Pre-Selection of Ground Motion Prediction Equations

Report produced in the context of the Global Project
"GEM Ground Motion Prediction Equations"

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ABSTRACT

Within Task 2 of the GEM Global GMPEs project it is planned to undertake selection, testing and possible modification of published ground-motion prediction equations (GMPEs) for use in the seismic hazard assessment of the entire globe within the GEM project. The first stage of this process is a pre-selection from the over 300 empirical and simulation-based GMPEs that are currently available [Douglas, 2011] to retain a subset of the most recent and robust models. While making this pre-selection it is important to retain a sufficient number of models so that the potentially large epistemic uncertainty within the prediction of earthquakes ground motions (e.g., Douglas, [2010]) is recognised. Also, the GMPEs pre-selected in Task 2 will be further winnowed down in Task 3 of the project to retain the final selection proposed for use in the seismic hazard assessment of GEM. The purpose of this short report is to present a pre-selection of available models for all the seismotectonic regimes present on Earth. The selection criteria adopted in this study are consistent with the deliverables provided by Tasks 1a in terms of predictive parameters to use for ground-motion modelling and their proper ranges. The authors of this report partially benefitted from the experience gained in GMPEs pre-selection for SHARE [Douglas, 2009] and GEM1 [Douglas *et al*, 2009] projects.

Keywords: GMPE, attenuation, ground motion, hazard

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1 Introduction

The globe can be divided into these broad classes:

- Stable continental regions (SCRs), which can possibly be divided further into shield and continental/foreland;
- Subduction zones, which includes intraslab and interface earthquakes (and potentially fore-arc and back-arc locations);
- Active regions with shallow crustal seismicity;
- Volcanic zones;
- Areas of deep focus non-subduction earthquakes, such as Vrancea (Romania);
- Areas where the travel paths are mainly through oceanic crust, such as coastal Portugal.

Only models for the prediction of horizontal linear elastic response spectral ordinates for 5% damping are considered in this report since this is thought to be the main focus of the seismic hazard assessments to be made in GEM. It is likely, however, that models for the prediction of peak ground velocity (PGV) will also be useful. In addition, mining-induced seismicity is not considered as a priority for GEM and, therefore, no models for the prediction of shaking from mining-induced events are included. Note, however, that it some parts of the world (e.g., southern Poland) mining-induced seismicity is the largest contribution to seismic hazard.

2 Pre-Selection Criteria

Due to the vast number of available GMPEs within the literature it is necessary to define criteria to winnow down the models to a more manageable number although recognizing the necessity to retain sufficient models to account for epistemic uncertainty in the prediction of shaking. For this pre-selection it was decided to apply the seven criteria proposed by Cotton *et al* [2006]:

- the model is from a clearly irrelevant tectonic regime;
- the model is not published in an international peer-reviewed journal;
- the documentation of model and its underlying dataset is insufficient;
- the model has been superseded by more recent publications;
- the frequency range of the model is not appropriate for engineering application;
- the model has an inappropriate functional form;
- the regression method or regression coefficients are judged to be inappropriate.

Criterion 1 was applied to retain only models relevant for the broad classes listed above (e.g., only subduction zone models were considered for these regions). Criterion 2 was applied to reject GMPEs that had not been published in a journal that is listed by ISI Web of Knowledge, which is a standard reference for bibliographic information, except for models for SCRs which are often only published in the grey literature. Criterion 3 was applied to reject those studies that do not provide detailed information on the dataset used to derive the GMPEs presented. Criterion 4 has been applied to reject GMPEs for areas for which more recent models have been published using larger datasets even if the more recent models have not been derived by the same author teams. For example, the model of Field [2000] for southern California has been rejected since the data he used is a subset of the NGA database used by the NGA teams in developing their models. Criterion 5 leads to all peak ground acceleration (PGA)-only models being rejected as well as those that do not provide coefficients for periods less than 0.04s (25Hz) (that can be assumed to approximate PGA) and up to at least 2s (0.5Hz). This criterion removes models such as that by Ghasemi *et al* [2009] who do not provide coefficients for periods less than 0.05s and the GMPEs by Bommer *et al* [2007] who do not provide coefficients for periods greater than 0.5s. Criterion 6 has been applied to exclude models that do not use moment magnitude (M_w) (since there are difficulties and uncertainties in converting between other magnitude scales, especially M_L, and M_w, the standard magnitude scale for seismic hazard assessments) and to exclude models that do not allow the prediction of ground motions at rock sites (e.g., Crouse, [1991]). Criterion 7 has been applied, in particular, to exclude those models based on simulations whose standard deviations were computed without taking into account modelling variability (e.g., Hwang and Huo, [1997]). Also models that are not thought to be provide reliable predictions over a wide range of magnitudes (roughly M_w 5 to 7.5) and near-source distances (roughly r_{jb}=0 km) to at least 100 km are rejected since this is the focus of seismic hazard assessments in GEM. The choices operated for this study reflect the decision from Task 1a to reject models which would require more than half magnitude unit extrapolation. This means that many local and regional models are rejected since they often only provide reliable predictions up to about M_w 6.5. Because of the global nature of the project, it was aimed to select models for different geographical regions even if they were of varying quality rather than to select many models for the same region (this is particularly true for SCRs where most robust models are for eastern North America).

Note that the criteria of Cotton *et al* [2006] have been updated by Bommer *et al* [2010] to make them more objective and stronger. It was decided, however, that for a pre-selection process that the Bommer *et al* [2010] proposals would be too strict.

These criteria have been applied to the empirical and simulation-based GMPEs (and stochastic models) listed in the report of Douglas [2011]. Note that stochastic models without fitted functional forms are also considered even though these would require functions to be fitted to predictions for easy use within GEM. Models derived using the hybrid empirical-stochastic approach of Campbell [2003] have also been considered although within GEM Global GMPEs this method may be used to adjust some models. If this is done then it should not be applied to these hybrid models but rather to the empirical GMPEs underlying these hybrid models. Non-parametric models (e.g., those represented by neural networks) are not considered because of the difficult in using them in practice and because of doubts over their extrapolation outside the range of data. Overall the aim was to retain between ten and twenty models for further examination for each tectonic type.

3 Pre-Selected Models

The following sections list the GMPEs that have been retained for each seismotectonic regime. The models tested by Allen and Wald [2009] for Global ShakeMap purposes and those GMPEs used by Petersen *et al* [2008] for the construction of the US National Seismic Hazard Maps are, in general, subsets of the models pre-selected here for GEM Global GMPEs.

Note that this pre-selection was performed in April 2011. During the duration of the GEM Global GMPEs project many new GMPEs will be published (on average a dozen new models are published every year, according to Douglas [2011]) but it is not planned within GEM Global GMPEs to repeat this pre-selection to account for these models.

3.1 STABLE CONTINENTAL REGIONS

The following ten models are pre-selected for stable continental regions (SCRS):

- Atkinson [2008] as modified by Atkinson and Boore [2011]: Referenced empirical model for eastern North America
- Atkinson and Boore [2006] as modified by Atkinson and Boore [2011]: Extended stochastic model for eastern North America
- Campbell [2003]: Hybrid model for eastern North America
- Douglas *et al* [2006]: Hybrid model for southern Norway
- Frankel *et al* [1996] as parameterized by EPRI [2004]: Stochastic model for eastern North America
- Raghu Kanth and Iyengar [2006, 2007]: Peninsular India
- Silva *et al* [2002]: Stochastic model for eastern North America
- Somerville *et al* [2009]: Simulation-based models for Australia
- Pezeshk *et al* [2011]: Hybrid model for eastern North America
- Toro *et al* [1997] modified by Toro [2002]: Stochastic model for eastern North America

Notwithstanding the older publication date, Campbell's [2003] Hybrid empirical model for eastern North America has been preferred to his 2007 model based on the recommendation received from its author (K. Campbell, written communication, [2011]).

Despite the fact that the Somerville *et al* [2001] simulation-based model for Eastern-Northern America is currently implemented in the US National Seismic Hazard Map [Petersen *et al*, 2008], we rejected it because it is stated to be used for $M_w \geq 6.0$; such characteristic contrasts with the choice of considering M_w 5.0 as a lower bound for a given GMPE validity.

Among the other models published for SCRs, Zheng and Wong [2004] simulation-based model for southern China has been rejected due to the limited amount of underlying data, poor choice of kappa values, unjustified use of Atkinson and Silva [2000] two-corner source spectrum and scaling, and assumed absence of crustal amplification.

Notwithstanding the Tavakoli and Pezeshk [2005] hybrid model for eastern North America is one of the models included in the current US National Seismic Hazard Map [Petersen *et al*, 2008], we chose to exclude it considering the fact that has been superseded by the more recent Pezeshk *et al* [2011] model.

3.2 SUBDUCTION ZONES

The following nine models are pre-selected for subduction zones, which include intraslab and interface earthquakes:

- BC Hydro [2011]: Worldwide
- Arroyo *et al* [2010]: Interface model for Mexico (complementary to Garcia *et al* [2005])
- Atkinson and Boore [2003]: Worldwide
- Garcia *et al* [2005]: Intraslab model for Mexico (complementary to Arroyo *et al* [2010])
- Kanno *et al* [2006]: Japan
- Lin and Lee [2008]: Taiwan
- McVerry *et al* [2006]: New Zealand
- Youngs *et al* [1997]: Worldwide
- Zhao *et al* [2006]: Japan

For the present application, we choose not to include specific models for potentially fore-arc and back-arc locations, due to the paucity of available models and to their complex implementation in the hazard engine.

Among the other models published for subduction zones, we excluded Gupta [2010] referenced-empirical model for intraslab earthquakes in Indo-Burmese subduction zone. Reasons to support this choice rely on the limited amount or recorded ground motions (3 in-slab quakes with Mw 6.3, 6.4, and 7.2, recorded at distances of 160—370 km in north-eastern India), on the absence of provided residuals to support the distance scaling, and on not enough data to support magnitude scaling.

We also rejected Megawati and Pan [2010] simulation-based model for Sumatran interface events; this model is derived only for very hard rock sites (Vs30=3400 m/s), and for large distances (distance to center of fault = 200 – 1500 km).

The unsuitably high Mmin. used to derive the model is an exclusion criteria applied to the Atkinson and Macias [2008] model and to the Gregor *et al* [2002] stochastic-simulation model. The latter is in fact only valid for subduction interface earthquakes with Mw between 8 and 9.

Despite the fact that the Si and Midorikawa [2000] model is one of the few subduction GMPE models that predicts PGV for crustal earthquakes as well as both types of subduction earthquakes, we chose to exclude it because of its limited application to PGV and PGA (as the paper's title states). We propose to overcome this problem by including instead the Kanno *et al* [2006] model, which is so far the only state-of-the-art model for subduction events providing coefficients for both PGV and SA. This model can in fact be used to investigate the applicability of equations for converting between SA and PGV for subduction earthquakes, one of them being the conversion from PSA at 0.5s or 1s to PGV as proposed by Bommer and Alarcon [2006].

It should be noted that the epistemic uncertainty associated with the prediction of ground motions from subduction events seems to be higher than the uncertainty in the prediction of shaking from shallow crustal earthquakes [e.g., Douglas, 2010].

Finally, the Zhao [2010] modification to the 2006 model was not included among the preselected group because the coefficients were not public during the timeline of this task.

3.3 ACTIVE REGIONS WITH SHALLOW CRUSTAL SEISMICITY

These nine models derived for broad areas of shallow crustal seismicity are pre-selected:

- Abrahamson and Silva [2008]: NGA model using worldwide data
- Akkar and Bommer [2010]: Model using Mediterranean and Middle Eastern data
- Boore and Atkinson [2008] as modified by Atkinson and Boore [2011]: NGA model using worldwide data
- Campbell and Bozorgnia [2008] : NGA model using worldwide data
- Cauzzi and Faccioli [2008]: updated by Faccioli *et al* [2010]: Model using worldwide data (mainly Japanese)
- Chiou and Youngs [2008]: NGA model using worldwide data
- Kanno *et al* [2006]: Model using mainly Japanese data
- McVerry *et al* [2006]: Model using mainly New Zealand data
- Zhao *et al* [2006]: Model using mainly Japanese data

The model of McVerry *et al* [2006] for New Zealand was retained as pre-selected thanks to an allowed exception to the selection criteria. In fact, this model was published in the Bulletin of the New Zealand Society of Earthquake Engineering, which is currently not listed in ISI Web of Knowledge; however, since this model is currently a standard in New Zealand it was decided that it should be included even though strictly it fails this criterion.

The commonly-used model of Berge-Thierry *et al* [2003] has not been pre-selected for GEM Global GMPEs due to its use of surface-wave magnitude (Ms), its non-consideration of the effect of style of faulting and its use of a binary soil/rock classification. In addition, it can be considered to have been superseded by more recent models using Mediterranean and Middle Eastern data (e.g., Ambraseys *et al*, [2005]; Akkar and Bommer, [2010]).

Also the Ambraseys *et al* [2005] model derived from Mediterranean and Middle Eastern data is to be excluded because it has been in turn superseded by Akkar and Bommer [2007, 2010].

The recent model by Cotton *et al* [2008] is also not included because of the unusually high spectral levels predicted on soil, perhaps linked to peculiarities of shallow geological conditions at the recording sites, all belonging to the Kik-Net of Japan.

The NGA model by Idriss [2008] is excluded because of the inappropriate definition of site classes (if fact the model accounts only for two site classes, with $V_{S,30} > 900$ m/sec and $450 < V_{S,30} < 900$ m/sec, respectively) and use of standard least-squares regression rather than maximum-likelihood or random-effects modelling.

Pankow and Pechmann [2004, 2006] model (an updated of the Spudich *et al*, [1999], SEA99 model) is rejected because it is based on limited data and it is superseded by the NGA models.

Note that a number of recent regional models fail the selection criteria of Cotton *et al* [2006] since they use local magnitude and/or they are derived for a limited magnitude range.

3.4 VOLCANIC ZONES

Only these studies explicitly mention the prediction of ground motions in volcanic zones and pass the selection criteria of Cotton *et al* [2006] (although they are not for the prediction of ground motion from volcano-associated earthquakes):

- McVerry *et al* [2006] (for crustal and subduction earthquakes)
- Zhao *et al* [2006] (for subduction earthquakes)

Atkinson [2010] has recently published an article on the application of her referenced-empirical technique to Hawaiian data, but these data were not from volcanic events. De Natale *et al* [1988] developed a stochastic model for volcanic events in the Campi Flegrei fields in Italy, which has been used for the Italian National Seismic hazard Map [Working Group 2004, Appendix 3]. For the purpose of the current project, it is suggested to adopt the fitting of the De Natale et al [1988] functions to the predicted ground motions as parameterized in the internal document for WP4 – SHARE [Faccioli *et al*, 2011]; this fitting has been applied to point source representation with l/r geometric spreading and k for near site attenuation.

Considering the fact that the group retains only one model, recommendations of Task 2 to Task 3 are to scale the model up and down based on the spread of models for crustal earthquakes so that the uncertainties have comparable levels. However, it is also suggested that, at a global scale, the prediction of earthquake ground motions in volcanic zones is not a priority for GEM and therefore the lack of an explicit model for the prediction of ground motions from volcanic earthquakes is not a big problem.

3.5 AREAS OF DEEP FOCUS NON-SUBDUCTION EARTHQUAKES, SUCH AS VRANCEA, ROMANIA

Only this model passes the selection criteria of Cotton *et al* [2006] for this type of region (although the authors do not list the derived coefficients within their article, the derivation method is non-standard and the GMPEs are difficult to use since they model azimuthal dependency):

- Sokolov *et al* [2008]

Therefore, it is recommended that some of the subduction-zone models (for intraslab) are compared to available data from such zones in order to select the most appropriate GMPEs for such earthquakes.

3.6 AREAS WHERE THE TRAVEL PATHS ARE MAINLY THROUGH OCEANIC CRUST, SUCH AS COASTAL PORTUGAL

There are thought to be no available models for the prediction of ground motions in this type of area, except for the simulation-based model of Carvalho [2008] but this has not yet been published in English. Therefore, it is suggest that models for active zones and SCRs (as used by Vilanova and Fonseca [2007] for their hazard assessment of Portugal), as well as for intraslab (Abrahamson, personal communication, [2011]) are tested against data from these regions to check which models are most appropriate.

4 Summary Tables of Pre-selected GMPE Models

The following tables present the main characteristics of the selected GMPEs, distinguished on the basis of the tectonic area of pertinence. The format of these tables and their content follows the reports of Douglas [2004, 2006, 2008, and 2011] with some minor changes in notation and verbiage. The meanings of abbreviations are provided at the end of these tables.

Table 4.1 Attributes of pre-selected models for stable continental regions (SCR)

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
Atkinson [2008] as modified by Atkinson and Boore [2011]	Eastern North America	ENA observations from Atkinson and Boore [2006]		4.3	7.6	Mw	10	1000+	R_{jb}	1-Vs30=760 m/s	6, PGA, PGV	0.1	5	Referenced empirical approach		
Atkinson [2006] as modified by Atkinson and Boore [2011]	Eastern North America	34800[1]	10	3.5	8	Mw	1	1000	R_{rup}	1,C	24, PGA, PGV	0.025	5	G	1	R
Campbell [2003]	Eastern North America	Hybrid empirical GM simulations		+5	8.2	Mw	0	1000	R_{rup}	1-Vs30=2.8 km/sec	16, PGA, (0.01 s)	0.02	4	G	1	R
Douglas *et al* [2006]	Southern Norway	Hybrid Empirical GM simulations		+4.5	7.5	Mw	1	1000	R_{jb}	1-rock sites	14	0.02	2	G	1	R,N,S
Frankel *et al* [1996] as parameterized by EPRI [2004]	Central Eastern North America	Stochastic simulations				Mw					7					
Raghu Kanth and Iyengar [2006, 2007]	Peninsular India	900	9[2]	4[2]	8[2]	Mw	1[2]	300[2]	R_{hypo}	Bedrock Vs30 ~ 3600 m/sec + conversion for NEHRP A,B,C	27, PGA	-.-1	4	U	2	A

[1]Simulated records
[2]Spectral acceleration values are simulated for moment magnitude (Mw) ranging from 4 to 8 in increments of 0.5 units. The distance parameter is varied in intervals of log10 (repi) = 0.13.

Table 4.1 Continued

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
Silva *et al* [2002]	Central and Eastern North America, Mid-Continent and Gulf Coast Areas	300[3]	5[3]	4.5[3]	7.5[3]	Mw	1[3]	400[3]	R_{rup}	[4]	26, PGA, PGV, PGD	0.01	10	U	2	A
Somerville *et al* [2009]	Australia (cratonic and non-cratonic)			5	7.5[3]	Mw	0	500	R_{jb}	1-rock Vs30=865 m/sec	22, PGA, PGV	0.01	10	U[5]	1M	T6
Pezeshk [2011]	Eastern North America		7[7]	5[7]	8[7]	Mw	1[7]	1000[6]	R_{rup}	1-hard rock Vs30≥2000 m/sec or NEHRP A	22, PGA	0.01	10	I50	1	A8
Toro et al [1997] modified by Toro [2002]	Eastern North America	Stochastic simulations		5	8	Mw	1	1000	R_{jb}	1-Vs30=2.8 km/sec	7, PGA	0.05	4	G	1	R

[3]Three hundred stochastic point-source simulations reflecting parametric variability are made at distances of 1, 5, 10, 20,l 50, 75, 200, and 400 km. At each distance, five magnitudes are used: M4.5, 5.5, 6.5, 7.5 and 8.5.
[4]Random vibration theory (RVT) used to assess the site response, where a profile randomization scheme has been developed that varies both layer velocity and thickness.
[5]Fault locations and orientations are not known (probably the geometric mean).
[6]Source model developed for thrust-faulting. The style of faulting in Australia is predominantly reverse, with strike-slip faulting occurring together with thrust faulting.
[7]Hybrid empirical method, moments magnitudes 5.0 to 8.0 in 0.5 magnitude unit increments, and for 24 rupture distances (R_{rup}) logarithmically spaced from 1 to 1000 km.
[8]Generic style of faulting for NGS models.

