Selection of ground-motion prediction equations for GEM1

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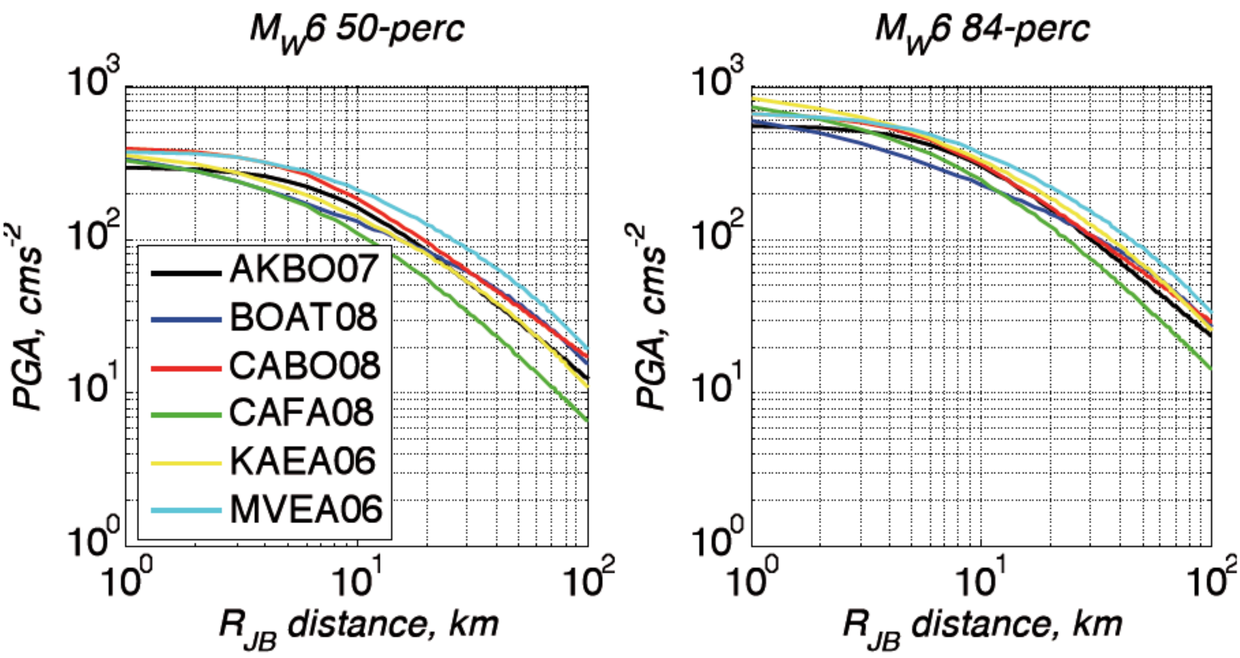

This is an external report, produced within the scope of the GEM1 project. GEM1 was a focused pilot project of the Global Earthquake Model initiative, which ran from January 1st 2009 to March 31st 2010 and was aimed at generating GEM's first products and developing GEM's initial IT infrastructure. The technical achievements of GEM1 have been summarised in a series of 10 reports; 6 internal and 4 external GEM1 reports. The internal reports are based on the achievements of the GEM1 team, the external reports are written by external experts who had been awarded a sub-contract to carry out a specific task. In addition to reading this external reports, it is suggested to also read the rest of the GEM1 reports and in particular the GEM1 Executive Summary. These can be downloaded from www.globalquakemodel.org/node/747

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1. Scope

This document describes a selection of published ground-motion prediction equations (GMPEs) (also known as attenuation relations or ground-motion models) and their features, for use in the seismic hazard assessment to be performed at the global scale in GEM1. Such a scale of application obviously requires that all the significant tectonic regimes affecting the generation of earthquakes that can cause damage to the built environment be taken into account in the selection. This requirement marks a first difference with respect to, for instance, those of the SHARE project, focussed on Europe and neighbouring countries only. The extension to the global scale requires dealing with many large regions belonging to different tectonic regimes where no strong-motion data have ever been recorded and no GMPEs directly based on strong-motion data been proposed. The whole of Africa, leaving out Algeria and Egypt, is a striking example of this situation, as are vast areas of Asia.

