.5\,\mathrm{km} \end{aligned}$$

  where $\psi_1 = 1.45 \pm 0.24$, $\psi_2 = 1.00 \pm 0.01$, $\psi_3 = 0.31 \pm 0.09$, $\eta_1 = 0.0073 \pm 0.0003$, $\rho = -0.30 \pm 0.06$, $\sigma_e = 0.170$ (inter-earthquake) and $\sigma_r = 0.361$ (intra-earthquake).

- Classify station into four classes using the NEHRP categories using geological maps:

  B Rock. Amplification from category C 0.79.

  C Soft rock or stiff soil. Amplification from category C 1.00.

  D Soft soil. Amplification from category C 1.35.

  E Bay mud. Amplification from category D 1.64.

  The amplifications (from Boore *et al.* (1997)) are used to correct for site effects.

  For some stations in the broadband Berkeley Digital Seismic Network, which are in seismic vaults and mine adits and therefore have low site amplifications, use one-half the above site amplifications.

- Use data from August 1999 and December 2002 from the northern California ShakeMap set of data. Extend set to larger earthquakes by adding data from nine previous large northern California earthquakes.

- Focal depths, $0.1 \leq h \leq 28..8\,\mathrm{km}$.

- Use hypocentral distance because this distance is available to ShakeMap immediately after an earthquake. Note that this is a poor predictor of near-field ground motion from extended faults.

- Plot decay of PGA with distance for two moderate earthquakes ($\mathbf{M} = 4.9$, $\mathbf{M} = 3.9$) and find decay is poorly fit by a power-law function of distance and that fitting such an equation who require $\mathrm{PGA} \propto r^{-2}$, which they believe is physically unrealistic for body-wave propagation.

- Find that PGAs flatten or even increase at large distances, which is believed to be due to noise. Hence use a magnitude-dependent limit of $r_{\max} = 100(\mathbf{M} - 2) \leq 400\,\mathrm{km}$, determined by inspecting PGA and PGV data for all events, to exclude problem data.
- Fit data from each event separately using $\log \mathrm{PGA} = \psi - \eta r - \log g(r) + \log s_{\mathrm{BJF}}$. Find η varies between four groups: events near Eureka triple junction, events within the Bay Area, events near San Juan Bautista and those in the Sierras and the western Mojave desert.
- Use a numerical search to find the segmentation magnitude $\mathbf{M}'$. Choose $\mathbf{M}' = 5.5$ as the segmentation magnitude because it is the lowest segmentation magnitude within a broad minimum in the χ^2 error for the regression.
- Fit magnitude-dependent part of the equation to the PGA values scaled to $10\,\mathrm{km}$ and site class C.
- Note that the PGAs predicted are significantly higher than those given by equations derived by Joyner & Boore (1981) and Boore *et al.* (1997) because of use of hypocentral rather than fault distance.
- Recompute site amplifications relative to category C as: for B 0.84 ± 0.03, for D 1.35 ± 0.05 and for E 2.17 ± 0.15.

3.163 *Bommer* et al. *(2003)*

- Ground motion model is:

$$\log y = C_1 + C_2 M + C_4 \log(\sqrt{r^2 + h^2}) + C_A S_A + C_S S_S + C_N F_N + C_R F_R$$

  where y is in g, $C_1 = -1.482$, $C_2 = 0.264$, $C_4 = -0.883$, $h = 2.473$, $C_A = 0.117$, $C_S = 0.101$, $C_N = -0.088$, $C_R = -0.021$, $\sigma_1 = 0.243$ (intra-event) and $\sigma_2 = 0.060$ (inter-event).

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

  R Rock: $V_s > 750\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 0, S_S = 0$, 106 records.

  A Stiff soil: $360 < V_s \leq 750\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 1, S_S = 0$, 226 records.

  S Soft soil: $180 < V_s \leq 360\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 0, S_S = 1$, 81 records.

  L Very soft soil: $V_s \leq 180\,\mathrm{ms}^{-1}$, $\Rightarrow S_A = 0, S_S = 1$, 3 records.

- Use same data as Ambraseys *et al.* (1996).
- Use three faulting mechanism categories:

  S Strike-slip: earthquakes with rake angles (λ) $-30 \leq \lambda \leq 30°$ or $\lambda \geq 150°$ or $\lambda \leq -150°$, $\Rightarrow F_N = 0, F_R = 0$, 47 records.

N Normal: earthquakes with $-150 < \lambda < -30^\circ$, $\Rightarrow F_N = 1, F_R = 0$, 146 records.

R Reverse: earthquakes with $30 < \lambda < 150^\circ$, $\Rightarrow F_R = 1, F_N = 0$, 229 records.

Earthquakes classified as either strike-slip or reverse or strike-slip or normal depending on which plane is the main plane were included in the corresponding dip-slip category. Some records (137 records, 51 normal, 10 strike-slip and 76 reverse) from earthquakes with no published focal mechanism (80 earthquakes) were classified using the mechanism of the mainshock or regional stress characteristics.

- Try using criteria of Campbell (1997) and Sadigh *et al.* (1997) to classify earthquakes w.r.t. faulting mechanism. Also try classifying ambiguously classified earthquakes as strike-slip. Find large differences in the faulting mechanism coefficients with more stricter criteria for the rake angle of strike-slip earthquakes leading to higher C_R coefficients.
- Note that distribution of records is reasonably uniform w.r.t. to mechanism although significantly fewer records from strike-slip earthquakes.
- Try to use two-stage maximum-likelihood method as employed by Ambraseys *et al.* (1996) but find numerical instabilities in regression.
- Also rederive mechanism-independent equation of Ambraseys *et al.* (1996) using one-stage maximum-likelihood method.

3.164 Campbell & Bozorgnia (2003c), Campbell & Bozorgnia (2003a), Campbell & Bozorgnia (2003b) & Bozorgnia & Campbell (2004b)

- Ground motion model is:

$$\begin{aligned}
\ln Y &= c_1 + f_1(M_w) + c_4 \ln \sqrt{f_2(M_w, r_{\mathrm{seis}}, S)} + f_3(F) + f_4(S) \\
&\quad + f_5(\mathrm{HW}, F, M_w, r_{\mathrm{seis}}) \\
\text{where}\quad f_1(M_w) &= c_2 M_w + c_3(8.5 - M_w)^2 \\
f_2(M_w, r_{\mathrm{seis}}, S) &= r_{\mathrm{seis}}^2 + g(S)^2(\exp[c_8 M_w + c_9(8.5 - M_w)^2])^2 \\
g(S) &= c_5 + c_6(S_{VFS} + S_{SR}) + c_7 S_{FR} \\
f_3(F) &= c_{10} F_{RV} + c_{11} F_{TH} \\
f_4(S) &= c_{12} S_{VFS} + c_{13} S_{SR} + c_{14} S_{FR} \\
f_5(\mathrm{HW}, F, M_w, r_{\mathrm{seis}}) &= \mathrm{HW} f_3(F) f_{\mathrm{HW}}(M_w) f_{\mathrm{HW}}(r_{\mathrm{seis}}) \\
\mathrm{HW} &= \begin{cases} 0 & \text{for } r_{\mathrm{jb}} \geq 5\,\mathrm{km} \text{ or } \delta > 70^\circ \\ (S_{VFS} + S_{SR} + S_{FR})(5 - r_{\mathrm{jb}})/5 & \text{for } r_{\mathrm{jb}} < 5\,\mathrm{km} \text{ and } \delta \leq 70^\circ \end{cases} \\
f_{\mathrm{HW}}(M_w) &= \begin{cases} 0 & \text{for } M_w < 5.5 \\ M_w - 5.5 & \text{for } 5.5 \leq M_w \leq 6.5 \\ 1 & \text{for } M_w > 6.5 \end{cases} \\
f_{\mathrm{HW}}(r_{\mathrm{seis}}) &= \begin{cases} c_{15}(r_{\mathrm{seis}}/8) & \text{for } r_{\mathrm{seis}} < 8\,\mathrm{km} \\ c_{15} & \text{for } r_{\mathrm{seis}} \geq 8\,\mathrm{km} \end{cases}
\end{aligned}$$

where Y is in g, r_{jb} is the distance to the surface projection of rupture and δ is the dip of the fault; for uncorrected horizontal PGA: $c_1 = -2.896$, $c_2 = 0.812$, $c_3 = 0.0$, $c_4 = -1.318$, $c_5 = 0.187$, $c_6 = -0.029$, $c_7 = -0.064$, $c_8 = 0.616$, $c_9 = 0$, $c_{10} = 0.179$, $c_{11} = 0.307$, $c_{12} = -0.062$, $c_{13} = -0.195$, $c_{14} = -0.320$, $c_{15} = 0.370$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.964$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132\ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.263$; for corrected horizontal PGA: $c_1 = -4.033$, $c_2 = 0.812$, $c_3 = 0.036$, $c_4 = -1.061$, $c_5 = 0.041$, $c_6 = -0.005$, $c_7 = -0.018$, $c_8 = 0.766$, $c_9 = 0.034$, $c_{10} = 0.343$, $c_{11} = 0.351$, $c_{12} = -0.123$, $c_{13} = -0.138$, $c_{14} = -0.289$, $c_{15} = 0.370$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.920$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132\ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.219$; for uncorrected vertical PGA: $c_1 = -2.807$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.391$, $c_5 = 0.191$, $c_6 = 0.044$, $c_7 = -0.014$, $c_8 = 0.544$, $c_9 = 0$, $c_{10} = 0.091$, $c_{11} = 0.223$, $c_{12} = -0.096$, $c_{13} = -0.212$, $c_{14} = -0.199$, $c_{15} = 0.630$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 1.003$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132\ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.302$; and for corrected vertical PGA: $c_1 = -3.108$, $c_2 = 0.756$, $c_3 = 0$, $c_4 = -1.287$, $c_5 = 0.142$, $c_6 = 0.046$, $c_7 = -0.040$, $c_8 = 0.587$, $c_9 = 0$, $c_{10} = 0.253$, $c_{11} = 0.173$, $c_{12} = -0.135$, $c_{13} = -0.138$, $c_{14} = -0.256$, $c_{15} = 0.630$ and $\sigma = c_{16} - 0.07M_w$ for $M_w < 7.4$ and $\sigma = c_{16} - 0.518$ for $M_w \geq 7.4$ where $c_{16} = 0.975$ or $\sigma = c_{17} + 0.351$ for $\mathrm{PGA} \leq 0.07\,\mathrm{g}$, $\sigma = c_{17} - 0.132\ln(\mathrm{PGA})$ for $0.07\,\mathrm{g} < \mathrm{PGA} < 0.25\,\mathrm{g}$ and $\sigma = c_{17} + 0.183$ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$ where $c_{17} = 0.274$.

- Use four site categories:

Firm soil Generally includes soil deposits of Holocene age (less than 11,000 years old) described on geological maps as recent alluvium, alluvial fans, or undifferentiated Quaternary deposits. Approximately corresponds to $V_{s,30} = 298 \pm 92\,\mathrm{ms}^{-1}$ and NEHRP soil class D. Uncorrected PGA: 534 horizontal records and 525 vertical records and corrected PGA: 241 horizontal records and 240 vertical records. $S_{VFS} = 0$, $S_{SR} = 0$ and $S_{FR} = 0$.

Very firm soil Generally includes soil deposits of Pleistocene age (11,000 to 1.5 million years old) described on geological maps as older alluvium or terrace deposits. Approximately corresponds to $V_{s,30} = 368 \pm 80\,\mathrm{ms}^{-1}$ and NEHRP soil class CD. Uncorrected PGA: 168 horizontal records and 166 vertical records and corrected PGA: 84 horizontal records and 83 vertical records. $S_{VFS} = 1$, $S_{SR} = 0$ and $S_{FR} = 0$.

Soft rock Generally includes sedimentary rock and soft volcanic deposits of Tertiary age (1.5 to 100 million years old) as well as 'softer' units of the Franciscan Complex and other low-grade metamorphic rocks generally described as melange, serpentine and schist. Approximately corresponds to $V_{s,30} = 421 \pm 109\,\mathrm{ms}^{-1}$ and NEHRP soil class CD. Uncorrected PGA: 126 horizontal records and 124 vertical records and corrected PGA: 63 horizontal records and 62 vertical records. $S_{SR} = 1$, $S_{VFS} = 0$ and $S_{FR} = 0$.

Firm rock Generally include older sedimentary rocks and hard volcanic deposits, high-grade metamorphic rock, crystalline rock and the 'harder' units of the Franciscan Complex generally described as sandstone, greywacke, shale, chert and greenstone. Approximately corresponds to $V_{s,30} = 830 \pm 339\,\mathrm{ms}^{-1}$ and NEHRP soil class BC. Uncorrected PGA: 132 horizontal records and 126 vertical records and corrected PGA: 55 horizontal records and 54 vertical records. $S_{FR} = 1$, $S_{VFS} = 0$ and $S_{SR} = 0$.

Note that for generic soil (approximately corresponding to $V_{s,30} = 310\,\mathrm{ms}^{-1}$ and NEHRP site class D) use $S_{VFS} = 0.25$, $S_{SR} = 0$, $S_{FR} = 0$ and for generic rock (approximately corresponding to $V_{s,30} = 620\,\mathrm{ms}^{-1}$ and NEHRP site class C) use $S_{SR} = 0.50$, $S_{FR} = 0.50$ and $S_{VFS} = 0$.

- Use four fault types but only model differences between strike-slip, reverse and thrust:

Normal Earthquakes with rake angles between $202.5°$ and $337.5°$. 4 records from 1 earthquake.

Strike-slip Includes earthquakes on vertical or near-vertical faults with rake angles within $22.5°$ of the strike of the fault. Also include 4 records from 1975 Oroville normal faulting earthquake. Uncorrected PGA: 404 horizontal records and 395 vertical records and corrected PGA: 127 horizontal and vertical records. $F_{RV} = 0$ and $F_{TH} = 0$

Reverse Steeply dipping earthquakes with rake angles between $22.5°$ and $157.5°$. Uncorrected PGA: 186 horizontal records and 183 vertical records and corrected PGA: 58 horizontal records and 57 vertical records. $F_{RV} = 1$ and $F_{TH} = 0$.

Thrust Shallow dipping earthquakes with rake angles between $22.5°$ and $157.5°$. Includes some blind thrust earthquakes. Uncorrected PGA: 370 horizontal records and 363 vertical records and corrected PGA: 258 horizontal records and 255 vertical records. $F_{TH} = 1$ and $F_{RV} = 0$.

Note that for generic (unknown) fault type use $F_{RV} = 0.25$ and $F_{TH} = 0.25$.

- Most records from $5.5 \leq M_w \leq 7.0$.
- Note that equations are an update to equations in Campbell (1997) because they used a somewhat awkward and complicated set of ground motion models because there used a mixture of functional forms. Consider that the new equations supersede their previous studies.
- Uncorrected PGA refers to the standard level of accelerogram processing known as Phase 1. Uncorrected PGAs are either scaled directly from the recorded accelerogram or if the accelerogram was processed, from the baseline and instrument-corrected Phase 1 acceleration time-history.
- Corrected PGA measured from the Phase 1 acceleration time-history after it had been band-pass filtered and decimated to a uniform time interval.
- Restrict data to within $60\,\mathrm{km}$ of seismogenic rupture zone ($r_{\mathrm{seis}} \leq 60\,\mathrm{km}$) of shallow crustal earthquakes in active tectonic regions which have source and near-source attenuation similar to California. Most data from California with some from Alaska, Armenia, Canada, Hawaii, India, Iran, Japan, Mexico, Nicaragua, Turkey and Uzbekistan. Note some controversy whether this is true for all earthquakes (e.g. Gazli and Nahanni). Exclude subduction-interface earthquakes.

- Restrict earthquakes to those with focal depths $< 25\,\mathrm{km}$.
- Exclude data from subduction-interface earthquakes, since such events occur in an entirely different tectonic environment that the other shallow crustal earthquakes, and it has not been clearly shown that their near-source ground motions are similar to those from shallow crustal earthquakes.
- Restrict to $r_{\mathrm{seis}} \leq 60\,\mathrm{km}$ to avoid complications related to the arrival of multiple reflections from the lower crust. Think that this distance range includes most ground-motion amplitudes of engineering interest.
- All records from free-field, which define as instrument shelters or non-embedded buildings < 3 storeys high and < 7 storeys high if located on firm rock. Include records from dam abutments to enhance the rock records even though there could be some interaction between dam and recording site. Exclude records from toe or base of dam because of soil-structure interaction.
- Do preliminary analysis, find coefficients in f_3 need to be constrained in order to make Y independent on M_w at $r_{\mathrm{seis}} = 0$, otherwise Y exhibits 'oversaturation' and decreases with magnitude at close distances. Therefore set $c_8 = -c_2/c_4$ and $c_9 = -c_3/c_4$.
- Functional form permits nonlinear soil behaviour.
- Do not include sediment depth (depth to basement rock) as a parameter even though analysis of residuals indicated that it is an important parameter especially at long periods. Do not think its exclusion is a serious practical limitation because sediment depth is generally not used in engineering analyses and not included in any other widely used attenuation relation.
- Do not apply weights during regression analysis because of the relatively uniform distribution of records w.r.t. magnitude and distance.
- To make regression analysis of corrected PGA more stable set c_2 equal to value from better-constrained regression of uncorrected PGAs.
- Examine normalised residuals $\delta_i = (\ln Y_i - \ln \bar{Y})/\sigma_{\ln(\mathrm{Unc.PGA}}$ where $\ln Y_i$ is the measured acceleration, $\bar{Y}$ is the predicted acceleration and $\sigma_{\ln(\mathrm{Unc.PGA}}$ is the standard deviation of the uncorrected PGA equation. Plot δ_i against magnitude and distance and find models are unbiased.
- Consider equations valid for $M_w \geq 5.0$ and $r_{\mathrm{seis}} \leq 60\,\mathrm{km}$. Probably can be extrapolated to a distance of $100\,\mathrm{km}$ without serious compromise.
- Note that should use equations for uncorrected PGA if only an estimate of PGA is required because of its statistical robustness. If want response spectra and PGA then should use corrected PGA equation because the estimates are then consistent.
- Note that should include ground motions from Kocaeli (17/8/1999, $M_w = 7.4$), Chi-Chi (21/9/1999, $M_w = 7.6$), Hector Mine (16/10/1999, $M_w = 7.1$) and Duzce (12/11/1999,

$M_w = 7.1$) earthquakes but because short-period motions from these earthquakes was significantly lower than expected their inclusion could lead to unconservative estimated ground motions for high magnitudes.

- Prefer the relationship for σ in terms of PGA because statistically more robust. Note that very few records to constrain value of σ for large earthquakes but many records to constrain σ for $\mathrm{PGA} \geq 0.25\,\mathrm{g}$.
- Find that Monte Carlo simulation indicates that all regression coefficients statistically significant at 10% level.

3.165 Sigbjörnsson & Ambraseys (2003)

- Ground motion model is:

$$
\begin{aligned}
\log_{10}(\mathrm{PGA}) &= b_0 + b_1 M - \log_{10}(R) + b_2 R \\
R &= \sqrt{D^2 + h^2}
\end{aligned}
$$

  where PGA is in g, $b_0 = -1.2780 \pm 0.1909$, $b_1 = 0.2853 \pm 0.0316$, $b_2 = -1.730 \times 10^{-3} \pm 2.132 \times 10^{-4}$ and $\sigma = 0.3368$ ($\pm$ indicates the standard deviation of the coefficients). h was fixed arbitrarily to $8\,\mathrm{km}$.

- Use data from ISESD (Ambraseys *et al.*, 2003). Select using $d_e < 1000\,\mathrm{km}$, $5 \leq M \leq 7$ (where M is either M_w or M_s).
- Focal depths $< 20\,\mathrm{km}$.
- Only use data from strike-slip earthquakes.
- Note that coefficient of variation for b coefficients is in range 11 to 15%.
- Note that b_0 and b_1 are very strongly negatively correlated (correlation coefficient of -0.9938), believed to be because PGA is governed by $b_0 + b_1 M$ as D approaches zero, but they are almost uncorrelated with b_2 (correlation coefficients of -0.0679 and -0.0076 for b_0 and b_1 respectively), believed to be because of zero correlation between M and D in the data used.
- Also derive equation using $\log_{10}(\mathrm{PGA}) = b_0 + b_1 M + b_2 R + b_3 \log_{10}(R)$ (do not report coefficients) and find slightly smaller residuals but similar behaviour of the b parameters.
- Plot distribution of residuals (binned into intervals of 0.25 units) and the normal probability density function.

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
$M_{\min}$	Magnitude of smallest earthquake
$M_{\max}$	Magnitude of largest earthquake
M scale	Magnitude scale (scales in brackets refer to those scales which the main M values were sometimes converted from, or used without conversion, when no data existed), where:

m_b	Body-wave magnitude
M_C	Chinese surface wave magnitude
M_{CL}	Coda length magnitude
M_D	Duration magnitude
M_{JMA}	Japanese Meteorological Agency magnitude
M_L	Local magnitude
M_{bLg}	Magnitude calculated using Lg amplitudes on short-period, vertical seismographs
M_s	Surface-wave magnitude
M_w	Moment magnitude

$d_{\min}$	Shortest source-to-site distance
$d_{\max}$	Longest source-to-site distance
d scale	Distance measure, where:

d_c	Distance to rupture centroid
d_e	Epicentral distance
d_E	Distance to energy centre

  - d_f Distance to projection of rupture plane on surface (Joyner & Boore, 1981)
  - d_h Hypocentral (or focal) distance
  - d_q Equivalent hypocentral distance (EHD) (Ohno *et al.*, 1993)
  - d_r Distance to rupture plane
  - d_s Distance to seismogenic rupture plane (assumes near-surface rupture in sediments is non-seismogenic) (Campbell, 1997)

- S Number of different site conditions modelled, where:
  - C Continuous classification
  - I Individual classification for each site
- C Use of the two horizontal components of each accelerogram, where:
  - B Both components
  - C Randomly chosen component
  - G Geometric mean
  - L Larger component
  - M Mean (not stated what type)
  - O Randomly oriented component
  - R Resolved component
  - 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
  - 2 Two-stage (Joyner & Boore, 1981)
  - 2M Maximum likelihood two-stage (Joyner & Boore, 1993)
  - 2W Two-stage with second staged weighted as described in Joyner & Boore (1988)
  - O Other (see section referring to study)
  - U Unknown (often probably ordinary one-stage regression)
- M Source mechanisms (and tectonic type) of earthquakes (letters in brackets refer to those mechanism which are separately modelled), where:
  - A All (this is assumed if no information is given in the reference)
  - B Interslab

F Interface

I Intraplate

N Normal

O Oblique

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
Esteva & Rosenblueth (1964)	W. USA	46*	-	U	U	U	U	15*	450*	d_h	1	U	U	A
Kanai (1966)	California & Japan	U	-	U	U	U	U	U	U	d_r	C	U	U	A
Milne & Davenport (1969)	W. USA	U	-	U	U	U	U	U	U	d_e	1	U	U	A
Esteva (1970)	W. USA	U	-	U	U	U	U	15*	500*	d_h	1	U	U	A
Denham & Small (1971)	Yonki, New Guinea	8	-	8	U	U	M_L[1]	U	U	d_h	1	U	U	A
Donovan (1973)	Mostly W. USA but 100+ foreign	678	-	U	<5	>8	U	3*	450*	d_h	1	U	U	A
Denham *et al.* (1973)	Papua New Guinea	25	-	25	5.2	8.0	M_L	80*	300	U	1	U	1	A
Esteva & Villaverde (1973) & Esteva (1974)	W. USA	U	-	U	U	U	U	15*	150*	d_h	1	B	U	A
Orphal & Lahoud (1974)	California	140	-	31	4.1	7.0	M_L	15	350	d_h	1	U	O	A
Ambraseys (1975b), Ambraseys (1975a) & Ambraseys (1978a)	Europe	58	-	U[2]	3.5	5.0	M_L	5	35	d_h	1	U[3]	U	A
Trifunac & Brady (1975),Trifunac (1976) & Trifunac & Brady (1976)	W. USA	181	181	57	3.8	7.7	Mostly M_L	6[4]*	400[5]*	d_e	3	B	O	A
Blume (1977)	California & W. Nevada	795[6]	-	U	U	U	M_L	U	U	d_h	2 (1)	B	U	A
McGuire (1977)	W. USA	34	-	22	5.3	7.6	M_L	14	125	d_h	1	B	U	A
Milne (1977)	W. USA	200*	-	U	3.5	7.7	U	1	380	d_h	1	U	U	A
Ambraseys (1978b)	Europe & Middle East	162	-	U	3.0*	6.6	m_b	0*	30*	d_h	1	L	O	A

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[1] State that it is Richter magnitude which assume to be M_L

[2] Ambraseys & Bommer (1995) state that uses 38 earthquakes.

[3] Ambraseys & Bommer (1995) state that uses larger component.

[4] Note only valid for $R \geq 20\,\mathrm{km}$

[5] Note only valid for $R \leq 200\,\mathrm{km}$

[6] Total earthquake components (does not need to be multiplied by two) for magnitude and distance dependence. Uses 2713 underground nuclear explosion records for site dependence.

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
Donovan & Bornstein (1978)	W. USA	59	-	10	5.0	7.7	U[7]	0.1	321	d_E, d_r and d_h	1	B	O	A
Faccioli (1978)	Mostly W. USA & Japan, some foreign	47[8]	-	23	4.9	7.8	U[9]	15	342	d_h	1	B	U	A
McGuire (1978)	W. USA	70	-	17+*	4.5*	7.7	U[10]	11*	210*	d_h	2	B	U	A
A. Patwardhan *et al.* (1978)[11]	Worldwide	63 (32)	-	25 (23)	4 (5.3)	7.7 (7.8)	M_s	U	U	d_r	2	B	U	A
Cornell *et al.* (1979)	W. USA	70	-	U	U	U	M_L	U	U	d_h	1	C	U	A
Aptikaev & Kopnichev (1980)	Worldwide	Many 100s	- (70*)	U (59)	U	U	U	U	U	d_h	1	U	U	A (T, TS, S, SN, N)[12]
Blume (1980)	W. USA	816	-	U	2.1	7.6	U	0	449	d_h	1	B	1, O	A
Iwasaki *et al.* (1980)	Japan	301	-	51	>5.0	<7.9	M_L[13]	<20	>200	d_e	4	U	1	A
Ohsaki *et al.* (1980a)	Japan	75	75	U	4	7.4	U	6	500	d_h	1	U	1	A
Campbell (1981)	W. USA+8 foreign	116	-	27	5.0	7.7	M_L for $M < 6.0$ and M_s otherwise	0.08	47.7	d_r	1	M	O	A
Chiaruttini & Siro (1981)	Europe & Mid. East	224	-	117	2.7	7.8	M_L (m_b)	3	480	d_h	1	L	1	A
Joyner & Boore (1981)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	2	L	2	A
Bolt & Abrahamson (1982)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	1	L	O	A
PML (1982)	Europe + USA + others	113	-	32	4.3	8	M_s	0.1	330	d_h or d_r	1	U	U	A
Schenk (1982)	Unknown	3500	-	U	2.5	6.5	M_s	2	600	d_h	1	U	O	A

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[7] Idriss (1978) finds magnitudes to be mixture of M_L and M_s.

[8] Total earthquake components (does not need to be multiplied by two)

[9] Idriss (1978) believes majority are M_s.

[10] Idriss (1978) finds magnitudes to be mixture of M_L, m_b and M_s.

[11] Reported in Idriss (1978).

[12] Assume dip-slip means normal mechanism.