Table 4.2 Attributes of pre-selected models for subduction zones.

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
BC Hydro[2011]	Japan, Taiwan, Cascadia, Mexico, Peru, Chile, Alaska, and Solomon Islands	Interface = 1378; Intraslab = 3946	Interface = 46; Intraslab = 76	Interface = 6.5; Intraslab = 5.0	Interface = 8.4; Intraslab = 7.9	Mw	Interface = 5; Intraslab = 34	Interface = 551; Intraslab = 991	R_{rup}, R_{hypo}[1]	C (Vs30)	PGA, 105	0.01	10.0	G[2]	1M	B,F
Arroyo *et al* [2010]	Forearc regions of Mexico	Interface = 418	Interface = 40	5.0	8.0	Mw	20	400	(R_{hypo} for Mw < 6)	3[3]	PGA, 29	0.04	5	G	O	F
Atkinson and Boore [2003]	Alaska, Cascadia, Chile, Japan, Mexico, and Peru[4]	Interface = 349; Intraslab = 761[5]	Interface = 49; Intraslab = 30[6]	Interface = 5.5; Intraslab = 5.0	Interface = 8.3; Intraslab = 7.9	Mw	Interface = 5; Intraslab = 34	Interface = 420; Intraslab = 575[5]	R_{rup}	4[8]	PGA, 7	0.04	3	C	1M	F,B

[1]R is R_{rup} for interface cents, while it is R_{hypo} for intraslab events.
[2]Geometric mean but Taiwan data was computed based on GMRotI.
[3]Three site classes are modelled following New Zealand site classification, based on surface geology description, geotechnical properties, Vs30 values, predominant period (T_g) and depth to bedrock.
[4]Regions contributing interface data.
[5]Number of horizontal components in the interface dataset.
[6]The value listed includes both subduction and crustal records, and no breakdown of record numbers by source type is given in the publication.
[7]Only data from events up to 300 km were used for final regression.
[8]NEHRP site classes are based on Vs30 values: B through E.

Table 4.2 Continued.

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
Garcia *et al* [2005]	Central Mexico	Intraslab = 267	Interface = 16;	5.2	7.4	Mw	40	400	R_{rup} for Mw≥6.5, R_{hypo} otherwise	I[3]	PGA, PGC, 15	0.04	5	G[9]	1M	B
Kanno *et al* [2006]	Japan + foreign data	Interface + crustal I= 3769; Intraslab = 8150	Interface = 83; Intraslab = 111	Interface = 5.2 Intraslab = 5.5	Interface + crustal= 8.2 Intraslab = 5.5	Mw	Interface + crustal= 1 Intraslab = 30	Interface + crustal= 400 Intraslab = 500	R_{hypo}	C (Vs30)	PGA, PVD, 36	0.05	5	R	2M	A
Lin and Lee [2008]	NE Taiwan + 10 foreign	Interface = 873; Intraslab = 3950	Interface = 17; Intraslab = 37	Interface = 5.3; Intraslab = 4.1	Interface = 8.1; Intraslab = 6.7	Mw (ML)	Interface = 20; Intraslab = 40	Interface = 40; Intraslab = 600[5]	R_{hypo}	2	PGA, 27	0.01	5	G	1W	A (B,F)
McVerry et al [2006]	New Zealand + 66 foreign	535[10]	Interface = 6?; Intraslab = 19?	5.08 (or 5.2?)	7.09 (or 6.8?)	Mw	6 (or 30?)	400	R_c (R_{rup})	3[3]	PGA, 11	0.075	3	L,G	1M	C (R,OR ,S&N) &F,B

[9]Call is "quadratic mean," which is assumed to be the geometric mean.
[10]The value listed includes both subduction and crustal records, and no breakdown of record numbers by source type is given in the publication.

Table 4.2 Continued.

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
Youngs *et al* [1997]	Alaska, Cascadia, Chile, Japan, and the Solomon Islands	Interface + crustal I= 181; Intraslab = 53	Interface = 57; Intraslab = 26	Interface = 5.0; Intraslab = 5.0	Interface = 8.2; Intraslab = 7.8	Mw	Interface = 8.5; Intraslab = 45	Interface = 551; Intraslab = 744	R_{rup}, R_{hypo} in a few cases	2[11]	PGA, 11	0.075	3 (or 4?)	G[9]	1M	NT (N,T)
Zhao *et al* [2006] modified by Zhao [2010]	Japan + 208 foreign crustal near-source records	Interface + crustal I= 1508; Intraslab = 1725 Crustal = 1285	289[12]	5	8.3	Mw	0	300	R_{rup}	4[13]	PGA, 20	0.05	5	G	1M	C(R, S/N) & F,B

[11]Generic rock and soil consistent with those proposed by Boore, *et al* [2003].
[12]No breakdown of event number by source type is given in the publication.
[13]Four site classes are determined based on Vs30 values and predominant period (T_g) of the site.

Table 4.3 Attributes of pre-selected models for regions with shallow crustal seismicity.

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
Abrahamson and Silva [2008]	World wide shallow crustal	500-2754	64-135	4.27[1]	7.9[2]	Mw	0.06	200	R_{rup},	C	PGA, 22	0.01	10.0	150	1M	A (N,S, R)
Akkar and Bommer [2010]	Middle East	532	131	5.0	7.6	Mw	0	99	R_{jb}	3	A, 60	0.05	3	G	1M	(N,S, P)
Boore and Atkinson [2008] as modified by Atkinson and Boore [2011]	World-wide shallow crustal	600-1574	18-58	4.27-5.00[3]	7.9[4]	Mw	0	280[5]	R_{jb}	C	21	0.01	10	150	2M	(N,S, R, U)
Campbell and Bozorgnia [2008]	World-wide shallow crustal															
Cauzzi and Faccioli [2008] updated by Faccioli et al [2010]	World-wide shallow crustal															

[1]R is R_{rup} for interface cents, while it is R_{hypo} for intraslab events.
[2]Geometric mean but Taiwan data was computed based on GMRotI.
[3]Three site classes are modelled following New Zealand site classification, based on surface geology description, geotechnical properties, Vs30 values, predominant period (T_g) and depth to bedrock.
[4]Regions contributing interface data.
[5]Number of horizontal components in the interface dataset.
[6]The value listed includes both subduction and crustal records, and no breakdown of record numbers by source type is given in the publication.
[7]Only data from events up to 300 km were used for final regression.
[8]NEHRP site classes are based on Vs30 values: B through E.

Table 4.3 Continued.

Reference	Area	H	E	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	S	T_s	T_{min}	T_{max}	C	R	M
Choi and Youngs [2008]	World-wide shallow crustal	≤1950[8]	≤125	4.265[9]	7.90[10]	Mw	0.06	0.2[11]	R_{rup},	C	PGA, 22	0.01	10.0	150	1M	A (N,S, R, HW, AS)
Kanno *et al* [2006]																
McVerry *et al* [2006]																
Zhao *et al* [2006]																

[8]Due to filtering, number of records and earthquakes depends on period.
[9]Believe that model can be extrapolated down to 4.0.
[10]Believe that model can be extrapolated up to 8.5 km for strike-slip faulting and 8.0 for reverse faulting.
[11]Believe that model valid to 0 km.
[12]Believe that model valid to 200 km.

Table 4.4 Attributes of pre-selected models for volcanic regions.

Reference	**Area**	**H**	**E**	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	**S**	T_s	T_{min}	T_{max}	**C**	**R**	**M**
De Natale *et al* [1988] as parametrized by Faccioli *et al* [2011]	Volcanic areas in Italy	350 simulated		0.01	78	Mw	3.5	5								
McVerry *et al* [2006]																
Zhao *et al* [2006]																

Table 4.5 Attributes of pre-selected models for regions with deep-focus non-subduction zone seismicity

Reference	**Area**	**H**	**E**	M_{min}	M_{max}	M_{scale}	r_{min}	r_{max}	R_{scale}	**S**	T_s	T_{min}	T_{max}	**C**	**R**	**M**
Sokolov *et al* [2008]	Vrancea, Romania	Simulated		5	78	8	1	500	R_{epi}	1	PGA, PGS, 13	0.1	3	L	O	R

Where:

H Number of horizontal records (if both horizontal components are used then multiply by two to get total number)

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:

Mw Moment magnitude

ML Local magnitude

r min Shortest source-to-site distance

r max Longest source-to-site distance

r scale Distance metric, where (when available the *de facto* standard abbreviations of Abrahamson and Shedlock [1997] are used):

Rjb Distance to projection of rupture plane on surface [Joyner and Boore, 1981]

Rhypo Hypocentral (or focal) distance

Rrup Distance to rupture plane

Rc Distance to rupture centroid

S Number of different site conditions modelled, where:

C Continuous classification

I Individual classification for each site

C Use of the two horizontal components of each accelerogram (see Beyer and Bommer [2006]), where:

G Geometric mean

I50 GMrotI50 [Boore *et al*, 2006].

C Randomly chosen component

L Larger component

R Resolved component

U Unknown

R Regression method used, where:

1 Ordinary one-stage

1M Maximum likelihood one-stage or random-effects (Abrahamson and Youngs [1992]; Joyner and Boore [1993])

2M Maximum likelihood two-stage [Joyner and Boore, 1993]

U Unknown (often probably ordinary one-stage regression)

1W Weighted one-stage

M Source mechanisms (and tectonic type) of earthquakes (letters in brackets refer to those mechanism that are separately modelled), where:

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

AS Aftershock

B Interslab

C Shallow crustal

F Interface

HW Hanging wall

I Intraplate

N Normal

O Oblique or odd [Frohlich and Apperson, 1992]

R Reverse

S Strike-slip

T Thrust

U Unspecified

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

*T*min Minimum period for which attenuation equation is derived

*T*max Maximum period for which attenuation equation is derived.

5 Functional Forms and Main Attributes for Pre-selected GMPE models

PART 1: EQUATIONS FOR STABLE CONTINENTAL REGIONS (SCRS)

5.1 ATKINSON [2008] AS MODIFIED BY ATKINSON AND BOORE [2011]: REFERENCED EMPIRICAL MODEL FOR EASTERN NORTH AMERICA

Functional original form of Atkinson [2008] is:

$$\log F = c_0 + c_1 R_{JB} + c_2 R_{JB}^2$$

where *F* is the multiplying adjustment factor to be applied to the prediction from the Boore and Atkinson [2008] GMPEs (YBA08) to obtain:

$$Y_{ENA} = F Y_{BA08}$$

Response variables are the same of Boore and Atkinson [2008] for shallow crustal earthquakes in active tectonic regions.

The revision of 2011 is based on the "referenced empirical approach", in which the Boore and Atkinson [2008] GMPE (as modified by Atkinson and Boore [2011]) is used as a basis, modified with a correction factor obtained by regressing the residuals of the ENA data with respect to the said GMPE, once the ground motions are adjusted to B/C conditions (760 m/sec).

$$Y'_{ENA} = Y_{FBA08}\ FENA$$

Notes:

- Approach is constrained to follow the overall scaling behaviour of ground motion that is observed in better-instrumented active tectonic regions, and is apt to shed light on the epistemic uncertainties of other approaches, such as the stochastic method.
- The revision affects all magnitudes.
- The mean trends are well fit by the function (in log(10) units):

  log FENA = c(T) + d(T) Rjb

  where T is period. The authors provide a table (Table 4) which lists the residual factor log FENA for PSA at periods of 0.05 sec to 5.0 sec, PGA, and PGV. The also state that, for periods <0.05 sec, the value at 0.05 sec may be used, whereas for periods >5.0 sec, the value at 5.0 sec may be used. For intermediate periods, the coefficients may be linearly interpolated against log (period).

5.2 ATKINSON AND BOORE [2006] AS MODIFIED BY ATKINSON AND BOORE [2011]: EXTENDED STOCHASTIC MODEL FOR EASTERN NORTH AMERICA

Functional form:

$$\begin{aligned}\text{Log PSA} = {} & c_1 + c_2\mathbf{M} + c_3\mathbf{M}^2 + (c_4 + c_5\mathbf{M})f_1 \\ & + (c_6 + c_7\mathbf{M})f_2 + (c_8 + c_9\mathbf{M})f_0 \\ & + c_{10}R_{\text{cd}} + S,\end{aligned}$$

where $f_0 = \max(\log(R_0/R_{\text{cd}}), 0)$; $f_1 = \min(\log R_{\text{cd}}, \log R_1)$; $f_2 = \max(\log(R_{\text{cd}}/R_2), 0)$; $R_0 = 10$; $R_1 = 70$; $R_2 = 140$;

and $S = 0$ for hard-rock sites

where Y is either PGA, PGV or 5% damped PSA up to 5s.

Notes:

- Because of paucity of recorded ENA ground motions in selected magnitude-distance range, GMPEs are derived from a simulated ground-motion database (generated with the EXSIM stochastic code, specifying parameters of geometric spreading and frequency dependent *Q*, and a distance-dependent duration).
- Simulated motions are developed from a seismological model of source, path, and site parameters, obtained using empirical data from small to moderate ENA earthquakes. The key model parameters are the attenuation function, as calibrated from small-to-moderate magnitude data in ENA [Atkinson, 2004], and the stress parameter, which was set to an average value of 140 bars. Functions are then fitted to simulated ground motion.
- The revision of 2011 suggests that a magnitude-dependent stress parameter (Δσ) should be used in the AB06 predictions to change the magnitude scaling of motions, such that eastern motions scale with magnitude in approximately the same way as do western motions

  $\log \Delta\sigma = 3.45 - 0.2\text{ M}$ for $\text{M} \geq 5$
- For M < 5, the authors recommend capping the stress drop at the value of 280 bars.
- The adjusted (AB06’) equation predicts larger short-period motions at moderate magnitudes to better match ENA data.
- Authors stress importance on relationship between catalogue magnitudes (largely Nuttli magnitude, MN) and moment magnitude, whose adjustment by 0.1 to 0.2 units could cause the average ratios of observations to predictions for the plotted data at $R_{jb} < 50$ km to go to unity.

5.3 CAMPBELL [2003]: HYBRID MODEL FOR EASTERN NORTH AMERICA

Functional form:

$$\ln Y = c_1 + f_1(M_W) + f_2(M_W, r_{\text{rup}}) + f_3(r_{\text{rup}})$$

where:

$$f_1(M_W) = c_2 M_W + c_3(8.5 - M_W)^2,$$

$$f_2(M_W, r_{rup}) = c_4 \ln R + (c_5 + c_6 M_W) r_{rup},$$

$$R = \sqrt{r_{rup}^2 + [c_7 \exp(c_8 M_W)]^2},$$

$$f_3(r_{rup}) = \begin{cases} 0 & \text{for } r_{rup} \leqslant r_1 \\ c_7(\ln r_{rup} - \ln r_1) & \text{for } r_1 < r_{rup} \leqslant r_2 \\ c_7(\ln r_{rup} - \ln r_1) + \\ \quad c_8(\ln r_{rup} - \ln r_2) & \text{for } r_{rup} > r_2 \end{cases}.$$

Y is the geometric mean of the two horizontal components of PGA or 5% damped PSA in g, M_W is moment magnitude, r_{rup} is closest distance to fault rupture in km, r_1=70 km, and r_2=130 km. The aleatory standard deviation is given by:

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12} M_W & \text{for } M_W < M_1 \\ c_{13} & \text{for } M_W \geqslant M_1 \end{cases},$$

where $M_1 = 7.16$.

Notes:

- Based on hybrid empirical method that uses the ratio of stochastic or theoretical ground motion estimates to adjust empirical ground-motion relations developed for one region (host, in this case western North America, WNA) to use in another region (target, in this case Eastern North America, ENA). The transfer from one region to another accounts for differences in stress drop, source properties, crustal attenuation, regional crustal structure, and generic-rock site profiles between the two regions.
- The model obtained is considered appropriate for ENA hard rock sites with a shear-wave velocity of 2800 m/sec.

5.4 DOUGLAS *ET AL* [2006]: HYBRID MODEL FOR SOUTHERN NORWAY

Functional form:

$$\ln Y = c_1 + f_1(M_w) + f_2(M_w, d_{jb}) + f_3(d_{jb}),$$

where

$$f_1(M_w) = c_2 M_w + c_3(8.5 - M_w)^2$$

$$f_2(M_w, d_{jb}) = c_4 \ln R + (c_5 + c_6 M_w) d_{jb},$$
$$R = \sqrt{d_{jb}^2 + [c_7 \exp(c_8 M_w)]^2}$$

$$\begin{aligned} f_3(d_{jb}) &= 0 && \text{for } d_{jb} \le r_1 \\ f_3(d_{jb}) &= c_9(\ln d_{jb} - \ln r_1) && \text{for } r_1 < d_{jb} \le r_2, \\ f_3(d_{jb}) &= c_9(\ln d_{jb} - \ln r_1) + c_{10}(\ln d_{jb} - \ln r_2) && \text{for } d_{jb} > r_2 \end{aligned}$$

r_1 = 70 km and r_2 =130 km.

Y is either PGA or SA up to 2 s, in ms^{-2}.

Notes:

- Developed for sites in southern Spain and in southern Norway using composite approach that employs GMPEs developed from recorded data from different parts of the world, adjusted to convert the differing choices of independent parameters to a single one. After this the equations were modified to account for differences between the host and the target regions using the stochastic method to compute the host-to-target conversion factors (using the computer program CHEEP). Finally, similar to Atkinson and Boore [2006], functions were fitted to the derived ground-motion estimates to obtain sets of seven individual equations for use in probabilistic seismic hazard assessment for southern Spain and southern Norway.
- Methodology adopted calls for the setting up of independent logic trees for the median values and for the sigma values, in order to properly separate epistemic and aleatory uncertainties after the corrections and the conversions.

5.5 FRANKEL *ET AL* [1996] AS PARAMETERIZED BY EPRI [2004]

In the EPRI [2004] report for CEUS Ground Motion, a parametric form of the USGS model was fit to the ground motion values provided by Frankel [2002]. In addition, this model was converted from point-source to Joyner-Boore distance by simulating a data set in terms of moment magnitude and Joyner-Boore distance and fitting this simulated data set.