The selection presented in this document was made from over 250 GMPEs that are currently available (Douglas, 2004, 2006, 2008), to retain a subset of some of the most recent and robust models. Note that, GMPEs developed based on observed macroseismic intensities and a subsequent conversion to instrumental strong-motion parmeters (e.g. Battis, 1981) have not been considered, due to their generally larger aleatory variabilities and since they are no longer considered best practice. It is important to retain a sufficient number of models so that the potentially large epistemic uncertainty, due to a lack of data and knowledge, within the prediction of earthquake ground motions can be captured. The purpose of this report is to present a selection of available models for all the main seismotectonic regimes present at a global scale. These can be divided into the following five broad classes, which are standard categories for ground-motion prediction (e.g. Abrahamson & Shedlock, 1997):

- Stable continental regions (SCRs), such as eastern North America;
- Subduction zones, such as those on the Pacific rim;
- Active regions with shallow crustal seismicity, such as most parts of Italy;
- Volcanic zones, such as the Azores;
- Areas of deep focus non-subduction earthquakes, such as Vrancea (Romania);

It should be noted that some researchers believe that ground motions from earthquakes in oceanic crust but recorded onshore, e.g. the Lisbon 1755 earthquake, could be potentially different in character to shaking from earthquakes in active or stable regions. However, since such a situation is thought to be confined to geographically small areas (e.g. coastal Portugal) and because of few strong-motion data from these regions, it was decided not to include an additional tectonic class for these regions. To attempt to model the larger epistemic uncertainty in the prediction of ground motions in these regions we include both models from active and SCRs in the proposed weighting scheme for these areas.

Only models for the prediction of horizontal peak ground acceleration and horizontal linear elastic response spectral ordinates for 5% of critical damping are considered herein since this is the focus of the seismic hazard assessments made in GEM1. In addition, mining-induced seismicity is not considered in GEM1 and, therefore, no models for the prediction of shaking from mining-induced events are included. It is noted here in passing that for certain parts of the world (e.g. mining areas of Poland and South Africa) mining-related earthquakes pose the highest contributor to seismic hazard, at least for short return periods.

2. Selection criteria

The vast number of GMPEs available in the literature makes it necessary to adopt criteria to winnow down the models to a more manageable number, recognising at the same time the need to retain sufficient models to account for epistemic uncertainty in the prediction of shaking. For this selection it was decided to reject models based on the seven exclusion criteria proposed by Cotton et al. (2006), with one modification to criterion 6, which are the following:

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;

1. the model has been superseded by more recent publications;
2. the frequency range of the model is not appropriate for engineering application;
3. the model has an inappropriate functional form (this has been interpreted here in particular regarding a consideration of site classification and style of faulting within the model);
4. 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 regions of subduction). Criterion 2 was applied to reject GMPEs that had not been published in a journal that is listed by ISI Web of Knowledge[1], which is a standard reference for bibliographic information. 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 in converting between other magnitude scales, particularly local magnitude 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). The same criterion has been extended to include preferably those models that take style of faulting somehow into account. Finally, 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 & Huo, 1997).

These criteria have been applied to the empirical GMPEs listed in the reports of Douglas et al. (2004, 2006, 2008) plus the few additional models published in 2009 or accidentally missed by these compilations.

The issue of assigning weights to the different GMPEs for use in PSHA is discussed in a later section of this report. Since testing the proposed models is not within the scope of GEM1, we relied upon previous studies in which some of the models have actually been tested against the data, such as Douglas & Mohais (2009) for subduction zone GMPEs in the Lesser Antilles.

In addition, simulation-based GMPEs identified through a thorough literature search were taken into account. Note that only simulation-based GMPEs with fitted functional forms are considered here since these are straightforward to use within seismic hazard assessment. Models derived using the hybrid empirical-stochastic approach of Campbell (2003) have also been considered.

Section 4 below summarizes in table form the main features of the GMPEs that have been retained for each seismotectonic regime, in the same order as listed in Section 1. The models tested by Allen & Wald (2009) for Global ShakeMap purposes and the GMPEs used by Petersen et al. (2008) for

[1] An exception was made for the model of McVerry et al. (2006) for New Zealand since 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. 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 construction of the US National Seismic Hazard Maps are, in general, subsets of the models selected here.

3. Linking the GEM1 database with the proposed GMPEs

The tectonic regionalisation and GMPE weighting scheme herein proposed for GEM1 is contained within the associated database files (Matlab .mat files) that can be run through the provided Matlab viewer. For consistency with standard seismological practice, and also because of easy availability of the associated polygons, the Flinn - Engdahl (FE) regionalisation of the globe has been chosen as a support of this database. The FE regionalisation divides the world into over 700 regions based on political and tectonic provinces and hence it is an appropriate choice (if slightly too detailed) for GEM1. For each of the five tectonic types considered here, listed in Sect. 1 (active, subduction, SCR, volcanic and Vrancea-type), we assessed whether seismicity associated with this type could occur in a given FE region based on the work of Johnson et al. (1994), Bird (2003) and our own knowledge. If the considered type of seismicity could occur in a FE region then non-zero weights were assigned to the GMPEs selected for such tectonic regimes. This process was undertaken for all five tectonic types and all 700+ FE regions.