[13] State that it is Richter magnitude which assume to be M_L

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
Brillinger & Preisler (1984)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	2	L	1M	A
Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	C	L	2	A
Kawashima *et al.* (1984) & Kawashima *et al.* (1986)	Japan	197	-	90	5.0	7.9	M_{JMA}	5*	550*	d_e	3	R	1	A
McCann Jr. & Echezwia (1984)	N. America + foreign	83	-	18	$5.0+$	U	M_w	U	U	d_r	1	U	O	A
Schenk (1984)	Unknown	3500	-	U	2.5	6.5	U	2	600	d_h	1	U	O	A
Xu *et al.* (1984)	N. China	19	-	10	4.5	7.8	M_w (M_L for $M < 6.0$, M_s for $M \geq 6.0$)	10.1	157	d_e	1	L	1	A
Brillinger & Preisler (1985)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	2	L	1M	A
Kawashima *et al.* (1985)	Japan	-	119	90*	5.0*	7.5*	M_{JMA}	5*	500*	d_e	3	-	1	A
Peng *et al.* (1985b)	N.E. China	73	-	20	3.7	7.8	M_C	2	442.5	d_e	1	U	1	A
Peng *et al.* (1985a)	Tangshan region, China	93	87	19	2.9	5.3	M_L	2*	50*	d_e	1	L	2	A
PML (1985)	USA + Europe + others	203	-	46	3.1	6.9	M_s	0.1	40	d_r	1	U	U	A (S, T)
McCue (1986)	E. Australia	U	-	U	1.7	5.4	M_L	2.5	134	d_h	1	U	U	A
C.B. Crouse (1987)[14]	S. California	U	-	U	U	U	M_s	U	U	d_r	1	B	U	A

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[14] Reported in Joyner & Boore (1988).

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
Krinitzsky *et al.* (1987) & Krinitzsky *et al.* (1988)	Plate boundaries[15]	389[16]	-	U	5.0*	7.4*[17]	M[18]	7*[19]	200*[20]	d_h[21]	2	B	O	A
Sabetta & Pugliese (1987)	Italy	95	-	17	4.6	6.8	M_s for $M \geq 5.5$, M_L otherwise	1.5, 1.5	179, 180	Both d_f & d_e	2	L	1	A
K. Sadigh (1987)[22]	W. USA + others	U	-	U	U	U	M_w	U	U	d_r	2	B	U	A (S, R)
Singh *et al.* (1987)	Mexico	16	-	16	5.6	8.1	M_s	282	466	d_r	1	U	1	A
Algermissen *et al.* (1988)	Vicinity of San Salvador	82	-	U	U	U	M_s	U	U	d_h	1	M	U	A
Annaka & Nozawa (1988)	Japan	U	-	45	U	U	U	U	U	U	1	U	1	A
K.W. Campbell (1988)[23]	Worldwide	U	-	U	≥ 5	U	M_L for $M < 6.0$ and M_s otherwise	U	<50	d_s	2	M	U	A (S, R)
Fukushima *et al.* (1988) & Fukushima & Tanaka (1990)	Japan+200 W. USA	486+200	-	28+15	4.6(5.0)	8.2(7.7)	M_s (M_{JMA})	16 (0.1)	303 (48)	d_h, d_r for 2 Japanese & all US	4	G	2	A
Gaull (1988)	S.W. W. Australia	25+	-	12+	2.6	6.9	M_L	2.5	175	d_h	1	U	O	A
Joyner & Boore (1988)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	2	L, O	2W	A
McCue *et al.* (1988)	S.E. Australia	62	-	U	0.5*	6*	M_L	5*	833	d_e	1	U	O	A
Petrovski & Marcellini (1988)	Europe	120	120	46	3	7	U	8	200	d_h	1	L	1	A

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[15] Also derive equations for Japan subduction zones.

[16] 195 for subduction zone equations.

[17] >7.5 for subduction zone equations.

[18] Call magnitude scale Richter magnitude, which note is equivalent to M_w for $M \leq 8.3$, M_L for $M < 5.9$ and M_s for $5.9 \leq M \leq 8.0$.

[19] About 15km for subduction zone equations.

[20] About 400km for subduction zone equations.

[21] d_e for subduction zone equations.

[22] Reported in Joyner & Boore (1988).

[23] Reported in Joyner & Boore (1988).

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
Tong & Katayama (1988)	Kanto (Japan)	<227	-	<27	4.5*	7.9*	U	10*	750*	d_e	C	L	O	A
Yamabe & Kanai (1988)	Japan	U	-	22	5.3	7.9	U	U	U	d_h	1	U	O	A
Youngs *et al.* (1988)	Worldwide subduction zones	197+389	-	60	5	8.1 (8.2)[24]	M_w (M_s, m_b)	15* (20*)	450* (450*)	d_r, d_h for $M_w \lesssim 7.5$	1	G	1W	A (B,F)
Abrahamson & Litehiser (1989)	$75\%+$ California, rest foreign	585	585	76	5.0	8.1	M_s for $M_s \geq 6.0$, M_L (m_b) otherwise	0.08	400	d_r	1	L	O	A (R & RO, I)
Campbell (1989)	W. N. America + 3 from Managua	190	-	91	2.9	5.0	M_L	0.6	18.3	d_e	1	M	O	A
Alfaro *et al.* (1990)	Guatemala, Nicaragua & El Salvador	20	-	12	4.1	7.5	M_s	1	27	d_e	1	L	U	A
Ambraseys (1990)	W. N. America	182	-	23	5.03	7.7	M_w (M_L)	0.5	370	d_f	2	L	2	A
Campbell (1990)	Unknown	U	-	U	U	U	M_L for $M < 6$, M_s for $M \geq 6$	U	U	d_s	1	U	U	A
Dahle *et al.* (1990b) & Dahle *et al.* (1990a)	Worldwide intraplate regions	87	-	56	2.9	7.8	M_s (M_L, m_b, M_{CL})	6	1300	d_h	1	L	2	A
Jacob *et al.* (1990)	E. N. America	U	-	8	1.8	6.4	m_b	≤ 20	820	U[25]	1	U	O	A
Sen (1990)	Whittier Narrows area	72*	-	11	2.2	3.5	M_L	12*	21*	d_h	1	U	1M	A (T)
Sigbjörnsson (1990)	Iceland	U	-	U	U	5.8[26]	U	U	U	d_f	1	U	U	A
Tsai *et al.* (1990)	Worldwide	<217	-	<51	4.9*	7.4	M_w	3*	150*	d_r	1	M	U	T (S,O)
Ambraseys & Bommer (1991) & Ambraseys & Bommer (1992)	Europe & Mid. East	529	459	H:219, V:191	4	7.34	M_s	1	H:313, V:214	d_f for $M_s \gtrsim 6.0$, d_e otherwise	1	L	1, 2	A

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[24] Consider equations valid for $M_w \leq 8$

[25] Free (1996) believes it is d_h.

[26] This is M_s.

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
Crouse (1991)	Worldwide subduction zones	697[27]	-	U	4.8	8.2	M_w (M_s, M_{JMA})	>8	>866	d_E, d_h for $M < 7.5$	1	B	1	A
Garcìa-Fernàndez & Canas (1991) & Garcia-Fernandez & Canas (1995)	Iberia[28]	57	367	U	3.1	5.0	m_{bLg}	U	U	d_e	1	-	1	A
Huo & Hu (1991)	W. USA with 25 foreign	383+25	-	14+2	5.0	7.4 (7.3)	M_L or m_b for $M < 6.0$ and M_s otherwise	0.1	227 (265)	d_f	2	B	O	A
I.M. Idriss (1991) reported in Idriss (1993)	Unknown	572	-	30*	4.6	7.4	M_L for $M < 6$, M_s for $M \geq 6$	1	100	d_r, d_h for $M < 6$	1	U	U	A
Niazi & Bozorgnia (1991)	SMART-1 array, Taiwan	236	234	12	3.6	7.8	M_L (M_D) for $M_L < 6.6$, else M_s	3.1[29]	119.7[29]	d_h	1	M	2W	A
Rogers *et al.* (1991)	Worldwide	1241	-	180*	5.3*	8.1*	M_L for $M \leq 6$, M_s for $6 < M < 8$ and M_w for $M \geq 8$	4*	400*	d_r if have, d_h otherwise	6	L	1	A
Abrahamson & Youngs (1992)	Unknown	U	-	U	U	U	U	U	U	U	1	U	1M	A (U, U)
Ambraseys *et al.* (1992)	USA + Europe + others	504	-	45	3.1	6.87	M_s	0.5	39	d_f, d_e for some	1	L	1	A
Kamiyama *et al.* (1992) & Kamiyama (1995)	Japan	357	-	82	4.1	7.9	M_{JMA}	3.4	413.3	d_h	I	B	O	A

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[27] Total number of components, does not need to be multiplied by two.

[28] Also present equations for SSE (using 140 records) and NE Iberia (using 107 records).

[29] Distance to centre of array

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
Sigbjörnsson & Baldvinsson (1992)	Iceland	262	-	39	2.0	6.0	U	2	80	d_f	2	B,L	2	A
Taylor Castillo *et al.* (1992)	Nicaragua, El Salvador & Costa Rica	89	-	27	3.0	7.6	M_s	6	210	d_h	1	L	U	A
Tento *et al.* (1992)	Italy	137	-	40	4	6.6	M_L	3.2	170	d_f for $M_L \geq 5.7$, d_e otherwise	1	L	2	A
Theodulidis & Papazachos (1992)	Greece+16 foreign	105+16[30]	-	36+4	4.5 (7.2)	7.0 (7.5)	M_s, M_w, M_{JMA}	1 (48)	128 (236)	d_e	2	B	O	A
Boore *et al.* (1993) & Boore *et al.* (1997)	W. N. America	271	-	20	5.1[31]	7.7	M_w	0	118.2	d_f	3	L, G	2M	A
Campbell (1993)	Worldwide	U	-	U	U[32]	U	M_L for $M < 6.0$ and M_s otherwise	U	U[33]	d_s	2	M	O	A (T,S)
McVerry *et al.* (1993) & McVerry *et al.* (1995)	New Zealand	256	-	31*	5.1	7.3	M_w	13	312	d_c or d_h	1	L	1	A, R
Sadigh *et al.* (1993) & Sadigh *et al.* (1997)	California with 4 foreign	960+4	U	119+2	3.8 (6.8)	7.4 (7.4)	M_w	0.1 (3)	305 (172)[34]	d_r for some, d_h for small ones	2	G	U	A(R,S)
Singh *et al.* (1993)	Nicaragua, El Salvador & Costa Rica	89	-	27	3.0	7.6	M_s	6	210	d_h	1	V	O	A
Sun & Peng (1993)	W. USA with 1 foreign	150+1	-	42+1	4.1	7.7	M_L for $M < 6$, else M_s	2*	150*	d_e	C	R	1	A

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[30] Total number of components does not need to be multiplied by two

[31] Boore *et al.* (1997) revise this magnitude to 5.87. New minimum magnitude is 5.2.

[32] Considers equation valid for $M \geq 4.7$.

[33] Considers equation valid for $d \leq 300\,\mathrm{km}$.

[34] Equations stated to be for distances up to $100\,\mathrm{km}$

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
Ambraseys & Srbulov (1994)	Worldwide	947	-	76	5.0	7.7	M_s	1	375	d_f, d_e	1	L	2W	A
Boore *et al.* (1994a) & Boore *et al.* (1997)	W. N. America	271 (70)	-	20 (9)	5.1[35] (5.3)	7.7 (7.4)	M_w	0	118.2 (109)	d_f	C	L, G	1M, 2M	A (R,S)[36]
Fukushima *et al.* (1994) & Fukushima *et al.* (1995)	3 vertical arrays in Japan	285	284	42	5.0	7.7	M_{JMA}	60*	400*	d_h	I	B	1,2	A
Lawson & Krawinkler (1994)	W. USA	250+	-	11	5.8	7.4	M_w	U	100	d_f	3	U	1M	A
Lungu *et al.* (1994)	Romania	≈ 300	125	4	6.3	7.4	M_w	U	U	d_h	1	U	1	A
Musson *et al.* (1994)	UK + 30* foreign	15 + 30*	-	4+16	3 (3.7)	3.5 (6.4)	M_L	70* (>1.3)	>477.4 (200*)	d_h	1	U[37]	O	A
Radu *et al.* (1994), Lungu *et al.* (1995a) & Lungu *et al.* (1996)	Romania	106	-	3	6.7(M_L) or 7.0(M_w)	7.2(M_L) or 7.5(M_w)	U[38]	90*	320*	d_h	1	L	1	A
Ramazi & Schenk (1994)	Iran	83	83	20	5.1	7.7	M_s[39]	≤ 8	≥ 180	d_h for most, d_r for 19[40]	2	U	U	A
Xiang & Gao (1994)	Yunnan, China + 114 W. N. America	131+114	-	U	2.5*	7.6*	M_s (M_L)	2*	120*	d_e	1	L	U	A
Ambraseys (1995)	Europe and Mid. East	830	620	334	4.0	7.3	M_s	0*	260*	d_f for $M_s > 6.0$, d_e otherwise	1	L	2W	A
Dahle *et al.* (1995)	Cen. America	280	-	72	3*	8*	M_w (M_s, m_b,M_D)	6*	490*	d_h	2	L	1B	A

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[35] Boore *et al.* (1997) revise this magnitude to 5.87. New minimum magnitude is 5.2.

[36] Coefficients given in Boore *et al.* (1994b)

[37] Free (1996) believes it is largest horizontal component.

[38] It is not clear whether use Richter magnitude (M_L) or M_w.

[39] Some may be m_b because in their Table 1 some earthquakes to not have M_s given but do have m_b. If so new minimum is 5.0.

[40] They state it is 'closest distance from the exposure of ruptured part of the fault, instead of focal distances' so may not be rupture distance.

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
Lee *et al.* (1995)	W. N. America	1926	1926	297	1.7	7.7	Usually M_L for $M \leq 6.5$ and M_s for $M > 6.5$	2	200+	d_h	9, 3 × C	U	1	A
Lungu *et al.* (1995b)	Romania	106	-	3	6.7(M_L) or 7.0(M_w)	7.2(M_L) or 7.5(M_w)	U[41]	U	U	d_h	1	L	1	A
Molas & Yamazaki (1995)	Japan	2166	-	387	4.1*	7.8*	M_{JMA}	8*	1000*	d_r for 2 earthquakes, d_h otherwise	I	L	O	A
Sarma & Free (1995)	E. N. America[42]	77	-	33	2.8	5.9	M_w (m_b, M_L, M_s)	0	820	d_f or d_e	2	U	1	A
Ambraseys *et al.* (1996) & Simpson (1996)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	d_f for $M_s > 6.0$, d_e otherwise	3	L	2W[43]	A
Ambraseys & Simpson (1996) & Simpson (1996)	Europe & Mid. East	-	417	157	4.0	7.9	M_s (unspecified)	0	260	d_f for $M > 6.0$, d_e otherwise	3	-	2W[44]	A
Aydan *et al.* (1996)	Turkey	27*	23*	19*	3.5*	7.6*	M_s	10*	350*	d_h	1	U	1	A
Bommer *et al.* (1996)	El Salvador & Nicaragua	36	-	20	3.7	7.0	M_s	62	260	d_h	1	L	U	A
Crouse & McGuire (1996)	Cen. & S. California	238	-	16	6.0	7.7	M_s	0.1	211	d_r	4	G	1W	R,S (R,S)
Free (1996) & Free *et al.* (1998)	Stable continental regions	558	478	H: 222, V: 189	1.5	6.8	M_w	0	820	d_f for some, d_e for most	2	L	1	A

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[41] It is not clear whether use Richter magnitude (M_L) or M_w.

[42] Also derive equations for Australia and N. E. China

[43] Ambraseys *et al.* (1996) state it is two-stage of Joyner & Boore (1981) but in fact it is two-stage method of Joyner & Boore (1988).

[44] Ambraseys *et al.* (1996) state it is two-stage of Joyner & Boore (1981) but in fact it is two-stage method of Joyner & Boore (1988).

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
Ohno *et al.* (1996)	California	248	-	17	5.0	7.5	M_w (M_L)	7.2	99.6	d_q for $M > 5.3$, d_h otherwise	2	B	2M	A
Romeo *et al.* (1996)	Italy	95	-	17	4.6*	6.8*	M_w	1.5, 1.5	179, 180	Both d_f & d_e	2	L	1	A
Sarma & Srbulov (1996)	Worldwide	350	-	114	3.9	7.7	M_s	1	213	d_f & d_e	1	B, L	U	A
Singh *et al.* (1996)	Himalayas	86	-	5	5.7	7.2	m_b	33.15	340.97	d_h	1	U	1	A
Spudich *et al.* (1996) & Spudich *et al.* (1997)	Worldwide extensional regimes	128	-	30	5.10	6.90	M_w	0	102.1	d_f	2	G, O	2M	NS
Stamatovska & Petrovski (1996)	Romania, Bulgaria & former Yugoslavia	190[45]	-	4	6.1	7.2	M_L[46]	10*	310*	d_e	1	B	1	A
Campbell (1997), Campbell (2000), Campbell (2001) & Campbell & Bozorgnia (1994)	Worldwide	645	225	H:47, V:26	4.7	H:8.0, V:8.1	M_w	3	60	d_s	3	G	1	A(S,R,N)
Munson & Thurber (1997)	Hawaii	51	-	22	4.0	7.2	M_s for $M_s \geq 6.1$, M_L otherwise	0	88	d_f	2	L	2M	A
Rhoades (1997)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	1	L	O	A
Schmidt *et al.* (1997)	Costa Rica	200	-	57	3.3	7.6	M_w (M_s, m_b, M_D)	6.1	182.1	d_h	3	L, B	O	A
Youngs *et al.* (1997)	Worldwide subduction zones	476	-	164	5.0	8.2	M_w (M_s,m_b)	8.5	550.9	d_r, d_h for some	2	G	1M	NT
Zhao *et al.* (1997)	NZ with 66 foreign	461[47]+66	-	49+17	5.08	7.23(7.41)	M_w	11 (0.1)	573 (10)	d_r for some, d_c for most	2	U	1	A(R)

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[45] Total number of components. Does not need to be multiplied by two.

[46] Called Richter magnitude.

[47] Includes some not used for regression

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
Bouhadad *et al.* (1998)	Algeria	U	-	2	5.6	6.1	M_s	20	70	d_h	1	L, M	1	A
Costa *et al.* (1998)	Friuli	80*	80*	20*	1.3*	4.3*	M_D	3*	66*	d_h	1	U	1	A
Manic (1998)	N.W. Balkans	276[48]	-	56	4	7	M_s	U	U	d_h	2	B	1	A
Rinaldis *et al.* (1998)	Italy & Greece	137*	-	24*	4.5	7	M_s or M_w	7	138	d_e	2	U	O	A (N,ST)
Sadigh & Egan (1998)	California with 4 foreign	960+4	-	119+2	3.8	7.4	M_w	0.1	305[49]	d_r for some, d_h for small ones	2	G	U	A(R,SN)
Sarma & Srbulov (1998)	Worldwide	690[50]	-	113	3.9	7.7	M_s (U)	0	197	d_f, d_e	2	B	1	A
Sharma (1998)	Indian Himalayas	66	-	5	5.5	6.6	U	8	248	d_h	1	L	1W	A
Smit (1998)	Switzerland + some from S. Germany	$\ll$ 1546	<1546	H: <120, V: 120	2.0	5.1	M_L	1	290	d_h	1	U	2	A
Cabañas *et al.* (1999), Cabañas *et al.* (2000) & Benito *et al.* (2000)	Mediterranean region[51]	U	U	U	2.5	7.0	M_s[52]	0	250	d_e[53]	4	L	1	A
Chapman (1999)	W. N. America	304	-	23	5.0	7.7	M_w	0.1	189.4	d_f	3	G	2M	A
Cousins *et al.* (1999)	NZ with 66 foreign	610+66	-	25+17	5.17	7.09(7.41)	M_w	0.1	400	d_r for some, d_c for most	3	U	U	A(R)
Ólafsson & Sigbjörnsson (1999)	Iceland	88[54]	-	17	3.4	5.9	M_w[55]	2	112	d_e	1	B	1	A
Spudich *et al.* (1999)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	d_f	2	G, O	1M	NS
Wang *et al.* (1999)	Tangshan, N. China	44	-	6	3.7	4.9	M_s (M_L)	2.1	41.3	d_e	1	L	1	A

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[48] Total number of components do not need to be multiplied by two.

[49] Equations stated to be for distances up to $100\,\mathrm{km}$

[50] Total number of components do not need to be multiplied by two.

[51] Also derive equations for Spain.

[52] Also derive equations using M_L.

[53] Also derive equations using d_h.

[54] Total number of components. Does not need to be multiplied by two.

[55] Equation given in terms of $\log M_0$.

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
Zaré *et al.* (1999)	Iran	468	468	47*	2.7	7.4	M_w (M_s, m_b, M_L)	4	224	d_h (d_r for 2)	4	B	2M	R, RS & S
Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)	Worldwide	186	183	44	5.83	7.8	M_s	0	15	d_f	3	L	1	A
Bozorgnia *et al.* (2000)	Worldwide	2823	2823	48	4.7	7.7	M_w	U	$\leq$ 60	d_s	4	G	U	A (R,S,T)
Campbell & Bozorgnia (2000)	Worldwide	960[56]	941[57]	49[58]	4.7	7.7	M_w	1*	60*	d_s	4	G	1	A (S,R,T)
Jain *et al.* (2000)	Central Himalayas	32 (117)	-	3	5.5	7.0	U	2 (4)	152 (322)	d_e	1	U	1	T
Kobayashi *et al.* (2000)	Japan	U	-	U	5.0	7.8	M_w	0.9*	400*	U	4	B	1M	A
Monguilner *et al.* (2000a)	W. Argentina	54[59]	-	10[59]	4.3[59]	7.4	M_s if M_L & $M_s > 6$, M_L otherwise	11[59]	350[59]	d_h	2	U	1W	A
Sharma (2000)	Indian Himalayas	-	66	5	5.5	6.6	U	8	248	d_h	1	-	1W	A
Si & Midorikawa (2000)	Japan	856	-	21	5.8	8.3	M_w	0*	280*	Both d_q & d_r	2	L	O	A
Smit *et al.* (2000)	Caucasus	84	-	26	4.0	7.1	M_s	4	230	d_e[60]	1	L	2	A
Takahashi *et al.* (2000)	Japan+166 foreign	1332	-	U+7*	5* (5.8*)	8.3* (8*)	M_w	1* (0.1*)	300* (100*)	d_r, d_h for some	4	G	O	A
Wang & Tao (2000)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	d_f	2	L	O	A
Chang *et al.* (2001)	Taiwan	4720[61], 2528[62]	-	45[61], 19[62]	4.1[61], 4.6[62]	7.0[61], 6.3[62]	M_w (M_L for $M_L < 6.5$)	0[61], 40.2[62]	264.4[61], 272.4[62]	d_e[61], d_h[62]	1	G	2	A
Lussou *et al.* (2001)	Japan	3011	3011	102	3.7	6.3	M_{JMA}	4*	600*	d_h	4	B	2	A

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[56] Equation for corrected PGA uses 443 records.

[57] Equation for corrected PGA uses 439 records.

[58] Equation for corrected PGA uses data from 36 earthquakes.

[59] Assuming they use same data as Monguilner *et al.* (2000b).

[60] Smit *et al.* (2000) give d_h but this is typographical error (Smit, 2000).

[61] Shallow crustal records.

[62] Subduction records.

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
Chen & Tsai (2002)	Taiwan	424	-	48	U	U	M_L	U	U	d_h	1	U	O	A
Gregor *et al.* (2002)	Shallow crustal worldwide (mainly California)	993	993	68	4.4	7.4	M_w	0.1	267.3	d_r	2	U	1M	A (S, R/O, T)
Gülkan & Kalkan (2002)	Turkey	93[63]	-	19	4.5	7.4	M_w	1.20	150	d_f, d_e	3	L, R	1	A
Khademi (2002)	Iran	160	160	28*	3.4*	7.4	M_w (m_b for $M_s < 5$ and M_s otherwise)	0.1*	180*	d_f, d_e for $M < 5.9$	2	L	O	A
Margaris *et al.* (2002a) & Margaris *et al.* (2002b)	Greece	744	-	142	4.5	7.0	M_w	1	150	d_e	3	B	O	A
Schwarz *et al.* (2002)	N.W. Turkey	683	683	U	0.9*	7.2	M_L	0*	250*	d_e	3	U	1	A
Stamatovska (2002)	Romania	190[64]	-	4	6.1	7.2	U	10*	310*	d_e	1	B	1	A
Tromans & Bommer (2002)	Europe	249	-	51	5.5	7.9	M_s	1	359	d_f	3	L	2	A
Zonno & Montaldo (2002)	Umbria-Marche	161	-	15	4.5	5.9	M_L	2*	100*	d_e	2	L	2	N, O
Alarcón (2003)	Colombia	47	-	U	4.0	6.7	M_s	49.7	322.4	d_h	1	U	U	A
Alchalbi *et al.* (2003)	Syria	49	49	10	3.5	5.8	M_{CL}	21	400	d_h	2	U	1	A
Atkinson & Boore (2003)	Subduction zones	1200+	-	43*	5.5	8.3	M_w	11*	550*	d_r	4	C	1M	F, B
Boatwright *et al.* (2003)	N. California	4028	-	104	3.3	7.1	Mainly M_w, M_L for some	1*	370*	d_h	4	U	O	A
Bommer *et al.* (2003)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	d_f for $M_s > 6.0$, d_e otherwise	3	L	1M	A (S, R, N)

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[63] This is total number of horizontal components used. They come from 47 triaxial records.

[64] This is total number of components. Does not need to be multiplied by two.

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
Campbell & Bozorgnia (2003c), Campbell & Bozorgnia (2003a) & Bozorgnia & Campbell (2004b)	Worldwide	443[65]	439[66]	36[67]	4.7	7.7	M_w	2*	60*	d_s	4	G	1	A (S & N, R, T)
Sigbjörnsson & Ambraseys (2003)	Europe & Middle East	465	-	U	5*	7*	M_w or M_s	1*	500*	d_f if available, d_e otherwise	1	L	1	S

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[65] There are 960 components for uncorrected PGA.

[66] There are 941 components for uncorrected PGA.

[67] For horizontal corrected records. There are 49 for horizontal uncorrected PGA. There are 34 for vertical corrected records and 46 for vertical uncorrected PGA.

5. SUMMARY OF PUBLISHED ATTENUATION RELATIONS FOR SPECTRAL ORDINATES

5.1 *Johnson (1973)*

- Ground motion model is:

$$\mathrm{PSRV} = C10^{\alpha m_b} R^m$$

- Response parameter is pseudo-velocity for 5% damping.
- Most (76%) records from $R < 70\,\mathrm{km}$.
- Uses only shallow focus earthquakes of 'normal' or less depth, to minimize variables, except for one record from deeper earthquake ($m_b = 6.5$, $R = 61.1\,\mathrm{km}$) which produces no distortion in statistical calculations.

5.2 *Kobayashi & Nagahashi (1977)*

- Ground motion model is:

$$\log_{10} S_{V0} = a(\omega)M - b(\omega)\log_{10} x - c(\omega)$$

- Response parameter is velocity for unspecified[1] damping.
- Do regression iteratively. Assume $a(\omega)$, $b(\omega)$ and $c(\omega)$. Find amplification factors, $G_i(\omega)$, for each response spectra, $R_i(\omega)$: $G_i = R_i(\omega)/S_{V0}$. Calculate amplification factor, G, for each site: $G = \sqrt[n]{\prod_{i=1}^{n} G_i(\omega)}$. Estimate bedrock spectrum, $B_i(\omega)$, for each record: $B_i(\omega) = R_i(\omega)/G(\omega)$. Find $a(\omega)$, $b(\omega)$ and $c(\omega)$ by least squares. Repeat these steps until convergence. Hence find attenuation relation for bedrock and amplification function for each site.