The procedure is described as follows: at a given Joyner-Boore distance, earthquake point source depths were simulated for a range of magnitudes using the point-source depth distributions proposed by Silva et al. [2002]. These consist of lognormal distributions with the parameters listed in an annex table. For each simulation the depth and the Joyner-Boore distance were used to compute the corresponding point source distance. The median ground motion for the given magnitude and point source distance was then computed using the model proposed by Frankel *et al* [1996]. The model parameters for magnitudes M ≥ 5 were used. The parameters were interpolated to provide coefficients at the 7 spectral frequencies used in this analysis. The resulting simulated data sets were then fit with the following functional forms:

$$\begin{aligned}\ln(SA) = C_1 + C_2 m + C_3 m^2 &+ (C_4 + C_5 m) \times \min\{\ln(r'), \ln(70)\} \\ &+ (C_6 + C_7 m) \times \max[\min\{\ln(r'/70), \ln(130/70)\}, 0] \\ &+ (C_8 + C_9 m) \times \max\{\ln(r'/130), 0\} \\ &+ C_{10} r'\end{aligned}$$

$$r' = \sqrt{r_{JB}^2 + h^2} \qquad h = \exp(C_{11} + C_{12} m)$$

The model parameters are listed in a provided table.

The 1996 model is considered a spectral, Single-corner model obtained via simulations imposing median stress drop of 150 bars, distance-dependent geometric spreading (1/R for R < 70 km; 1/70 for 70 ≤ R ≤ 130 km; $(130/R)^{1/2}/70$ for R > 130 km), Q(f) of $680f^{0.36}$, duration of $1/f$A+0.05R, kappa of 0.01 and validity for hard rock sites with surface shear wave velocity of 2.8 km/sec. The model includes amplifications for Fourier spectral values which are intended to represent a hypothetical NEHRP B-C boundary site for the CEUS.

In the EPRI Report, the basis for the Frankel *et al* [1996] aleatory values are debated because is not clear from their documentation.

5.6 RAGHU KANTH AND IYENGAR [2006; 2007]: PENINSULAR INDIA (PI)

The attenuation equation is of the form borrowed by Atkinson and Boore [1995], i.e.:

$$\ln(y_{br}) = c_1 + c_2(M-6) + c_3(M-6)^2 \quad - \ln(r) - c_4 r + \ln(\varepsilon_{br}).$$

Where $y_{br} = (S_a/g)$ is ratio of spectral acceleration at bedrock level to acceleration due to gravity. M and r refers to moment magnitude and hypocentral distance respectively. The coefficients of the above equation are obtained from the simulated database of Sa by a two-step stratified regression following Joyner and Boore [1981].

Notes:

- Derive empirical equations for 5% damped response spectra, corresponding to bedrock conditions in PI (Vs nearly equal to 3.6 km/sec). Correction factors are also found for various other sites defined in terms of $V_{S,30}$ of the soil, for the NEHRP sites A: ($V_{S,30}$ > 1.5 km/sec); B: (0.76 km/sec < $V_{S,30}$ ≤ 1.5 km/sec); C: (0.36 km/sec < $V_{S,30}$ ≤ 0.76 km/sec) and D: (0.18 km/sec < $V_{S,30}$ ≤ 0.36 km/sec). The site coefficient Fs, (s = A, B, C, D) defined as the ratio of spectral acceleration at the surface to the bedrock value is determined for all the 27 natural periods
- Provides 3 different set of coefficients for the three regions in Peninsular India: the Koyna–Warna (K–W) region, the southern India (SI) region and the Western–Central (W–C) region.
- The results of the derived equation are compared with instrumental data from the Koyna earthquake (Mw = 6.5) of 11 December 1967 and the Bhuj earthquake (Mw = 7.7) of 26 January 2001.
- Compares with Toro *et al* [1997], Hwang *et al* [1997], Campbell [2003] and Atkinson and Boore [2006], and find that the observable differences are mainly attributed to the different quality factors, stress drop ranges, and the definition of source-to-site distance. The differences in the spectral values between Atkinson and Boore [2006] and PI relation can be attributed to the point source assumption in the seismological model used. The standard error obtained here is of the same order as reported by others in the past.
- Compares with the BIS code IS-1893 [2002] scaled by a zonal factor presumably representing the expected PGA in the zone, and finds that, for rock sites that are commonly met in PI, the code spectrum underestimates seismic forces on high-frequency structures; on the other hand, at soft soil sites the code overestimates forces on long-period structures.
- To derive ground motions, the authors applied a stochastic computer simulation for point-source, consisting of three steps [Boore 1983, 2003]. Among the parameters used, the authors chose a single-corner Brune model, a geometrical attenuation term and stress drop consistent with Singh *et al* [1999], 3 different quality factors Q for the Koyna–Warna (K–W) region, for the southern India (SI) region and for the Western–Central (W–C) region.

- Spectral acceleration values are simulated for moment magnitude (Mw) ranging from 4 to 8 in increments of 0.5 units. The distance parameter is varied in intervals of $\log10_{(repi)} = 0.13$. In all, there are 101 pairs of magnitudes and distances.
- For each magnitude, 100 samples of seismic parameters are used. Thus, the database consists of 10, 100 Sa samples from 900 simulated earthquakes.

5.7 SILVA *ET AL* [2002]

Functional form is

$$\ln y = C_1 + C_2 \mathrm{M} + (\mathrm{C}_6 + \mathrm{C}_7 \mathrm{M}) * \ln(\mathrm{R} + e^{\mathrm{C}_4}) + \mathrm{C}_{10} (\mathrm{M} - 6)^2$$

where R is taken as a closest distance to the surface projection of the rupture surface.

Model developed for Central and Eastern North America, Mid-Continent and Gulf Coast Areas.

To generate data, which consists of 5% damped spectral acceleration, peak acceleration, peak particle velocity, and peak displacements, for the regression analyses, 300 simulations reflecting parametric variability are made at distances of 1, 5, 10, 20, 50, 75, 100, 200, and 400 km. At each distance, five magnitudes are used: M 4.5, 5.5, 6.5, 7.5, and 8.5.

Notes:

- Provides different regression coefficients according to the area (mid-Continent or Gulf Area), the stochastic model (single-corner or two-corner) and stress drop (medium, low or high magnitude dependent, stress drop; single medium, low or high stress drop; constant medium, low or high stress drop; constant medium, low, or high stress drop plus saturation).
- Epistemic variability or uncertainty in mean estimates of ground motions is assumed to be accommodated in the use of the three mean stress drop single corner models and the double corner model, all with appropriate weights. The model variability is added to the variability resulting from the regression analyses (parametric plus regression variability) to represent the total variability associated with median estimates of ground motions.
- Simulations have been obtained via single-corner and two-corner stochastic approaches, where the models had:
  a. Fixed Parameters:
     - Regional Crustal Model: the Midcontinent and Gulf Coast models from EPRI [1993]; also in Toro et al., [1997], with Moho at depth of about 40 km
     - Rock and Soil Generic Profiles: used to compute the crustal amplification. The site response was assessed employing random vibration theory (RVT), which in this case considers only SH waves with normal incidence, travelling through randomly varying profiles which vary both layer velocity and thickness.
     - Kappa: a kappa value of 0.006 sec is assumed to apply for the crystalline basement and below (Silva and Darragh, [1995]; EPRI, [1993]).
     - G/Gmax and Hysteric Damping Curves, Finite Source Rise Time, Finite Source Rupture Velocity
     - Duration model: taken as the inverse corner frequency plus a smooth distance term of 0.05 times the hypocentral distance.

b. Free Parameters

- Regional Q(f) Model: from Silva et al. [1997], based on inversions of CEUS recordings (Midcontinent region) and inversions of regional LRSM recordings (Gulf Coast region).
- Point Source Stress Drop: scales with magnitude based on point-source inversions of the Abrahamson and Silva [1997] empirical attenuation relation. For the CEUS, the stress drop values are constrained by the M 5.5 stress drop of 160 bars. When double corner model is used, there is no variation of the stress drop with magnitude.
- Source Depth: assumed to be magnitude dependent and is based on the depth distribution of stable continental interiors and margins [EPRI, 1993].
- Finite Source Slip Model and Nucleation Point.

5.8 SOMERVILLE *ET AL* [2009]: SIMULATION-BASED MODELS FOR AUSTRALIA

Functional form:

for $M < m_1$, $r < r_1$

$$\ln Sa(g) = c_1 + c_2(M - m_1) + c_3 \ln R + c_4(M - m_1)\ln R + c_5 r + c_8(8.5 - M)^2$$

for $M < m_1$, $r \geq r_1$

$$\ln Sa(g) = c_1 + c_2(M - m_1) + c_3 \ln R_1 + c_4(M - m_1)\ln R + c_5 r + c_6(\ln R - \ln R_1) + c_8(8.5 - M)^2$$

for $M \geq m_1$, $r < r_1$

$$\ln Sa(g) = c_1 + c_7(M - m_1) + c_3 \ln R + c_4(M - m_1)\ln R + c_5 r + c_8(8.5 - M)^2$$

for $M \geq m_1$, $r \geq r_1$

$$\ln Sa(g) = c_1 + c_7(M - m_1) + c_3 \ln R_1 + c_4(M - m_1)\ln R + c_5 r + c_6(\ln R - \ln R_1) + c_8(8.5 - M)^2$$

where

$Sa(g)$	is spectral acceleration in g for rock sites having V_s30 of 865 m/sec
m_1	= 6.4
r_1	= 50 km
h	= 6 km
R	$= \sqrt{r^2 + h^2}$
R_1	$= \sqrt{r_1^2 + h^2}$
M	is moment magnitude in the range of 5.0 to 7.5
r	= Joyner Boore distance in the range of 0 to 500 km

Notes:

- Provides two separate models: one for cratonic and the other for non-cratonic regions of Australia. The model for non-cratonic Australia (coastal margins and Eastern Regions) is obtained by combining the ground motion simulations of the five non-cratonic cases with similar ground motion models (the Lachlan Fold Belt, the Sydney Basin, and the Perth Basin non-cratonic models); the model for cratonic Australia (Western Regions) is obtained by combining the ground simulations of the Yilgarn Craton, the Lachlan Fold Belt and Perth Basin cratonic models. Notes that the Yilgarn Craton ground motion model is quite different from the other five models, which are all quite similar to each other.
- Notes that the cratonic ground motion model is quite similar to the model developed using Yilgarn Craton data by Liang et al. [2008] model, and less similar to the models for stable regions of eastern North America by Toro et al. [1997] and Atkinson and Boore [2006]. Notes that the non-cratonic ground motion model is more similar to models for tectonically active regions such as Boore and Atkinson [2008] than the Toro et al. [1997] model for tectonically stable eastern North America.

- Ground motions are referred to rock site conditions (Vs30 of 865 m/sec). Kappa values of 0.006 and 0.04 respectively are used for the cratonic and non-cratonic models.
- Ground motions were simulated using the hybrid method of Graves and Pitarka [2004] and Graves *et al* [2007], for magnitudes from Mw 5 to 7.5 (with a 0.5 unit increment) for six combinations of earthquake source and crustal structure. All earthquakes were assumed to occur on reverse faults with dip angles of 45°, at a 10 km depth (eastern Australia) or in the range 0-5 km depth (southwestern Australia). The source model was developed for thrust-faulting because the style of faulting in Australia is predominantly reverse, with strike-slip faulting occurring together with thrust faulting.
- The strong motion simulations use earthquake source scaling relations that are consistent with the source parameters of Australian earthquakes, and Green's functions that are calculated from known crustal structure models of Australia.
- In western Australia, authors used the rupture models of the four earthquakes to constrain the scaling relationship between seismic moment and rupture area. Other aspects of the source scaling relations were derived from the scaling relations for earthquakes in eastern North America [Somerville *et al*, 2001]. In eastern Australia the authors have used the relations for Western Australia as well as the relations for the western United States [Somerville *et al*, 1999].
- The random effects model of Abrahamson and Youngs [1992] is used to develop the ground motion model. The functional form follows Abrahamson and Silva [1997], with a modification to allow for a change in slope at a specified distance (50 km). The ground motion model is for thrust faulting, because the style of faulting in Australia is predominantly reverse, with strike-slip faulting occurring together with thrust faulting.
- The authors suggest that hanging wall effects are not explicitly incorporated because this effect is already adequately represented through the use of R_{JB} as the distance metric.
- The model coefficients are not smoothed across periods.
- The predictions of the non-cratonic ground motion model were compared with recordings of the Mw 4.47 Thomson Reservoir earthquake of 26 September 1996.

5.9 PEZESHK *ET AL* [2011]: HYBRID MODEL FOR EASTERN NORTH AMERICA

The functional form is:

$$\begin{aligned}\log(\overline{Y}) = c_1 + c_2 M_W + c_3 M_W^2 + (c_4 + c_5 M_W) \times \min\{\log(R), \log(70)\} \\ + (c_6 + c_7 M_W) \times \max[\min\{\log(R/70), \log(140/70)\}, 0] \\ + (c_8 + c_9 M_W) \times \max\{\log(R/140), 0\} + c_{10} R\end{aligned} \qquad (1)$$

where

$$R = \sqrt{R_{rup}^2 + c_{11}^2} \qquad (2)$$

where $\overline{Y}$ is the median value of PGA or PSA (g), M_W is the moment magnitude, and R_{rup} is the closest distance to fault rupture (km).

The mean aleatory standard deviation of $\log(\bar{Y})$ to be associated with the predictions is defined as a function of earthquake magnitude and is modelled as follows:

$$\sigma_{\log(\bar{Y})} = \begin{cases} c_{12}M_w + c_{13} & M \le 7 \\ -6.95\times10^{-3}M_w + c_{14} & M > 7 \end{cases} \tag{3}$$

The total aleatory standard deviation may be derived by adding the standard deviation of the regression to the aleatory standard deviation from equation (6) as follows

$$\sigma^T_{\log\bar{Y}} = \sqrt{\sigma^2_{\log\bar{Y}} + \sigma^2_{\mathrm{Reg}}} \tag{4}$$

where σ_{Reg} is the standard deviation of the regression performed to fit the model to ground motion estimates.

The model is evaluated for moment magnitudes 5.0 to 8.0 in 0.5 magnitude unit increments, and for 24 rupture distances (R_{rup}): 1, 2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 180, 200, 250, 300, 400, 500, 600, 700, 800, and 1000 km.

Median hybrid empirical estimates of ENA ground motion are obtained by scaling the WNA empirical relations (NGA Models) using theoretical modification factors. The hybrid empirical method is applied for $R_{rup} \le 70\,\mathrm{km}$ and hybrid empirical estimations are supplemented with stochastic ENA predictions for beyond 70 km in order to extend the GMPEs up to 1000 km, following method proposed by Campbell [2003],

Regression coefficients are calculated using a nonlinear least-square method, for a generic style of faulting (as defined in the NGA models).

The model is proposed for hard-rock sites with near-surface shear-wave velocity $\beta_s \ge 2\,\mathrm{km/s}$, or NEHRP site class A.

Authors employed the seismological model parameters used in Atkinson and Boore [2006], Atkinson et al. (2009), and Boore [2009] for ENA, and parameters used in Atkinson and Silva [2000] for WNA to simulate ground motions.

Notes:

- Authors compare predicted motions curves with Atkinson and Boore [2011] – referred as AB06', after considering proper amplification factors corrections, for PGA and PSA at periods of 0.1, 0.2, 0.50, 1.0, and 4.0 sec for magnitudes 5 and 7 and R_{rup} distances between 1 and 1000 km, and they found that the AB06' model has larger values at very close distances in comparison to Tavakoli and Pezeshk [2005] and this study. However, the two models predict similar values for distances greater than 10 km at all magnitudes and frequencies.
- With respect to Tavakoli and Pezeshk [2005], predictions of this study are similar to those at high frequencies for magnitude 5; however, they are larger for magnitude 7. For larger periods, Tavakoli and Pezeshk [2005] amplitudes are higher for all magnitudes.
- With respect to the database [1] by Assatourians and Atkinson [2010] for Mw 4.8-5.06 for the NEHRP A site class, the spectral accelerations predicted in this study at 0.2 and 1.0 sec for Mw 5.0 under-predicts the observations at close distances (60 km). In general, there is a good agreement between the ground-motion predictions of this study and the ENA database at large distances.

5.10 TORO *ET AL* [1997] MODIFIED BY TORO [2002]: STOCHASTIC MODEL FOR EASTERN NORTH AMERICA

Functional form:

$$\ln Y = c_1 + c_2(M-6) + c_3(M-6)^2 - c_4 \ln R_M - (c_5 - c_4)\max[\ln(R_M/100),0] - c_6 R_M$$
$$R_M = \sqrt{R_{jb}^2 + C_7^2}$$

where Y is spectral acceleration or peak ground acceleration in g up to 2 sec.

Notes:

- The attenuation equations are derived from the predictions of a stochastic ground-motion model (based on Brune's ω-square source model), for rock sites in Central and Eastern North America (for two crustal regions and two magnitude scales
- Uncertainties in model parameters, as well as those associated to the ground motion model are considered.

PART 2: EQUATIONS FOR SUBDUCTION ZONES

5.11 BC HYDRO [2011]: WORLDWIDE

Functional form:

$$\begin{aligned}\ln(Sa) = {} & \theta_1 + \theta_4 * \Delta C_1 + (\theta_2 + \theta_{14} * F_{event} + \theta_3 * (M-7.8)) * \ln\left(R + C_4 * \exp[(M-6)*\theta_9]\right) + \\ & \theta_6 * R + \theta_{10} * F_{event} + f_{Mag}(M) + f_{depth}(Z_h) + f_{FABA}(R) + \\ & f_{site}(PGA_{1000}, V_{S30})\end{aligned}$$

where M equals magnitude and Zh equals hypocentral depth (km).

$$R = \begin{cases} Rupture\,Distance & for\,Interface\ Events \\ Hypocentral\,Distance & for\,Intraslab\ Events \end{cases}$$

$$F_{event} = \begin{cases} 0 & Interface\ Events \\ 1 & Intraslab\ Events \end{cases}$$

$$F_{FABA} = \begin{cases} 0 & Forearc\ or\ Unknown\ Sites \\ 1 & Backarc\ Sites \end{cases}$$

Base Model for Magnitude Scaling:

$$f_{Mag}(M) = \begin{cases} \theta_4 * (M - (C_1 + \Delta C_1)) + \theta_{13} * (10 - M)^2 & for\ M \le C_1 + \Delta C_1 \\ \theta_5 * (M - (C_1 + \Delta C_1)) + \theta_{13} * (10 - M)^2 & for\ M > C_1 + \Delta C_1 \end{cases}$$

where $C_1 = 7.8$. Values of ΔC_1 capture the epistemic uncertainty in the break in the magnitude scaling.