FE regions for oceanic areas far from land were assigned to a sixth category and no GMPEs were assigned. When a user clicks on the global map (within the Matlab viewer) the programs search the files to return all the GMPEs and weights assigned to the FE region associated with the coordinates requested. Since global tectonics are complex, some parts of the world are associated with more that one type of seismicity and hence some FE regions have recommended GMPEs for different tectonic regimes. For example, if the user selects a location in New Zealand the programs will return three lists of GMPEs and weights (adding each time up to unity) associated with active, subduction and volcanic seismicity.

4. Summary table of selected GMPEs

Table 1. The following table presents the main characteristics of the selected GMPEs. The format of these tables and their content follows the reports of Douglas (2004, 2006, 2008) with some minor changes of notation. See end of table for meanings of abbreviations.

Reference	Area	H	E	M_{min}	M_{max}	M scale	d_{min}	d_{max}	d scale	S	T_S	T_{min}	T_{max}	C	R	M
STABLE CONTINENTAL REGIONS																
Atkinson (2008)	Eastern North America	ENA observations from Atkinson & Boore (2006)		4.3	7.6	M_w	10	1000+	r_{jb}	I, only Vs30 = 760 m/s	6, PGA, PGV	0.1	5	Referenced empirical approach, see Boore and Atkinson (2008)		
Atkinson & Boore (2006)	Eastern North America	34800 simulated records	10	3.5	8	M_w	1	1000	r_{rup}	I,C	24, PGA, PGV	0.025	5	G	1	R
Campbell (2003)	Eastern North America	Hybrid empirical, gmpes + simulations		5	8.2	M_w	0	1000	r_{rup}	I, only Vs30= 2.8km/s	16, PGA (0.01 s)	0.02	4	G	1	R
Douglas et al. (2006)	Southern Norway	Hybrid empirical, gmpes + simulations		4.5	7.5	M_w	1	1000	r_{jb}	I, rock sites	14	0.02	2	G	1	R,N,S
Tavakoli & Pezeshk (2005)	Eastern North America	Hybrid empirical, gmpes + simulations		5	8.2	M_w	0	1000	r_{rup}	I, soft and hard rock sites	13, PGA	0.05	4	G	1	R
Toro et al. (1997)	Eastern North America	Stochastic simulations		5	8	M_w	1	1000	R_{jb}	I, only Vs30= 2.8km/s	7, PGA	0.03	2	G	1	R

SUBDUCTION ZONES															
Atkinson & Boore (2003)	Worldwide	1200+	43*	5.5	8.3	M_w	11*	550*	r_{rup}	4,I	7, PGA	0.04	3	C	1M	F,B
Atkinson & Macias (2009)	Cascadia	Simulations		7.5	9	M_w	30*	400*	r_{rup}	I, NEHR PB/C boundary	24, PGA	0.05	10	G	2M	F
Garcia et al. (2005)	Central Mexico	277	16	5.2	7.4	M_w	4*	400*	r_{rup} for Mw>6.5, r_{hypo} otherwise	1	15, PGA	0.04	5	G	1M	B
Zhao et al. (2006)	Japan+Iran +WUS	2763-4518+208	<249+20	5	8.3	M_w	0*	300*	dr	5	20, PGA	0.05	5	G	1M	C(R, S/N) & F,B
Kanno et al. (2006)	Japan + some foreign	3205-3392+331-377 (shallow) & 7721-8150 (deep)	70-73+10 & 101-111	5.0* (6.1) 5.5*	8.2* (7.4) 8.0*	M_w (M_{JMA})	1* (1.5*) & 30	450* (350*) & 450*	r_{rup} (r_{hypo} for some)	C	37, PGA	0.05	5	R	2M	A
McVerry et al. (2006)	New Zealand	435	49	5.08	7.09	M_w	6	400	dc (r_{rup})	3	11, PGA	0.075	3	L, G	1M	C(R,OR,S,N) & F,B
Youngs et al. (1997)	Worldwide	≤476	≤164	5	8.2	M_w (M_S, m_b)	8.5	550.9	r_{rup}, r_{hypo} for some	2	11, PGA	0.075	3	G	1M	NT (N,T)
ACTIVE TECTONIC REGIONS															