5.3 *McGuire (1977)*

- See Section 3.13.
- Response parameter is pseudo-velocity for 0, 2, 5 and 10% damping.
- Residuals pass Kolmogorov-Smirnov goodness-of-fit test at 5% significance level for normal distribution, so it is concluded that pseudo-velocities are lognormally distributed.

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[1] It is probably 5%.

- Feels that using 16 natural periods presents a very good picture of spectral trends throughout entire period range.
- Only gives graphs of coefficients not actual calculated values.

5.4 Trifunac (1977) & Trifunac & Anderson (1978a)

- Ground motion model is:

  $$\log_{10}[\mathrm{SA}(T), p] = M + \log_{10} A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v - f(T)M^2 - g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.

- Uses three site categories:

$s = 0$ Alluvium. 63% of data.
$s = 1$ Intermediate. 23% of data.
$s = 2$ Basement rock. 8% of data.

- Response parameter is acceleration for 0, 2, 5, 10 and 20% damping.
- Note that do not believe the chosen independent parameters are the best physical characterization of strong shaking but they are based on instrumental and qualitative information available to the engineering community in different parts of the USA and the world.
- Data from free-field stations and basements of tall buildings, which assume are not seriously affected by the surroundings of the recording station. Note that detailed investigations will show that data from basements of tall buildings or adjacent to some other large structure are affected by the structures but do not consider these effects.
- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1 - b(T)]/2f(T)$. For $M > M_{\max}$ replace $f(T)M^2$ by $f(T)(M - M_{\max})^2$ and for $M < M_{\min}$ replace M by $M_{\min}$ everywhere to right of $\log_{10} A_0(R)$.
- Use almost same data as Trifunac (1976). See Section 3.11.
- Use same regression method as Trifunac (1976). See Section 3.11.
- Note that need to examine extent to which computed spectra are affected by digitization and processing noise. Note that routine band-pass filtering with cut-offs of 0.07 and $25\,\mathrm{Hz}$ or between 0.125 and $25\,\mathrm{Hz}$ may not be adequate because digitisation noise does not have constant spectral amplitudes in respective frequency bands and because noise amplitudes depend on total length of record.

- Find approximate noise spectra based on 13 digitisations of a diagonal line processed using the same technique used to process the accelerograms used for the regression. Linearly interpolate noise spectra for durations of 15, 30, 60 and $100\,\mathrm{s}$ to obtain noise spectra for duration of record and then subtract noise spectrum from record spectrum. Note that since $\mathrm{SA}(y_1 + y_2) \neq \mathrm{SA}(y_1) + \mathrm{SA}(y_2)$ this subtraction is an approximate method to eliminate noise which, empirically, decreases the distortion by noise of the SA spectra when the signal-to-noise ratio is small.

- Note that p is not a probability but for values of p between 0.1 and 0.9 it approximates probability that $\mathrm{SA}(T)_{,p}$ will not be exceeded given other parameters of the regression.

- $-g(T)R$ term represents a correction to average attenuation which is represented by $\log_{10} A_0(R)$.

- Do not use data filtered at $0.125\,\mathrm{Hz}$ in regression for $T > 8\,\mathrm{s}$.

- Due to low signal-to-noise ratio for records from many intermediate and small earthquakes only did regression up to $12\,\mathrm{s}$ rather than $15\,\mathrm{s}$.

- Smooth coefficients using an Ormsby low-pass filter along the $\log_{10} T$ axis.

- Only give coefficients for 11 selected periods. Give graphs of coefficients for other periods.

- Note that due to the small size of $g(T)$ a good approximation would be $\log A_0(R) + R/1000$.

- Note that due to digitisation noise, and because subtraction of noise spectra did not eliminate all noise, $b(T)$, $c(T)$ and $f(T)$ still reflect considerable noise content for $T > 1 - -2\,\mathrm{s}$ for $M \approx 4.5$ and $T > 6 - -8\,\mathrm{s}$ for $M \approx 7.5$. Hence predicted spectra not accurate for periods greater than these.

- Note that could apply an optimum band-pass filter for each of the accelerograms used so that only selected frequency bands remain with a predetermined signal-to-noise ratio. Do not do this because many data points would have been eliminated from analysis which already has only a marginal number of representative accelerograms. Also note that such correction procedures would require separate extensive and costly analysis.

- Note that low signal-to-noise ratio is less of a problem at short periods.

- Compare predicted spectra with observed spectra and find relatively poor agreement. Note that cannot expect using only magnitude to characterise source will yield satisfactory estimates in all cases, especially for complex earthquake mechanisms. Additional parameters, such as a better distance metric than epicentral distance and inclusion of radiation pattern and direction and velocity of propagating dislocation, could reduce scatter. Note, however, that such parameters could be difficult to predict *a priori* and hence may be desirable to use equations no more detailed than those proposed so that empirical models do not imply smaller uncertainties than those associated with the input parameters.

- Plot fraction of data points, p_a which are smaller than spectral amplitude predicted for p values between 0.1 and 0.9. Find relationship between p_a and p. Note that response spectral amplitudes should be nearly Rayleigh distributed, hence $p_a(T) = \{1 - \exp[-\exp(\alpha(T)p + \beta(T)]\}^{N(T)}$. Find α, β and N by regression and smoothed by eye. $N(T)$ should correspond to the number of peaks of the response of a single-degree-of-freedom system with period T but best-fit values are smaller than the value of $N(T)$ derived from independent considerations.

5.5 Faccioli (1978)

- See Section 3.17.
- Response parameter is pseudo-velocity for 5% damping.
- Plots all spectra. 2 records have abnormally high values in long period range, so remove and repeat. Results practically unaffected so leave them in.
- Notes that due to small size of sample, site and source correlation can introduce some error in coefficients because all data treated as statistically independent. Assume correlations are small so neglect error.

5.6 McGuire (1978)

- See Section 3.18.
- Response parameter is pseudo-velocity for 2% damping.

5.7 Trifunac (1978) & Trifunac & Anderson (1978b)

- Ground motion model is (from definition of local magnitude scale):

  $$\log[\mathrm{PSV}(T)_{,p}] = M + \log A_0(R) - a(T)p - b(T)M - c(T) - d(T)s - e(T)v - f(T)M^2 - g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses three site categories:

  $s = 0$ Alluvium. 63% of data.

  $s = 1$ Intermediate. 23% of data. Notes that ideally would not need but had to be introduced because in some cases difficult to make a choice in complex geological environment or because of insufficient data.

  $s = 2$ Basement rock. 8% of data.
- Use same data as Trifunac & Anderson (1978a). See Section 5.4.

- Use same regression method as Trifunac & Anderson (1978a). See Section 5.4.
- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1-b(T)]/2f(T)$. For $M > M_{\max}$ replace M by $M_{\max}$ everywhere and for $M < M_{\min}$ replace M by $M_{\min}$ in $b(T)M$ and $f(T)M^2$. This gives linear growth for $M < M_{\min}$, parabolic growth for $M_{\min} \leq M \leq M_{\max}$ and constant amplitude for $M > M_{\max}$.
- 98 records from San Fernando earthquake (9/2/1971) but regression method eliminated 70% of these before computing the coefficients.
- Epicentral distance used for simplicity, consistency with earlier studies and for lack of significantly better choice. Distance measure chosen has small effect whenever epicentral distance greater than several source dimensions.
- Notes that recording and processing noise in signal means that quality of coefficients diminishes for $T > 2\,\mathrm{s}$. Equations not recommended for periods longer than those for which selected spectral amplitudes plotted.
- Notes that equations should be considered only as preliminary and an empirical approximation to a complicated physical problem.
- Notes that data are limited to narrow magnitude interval, most data comes from alluvium sites and about half comes from one earthquake.
- Only gives coefficients for 11 periods. Graphs of coefficients for other periods.

5.8 Trifunac & Anderson (1978c)

- Ground motion model is (from definition of local magnitude scale):

  $$\log[\mathrm{PSV}(T)_{,p}] = M+\log A_0(R)-a(T)p-b(T)M-c(T)-d(T)s-e(T)v-f(T)M^2-g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, p is confidence level and v is component direction ($v = 0$ for horizontal and 1 for vertical). $\log A_0(R)$ not given here due to lack of space.
- Response parameter is velocity for 0, 2, 5, 10 and 20% damping.
- Uses three site categories:

  $s = 0$ Alluvium. 63% of data.

  $s = 1$ Intermediate. 23% of data. Notes that ideally would not need but had to be introduced because in some cases difficult to make a choice in complex geological environment or because of insufficient data.

  $s = 2$ Basement rock. 8% of data.
- Use same data as Trifunac & Anderson (1978a). See Section 5.4.

- Use same regression method as Trifunac & Anderson (1978a). See Section 5.4.
- Equation constrained to interval $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b(T)/2f(T)$ and $M_{\max} = [1-b(T)]/2f(T)$. For $M > M_{\max}$ replace M by $M_{\max}$ everywhere and for $M < M_{\min}$ replace M by $M_{\min}$ in $b(T)M$ and $f(T)M^2$. This gives linear growth for $M < M_{\min}$, parabolic growth for $M_{\min} \leq M \leq M_{\max}$ and constant amplitude for $M > M_{\max}$.
- Only gives coefficients for 11 periods. Graphs of coefficients for other periods.

5.9 *Cornell* et al. *(1979)*

- See Section 3.20.
- Response parameter is pseudo-velocity for 0, 2 and 10% damping.
- Consider different paths, e.g. going through intensities, Fourier spectra and PGA, to predict PSV. Note that direct paths have minimum variance but that going through intermediate steps does not significantly increase prediction uncertainty provided that intermediate parameters are representative of frequency band of structural system.
- Do not give coefficients.

5.10 *Trifunac & Lee (1979)*

- Ground motion model is:

  $$\log_{10} \mathrm{PSV}(T) = M + \log_{10} A_0(R) - b(T)M - c(T) - d(T)h - e(T)v - f(T)M^2 - g(T)R$$

  where $\log A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L and v is component direction ($v = 0$ for horizontal 1 for vertical).
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Use depth of sedimentary deposits, h, to characterise local geology.
- Depths of sedimentary and alluvial deposits at stations used are between 0 and about $6\,\mathrm{km}$ and most are less than about $4\,\mathrm{km}$.
- Use data and regression technique of Trifunac & Anderson (1978a), see Section 5.4.
- Note no obvious physical reason why dependence of PSV on h should be linear. Try including terms with h^2, h^3 and higher powers of h but they lead to values which are undistinguishable from zero at 95% confidence level.
- Approximate significance tests show that coefficients are significantly different from zero in large subregions of the complete period range.
- Only give coefficients for 11 periods. Graphs of coefficients for other periods.

- Note results are only preliminary.
- Note amount of data too small to include more sophisticated independent parameters.

5.11 Ohsaki et al. (1980b)

- Ground motion model is:

$$\log S_v = a'M - b'\log x - c'$$

- Response parameter is velocity for 5% damping.
- Use two soil conditions:

Group A Hard rock: geology consists of granite, andesite and shale of Miocene or earlier geological age, having S wave velocity $\gtrsim 1500\,\mathrm{ms}^{-1}$ or P wave velocity $\gtrsim 3000\,\mathrm{ms}^{-1}$, 60 records

Group B Rather soft rock: geology consists of mudstone of Pliocene or late Miocene age, having S wave velocity of about 500–$1000\,\mathrm{ms}^{-1}$, 35 records.

- Use records where geological and geotechnical conditions investigated in detail and considered to represent free-field rock motions. Exclude records suspected to be amplified by surface soil or affected by high topographical relief.
- Most records from $\geq 30\,\mathrm{km}$.
- Do regression on both site categories separately and give graphs of coefficients not tables.

5.12 Ohsaki et al. (1980a)

- See Section 3.24.
- Response parameter is velocity for 5% damping.
- Also give smoothed results using correction factors based on derived PGV equation.

5.13 Trifunac (1980)

- Ground motion model is:

$$\log_{10}\mathrm{PSV}(T) = \begin{cases} M - \log_{10} A_0(R) - b(T)M_{\min} - c(T) - d(T)h - e(T)v \\ \quad - f(T)M_{\min}^2 - g(T)R \\ \quad \text{for } M \leq M_{\min} \\ M - \log_{10} A_0(R) - b(T)M - c(T) - d(T)h - e(T)v \\ \quad - f(T)M^2 - g(T)R \\ \quad \text{for } M_{\min} < M < M_{\max} \\ M_{\max} - \log_{10} A_0(R) - b(T)M_{\max} - c(T) - d(T)h - e(T)v \\ \quad - f(T)M_{\max}^2 - g(T)R \\ \quad \text{for } M \geq M_{\max} \end{cases}$$

where $\log_{10} A_0(R)$ is an empirically determined attenuation function from Richter (1958) used for calculation of M_L, v is component direction ($v = 0$ for horizontal and 1 for vertical), $M_{\min} = -b(T)/(2f(T))$ and $M_{\max} = (1 - b(T))/(2f(T))$.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Characterises site condition by depth of sedimentary and alluvial deposits beneath station, h. Uses records with $0 \leq h \leq 6\,\mathrm{km}$, with most $< 4\,\mathrm{km}$.
- Performs analysis to minimize possible bias due to uneven distribution of data among magnitude, site conditions and from abundance of data for some earthquakes.
- Tries terms with higher powers of h but coefficients are undistinguishable from zero at 95% confidence level.
- Assumes probability that $\log_{10}\mathrm{PSV}(T) - \log_{10}\bar{\mathrm{PSV}}(T) \leq \epsilon$, where $\log_{10}\mathrm{PSV}(T)$ is measured PSV and $\bar{\mathrm{PSV}}(T)$ is predicted PSV and ϵ is a probability, can be expressed as $p(\epsilon, T) = [1 - \exp(-\exp(\alpha(T)\epsilon(T) + \beta(T)))]^{N(T)}$. This assumption passes Kolmogorov-Smirnov and χ^2 tests at 95% level.
- Finds $a(T)$ through $g(T)$ significantly different than zero for large subregions of whole period range. $d(T)$ is only significantly different than zero for $T \gtrsim 0.3\,\mathrm{s}$.
- Gives coefficients of smoothed results for 11 periods.
- Notes only preliminary. Improvements should be based on physical nature of phenomenon using a functional form predicted by theory and experiment but due to lack of data cannot be done.

5.14 Devillers & Mohammadioun (1981)

- Ground motion model is:

$$V(f) = C 10^{\alpha M} R^n$$

- Response parameter is pseudo-velocity for 2, 5, 10 and 20% damping.
- Most records from between 20 and $40\,\mathrm{km}$. No records from $R < 10\,\mathrm{km}$ so equation does not apply there.
- Eliminate suspect and/or redundant (San Fernando) records.
- Split data into intensity groups: VI (126 records), VII (56 records), V+VI (186 records), VI+VII (182 records) and VII+$\geq$ VIII (70 records) and calculates coefficients for each group.
- Note not adjusted for local site conditions. Try to distinguish effect but correlations do not reveal significant variations. Notes very few records on hard rock.
- Do not give coefficients only graphs of results.

5.15 Kobayashi & Midorikawa (1982)

- Ground motion model is:

$$\begin{aligned}\log \mathrm{Sv}_0(T) &= a(T)(\log M_0 - c) - b(T)\log X + d\\ \text{where } a(T) &= a_1 + a_2 \log T\\ \text{and: } b(T)) &= \begin{cases} b_1(\log T)^2 + b_2 \log T + b_3 & \text{for: } 0.1 \leq T \leq 0.3\,\mathrm{s}\\ b_4 - b_5 \log T & \text{for: } 0.3 \leq T \leq 5\,\mathrm{s}\end{cases}\end{aligned}$$

- Response parameter is velocity for 5% damping.
- Magnitudes converted to seismic moment, M_0, by using empirical formula.
- Observed surface spectra divided by amplification over bedrock (assumed to have shear-wave velocity of $3\,\mathrm{kms}^{-1}$), calculated for each of the 9 sites.
- Note equation not for near field because earthquake is not a point source.

5.16 Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)

- See Section 3.32.
- Use data from Joyner & Boore (1982).
- Response parameter is pseudo-velocity for 5% damping.
- shear-wave velocity not significant, at 90%, for periods 0.1, 0.15 and $0.2\,\mathrm{s}$ but significant for longer periods.
- Regression using shear-wave velocity and depth to rock shows significant correlation (decreasing ground motion with increasing depth) for long periods but small coefficients. Short periods do not show significant correlation.
- State inappropriate to use depth to rock for present data due to limited correlation and because San Fernando data is analysed on its own does not show significant correlation.

5.17 Kawashima et al. (1984)

- See Section 3.33.
- Response parameter is acceleration for 5% damping.

5.18 Kawashima et al. (1985)

- See section 3.38.
- Response parameter is acceleration for 5% damping.
- Variation of a and b with respect to T is due to insufficient number of records.

5.19 Trifunac & Lee (1985)

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

  $$\log \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + b_3(T)v + b_5(T) + b_6(T)M^2$$

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

  $$\log \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)h + b_3(T)v + b_5(T) + b_6(T)M^2$$

  where

  $$\begin{aligned}\mathrm{Att}(\Delta, M, T) &= \begin{cases} A_0(T)\log_{10}\Delta & \text{for} \quad R \leq R_{\max} \\ A_0(T)\log_{10}\Delta_{\max} - (R - R_{\max})/200 & \text{for} \quad R > R_{\max}\end{cases} \\ \Delta &= S\left(\ln\frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2}\right)^{-1/2} \\ \Delta_{\max} &= \Delta(R_{\max}, H, S) \\ R_{\max} &= \frac{1}{2}(-\beta + \sqrt{\beta^2 - 4H^2})\end{aligned}$$

  $S_0 = S_0(T)$ represents the coherence radius of the source and can be approximated by $S_0 \sim C_sT/2$, C_s is shear-wave velocity in source region (taken to be $1\,\mathrm{kms}^{-1}$), T is period, S is 'source dimension' approximated by $S = 0.2$ for $M < 3$ and $S = -25.34 + 8.151M$ for $3 \leq M \leq 7.25$ and v is component direction ($v = 0$ for horizontal 1 for vertical).

- Use two types of site parameter:
  - Local geological site classification:

    $s = 0$ Sites on sediments.

    $s = 1$ Intermediate sites.

    $s = 2$ Sites on basement rock.
  - Depth of sediments from surface to geological basement rock beneath site, h.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.

- Equations only apply in range $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_1(T)/(2b_6(T))$ and $M_{\max} = -(1 + b_1(T))/(2b_6(T))$. For $M < M_{\min}$ use M only in first term of equation and $M_{\min}$ elsewhere and for $M > M_{\max}$ using $M_{\max}$ everywhere.

- Screen data to minimize possible bias in the model, which could result from uneven distribution of data among the different magnitude ranges and site conditions, or from excessive contribution to the database from several abundantly recorded earthquakes.

- Originally include a term linear in Δ, i.e. $b_4(T)\Delta/100$, but find that $b_4(T)$ is insignificant for most periods so deleted it.

- Use method of Trifunac & Anderson (1978a) for residuals, see Section 5.4.

5.20 Kamiyama & Yanagisawa (1986)

- Ground motion model is:

  $$\log_{10} V(T) = a(T)M_J - b(T)\log_{10}(\Delta+30) - d(T)D - c(T) + A_1(T)S_1 + \ldots + A_{N-1}(T)S_{N-1}$$

  where $S_i = 1$ for ith site and 0 otherwise.

- Response parameters are acceleration, velocity and displacement for 0, 2, 5 and 10% damping

- Model site amplification of each of the 26 sites individually by using S_i. Choose one site as bed rock site, which has S-wave velocity of about $1000\,\mathrm{ms}^{-1}$.

- Use records with PGA$>20\mathrm{gal}$ $(0.2\,\mathrm{ms}^{-2})$.

- Focal depths, D, between 0 and $130\,\mathrm{km}$, with most between 10 and $50\,\mathrm{km}$.

- Find no significant differences between site amplification spectra for different response parameters or different damping levels.

- Compare amplification spectra from regression for different sites with those predicted using S-wave theory and find good agreement.

- Coefficients only given for velocity for 5% damping.

5.21 C.B. Crouse (1987) reported in Joyner & Boore (1988)

- See Section 3.43.

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

5.22 Lee (1987) & Lee (1993)

- Ground motion model is:

  $$\begin{aligned}
  \log_{10}[\widehat{\mathrm{PSV}}(T)] &= M_< + \mathrm{Att}(\Delta, M, T) + \hat{b}_1(T)M_{<>} + \hat{b}_2(T)h + \hat{b}_3(T)v \\
  &\quad + \hat{b}_4(T)hv + \hat{b}_5(T) + \hat{b}_6(T)M_{<>}^2 + \hat{b}_7^{(1)}(T)S_L^{(1)} + \hat{b}_7^{(2)}(T)S_L^{(2)} \\
  \text{where } M_< &= \min(M, M_{\max}) \\
  M_{<>} &= \max(M_{\min}, M_<) \\
  M_{\min} &= -\hat{b}_1/(2\hat{b}_6(T)) \\
  M_{\max} &= -(1+\hat{b}_1(T))/(2\hat{b}_6(T))
  \end{aligned}$$

  where $v = 0$ for horizontal component, 1 for vertical, h is depth of sedimentary deposits beneath recording station and $\mathrm{Att}(\Delta, M, T)$ is same as Trifunac & Lee (1989) (see Section 5.30).

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.

- Uses three site categories:

$S_L = 0$ Rock: 1 sediment site ($h > 0$), 11 intermediate sites ($h \sim 0$) and 13 bedrock sites ($h = 0$) $\Rightarrow S_L^{(1)} = 0$ & $S_L^{(2)} = 0$.

$S_L = 1$ Stiff soil ($\leq 45 - 60\,\mathrm{m}$ deep): 37 sediment sites ($h > 0$), 24 intermediate sites ($h \sim 0$) and 3 bedrock sites ($h = 0$) $\Rightarrow S_L^{(1)} = 1$ & $S_L^{(2)} = 0$.

$S_L = 2$ Deep soil: 44 sediment sites ($h > 0$) and 2 intermediate sites ($h \sim 0$) $\Rightarrow S_L^{(1)} = 0$ & $S_L^{(2)} = 1$.

- For $M > 6.5$ uses different (unspecified) magnitude scales because for seismic risk analysis often catalogues do not specify scale and often estimates are not homogeneous.
- Free-field records with both soil and alluvial depth information.
- Screens data to minimize possible bias due to uneven distribution of soil classification or excessive contribution from several abundantly recorded earthquakes.
- Gives smoothed coefficients for 12 periods.
- Uses method of Trifunac (1980) for uncertainties.
- Also uses method where site coefficients, $\hat{b}_7^{(1)}$ & $\hat{b}_7^{(2)}$, are found from residues from equation without site coefficients; find similar results.

5.23 K. Sadigh (1987) reported in Joyner & Boore (1988)

- See Section 3.46.
- Response parameter is pseudo-acceleration for 5% damping.

5.24 Annaka & Nozawa (1988)

- See Section 3.49.
- Response parameter is acceleration for 5% damping.
- Give only graphs of coefficients.

5.25 Crouse et al. (1988)

- Ground motion model is:

$$\ln[\mathrm{PSV}(T)] = a + bM + c\ln[R] + dh$$

- Most data from shallow stiff soil and sedimentary deposits between about 5 and $25\,\mathrm{m}$ deep on Tertiary or older bedrock.

- Response parameter is pseudo-velocity for 5% damping.
- All earthquakes from Benioff-Wadati zones.
- Exclude data with magnitudes or distances well outside range of most selected records.
- Focal depths, h between 14 and $130\,\mathrm{km}$.
- No strong correlations between h, R and M.
- Try terms eM^2 and fR but find not significant (using t-test).
- Try term $R + C_1 \exp(C_2 M)$ instead of R; find similar standard errors.
- Find d is insignificant for 0.6 to $2\,\mathrm{s}$; find d does not significantly reduce standard errors.
- Find residuals are normally distributed (by plotting on normal probability paper and by Kolmogorov-Smirnov test).
- Split data by fault mechanism (thrust: 49 records, normal: 11 records, strike-slip: 4 records) and find attenuation equation for each subset; results are not significantly different (at 95% using F test). Also check by examining normal deviates (normalised residuals) for each subset and period; find no significant differences.
- Use 131 records from six other subduction zones (Nankai, Kuril, Alaska, Peru/N. Chile, Mexico and New Britain/Bougainville) to examine whether ground motions from all subduction zones are similar.
- Examine normal deviates for residuals between other zones' ground motion and N. Honshu equation. Find no significant differences (although obtain significant results for some periods and focal mechanisms) between N. Honshu, Kuril and Nankai motions. Find differences for Alaskan and Mexican data but could be due to site effects (because some data from soft soil sites). Find differences for Peru/N. Chile and New Britain/Bougainville which are probably source effects.
- Plot seismotectonic data (age, convergence rate, dip, contact width, maximum subduction depth, maximum historical earthquake (M_w), maximum rupture length, stress drop and seismic slip) against decreasing ground motion at stiff sites for $T > 0.8\,\mathrm{s}$. Find weak correlations for stress drop and M_w (if ignore Mexican data) but due to variability in stress drop estimates note lack of confidence in results.

5.26 Petrovski & Marcellini (1988)

- See Section 3.55.
- Response parameter is relative pseudo-velocity for 0.5%, 2%, 5% and 10% damping.

5.27 Yokota et al. (1988)

- Ground motion model is:

$$\log S_v(T) = a(T)M + b(T)\log X + c(T)$$

- Response parameter is velocity for 5% damping.
- Focal depths between about 20 and $100\,\mathrm{km}$.
- Records from two stations in lowlands of Tokyo $3.7\,\mathrm{km}$ apart.
- Also analyse another region, using 26 records from 17 earthquakes with distances between 95 and $216\,\mathrm{km}$. Note difference in results between regions.
- Analyses vertical spectra from three small regions separately, one with 24 records with $4.0 \leq M \leq 6.1$ and $60 \leq X \leq 100\,\mathrm{km}$, one with 22 records with $4.2 \leq M \leq 6.0$ and $68 \leq X \leq 99\,\mathrm{km}$ and one with 5 records with $4.4 \leq M \leq 6.0$ and $59 \leq X \leq 82\,\mathrm{km}$.
- Give no coefficients, only results.

5.28 Youngs et al. (1988)

- See Section 3.58.
- Ground motion model is:

$$\ln(S_v/a_{\max}) = C_6 + C_7(C_8 - M_w)^{C_9}$$

- Response parameter, S_v, is velocity[2] for 5% damping
- Develop relationships for ratio $S_v/a_{\max}$ because there is a much more data for PGA than spectral ordinates and use of ratio results in relationships that are consistent over full range of magnitudes and distances.
- Calculate median spectral shapes from all records with $7.8 \leq M_w \leq 8.1$ (choose this because abundant data) and $R < 150\,\mathrm{km}$ and one for $R > 150\,\mathrm{km}$. Find significant difference in spectral shape for two distance ranges. Since interest is in near-field ground motion use smoothed $R < 150\,\mathrm{km}$ spectral shape. Plot ratios $[S_v/a_{\max}(M_w)]/[S_v/a_{\max}(M_w = 8)]$ against magnitude. Fit equation given above, fixing $C_8 = 10$ (for complete saturation at $M_w = 10$) and $C_9 = 3$ (average value obtained for periods $> 1\,\mathrm{s}$). Fit C_7 by a linear function of $\ln T$ and then fix C_6 to yield calculated spectral amplifications for $M_w = 8$.
- Calculate standard deviation using residuals of all response spectra and conclude standard deviation is governed by equation derived for PGA.