Base Model for Depth Scaling:

$$f_{depth}(Z_h) = \theta_{11} * (Z_h - 60) * F_{event}$$

Base Model for Forearc / Backarc Scaling:

$$f_{FABA}(R) = \begin{cases} [\theta_7 + \theta_8 * Ln(\frac{\max[R,85]}{40})] * F_{FABA} & for\ F_{event} = 1 \\ [\theta_{15} + \theta_{16} * Ln(\frac{\max[R,100]}{40})] * F_{FABA} & for\ F_{event} = 0 \end{cases}$$

Base Model for Site Response:

$$f_{site}(PGA_{1000}, Vs30m) = \begin{cases} \theta_{12} * Ln(\frac{V_s^*}{V_{lin}}) - b * Ln(PGA_{1000} + c) + \\ \quad b * Ln(PGA_{1000} + c * (\frac{V_s^*}{V_{lin}})^n) & for \quad V_{S30} < V_{lin} \\ \theta_{12} * Ln(\frac{V_s^*}{V_{lin}}) + b * n * Ln(\frac{V_s^*}{V_{lin}}) & for \quad V_{S30} \geq V_{lin} \end{cases}$$

where

PGA_{1000} = Median PGA value for $V_{S,30}$ = 1,000 m/sec

and

$$V_s^* = \begin{cases} 1000.0 & for \quad V_{S30} > 1000 \\ V_{S30} & for \quad V_{S30} \leq 1000 \end{cases} \tag{3-9}$$

Notes:

- The functional form of the ground motion model is constrained to have a break in the magnitude scaling because notes a break in the magnitude scaling seen in the simulations (states that there is a weaker magnitude scaling for large (M > 8) magnitudes derived from finite-fault simulations as compared to the magnitude scaling obtained from the empirical data at smaller magnitudes). The epistemic uncertainty in the large magnitude level is captured by using three different alternatives for the transition magnitude: M7.3, M7.8, and M8.3.
- Combined with the break in the magnitude scaling, a combination of two models is used with the magnitude dependence of the fictitious depth constrained by the numerical simulations (θ_9=0.4) and the magnitude-dependent slope (θ_3) estimated from the empirical data, given the magnitude-dependent fictitious depth.
- Constrains C_4 to a value of 10 km because notes that the geometrical spreading terms are highly correlated with the saturation terms.
- Notes that, for the interface earthquakes, the inter-event residuals do not show a trend with hypocentral depth; however the depth scaling for intraslab earthquakes is modelled by a linear trend.
- For Japan, Cascadia and Taiwan, stations are also classified as back or fore-arc with respect to the volcanic front in each subduction region.
- Back-Arc Attenuation: separate distance attenuation is included for back-arc sites with separate slopes for interface and intraslab earthquakes.
- Site Amplification: the nonlinearity of the site amplification is constrained to be consistent with the Peninsula Range model Walling et al., [2008] used for two of the NGA relations (Abrahamson and Silva [2008]; Campbell and Bozorgnia, [2008]).

- Regression analysis: the random effect [Abrahamson and Youngs, 1992] method was used to find the maximum likelihood solution. The coefficients were estimated in a series of steps in which the coefficients were smoothed one or two at a time and then held fixed as the remaining unsmoothed coefficients were re-computed. To avoid having poorly recorded earthquakes impacting the scaling for magnitude, depth, and distance, only earthquakes with 5 or more recordings were used until the final regression run.
- Notes that the median model is not strongly affected by the inclusion of the poorly recorded earthquakes (with 2 to 4 records).
- Given the small number of aftershocks, the difference between mainshocks and aftershocks is not included in the model.
- Evaluates that the global model is over-predicting the available Cascadia data, but the long-period Cascadia ground motions are consistent with the global model.
- Database: the initial subduction zone ground motion dataset for this project was taken from the Atkinson and Boore [2003; 2008] dataset, which included a compilation of the earlier datasets of Crouse *et al* [1988], Crouse [1991], and Youngs *et al* [1997]. Additional subduction ground motion data were obtained for events in Japan (J. Zhao, 2008), Taiwan [Cheng, 2008], South and Central America [Pacific Engineering, 2008] and Mexico [Carrasco, 2008]. In the few cases where duplicate records were submitted, the more recent database source or the more region-specific database source was taken as the preferred source for any metadata information. The full dataset consists of 9946 ground-motion record pairs (two horizontal components) from 292 subduction zone earthquakes. A total of 3557 record pairs are from 163 interface events and 6389 record pairs are from 129 intraslab events. This number is further reduced by the application of a Magnitude-Distance dependent cut-off.
- For events with hypocentral depths less than 30 km, it was assumed that these events are interface events. For events with hypocentral depths deeper than 30 km, a search of the ISC seismicity catalogue [2] was performed to better determine the event magnitude, location, and hypocentral depth. For the depth estimates, any hypocentral depth determined from the pP seismic phase was given preference over other hypocentral depth estimates. A total of 34 out of the total of 292 events were classified as either aftershocks or foreshocks (events that occurred within a year of each other and were located within approximately 100-200 km of each other were considered to be dependent events).
- Excludes interface events with magnitudes less than 6.0.
- Excludes intraslab events with magnitudes less than 5.0.
- After removing the questionable data, data with missing key metadata, and the small magnitude data, the dataset was reduced to a total of 5,953 records from a total of 137 earthquakes.
- The Cascadia region dataset contains a total of 113 records from five earthquakes. For the intraslab records, the Cascadia dataset spans the magnitude range of 5.0 to 6.8 with distances and hypocentral depths between 48 and 522 km and 43 and 67 km, respectively.
- The Japan region dataset contains a total of 2,089 records from 58 earthquakes (26 interface events and 32 intraslab events). The largest interface event in this subset of data is the Mw 8.29 Tokachi-Oki earthquake. For the interface events, the dataset spans the magnitude range of 6.5 to 8.3 with distances between 25 and 551 km and hypocentral depths between 13 and 50 km. For the intraslab

events, the dataset spans the magnitude range of 5.1 to 7.8 with distances and hypocentral depths between 37 and 517 km and 31 and 166 km, respectively.

- A total of 287 records fall into the global region of South and Central America including Mexico. The 2001 Peru earthquake (Mw 8.4) has four recordings and is the largest earthquake in the regional dataset and total dataset. For the interface events, the dataset spans the magnitude range of 6.6 to 8.4, with distances between 13 and 424 km and hypocentral depths between 6 and 44 km. For the intraslab records, the dataset spans the magnitude range of 5.5 to 7.9, with distances and hypocentral depths between 34 and 991 km and 44 and 95 km, respectively.
- Data from Taiwan (3,291 records) represent over 50% of the total number of recordings in the dataset. All of these recordings were submitted by Cheng [2008] and were not part of either the Atkinson and Boore [2003; 2008] or Youngs *et al* [1997] datasets. There are only four interface events in the Taiwan dataset with a total of 855 recordings. The remaining 2,436 recordings are from intraslab earthquakes. For the interface events, the data set spans the magnitude range of 6.2 - 7.1 with distances between 51 and 279 km. For the intraslab records, the dataset spans the magnitude range of 5.0 to 6.0, with distances between 41 and 342 km and hypocentral depths between 57 and 130 km.
- The remaining regions contained in the dataset are the Alaska and Solomon Island regions, which contributes with 25 recordings.
- All of the events from the Solomon Islands have been classified as intraslab events spanning a range in magnitudes of 5.2 to 6.3 with hypocentral depths between 110 and 194 km. The Alaska dataset consists of five interface events and a single intraslab event.
- Magnitude-dependent distance limits are applied to the ground motion data set based on the PGA to avoid biasing (they used a censoring of the data at PGA levels of 0.03g to 0.04g), accepting the correlation of magnitude and distance resulting from a magnitude dependent cut-off distance. This cut-off, results in a further reduction of records used to derive the G.M. coefficients (their Table 3.1-8 shows the final selected earthquakes).
- Response spectra: for the earthquakes for which time histories were available, the 5% damped spectral acceleration response spectra were computed at a suite of 105 spectral periods between 0.01 and 10.0 seconds. For some older earthquakes in the dataset, ground-motion values were only available for PGA and 5% damped response spectral at 0.1, 0.2, 0.4, 1.0, 2.0, and 3.0 sec (assumption that the geometric mean of the two horizontal components was used). The useable period range was determined for each recording based on the corner frequencies of the filters used in the processing. For all of the computed response spectra, except for the Taiwan data, the geometric mean of the two horizontal components was computed. In contrast, the Taiwan data was computed based on GMRotI as defined in Boore *et al* [2006].
- Site Classification: in some cases, measured $V_{S,30}$ values are available but for most of the stations, correlations between site classifications and average $V_{S,30}$ values were used to estimate $V_{S,30}$. These correlations include the Geomatrix 3rd letter classification from Chiou *et al* [2008] and the NEHRP Classification from Atkinson and Boore [2003; 2008]. Provides a table with the correlated values.
- Distance measure: based on the lack of computed finite-fault models for the older and especially moderate magnitude sized earthquakes, it is assumed that the distance from the older events are hypocentral distances (B. Youngs, personal communication, [2008]). For the deep and relatively

small magnitude intraslab events, the difference between a rupture distance and the hypocentral distance will not be significant. For the shallow and large magnitude interface events, the difference in rupture distance versus hypocentral distance could be significant but couldn't be estimated at that point given the limited information. For the more recent events compiled in the dataset, both hypocentral distance and rupture distance are given in the flat file. Considers R as R_{rup} for Interface Events, while it is R_{hypo} for intraslab events.

5.12 ARROYO *ET AL* [2010]: INTERFACE MODEL FOR MEXICO

Ground-motion model is:

$$\begin{aligned} \ln \mathrm{SA}(T) &= \alpha_1(T) + \alpha_2(T)M_w + \alpha_3(T)\ln\left[\frac{E_1(\alpha_4(T)R) - E_1(\alpha_4(T)\sqrt{R^2+r_0^2})}{r_0^2}\right] \\ r_0^2 &= 1.4447 \times 10^{-5} e^{2.3026 M_w} \end{aligned}$$

where SA is in cm/sec^2, E1(x) is the exponential integral function. At PGA, the coefficients are as follows: α_1 = 2.4862, α_2 = 0.9392, α_3 = 0.5061, α_4 = 0.0150, b = 0.0181, σ = 0.7500 (total), σ_e = 0.4654 (inter-event) and σ_r = 0.5882 (intra-event).

Notes:

- All data are from rock (NEHRP B) sites. Data from stations with known, significant site amplification and those located in volcanic belt are excluded. Use H/V ratios to verify that stations are all on generic rock. Data from 56 different stations.
- Focal depths are between 10 and 29 km.
- Functional form is based on the analytical solution of a circular finite-source model and body waves, which also defines expression for r_0 (the radius of the circular fault based on Brune's model) using a stress drop of 100 bar in order to keep functional form as simple as possible. Note that functional form allows for oversaturation, whose existence is questionable.
- Select data of interplate, thrust-faulting events (interface) from permanent networks between 1985 and 2004 on the Pacific coast between Colima and Oaxaca (majority of data from Guerrero but some data from other regions, especially Oaxaca). Data from near-trench earthquakes whose high-frequency radiation is anomalously low are excluded. To focus on ground motions of engineering interest, exclude data from small (Mw ≤ 5.5) with few records that are only from distant stations (R > 100 km). Exclude data from > 400 km (use a larger distance than usual because of previously observed slow decay). To reduce potential variability of data, select only one record from two stations recording the same earthquake at less than 5 km (based on visual inspection of data).
- Data from 12–19 bit digital accelerographs (66% of data), which have flat response down to less than 0.1 Hz, and 24 bit broadband seismographs (34% of data), which have flat response for velocities between 0.01 and 30 Hz. Broadband data mainly from Mw < 6 and distances > 100 km. Sampling rates between 80 and 250 Hz. Instrumental responses and sampling rates mean data reliable up to 30 Hz.
- Roughly 45% of records from 20–100 km. Only 16 records from < 25 km and only 5 from 3 earthquakes with Mw > 7 and, therefore, note that any anomalous records will strongly influence

results in this distance range. State that more near-source data from large Mexican interplate earthquakes needed.

- Use Bayesian regression that accounts, for linear functions, for these correlations: (1) intra-event, (2) between coefficients and (3) between different periods. To linearize function perform regression as: for a given period and value of α_4, compute coefficients α_1, α_2 and α_3 through Bayesian analysis and iterate for different values of α_4 to find the value that gives best fit to data. This is repeated for each period. Note that this means the regression is not fully Bayesian. To obtain prior information on coefficients α_1, α_2 and α_3 use random vibration theory and theoretical expression for Fourier amplitude spectrum. Define other required prior parameters (co-variances etc.) using previous studies. Smooth α_4 w.r.t. period. Discuss differences between prior and posterior values and not that final results not over-constrained to mean prior values.
- Find that model systematically overestimates in whole period range but since less than 5% consider bias acceptable.
- Plot residuals w.r.t. Mw, distance and depth and find no significant trend. Note that even though focal depth is not included in model there is no significant dependence on it. Adjust observed near-source PGAs to a common distance of 16 km and include data from Mw 2.5 – 4.9 from R_{hypo} between 16 and 37 km. Compare to predictions. Note the large scatter (more than an order of magnitude) so note that statistical significance is low. Note that model matches observations reasonably well.

5.13 ATKINSON AND BOORE [2003]: WORLDWIDE

Functional form:

$$
\begin{aligned}
\log Y &= c_1 + c_2\mathrm{M} + c_3 h + c_4 R - g\log R + c_5\mathrm{sl}S_C + c_6\mathrm{sl}S_D + c_7\mathrm{sl}S_E \\
\text{where } R &= \sqrt{D_{\mathrm{fault}}^2 + \Delta^2} \\
\text{and } \Delta &= 0.00724\,10^{0.507\mathrm{M}} \\
\text{and sl} &= \begin{cases} 1 & \text{for} \quad \mathrm{PGA}_{rx} \le 100\,\mathrm{cms}^{-1}\mathrm{or} f \le 1\,\mathrm{Hz} \\ 1-(f-1)(\mathrm{PGA}_{rx}-100)/400 & \text{for} \quad 100 < \mathrm{PGArx} < 500\,\mathrm{cms}^{-1}(1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\ 1-(f-1) & \text{for} \quad \mathrm{PGA}_{rx} \ge 500\,\mathrm{cms}^{-1}(1\,\mathrm{Hz} < f < 2\,\mathrm{Hz} \\ 1-(\mathrm{PGA}_{rx}-100)/400 & \text{for} \quad 100 < \mathrm{PGArx} < 500\,\mathrm{cms}^{-1}(f \ge 2\,\mathrm{Hz} \\ 0 & \text{for} \quad \mathrm{PGA}_{rx} \ge 500\,\mathrm{cms}^{-1}(f \ge 2\,\mathrm{Hz}) \end{cases}
\end{aligned}
$$

Y is either PGA or PSA up to 3 s, in cm sec^{-2}, f (Hz) is frequency of interest, PGA_{rx} is predicted PGA on NEHRP site type B.

Notes:

- Use four site categories:

  B = NEHRP site class B, $V_{s,30}$ > 760 ms^{-1}, SC = 0, SD = 0 and SE = 0

  C = NEHRP site class C, 360 < $V_{s,30}$ < 760, ms^{-1} SC = 1, SD = 0 and SE = 0

  D = NEHRP site class D, 180 < $V_{s,30}$ < 360, ms^{-1} SD = 1, SC = 0 and SE = 0

  E = NEHRP site class E, $V_{s,30}$ < 180 ms^{-1}, SE = 1, SC = 0 and SD = 0.
- Classify event by type using focal depth and mechanism as: (a) in-slab, i.e., all earthquakes with normal mechanism and earthquakes with thrust mechanism at depths > 50 km or if occur on steeply dipping planes; (b) interface, i.e., earthquakes with thrust mechanism at depths < 50 km on shallow dipping planes. Exclude events of unknown type.

- Exclude events with focal depth h > 100 km.
- Exclude events that occurred within crust above subduction zones.

5.14 GARCIA *ET AL* [2005]: INTRASLAB MODEL FOR MEXICO (COMPLEMENTARY TO ARROYO *ET AL* [2010])

Functional form:

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

where Y is either PGA or PSA up to 5 s in cm sec^{-2}.

Notes:

- This GMPE does not strictly satisfy criterion 6 of Section 2 since it only applies for intraslab subduction earthquakes and not also interface events.
- All data from 51 hard (NEHRP B) sites.
- Focal depths: 35 ≤ H ≤ 138 km, most records (13 earthquakes, 249 records) from 35 ≤ H ≤ 75 km.
- Exclude data from Mw < 5.0 and R > 400 km.
- All data from intra-slab earthquakes.

5.15 KANNO *ET AL* [2006]: JAPAN

Ground-motion model is for D ≤ 30 km:

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

and for D > 30 km:

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

where pre is in cm/s^2. At PGA, coefficients are as follows: a1 = 0.56, b1 = - 0.0031, c1 = 0.26, d1 = 0.0055, a2 = 0.41, b2 = 0.0039, c2 = 1.56, σ1 = 0.37 and σ2 = 0.40.

Notes:

- Use $V_{s,30}$ to characterise site effects using correction formula: G = log(obs/pre) = p log $V_{s,30}$ + q. Derive p and q by regression analysis on residuals averaged at intervals of every 100m/sec in $V_{s,30}$. p = 0.55 and q = 1.35 for PGA. Note that the equation without site correction predicts ground motions at sites with $V_{s,30}$ ≈ 300 m/sec.
- Focal depths, D, for shallow events between 0 km and 30 km and for deep events between 30 km and about 180 km.
- Note that it is difficult to determine a suitable model form due to large variability of strong-motion data, correlation among model variables and because of coupling of variables in the model. Therefore choose a simple model to predict average characteristics with minimum parameters.

- Introduce correction terms for site effects and regional anomalies.
- Originally collect 91,731 records from 4967 Japanese earthquakes.
- Include foreign near-source data (from California and Turkey, which are compressional regimes similar to Japan) because insufficient from Japan.
- High-pass filter records with cut-off of 0.1 Hz. Low-pass filter analogue records using cut-offs selected by visual inspection.
- Choose records where: (1) Mw ≥ 5.5, (2) data from ground surface, (3) two orthogonal horizontal components available, (4) at least five stations triggered, and (5) the record passed this Mw-dependent source distance criterion: $f(Mw,X) \geq \log 10$ (for data from mechanical seismometer networks) or $f(Mw,X) \geq \log 2$ (for data from other networks) where $f(Mw,X) = 0.42Mw - 0.0033X - \log(X + 0.02510^{0.43Mw}) + 1.22$ (from a consideration of triggering of instruments).
- Examine data distributions w.r.t. amplitude and distance for each magnitude. Exclude events with irregular distributions that could be associated with a particular geological / tectonic feature (such as volcanic earthquakes).
- Do not include data from Chi-Chi 1999 earthquake because have remarkably low amplitudes, which could be due to a much-fractured continental margin causing different seismic wave propagation than normal.
- Data from 2236 different sites in Japan and 305 in other countries.
- Note relatively few records from large and deep events.
- Note that maybe best to use stress drop to account for different source types (shallow, interface or intraslab) but cannot use since not available for all earthquakes in dataset.
- Investigate effect of depth on ground motions and find that ground-motions amplitudes from earthquakes with $D > 30$ km are considerably different than from shallower events hence derive separate equations for shallow and deep events.
- Select 0.5 within function from earlier study.
- Weight regression for shallow events to give more weight to near-source data. Use weighting of 6.0 for $X \leq 25$ km, 3.0 for $25 < X \leq 50$ km, 1.5 for $50 < X \leq 75$ km and 1.0 for $X > 75$ km. Note that weighting scheme has no physical meaning.
- Note that amplitude saturation at short distances for shallow model is controlled by crustal events hence region within several tens of kilometers of large (Mw > 8.0) interface events falls outside range of data.
- Note standard deviation decreases after site correction term is introduced.
- Introduce correction to model anomalous ground motions in NE Japan from intermediate and deep earthquakes occurring in the Pacific plate due to unique Q structure beneath the island arc. Correction is: $\log(obs/pre) = (\alpha R_{tr} + \beta)(D - 30)$ where R_{tr} is shortest distance from site to Kuril and Izu-Bonin trenches. α and β are derived by regression on subset fulfilling criteria: hypocentre in Pacific plate, station E of 137° E and station has $V_{s,30}$ measurement. For PGA $\alpha = -6.73 \times 10^{-5}$ and $\beta = 2.09 \times 10^{-2}$. Find considerable reduction in standard deviation after correction. Note that R_{tr} may not be the best parameter due to observed bias in residuals for deep events.
- Examine normalised observed ground motions w.r.t. predicted values and find good match.