Akkar & Bommer (2007)	Europe and Middle East	532	131	5	7.6	M_w	0	99	r_{jb}, r_{epi} for small events	3	80, PGA, PGV	0.05	4	G	1WM	A
Boore & Atkinson (2008)	Worldwide	1574	58	4.27 (6)	7.9 (7)	M_w	0	280 (8)	r_{jb}	C	20, PGA, PGV	0.02	10	150	2M	A (N,R.S, U)
Campbell & Bozorgnia (2008)	Worldwide	1561	64	4.27 (9)	7.9 (10)	M_w	0.07	199.27	r_{rup}	C	20, PGA, PGV	0.02	10	150	1M	A (N,R.S, HW)
Cauzzi & Faccioli (2008)	Worldwide	1164	60	5	7.2	M_w	15*	150*	r_{hypo}	4 &C	400, PGA	0.05	20	G	2M	A (N, R, S)
Chiou & Youngs (2008)	Worldwide	1950	125	4.265 (17)	7.9 (18)	M_w	0.2* (19)	70* (20)	r_{rup}	C	21, PGA, PGV	0.02	10	I50	1M	A (N, R, S HW, AS)
Kanno et al. (2006)	Japan + some foreign	3205-3392+331-377 (shallow) & 7721-8150 (deep)	70-73+10 & 101-111	5.0* (6.1) 5.5*	8.2* (7.4) 8.0*	M_w (M_{JMA})	1* (1.5*) & 30	450* (350*) & 450*	r_{rup} (r_{hypo} for some)	C	37, PGA	0.05	5	R	2M	A
McVerry et al. (2006)	New Zealand	435	49	5.08	7.09	M_w	6	400	dc (r_{rup})	3	11, PGA	0.075	3	L,G	1M	C(R,OR,S,N) & F,B
Bindi et al. (2009)	Italy	561	107	4	6.9	M_w	1	100	r_{jb}, r_{epi}	3,I, see Sabetta and Pugliese (1987 and 1996)	21, PGA, PGV	0.03	2	L	1M	U

Danciu & Tselentis (2007)	Greece	335	151	4.5	6.9	M_w	0*	136	r_{epi}	3	31, PGA, PGV	0.1	4	A	1M	A (ST, N)
Douglas et al. (2006)	Southern Spain	Hybrid empirical, gmpes + simulations		4.5	7.5	M_w	1	1000	r_{jb}	I, rock sites	14	0.02	2	G	1	S
Kalkan & Gülkan (2004b and 2005)	Turkey	112	57	4	7.4	Mw (unspecified scales)	1.2	250	r_{jb}, r_{epi} for small events	3	46, PGA	0.1	2	L	1	A
VOLCANIC REGIONS																
McVerry et al. (2006)	New Zealand	435	49	5.08	7.09	M_w	6	400	dc (r_{rup})	3	11, PGA	0.075	3	L,G	1M	C(R,OR,S,N) & F,B
VRANCEA																
Sokolov et al. (2008)	Romania	Simulations		5	8	M_w	1	500	r_{epi}	I	PSA, PGA, PGV, the coefficients of the equation available from V. Sokolov			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
Mmin Magnitude of smallest earthquake
Mmax Magnitude of largest earthquake

M scale Magnitude scale (scales in brackets refer to those scales which the main M values were sometimes converted from, or used without conversion, when no data existed), where:
mb Body-wave magnitude

MJMA	Japanese Meteorological Agency magnitude
Ms	Surface-wave magnitude
Mw	Moment magnitude
dmin	Shortest source-to-site distance
dmax	Longest source-to-site distance
d scale	Distance measure, where (Abrahamson & Shedlock, 1997):
dc	Distance to rupture centroid
r_{epi}	Epicentral distance
r_{jb}	Distance to projection of rupture plane on surface (Joyner and Boore, 1981)
r_{hypo}	Hypocentral (or focal) distance
r_{rup}	Distance to rupture plane
S	Number of different site conditions modelled, where:
C	Continuous classification
I	Individual classification for each site
C	Use of the two horizontal components of each accelerogram, where:
C	Randomly chosen component
G	Geometric mean
L	Larger component
R	Resolved component
I50	GMrotI50 (Boore et al., 2006)
R	Regression method used, where:
1	Ordinary one-stage
1M	Maximum likelihood one-stage (Joyner and Boore, 1993)
1W	Weighted one-stage
2M	Maximum likelihood two-stage (Joyner and Boore, 1993)
Ts	Number of periods for which attenuation equations are derived
Tmin	Minimum period for which attenuation equation is derived
Tmax	Maximum period for which attenuation equation is derived