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[2] In paper conversion is made between S_v and spectral acceleration, S_a, suggesting that it is pseudo-velocity.

5.29 Kamiyama (1989)

- Ground motion model is:

$$\log_{10} V(\omega) = \log_{10} M_0 - a(\omega)\log_{10} r + b(\omega)\log_{10} L + e(\omega)r + c(\omega) + \sum_{j=1}^{N-1} A_j(\omega)S_j$$

  where $S_j = 1$ for site j and $S_j = 0$ otherwise.

- Response parameter is velocity for 0% damping.
- Uses same data as Kamiyama & Yanagisawa (1986).
- Uses same regression method as Kamiyama & Yanagisawa (1986).
- Focal depths between 0 and $130\,\mathrm{km}$.
- Uses fault length, L, for 52 records. For others where such data does not exist uses $M_0 = 10^{(1.5\log_{10} S+22.3)}$, $S = 10^{M-4.07}$ and $L = \sqrt{S/2}$ where S is fault area in km^2.
- Chooses hard slate site with shear-wave velocity of 1–$2\,\mathrm{kms}^{-1}$ as 'basic site'.
- Does not give coefficients, only graphs of coefficients.

5.30 Trifunac & Lee (1989)

- Ground motion model is:

$$\begin{aligned}
\log_{10}[\mathrm{PSV}(T)] &= M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)h + b_3(T)v + b_5(T) \\
&\quad + b_6(T)M^2 \\
\text{where } \mathrm{Att}(\Delta, M, T) &= A_0(T)\log_{10}\Delta \\
A_0(T) &= \begin{cases} -0.732025 & \text{for:} \quad T > 1.8\,\mathrm{s} \\ -0.767093 + 0.271556\log_{10} T - 0.525641(\log_{10} T)^2 \\ \hfill \text{for:} \quad T < 1.8\,\mathrm{s} \end{cases} \\
\Delta &= S\left(\ln\frac{R^2 + H^2 + S^2}{R^2 + H^2 + S_0^2}\right)^{-1/2} \\
S &= 0.2 + 8.51(M - 5)
\end{aligned}$$

  where $v = 0$ for horizontal component and 1 for vertical, Δ is representative distance, S_0 is correlation radius of source function (or coherence size of source) (which can be approximated by $C_sT/2$, where C_s is shear wave velocity), h is depth of sedimentary deposits beneath recording station and H is focal depth.

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Screen data to minimize possible bias due to uneven distribution of data among different magnitude ranges and site conditions or from excessive contribution to database from several abundantly recorded earthquakes.

- Include term, $b_4(T)\Delta/100$, but insignificant for most periods so remove.
- Equation only applies for $M_{\min} \leq M \leq M_{\max}$, where $M_{\min} = -b_1(T)/(2b_6(T))$ and $M_{\max} = -(1+b_1(T))/(2b_6(T))$. For $M \leq M_{\min}$ use $M_{\min}$ everywhere except first term. For $M \geq M_{\max}$ use $M_{\max}$ everywhere.
- Use method of Trifunac (1980) for uncertainties.
- Note estimates should only be used where signal to noise ratio (based on estimated digitisation noise) not much less than unity or slope in log-log scale is not significantly greater than -1.
- Also fit data to $\log_{10} \mathrm{PSV}(T) = M + \mathrm{Att}(\Delta, M, T) + b_1(T)M + b_2(T)s + b_3(T)v + b_5(T) + b_6(T)M^2$ (where $s = 0$ for sediment sites, 1 for intermediate sites and 2 for basement rock sites) because depth of sediment not always known.

5.31 Atkinson (1990)

- Ground motion model is:

$$\log y = c_1 + c_2(\mathbf{M} - 6) + c_3(\mathbf{M} - 6)^2 - \log R - c_4 R$$

- Response parameter is pseudo-velocity for 5% damping.
- All data from rock sites.
- Includes only if a reliable seismic moment estimate exists.
- Converts ECTN vertical seismograms to equivalent horizontal component by multiplying by 1.4.
- Includes Nahanni (western Canada) earthquakes because exhibit dominant characteristics of eastern North American shocks (low seismicity area, high horizontal compressive stress, thrust mechanisms dominant, no surface ruptures despite shallow focus and rocks have high seismic velocity).
- Excludes US digital strong-motion Saguenay records due to low resolution. Two effects on response spectra: i) high frequencies contaminated by a ‘mathematical noise’ floor, ii) significant errors in amplitudes of low to intermediate frequencies (severity dependent on resolution degree). Inclusion of such data could lead to significant misinterpretation of these earthquakes.
- Most records (66, 65%) from $R \geq 111\,\mathrm{km}$ and $\mathbf{M} \leq 5.22$.
- Examines residuals from equations. Finds no persistent trends except for Saguenay data ($\mathbf{M} = 6$) between $63 \leq R \leq 158\,\mathrm{km}$.
- Notes data very limited in large magnitude range and that one or two earthquakes are controlling predictions.

- Notes different regression technique could change predictions for large magnitudes but i) data too limited to warrant more sophisticated analysis and ii) may be other factors, in addition to number of recordings, which should be considered in weighting each earthquake.

5.32 Campbell (1990)

- See Section 3.63.
- Response parameter is pseudo-velocity for 5% damping.

5.33 Dahle et al. (1990b) & Dahle et al. (1990a)

- See Section 3.64.
- Response parameter is pseudo-velocity for 5% damping.
- Coefficients only given for 7 periods; graphs for others.

5.34 Tamura et al. (1990)

- Ground motion model is:

$$S_A(T_i, \mathrm{GC}) = a(T_i, \mathrm{GC})10^{b(T_i,\mathrm{GC})M}(\Delta + 30)^{C(T_i,\mathrm{GC})}$$

- Response parameter is acceleration for 2 and 5% damping.
- Use three site categories (GC) for which perform separate regression:

Group 1 Ground characteristic index $\lesssim 0.67$, 29 records.

Group 2 Ground characteristic index between about 0.67 and 1.50, 46 records.

Group 3 Ground characteristic index $\gtrsim 1.50$, 22 records.

where the ground characteristic index is calculated from statistical analysis of amplitude of records. Thought to reflect the characteristic of deep soil deposits at site (1.0 means amplification is average for Japan, < 1.0 or > 1.0 means amplification is lower or greater, respectively, than average for Japan).

- Records from JMA low-magnification mechanical seismographs (natural period $6\,\mathrm{s}$, damping ratio 0.55) which were instrument corrected (because sensitivity for periods $> 10\,\mathrm{s}$ is substantially suppressed) , filtered (cut-offs 1.3–$2\,\mathrm{s}$ and 20–$30\,\mathrm{s}$ chosen from a study of recording accuracy of instruments) and differentiated in frequency domain to find ground velocity and acceleration. Hence limit analysis to 2 to $20\,\mathrm{s}$.
- Do not use resultant of two horizontal components because two components not synchronous.

- Find difference in predicted ground motion using derived equations and those from earlier equations for short periods. Find that b for earlier equations increases almost linearly with logarithm of natural period, T, so find equation, by least squares, connecting b and $\log T$. Assume this equation holds for 2 to $20\,\mathrm{s}$ and so fix b and recalculate a and c; find predictions now agree.
- Only give graphs for original coefficients for 5% damping. Give tables of coefficients for preferred second analysis.

5.35 Tsai et al. (1990)

- See Section 3.68.
- Response parameter is acceleration for 5% damping.
- Also give equations for average acceleration for 2 period bands 0.12–$0.33\,\mathrm{s}$ and 0.07–$0.2\,\mathrm{s}$.

5.36 Crouse (1991)

- See Section 3.70.
- Response parameter is pseudo-velocity for 5% damping.
- Focal depths, h, between 10 and $238\,\mathrm{km}$.
- Notes that spectral database is biased to higher ground motions (because only higher ground motions are digitised). Suggest either using a different form of equation or impose constraints. Do not do either because (1) consider sample adequate for regression and (2) although overestimate smaller, more distant motion, it would properly estimate larger motions which are of greater concern for design applications.
- Sets p_3, p_5 and p_6 to those for PGA equation after trial regressions; does not appreciably affect standard deviation.
- Finds relatively larger standard deviation for 3.0 and $4.0\,\mathrm{s}$ which suggests form of equation may be inappropriate for longer periods.
- Plots normalised residuals (not shown) which show uniform distribution.

5.37 Dahle et al. (1991)

- Ground motion model is:

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

this equation assumes spherical spreading (S waves) to R_0 and cylindrical spreading with dispersion (Lg waves) for larger distances.

- Response parameter is pseudo-velocity for 5% damping.
- All data from solid rock sites.
- Follow-on study to Dahle *et al.* (1990b) and Dahle *et al.* (1990a) but remove Chinese and Friuli data and data from border zone of Eurasian plate, so data is a more genuine intraplate set.
- Use 395 records from Norwegian digital seismograms. Require that the Lg displacement amplitude spectra should have a signal-to-noise ratio of a least 4 in the frequency range 1–$10\,\mathrm{Hz}$, when compared to the noise window preceding the P-wave arrival.
- For the selected seismograms the following procedure was followed. Select an Lg window, starting at a manually picked arrival time and with a length that corresponds to a group velocity window between 2.6 and $3.6\,\mathrm{kms}^{-1}$. Apply a cosine tapering bringing the signal level down to zero over a length corresponding to 5% of the data window. Compute a Fast Fourier Transform (FFT). Correct for instrument response to obtain true ground motion displacement spectra. Bandpass filter the spectra to avoid unreasonable amplification of spectral estimates outside the main response of the instruments. Passband was between $0.8\,\mathrm{Hz}$ and 15 or $20\,\mathrm{Hz}$, dependent on sampling rate. The amplitude spectra obtained using the direct method, using $A = \Delta t\sqrt{ZZ^*}$ where Δt is time step and Z is Fourier transformed time-history and Z^* is its complex conjugate. Convert instrument corrected displacement Lg Fourier transforms to acceleration by double differentiation and an inverse FFT.
- Use 31 accelerograms from eastern N. America, N. Europe and Australia.
- Use $R_0 = 100\,\mathrm{km}$ although note that R_0 may be about $200\,\mathrm{km}$ in Norway.
- Correlation in magnitude-distance space is 0.20.
- Use a variant of the two-stage method to avoid an over-representation of the magnitude scaling terms at small magnitudes. Compute average magnitude scaling coefficients within cells of 0.2 magnitude units before the second stage.
- Resample data to make sure all the original data is used in a variant of the one-stage method. Compute new (resampled) data points as the average of one or more original points within a grid of cells $160\,\mathrm{km}$ by 0.4 magnitude units. Correlation in resampled magnitude-distance space is 0.10.
- Find estimated ground motions from one-stage method systematically higher than those from two-stage method particularly at short distances and large magnitudes. Effect more significant for low frequencies. Find that this is because one-stage method gives more weight to supplementary accelerograph data from near field of large earthquakes.
- Standard deviations similar for one- and two-stage equations.

- Scatter in magnitude scaling coefficients from first stage of two-stage method is greater for strong-motion data.
- Try fixing the anelastic decay coefficient (c_4) using a previous study's results. Find almost identical results.
- Remove 1 record from Nahanni earthquake ($M_s = 6.9$) and recompute; only a small effect.
- Remove 17 records from Saguenay earthquake ($M_s = 5.8$) and recompute; find significant effect for large magnitudes but effect within range of variation between different regression methods.

5.38 I.M. Idriss (1991) reported in Idriss (1993)

- See section 3.73.
- Response parameter is pseudo-acceleration for 5% damping.

5.39 Mohammadioun (1991)

- Ground motion model is:

$$\log \mathrm{PSV}(f) = k(f) + a(f)M + n(f)R$$

- Response parameter is pseudo-velocity for 5%.
- Records not baseline corrected so no equations for periods $> 2\,\mathrm{s}$.
- Does not split up data into subsets by intensity because risk of creating data populations which are not statistically significant.
- Notes that could be inconsistency with using both d_h and d_r.
- Notes that results are preliminary.
- Also analyses wide range of Californian data for 96 periods between 0.013 and $5\,\mathrm{s}$ split into two intensity dependent subsets: those records with site intensities VI-VII (326 records) and those with site intensities VII+ (156 records). Uses d_r except for Imperial Valley earthquake where uses d_E. Does not use include soil or other variables because poorly defined and lead to selection of records that are not statistically valid.

5.40 Benito et al. (1992)

- Ground motion model is:

$$\ln \begin{matrix}\mathrm{PSA}\\ \mathrm{PSV}\end{matrix} = c_1 + c_2 M + c_3 \ln(R + R_0) + c_4(R + R_0)$$

- Response parameters are pseudo-acceleration, PSA, and pseudo-velocity, PSV, for 5% damping[3].

- Use three soil conditions (revised when cross hole information was available):

$S = 0$ Hard and rock sites, 50 records.

$S = 1$ Intermediate soil, 10 records.

$S = 2$ Soft soil, 12 records.

- Use M_L because most suitable for distance range of majority of records.

- Try including $c_5 S$ term but find low significance values for c_5. Repeat regression for each soil category separately. Give results when coefficient of determination $R^2 > 0.80$, standard errors $< 25\%$ and coefficients have high significance levels.

- For PSA for $S = 0$ give coefficients for all periods, for $S = 1$ give coefficients for 0.17 to $0.2\,\mathrm{s}$ and for $S = 2$ give coefficients for 1 to $10\,\mathrm{s}$.

- Also consider Friuli records ($4.2 \leq M_L \leq 6.5$, epicentral distances between 2 and $192\,\mathrm{km}$, 14 records for $S = 0$, 23 records for $S = 1$ and 16 records for $S = 2$).

- Note need to include term in model reflecting explicitly local amplification dependent on natural period of soil as well as predominant period of incident radiation to bed rock.

5.41 Niazi & Bozorgnia (1992)

- See Section 3.74.

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

- For some periods ($0.20\,\mathrm{s}$ for vertical and 0.10 and $0.111\,\mathrm{s}$ for horizontal) constrain c_2 to zero so that predicted amplitude would not decrease with increasing magnitude at zero distance. Note that does not affect uncertainty.

- Note that long period filter cutoff may be too long for records from small shocks but if a shorter period was used then information on long period spectral ordinates would be lost. Note that insufficient data for well constrained results at $M = 5$ or $M > 7$.

- Find evidence for long period noise in d and in Degree of Magnitude Saturation ($\mathrm{DMS} = -(c_2 d/b) * 100$).

- Examine median and normalized standard deviation (coefficient of variation) and find evidence for decreasing uncertainty with increasing magnitude.

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[3] Although coefficients should only differ by a constant because $\mathrm{PSA} = (2\pi/T)\mathrm{PSV}$ they do not; hence response parameters are probably not those stated.

5.42 *Tento* et al. *(1992)*

- See Section 3.81.
- Response parameter is pseudo-velocity for 5% damping.
- Note that correction procedure significantly affects results for $T > 2\,\mathrm{s}$. Correction procedure introduces dishomogeneity and errors due to subjectivity of choice of low frequency filter limits.

5.43 *Boore* et al. *(1993) & Boore* et al. *(1997)*

- See Section 3.83
- Response parameter is pseudo-velocity for 2, 5, 10 and 20% damping.
- Cutoff distance is lesser of distance to first digitized record triggered by S wave, distance to closest non-digitized recording, and closest distance to an operational nontriggered instrument.
- Note that can only use response spectral values between 0.1 and $2\,\mathrm{s}$ because of low sampling rate of older data (sometimes only 50 samples/sec) and low signal to noise ratios and filter cutoffs.
- Site categories same as in Section 3.83 but due to smaller dataset number of records in each category is less. Class A: 12 records, B: 51 records, C: 49 records.
- Smoothed coefficients using a least-squares fit of a cubic polynomial.

5.44 *Caillot & Bard (1993)*

- Ground motion model is:

$$\ln y = \beta_1 + \beta_2 M + \beta_3 \ln \mathrm{HYPO} + \beta_4 S_1$$

- Response parameter is acceleration for 5% damping.
- Consider three site conditions but only retain two:
  1. Rock: ENEA/ENEL S0 classification $\Rightarrow S_1 = 0$, 49 records.
  2. Thin alluvium: depth of soil between 5 and $20\,\mathrm{m}$,ENEA/ENEL S1 classification $\Rightarrow S_1 = 1$, 34 records.
- Selected records have $d_e < 60\,\mathrm{km}$ and focal depth less than $30\,\mathrm{km}$. Data selected so that mean and standard deviation of magnitude and hypocentral distance in each site category are equal, in this case 5.1 and $20\,\mathrm{km}$ respectively.
- All records processed using common procedure. High pass filtered with $f_l = 0.5\,\mathrm{Hz}$, instrument corrected and low pass filtered with $f_h = 30\,\mathrm{Hz}$.

- Considered three things when choosing method of analysis:
    1. Attenuation equation must have some physical basis.
    2. Parameters must be available for original data set.
    3. Attenuation equation must be easy to use in a predictive manner.
- Hypocentral distance used because rupture not known for most earthquakes. Note that only important for magnitudes greater than about 6.5 and distances less than about $15\,\mathrm{km}$.
- Originally included another set of data (32 records) from thick soil with depth greater than about $20\,\mathrm{m}$ (ENEA/ENEL classification S2) but note that results for this category are much more uncertain, possibly due to diversity of geotechnical characteristics of soils. Therefore excluded.
- Regression was done using two-stage algorithm (Joyner & Boore, 1981) and a weighted one-stage method. Weight by splitting the magnitude and distance ranges into four intervals and weighting data in each interval inversely proportionally to number of points in the bin. Thus gives roughly equal weight to each part of magnitude-distance space.
- Note that results from two-stage regression for this set of data may be misleading because for some periods it does not bring any 'explanation' to the variance of initial data. The two-stage and normal one-stage and weighted one-stage yield significant changes in predictions.
- Repeat analysis using only S0 subset and using only S1 subset but no significant changes in magnitude or distance scaling between the two subsets so consider complete set and include a constant scaling between rock and shallow soil. If set is reduced to 53 records with similar spread of magnitude, distance and sites then difference between shallow soil and rock is not significant.
- Note that confidence interval should be given by formula in Weisburg (1985) not normal way of simply using standard deviation.

5.45 Campbell (1993)

- See Section 3.84.
- Response parameter is pseudo-acceleration for 5% damping.
- Notes that equation can predict smaller pseudo-acceleration than PGA for short periods, which is impossible in practice. Hence pseudo-acceleration for periods $\leq 0.2\,\mathrm{s}$ should be constrained to be $\geq$ PGA.

5.46 Sadigh et al. *(1993) & Sadigh* et al. *(1997)*

- See Section 3.86

- Ground motion model for deep soil is:

  $$\ln y = C_1 + C_2 M - C_3 \ln(r_{\mathrm{rup}} + C_4 \mathrm{e}^{C_5 M}) + C_6 + C_7 (8.5 - M)^{2.5}$$

  where C_6 is different for reverse and strike-slip earthquakes.

  Ground motion model for rock is:

  $$\ln y = C_1 + C_2 M + C_3 (8.5 - M)^{2.5} + C_4 \ln(r_{\mathrm{rup}} + \exp(C_5 + C_6 M)) + C_7 \ln(r_{\mathrm{rup}} + 2)$$

  where C_1 is different for reverse and strike-slip earthquakes.

  Vertical equations do not include C_7.
- Response parameter is acceleration for 5% damping.
- Perform analysis on spectral amplification $\ln(\mathrm{SA}/\mathrm{PGA})$.
- Give smooth coefficients.
- Find standard errors to be dependent on magnitude and fit to a linear relation.

5.47 *Sun & Peng (1993)*

- See section 3.88.
- Response parameter is acceleration for 5% damping.
- Coefficients not given.

5.48 *Boore* et al. *(1994a) & Boore* et al. *(1997)*

- See Section 3.90
- Find no evidence for magnitude dependent uncertainty for spectral values.
- Find no evidence for amplitude dependent uncertainty for spectral values.
- Note that effect of basin-generated surface waves can have an important effect but probably not at periods between 0.1 and $2\,\mathrm{s}$.

5.49 *Climent* et al. *(1994)*

- Inspect observed and predicted values and conclude no clear difference between upper-crustal and subduction zone ground motions. Equations are for region regardless of earthquake source type.

5.50 *Fukushima* et al. *(1994) & Fukushima* et al. *(1995)*

- See Section 3.91.
- Response parameter is pseudo-velocity for 5% damping.
- Only give graphs of coefficients.
- Note possible noise contamination, for periods $< 0.1\,\mathrm{s}$, in coefficients.

5.51 *Lawson & Krawinkler (1994)*

- See Section 3.92.
- Response parameter is acceleration for 5% damping.

5.52 *Lee & Manić (1994) & Lee (1995)*

- Ground motion model is:

$$
\begin{aligned}
\log_{10}\widehat{\mathrm{PSV}} &= M_{<} + \mathrm{Att} + b_1 M_{<>} + b_2^{(1)} S^{(1)} + b_2^{(2)} S^{(2)} + b_3 v + b_4 + b_5 M_{<>}^2 \\
&\quad + b_6^{(1)} S_L^{(1)} \\
M_{<} &= \min(M, M_{\max}) \\
\text{where } M_{\max} &= \frac{-(1+b_1)}{2b_5} \\
M_{<>} &= \max(M_{<}, M_{\min}) \\
\text{where } M_{\min} &= \frac{-b_1}{2b_5} \\
\mathrm{Att} &= \begin{cases} A_0 \log_{10}\Delta & \text{for} \quad R \leq R_0 \\ A_0 \log_{10}\Delta_0 - \frac{(R-R_0)}{200} & \text{for} \quad R > R_0 \end{cases} \\
\text{with: } A_0 &= \begin{cases} -0.761 & \text{for} \quad T \geq 1.8\,\mathrm{s} \\ -0.831 + 0.313\log_{10} T - 0.161(\log_{10} T)^2 & \text{for} \quad T < 1.8\,\mathrm{s} \end{cases} \\
\Delta &= S\left[\ln\left(\frac{R^2+H^2+S^2}{R^2+H^2+S_0^2}\right)\right]^{-\frac{1}{2}} \\
\Delta_0 &= \Delta(R_0) \\
\text{where } R_0 &= \frac{1}{2}\left\{\frac{-200A_0(1-S_0^2/S^2)}{\ln 10} + \left[\left[\frac{200A_0(1-S_0^2/S^2)}{\ln 10}\right]^2 - 4H^2\right]\right\}
\end{aligned}
$$

  where Δ is 'representative' distance, S is 'size' of fault, S_0 is coherence radius of source and v is component orientation ($v = 0$ for horizontal, $v = 1$ for vertical).

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Consider three geological site conditions:

$s = 0$ Sediment: $\Rightarrow S^{(1)} = 0, S^{(2)} = 0$, 151 records.
$s = 1$ Intermediate sites: $\Rightarrow S^{(1)} = 1, S^{(2)} = 0$, 106 records.
$s = 2$ Basement rock: $\Rightarrow S^{(1)} = 0, S^{(2)} = 1$, 54 records.

- Consider three local site categories but only retain two:

$s_L = 0$ Rock: $\Rightarrow S_L^{(1)} = 0$, 100 records.
$s_L = 1$ Stiff soil: $\Rightarrow S_L^{(1)} = 1$, 205 records.

- Cannot include those records from deep soil sites ($s_L = 2$) because only six records.
- Most earthquakes are shallow, depth $H < 25\,\mathrm{km}$.
- Most records have epicentral distances, $R < 50\,\mathrm{km}$.
- Most have magnitudes between 3 and 6.
- Only use records with high signal-to-noise ratio. Quality of records is not adequate for response spectrum calculation outside range 0.04 to $2\,\mathrm{s}$.
- Analysis performed using residue 2-step method. In first step use only records from $M \geq 4.25$ to force a concave form to magnitude scaling (if all records used then find a convex parabola), s_L parameter is not included. In second step find s_L dependence from residuals of first stage including all magnitudes.
- Give expressions to describe distribution of residuals so that can find confidence limits, unlike normal standard deviation based method, see Trifunac (1980).
- Note difference between western USA and Yugoslavian ground motions.

5.53 Mohammadioun (1994a)

- Ground motion model is:

$$\log \mathrm{SR}(f) = k(f) + \alpha(f)M + n(f)\log R$$

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Uses records from rock sites ($V_s \geq 750\,\mathrm{ms}^{-1}$).
- Half of records from $R < 30\,\mathrm{km}$ and significant number from $R < 10\,\mathrm{km}$.
- Most (82%) records from earthquakes with $6.2 \leq M \leq 7.0$.
- Coefficients not given, only results.

5.54 Mohammadioun (1994b)

- Ground motion model is:

$$\log V(f) = k(f) + \alpha(f)M + n(f)\log R$$

- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Choose W. USA to make data as homogeneous as possible in terms of seismotectonic context and parameter quality.
- Notes recording site-intensities may only be average intensity values, thereby neglecting possible microzoning effects.
- Uses M_L because generally available and uniformly determined. Notes may not be best choice.
- Records from free-field and typical of different intensity classes.
- Does regression for records associated with three different intensities: V (184 records, $5.5 \lesssim R \lesssim 200\,\mathrm{km}$), VI (256 records, $3 \lesssim R \lesssim 250\,\mathrm{km}$, VII (274 records, $1 \lesssim R \lesssim 150\,\mathrm{km}$) and four different intensity groups: V-VI, VI-VII, VII and more (extra 25 records, $1 \lesssim R \lesssim 100\,\mathrm{km}$) and V and less (extra 30 records, $25 \lesssim R \lesssim 350\,\mathrm{km}$.
- Graph of $\alpha(f)$ given for horizontal component for the four intensity groups and graph of $n(f)$ for vertical component for intensity VI.

5.55 Musson et al. (1994)

- See section 3.94.
- Response parameter is pseudo-velocity for 5% damping.
- More data because use analogue records as well.

5.56 Theodulidis & Papazachos (1994)

- Use same data, equation and procedure as Theodulidis & Papazachos (1992), see Section 3.82.
- Response parameter is pseudo-velocity for 0, 2, 5, 10 and 20% damping.
- Note lack of near-field data ($R < 20\,\mathrm{km}$, $M > 6.2$) to constrain R_0.
- Only give graphs of original coefficients but give table of smoothed (using a $(\frac{1}{4}+\frac{1}{2}+\frac{1}{4}$ running average along $\log T$) coefficients for 13 periods and all 5 damping levels.
- Note large residuals for $T > 0.5\,\mathrm{s}$ due mainly to different digitising and processing procedures which significantly affect long period spectral values.

- Check histograms of residuals for 0.1, 0.3, 0.5, 1, 3 and $5\,\mathrm{s}$ and find similar to normal distribution.
- Note no data from $R < 30\,\mathrm{km}$ for $M > 6.5$ so state caution is required for use of equations in that range. Also suggest do not use equations for $M > 7.5$ or for $R > 130\,\mathrm{km}$.
- Note may not apply for very soft soils.
- Note lack of data.

5.57 *Dahle* et al. *(1995)*

- See Section 3.99.
- Derive spectral attenuation relations for almost double number of periods given. Coefficients smoothed using a third degree polynomial.