- Examine residuals w.r.t. distance and predicted values. Find residuals decrease with increasing predicted amplitude and with decreasing distance. Note that this is desirable from engineering point of view; however, note that it may be due to insufficient data with large amplitudes and from short distances.
- Examine total, intra-event and inter-event residuals w.r.t. D for D > 30 km. When no correction terms are used, intra-event residuals are not biased but inter-event residuals are. Find mean values of total error increase up to D = 70 km and then are constant. Find depth correction term reduces intra-event residuals considerably but increases inter-event error slightly. Overall bias improves for D < 140 km. Find site corrections have marginal effect on residuals.
- Find no bias in residuals w.r.t. magnitude.
- Response parameter is acceleration for 5% damping.
- Note the poorer correlation between residuals and $V_{s,30}$ for short periods could be due to higher modal effects or to nonlinear effects (although note that few records where nonlinear effects are likely).

5.16 LIN AND LEE [2008]: TAIWAN

Ground-motion model is:

$$\ln(y) = C_1 + C_2 M + C_3 \ln(R + C_4 e^{C_5 M}) + C_6 H + C_7 Z_t$$

where y is in g. Coefficients for PGA are: C_1 = - 2.5, C_2 = 1.205, C_3 = - 1.905, C_4 = 0.516, C_5 = 0.6325, C_6 = 0.0075, C_7 = 0.275 and σ = 0.5268 for rock sites and C_1 = - 0.9, C_2 = 1.00, C_3 = - 1.90, C_4 = 0.9918, C_5 = 0.5263, C_6 = 0.004, C_7 = 0.31 and σ = 0.6277 for soil sites.

Notes

- Use two site categories (separate equations for each):
  - Rock B and C type sites
  - Soil D and E type sites
- Use two earthquake types:
  - Interface: Shallow angle thrust events occurring at interface between subducting and overriding plates. Classified events using 50 km maximum focal depth for interface events. 12 events from Taiwan (819 records) and 5 from elsewhere (54 records). Zt = 0.
  - Intraslab: Typically high-angle normal-faulting events within the subducting oceanic plate. 32 events from Taiwan (3865 records) and 5 from elsewhere (85 records). Zt = 1.
  - Focal depths, H, between 3.94 and 30 km (for interface) and 43.39 and 161 km (for intraslab).
- Develop separate ML-Mw conversion formulae for deep (H > 50 km) and shallow events.
- Use data from TSMIP and the SMART-1 array.
- Lack data from large Taiwanese earthquake (especially interface events). Therefore, add data from foreign subduction events (Mexico, western USA and New Zealand). Note that future study should examine suitability of adding these data.
- Exclude poor-quality records by visual screening of available data. Baseline correct records.
- Weight data given the number of records from different sources (Taiwan or elsewhere).

- Focus on data from foreign events since results using only Taiwanese data are not reliable for large magnitudes. Note that should use maximum-likelihood regression method.
- Compare predicted and observed PGAs for the two best recorded events (interface Mw6.3 H = 6 km and intraslab Mw5.9 H = 39 km) and find good fit.
- Examine residuals and find that a normal distribution fits them very well using histograms.
- From limited analysis find evidence for magnitude-dependent σ but do not give details.
- Note that some events could be mislocated but that due to large distances of most data this should not have big impact on results.

5.17 MCVERRY *ET AL* [2006]: NEW ZEALAND

Ground-motion model for crustal earthquakes is:

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

Ground-motion model for subduction earthquakes is:

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

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

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

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

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

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

- Use site classes (combine A and B together and do not use data from E):
    A. Strong rock. Strong to extremely-strong rock with: a) unconfined compressive strength > 50 MPa, and b) $V_{s,30}$ > 1500 m/sec, and c) not underlain by materials with compressive strength < 18 MPa or Vs < 600 m/sec.
    B. Rock. Rock with: a) compressive strength between 1 and 50 MPa, and b) $V_{s,30}$ > 360 m/sec, and c) not underlain by materials having compressive strength < 0.8 MPa or Vs < 300 m/sec.

C. $\delta C = 1$, $\delta D = 0$ Shallow soil sites. Sites that: (a) are not class A, class B or class E sites, and (b) have low-amplitude natural period, T, ≤ 0.6 sec, or (c) have soil depths ≤ the depths listed in Table 5.1:

Table 5.1: Soil depths for different soil sites considered in the McVerry *et al* [2006] model

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

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

E. Very soft soil sites. Sites with: a) > 10 m of very soft soils with undrained shear—strength < 12.5 kPa, b) > 10 m of soils with SPT N values < 6, (c) > 10 m of soils with Vs < 150 m/sec, or (d) > 10 m combined depth of soils with properties as described in (a), (b) and (c).

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

- • Classify earthquakes in three categories:

a. Crustal Earthquakes occurring in the shallow crust of overlying Australian plate. 24 earthquakes. Classify into:
   - o Strike-slip: $-33 \le \lambda \le 33°$, $147 \le \lambda \le 180°$ or $-180 \le \lambda \le -147°$ where λ is the rake. 6 earthquakes. Centroid depths, Hc, $4 \le Hc \le 13$ km. $5.20 \le Mw \le 6.31$. CN = 0, CR = 0.
   - o Normal: $-146 \le \lambda \le -34°$. 7 earthquakes. $7 \le Hc \le 17$ km. $5.27 \le Mw \le 7.09$. CN = -1, CR = 0.
   - o Oblique-reverse: $33 \le \lambda \le 66°$ or $124 \le \lambda \le 146°$. 3 earthquakes. $5 \le Hc \le 19$ km. $5.75 \le Mw \le 6.52$. CR = 0.5, CN = 0.
   - o Reverse: $67 \le \lambda \le 123°$. 8 earthquakes. $4 \le Hc \le 13$ km. $5.08 \le Mw \le 7.23$. CR = 1, CN = 0.

b. Interface Earthquake occurring on the interface between Pacific and Australian plates with Hc < 50 km. 5 reverse and 1 strike-slip with reverse component. Use data with $15 \le Hc \le 24$ km. Classify using location in 3D space. 6 earthquakes. $5.46 \le Mw \le 6.81$. SI = 1, DS = 0.

c. Slab Earthquakes occurring in slab source zone within the subducted Pacific plate. Predominant mechanism changes with depth. 19 earthquakes. $26 \le Hc \le 149$ km. Split into shallow slab events with Hc ≤ 50 km (9 normal and 1 strike-slip, 5.17 ≤ Mw ≤ 6.23) and deep slab events with Hc > 50 km (6 reverse and 3 strike-slip, 5.30 ≤ Mw ≤ 6.69). SI = 0, DS = 1 (for deep slab events).

- Note seismicity cross sections not sufficient to distinguish between interface and slab events, also require source mechanism.
- Find that mechanism is not a significant extra parameter for motions from subduction earthquakes.
- State that model is not appropriate for source-to-site combinations where the propagation path is through the highly attenuating mantle wedge.
- Note magnitude range of New Zealand is limited with little data for large magnitudes and from short distances. Most data from d > 50 km and Mw < 6.5.
- Only include records from earthquakes with available Mw estimates because correlations between ML and Mw are poor for New Zealand earthquakes. Include two earthquakes without Mw values (Ms was converted to Mw) since they provide important data for locations within and just outside the Central Volcanic Region.
- Only include data with centroid depth, mechanism type, source-to-site distance and a description of site conditions.
- Only include records with PGA above these limits (dependent on resolution of instrument):

  1. Acceleroscopes (scratch-plates): 0.02*g*
  2. Mechanical-optical accelerographs: 0.0*g*
  3. Digital 12-bit accelerographs: 0.004 *g*
  4. Digital 16-bit accelerographs: 0.0005 *g*
- Exclude data from two sites: Athene A (topographic effect) and Hanmer Springs (site resonance at 1.5–1.7 Hz) that exhibit excessive amplifications for their site class.
- Exclude data from sites of class E (very soft soil sites with ≥≈ 10m of material with Vs < 150 m/sec) to be consistent with Abrahamson and Silva [1997] and *Youngs et al* [1997]. Not excluded because of large amplifications but because spectra appear to have site-specific characteristics.
- Exclude records from bases of buildings with > 4 storys because may have been influenced by structural response.
- Exclude data from very deep events with travel paths passing through the highly attenuating mantle.
- Only use response spectral ordinates for periods where they exceed the estimated noise levels of the combined recording and processing systems.
- Lack of data from near-source. Only 11 crustal records from distances < 25 km with 7 of these from 3 stations. To constrain model at short distances include overseas PGA data using same criteria as used for New Zealand data. Note that these data were not intended to be comprehensive for 0–10 km range but felt to be representative. Note that it is possible New Zealand earthquakes may produce PGAs at short distances different that those observed elsewhere but feel that it is better to constrain the near-source behaviour rather than predict very high PGAs using an unconstrained model.
- In order to supplement limited data from moderate- and high-strength rock and from the volcanic region, data from digital seismographs were added.
- Data corrected for instrument response.

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

- Compare predictions to observed ground motions in 21/08/2003 Fiordland interface (Mw7.2) earthquake and its aftershocks. Find ground motions, in general, underestimated.

5.18 YOUNGS *ET AL* [1997]: WORLDWIDE

Functional form:

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).

$$\ln(\mathrm{SA}/\mathrm{PGA}) = B_1 + B_2(10 - \mathbf{M})^3 + B_3 \ln \left[r_{\mathrm{rup}} + \mathrm{e}^{\alpha_1 + \alpha_2 \mathbf{M}} \right]$$

where α_1 and α_2 are set equal to C_4 and C_5 of appropriate PGA equation.

Notes:

- 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:
  - Zr = 1, Zds = 0, Zss = 0 Rock: consists of at most about a meter of soil over weathered rock, 96 records;
  - Zds = 1, Zr = 0, Zss = 0 Deep soil: depth to bedrock is greater than 20m, 284 records;
  - Zss = 1, Zds = 0, Zr = 0 Shallow soil: depth to bedrock is less than and a significant velocity contrast may exist within 30m of surface, 96 records.
- Consider tectonic type: interface (assumed to be thrust) (98 records) Zt =0, intraslab (assumed to be normal) (66 records) Zt = 1.
- Focal depths, H, between 10 and 229 km.

5.19 ZHAO *ET AL* [2006]: JAPAN

Functional form:

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

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

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

  a. Hard rock NEHRP site class A, $V_{s,30} > 1100$ m/sec. 93 records. Use C_H.

  b. SC I Rock, NEHRP site classes A+B, $600 < V_{s,30} \leq 1100$ m/sec, T < 0.2 s. 1494 records. Use C_1.

  c. SC II Hard soil, NEHRP site class C, $300 < V_{s,30} \leq 600$ m/sec, 0.2 ≤ T < 0.4 s. 1551 records. Use C_2.

  d. SC III Medium soil, NEHRP site class D, $200 < V_{s,30} \leq 300$ m/sec, 0.4 ≤ T < 0.6 s. 629 records. Use C_3.

  e. SC IV Soft soil, NEHRP site classes E+F, $V_{s,30}$ · 200 m/sec, T ¸ 0.6 s. 989 records. Use C_4.

  Site class unknown for 63 records.

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

- Classify events into three source types:

  a. Crustal.

  b. Interface. Use SI .

  c. Slab. Use SS and SSL.

  and into four mechanisms using rake angle of ±45° as limit between dip-slip and strike-slip earthquakes except for a few events where bounds slightly modified:

  a. Reverse. Use FR if also crustal event.

  b. Strike-slip

  c. Normal

  d. Unknown

- Distribution of records by source type, faulting mechanism and region is given in following Table 5.2

Table 5.2: Distribution of records by source type, faulting mechanism and region of the database used in the Zhao et al. [2006] model

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

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

- Conduct extensive analysis on inter- and intra-event residuals. Find predictions are reasonably unbiased w.r.t. magnitude and distance for crustal and interface events and not seriously biased for slab events.
- Do not smooth coefficients.
- Do not impose constraints on coefficients. Check whether coefficient is statistically significant.
- Note that the assumption of the same anelastic attenuation coefficient for all types and depths of earthquakes could lead to variation in the anelastic attenuation rate in a manner that is not consistent with physical understanding of anelastic attenuation.
- Derive C_H using intra-event residuals for hard rock sites.
- Residual analyses show that assumption of the same magnitude scaling and near-source characteristics for all source types is reasonable and that residuals not have a large linear trend w.r.t. magnitude. Find that introducing a magnitude-squared term reveals different magnitude scaling for different source types and a sizable reduction in inter-event error. Note that near-source behaviour mainly controlled by crustal data. Derive correction function from inter-event residuals of each earthquake source type separately to avoid trade-offs. Form of correction is: $\log_e(S_{MSst}) = P_{st}(Mw - MC) + Q_{st}(Mw - MC)^2 + W_{st}$. Derive using following three-step process:
  a. Fit inter-event residuals for earthquake type to a quadratic function of Mw – MC for all periods.
  b. Fit coefficients P_{st} for (Mw - MC) and Q_{st} for $(Mw - MC)^2$ (from step 1) where subscript st denotes source types, to a function up to fourth order of $\log_e(T)$ to get smoothed coefficients.
  c. Calculate mean values of differences between residuals and values of $P_{st}(Mw - MC) + Q_{st}(Mw - MC)^2$ for each earthquake, W_{st}, and fit mean values W_{st} to a function of $\log_e(T)$.
- For PGA, $Q_C = W_C = Q_I = W_I = 0$, $\tau_C = 0.303$, $\tau_I = 0.308$, $P_S = 0.1392$, $Q_S = 0.1584$, $W_S = -0.0529$ and $\tau_S = 0.321$. Since magnitude-square term for crustal and interface is not significant at short periods when coefficient for magnitude-squared term is positive, set all coefficients to zero. Find similar predicted motions if coefficients for magnitude-squared terms derived simultaneously with other coefficients even though the coefficients are different than those found using the adopted two-stage approach.
- Compare predicted and observed motions normalized to Mw7 and find good match for three source types and the different site conditions. Find model overpredicts some near-source ground motions from SC III and SC IV that is believed to be due to nonlinear effects.
- In the model update in 2010, a geometric attenuation function is proposed so that the revised model shows a large increase in the maximum likelihood from the random effects methodology, the elimination of bias in the distribution of residuals with respect to source distance, and much improved fitting for well-recorded earthquakes.
- The dataset used is the same as the 2006 models but sites not classifiable are removed; in total, 4451 strong-motion records from 248 earthquakes in Japan are used. The near-source records from California and Iran from the 2006 study are also used.
- The source distance for a large event is the shortest distance from the site to a known rupture plane, and the hypocentral distance is used for smaller events.
- The new attenuation functions for shallow crustal earthquakes (within a depth of 25 km) can be written as:

$$\begin{aligned}\log_e(y_{i,j}) &= aM_{wi} + f_{\mathrm{Cr}}(M_{wi}) - b_{\mathrm{Cr}}x_{i,j} - \log_e(r_{i,j}) \\ &- g_{\mathrm{Cr}}(r_{i,j}) - b_{\mathrm{VCr}}x_{Vi,j} + e_{\mathrm{Cr}}(h - h_c)\delta_h \\ &+ F_R\delta_R + C_k + \xi_{i,j} + \eta_i.\end{aligned}$$

where $f_{\mathrm{Cr}}(M_{\mathrm{w}}) = a_{\mathrm{Cr}}(M_{\mathrm{w}} - M_{\mathrm{C}})^2$

The additional geometric attenuation term is:

$$g_{\mathrm{Cr}}(r) = \frac{h_m - h}{h_m - h_{\mathrm{crc}}}\begin{cases} a_1 \ln(r) & \text{for } x \le x_1 \\ a_1\ln(r_1) + a_2[\ln(r) - \ln(r_1)] & \text{for } x_1 \le x < x_2 \\ a_1\ln(r_1) + a_2[\ln(r_2) - \ln(r_1)] + a_3[\ln(r) - \ln(r_2)] & \text{for } x_2 \le x < x_3 \\ a_1\ln(r_1) + a_2[\ln(r_2) - \ln(r_1)] + a_3[\ln(r_3) - \ln(r_2)] + a_4[\ln(r) - \ln(r_3)] & \text{for } x \ge x_3 \end{cases},$$

where h is the focal depth; h_m and h_{crc} are depth terms; and x_1, x_2, x_3 are distance constants. The depth scaling for the geometric attenuation term leads to $g_{Cr}(r)= 0$ when $h = h_m$ and the depth scaling term equals 1.0 when $h = h_{crc}$. Note that h_{crc} is smaller than h_m and the depth scaling term is always positive because h is always less than h_m.

The distances in the above equation are defined by:

$$r_m = x_m + c\exp(dM_{\mathrm{w}}) \qquad m = 1, 2, \text{ and } 3.$$

For shallow subduction interface earthquakes:

$$\begin{aligned}\log_e(y_{i,j}) &= aM_{wi} + f_{\mathrm{Int}}(M_{wi}) - b_{\mathrm{Int}S}x_{i,j} - b_{\mathrm{VIns}}x_{Vi,j} \\ &- \log_e(r_{i,j}) + e_{\mathrm{Int}}(h - h_c)\delta_h + C_k + S_{\mathrm{Int}} \\ &+ \xi_{i,j} + \eta_i.\end{aligned}$$

where $f_{\mathrm{Int}}(M_{\mathrm{w}}) = a_{\mathrm{Int}}(M_{\mathrm{w}} - M_{\mathrm{I}})^2$

For deep subduction interface earthquakes:

$$\begin{aligned}\log_e(y_{i,j}) &= aM_{wi} + f_{\mathrm{Int}}(M_{wi}) - b_{\mathrm{Int}D}x_{i,j} - \log_e(r_{i,j}) \\ &- b_{\mathrm{VInt}S}x_{Vi,j} + e_{\mathrm{Int}}(h - h_c)\delta_h + C_k \\ &+ S_{\mathrm{Int}} + \xi_{i,j} + \eta_i.\end{aligned}$$

where $f_{\mathrm{Slb}}(M_{\mathrm{w}}) = a_{\mathrm{Slb}}(M_{\mathrm{w}} - M_{\mathrm{S1}})(M_{\mathrm{w}} - M_{\mathrm{S2}})(M_{\mathrm{w}} - M_{\mathrm{S3}})$, $r_{i,j} = x_{i,j} + c\exp(dM_{\mathrm{w}i})$,

$$\delta_h = \begin{cases} 1 & h > h_c \\ 0 & h \le h_c \end{cases}, \quad \text{and} \quad \delta_R = \begin{cases} 1 & \text{for crustal events with reverse faulting mechanism} \\ 0 & \text{for all other crustal events} \end{cases}$$

For subduction slab earthquakes:

$$\begin{aligned}\log_e(y_{i,j}) &= aM_{wi} + f_{\mathrm{Slb}}(M_{wi}) - b_{\mathrm{Slb}}x_{i,j} - \log_e(r_{i,j}) \\ &+ g_{\mathrm{Slb1}}(r_{i,j}) + g_{\mathrm{Slb2}}(r_{i,j}) - b_{\mathrm{VSlb}}x_{Vi,j} \\ &+ e_{\mathrm{Slb}}(h - h_c)\delta_h + C_k + S_{\mathrm{Slb}} + \xi_{i,j} + \eta_i\end{aligned}$$

where $x_{Vi;j}$ is the horizontal distance passing through a volcanic zone along the straight line between the epicenterand a recording station, and b_V is the anelastic attenuation term for volcano effect. The following geometric attenuation functions are proposed for subduction slab events

$$g_{\mathrm{SIb1}}(r) = \frac{h - h_1}{h_{\mathrm{SIbc}} - h_1}\delta(h - h_1)\begin{cases} a_5 \ln(r) & \text{for } x \le x_4 \\ a_5 \ln(r_4) + a_6[\ln(r) - \ln(r_4)] & \text{for } x_4 \le x < x_5 \\ a_5 \ln(r_4) + a_6[\ln(r_5) - \ln(r_4)] + a_7[\ln(r) - \ln(r_5)] & \text{for } x \ge x_5 \end{cases}$$

and $\delta(h - h_1) = \begin{cases} 1 & h \ge h_1 \\ 0 & h < h_1 \end{cases}$, where h_1 is a depth term, h_{SIbc} is a depth constant so that the depth scaling term equals 1.0 when h = h_{SIbc}, and x_4 and x_5 are distance constants.

Also,

$$g_{\mathrm{SIb2}}(r) = \frac{h - h_2}{h_{\mathrm{SIb}d} - h_2}\begin{cases} a_8 \ln(r) & \text{for } x < x_6 \\ a_8 \ln(r_6) + a_9[\ln(r) - \ln(r_6)] & \text{for } x \ge x_6 \end{cases}$$

where h_2 is a depth term, h_{SIbd} is a depth constant such that the depth scaling term equals 1.0 when h = h_{SIbd} and x_6 is a distance constant. Note that the geometric attenuation rate changes from negative to positive when the depth of an earthquake increases from h < h_2 to h > h_2. The distance term r_m is defined by

$$r_m = x_m + c\exp(dM_{\mathrm{w}}) \qquad m = 4, 5, \text{ and} 6.$$

- Provides a table with all the depths and distance constants, which are determined by the maximum likelihood method and tested for significance (t-test). Describes the procedure to obtain significant parameters at all periods in the case of one or more parameter not significant at some period; this process involves smoothing, interpolation or extrapolation, several step regressions, application of t-test and Akaike Information Criterion.
- Notes that when a parameter necessary for eliminating bias in the residuals distribution w.r.t. to magnitude or source distance is added, the model prediction error is hardly reduced. However, it will lead to a significant increase in the maximum likelihood of the random effects model.
- Justification for the model update:
- Inspects residual w.r.t. the Tottori recordings (shallow crustal) and find that the 2006 model lead to biased residuals with the data in a distance range of 60–80 km being overpredicted on average and the data in 90–120 km being underpredicted. Ascribes the bias to the effect of the constructive interference for Moho reflection.
- Inspects residuals w.r.t. two large subduction interface earthquakes (the Tokachi earthquake in 2003, Mw 8:3 and a depth of 23 km, and one large aftershock with Mw 7:4 at a focal depth of 50 km) for the 2006 models and finds that the residuals for both shallow and deep interface events are biased for all spectral periods, with the deep events requiring a negative additional anelastic attenuation rate and the shallow interface earthquakes requiring a positive additional anelastic attenuation rate to eliminate the bias. The difference in the required attenuation rates is similar for all spectral periods, suggesting that the difference may be due to the propagation path (geometric attenuation) rather than the anelastic attenuation rate only.
- Inspects residuals w.r.t. three subduction slab earthquakes with different magnitudes and focal depths (Mw 6.8 and a focal depth of 50 km - 24 March 2001, Mw 7.03 and a focal depth of 68 km - 26 May 2003, and Mw 6.5 with a focal depth of 124 km - 2 December 2001) for 2006 model. Finds that records from deep subduction earthquakes tend to either attenuate very slowly or not

attenuate at all with increasing distance beyond some large threshold, and the threshold distance tends to decrease with increasing focal depth. Suggests a possible reason for the underprediction of the ground motion resulting from the deep slab earthquakes could be related to constructive interference between the direct arrivals of seismic waves that travel from a deep slab earthquake through the mantle with a relatively low Q, with the waves that propagate within the slab with high-Q and high shear-wave velocity and eventually come out of the slab. An alternative explanation relies on the constructive interference between the direct arrivals and the seismic waves that travel a long distance within the high-Q slab in the strike direction.

- Proposed Method of Modeling Volcanic Front: for a given record, the horizontal distance within any of the low-Q zones is computed if the straight line between the site and the hypocentral location passes through a low-Q zone. The intraevent residuals for a given period are then plotted against the computed horizontal distances within the low-Q zones. The slopes of the straight lines fitted to the residual for the different types of earthquakes represent the values of the additional anelastic attenuation rates for the volcanic paths.

PART 3 - EQUATIONS FOR ACTIVE REGIONS WITH SHALLOW CRUSTAL SEISMICITY

5.20 ABRAHAMSON AND SILVA [2008]: NGA MODEL USING WORLDWIDE DATA

Ground-motion model is:

$$
\begin{aligned}
\ln \mathrm{Sa}(\mathrm{g}) &= f_1(M, R_{rup}) + a_{12}F_{RV} + a_{13}F_{NM} + a_{15}F_{AS} + f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) \\
&\quad + F_{HW} f_4(R_{jb}, R_{rup}, R_x, W, \delta, Z_{TOR}, M) + f_6(Z_{TOR}) + f_8(R_{rup}, M) \\
&\quad + f_{10}(Z_{1.0}, V_{S30}) \\
f_1(M, R_{rup}) &= \begin{cases} a_1 + a_4(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for } M \le c_1 \\ a_1 + a_5(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) & \text{for } M > c_1 \end{cases} \\
R &= \sqrt{R_{rup}^2 + c_4^2} \\
f_5(\widehat{\mathrm{PGA}_{1100}}, V_{S30}) &= \begin{cases} a_{10}\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) - b\ln(\widehat{\mathrm{PGA}_{1100}} + c) \\ \quad + b\ln\left(\widehat{\mathrm{PGA}_{1100}} + c\left(\frac{V_{S30}^*}{V_{LIN}}\right)^n\right) & \text{for } V_{S30} < V_{LIN} \\ (a_{10} + bn)\ln\left(\frac{V_{S30}^*}{V_{LIN}}\right) & \text{for } V_{S30} \ge V_{LIN} \end{cases}
\end{aligned}
$$

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

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

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

$$
\begin{aligned}
\text{where}\quad T_1(R_{jb}) &= \begin{cases} 1-\frac{R_{jb}}{30} & \text{for} \quad R_{jb} < 30\,\mathrm{km} \\ 0 \quad \text{for} \quad R_{jb} \geq 30\,\mathrm{km} \end{cases} \\
T_2(R_x, W, \delta) &= \begin{cases} 0.5+\frac{R_x}{2W\cos(\delta)} & \text{for} \quad R_x \leq W\cos(\delta) \\ 1 \quad \text{for} \quad R_x > W\cos(\delta) \quad \text{or} \quad \delta = 90^\circ \end{cases} \\
T_3(R_x, Z_{TOR}) &= \begin{cases} 1 \quad \text{for} \quad R_x \geq Z_{TOR} \\ \frac{R_x}{Z_{TOR}} \quad \text{for} \quad R_x < Z_{TOR} \end{cases} \\
T_4(M) &= \begin{cases} 0 \quad \text{for} \quad M \leq 6 \\ M-6 \quad \text{for} \quad 6 < M < 7 \\ 1 \quad \text{for} \quad M \geq 7 \end{cases} \\
T_5(\delta) &= \begin{cases} 1-\frac{\delta-30}{60} \quad \text{for} \quad \delta \geq 30 \\ 1 \quad \text{for} \quad \delta < 30 \end{cases} \\
f_6(Z_{TOR}) &= \begin{cases} \frac{a_{16}Z_{TOR}}{10} \quad \text{for} \quad Z_{TOR} < 10\,\mathrm{km} \\ a_{16} \quad \text{for} \quad Z_{TOR} \geq 10\,\mathrm{km} \end{cases} \\
f_8(R_{rup}, M) &= \begin{cases} 0 \quad \text{for} \quad R_{rup} < 100\,\mathrm{km} \\ a_{18}(R_{rup}-100)T_6(M) \quad \text{for} \quad R_{rup} \geq 100\,\mathrm{km} \end{cases} \\
\text{where}\quad T_6(M) &= \begin{cases} 1 \quad \text{for} \quad M < 5.5 \\ 0.5(6.5-M)+0.5 \quad \text{for} \quad 5.5 \leq M \leq 6.5 \\ 0.5 \quad \text{for} \quad M > 6.5 \end{cases}
\end{aligned}
$$

$$
\begin{aligned}
f_{10}(Z_{1.0}, V_{S30}) &= a_{21}\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}(V_{S30})+c_2}\right) + \begin{cases} a_{22}\ln\left(\frac{Z_{1.0}}{200}\right) \quad \text{for} \quad Z_{1.0} \geq 200 \\ 0 \quad \text{for} \quad Z_{1.0} < 200 \end{cases} \\
\text{where}\quad \ln[\hat{Z}_{1.0}(V_{S30})] &= \begin{cases} 6.745 \quad \text{for} \quad V_{S30} < 180\,\mathrm{m/s} \\ 6.745-1.35\ln\left(\frac{V_{S30}}{180}\right) \quad \text{for} \quad 180 \leq V_{S30} \leq 500\,\mathrm{m/s} \\ 5.394-4.48\ln\left(\frac{V_{S30}}{500}\right) \quad \text{for} \quad V_{S30} > 500\,\mathrm{m/s} \end{cases} \\
a_{21} &= \begin{cases} 0 \quad \text{for} \quad V_{S30} \geq 1000 \\ \frac{-(a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right)}{\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right)} \quad \text{for} \quad (a_{10}+bn)\ln\left(\frac{V_{S30}^*}{\min(V_1,1000)}\right)+e_2\ln\left(\frac{Z_{1.0}+c_2}{\hat{Z}_{1.0}+c_2}\right) < 0 \\ e_2 \quad \text{otherwise} \end{cases} \\
e_2 &= \begin{cases} 0 \quad \text{for} \quad T < 0.35\,\mathrm{s} \quad \text{or} \quad V_{S30} > 1000 \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{T}{0.35}\right) \quad \text{for} \quad 0.35 \leq T \leq 2\,\mathrm{s} \\ -0.25\ln\left(\frac{V_{S30}}{1000}\right)\ln\left(\frac{2}{0.35}\right) \quad \text{for} \quad T > 2\,\mathrm{s} \end{cases} \\
a_{22} &= \begin{cases} 0 \quad \text{for} \quad T < 2\,\mathrm{s} \\ 0.0625(T-2) \quad \text{for} \quad T \geq 2\,\mathrm{s} \end{cases}
\end{aligned}
$$

The model for the standard deviation is:

$$
\begin{aligned}
\sigma_B(M,T) &= \sqrt{\sigma_0^2(M,T)-\sigma_{Amp}^2(T)} \\
\sigma(T,M,\widehat{\mathrm{PGA}}_{1100},V_{S30}) &= \begin{bmatrix} \sigma_B^2(M,T)+\sigma_{Amp}^2(T) \\ +\left(\frac{\partial \ln \mathrm{Amp}(T,\widehat{\mathrm{PGA}}_{1100},V_{S30})}{\partial \ln \mathrm{PGA}_{1100}}\right)^2 \sigma_B^2(M,\mathrm{PGA}) \\ +2\left(\frac{\partial \ln \mathrm{Amp}(T,\widehat{\mathrm{PGA}}_{1100},V_{S30})}{\partial \ln \mathrm{PGA}_{1100}}\right) \\ \times\sigma_B(M,T)\sigma_B(M,\mathrm{PGA})\rho_{\epsilon/\sigma}(T,\mathrm{PGA}) \end{bmatrix}^{1/2} \\
\frac{\partial \ln \mathrm{Amp}(T,\widehat{\mathrm{PGA}}_{1100},V_{S30})}{\partial \ln \mathrm{PGA}_{1100}} &= \begin{cases} 0 \quad \text{for} \quad V_{S30}\geq V_{LIN} \\ \frac{-b(T)\widehat{\mathrm{PGA}}_{1100}}{\widehat{\mathrm{PGA}}_{1100}+c}+\frac{-b(T)\widehat{\mathrm{PGA}}_{1100}}{\widehat{\mathrm{PGA}}_{1100}+c\left(\frac{V_{S30}}{V_{LIN}}\right)^n} \quad \text{for} \quad V_{S30}<V_{LIN} \end{cases} \\
\sigma_0(M) &= \begin{cases} s_1 \quad \text{for} \quad M<5 \\ s_1+\left(\frac{s_2-s_1}{2}\right)(M-5) \quad \text{for} \quad 5\leq M\leq 7 \\ s_2 \quad \text{for} \quad M>7 \end{cases} \\
\tau_0(M) &= \begin{cases} s_3 \quad \text{for} \quad M<5 \\ s_3+\left(\frac{s_4-s_3}{2}\right)(M-5) \quad \text{for} \quad 5\leq M\leq 7 \\ s_4 \quad \text{for} \quad M>7 \end{cases}
\end{aligned}
$$

where Sa is in g, PGAˆ$_{1100}$ is median peak acceleration for $V_{S,30}$ = 1100 m/sec, σ_B and τ_B (= $\tau_0(M, T)$) are intra-event and inter-event standard deviations, σ_0 and τ_0 are intra-event and inter-event standard deviations of the observed ground motions for low levels of outcrop rock motions (directly from regression), σ_{amp} is intra-event variability of the site amplification factors (assumed equal to 0.3 for all periods based on 1D site response results).

Notes:

- At PGA, coefficients are the following: c_1 = 6.75, c_4 = 4.5, a_3 = 0.265, a_4 = -0.231, a_5 = -0.398, N = 1.18, c = 1.88, c_2 = 50, V_{LIN} = 865.1, b = -1.186, a_1 = 0.804, a_2 = -0.9679, a_8 = -0.0372, a_{10} = 0.9445, a_{12} = 0.0000, a_{13} = -0.0600, a_{14} = 1.0800, a_{15} = -0.3500, a_{16} = 0.9000, a_{18} = -0.0067, s_1 = 0.590 and s_2 = 0.470 for $V_{S,30}$ estimated, s1 = 0.576 and s_2 = 0.453 for $V_{S,30}$ measured, s_3 = 0.470, s_4 = 0.300 and ρ(T, PGA) = 1.000.
- Characterise sites using $V_{S,30}$ and depth to engineering rock (V_s = 1000 m/sec), $Z_{1.0}$.
- Prefer $V_{S,30}$ to generic soil/rock categories because it is consistent with site classification in current building codes. Note that this does not imply that 30 m is key depth range for site response but rather that $V_{S,30}$ is correlated with entire soil profile.
- Classify events in three fault mechanism categories:
- FRV = 1, FNM = 0 Reverse, reverse/oblique. Earthquakes defined by rake angles between 30 and 150±.
- FRV = 0, FNM = 1 Normal. Earthquakes defined by rake angles between -60 and -120°.
- FRV = 0, FNM = 0 Strike-slip. All other earthquakes.
- Believe that model applicable for 5 ≤ Mw ≤ 8.5 (strike-slip) and 5 ≤ Mw ≤ 8.0 (dip-slip) and 0 ≤ dr ≤ 200 km.
- Use simulations for hard-rock from 1D finite-fault kinematic source models for 6.5 ≤ Mw ≤ 8.25, 3D basin response simulations for sites in southern California and equivalent- linear site response simulations to constrain extrapolations beyond the limits of the empirical data.
- Select data from the Next Generation Attenuation (NGA) database (flat-file version 7.2).

- Include data from all earthquakes, including aftershocks, from shallow crustal earthquakes in active tectonic regions under assumption that median ground motions from shallow crustal earthquakes at dr < 100 km are similar. This assumes that median stress-drops are similar between shallow crustal events in: California, Alaska, Taiwan, Japan, Turkey, Italy, Greece, New Zealand and NW China. Test assumption by comparing inter-event residuals from different regions to those from events in California. Since aim is for model for California and since difference in crustal structure and attenuation can affect ground motions at long distances exclude data from dr > 100 km from outside western United States.
- Also exclude these data: events not representative of shallow crustal tectonics, events missing key source metadata, records not representative of free-field motion, records without a $V_{S,30}$ estimate, duplicate records from co-located stations, records with missing horizontal components or poor quality accelerograms and records from western USA from dr > 200 km.
- Classify earthquakes by event class: AS (aftershock) (FAS = 1); MS (mainshock), FS (foreshock) and swarm (FAS = 0). Note that classifications not all unambiguous.
- Use depth-to-top of rupture, Z_{TOR}, fault dip in degrees, δ and down-dip rupture width, W.
- Use r_{jb} and R_x (horizontal distance from top edge of rupture measured perpendicular to fault strike) to model hanging wall effects. For hanging wall sites, defined by vertical projection of the top of the rupture, F_{HW} = 1. T_1, T_2 and T_3 constrained by 1D rock simulations and the Chi-Chi data. T_4 and T_5 constrained by well-recorded hanging wall events. Only a14 was estimated by regression. State that hanging-wall scaling is one of the more poorly-constrained parts of model14. Model for T_5 reported here is that given in 2009 errata. In original reference: $T_5 = 1-(\delta -70)/20$ for $\delta \geq 70$ and 1 otherwise).
- Records well distributed w.r.t. Mw and r_{rup}.
- For four Chi-Chi events show steep distance decay than other earthquakes so include a separate coefficient for the ln(R) term for these events so they do not have a large impact on the distance scaling. Retain these events since important for constraining other aspects of the model, e.g., site response and intra-event variability.
- Only used records from $5 \leq M \leq 6$ to derive depth-to-top of rupture (Z_{TOR}) dependence to limit the effect on the relation of the positive correlation between Z_{TOR} and M.
- Constrain (outside the main regression) the large distance (R_{rup} > 100 km) attenuation for small and moderate earthquakes ($4 \leq M \leq 5$) using broadband records of 3 small (M4) Californian earthquakes because limited data for this magnitude-distance range in NGA data set.
- Note difficult in developing model for distinguishing between shallow and deep soil sites due to significant inconsistencies between $V_{S,30}$ and depth of soil ($Z_{1.0}$), which believe to be unreliable in NGA Flat-File. Therefore, develop soil-depth dependence based on 1D (for $Z_{1.0}$ < 200 m) and 3D (for $Z_{1.0}$ > 200 m) site response simulations. Motion for shallow soil sites do not fall below motion for $V_{S,30}$ = 1000 m/sec.
- T_D denotes period at which rock ($V_{S,30}$ = 1100 m/sec) spectrum reaches constant displacement.
- Using point-source stochastic model and 1D rock simulations evaluate magnitude dependence of T_D as log10(TD) = -1.25 + 0.3M. For T > T_D compute rock spectral acceleration at T_D and then scale this acceleration at T_D by $(T_D/T)^2$ for constant spectral displacements. The site response and soil depth scaling is applied to this rock spectral acceleration, i.e.,

$$\mathrm{Sa}(T_D, V_{S30} = 1100)\frac{T_D^2}{T^2} + f_5(\mathrm{PG\hat{A}}_{1100}, V_{S30}, T) + \quad f_{10}(Z_{1.0}, V_{S30}, T)$$

- Reduce standard deviations to account for contribution of uncertainty in independent parameters M, R_{rup}, Z_{TOR} and $V_{S,30}$.
- Note that regression method used prevents well-recorded earthquakes from dominating regression.
- Examine inter-event residuals and find that there is no systemic trend in residuals for different regions. Find that residuals for M > 7.5 are biased to negative values because of full-saturation constraint. Examine intra-event residuals and find no significant trend in residuals.
- Although derive hanging-wall factor only from reverse-faulting data suggest that it is applied to normal-faulting events as well.
- State that should use median PGA_{1100} for nonlinear site amplification even if conducting a seismic hazard analysis for above median ground motions.
- State that if using standard deviations for estimated $V_{S,30}$ and $V_{S,30}$ is accurate to within 30% do not need to use a range of $V_{S,30}$ but if using measured-$V_{S,30}$ standard deviations then uncertainty in measurement of $V_{S,30}$ should be estimated by using a range of $V_{S,30}$ values.
- State that if do not know $Z_{1.0}$ then use median $Z_{1.0}$ estimated from equations given and do not adjust standard deviation.