5.58 *Lee & Trifunac (1995)*

- Based on Lee *et al.* (1995). See Section 3.100.
- Response parameter is pseudo-velocity for 5% damping (also use 0, 2, 10 and 20% damping but do not report results).
- Before regression, smooth the actual response spectral amplitudes along the $\log_{10} T$ axis to remove the oscillatory ('erratic') nature of spectra.
- State that for small earthquakes ($M \approx 3$) equations only valid up to about $1\,\mathrm{s}$ because recorded spectra are smaller than recording noise for longer periods.
- Only give coefficients for 0.04, 0.06, 0.10, 0.17, 0.28, 0.42, 0.70, 1.10, 1.90, 3.20, 4.80 and $8.00\,\mathrm{s}$ but give graphs for rest.
- Assume that distribution of residuals from last step can be described by probability function:

  $$p(\epsilon, T) = [1 - \exp(-\exp(\alpha(T) + \beta(T)))]^{n(T)}$$

  where $p(\epsilon, T)$ is probability that $\log \mathrm{PSV}(T) - \log \widehat{\mathrm{PSV}}(T) \leq \epsilon(T)$, $n(T) = \min[10, [25/T]]$, $[25/T]$ is integral part of $25/T$. Arrange residuals in increasing order and assign an 'actual' probability of no exceedance, $p^{*}(\epsilon, T)$ depending on its relative order. Estimate $\alpha(T)$ and $\beta(T)$ by least-squares fit of $\ln(-\ln(1 - p^{1/n(T)})) = \alpha(T)\epsilon(T) + \beta(T)$. Test quality of fit between $\hat{p}(\epsilon, T)$ and $p^{*}(\epsilon, T)$ by χ^2 and Kolmogorov-Smirnov tests. For some periods the χ^2 test rejects the fit at the 95% level but the Kolmogorov-Smirnov test accepts it.

5.59 Ambraseys et al. (1996) & Simpson (1996)

- See Section 3.104.
- Response parameter is acceleration for 5% damping.
- Do no smoothing because if plotted on a normal scale then smoothing should be done on T, but if on log-log plot then smoothing should be done on $\log T$.

5.60 Ambraseys & Simpson (1996) & Simpson (1996)

- See Section 3.105.
- Response parameter is acceleration for 5% damping.

5.61 Bommer et al. (1996)

- See section 3.107.
- Response parameter is pseudo-velocity for unspecified damping.

5.62 Crouse & McGuire (1996)

- See section 3.108.
- Response parameter is pseudo-velocity for 5% damping.
- Find k_1 not significantly different than 1 for $T \leq 0.15\,\mathrm{s}$ and k_2 not significantly different than 1 for $T \leq 0.50\,\mathrm{s}$.

5.63 Free (1996) & Free et al. (1998)

- See Section 3.109.
- Response parameter is acceleration for 5% damping.
- Finds including focal depth, h, explicitly has dramatic effect on predicted spectra at short distances but insignificant effect at large distances.
- Repeats analysis using only E. N. American data. Finds significantly larger amplitudes than predictions from combined set for short and intermediate distances for periods $> 0.3\,\mathrm{s}$ but similar spectra for large distances.

5.64 Molas & Yamazaki (1996)

- Based on Molas & Yamazaki (1995), see Section 2.88 of Douglas (2001a).
- Response parameters are absolute acceleration and relative velocity for 5% damping.

5.65 Ohno et al. (1996)

- See Section 3.110.
- Response parameter is acceleration for 5% damping.
- Plot amplitude factors from first stage against M_w; find well represented by linear function.
- Do not give table of coefficients only graphs of coefficients.

5.66 Sabetta & Pugliese (1996)

- Ground motion model used is:

$$\log_{10} Y = a + bM - \log_{10}\sqrt{d^2 + h^2} + e_1 S_1 + e_2 S_2$$

- Response parameter, Y, is pseudo-velocity for 5% damping
- Use data from Sabetta & Pugliese (1987).
- Remove anelastic decay term because it was not significant at $\alpha = 0.1$ and sometimes it was positive. Originally geometrical decay coefficient c was allowed to vary but find it is close to -1 so constrain.
- Use three site categories:

$S_1 = 1, S_2 = 0$ Shallow: depth $H \leq 20\,\mathrm{m}$ alluvium $400 \leq V_s \leq 800\,\mathrm{ms}^{-1}$.
$S_1 = 0, S_2 = 1$ Deep: depth $H > 20\,\mathrm{m}$ alluvium $400 \leq V_s \leq 800\,\mathrm{ms}^{-1}$.
$S_1 = 0, S_2 = 0$ Stiff: $V_s > 800\,\mathrm{ms}^{-1}$.

- Accelerograms digitised at 400 samples/sec. Bandpass frequencies chosen by an analysis of signal and fixed trace Fourier spectra. f_{min} between 0.2 and $0.7\,\mathrm{Hz}$ most about $0.3\,\mathrm{Hz}$ and f_{max} between 20 and $35\,\mathrm{Hz}$ most about $25\,\mathrm{Hz}$. Instrument correction applied.
- Use one-stage method although two-stage method yields similar results.
- Also present smoothed coefficients.

5.67 *Spudich* et al. *(1996) & Spudich* et al. *(1997)*

- See Section 3.114
- Response parameter is pseudo-velocity for 5% damping.
- Only use spectral values within the passband of the filter used to correct records hence number of records used for each period varies, lowest number is 99 for periods between 1.7 and $2.0\,\mathrm{s}$.
- Smooth coefficients using cubics or quadratics.

5.68 *Abrahamson & Silva (1997)*

- Ground motion model is[4]:

$$
\begin{aligned}
\ln \mathrm{Sa} &= f_1 + F f_3 + HW f_{HW}(M) f_{HW}(R_{\mathrm{rup}}) + S f_5 \\
f_1 &= \begin{cases} a_1 + a_2(M-c_1) + a_{12}(8.5-M)^n + [a_3 + a_{13}(M-c_1)]\ln R & \text{for } M \leq c_1 \\ a_1 + a_4(M-c_1) + a_{12}(8.5-M)^n + [a_3 + a_{13}(M-c_1)]\ln R & \text{for } M > c_1 \end{cases} \\
\text{where } R &= \sqrt{r_{\mathrm{rup}} + c_4^2} \\
f_3 &= \begin{cases} a_5 & \text{for } M \leq 5.8 \\ a_5 + \frac{a_6-a_5}{c_1-5.8}(M-5.8) & \text{for } 5.8 < M < c_1 \\ a_6 & \text{for } M \geq c_1 \end{cases} \\
f_{HW}(M) &= \begin{cases} 0 & \text{for } M \leq 5.5 \\ M-5.5 & \text{for } 5.5 < M < 6.5 \\ 1 & \text{for } M \geq 6.5 \end{cases} \\
f_{HW}(r_{\mathrm{rup}}) &= \begin{cases} 0 & \text{for } r_{\mathrm{rup}} < 4 \\ a_9 \frac{r_{\mathrm{rup}}-4}{4} & \text{for } 4 < r_{\mathrm{rup}} < 8 \\ a_9 & \text{for } 8 < r_{\mathrm{rup}} < 18 \\ a_9\left(1 - \frac{r_{\mathrm{rup}}-18}{7}\right) & \text{for } 18 < r_{\mathrm{rup}} < 24 \\ 0 & \text{for } r_{\mathrm{rup}} > 25 \end{cases} \\
f_5 &= a_{10} + a_{11}\ln(\widehat{\mathrm{PGA}} + c_5)
\end{aligned}
$$

  where $\widehat{\mathrm{PGA}}$ is expected peak acceleration on rock as predicted by the attenuation equation with $S = 0$.

- Response parameter is acceleration for unspecified[5] damping.
- Use two site categories:

---

[4] f_3 given in Abrahamson & Silva (1997) was modified to ensure homogeneity and a linear variation in f_3 with magnitude.

[5] It is probably 5%.

$S = 0$ Rock: rock ($V_s > 600\,\mathrm{ms}^{-1}$), very thin soil ($< 5\,\mathrm{m}$) over rock or soil 5 to $20\,\mathrm{m}$ thick over rock.

$S = 1$ Deep soil: deep soil in narrow canyon (soil $> 20\,\mathrm{m}$ thick and canyon $< 2\,\mathrm{km}$ wide) or deep soil in broad canyon (soil $> 20\,\mathrm{m}$ thick and canyon $> 2\,\mathrm{km}$ wide).

- All records reprocessed using common procedure. Interpolated to 400 samples/sec, low-pass filtering with corner frequency selected for each record based on visual examination of Fourier amplitude spectrum, instrument corrected, decimated to 100 to 200 samples/sec depending on low-pass corner frequency, baseline correction using 0 to 10 degree polynomial, high-pass filtered based on integrated displacements.
- Only use response spectral data within frequency band $1.25f_h$ to $0.8f_l$ to avoid effects of filter roll-off. Hence number of records used for regression at each period varies, minimum number is less than 100 records for $0.01\,\mathrm{s}$.
- Well distributed dataset in terms of magnitude and distance.
- Supplement data with records from Gazli, Friuli, Tabas, Taiwan, Nahanni and Spitak.
- Consider source mechanism: reverse $\Rightarrow F = 1$, reverse/oblique $\Rightarrow F = 0.5$, others (strike-slip and normal) $\Rightarrow F = 0$).
- Consider hanging wall effect: if over hanging wall $HW = 1$, otherwise $HW = 0$.
- Note that interpretation of c_4 is not clear for their distance measure but yields better fit.
- Model nonlinear soil response by f_5.
- Model uncertainty as magnitude dependent.
- Fix some coefficients to be independent of period so that response spectral values vary smoothly with distance, magnitude and period.
- Smooth coefficients using piecewise continuous linear fits on log period axis. For highly correlated coefficients, smooth one coefficient and re-estimate other coefficients.

5.69 Atkinson (1997)

- Ground motion model used is:

$$\begin{aligned}\log \mathrm{PSA} &= c_0 + c_1(M_w - 6) + c_2(M_w - 6)^2 + c_3h - c_{a_1}\log R - c_{a_2}R + c_sS \\ \text{with: } c_{a_2} &= c_{a_3} + c_{a_4}h\end{aligned}$$

- Response parameter is pseudo-acceleration for 5% damping.
- Uses two site categories (no soil profiles were available for Cascadia region):

$S = 0$ Rock: average V_s assumed to be about $2000\,\mathrm{ms}^{-1}$

$S = 1$ Soil: average V_s assumed to be about $255\,\mathrm{ms}^{-1}$ (although includes some soft soil sites with average V_s about $125\,\mathrm{ms}^{-1}$).

- Tectonic type of earthquakes used: crustal, subcrustal and subduction
- Most Cascadia data is from seismograms. Converts vertical measurements from these to one horizontal component.
- Supplements in large magnitude range ($6.7 < M_w \leq 8.2$) with data from 9 subduction earthquakes in Alaska, Mexico, Japan and Chile
- Most magnitudes below 5.3 and no data between 6.8 and 7.5.
- Focal depths between 1 and $60\,\mathrm{km}$
- Only uses events recorded at 3 or more stations. Improves ability of regression to distinguish between magnitude and distance dependencies in data.
- Most low magnitude events were recorded on rock and most high magnitude events were on soil. Thus to stabilize regression takes the coefficients c_s from Boore *et al.* (1994a) and not derived from this data.
- Magnitude partitioning, in first step, into 0.5 unit intervals gave evidence for magnitude dependent attenuation. Uses $c_{a_1} = 1$ for $4.1 \leq M_w \leq 6.7$ and $c_{a_1} = 0.5$ (largest which yielded positive c_{a_2}) for $M_w \geq 7.5$. Thought to show breakdown of point source assumption.
- Demonstrates depth dependence in anelastic decay by performing regression in four $15\,\mathrm{km}$ deep subsets for range $4.1 \leq M_w \leq 6.7$. c_{a_3} and c_{a_4} then finds by regression for each period. No depth dependence for $M_w \geq 7.5$ because of lack of different depths.
- Includes depth dependence in second step because gave better fit for short periods.
- Checks dependence on crustal, interface and intra-slab events; finds no dependence.

5.70 Campbell (1997), Campbell (2000) & Campbell (2001)

- See Section 3.116
- Ground motion model (horizontal component) is:

$$\begin{aligned}
\ln \mathrm{SA}_H &= \ln A_H + c_1 + c_2 \tanh[c_3(M - 4.7)] + (c_4 + c_5 M) R_{\mathrm{SEIS}} + 0.5 c_6 S_{\mathrm{SR}} \\
&\quad + c_6 S_{\mathrm{HR}} + c_7 \tanh(c_8 D)(1 - S_{\mathrm{HR}}) + f_{\mathrm{SA}} \\
f_{\mathrm{SA}} &= \begin{cases} 0 & \text{for} \quad D \geq 1\,\mathrm{km} \\ c_6(1 - S_{\mathrm{HR}})(1 - D)(1 - 0.5 S_{\mathrm{SR}}) & \text{for} \quad D < 1\,\mathrm{km} \end{cases}
\end{aligned}$$

- Ground motion model (vertical component) is:

$$\begin{aligned}
\ln \mathrm{SA}_V &= \ln \mathrm{SA}_H + c_1 + b_2 M + c_2 \tanh[d_1(M - 4.7)] + c_3 \tanh[d_2(M - 4.7)] \\
&\quad + b_3 \ln[R_{\mathrm{SEIS}} + b_4 \exp(b_5 M)] + b_6 \ln[R_{\mathrm{SEIS}} + b_7 \exp(b_8 M)] + b_9 F \\
&\quad + [c_4 \tanh(d_3 D) + c_5 \tanh(d_4 D)](1 - S_{\mathrm{SR}})
\end{aligned}$$

- Response parameter is pseudo-acceleration for 5% damping.
- Notes importance of depth to basement rock, D, for modelling long period site response. For shallow sediments defines D as depth to top of Cretaceous or older deposits, for deep sediments determine D from crustal velocity profiles where define basement as crystalline basement rock or sedimentary deposits having a P-wave velocity $\geq 5\,\mathrm{kms}^{-1}$ or shear-wave velocity $\geq 3\,\mathrm{kms}^{-1}$ (called 'seismic basement' by geophysicists).
- Uses different data than for PGA equations hence: reverse (3), thrust (H:9, V:6), reverse-oblique (2) and thrust-oblique (0), total (H:14, V:11) (H:140 records, V:85 records), strike-slip (H:124 records, V:88 records). Only two normal faulting earthquakes in horizontal set of records (contributing 2 records) so a difference in not modelled although $F = 0.5$ is given as first approximation (later revised to $F = 0$) to use as for PGA case.
- Only excludes records from toe and base of dams, included those from buildings and bridge columns which were excluded from PGA study, because of lack of data.
- Uses weighted regression analysis. Assigns recordings from a given earthquake that fell within the same distance interval (ten logarithmical spaced) same weight as those recordings from other earthquakes that fell within the same distance interval. Gives recordings from a given earthquake that occurred at the same site location the same cumulative weight as a single recording at that distance, thus reducing the bias.
- Performs analysis on spectral ratio $\ln(\mathrm{PSA}/\mathrm{PGA})$ because of unacceptably large period-to-period variability in regression coefficients when direct regression is applied and strongly correlated coefficients. Notes that are too many regression coefficients so it was necessary to perform analysis in many steps, at each step different coefficients are determined and detrended and residuals examined to find appropriate functional forms for trends present. Yields more stable results.
- No consideration of nontriggering instruments made, unlike PGA study.

5.71 *Schmidt* et al. *(1997)*

- See Section 3.119.
- Response parameter is pseudo-velocity for 5% damping.

5.72 *Youngs* et al. *(1997)*

- See Section 3.120.
- Ground motion model used is:

$$\ln(\mathrm{SA}/\mathrm{PGA}) = B_1 + B_2(10 - \mathbf{M})^3 + B_3 \ln\left[r_{\mathrm{rup}} + \mathrm{e}^{\alpha_1 + \alpha_2 \mathbf{M}}\right]$$

  where α_1 and α_2 are set equal to C_4 and C_5 of appropriate PGA equation.

- Response parameter, SA, is acceleration for 5% damping.
- Do analysis on response spectral amplification because digitised and processed accelerograms used for spectral attenuation is only a subset of PGA database and they are often those with strongest shaking. Hence analysis directly on spectral accelerations may be biased.
- Smooth coefficients.

5.73 Bommer et al. (1998)

- Ground motion model is:

$$
\begin{aligned}
\log(\mathrm{SD}) &= C_1 + C_2 M + C_4 \log r + C_A S_A + C_S S_S \\
r &= \sqrt{d^2 + h_0^2}
\end{aligned}
$$

- Response parameter is displacement for 5, 10, 15, 20, 25 and 30% damping.
- Use three site conditions:

  R Rock: $V_s > 750\,\mathrm{ms}^{-1}$, $S_A = 0$, $S_S = 0$, 30–45 records.
  A Stiff soil: $360 < V_s \le 750\,\mathrm{ms}^{-1}$, $S_A = 1$, $S_S = 0$, 56–92 records.
  S Soft soil: $180 < V_s \le 360\,\mathrm{ms}^{-1}$, $S_A = 0$, $S_S = 1$, 32–43 records.

- Use subset of data of Ambraseys *et al.* (1996) (see 3.104) data with a few changes and exclusion of records from earthquakes with $M_s < 5.5$ because ground motion at long periods was of interest and to increase likelihood of acceptable single-to-noise ratio at longer periods.
- Each record individually filtered. Firstly filter record with sharp low cut-off at $0.1\,\mathrm{Hz}$ and plot velocity and displacement time-histories. Check, visually, whether contaminated by noise and if so increase cutoff frequency by small amount and repeat procedure until resulting velocity and displacement time-histories are deemed acceptable and no significant improvement is observed by further increase of cutoff frequency. Instrument correction not applied because high frequency distortion caused by transducer characteristics not important for displacement spectra. Only use each record for regression for periods up to $0.1\,\mathrm{s}$ less than filter cutoff used for that record to avoid distortion by filter, hence as period increases number of data points decreases.
- Regression procedure same as Ambraseys *et al.* (1996), see 3.104.

5.74 Perea & Sordo (1998)

- Ground motion model is:

$$
\ln \mathrm{Pa} = \beta_1 + \beta_2 M + \beta_3 \ln(R + 25)
$$

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

- All records from five medium soft soil sites.
- Use m_b for $M < 6$ and M_s otherwise, because m_b is more representative of released energy for small earthquakes and M_s better represents energy release for large earthquakes because m_b saturates starting from $M > 6$.
- Try including anelastic decay term, $\beta_4 R$ but it does not significantly affect standard deviation.
- Also repeat analysis for three other zones. Zone 1: 3 earthquakes, 3 records ($5.0 \leq M \leq 6.4$, $80 \leq R \leq 156\,\mathrm{km}$) for which conclude has too limited data for reliable equation. Zone 3[6]: 11 earthquakes, 13 records ($4.5 \leq M \leq 7.7$, $251 \leq R \leq 426\,\mathrm{km}$) for which find fits spectra of medium sized shocks better than large shocks because of lack of data for large earthquakes. Zone 4: 4 earthquakes, 7 records ($5.1 \leq M \leq 6.2$, $356 \leq R \leq 573\,\mathrm{km}$) for which find β_2 is negative and β_3 is positive for some periods (which is nonphysical) which state is due to limited number of earthquakes and their similar epicentral distances.
- Find fit spectra of medium sized earthquakes than large earthquakes because of lack of data from large earthquakes.
- Only give graphs of coefficients.

5.75 Shabestari & Yamazaki (1998)

- Ground motion model is:

  $$\log y(T) = b_0(T) + b_1(T)M + b_2(T) - \log r + b_4(T)h + c_i(T)$$

  where $c_i(T)$ is the station coefficient, reflecting relative site effect for each period, assuming zero mean for all stations.
- Response parameters are acceleration and velocity for 5% damping.
- Include at least five earthquakes with $M_{\mathrm{JMA}} \geq 7.2$.
- Exclude earthquakes with focal depths, h, equal to $0\,\mathrm{km}$ or greater than $200\,\mathrm{km}$.
- Exclude records with vectorial composition of PGA less than $0.01\,\mathrm{ms}^{-2}$.
- Use three-stage iterative partial regression method.
- For $T \geq 6\,\mathrm{s}$ constrain horizontal anelastic coefficient to zero because get positive coefficient.
- See Yamazaki *et al.* (2000) for examination of station coefficients.

5.76 Chapman (1999)

- See Section 3.131.
- Response parameter is pseudo-velocity for 2, 5 and 10% damping.

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[6] The following values are from their Table 1 which does not match with their Figure 3.

5.77 Spudich et al. (1999)

- See Section 3.134.
- Response parameter is pseudo-velocity for 5% damping.
- Use only use response spectral data within frequency band $1.25f_h$ to $0.75f_l$ to avoid effects of filter roll-off. Eight records were not processed like the rest so use only response spectral values within 0.1 to $1\,\mathrm{s}$. Hence number of records used for regression at each period varies, minimum number used is 105 records for $2\,\mathrm{s}$.
- Give smoothed coefficients using cubic function.

5.78 Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)

- See Section 3.137.
- Response parameter is acceleration for 5% damping.
- Find b_2 and b_3 significantly different than 0 at 5% level for all periods but b_A and b_S not significant for many periods (especially for vertical component).
- Find deamplification for vertical component on soft and stiff soil compared with rock. Check by removing all 34 Northridge records (many of which were on soft soil) and repeat analysis; find little change.
- Also derive equations for horizontal response under influence of vertical acceleration using a bending SDOF model; find little change in response.

5.79 Bozorgnia et al. (2000)

- See Section 3.138.
- Response parameter is acceleration for 5% damping.
- Different set of data than for PGA hence: strike-slip: 20 earthquakes (including one normal faulting shock), reverse: 7 earthquakes and thrust: 6 earthquakes.
- Find considerable period-to-period variability in coefficients causing predicted spectra to be very jagged near limits of magnitude and distance ranges so carried out partial smoothing of coefficients.

5.80 Campbell & Bozorgnia (2000)

- See Section 3.139.
- Response parameter is pseudo-acceleration for 5% damping.

5.81 Chou & Uang (2000)

- Ground motion model is:

$$\log Y = a + b(M-6) + c(M-6)^2 + d\log(D^2+h^2)^{1/2} + eG_c + fG_d$$

- Response parameter is pseudo-velocity for 5% damping.
- Use three site categories (based on average shear-wave velocity, V_s, over top $30\,\mathrm{m}$):

Classes A+B Hard rock or rock: $V_s > 760\,\mathrm{ms}^{-1}$, $G_c = 0$, $G_d = 0$, 35 records.
Class C Very dense soil and soft rock: $360 < V_s \leq 760\,\mathrm{ms}^{-1}$, $G_c = 1$, $G_d = 0$, 97 records.
Class D Stiff soil: $180 \leq V_s \leq 360\,\mathrm{ms}^{-1}$, $G_c = 0$, $G_d = 1$, 141 records.

- Records from free-field or ground level of structures no more than two storeys in height.
- Smooth coefficients using cubic polynomial.
- Do not give coefficients for all periods.
- Find cannot use equation to predict near-field ground motions.

5.82 Kawano et al. (2000)

- Ground motion model is:

$$\log S_i(T) = a(T)M - \{b(T)X_{eq} + \log X_{eq}\} + c_i(T)$$

  where $c_i(T)$ is an individual site amplification factor for each of 12 stations.
- Response parameter is acceleration for 5% damping.
- Focal depths between 0 and $60\,\mathrm{km}$.
- Use data either recorded at ground surface where $0.5 \leq V_s \leq 2.7\,\mathrm{kms}^{-1}$ $(1.7 \leq V_p \leq 5.5\,\mathrm{kms}^{-1})$ or obtained by analytically removing effects of uppermost surface layers of ground from underground observation data (or by stripping-off analysis) using underground structure.
- Use only ground motion after arrival of first S wave because most important for aseismic design.
- Do not give table of coefficients, only graphs of coefficients.
- Define amplification factors, $d_i(T) = c_i(T) - c_0(T)$ for horizontal motion and $d_i(T) = c_{v,i}(T) - c_0(T)$ for vertical motion, where $c_0(T)$ is the regression coefficient for data observed at ground layer equivalent to seismic bedrock.
- Find $S_h(T) = S_b(T)\alpha_h(T)\beta_h(T)$ where $S_b(T)$ is $S_0(T)$. $\alpha_h(T) = (V_s/V_{s,b})^{-\delta_h(T)}$ for $T \leq T_{s,1}$ and $\alpha_h(T) = \alpha_h(T_{s,1})$ for $T > T_{s,1}$ where $T_{s,1}$ is the primary predominant period of surface layer. $\beta_h(T) = 1$ for $T \leq T_{s,1}$, $\beta_h(T) = (T/T_{s,1})^{-\log(\alpha_h(T_{s,1}))}$ for $10T_{s,1} > T > T_{s,1}$ and $\beta_h(T) = 10^{-\log(\alpha_h(T_{s,1}))}$ for $T \geq 10T_{s,1}$. $V_{s,b} = 2.2\,\mathrm{kms}^{-1}$. Similar relationships are defined for vertical motion, $S_v(T)$.

- Note that relation does not include effect of source mechanism or rupture propagation, so probably less valid in near-fault region.

5.83 Kobayashi et al. (2000)

- See Section 3.141.
- Response parameter is pseudo-velocity for 5% damping.
- Use significantly less records for $T > 1.5\,\mathrm{s}$.

5.84 McVerry et al. (2000)

- Ground motion model for crustal earthquakes is (using form from Abrahamson & Silva (1997), see Section 5.68):

  $$\begin{aligned}\ln \mathrm{SA}'(T) &= C_1(T) + C_{4AS}(M-6) + C_{3AS}(T)(8.5-M)^2 + C_5(T)r \\ &\quad + (C_8(T) + C_{6AS}(M-6))\ln(r^2 + C_{10AS}^2(T))^{1/2} + C_{46}(T)r_{\mathrm{VOL}} \\ &\quad + \{C_2(T)r + C_{44}(T) + (C_9(T) + C_7(T)(M-6))(\ln(r^2 + C_{10AS}^2(T))^{1/2} \\ &\quad - \ln C_{10AS})\} \\ &\quad + \{C_{29}(T)\} \\ &\quad + \{C_{30AS}(T)\ln(\mathrm{PGA}'_{WA} + 0.03) + C_{43}(T)\} \\ &\quad + C_{32}\mathrm{CN} + C_{33AS}(T)\mathrm{CR}\end{aligned}$$

  Also add on hanging wall term, see Section 5.68. Subscript AS denotes those coefficients from Abrahamson & Silva (1997). Three parts of equation within $\{\ldots\}$ are for site conditions MA/SA, Class B and Class C respectively. PGA'_{WA} is the predicted PGA ($\mathrm{SA}'(0)$) for weak rock category. $\mathrm{CN} = -1$ for normal mechanism and 0 otherwise. $\mathrm{CR} = 0.5$ for reverse/oblique, 1.0 for reverse and 0 otherwise. Ground motion model for subduction zone earthquakes is (using form from Youngs *et al.* (1997), see Section 5.72):

  $$\begin{aligned}\ln \mathrm{SA}'(T) &= C_{11}(T) + [C_{12Y} + (C_{17Y}(T) - C_{17}(T))C_{19Y}] \\ &\quad + C_{13Y}(T)(10-M)^3 + C_{17}(T)\ln(r + C_{18Y}\exp(C_{19Y}M)) + C_{20}(T)H_C \\ &\quad + C_{24}(T)\mathrm{SI} + C_{46}(T)r_{\mathrm{VOL}}(1-\mathrm{DS}) \\ &\quad + \{C_{44}(T) + C_{16}(T)(\ln(r + C_{18Y}\exp(C_{19Y}M)) \\ &\quad - \ln(C_{18Y}\exp(C_{19Y}M)))\} \\ &\quad + \{C_{29}(T)\} \\ &\quad + \{C_{30Y}(T)\ln(\mathrm{PGA}'_{WA} + 0.03) + C_{43}(T)\}\end{aligned}$$

  Subscript Y denotes those coefficients from Youngs *et al.* (1997). Three parts of equation within $\{\ldots\}$ are for site conditions MA/SA, Class B and Class C respectively. $\mathrm{SI} = 1$ for subduction interface and 0 otherwise. $\mathrm{DS} = 1$ for deep slab and 0 otherwise. r_{VOL} is length of path that lies in the volcanic zone.