5.21 AKKAR AND BOMMER [2010]: MODEL USING MEDITERRANEAN AND MIDDLE EASTERN DATA

Ground-motion model is:

$$\log y = b_1 + b_2 M + b_3 M^2 + (b_4 + b_5 M)\log\sqrt{R_{\mathrm{jb}}^2 + b_6^2} + b_7 S_S + b_8 S_A + b_9 F_N + b_{10} F_R$$

where y is in cm/sec^2. At PGA, coefficients are as follows: b_1 = 1.04159, b_2 = 0.91333, b_3 = -0.08140, b_4 = -2.92728, b_5 = 0.28120, b_6 = 7.86638, b_7 = 0.08753, b_8 = 0.01527, b_9 = -0.04189, b_{10} = 0.08015, σ1 = 0.2610 (intra-event) and σ2 = 0.0994 (inter-event).

Notes:

- Use three site categories:
  a. Soft soil S_S = 1, S_A = 0.
  b. Stiff soil S_A = 1, S_S = 0.
  c. Rock S_S = 0, S_A = 0.
- Use three faulting mechanism categories:
  d. Normal F_N = 1, F_R = 0.
  e. Strike-slip F_N = 0, F_R = 0.
  f. Reverse F_R = 1, F_N = 0.
- Use same data as Akkar and Bommer [2007] but repeat regression analysis for pseudo-spectral acceleration (rather than for spectral displacement), assuming homoscedastic variability, reporting the coefficients to five decimal places and not applying any smoothing. These changes made due to shortcomings revealed in GMPEs of Akkar and Bommer [2007] after their use in various projects that required, for example, extrapolation outside their magnitude range of applicability

- Examine total, inter- and intra-event residuals w.r.t. Mw and r_{jb} and found no apparent trends (shown for a selection of periods). Note that some plots suggest magnitude-dependent variability but insufficient data to constrain it.
- Response parameter is pseudo-acceleration for 5% damping.
- Derive equations up to 4 s but only report coefficients to 3 sec because of a significant drop in available data at this period and because of the related issue of a sudden change in σ (particularly intra-event σ) at 3.2 sec.

5.22 BOORE AND ATKINSON [2008] AS MODIFIED BY ATKINSON AND BOORE [2011]: NGA MODEL USING WORLDWIDE DATA

Functional form:

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

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

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

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

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

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

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

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

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

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

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

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

where is either PGA in , PGV in cm sec^{-2} or PSA(T;5%) in g up to 10 sec. M_h = 6.75 hinge magnitude), V_{ref} = 760 $msec^{-1}$(specified reference velocity corresponding to the NEHRP B/C boundary), a_1 = 0.03*g* (threshold for linear amplification), a_2 = 0.09*g* (threshold for nonlinear amplification), pga_low = 0.06*g* (for transition between linear and nonlinear behaviour), pga4nl is predicted PGA in g for V_{ref} with $F_s = 0$, $V_1 = 180\ ms^{-1}$, $V_2 = 300\ m\ sec^{-1}$.

Notes:

- Characterise sites using $Vs_{,30}$. Believe equations applicable for $180 < Vs_{,30} \leq 1300\ m\ sec^{-1}$. Bulk of data from NEHRP C and D sites (soft rock and firm soil) and very few data from A sites (hard rock).
- Focal depths between 2and 31 km with most < 20 km.
- Use three faulting mechanism categories using P and T axes:
  a. SS Strike-slip. Plunges of T and P axes , 40^o. 35 earthquakes. Dips between 55 and 90^o. $4.3 \leq M \leq 7.9$. SS = 1, U = 0, NS = 0, RS = 0.
  b. RS Reverse. Plunge of T axis > 40^o. 12 earthquakes. Dips between 12 and 70^o. $5.6 \leq M \leq 7.6$. RS = 1, U = 0, SS = 0 , NS = 0.
  c. NS Normal. Plunge of P axis > 40^o. 11 earthquakes. Dips between 30 and 70^o. $5.3 \leq M \leq 6.9$. NS = 1, RS = 0, U = 0, SS = 0.
- Exclude singly-recorded earthquakes.
- Use estimated s for earthquakes with unknown fault geometries.
- Lack of data at close distances for small earthquakes.
- Three events (1987 Whittier Narrows, 1994 Northridge and 1999 Chi-Chi) contribute large proportion of records (7%, 10%, and 24%).
- Believe that models provide a useful alternative to more complicated NGA models as they are easier to implement in many applications.
- Constant number of records to 1 sec, slight decrease at 2 sec and a rapid fall off in number of records for periods > 2 sec.
- For long periods very few records for small earthquakes (M < 6.5) at any distance so magnitude scaling at long periods poorly determined for small events.
- No data from normal-faulting events for 7.5 sec so assume ratio of motions for normal and unspecified faults is same as for 10 sec.
- Chi-Chi data major controlling factor for predictions for periods > 5 sec even for small events.

Revision for the 2011 models: the revisions for WNA affect only those events with **M** ≤ 5.75.

- Uses SMM (small-to-moderate magnitude) database, contains the geometric mean of the horizontal-component response spectra (PSA, the 5% damped pseudo-acceleration) at 3 periods (0.3, 1 and 3 sec), and peak ground acceleration (PGA) and velocity (PGV). Use prediction for unknown focal mechanism because this information is unknown for many of the SMM events.
- Use the geometric mean of the horizontal components because it is assumed, on average, to be equivalent to the orientation-independent horizontal-component mean used in the NGA database (Boore, 2010).
- Adjustments to the BA08 equations obtained from the Referenced Empirical Approach [Atkinson, 2008], by using the ratio
- (Observed / Predicted) with the distance range $R_{jb} \leq 100$ km as a multiplier on the BA08 GMPE.
- The frequency-independent model which represents the residual trends is:

$\log FBA08 = a - b \log(R_{jb}+10)$

where a controls the near-source level of the residual in log units, b controls the decay slope with distance, and the "+10" mimics the observed amplitude saturation at close distances.

- For **M** > 5.75, note that $a = b = 0$, indicating that no adjustment to the BA08 equations is required at higher magnitudes. Thus the adjusted BA08 equations (BA08'), which can be used to predict ground-motion amplitudes for California events of **M** ≥ 3.5 (Y') are simply:

  Y' = Y FBA08

  where Y' is the adjusted ground motion parameter value (PSA at a specific period, or PGA or PGV), Y is the predicted amplitude according to BA08, and the multiplicative function FBA08 is specified (in log10 units) by the following equation, which has a truncated linear form (on a log scale) with saturation at close distances:

  $\log FBA08 = \max(0, 3.888-0.674\mathbf{M}) - \max(0, 2.933-0.510\mathbf{M}) \log(Rjb+10)$

5.23 CAMPBELL AND BOZORGNIA [2008]: NGA MODEL USING WORLDWIDE DATA

Functional form:

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

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

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

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

$$f_{fltZ} = \begin{cases} Z_{TOR} & for \;\; Z_{TOR} < 1 \\ 1 & for \;\; Z_{TOR} \geq 1 \end{cases}$$

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

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

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

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

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

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

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

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

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

where is either PGA in , PGV in cm sec^{-2}, PGD in cm or PSA(T;5%) in *g*.

$\sigma_{\ln Y_B} = (\sigma_{\ln Y}^2 - \sigma_{\ln AF}^2)^{1/2}$ is standard deviation at base of site profile. Assume that $\sigma_{\ln AF} \approx 0.3$ based on previous studies for deep soil sites. $\sigma_{Arb} = \sqrt{\sigma_T^2 + \sigma_C^2}$ for estimating aleatory uncertainty of arbitrary horizontal component.

Notes:

- Characterise sites using $V_{S,30}$. Account for nonlinear effects using A_{1100}, median estimated PGA on reference rock outcrop ($V_{S,30}$ = 1100 ms^{-1}) in g. Believe model applicable for $V_{S,30}$ 150 – 1500 m sec^{-1} .

- Use depth to 2.5 km sec^{-1} shear-wave velocity horizon (basin or sediment depth) in kilometers, $Z_{2.5}$. Note high correlation between $Vs_{,30}$ and $Z_{2.5}$. Provide relationships for predicting $Z_{2.5}$ based on other site parameters. Believe model applicable for $Z_{2.5}$ 0 – 10 km.
- Use three faulting mechanism categories based on rake angle λ:
  a. Reverse and reverse-oblique: $30 < \lambda < 150^o$. 17 earthquakes. $F_{RV} = 1$ and $F_{NM} = 0$.
  b. Normal and normal-oblique: $-150 < \lambda < 30^o$. 11 earthquakes. $F_{NM} = 1$ and $F_{RV} = 0$.
  c. Strike-slip: All other rake angles. 36 earthquakes. $F_{RV} = 0$ and $F_{NM} = 0$
- Use data from PEER Next Generation Attenuation (NGA) Flatfile.
- Include depth to top of coseismic rupture plane, Z_{TOR}, which find important for reverse-faulting events. Believe model applicable for Z_{TOR} 0 – 15 km; for default options on the Z_{TOR} values, the following table 5.3 can be used [Harmsen and Zeng, 2008], well suited for logic trees in PSHAs.

Table 5.3: Default options on the Z_{TOR} values

Magnitude range	Pr [ztor=0]	Pr [ztor=2 km]	Pr [ztor=4 km]
6.5≤M≤6.75	0.333	0.333	0.333
6.75<M≤7.0	0.5	0.5	0
7.0 < M	1.0	0	0

- Include dip of rupture plane, δ. Believe model applicable for δ 15 – 90^o.
- If PSA < PGA for T ≤ 0.25 sec then set PSA equal to PGA, to be consistent with definition of PSA (occurs for large distances and small magnitudes).
- Due to cut-off frequencies used number of records available for periods > 4 – 5 sec falls off significantly. Majority of earthquakes at long periods are for and 6.5 ≤ M ≤ 7.9, and 70% are from 1999 Chi-Chi earthquake.
- To extend model to longer periods and small magnitudes constrain the magnitude-scaling term using empirical observations and simple seismological theory.

5.24 CAUZZI AND FACCIOLI [2008]: UPDATED BY FACCIOLI *ET AL* [2010]: MODEL USING WORLDWIDE DATA (MAINLY JAPANESE)

Functional form:

$$\log_{10} y = a_1 + a_2 M_w + a_3 \log_{10} R + a_B S_B + a_C S_C + a_D S_D$$

where is either PGA in ms^{-2} or DRS(T;ζ) up to 20s.

Notes:

- R is hypocentral distance. There is no saturation term. Hence, at short distances the GMPE should strictly be used in the range constrained by data, i. e. R ≥ 15 km irrespective of magnitude.
- Use four site categories based on Eurocode 8: Rock-like $Vs_{,30} \geq 800$ m sec^{-1}, $S_B = S_C = S_D = 0$. Stiff ground $360 \leq Vs_{,30} < 800$ m sec^{-1} , $S_B = 1$ $S_C = S_D = 0$. Very soft ground $Vs_{,30} < 180$ m sec^{-1}, $S_D = 1$ $S_B = S_C = 0$.
- Use mechanism classification scheme of Boore and Atkinson [2007] based on plunges of P-, T- and B-axes: Normal 16 earthquakes. 5 ≤ M ≤ 6.9. Strike-slip 32 earthquakes. 5 ≤ M ≤ 7.2. Reverse 12 earthquakes. 5.3 ≤ M ≤ 6.6.

- Developed for use in displacement-based design.
- Select records with minimal long-period noise so that the displacement ordinates are reliable. Restrict selection to digital records because their displacement spectra are not significantly affected by correction procedure and for which reliable spectral ordinates up to at least 10s are obtainable. Include 9 analogue records from 1980 Irpinia (M_w 6.9) earthquake after careful scrutiny of long-period characteristics.
- Use data from K-Net and Kik-Net (Japan) (84%); California (5%); Italy, Iceland and Turkey (5%); and Iran (6%). Try to uniformly cover magnitude-distance range of interest. All data from M > 6.8 are from events outside Japan.
- Exclude data from subduction zone events.
- Focal depths between 2 and 22 km. Exclude earthquakes with focal depth > 22 km to be in agreement with focal depths of most Italian earthquakes.
- Consider style-of-faulting by adding terms: $a_N E_N + a_R E_R + a_S E_S$ where E_x are dummy variables for normal, reverse and strike-slip mechanisms.
- Replace terms: $a_B S_B + a_C S_C + a_D S_D$ by $b_V \log_{10}(V_{s,30}/V_a)$ so that site amplification factor is continuous. $V_{s,30}$ available for about 85% of records. To be consistent between both approaches constrain V_a to equal 800 m sec^{-1}. Find b_v closely matches theoretical values 1 close to resonance period and 0.5 at long periods.
- Provide equations for DRS(T) prediction for 5, 10, 20 and 30% damping and report as Electronic Supplementary Material.
- In the Faccioli et al. [2010] update:
- Ground-motion model is:

$$\begin{aligned}\log_{10}\mathrm{DRS}(T) &= a_1 + a_2 M_w + a_3 \log_{10}(R_{rup} + a_4 10^{a_5 M_w}) \\ &\quad + a_B S_B + a_C S_C + a_D S_D + a_N E_N + a_R E_R + a_S E_S\end{aligned}$$

  where DRS(T) is in cm/sec^2. At PGA, a1 = -1.18, a2 = 0.559, a3 = -1.624, a4 = 0.018, a5 = 0.445, aB = 0.25, aC = 0.31, aD = 0.33, aN = -0.01, aR = 0.09, aS = -0.05, k1 = 2.03, k2 = -0.138, k3 = -0.962 and σ = 0.3616.
- Use four Eurocode 8 classes:
  a. Rock. $S_B = S_C = S_D = 0$.
  b. Stiff soil. $S_B = 1$, $S_C = S_D = 0$.
  c. Medium-dense soil deposits. $S_C = 1$, $S_B = S_D = 0$.
  d. Soft soil deposits. $S_D = 1$, $S_B = S_C = 0$.
- Use three faulting mechanisms:
  a. Normal $E_N = 1$, $E_R = E_S = 0$.
  b. Reverse $E_R = 1$, $E_N = E_S = 0$.
  c. Strike-slip $E_S = 1$, $E_N = E_R = 0$.
- Update of Cauzzi and Faccioli [2008] using more data and r_{rup} rather than r_{hypo} because this is more appropriate close to large earthquakes.
- Find that differences between r_{rup} and r_{hypo} are not statistically significant for Mw ≤ 5.7 so use r_{hypo} below this threshold.

- Most data from Japan.
- Use a subset of data to decide on the best functional form, including forms with Mw^2 and/or distance-saturation terms and site classes or $V_{S,30}$ directly.
- Carefully examine (not show) fit between predicted and observed spectra in near-source region and find distance-saturation term provides best fit.
- Note that Mw^2 term has negligible impact on σ but improves predictions for large Mw.
- Drops Mw^2 from final functional form.
- Find site terms significantly reduce σ.
- Effect of style of faulting terms on σ is minimal but does improve predictions.
- Note that functional form means that one-step rather than two-step approach must be used that means that effects of magnitude and distance cannot be decoupled and σ's are larger.
- Compare predictions and observations for two records and find overprediction in one case and underprediction in other, which relate to the approximation of the model and not an error in determination of coefficients.
- Test model against data (4.5 ≤ Mw ≤ 6.9, r_{rup} < 150 km) from the Italian Accelerometric Archive (ITACA) using residual plots and method of Scherbaum *et al* [2004].
- Find that good ranking is obtained using approach of Scherbaum et al. [2004]. Find trends in residual plots, which correct using functions, with coefficients k1, k2, and k3, fit to the residuals. ki can be added to ai to obtain corrected coefficients (a4 and a5 are unchanged).
- Note that improvements to Cauzzi and Faccioli [2008] are still on going.

5.25 CHIOU AND YOUNGS [2008]: NGA MODEL USING WORLDWIDE DATA

Functional form:

$$\begin{aligned}\ln(y) &= \ln(y_{ref}) + \phi_1 \min\left[\ln\left(\frac{V_{S30}}{1130}\right), 0\right] \\ &+ \phi_2 \{e^{\phi_3[\min(V_{S30},1130)-360]} - e^{\phi_3(1130-360)}\} \ln\left(\frac{y_{ref}e^{\eta} + \phi_4}{\phi_4}\right) \\ &+ \phi_5 \left\{1 - \frac{1}{\cosh[\phi_6 \max(0, Z_{1.0} - \phi_7)]}\right\} + \frac{\phi_8}{\cosh[0.15\max(0, Z_{1.0} - 15)]}\end{aligned}$$

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

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

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

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

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

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

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

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

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

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

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

where is either PGA in , PGV in cm sec^{-2} or PSA(T) up to 10 sec. σ_T is the total variance for ln(y) and is approximate based on the Taylor series expansion of the sum of the interevent and intra-event variances. σ_{NL0} is the equation for evaluated for η = 0.

Notes:

- Characterise sites using $Vs_{,30}$. $F_{Inferred}$ = 1 if $Vs_{,30}$ inferred from geology and 0 otherwise. $F_{Measured}$ = 1 if $Vs_{,30}$ is measured and 0 otherwise. Believe model applicable for $Vs_{,30}$ 150 – 1500 m sec^{-1}.

  Use depth to shear-wave velocity of 1.0 km sec^{-1}, $Z_{1.0}$, to model effect of near-surface sediments since 1 km/sec similar to values commonly used in practice for rock, is close to reference $Vs_{,30}$ and depth to this velocity more likely to be available. For stations without $Z_{1.0}$ use this empirical relationship: $\ln(Z_{1.0}) = 28.5 - \frac{3.82}{8}\ln(V_{S30}^8 + 378.7^8)$

- Focal depths less than 20 km and $Z_{1.0} \leq 15$ km. Therefore note that application to regions with very thick crusts is extrapolation outside range of data used to develop model. For guidance on Z_{TOR} use table given in notes under GMPEs by Campbell and Bozorgnia [2008].

- Include data from aftershocks, because they provide additional information on site model coefficients, allowing for systematic differences in ground motions with mainshock motions. AS =1 if event aftershock and 0 otherwise.

- Choose reference site $Vs_{,30}$ to be 1130 m sec^{-1} because expected that no significant nonlinear site response at that velocity and very few records with $Vs_{,30}$ > 1100 m sec^{-1} in NGA database. Functional form adopted for nonlinear site response able to present previous models from empirical and simulation studies.

5.26 KANNO ET AL. [2006]: MODEL USING MAINLY JAPANESE DATA

See section 5.15

5.27 MCVERRY *ET AL* [2006]: MODEL USING MAINLY NEW ZEALAND DATA

See section 5.17.

5.28 ZHAO *ET AL* [2006]: MODEL USING MAINLY JAPANESE DATA

See Section 5.19.

PART 4: EQUATIONS FOR VOLCANIC ZONES

5.29 DE NATALE *ET AL* 1988 AS PARAMETERIZED BY FACCIOLI *ET AL* [2010B]: STOCHASTIC MODEL FOR CAMPI FLEGREI, ITALY, AND SHALLOW-FOCUS EARTHQUAKES IN VOLCANIC ZONES IN EUROPE

De Natale *et al* [1988] analyzed 40 digitally recorded velocity histories of small earthquakes with 0.7≤ *ML*≤ 3.2, at distances of few km (typically 3 to 6 km) in the “Campi Flegrei” area (near Naples, Italy), and were able to accurately reproduce the observed PGA and PGV dependence on seismic moment through the stochastic method of Boore *et al* [1983].

Faccioli *et al* [2010b] carried out numerical simulations consistently with De Natale *et al* [1988] approach, by simulating 350 accelerograms for each magnitude-distance pair, where they sampled 21 hypocentral distances between 0.01 and 78 km (the intervals are constant in the log(*R*)] and 4 magnitude values (3.5, 4, 4.5, and 5). The simulations adopt distance decay as *1/r*, stress drop values, Δσ, between 5 and 90 bar, an S wave velocity β of 2.0 km/sec and a high frequency decay *e-πκf* with κ = 0.015. For each magnitude, distance and Δσ value, 50 accelerograms were generated.

Seven Δσ values were chosen in the indicated range, by analyzing strong-motion records (appropriately selected) available for volcanic zones in Central and Southern Italy. Majority of the sites are on category EC8 A (only one site is on deep soil sediments).

They produced attenuation tables appropriate for shallow-focus earthquakes in volcanic zones of Europe, to be used by the SHARE WP4, and provided a table with values of sigma, which is considered to be a function of period and of magnitude.

They compared the median attenuation with the Faccioli *et al* [2010a] curves and fpimd a good agreement at Mw 4 up to 20 km of focal distance. It can be assumed, therefore, that the simulation procedure adopted [De Natale *et al*, 1988] may not be suitable for focal distances higher than about 20 km.

5.30 MCVERRY *ET AL* [2006]: NEW ZEALAND

See Section 5.17

5.31 ZHAO *ET AL* [2006]: MODEL USING MAINLY JAPANESE DATA

See Section 5.19

References

Abrahamson N.A., Silva W.J. [2008] "Summary of the Abrahamson and Silva NGA ground-motion relations," *Earthquake Spectra*, Vol. 24, pp. 67–97.

Akkar S., Bommer J.J. [2010] "Empirical equations for the prediction of PGA, PGV and spectral accelerations in Europe, the Mediterranean region and the Middle East," *Seismological Research Letters*, Vol. 81, No. 2, pp. 195–206.

Allen T., Wald D.J. [2009] "On the use of high-resolution topographic data as a proxy for seismic site conditions (VS30)," *Bulletin of the Seismological Society of America*, Vol. 99, No. 2A, pp. 935-943.

Ang H.S., Tang W.H. [1975] *Probability Concepts in Engineering Planning and Design*, Vol. I, John Wiley and Sons, Inc., New York, Hyd. Div. Proc. ASCE

Arroyo D., García D., Ordaz M., Mora M.A., Singh S.K. [2010] "Strong ground-motion relations for Mexican interplate earthquakes," *Journal of Seismology*, Vol. 14, No. 4, pp. 769–785.

Atkinson G.M. [2008] "Ground-motion prediction equations for eastern North America from a referenced empirical approach: Implications for epistemic uncertainty," *Bulletin of the Seismological Society of America*, Vol. 98, No. 3, pp. 1304–1318.

Atkinson G.M. [2010] "Ground-motion prediction equations for Hawaii from a referenced empirical approach," *Bulletin of the Seismological Society of America*, Vol. 100, No. 2, pp. 751–761.

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*, Vol. 93, No. 4, pp. 1703–1729.

Atkinson G.M., Boore D.M. [2006] "Earthquake ground-motion prediction equations for eastern North America," *Bulletin of the Seismological Society of America*, Vol. 96, No. 6, pp. 2181–2205.

Atkinson G.M., Boore D.M. [2008] "Erratum: Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions," *Bulletin of the Seismological Society of America*, Vol. 98, No. 5, pp. 2567–2569.

Atkinson G.M., Boore D.M. [2011] "Modifications to existing ground-motion prediction equations in light of new data," *Bulletin of the Seismological Society of America*, Vol. 101, No. 3, pp. 1121–1135.

Atkinson G.M., Macias M. [2009] "Predicted ground motions for great interface earthquakes in the Cascadia subduction zone," *Bulletin of the Seismological Society of America*, Vol. 99, No. 3, pp. 1552–1578.

Boatwright J., Blair L., Catchings R., Goldman M., Perosi F., Steedman C. [2004] "Using twelve years of USGS refraction lines to calibrate the Brocher and others (1997) 3D velocity model of the Bay Area," *USGS Open File Report 2004–1282*.

Boore DM. [2004] "Estimating Vs30 (or NEHRP site classes) from shallow velocity models (depth < 30 m)," *Bulletin of the Seismological Society of America*, Vol. 94, pp. 591–597.

Boore D.M., Atkinson G.M. [2008] "Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0:01 s and 10:0 s," *Earthquake Spectra*, Vol. 24, No. 1, pp. 99–138.

Boore D.M., Thompson E.M., Cadet H. [2011] "Regional correlations of Vs30 and velocities averaged over depths less than and greater than 30 m," *Bulletin of the Seismological Society of America*, Vol. 101, No. 6, pp. 3046–3059.

Bose M., Sokolov V., Wenzel F. [2009] "Shake map methodology for intermediate-depth Vrancea (Romania) earthquakes," *Earthquake Spectra*, Vol. 25, No. 3, pp. 497–514.

Brocher T.M., Parsons T., Blakely,R.J. *et al* [2001] "Upper crustal structure in Puget Lowland, Washington: Results from the 1998 Seismic Hazards Investigation in Puget Sound," *Journal of Geophysical Research-Solid Earth*, Vol. 106, No. B7, pp. 13541–13564.

Brocher T.M. [2005] "Compressional and shear wave velocity versus depth in the San Francisco Bay Area, California: Rules for USGS Bay area velocity model 05.0.0," *USGS Open-File Report 2005–1317*, 58 pgs.

Cadet H., Duval A.-M. [2009] "A shear wave velocity study based on the KiK-net borehole data: A short note," *Seismological Research Letters*, Vol. 80, pp. 440–445.

Campbell K.W. [2003] "Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America," *Bulletin of the Seismological Society of America*, Vol. 93, No. 3, pp. 1012–1033.

Campbell K.W., Bozorgnia Y. [2007] "Campbell-Bozorgnia NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters," *PEER Report No. 2007/02*, Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Campbell K.W., Bozorgnia Y. [2008] "NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0:01 to 10 s.," *Earthquake Spectra*, Vol. 24, No. 1, pp. 139–171.

Cauzzi, C., Faccioli, E. [2008] "Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records," *Journal of Seismology*, Vol. 12, No. 4, pp 453–475.

CEN [2004] "Eurocode 8 - design of structures for earthquake resistance. Part 1: general rules, seismic actions and rules for buildings," European standard EN 1998-1, European Committee for Standardization, Brussels.

Chiou B.S.J., Youngs R.R. [2008a] "An NGA model for the average horizontal component of peak ground motion and response spectra," *Earthquake Spectra*, Vol. 24, No. 1, pp. 173–215.

Chiou B.S.J., Youngs R.R. [2008b] "Chiou and Youngs PEER-NGA empirical ground motion model for the average horizontal component of peak acceleration, peak velocity, and pseudo-spectral acceleration for spectral periods of 0.01 to 10 seconds," *Final Report,* Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA.

Di Alessandro C., Bonilla L.F., Boore D.M., Rovelli A., Scotti O. [2011] "Predominant-period site classification for response spectra prediction equations in Italy", *Bulletin of the Seismological Society of America*, Vol. 102, No. 2, 680–695.

Douglas J., Bungum H., Scherbaum F. [2006] "Ground-motion prediction equations for southern Spain and southern Norway obtained using the composite model perspective," *Journal of Earthquake Engineering*, Vol. 10, No. 1, pp. 33–72.

Faccioli E., Bianchini A., Villani M. [2010] "New ground motion prediction equations for T > 1 s and their influence on seismic hazard assessment," *Proceedings of Symposium on Long-Period Ground Motion and Urban Disaster Mitigation*, University of Tokyo, Japan.

Farr T.G., Kobrick M. [2000] "Shuttle radar topography mission produces a wealth of data," *EOS Transactions*, Vol. 81, pp. 583–585.

Franke, A., Mueller C., Barnhard T., Perkins D., Leyendecker E., Dickman N., Hanson S., Hopper M. [1996] "National seismic hazard maps: Documentation," *USGS Open-File Report* 96-532, 69 pgs.

Fumal T.E., Tinsley J.C. [1985] "Mapping shear-wave velocities of near-surface geologic materials," in "Evaluating Earthquake Hazards in the Los Angeles Region-An Earth-Science Perspective.," (Ed. J.I. Ziony), *U.S. Geological Survey Professional Paper 1360*, pp. 101–126.

Garcia D., Singh S.K., Herraiz M., Ordaz M., Pacheco J.F. [2005] "Inslab earthquakes of central Mexico: Peak ground-motion parameters and response spectra," *Bulletin of the Seismological Society of America*, Vol. 95, No. 6, pp. 2272–2282.

Goto H., Sawada S., Morikawa H., Kiku H., Ozalaybey S. [2005] "Modeling of 3D subsurface structure and numerical simulation of strong ground motion in the Adapazari Basin during the 1999 Kocaeli earthquake, Turkey," *Bulletin of the Seismological Society of America*, Vol. 95, No. 6, pp. 2197–2215.

Graves R.W. [1994] "Simulating the 3D Basin Response in the Portland and Puget Sound regions from large subduction zone earthquakes," *USGS Award 1434–93-G-2327*, Annual Technical Report.

Hardebeck J. L., Michael, A. J., Brocher T. M. [2007] "Seismic velocity structure and seismotectonics of the eastern San Francisco Bay region, California," *Bulletin of the Seismological Society of America*, Vol. 97, pp. 826–842.

Iwahashi J., Pike R.J. [2007] "Automated classifications of topography from DEMs by an unsupervised nested-means algorithm and a three-part geometric signature," *Geomorphology*, Vol. 86, No. 3-4, pp. 409–440.

Iwahashi J., Kamiya I., Matsuoka M. [2010] "Regression analysis of Vs30 using topographic attributes from a 50-m DEM," *Geomorphology*, Vol. 117, No. 1-2, pp. 202-205.

Kagawa T., Zhao B., Miyakoshi K., Irikura K. [2004] "Modeling of 3D basin structures for seismic wave simulations based on available information on the target area: case study of the Osaka Basin, Japan," *Bulletin of the Seismological Society of America*, Vol. 94, No. 4, pp. 1353–1368.

Kanno T., Narita A., Morikawa N., Fujiwara H, Fukushima Y. [2006] "A new attenuation relation for strong ground motion in Japan based on recorded data," *Bulletin of the Seismological Society of America*, Vol. 96, No. 3, pp. 879–897.

Kohler M.D., Magistrale H., Clayton R.W. [2003] "Mantle heterogeneities and the SCEC Reference Three-Dimensional Seismic Velocity Model Version 3," *Bulletin of the Seismological Society of America*, Vol. 93, pp. 757–774.

Lin G., Thurber C.H., Zhang H., Hauksson E., Shearer P.M., Waldhauser F., Brocher T.M., Hardebeck J. [2010] "A California statewide three-dimensional seismic velocity model from both absolute and differential times," *Bulletin of the Seismological Society of America*, Vol. 100, No. 1, pp. 225–240.

Lin P.-S., Lee C.T. [2008] "Ground-motion attenuation relationships for subduction-zone earthquakes in northeastern Taiwan," *Bulletin of the Seismological Society of America*, Vol. 98, No. 1, pp. 220–240.

Magistrale H., Day S., Clayton R.W., Graves R.W. [2000] "The SCEC Southern California reference three-dimensional seismic velocity model version 2," *Bulletin of the Seismological Society of America*, Vol. 90, pp. S65–S76.

McVerry G.H., Zhao J.X., Abrahamson N.A., Somerville P.G. [2006] "New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes," *Bulletin of the New Zealand Society of Earthquake Engineering*, Vol. 39, No. 4, pp. 1–58.

Moss R.E.S. [2008] "Quantifying measurement uncertainty of thirty-meter shear-wave velocity," *Bulletin of the Seismological Society of America*, Vol. 98, No. 3, pp. 1399–1411.

Okada Y., Kasahara K., Hori S., Obara K., Sekiguchi S., Fujiwara H., Yamamoto A. [2004] "Recent progress of seismic observation networks in Japan—Hi-net, F-net, K-NET and KiK-net," *Earth Planets Space*, Vol. 56, xv-xxviii.

PEER GEM – Global GMPEs Task 2 WG: Douglas J., Cotton F., Abrahamson N.A., Akkar S., Boore D.M., Di Alessandro C. (2011) Pre-selection of ground-motion prediction equations (Task 2), Global GMPEs, Available from www.nexus.globalquakemodel.org/gem-gmpes/posts/.

Pezeshk S., Zandieh A., Tavakoli B. [2011] "Hybrid empirical ground-motion prediction equations for eastern North America using NGA models and updated seismological parameters," *Bulletin of the Seismological Society of America*, Vol. 101, No. 4, pp. 1859–1870.

Pilz M., Parolai S., Picozzi M., *et al* [2010] "Shear wave velocity model of the Santiago de Chile basin derived from ambient noise measurements: a comparison of proxies for seismic site conditions and amplification," *Geophysical Journal International*, Vol. 182, No. 1, 355–367.

Raghu Kanth S.T.G., Iyengar R.N. [2006] "Seismic hazard estimation for Mumbai city," *Current Science*, Vol. 91, No. 11, pp. 1486–1494.

Raghu Kanth S.T.G., Iyengar R.N. [2007] "Estimation of seismic spectral acceleration in peninsular India," *Journal Earth System Science*, Vol. 116, No. 3, pp. 199–214.

Sato T., Graves R.W., Somerville P.G. [1999] 3-D finite-difference simulations of long-period strong motions in the Tokyo metropolitan area during the 1990 Odawara earthquake (MJ 5.1) and the great 1923 Kanto earthquake (MS 8.2) in Japan," *Bulletin of Earthquake Engineering*, Vol. 89, pp. 579–607.

Scasserra G., Stewart J.P., Kayen R.E., Lanzo G. [2009] "Database for earthquake strong motion studies in Italy," *Journal of Earthquake Engineering*, Vol. 13, No. 6, pp. 852–881.

Silva W.J., Gregor N., Darragh R. [2002] "Development of regional hard rock attenuation relations for central and eastern North America," *Report from Pacific Engineering and Analysis*, El Cerrito, California, 57 pgs.

Sokolov V., Bonjer K.P., Wenzel F., Grecu G., Radulian M. [2008] "Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes," *Bulletin of Earthquake Engineering*, Vol. 6, No. 3, pp. 367–388.

Somerville P.G., Graves R.W., Collins N., Song S.G., Ni S., Cummins P. [2009] "Ground motion models for Australian earthquakes," *Report to Geoscience Australia*, URS Corporation.

Symons, N.P., Crosson, R.S. [1997] "Seismic velocity structure of the Puget Sound region from 3-D non-linear tomography," *Geophysical Research Letters*, Vol. 24, No. 21, pp. 2593-2596.

Thompson E.M., Baise L.G., Kayen R.E., Morgan E.C., Kaklamanos J. [2011] "Multiscale site response mapping: A case study of Parkfield, California," *Bulletin of the Seismological Society of America*, Vol. 101, No. 3, pp. 1081–1100.

Toro G.R., Abrahamson N.A., Schneider J.F. [1997] "Model of strong ground motions from earthquake in central and eastern North America: Best estimates and uncertainties," *Seismological Research Letters*, Vol. 68, No. 1, pp. 41–57.

Wald D.J., Allen T.I. [2007] "Topographic slope as a proxy for seismic site conditions and amplification," *Bulletin of the Seismological Society of America*, Vol. 97, No. 5, pp. 1379–1395.

Wills C.J., Clahan K.B. [2006] "Developing a map of geologically defined site- condition categories for California," *Bulletin of the Seismological Society of America*, Vol. 96, pp. 1483–1501.

Wills C.J., Gutierrez C. [2008] "Investigation of geographic rules for improving site-conditions mapping," *Calif. Geological Survey Final Technical Report*, 20 pgs. (Award No. 07HQGR0061).

Yong A., Hough S.E., Abrams M.J. *et al* [2008a] "Preliminary results for a semi-automated quantification of site effects using geomorphometry and ASTER satellite data for Mozambique, Pakistan and Turkey, *Journal Earth System Science*, Vol. 117, No. 2, pp. 797–808.

Yong A., Hough S.E., Abrams M.J. [2008b] "Site characterization using integrated imaging analysis methods on satellite data of the Islamabad, Pakistan, Region," *Bulletin of the Seismological Society of America*, Vol. 98, No. 6, pp. 2679–2693.

Yong A., Hough S.E., Iwahashi J., Braverman A. [2011] "A terrain-based site characterization map of California with implications for the contiguous United States," *Bulletin of the Seismological Society of America*, Vol. 102, No. 1, pp. 114–128.

Youngs R.R., Chiou B.S.J., Silva W.J., Humphrey J.R. [1997] "Strong ground motion attenuation relationships for subduction zone earthquakes," *Seismological Research Letters*, Vol. 68, No. 1, pp. 58–73.

Zhao J.X. [2010] "Geometric spreading functions and modeling of volcanic zones for strong-motion attenuation models derived from records in Japan," *Bulletin of the Seismological Society of America*, Vol. 100, No. 2, pp. 712–732.

Zhao J.X., Zhang J., Asano A., Ohno Y., Oouchi T., Takahashi T., Ogawa H., Irikura K., Thio H.K., Somerville P.G., Fukushima Y. Fukushima, F. [2006] "Attenuation relations of strong ground motion in Japan using site classification based on predominant period," *Bulletin of the Seismological Society of America*, Vol. 96, No. 3, pp. 898–913.

Website references

1. Pacific Earthquake Engineering Research Center (PEER)

NGA-West 2 Project.

[Available at http://peer.berkeley.edu/ngawest2/]

2. United States Geological Survey

Earthquake Hazard Program

[Available at http://earthquake.usgs.gov/hazards/apps/vs30/custom.php]

3. Geospatial Information Authority of Japan (GSI)

Automated terrain classification map using SRTM 30

[Available at http://gisstar.gsi.go.jp/terrain/front_page.htm]

4. Southern California Earthquake Center (SCEC)

Three-Dimensional Community Velocity Model for Southern California (CVM-Version 4)

[Available at http://www.data.scec.org/3Dvelocity]