- Response parameter is acceleration for 5% damping.
- Use four site conditions (mostly based on geological descriptions rather than measured shear-wave velocity):

WA	Weak rock sites, or sites with soil layer of thickness $\leq 3\,\mathrm{m}$ overlying weak rock.
MA/SA	Moderate-strength or strong rock sites, or sites with soil layer of thickness $\leq 3\,\mathrm{m}$ overlying moderate-strength or strong rock.
Class B	Intermediate soil sites or sites with soil layer of thickness $> 3\,\mathrm{m}$ overlying rock.
Class C	Flexible or deep soil sites with natural periods $> 0.6\,\mathrm{s}$.

  Justify soil categories using statistical studies of residuals at early stage. Exclude response spectra from very soft soil sites ($V_s < 150\,\mathrm{ms}^{-1}$ for depths of $\gtrsim 10\,\mathrm{m}$).

- Use data for PGA equation from Zhao *et al.* (1997), see Section 3.121.
- Exclude records from bases of buildings with >4 storeys.
- Use less records for long periods because noise.
- Lack of data prevent development of robust model purely from NZ data. Plot residuals of predicted response using published attenuation relations (base models) for other areas to find relations which gave good representations of NZ data. Then modify some coefficients to improve match; imposing constraints so that the selected models control behaviour at short distances where NZ data lacking. Require crustal and subduction zone expressions for rock sites to match magnitude dependence of base models at $r = 0\,\mathrm{km}$. Constrain coefficients that occur nonlinearly and nonlinear site response coefficient for Class C to base model values.
- Find anelastic attenuation term and additive terms for shallow slab earthquakes for subduction earthquakes not statistically significant. Also differences in attenuation rates for shallow slab, deep slab and interface earthquakes not statistically significant.
- Exclude deep slab earthquakes because of high attenuation in mantle; note equation should not be used for such earthquakes.
- Different attenuation rate for site category MA/SA because of magnitude dependence apparent in residuals for simpler model.
- Eliminate nonlinear site response term for Class B because find unacceptable (positive) values of coefficient and constraining to negative values produces poorer fit.
- Predicted PGA ($\mathrm{SA}'(0)$) from response spectrum set of records considerably smaller than those, $\mathrm{SA}(0)$, from the complete PGA set of records. Thus scale $\mathrm{SA}'(T)$ by ratio $\mathrm{SA}(0)/\mathrm{SA}'(0)$.
- Standard error has a magnitude dependent intra-event component and a magnitude independent inter-event component.
- Note lack of data for large magnitude subduction zone earthquakes and large magnitude near source data for crustal earthquakes.

- Do not give coefficients, only predictions.

5.85 Monguilner et al. (2000b)

- Ground motion model is:

  $$\log S_A(T) = A(\Delta, T) + M + b_1(T) + b_2(T)M + b_3(T)s + b_4(T)v + b_5(T)M^2 + e_p(i)$$

  where $A(\mathrm{DE}, H, S, T) = A_0(T) \log \Delta(\mathrm{DE}, H, M)$, $\Delta = (\mathrm{DE}^2 + H^2 + S^2)^{\frac{1}{2}}$, H is focal depth, p is the confidence level, s is from site classification (details not given in paper) and v is component direction (details not given in paper although probably $v = 0$ for horizontal direction and $v = 1$ for vertical direction).

- Response parameter is pseudo-acceleration for unknown damping level.
- Use same data and weighting method as Monguilner *et al.* (2000a) (see Section 3.142).
- Find $A_0(T)$ by regression of the Fourier amplitude spectra of the strong-motion records.
- Estimate fault area, S, using $\log S = M_s + 8.13 - 0.6667 \log(\sigma\Delta\sigma/\mu)$.
- Equation only valid for $M_{\min} \leq M \leq M_{\max}$ where $M_{\min} = -b_2/(2b_5(T))$ and $M_{\max} = -(1 + b_2(T))/(2b_5(T))$. For $M < M_{\min}$ use M for second term and $M = M_{\min}$ elsewhere. For $M > M_{\max}$ use $M = M_{\max}$ everywhere.
- Examine residuals, $\epsilon(T) = \log S_A(T) - \log S'_A(T)$ where $S'_A(T)$ is the observed pseudo-acceleration and fit to the normal probability distribution, $p(\epsilon, T) = \int \exp[-(x - \mu(T))/\sigma(T)]^2/(\sigma(T)\sqrt{2\pi})$, to find $\mu(T)$ and $\sigma(T)$. Find that the residuals fit the theoretical probably distribution at the 5% level using the χ^2 and KS[7] tests.
- Do not give coefficients, only graphs of coefficients.

5.86 Shabestari & Yamazaki (2000)

- Ground motion model is:

  $$\log y(T) = b_0(T) + b_1(T)M + b_2(T) - \log r + b_4(T)h + c_i(T)$$

  where $c_i(T)$ is the station coefficient, reflecting the relative site effect for each period, assuming zero mean for all stations.

- Response parameters are acceleration and velocity for 5% damping.
- Depths between 1 (includes earthquakes with depths reported as $0\,\mathrm{km}$) and $158\,\mathrm{km}$. Exclude earthquakes with focal depths greater than $200\,\mathrm{km}$.
- Exclude records with vectorial composition of PGA less than $0.01\,\mathrm{ms}^{-2}$.

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[7] Probably this is Kolmogorov-Smirnov.

- Exclude data from stations which have recorded less than two records, because the station coefficient could not be determined adequately. Use records from 823 stations.
- Most records from distances between 50 and $300\,\mathrm{km}$.
- Use three-stage iterative partial regression method.
- For $T \geq 5\,\mathrm{s}$ constrain horizontal anelastic coefficient to zero because get positive coefficient.

5.87 Smit et al. (2000)

- See Section 3.145.
- Response parameter is acceleration for 5% damping.

5.88 Takahashi et al. (2000)

- See Section 3.146.
- Response parameter is pseudo-velocity for 5% damping.
- For periods $\geq 1\,\mathrm{s}$ long period noise in records leads to reduction in number of records.
- Set b and e to zero at long periods because estimates not statistically significant.
- Find that soft soil site correction terms may be affected by different processing procedures for data from different sources.

5.89 Lussou et al. (2001)

- See Section 3.149.
- Response parameter is pseudo-acceleration for 5% damping.

5.90 Gülkan & Kalkan (2002)

- See Section 3.152.
- Response parameter is acceleration for 5% damping.

5.91 Khademi (2002)

- See Section 3.153.
- Response parameter is acceleration for 5% damping.

5.92 Manic (2002)

- Ground motion model is:

$$\begin{aligned}\log \mathrm{PSV}(T) &= c_1(T) + c_2(T)M + c_3(T)\log(R) + c_4(T)S_A \\ \text{where } R &= (d^2 + d_0^2)^{1/2}\end{aligned}$$

- Response parameter is pseudo-velocity for 5% damping,
- Uses two site categories:

$S_A = 0$ Rock, $V_{s,30} > 750\,\mathrm{ms}^{-1}$.

$S_A = 1$ Stiff soil, $360 < V_{s,30} \leq 750\,\mathrm{ms}^{-1}$.

Soft soil sites ($V_s \leq 360\,\mathrm{ms}^{-1}$) do not exist in set of records.

- Use technique of Ambraseys *et al.* (1996) to find the site coefficient $c_4(T)$, i.e. use residuals from regression without considering site classification.
- Derives separate equations for M_s and M_L and for d_f and d_e.

5.93 Schwarz et al. (2002)

- See Section 3.155.
- Response parameter is acceleration for 5% damping.

5.94 Zonno & Montaldo (2002)

- See Section 3.158.
- Response parameter is pseudo-velocity for 5% damping.

5.95 Alarcón (2003)

- See Section 3.159.
- Response parameter is acceleration for 0, 5 and 10% damping but only report coefficients for 5% damping.
- Derive equations for 84[8] periods but only reports coefficients for 11 periods.

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[8] On page 8 of paper it says 88 periods.

5.96 Atkinson & Boore (2003)

- See Section 3.161.
- Response parameter is pseudo-acceleration for 5% damping.

5.97 Berge-Thierry et al. (2003)

- Ground motion model is:

  $$\log_{10}\mathrm{PSA}(f) = a(f)M + b(f)d - \log_{10}d + c_1(f) + c_2(f)$$

  where $c_1(f)$ is for rock sites and $c_2(f)$ is for alluvium sites.

- Use two site categories based on V_s where V_s is the average shear-wave velocity in top $30\,\mathrm{m}$:

  1. Rock, $V_s > 800\,\mathrm{ms}^{-1}$.
  2. Alluvium, $300 < V_s < 800\,\mathrm{ms}^{-1}$.

  Note that some uncertainty in site classification due to lack of V_s values at many stations.

- Response parameter is spectral acceleration for 5%, 7%, 10% and 20% damping.
- Note that not enough data to derive an equation using only French data so had to use European and US data.
- Use only records from earthquakes with focal depth $\leq 30\,\mathrm{km}$ so as to be consistent with shallow crustal earthquakes in France.
- Predominately use corrected data from Ambraseys *et al.* (2000).
- Supplement European data with some data from western USA to improve the magnitude and distance distribution.
- Exclude records from Ambraseys *et al.* (2000) from earthquakes with $M_s < 4$.
- Exclude records from Ambraseys *et al.* (2000) with record lengths $< 10\,\mathrm{s}$.
- Exclude records from Ambraseys *et al.* (2000) with poor visual quality.
- Exclude records from Ambraseys *et al.* (2000) from non-free-field stations or those inside a building on the third floor or higher.
- Exclude records from Ambraseys *et al.* (2000) from stations with unknown or very soft soil site conditions.
- Processing procedure of records from Ambraseys *et al.* (2000) is: baseline correct uncorrected record, re-sample record to $0.01\,\mathrm{s}$ time-step and bandpass filtered using a elliptical filter with cut-offs of 0.25 and $25\,\mathrm{Hz}$ because most instruments were SMA-1s with natural frequency of $25\,\mathrm{Hz}$ and damping of 60%. No instrument correction was applied because instrument characteristics are not known.

- Only use US records from earthquakes with $M > 6$.
- Use the already corrected records from USGS and CDMG.
- Most data from rock sites is from earthquakes with $M < 6$.
- 49.7% of data is from Italy and 16.9% is from USA. All other countries contribute less than 10% each.
- Use hypocentral distance because believe it accounts for both point and extended sources.
- Use uniformly calculated M_s for data from Ambraseys *et al.* (2000) and M_w for data from W. USA, which believe is equivalent for M_s for $M_w > 6$.
- Coefficients only reported for horizontal spectral acceleration for 5% damping.
- Note that recent data, e.g. Chi-Chi, shows saturation of ground motions at short distances but data used only contains a few records at close distances so data not sufficient to model such phenomenon.
- Obtain positive $b(f)$ coefficients for periods $> 1s$ which believe is due to low frequency noise and surface waves.
- Believe that small difference between estimated rock and alluvium motions could be due to incorrect site classification at some stations.
- Repeat regression using a randomly selected half of the data. Find very small differences between predicted ground motions using half or complete data set so believe equation is stable.
- Repeat regression excluding data from W. USA and find very small differences between predicted ground motions so believe equation is not influenced by data from W. USA.
- Repeat regression using M_w rather than M_s if available and find that predicted ground motions are different but that the predictions using M_s are higher than those using M_w so note that equation using M_s is conservative hence it is useful in a nuclear safety assessment.
- Repeat regression using d_r rather than d_h and find that predicted ground motions using d_h are higher than when d_r is used because using d_h places source further from source of energy.
- Plot residuals for 0.03 and $2\,\mathrm{s}$ and find not systematic bias in residuals.

5.98 Bommer et al. (2003)

- See Section 3.163.
- Response parameter is acceleration for 5% damping.

5.99 Campbell & Bozorgnia (2003c), Campbell & Bozorgnia (2003a) & Bozorgnia & Campbell (2004b)

- See Section 3.164.
- Response parameter is pseudo-acceleration for 5% damping.
- To make regression analysis more stable set c_2 equal to value from better-constrained regression of uncorrected PGAs.
- Do limited amount of smoothing of regression coefficients to reduce the considerable amount of period-to-period variability in the regression coefficients that caused variability in predicted pseudo-acceleration especially for small distances and large magnitudes.

5.100 Fukushima *et al.* (2003)

- Ground motion model is:

$$\log \mathrm{Sa}(f) = a(f)M - \log(R + d(f)10^{e(f)M}) + b(f)R + c_1\delta_1 + c_2\delta_2$$

- Use two site categories:

  1. Rock sites with $V_s > 800\,\mathrm{ms}^{-1}$. $\delta_1 = 1$ and $\delta_2 = 0$.
  2. Soil sites with $V_s < 800\,\mathrm{ms}^{-1}$. $\delta_2 = 1$ and $\delta_1 = 0$.

  Note that some data (Turkish and Japanese) are associated with liquefaction phenomena and so probably $V_s < 300\,\mathrm{ms}^{-1}$.

- Choose functional form to include effect of amplitude saturation close to source.
- Note that negative Q values obtained in some ground motion estimation equations may be due to the lack of amplitude saturation terms.
- Do not investigate effect of rupture mechanism, directivity, and the hanging wall effect because of a lack of data.
- Use same set of data as Berge-Thierry *et al.* (2003) but with the addition of records from the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes, which are used to help constrain the near-source characteristics. In total use 399 records from west Eurasia, 162 from USA, 154 from Hyogo-ken Nanbu and 25 from Kocaeli.
- Remove records from distances greater than the distance at which the predicted PGA is less than $10\,\mathrm{cms}^{-2}$ (the average trigger level plus the standard error of observation) as predicted by a previously derived ground motion prediction equation that agrees well with the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes although they note the process should be iterative.

- Use only records from earthquakes with $M \geq 5.5$ so as to allow the use of a linear magnitude dependence.
- Due to the nonlinear functional form adopt a iterative method to find $d(f)$ and $e(f)$. However, due to the lack of near-source data an accurate value of $e(f)$ cannot be found therefore set $e(f)$ to 0.42, which gives accelerations that agree with the observed peak accelerations in the 1995 Hyogo-ken Nanbu and 1999 Kocaeli earthquakes.
- Bandpass filter records with cut-offs of 0.25 and $25\,\mathrm{Hz}$. Note that due to the presence of many records from analogue instruments the results for frequencies higher than $10\,\mathrm{Hz}$ are less reliable than those for lower frequencies.
- Find that for frequencies $> 0.4\,\mathrm{Hz}$ the $b(f)$ coefficient corresponds to positive Q values. For lower frequencies the value of $b(f)$ correspond to negative Q values, which note could be due to instrumental noise or the effect of surface waves that are not well represented by the functional form adopted.
- Note that the small difference between predicted rock and soil motions may be due to intrinsic rock amplification due to rock weathering or inappropriate site classification for some records (e.g. those from the 1999 Kocaeli earthquake, which are all considered to be on soil).
- Plot residuals with respect to regional origin (Hyogo-ken Nanbu, USA, western Eurasian and Kocaeli) and find no clear bias or trend.
- Note that most of the used near-fault records come from strike-slip earthquakes and so the equation may be only should be used for prediction of strike-slip motions.
- Note that the site classification scheme adopted is very basic but lack information for more sophisticated method.

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:

Ts	Number of periods for which attenuation equations are derived
T_{min}	Minimum period for which attenuation equation is derived
T_{max}	Maximum period for which attenuation equation is derived

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
Johnson (1973)	W. USA	41	-	23	5.3	7.7	m_b	6.3	149.8	d_e	1	14	0.055	2.469	M	1	A
Kobayashi & Nagahashi (1977)	Japan	U	-	U	5.4*	7.9*	U	60*	210*	d_h	I	U	0.1	5	R[1]	O	A
McGuire (1977)	W. USA	34	-	22	5.3	7.6	M_L	14	125	d_h	1	16	0.1	8	B	U	A
Trifunac (1977) & Trifunac & Anderson (1978a)	W. USA	182	182	46	3.8	7.7	Mostly M_L	6[2]*	400[3]*	d_e	3	91	0.04	12	B	O	A
Faccioli (1978)	W. USA, Japan, Papua New Guinea, Mexico & Greece	26[4]	-	11	5.3	7.8	U	15	342	d_h	1	15	0.1	4	B	U	A
McGuire (1978)	W. USA	70	-	17+*	4.5*	7.7	U[5]	11*	210*	d_h	2	1	1	1	B	U	A
Trifunac (1978) & Trifunac & Anderson (1978b)	W. USA	182	182	46	3.8	7.7	Mostly M_L	6[6]*	400[7]*	d_e	3	91	0.04	12	B	O	A
Trifunac & Anderson (1978c)	W. USA	182	182	46	3.8	7.7	Mostly M_L	6[8]*	400[9]*	d_e	3	91	0.04	12	B	O	A
Cornell *et al.* (1979)	W. USA	70	-	U	U	U	M_L	U	U	d_h	1	7	0.17	5	C	U	A

continued on next page

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[1] They state it is two dimensional response spectrum which assume to be resolved component.

[2] Note only valid for $R \geq 20\,\mathrm{km}$

[3] Note only valid for $R \leq 200\,\mathrm{km}$

[4] Total earthquake components (does not need to be multiplied by two)

[5] Idriss (1978) finds magnitudes to be mixture of M_L, m_b and M_s.

[6] Note only valid for $R \geq 20\,\mathrm{km}$

[7] Note only valid for $R \leq 200\,\mathrm{km}$

[8] Note only valid for $R \geq 20\,\mathrm{km}$

[9] Note only valid for $R \leq 200\,\mathrm{km}$

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
Trifunac & Lee (1979)	W. N. America	U	U	U	U	U	U	U	U	d_e	3	91	0.04	15	U	U	A
Ohsaki *et al.* (1980b)	Japan	95	-	29+	3.9*	7.2*	U	3*	500*	d_h	2	86	0.02	5	U	1	A
Ohsaki *et al.* (1980a)	Japan	75	-	U	4	7.4	U	6	500	d_h	1	U	0.02	5	U	1	A
Trifunac (1980)	W. USA	U	-	U	U	U	U	U	U	d_e	C	91	0.04	7.5	U	U	A
Devillers & Mohammadioun (1981)	W. USA	186	-	U	3.3*	7.7*	U	$\geq$ 10	250*	d_h	1	46	0.04	10	U	1	A
Kobayashi & Midorikawa (1982)	Japan	45	-	U	5.1	7.5	U	50	280	d_h	1	U	0.1	5	U	O	A
Joyner & Fumal (1984), Joyner & Fumal (1985) & Joyner & Boore (1988)	W. N. America	U	-	U	5.0	7.7	$M_w(M_L)$	U	U	d_f	C	12	0.1	4	L	U	A
Kawashima *et al.* (1984)	Japan	197	-	90	5.0	U	M_{JMA}	U	U	d_e	3	10	0.1	3	R	1	A
Kawashima *et al.* (1985)	Japan	-	119	90*	5.0*	7.5*	M_{JMA}	5*	500*	d_e	3	10	0.1	3	-	1	A
Trifunac & Lee (1985)	W. N. America	438	438	104	U	U	U	U	U	d_h	3, C	91	0.04	15	U	U	A
Kamiyama & Yanagisawa (1986)	Japan	228	-	69	4.5	7.9	M_{JMA}	3	323	d_e	I	45	0.1	10	U	1	A
C.B. Crouse (1987)[10]	S. California	U	-	U	U	U	M_s	U	U	d_r	1	10	0.05	6	B	U	A
Lee (1987) & Lee (1993)	Mostly California	494	494	106	U	U	M_L for $M \lesssim 6.5$, others for $M > 6.5$	U	U	d_e	3	91	0.04	15	B	U	A

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[10] Reported in Joyner & Boore (1988).

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
K. Sadigh (1987)[11]	W. USA + others	U	-	U	U	U	M_w	U	U	d_r	2	7	0.1	4	B	U	A (S, R)
Annaka & Nozawa (1988)	Japan	U	-	45	U	U	U	U	U	U	1	U	0.04*	4*	U	1	A
Crouse *et al.* (1988)	N. Honshu	64	-	U	5.1	8.2	M_w, M_s & M_{JMA} for < 7.5	42	407	d_E, d_h for $M < 7.5$	1	10	0.1	4	B	1	A
Petrovski & Marcellini (1988)	Europe	120	120	46	3	7	U	8	200	d_h	1	26	0.02	5	L	1	A
Yokota *et al.* (1988)	Tokyo	154	24	75 (U)	4.0	6.1	M_{JMA}	59 (60)	206 (100)	d_h	1	U	0.1 (0.05)	10 (5)	U	U	A
Youngs *et al.* (1988)	Worldwide subduction zones	20 + 197 + 389	-	16* (60)	5.6* (5)	8.1* (8.1, 8.2)[12]	M_w (M_s, m_b)	U (15*, 20*)	U (450*, 450*)	d_r, d_h for $M_w \lesssim 7.5$	1	15	0.07	4	G	1W	A (B,F)
Kamiyama (1989)	Japan	228	-	U	4.1	7.9	M_{JMA}	3	350	d_e	I	U	0.05*	10*	U	1	A
Trifunac & Lee (1989)	Mostly California	438	438	104	U	U	U	U	U	d_e	C	12	0.04	14	B	U	A
Atkinson (1990)	E. N. America + 10 others	92+10[13]	-	8+3	3.60 (5.16)	6.00 (6.84)	M_w	8 (8)	1215 (23)	d_h	1	4	0.1	1	B	2	A
Campbell (1990)	Unknown	U	-	U	U	U	M_L for $M < 6$, M_s for $M \geq 6$	U	U	d_s	1	15	0.04	4	U	U	A
Dahle *et al.* (1990b) & Dahle *et al.* (1990a)	Worldwide intraplate regions	87	-	56	2.9	7.8	M_s (M_L, m_b, M_{CL}	6	1300	d_h	1	89	0.025	4	L	2	A
Tamura *et al.* (1990)	Japan	97	-	7	7.1	7.9	M_{JMA}	U	U	d_e	3	13	2	20	L	1, O	A

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[11] Reported in Joyner & Boore (1988).

[12] Consider equations valid for $M_w \leq 8$

[13] Total earthquake components (does not need to be multiplied by two). 79+10 records for 0.1 s equation.

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
Tsai *et al.* (1990)	Worldwide	<88	-	<51	4.9*	7.4	M_w	3*	150*	d_r	1	14	0.07	1	U	M	T (S,O)
Crouse (1991)	Worldwide subduction zones	235	-	U	5.1	8.2	M_w (M_s, M_{JMA})	>8	>469	d_E, d_h for $M < 7.5$	1	10	0.1	4	B	1	A
Dahle *et al.* (1991)	Intraplate (particularly Norway)	395+31	-	136+11	2.4*(4.1)	5.2*(6.9)	M_s (M_L,M_{CL})	20* (9.7)	1200* (1300)	d_h	1	4[14]	0.1	1	L	O	A
I.M. Idriss (1991)[15]	Unknown	572	-	30*	4.6	7.4	M_L for $M < 6$, M_s for $M \geq 6$	1	100	d_r, d_h for $M < 6$	1	23	0.03	5	U	U	A
Mohammadioun (1991)	Italy	144	-	46	3.0	6.5	U	6	186	d_h, 1 eq. with d_r	1	81	0.013	1.95	B	U	A
Niazi & Bozorgnia (1992)	SMART-1 array, Taiwan	236	234	12	3.6	7.8	M_L (M_D) for $M_L < 6.6$, else M_s	3.1[16]	119.7[16]	d_h	1	23	0.03	10	M	2W	A
Benito *et al.* (1992)	Campano Lucano	84	-	U	4.7	6.5	M_L	3.4*	142*	d_h	3	15	0.04	10	L	1	A
Tento *et al.* (1992)	Italy	137	-	40	4	6.6	M_L	3.2	170	d_f for $M_L \geq 5.7$, d_e otherwise	1	12	0.04	2.75	L	2	A
Boore *et al.* (1993) & Boore *et al.* (1997)	W. N. America	112	-	14	5.30	7.70	M_w	0	109	d_f	3	46	0.1	2	L, G	2M	A
Caillot & Bard (1993)	Italy	83	-	≤ 40	3.2	6.8	M_s if M_L & $M_s \geq 6.0$ else M_L	10	63	d_h	2	25	0.05	1.98	U	2, 1W	A

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[14] Consider more than 4 natural periods but results not reported.

[15] Reported in Idriss (1993).

[16] Distance to centre of array

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 (1993)	Worldwide	U	-	U	U[17]	U	M_L for $M < 6.0$ and M_s otherwise	U	U[18]	d_s	2	15	0.04	4	M	O	A (T,S)
Sadigh *et al.* (1993) & Sadigh *et al.* (1997)	California with 4 foreign	960+4	U	119+2	3.8 (6.8)	7.4 (7.4)	M_w	0.1 (3)	305 (172)[19]	d_r for some, d_h for small ones	2	21	0.05[20]	7.5[21]	G	U	A(R,S)
Sun & Peng (1993)	W. USA with 1 foreign	150+1	-	42+1	4.1	7.7	M_L for $M < 6$, else M_s	2*	150*	d_e	C	U	0.04	10	R	1	A
Boore *et al.* (1994a) & Boore *et al.* (1997)	W. N. America	112 (70)	-	14 (9)	5.30	7.70 (7.40)	M_w	0	109	d_f	C	46	0.1	2	L, G	1M, 2M	A (R,S)[22]
Climent *et al.* (1994)	Central America & Mexico	280	U	72	U	U	U	U	U	U	U	U	0.05*	≥ 2	U	U	A
Fukushima *et al.* (1994) & Fukushima *et al.* (1995)	3 vertical arrays in Japan	285	284	42	5.0	7.7	M_{JMA}	60*	400*	d_h	I	U	0.05	2	B	1,2	A
Lawson & Krawinkler (1994)	W. USA	250+	-	11	5.8	7.4	M_w	U	100	d_f	3	38	0.1	4	U	1M	A
Lee & Manić (1994) & Lee (1995)	Former Yugoslavia	313	313	183	3.75	7.0	U	4	250	d_e	6	12	0.04	2	U	2R	A

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[17] Considers equation valid for $M \geq 4.7$.

[18] Considers equation valid for $d \leq 300\,\mathrm{km}$.

[19] Equations stated to be for distances up to $100\,\mathrm{km}$

[20] Minimum period for vertical equations is $0.04\,\mathrm{s}$.

[21] Maximum period for vertical equations is $3\,\mathrm{s}$.

[22] Coefficients given in Boore *et al.* (1994b).

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
Mohammadioun (1994a)	California	108[23]	56	23	5.3	7.7	M_L	3	136	Often d_r, d_h in far field	1	96	0.013	5	B	1	A
Mohammadioun (1994b)	W. USA	530[24]	≈ 265	U	U	U	M_L	1	250	d_r, d_E if more appropriate, d_h in far field	1	96	0.013	5	B	1	A
Musson *et al.* (1994)	UK + 28* foreign	88*+28*[25]	-	15+16	3 (3.7)	4.1 (6.4)	M_L	70* (>1.3)	>477.4 (200*)	d_h	1	4	0.1	1	U[26]	O	A
Theodulidis & Papazachos (1994)	Greece+16 foreign	105+16[27]	-	36+4	4.5 (7.2)	7.0 (7.5)	M_s, M_w, M_{JMA}	1 (48)	128 (236)	d_e	2	73	0.05	5	B	O	A
Dahle *et al.* (1995)	Cen. America	280	-	72	3*	8*	M_w (M_s, m_b, M_D)	6*	490*	d_h	2	8	0.025	4	L	1B	A
Lee & Trifunac (1995)	W. N. America	1926	1926	297	1.7	7.7	Usually M_L for $M \leq 6.5$ and M_s for $M > 6.5$	2	200+	d_h	9, 3 × C	91	0.04	15	U	1	A
Ambraseys *et al.* (1996)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	d_f for $M > 6.0$, d_e otherwise	3	46	0.1	2	L	2	A
Ambraseys & Simpson (1996)	Europe & Mid. East	-	417	157	4.0	7.9	M_s (unspecified)	0	260	d_f for $M > 6.0$, d_e otherwise	3	46	0.1	2	L	2	A
Bommer *et al.* (1996)	El Salvador & Nicaragua	36	-	20	3.7	7.0	M_s	62	260	d_h	1	10	0.1	2	L	U	A

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[23] Total number, does not need to be multiplied by two.

[24] Total number, does not need to be multiplied by two.

[25] There are 116 records in total.

[26] Free (1996) believes it is largest horizontal component.

[27] Total number of components 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
Crouse & McGuire (1996)	Cen. & S. California	238	-	16	6.0	7.7	M_s	0.1	211	d_r	4	14	0.04	14	G	1W	R,S (R,S)
Free (1996) & Free *et al.* (1998)	Stable continental regions	399–410	347–477	H: 137–138, V: 126–132	1.5	6.8	M_w	0	820	d_f for some, d_e for most	2	52	0.04	2	L	1	A
Molas & Yamazaki (1996)	Japan	2166	-	387	4.1	7.8	M_{JMA}	8*	1000*	d_r for 2 earthquakes, d_h otherwise	I	12	0.1	4	L	O	A
Ohno *et al.* (1996)	California	248	-	17	5.0	7.5	M_w (M_L)	7.2	99.6	d_q for $M > 5.3$, d_h otherwise	2	U	0.02	2	B	2M	A
Sabetta & Pugliese (1996)	Italy	95	95	17	4.6	6.8	M_s if M_L & $M_s \geq 5.5$ else M_L	1.5, 1.5	179, 180[28]	Both d_f & d_e	3	14	0.04	4	L	1	A
Spudich *et al.* (1996) & Spudich *et al.* (1997)	Worldwide extensional regimes	99–118	-	27–29	5.10	6.90	M_w	0	102.1	d_f	2	46	0.1	2	G, C	2M	NS
Abrahamson & Silva (1997)	California with some others	≤ 655*	≤ 650*	≤ 58	4.4	7.4	U	0.1	220*	d_r	2	28	0.01	5	G	1M	A (S,O,T)
Atkinson (1997)	Cascadia with some foreign	U	-	11+9	4.1	6.7(8.2)	M_w	20*	580*	d_c for some, d_h for small ones	2	12	0.1	2	B	2	A

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[28] State equations should not be used for distances $> 100\,\mathrm{km}$

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 (1997), Campbell (2000) & Campbell (2001)	Worldwide	266 [29]	173	H:30, V:22	4.7	8.1	M_s for $M_s \geq 6$, M_L for $M_s < 6$	3	50	d_s	3	13	0.05	4	G	IW	A (S,R,N)
Schmidt *et al.* (1997)	Costa Rica	200	-	57	3.3	7.6	M_w (M_s, m_b, M_D)	6.1	182.1	d_h	3	7	0.025	4	L, B	O	A
Youngs *et al.* (1997)	Worldwide subduction zones	≤ 476	-	≤ 164	5.0	8.2	M_w (M_s,m_b)	8.5	550.9	d_r, d_h for some	2	11	0.075	3	G	1M	NT (N,T)
Bommer *et al.* (1998)	Europe & Mid. East	121–183	-	34–43	5.5	7.9	M_s	3	260	d_f for most, d_e otherwise	3	66	0.04	3	L	2	A
Perea & Sordo (1998)	Urban area of Puebla, Mexico	10[30]	-	8	5.8	8.1	m_b for $M < 6$, M_s otherwise	274	663	d_e	1	195	0.01	3.5	L	1	A
Shabestari & Yamazaki (1998)	Japan	3990	-	1020	U	8.1	M_{JMA}	U	U	d_r	U	35	0.04	10	L	O	A
Chapman (1999)	W. N. America	304	-	23	5.0	7.7	M_w	0.1	189.4	d_f	3	24	0.1	2	G	2M	A
Spudich *et al.* (1999)	Worldwide extensional regimes	105–132	-	$\leq$ 38	5.1	7.2	M_w	0	99.4	d_f	2	46	0.1	2	G	1M	NS
Ambraseys & Douglas (2000), Douglas (2001b) & Ambraseys & Douglas (2003)	Worldwide	186	183	44	5.83	7.8	M_s	0	15	d_f	3	46	0.1	2	L	1	A
Bozorgnia *et al.* (2000)	Worldwide	1308	1308	33	U	U	M_w	U	≤ 60	d_s	4	U	0.05	4	G	U	A (R,S,T)

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[29] Typographic error in Table 3 of Campbell (1997) does not match number of recordings in Table 4

[30] Typographical error in Figure 3b) of Perea & Sordo (1998) because it does not match their Table 1.

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 (2000)	Worldwide	275–435	274–434	$\leq$ 36	$\geq$ 4.7	$\leq$ 7.7	M_w	$\geq$ 1*	$\leq$ 60*	d_s	4	14	0.05	4	G	1	A (S,R,T)
Chou & Uang (2000)	California	273	-	15	5.6	7.4	M_w	0*	120	d_f	3	25	0.1	3	G	2M	A
Kawano *et al.* (2000)	Japan	107	107	44	5.5	7.0	M_{JMA}	27	202	d_q	I, C	U	0.02	5	U	O	A
Kobayashi *et al.* (2000)	Japan	U	-	U	5.0	7.8	M_w	0.9*	400*	U	4	17	0.1	5	B	1M	A
McVerry *et al.* (2000)	NZ with 66 foreign	$\leq$ 224 (461+66)	-	(51+17)	(5.08)	(7.23(7.41))	M_w	(0.1)	(573)	(d_r for some, d_c for most)	4	U	0.01*	4*	U	O	A (N, R, RO)
Monguilner *et al.* (2000b)	W. Argentina	54	54	10	4.3	7.4	M_s if M_L & $M_s > 6$, M_L otherwise	11	350	d_h	2	200	0.1	6	U	1W	A
Shabestari & Yamazaki (2000)	Japan	6017	-	94	5.0	6.6	M_{JMA}	7*	950*	d_r	I	35	0.04	10	L	O	A
Smit *et al.* (2000)	Caucasus	84	-	26	4.0	7.1	M_s	4	230	d_h	1	22	0.05	1	L	2	A
Takahashi *et al.* (2000)	Japan+166 foreign	≤1332	-	U+7*	5* (5.8*)	8.3* (8*)	M_w	1* (0.1*)	300* (100*)	d_r, d_h for some	4	20	0.05	5	G	O	A
Lussou *et al.* (2001)	Japan	3011	3011	102	3.7	6.3	M_{JMA}	4*	600*	d_h	4	63	0.02	10	B	2	A
Gülkan & Kalkan (2002)	Turkey	93[31]	-	19	4.5	7.4	M_w	1.20	150	d_f, d_e	3	46	0.1	2	L, R	1	A
Khademi (2002)	Iran	160	160	28*	3.4*	7.4	M_w (m_b for $M_s < 5$ and M_s otherwise)	0.1*	180*	d_f, d_e for $M < 5.9$	2	13	0.05	4	L	O	A
Manic (2002)	Former Yugoslavia	153[32]	77	19	4.0 and 4.2	6.9 and 7.0	M_s and M_L	0 and 0	110 and 150	d_f and d_e	2	14	0.04	4	B	1	A

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[31] This is total number of horizontal components used. They come from 47 triaxial records.

[32] This is total number of components. 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
Schwarz *et al.* (2002)	N.W. Turkey	683	683	U	0.9*	7.2	M_L	0*	250*	d_e	3	11	0.01	2	U	1	A
Zonno & Montaldo (2002)	Umbria-Marche	161	-	15	4.5	5.9	M_L	2*	100*	d_e	2	14	0.04	4	L	2	N, O
Alarcón (2003)	Colombia	45 or 47	-	U	4.0	6.7	M_s	49.7	322.4	d_h	1	84	0.05	3	U	U	A
Atkinson & Boore (2003)	Subduction zones	1200+	-	43*	5.5	8.3	M_w	11*	550*	d_r	4	7	0.04	3	C	1M	F, B
Berge-Thierry *et al.* (2003)	Europe & Mid. East+163 from W. USA	802+163[33]	403+82[34]	130+8	4.0 (5.8)	7.9 (7.4)	M_s (M_w for W. USA)	4	330	d_h	2	143	0.03	10	B	2	A
Bommer *et al.* (2003)	Europe & Mid. East	422	-	157	4.0	7.9	M_s (unspecified)	0	260	d_f for $M_s > 6.0$, d_e otherwise	3	46	0.1	2	L	1M	A (S, R, N)
Campbell & Bozorgnia (2003c), Campbell & Bozorgnia (2003a) & Bozorgnia & Campbell (2004b)	Worldwide	443	439	36[35]	4.7	7.7	M_w	2*	60*	d_s	4	14	0.05	4	G	1	A (S & N, R, T)
Fukushima *et al.* (2003)	Mainly west Eurasia+some US and Japanese	399+341	-	40+10	5.5	7.4	M_w (M_s)	0.5	235	d_h (d_r for 2 earthquakes)	2	11	0.03	2	B	2	A

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[33] Total number of records. Does not need to be multiplied by two.

[34] 485 records in total but do not state number of vertical records from W. USA.

[35] For horizontal corrected records. There are 34 for vertical corrected records.

7. ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

Abrahamson, N. A., & Litehiser, J. J. 1989. Attenuation of vertical peak acceleration. *Bulletin of the Seismological Society of America*, **79**(3), 549–580.

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

Abrahamson, N. A., & Youngs, R. R. 1992. A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America*, **82**(1), 505–510.

Alarcón, J. E. 2003. Relaciones de atenuación a partir de espectros de respuesta para Colombia. *In: Proceedings of the Second Colombian Conference on Earthquake Engineering*. In Spanish.

Alchalbi, A., Costa, G., & Suhadolc, P. 2003 (Aug). Strong motion records from Syria: A preliminary analysis. *In: Skopje Earthquake 40 Years of European Earthquake Engineering (SE-40EEE)*.

Alfaro, C. S., Kiremidjian, A. S., & White, R. A. 1990. *Seismic zoning and ground motion parameters for El Salvador*. Tech. rept. 93. The John A. Blume Earthquake Engineering Center, Stanford University. Not seen. Reported in Bommer *et al.* (1996).

Algermissen, S. T., Hansen, S. L., & Thenhaus, P. C. 1988. *Seismic hazard evaluation for El Salvador*. Tech. rept. Report for the US Agency for International Development. Not seen. Reported in Bommer *et al.* (1996).

Ambraseys, N. 1975a. Ground motions in the near field of small-magnitude earthquakes. *Pages 113–136 of: Proceedings of the Commission on the Safety of Nuclear Installations, Organisation of Economic Cooperation in Europe*, vol. 1. Not seen. Reported in Ambraseys (1978a).

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., Smit, P., Berardi, R., Rinaldis, D., Cotton, F., & Berge, C. 2000. *Dissemination of European Strong-Motion Data*. CD-ROM collection. European Commission, Directorate-General XII, Environmental and Climate Programme, ENV4-CT97-0397, Brussels, Belgium.

Ambraseys, N. N. 1975b. Trends in engineering seismology in Europe. *Pages 39–52 of: Proceedings of Fifth European Conference on Earthquake Engineering*, vol. 3.

Ambraseys, N. N. 1978a. Middle East — a reappraisal of seismicity. *The Quarterly Journal of Engineering Geology*, **11**(1), 19–32.

Ambraseys, N. N. 1978b. Preliminary analysis of European strong-motion data 1965–1978. *Bulletin of the European Association of Earthquake Engineering*, **4**, 17–37.

Ambraseys, N. N. 1990. Uniform magnitude re-evaluation of European earthquakes associated with strong-motion records. *Earthquake Engineering and Structural Dynamics*, **19**(1), 1–20.

Ambraseys, N. N. 1995. The prediction of earthquake peak ground acceleration in Europe. *Earthquake Engineering and Structural Dynamics*, **24**(4), 467–490.

Ambraseys, N. N., & Bommer, J. J. 1991. The attenuation of ground accelerations in Europe. *Earthquake Engineering and Structural Dynamics*, **20**(12), 1179–1202.

Ambraseys, N. N., & Bommer, J. J. 1992. On the attenuation of ground accelerations in Europe. *Pages 675–678 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 2.

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. 1996. Prediction of vertical response spectra in Europe. *Earthquake Engineering and Structural Dynamics*, **25**(4), 401–412.

Ambraseys, N. N., & Srbulov, M. 1994. Attenuation of earthquake-induced ground displacements. *Earthquake Engineering and Structural Dynamics*, **23**(5), 467–487.

Ambraseys, N. N., Bommer, J. J., & Sarma, S. K. 1992 (Nov). *A review of seismic ground motions for UK design*. ESEE Report 92-8. Department of Civil Engineering, Imperial College, London.

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., Sigbjörnsson, R., Ólafsson, S., Suhadolc, P., & Costa, G. 2003. Internet site for European strong-motion data. *Bollettino di Geofisica Teorica ed Applicata*. In press.

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

Annaka, T., & Nozawa, Y. 1988. A probabilistic model for seismic hazard estimation in the Kanto district. *Pages 107–112 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Aptikaev, F., & Kopnichev, J. 1980. Correlation between seismic vibration parameters and type of faulting. *Pages 107–110 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 1.

Atkinson, G. M. 1990. A comparison of eastern North American ground motion observations with theoretical predictions. *Seismological Research Letters*, **61**(3–4), 171–180.

Atkinson, G. M. 1997. Empirical ground motion relations for earthquakes in the Cascadia region. *Canadian Journal of Civil Engineering*, **24**, 64–77.

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, Ö, 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., Rinaldis, D., Gorelli, V., & Paciello, A. 1992. Influence of the magnitude, distance and natural period of soil in the strong ground motion. *Pages 773–779 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 2.

Benito, B., Cabañas, L., Jiménez, M. E., Cabañas, C., López, M., Gómez, P., & Alvarez, S. 2000. Caracterización del movimiento del suelo en emplazamientos de la península ibérica y evaluacin del daño potencial en estructuras. proyecto daos. *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.

Blume, J. A. 1977. The SAM procedure for site-acceleration-magnitude relationships. *Pages 416–422 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I.

Blume, J. A. 1980. Distance partitioning in attenuation studies. *Pages 403–410 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Boatwright, J., Bundock, H., Luetgert, J., Seekins, L., Gee, L., & Lombard, P. 2003. The dependence of PGA and PGV on distance and magnitude inferred from northern California ShakeMap data. *Bulletin of the Seismological Society of America*, **93**(5), 2043–2055.

Bolt, B. A., & Abrahamson, N. A. 1982. New attenuation relations for peak and expected accelerations of strong ground motion. *Bulletin of the Seismological Society of America*, **72**(6), 2307–2321.

Bommer, J. J., Hernández, D. A., Navarrete, J. A., & Salazar, W. M. 1996. Seismic hazard assessments for El Salvador. *Geofísica Internacional*, **35**(3), 227–244.

Bommer, J. J., Elnashai, A. S., Chlimintzas, G. O., & Lee, D. 1998 (Mar). *Review and development of response spectra for displacement-based seismic design*. ESEE Report 98-3. Department of Civil Engineering, Imperial College, London.

Bommer, J. J., Douglas, J., & Strasser, F. O. 2003. Style-of-faulting in ground-motion prediction equations. *Bulletin of Earthquake Engineering*, **1**(2), 171–203.

Boore, D. M. 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *Bulletin of the Seismological Society of America*, **73**(6), 1865–1894.

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. 1993. *Estimation of response spectra and peak accelerations from western North American earthquakes: An interim report*. Open-File Report 93-509. U.S. Geological Survey. 70 pages.

Boore, D. M., Joyner, W. B., & Fumal, T. E. 1994a. *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. 1994b. *Ground motion estimates for strike- and reverse-slip faults*. Provided to the Southern California Earthquake Center and widely distributed as an insert in Boore *et al.* (1994a). Not seen. Reported in Boore *et al.* (1997).

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.

Bouhadad, Y., Laouami, N., Bensalem, R., & Larbes, S. 1998. Seismic hazard estimation in the central Tell Atlas of Algeria (Algiers-Kabylia). *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

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*. In press.

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.

Bozorgnia, Y., Campbell, K. W., & Niazi, M. 2000. Observed spectral characteristics of vertical ground motion recorded during worldwide earthquakes from 1957 to 1995. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 2671.

Brillinger, D. R., & Preisler, H. K. 1984. An exploratory analysis of the Joyner-Boore attenuation data. *Bulletin of the Seismological Society of America*, **74**(4), 1441–1450.

Brillinger, D. R., & Preisler, H. K. 1985. Further analysis of the Joyner-Boore attenuation data. *Bulletin of the Seismological Society of America*, **75**(2), 611–614.

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

Cabañas, L., Lopez, M., Benito, B., & Jiménez, 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)*.

Caillot, V., & Bard, P. Y. 1993. Magnitude, distance and site dependent spectra from Italian accelerometric data. *European Earthquake Engineering*, **VII**(1), 37–48.

Camacho, E., Lindholm, C., Dahle, A., & Bungum, H. 1997. Seismic hazard assessment in Panama. *Engineering Geology*, **48**(1-2), 1–6.

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. 1989. The dependence of peak horizontal acceleration on magnitude, distance, and site effects for small-magnitude earthquakes in California and eastern North America. *Bulletin of the Seismological Society of America*, **79**(5), 1311–1346.

Campbell, K. W. 1990 (Sep). *Empirical prediction of near-source soil and soft-rock ground motion for the Diablo Canyon power plant site, San Luis Obispo county, California*. Tech. rept. Dames & Moore, Evergreen, Colorado. Prepared for Lawrence Livermore National Laboratory. Not seen. Reported in Idriss (1993).

Campbell, K. W. 1993 (Jan). Empirical prediction of near-source ground motion from large earthquakes. *In: Proceedings of the International Workshop on Earthquake Hazard and Large Dams in the Himalaya*. Indian National Trust for Art and Cultural Heritage, New Delhi, India.

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. 2000. Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **71**(3), 352–354.

Campbell, K. W. 2001. Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters*, **72**(4), 474.

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. 1994 (Jul). Near-source attenuation of peak horizontal acceleration from worldwide accelerograms recorded from 1957 to 1993. *Pages 283–292 of: Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, vol. III.

Campbell, K. W., & Bozorgnia, Y. 2000 (Nov). New empirical models for predicting near-source horizontal, vertical, and V/H response spectra: Implications for design. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

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. 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.

Chang, T.-Y., Cotton, F., & Angelier, J. 2001. Seismic attenuation and peak ground acceleration in Taiwan. *Bulletin of the Seismological Society of America*, **91**(5), 1229–1246.

Chapman, M. C. 1999. On the use of elastic input energy for seismic hazard analysis. *Earthquake Spectra*, **15**(4), 607–635.

Chen, Y.-H., & Tsai, C.-C. P. 2002. A new method for estimation of the attenuation relationship with variance components. *Bulletin of the Seismological Society of America*, **92**(5), 1984–1991.

Chiaruttini, C., & Siro, L. 1981. The correlation of peak ground horizontal acceleration with magnitude, distance, and seismic intensity for Friuli and Ancona, Italy, and the Alpide belt. *Bulletin of the Seismological Society of America*, **71**(6), 1993–2009.

Chou, C.-C., & Uang, C.-M. 2000. Establishing absorbed energy spectra — an attenuation approach. *Earthquake Engineering and Structural Dynamics*, **29**(10), 1441–1455.

Climent, A., Taylor, W., Ciudad Real, M., Strauch, W., Villagrán, M., Dahle, A., & Bungum, H. 1994. *Spectral strong motion attenuation in Central America*. Tech. rept. 2-17. NORSAR. Not seen. Reported in Camacho *et al.* (1997) and Bommer *et al.* (1996).

Cornell, C. A., Banon, H., & Shakal, A. F. 1979. Seismic motion and response prediction alternatives. *Earthquake Engineering and Structural Dynamics*, **7**(4), 295–315.

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.

Cousins, W. J., Zhao, J. X., & Perrin, N. D. 1999. A model for the attenuation of peak ground acceleration in New Zealand earthquakes based on seismograph and accelerograph data. *Bulletin of the New Zealand Society for Earthquake Engineering*, **32**(4), 193–220.

Crouse, C. B. 1991. Ground-motion attenuation equations for earthquakes on the Cascadia subduction zones. *Earthquake Spectra*, **7**(2), 201–236.

Crouse, C. B., & McGuire, J. W. 1996. Site response studies for purpose of revising NEHRP seismic provisions. *Earthquake Spectra*, **12**(3), 407–439.

Crouse, C. B., Vyas, Y. K., & Schell, B. A. 1988. Ground motion from subduction-zone earthquakes. *Bulletin of the Seismological Society of America*, **78**(1), 1–25.

Dahle, A., Bugum, H., & Kvamme, L. B. 1990a. Attenuation modelling based on intraplate earthquake recordings. *Pages 121–129 of: Proceedings of Ninth European Conference on Earthquake Engineering*, vol. 4-A.

Dahle, A., Bungum, H., & Kvamme, L. B. 1990b. Attenuation models inferred from intraplate earthquake recordings. *Earthquake Engineering and Structural Dynamics*, **19**(8), 1125–1141.

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

Dahle, A., Climent, A., Taylor, W., Bungum, H., Santos, P., Ciudad Real, M., Linholm, C., Strauch, W., & Segura, F. 1995. New spectral strong motion attenuation models for Central America. *Pages 1005–1012 of: Proceedings of the Fifth International Conference on Seismic Zonation*, vol. II.

Denham, D., & Small, G. R. 1971. Strong motion data centre: Bureau of mineral resources, Canada. *Bulletin of the New Zealand Society for Earthquake Engineering*, **4**(1), 15–30.

Denham, D., Small, G. R., & Everingham, I.B. 1973. Some strong-motion results from Papua New Guinea 1967–1972. *Pages 2324–2327 of: Proceedings of Fifth World Conference on Earthquake Engineering*, vol. 2.

Devillers, C., & Mohammadioun, B. 1981. French methodology for determining site-adapted SMS (Séisme Majoré de Sécurité) spectra. *In: Transactions of the 6th International Conference on Structural Mechanics in Reactor Technology*, vol. K(a). K 1/9.

Donovan, N. C. 1973. A statistical evaluation of strong motion data including the February 9, 1971 San Fernando earthquake. *Pages 1252–1261 of: Proceedings of Fifth World Conference on Earthquake Engineering*, vol. 1.

Donovan, N. C., & Bornstein, A. E. 1978. Uncertainties in seismic risk analysis. *Journal of the Geotechnical Engineering Division, ASCE*, **104**(GT7), 869–887.

Douglas, J. 2001a (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. 2001b (Oct). *A critical reappraisal of some problems in engineering seismology*. Ph.D. thesis, University of 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.

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.

Esteva, L. 1970. Seismic risk and seismic design. *Pages 142–182 of:* Hansen, R.J. (ed), *Seismic Design for Nuclear Power Plants*. The M.I.T. Press.

Esteva, L. 1974. Geology and probability in the assessment of seismic risk. *In: Proceedings of the 2nd International Conference of the Association of Engineering Geology*. Not seen. Reported in Ambraseys (1978a).

Esteva, L., & Rosenblueth, E. 1964. Espectros de temblores a distancias moderadas y grandes. *Boletin Sociedad Mexicana de Ingenieria Sesmica*, **2**, 1–18. In Spanish.

Esteva, L., & Villaverde, R. 1973. Seismic risk, design spectra and structural reliability. *Pages 2586–2596 of: Proceedings of Fifth World Conference on Earthquake Engineering*, vol. 2.

Faccioli, E. 1978 (Jun). Response spectra for soft soil sites. *Pages 441–456 of: Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, vol. I.

Free, M. W. 1996. *The attenuation of earthquake strong-motion in intraplate regions*. Ph.D. thesis, University of London.

Free, M. W., Ambraseys, N. N., & Sarma, S. K. 1998 (Feb). *Earthquake ground-motion attenuation relations for stable continental intraplate regions*. ESEE Report 98-1. Department of Civil Engineering, Imperial College, London.

Fukushima, Y., & Tanaka, T. 1990. A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan. *Bulletin of the Seismological Society of America*, **80**(4), 757–783.

Fukushima, Y., Tanaka, T., & Kataoka, S. 1988. A new attenuation relationship for peak ground acceleration derived from strong-motion accelerograms. *Pages 343–348 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Fukushima, Y., Gariel, J.-C., & Tanaka, R. 1994. Prediction relations of seismic motion parameters at depth using borehole data. *Pages 417–422 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Fukushima, Y., Gariel, J.-C., & Tanaka, R. 1995. Site-dependent attenuation relations of seismic motion parameters at depth using borehole data. *Bulletin of the Seismological Society of America*, **85**(6), 1790–1804.

Fukushima, Y., Berge-Thierry, C., Volant, P., Griot-Pommera, D.-A., & Cotton, F. 2003. Attenuation relation for western Eurasia determined with recent near-fault records from California, Japan and Turkey. *Journal of Earthquake Engineering*, **7**(4), 573–598.

Garcìa-Fernàndez, M., & Canas, J. A. 1991. Estimation of regional values of peak ground acceleration from short-period seismograms. *Pages 533–539 of: Proceedings of the Fourth International Conference on Seismic Zonation*, vol. II.

Garcia-Fernandez, M., & Canas, J.A. 1992. Regional Lg-wave attenuation and estimates of peak ground acceleration in the Iberian peninsula. *Pages 439–443 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1.

Garcia-Fernandez, M., & Canas, J.A. 1995. Regional peak ground acceleration estimates in the Iberian peninsula. *Pages 1029–1034 of: Proceedings of the Fifth International Conference on Seismic Zonation*, vol. II.

Gaull, B. A. 1988. Attenuation of strong ground motion in space and time in southwest Western Australia. *Pages 361–366 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Gregor, N., Silva, W., & Darragh, B. 2002 (Jun.). *Development of attenuation relations for peak particle velocity and displacement*. Tech. rept. Pacific Engineering and Analysis, El Cerrito, U.S.A. A PEARL report to PG&E/CEC/Caltrans. On Internet at: `http://www.pacificengineering.org/rpts_page1.shtml`.

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

Huo, J., & Hu, Y. 1991. Attenuation laws considering the randomness of magnitude and distance. *Earthquake Research in China*, **5**(1), 17–36.

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.

Idriss, I. M. 1993. *Procedures for selecting earthquake ground motions at rock sites*. Tech. rept. NIST GCR 93-625. National Institute of Standards and Technology.

Iwasaki, T., Kawashima, K., & Saeki, M. 1980. Effects of seismic and geotechnical conditions on maximum ground accelerations and response spectra. *Pages 183–190 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Jacob, K. H., Gariel, J.-C., Armbruster, J., Hough, S., Friberg, P., & Tuttle, M. 1990 (May). Site-specific ground motion estimates for New York city. *Pages 587–596 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Jain, S. K., Roshan, A. D., Arlekar, J. N., & Basu, P. C. 2000 (Nov). Empirical attenuation relationships for the Himalayan earthquakes based on Indian strong motion data. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Johnson, R. A. 1973. An earthquake spectrum prediction technique. *Bulletin of the Seismological Society of America*, **63**(4), 1255–1274.

Johnston, A., *et al.* 1994. *The earthquakes of stable continental regions, Vol. 1: Assessment of large earthquake potential*. EPRI Report TR-102261. Electrical Power Research Institute, Palo Alto. Not seen. Cited in Free *et al.* (1998).

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. 1982. *Prediction of earthquake response spectra*. Open-File Report 82-977. U.S. Geological Survey. Not seen.

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*.

Joyner, W. B., & Fumal, T. E. 1984. Use of measured shear-wave velocity for predicting geologic site effects on strong ground motion. *Pages 777–783 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Joyner, W. B., & Fumal, T. E. 1985. Predictive mapping of earthquake ground motion. *Pages 203–220 of: Evaluating Earthquake Hazards in the Los Angeles Region — An Earth Science Perspective*. U.S. Geological Survey Professional Paper, no. 1360. Washington: United States Government Printing Office.

Kamiyama, M. 1989 (Oct). Regression analyses of strong-motion spectra in terms of a simplified faulting source model. *Pages 113–126 of: Proceedings of the Fourth International Conference on Soil Dynamics and Earthquake Engineering*.

Kamiyama, M. 1995. An attenuation model for the peak values of strong ground motions with emphasis on local soil effects. *Pages 579–585 of: Proceedings of the First International Conference on Earthquake Geotechnical Engineering*, vol. 1.

Kamiyama, M., & Yanagisawa, E. 1986. A statisical model for estimating response spectra of strong earthquake ground motions with emphasis on local soil conditions. *Soils and Foundations*, **26**(2), 16–32.

Kamiyama, M., O'Rourke, M.J., & Flores-Berrones, R. 1992 (Sep). *A semi-empirical analysis of strong-motion peaks in terms of seismic source, propagation path and local site conditions*. Tech. rept. NCEER-92-0023. National Center for Earthquake Engineering Research.

Kanai, K. 1966. Improved empirical formula for characteristics of stray [sic] earthquake motions. *Pages 1–4 of: Proc. jap. earthq. symp.* Not seen. Reported in Trifunac & Brady (1975).

Kawano, H., Takahashi, K., Takemura, M., Tohdo, M., Watanabe, T., & Noda, S. 2000. Empirical response spectral attenuations on the rocks with $\mathrm{VS} = 0.5$ to $3.0\,\mathrm{km/s}$ in Japan. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 0953.

Kawashima, K., Aizawa, K., & Takahashi, K. 1984. Attenuation of peak ground motion and absolute acceleration response spectra. *Pages 257–264 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Kawashima, K., Aizawa, K., & Takahashi, K. 1985. Attenuation of peak ground motions and absolute acceleration response spectra of vertical earthquake ground motion. *Proceedings of JSCE Structural Engineering/Earthquake Engineering*, **2**(2), 415–422.

Kawashima, K., Aizawa, K., & Takahashi, K. 1986. Attenuation of peak ground acceleration, velocity and displacement based on multiple regression analysis of Japanese strong motion records. *Earthquake Engineering and Structural Dynamics*, **14**(2), 199–215.

Khademi, M. H. 2002 (Sep). Attenuation of peak and spectral accelerations in the Persian plateau. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 330.

Kobayashi, H., & Midorikawa, S. 1982. A semi-empirical method for estimating response spectra of near-field ground motions with regard to fault rupture. *Pages 161–168 of: Proceedings of Seventh European Conference on Earthquake Engineering*, vol. 2.

Kobayashi, H., & Nagahashi, S. 1977. Response spectra on seismic bedrock during earthquake. *Pages 516–522 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I.

Kobayashi, S., Takahashi, T., Matsuzaki, S., Mori, M., Fukushima, Y., Zhao, J. X., & Somerville, P. G. 2000. A spectral attenuation model for Japan using digital strong motion records of JMA87 type. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 2786.

Krinitzsky, E. L., Chang, F. K., & Nuttli, O. W. 1987 (Sep). *State-of-the-art for assessing earthquake hazards in the United States; report 26, Parameters for specifying magnitude-related earthquake ground motions*. Tech. rept. U.S. Army Engineer Waterways Experimental Station. Miscellaneous paper S-73-1.

Krinitzsky, E. L., Chang, F. K., & Nuttli, O. W. 1988. Magnitude-related earthquake ground motions. *Bulletin of the Association of Engineering Geologists*, **XXV**(4), 399–423.

Lawson, R. S., & Krawinkler, H. 1994. Cumulative damage potential of seismic ground motion. *Pages 1079–1086 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 2.

Lee, V. W. 1987 (Jul). *Influence of local soil and geological site conditions on pseudo relative velocity spectrum amplitudes of recorded strong motion accelerations*. Tech. rept. CE 87-06. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Lee, V. W. 1993. Scaling PSV from earthquake magnitude, local soil, and geologic depth of sediments. *Journal of the Geotechnical Engineering Division, ASCE*, **119**(1), 108–126.

Lee, V. W. 1995. Pseudo relative velocity spectra in former Yugoslavia. *European Earthquake Engineering*, **IX**(1), 12–22.

Lee, V. W., & Manić, M. 1994. Empirical scaling of response spectra in former Yugoslavia. *Pages 2567–2572 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 4.

Lee, V. W., & Trifunac, M. D. 1995 (May). *Pseudo relative velocity spectra of strong earthquake ground motion in California*. Tech. rept. CE 95-04. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Lee, V. W., Trifunac, M. D., Todorovska, M. I., & Novikova, E. I. 1995 (Apr). *Empirical equations describing attenuation of peak of strong ground motion, in terms of magnitude, distance, path effects and site conditions*. Tech. rept. CE 95-02. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Lungu, D., Demetriu, S., Radu, C., & Coman, O. 1994. Uniform hazard response spectra for Vrancea earthquakes in Romania. *Pages 365–370 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Lungu, D., Coman, O., & Moldoveanu, T. 1995a (Aug). Hazard analysis for Vrancea earthquakes. Application to Cernavoda NPP site in Romania. *In: Proceedings of the 13th International Conference on Structural Mechanics in Reactor Technology*. Division K, Paper No. 538.

Lungu, D., Cornea, T., Craifaleanu, I., & Aldea, A. 1995b. Seismic zonation of Romania based on uniform hazard response ordinates. *Pages 445–452 of: Proceedings of the Fifth International Conference on Seismic Zonation*, vol. I.

Lungu, D., Cornea, T., Craifaleanu, I., & Demetriu, S. 1996 (Jun). Probabilistic seismic hazard analysis for inelastic structures on soft soils. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*.

Lussou, P., Bard, P. Y., Cotton, F., & Fukushima, Y. 2001. Seismic design regulation codes: Contribution of K-Net data to site effect evaluation. *Journal of Earthquake Engineering*, **5**(1), 13–33.

Manic, M. I. 1998. A new site dependent attenuation model for prediction of peak horizontal acceleration in Northwestern Balkan. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

Manic, M. I. 2002 (Sep). Empirical scaling of response spectra for the territory of north-western Balkan. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 650.

Margaris, B., Papazachos, C., Papaioannou, C., Theodulidis, N., Kalogeras, I., & Skarlatoudis, A. 2002a (Sep). Ground motion attenuation relations for shallow earthquakes in Greece. *In: Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*.

Margaris, B., Papazachos, C., Papaioannou, C., Theodulidis, N., Kalogeras, I., & Skarlatoudis, A. 2002b (Sep). Ground motion attenuation relations for shallow earthquakes in Greece. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 385.

McCann Jr., M. W., & Echezwia, H. 1984. Investigating the uncertainty in ground motion prediction. *Pages 297–304 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

McCue, K. 1986. Strong motion attenuation in eastern Australia. *In: Earthquake Engineering Symposium*. National Conference Publication 86/15. Institution of Engineers Australia. Not seen. Reported in Free (1996).

McCue, K., Gibson, G., & Wesson, V. 1988. Intraplate recording of strong motion in southeastern Australia. *Pages 355–360 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

McGuire, R. K. 1977. Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response. *Earthquake Engineering and Structural Dynamics*, **5**, 211–234.

McGuire, R. K. 1978. Seismic ground motion parameter relations. *Journal of the Geotechnical Engineering Division, ASCE*, **104**(GT4), 481–490.

McVerry, G. H., Dowrick, D. J., Sritharan, S., Cousins, W. J., & Porritt, T. E. 1993. Attenuation of peak ground accelerations in New Zealand. *Pages 23–38 of: Proceedings of the International Workshop on Strong Motion Data*, vol. 2. Not seen. Cited in McVerry *et al.* (1995).

McVerry, G. H., Dowrick, D. J., & Zhao, J. X. 1995 (November). Attenuation of peak ground accelerations in New Zealand. *Pages 287–292 of: Pacific Conference on Earthquake Engineering*, vol. 3.

McVerry, G. H., Zhao, J. X., Abrahamson, N. A., & Somerville, P. G. 2000. Crustal and subduction zone attenuation relations for New Zealand earthquakes. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 1834.

Milne, W. G. 1977. Seismic risk maps for Canada. *Page 930 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I. 2-508.

Milne, W. G., & Davenport, A. G. 1969. Distribution of earthquake risk in Canada. *Bulletin of the Seismological Society of America*, **59**(2), 729–754.

Mohammadioun, B. 1991. The prediction of response spectra for the anti-seismic design of structures specificity of data from intracontinential environments. *European Earthquake Engineering*, **V**(2), 8–17.

Mohammadioun, B. 1994a. Prediction of seismic motion at the bedrock from the strong-motion data currently available. *Pages 241–245 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Mohammadioun, G. 1994b. Calculation of site-adapted reference spectra from the statistical analysis of an extensive strong-motion data bank. *Pages 177–181 of: Proceedings of Tenth European Conference on Earthquake Engineering*, vol. 1.

Molas, G. L., & Yamazaki, F. 1995. Attenuation of earthquake ground motion in Japan including deep focus events. *Bulletin of the Seismological Society of America*, **85**(5), 1343–1358.

Molas, G. L., & Yamazaki, F. 1996. Attenuation of response spectra in Japan using new JMA records. *Bulletin of Earthquake Resistant Structure Research Center*, **29**(Mar), 115–128.

Monguilner, C. A., Ponti, N., & Pavoni, S. B. 2000a. Relationships between basic ground motion parameters for earthquakes of the Argentine western region. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper no. 1195.

Monguilner, C. A., Ponti, N., Pavoni, S. B., & Richarte, D. 2000b. Statistical characterization of the response spectra in the Argentine Republic. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper no. 1825.

Munson, C. G., & Thurber, C. H. 1997. Analysis of the attenuation of strong ground motion on the island of Hawaii. *Bulletin of the Seismological Society of America*, **87**(4), 945–960.

Musson, R. M. W., Marrow, P. C., & Winter, P. W. 1994 (May). *Attenuation of earthquake ground motion in the UK.* Tech. rept. AEA/CS/16422000/ZJ745/004. AEA Technology Consultancy Services (SRD) and British Geological Survey.

Niazi, M., & Bozorgnia, Y. 1991. Behaviour of near-source peak horizontal and vertical ground motions over SMART-1 array, Taiwan. *Bulletin of the Seismological Society of America*, **81**(3), 715–732.

Niazi, M., & Bozorgnia, Y. 1992. Behaviour of near-source vertical and horizontal response spectra at SMART-1 array, Taiwan. *Earthquake Engineering and Structural Dynamics*, **21**, 37–50.

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.

Ohno, S., Takemura, M., Niwa, M., & Takahashi, K. 1996. Intensity of strong ground motion on pre-quaternary stratum and surface soil amplifications during the 1995 Hyogo-ken Nanbu earthquake, Japan. *Journal of Physics of the Earth*, **44**(5), 623–648.

Ohsaki, Y., Watabe, M., & Tohdo, M. 1980a. Analyses on seismic ground motion parameters including vertical components. *Pages 97–104 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Ohsaki, Y., Sawada, Y., Hayashi, K., Ohmura, B., & Kumagai, C. 1980b. Spectral characteristics of hard rock motions. *Pages 231–238 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Ólafsson, S., & Sigbjörnsson, R. 1999. A theoretical attenuation model for earthquake-induced ground motion. *Journal of Earthquake Engineering*, **3**(3), 287–315.

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

Orphal, D. L., & Lahoud, J. A. 1974. Prediction of peak ground motion from earthquakes. *Bulletin of the Seismological Society of America*, **64**(5), 1563–1574.

Peng, K., Xie, L., Li, S., Boore, D. M., Iwan, W. D., & Teng, T. L. 1985a. The near-source strong-motion accelerograms recorded by an experimental array in Tangshan, China. *Physics of the Earth and Planetary Interiors*, **38**, 92–109.

Peng, K.-Z., Wu, F. T., & Song, L. 1985b. Attenuation characteristics of peak horizontal acceleration in northeast and southwest China. *Earthquake Engineering and Structural Dynamics*, **13**(3), 337–350.

Perea, T., & Sordo, E. 1998. Direct response spectrum prediction including local site effects. *In: Proceedings of Eleventh European Conference on Earthquake Engineering.*

Petrovski, D., & Marcellini, A. 1988. Prediction of seismic movement of a site: Statisical approach. *In: Proc. UN Sem. on Predict. of Earthquakes.* Lisbon, Portugal, 14–18 November.

PML. 1982. *British earthquakes*. Tech. rept. 115/82. Principia Mechanica Ltd., London. Not seen. Reported in Ambraseys *et al.* (1992).

PML. 1985. *Seismological studies for UK hazard analysis*. Tech. rept. 346/85. Principia Mechanica Ltd., London. Not seen. Reported in Ambraseys *et al.* (1992).

Radu, C., Lungu, D., Demetriu, S., & Coman, O. 1994 (Sep). Recurrence, attenuation and dynamic amplification for intermediate depth Vrancea earthquakes. *Pages 1736–1745 of: Proceedings of the XXIV General Assembly of the ESC*, vol. III.

Ramazi, H. R., & Schenk, V. 1994 (Sep). Preliminary results obtained from strong ground motion analzses [sic] of Iranian earthquakes. *Pages 1762–1770 of: Proceedings of the XXIV General Assembly of the ESC*, vol. III.

Rhoades, D. A. 1997. Estimation of attenuation relations for strong-motion data allowing for individual earthquake magnitude uncertainties. *Bulletin of the Seismological Society of America*, **87**(6), 1674–1678.

Richter, C. F. 1958. *Elementary Seismology*. San Francisco, USA: Freeman and Co.

Rinaldis, D., Berardi, R., Theodulidis, N., & Margaris, B. 1998. Empirical predictive models based on a joint Italian & Greek strong-motion database: I, peak ground acceleration and velocity. *In: Proceedings of Eleventh European Conference on Earthquake Engineering*.

Rogers, A. M., Perkins, D. M., Hampson, D. B., & Campbell, K. W. 1991. Investigations of peak acceleration data for site effects. *Pages 229–236 of: Proceedings of the Fourth International Conference on Seismic Zonation*, vol. II.

Romeo, R. W., Tranfaglia, G., & Castenetto, S. 1996. Engineering-developed relations derived from the strongest instrumentally-detected Italian earthquakes. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*. Paper no. 1466.

Sabetta, F., & Pugliese, A. 1987. Attenuation of peak horizontal acceleration and velocity from Italian strong-motion records. *Bulletin of the Seismological Society of America*, **77**(5), 1491–1513.

Sabetta, F., & Pugliese, A. 1996. Estimation of response spectra and simulation of nonstationary earthquake ground motions. *Bulletin of the Seismological Society of America*, **86**(2), 337–352.

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.

Sadigh, K., Chang, C.-Y., Abrahamson, N. A., Chiou, S. J., & Power, M. S. 1993 (Mar). Specification of long-period ground motions: Updated attenuation relationships for rock site conditions and adjustment factors for near-fault effects. *Pages 59–70 of: Proceedings of ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control*.

Sadigh, K., Chang, C.-Y., Egan, J. A., Makdisi, F., & Youngs, R. R. 1997. Attenuation relationships for shallow crustal earthquakes based on California strong motion data. *Seismological Research Letters*, **68**(1), 180–189.

Sadigh, R. K., & Egan, J. A. 1998. Updated relationships for horizontal peak ground velocity and peak ground displacement for shallow crustal earthquakes. *In: Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*.

Sarma, S. K., & Free, M. W. 1995 (November). The comparision of attenuation relationships for peak horizontal acceleration in intraplate regions. *Pages 175–184 of: Pacific Conference on Earthquake Engineering*, vol. 2.

Sarma, S. K., & Srbulov, M. 1996. A simplified method for prediction of kinematic soil-foundation interaction effects on peak horizontal acceleration of a rigid foundation. *Earthquake Engineering and Structural Dynamics*, **25**(8), 815–836.

Sarma, S. K., & Srbulov, M. 1998. A uniform estimation of some basic ground motion parameters. *Journal of Earthquake Engineering*, **2**(2), 267–287.

Schenk, V. 1982. Peak particle ground motions in earthquake near-field. *Pages 211–217 of: Proceedings of Seventh European Conference on Earthquake Engineering*, vol. 2.

Schenk, V. 1984. Relations between ground motions and earthquake magnitude, focal distance and epicentral intensity. *Engineering Geology*, **20**(1/2), 143–151.

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)*.

Sen, M. K. 1990 (May). Deep structural complexity and site response in Los Angeles basin. *Pages 545–553 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Shabestari, K. T., & Yamazaki, F. 2000. Attenuation relation of response spectra in Japan considering site-specific term. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 1432.

Shabestari, T. K., & Yamazaki, F. 1998. Attenuation of JMA seismic intensity using recent JMA records. *Pages 529–534 of: Proceedings of the 10th Japan Earthquake Engineering Symposium*, vol. 1. Not seen. Reported in Shabestari & Yamazaki (2000).

Sharma, M. L. 1998. Attenuation relationship for estimation of peak ground horizontal acceleration using data from strong-motion arrays in India. *Bulletin of the Seismological Society of America*, **88**(4), 1063–1069.

Sharma, M. L. 2000. Attenuation relationship for estimation of peak ground vertical acceleration using data from strong motion arrays in India. *In: Proceedings of Twelfth World Conference on Earthquake Engineering*. Paper No. 1964.

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. 1990. Strong motion measurements in Iceland and seismic risk assessment. *Pages 215–222 of: Proceedings of Ninth European Conference on Earthquake Engineering*, vol. 10-A.

Sigbjörnsson, R., & Ambraseys, N. N. 2003. Uncertainty analysis of strong ground motion. *Bulletin of Earthquake Engineering*. In press.

Sigbjörnsson, R., & Baldvinsson, G. I. 1992. Seismic hazard and recordings of strong ground motion in Iceland. *Pages 419–424 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1. Rotterdam, The Netherlands: A. A. Balkema. Madrid, Spain. 19–24 July.

Simpson, K. A. 1996. *Attenuation of strong ground-motion incorporating near-surface foundation conditions*. Ph.D. thesis, University of London.

Singh, R. P., Aman, A., & Prasad, Y. J. J. 1996. Attenuation relations for strong seismic ground motion in the Himalayan region. *Pure and Applied Geophysics*, **147**(1), 161–180.

Singh, S. K., Mena, E., Castro, R., & Carmona, C. 1987. Empirical prediction of ground motion in Mexico City from coastal earthquakes. *Bulletin of the Seismological Society of America*, **77**(5), 1862–1867.

Singh, S. K., Gutierreez, C., Arboleda, J., & Ordaz, M. 1993. *Peligro sísmico en El Salvador*. Tech. rept. Universidad Nacional Autónoma de México, México. Not seen. Reported in Bommer *et al.* (1996).

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

Smit, P. 2000 (Dec). Personal communication 4/12/2000.

Smit, P., Arzoumanian, V., Javakhishvili, Z., Arefiev, S., Mayer-Rosa, D., Balassanian, S., & Chelidze, T. 2000. The digital accelerograph network in the Caucasus. *In:* Balassanian, S. (ed), *Earthquake Hazard and Seismic Risk Reduction — Advances in Natural and Technological Hazards Research*. Kluwer Academic Publishers. Presented at 2nd International Conference on Earthquake Hazard and Seismic Risk Reduction, Yerevan, Armenia, 15/9/1998–21/9/1998.

Spudich, P., Fletcher, J., Hellweg, M., Boatwright, J., Sullivan, C., Joyner, W., Hanks, T., Boore, D., McGarr, A., Baker, L., & Lindh, A. 1996. *Earthquake ground motions in extensional tectonic regimes*. Open-File Report 96-292. U.S. Geological Survey. Not seen. Reported in Spudich *et al.* (1997).

Spudich, P., Fletcher, J. B., Hellweg, M., Boatwright, J., Sullivan, C., Joyner, W. B., Hanks, T. C., Boore, D. M., McGarr, A., Baker, L. M., & Lindh, A. G. 1997. SEA96 — A new predictive relation for earthquake ground motions in extensional tectonic regimes. *Seismological Research Letters*, **68**(1), 190–198.

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.

Stamatovska, S. 2002 (Sep). A new azimuth dependent empirical strong motion model for Vranchea subduction zone. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper reference 324.

Stamatovska, S., & Petrovski, D. 1996. Empirical attenuation acceleration laws for Vrancea intermediate earthquakes. *In: Proceedings of Eleventh World Conference on Earthquake Engineering*. Paper no. 146.

Sun, F., & Peng, K. 1993. Attenuation of strong ground motion in western U.S.A. *Earthquake Research in China*, **7**(1), 119–131.

Takahashi, T., Kobayashi, S., Fukushima, Y., Zhao, J. X., Nakamura, H., & Somerville, P. G. 2000 (Nov). A spectral attenuation model for Japan using strong motion data base. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Tamura, K., Sasaki, Y., & Aizawa, K. 1990 (May). Attenuation characteristics of ground motions in the period range of 2 to 20 seconds — for application to the seismic design of long-period structures. *Pages 495–504 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

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.

Tento, A., Franceschina, L., & Marcellini, A. 1992. Expected ground motion evaluation for Italian sites. *Pages 489–494 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1.

Theodulidis, N. P., & Papazachos, B. C. 1992. Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, peak horizontal acceleration, velocity and displacement. *Soil Dynamics and Earthquake Engineering*, **11**, 387–402.

Theodulidis, N. P., & Papazachos, B. C. 1994. Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: II horizontal pseudovelocity. *Soil Dynamics and Earthquake Engineering*, **13**(5), 317–343.

Tong, H., & Katayama, T. 1988. Peak acceleration attenuation by eliminating the ill-effect of the correlation between magnitude and epicentral distance. *Pages 349–354 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Trifunac, M. D. 1976. Preliminary analysis of the peaks of strong earthquake ground motion – dependence of peaks on earthquake magnitude, epicentral distance, and recording site conditions. *Bulletin of the Seismological Society of America*, **66**(1), 189–219.

Trifunac, M. D. 1977. Forecasting the spectral amplitudes of strong earthquake ground motion. *Pages 139–152 of: Proceedings of Sixth World Conference on Earthquake Engineering*, vol. I.

Trifunac, M. D. 1978. Response spectra of earthquake ground motions. *Journal of the Engineering Mechanics Division, ASCE*, **104**(EM5), 1081–1097.

Trifunac, M. D. 1980. Effects of site geology on amplitudes of strong motion. *Pages 145–152 of: Proceedings of Seventh World Conference on Earthquake Engineering*, vol. 2.

Trifunac, M. D., & Anderson, J. G. 1978a. *Preliminary empirical models for scaling absolute acceleration spectra*. Tech. rept. 77-03. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Anderson, J. G. 1978b. *Preliminary empirical models for scaling pseudo relative velocity spectra*. Tech. rept. 78-04. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Anderson, J. G. 1978c. *Preliminary empirical models for scaling relative velocity spectra*. Tech. rept. 78-05. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

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.

Trifunac, M. D., & Lee, V. W. 1979. *Dependence of pseudo relative velocity spectra of strong motion acceleration on depth of sedimentary deposits*. Tech. rept. 79-02. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Lee, V. W. 1985. *Preliminary empirical model for scaling pseudo relative velocity spectra of strong earthquake acceleration in terms of magnitude, distance, site intensity and recording site condition*. Tech. rept. 85-04. Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.

Trifunac, M. D., & Lee, V. W. 1989. Empirical models for scaling pseudo relative velocity spectra of strong earthquake accelerations in terms of magnitude, distance, site intensity and recording site conditions. *Soil Dynamics and Earthquake Engineering*, **8**(3), 126–144.

Tromans, I. J., & Bommer, J. J. 2002 (Sep). The attenuation of strong-motion peaks in Europe. *In: Proceedings of Twelfth European Conference on Earthquake Engineering*. Paper no. 394.

Tsai, Y. B., Brady, F. W., & Cluff, L. S. 1990 (May). An integrated approach for characterization of ground motions in PG&E's long term seismic program for Diablo Canyon. *Pages 597–606 of: Proceedings of the Fourth U.S. National Conference on Earthquake Engineering*, vol. 1.

Vives, V., & Canas, J.A. 1992. Anelastic attenuation and pseudoacceleration relations in eastern Iberia. *Pages 299–304 of: Proceedings of Tenth World Conference on Earthquake Engineering*, vol. 1.

Wang, B.-Q., Wu, F. T., & Bian, Y.-J. 1999. Attenuation characteristics of peak accele-ration in north China and comparison with those in the eastern part of North America. *Acta Seismologica Sinica*, **12**(1).

Wang, G., & Tao, X. 2000 (Nov). A new two-stage procedure for fitting attenuation relationship of strong ground motion. *In: Proceedings of the Sixth International Conference on Seismic Zonation*.

Weisburg, S. 1985. *Applied Linear Regression*. 2nd edn. John Wiley & Sons.

Wells, D. L., & Coppersmith, K. J. 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America*, **84**(4), 974–1002.

Wiggins Jr., J. H. 1964. Construction of strong motion response spectra from magnitude and distance data. *Bulletin of the Seismological Society of America*, **54**(5), 1257–1269.

Xiang, J., & Gao, D. 1994. The attenuation law of horizontal peak acceleration on the rock site in Yunnan area. *Earthquake Research in China*, **8**(4), 509–516.

Xu, Z., Shen, X., & Hong, J. 1984. Attenuation relation of ground motion in northern China. *Pages 335–342 of: Proceedings of Eighth World Conference on Earthquake Engineering*, vol. II.

Yamabe, K., & Kanai, K. 1988. An empirical formula on the attenuation of the maximum acceleration of earthquake motions. *Pages 337–342 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Yamazaki, F., Wakamatsu, K., Onishi, J., & Shabestari, K. T. 2000. Relationship between geomorphological land classification and site amplification ratio based on JMA strong motion records. *Soil Dynamics and Earthquake Engineering*, **19**(1), 41–53.

Yokota, H., Shiba, K., & Okada, K. 1988. The characteristics of underground earthquake motions observed in the mud stone layer in Tokyo. *Pages 429–434 of: Proceedings of Ninth World Conference on Earthquake Engineering*, vol. II.

Youngs, R. R., Day, S. M., & Stevens, J. L. 1988. Near field ground motions on rock for large subduction earthquakes. *Pages 445–462 of: Proceedings of Earthquake Engineering & Soil Dynamics II*. Geotechnical Division, ASCE.

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.

Zaré, 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., Dowrick, D. J., & McVerry, G. H. 1997. Attenuation of peak ground acceleration in New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **30**(2), 133–158.

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