5. Functional forms and main features of GMPEs

EQUATIONS FOR STABLE CONTINENTAL REGIONS

The following GMPEs, all except one developed for Eastern North America, have been selected:

- Atkinson (2008): Referenced empirical model for eastern North America
- Atkinson & Boore (2006): Extended stochastic model for eastern North America
- Campbell (2003): Hybrid model for eastern North America
- Douglas et al. (2006): Hybrid model for southern Norway
- Tavakoli & Pezeshk (2005): Hybrid model for eastern North America
- Toro et al. (1997): Stochastic model for eastern North America

Other models exist for SCRs but they fail one or more of the selection criteria, in particular the requirement of a publication in an ISI-listed journal[2], or the fact that the authors have not considered modelling uncertainty when deriving their aleatory variabilities.

Atkinson (2008) – AT08

Functional form:

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

where *F* is the multiplying adjustment factor to be applied to the prediction from the Boore and Atkinson (2008) GMPEs (Y_{BA08}) 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.

Notes:

- Uses “referenced empirical approach”, in which the Boore and Atkinson (2008) GMPE 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.
- 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.

Atkinson & Boore (2006) – ATBO06

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[2] For example, some updated Toro et al. (1997) models have been developed (e.g. EPRI, 2004) but these have never been published in international peer-reviewed journals and can only be found in technical reports.

Functional form:

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

$$\text{where } f_0 = \max(\log(R_0/R_{cd}), 0); f_1 = \min(\log R_{cd}, \log R_1);$$
$$f_2 = \max(\log(R_{cd}/R_2), 0); R_0 = 10; R_1 = 70; R_2 = 140;$$
$$\text{and } S = 0 \text{ for hard-rock sites}$$

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 were developed from a seismological model of source, path, and site parameters, obtained using empirical data from small to moderate ENA earthquakes. Functions were then fitted to simulated ground motion.

Campbell (2003) – CA03

Functional form:

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

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=130km. The aleatory standard deviation is given by:

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

$$\text{where } M_1 = 7.16.$$

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.

Douglas et al. (2006) – DAEA06 for Southern Norway

Functional form:

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

where

$$\begin{aligned} f_1(M_w) &= c_2 M_w + c_3(8.5 - M_w)^2 \\ f_2(M_w, d_{jb}) &= c_4 \ln R + (c_5 + c_6 M_w) d_{jb}, \\ R &= \sqrt{d_{jb}^2 + [c_7 \exp(c_8 M_w)]^2} \end{aligned}$$

and

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

where $r_1 = 70\,\text{km}$ and $r_2 = 130\,\text{km}$.

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

Notes:

- Developed for sites in southern Spain (see below) 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.

Tavakoli & Pezeshk (2005) – TAPE05

Functional form:

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

$$f_1(M_w) = C_1 + C_2 M_w + C_3(8.5 - M_w)^{2.5}$$

$$f_2(r_{rup}) = \begin{cases} C_9 \ln(r_{rup} + 4.5) & r_{rup} \le 70 \text{ km} \\ C_{10} \ln\left(\frac{r_{rup}}{70}\right) + C_9 \ln(r_{rup} + 4.5) & 70 < r_{rup} \le 130 \text{ km} \\ C_{11} \ln\left(\frac{r_{rup}}{130}\right) + C_{10} \ln\left(\frac{r_{rup}}{70}\right) + C_9 \ln(r_{rup} + 4.5) & r_{rup} \ge 130 \text{ km} \end{cases}$$

$$f_3(M_w, r_{rup}) = (C_4 + C_{13} M_w) \ln R + (C_8 + C_{12} M_w) R$$

$$R = \sqrt{r_{rup}^2 + (C_5 \exp[C_6 M_w + C_7(8.5 - M_w)^{2.5}])^2}$$

$$\sigma_{\ln Y} = \begin{cases} C_{14} + C_{15} M_w & M_w < 7.2 \\ C_{16} & M_w \ge 7.2 \end{cases}$$

where *Y* is *PGA* or spectral acceleration in g up to 4 s.

Notes:

- Approach is similar to that of Campbell (2003), in that it uses a stochastic model (implemented through the stochastic code SMSIM) to derive modification factors from the ground motions in WNA to ground motions in ENA. Three empirical attenuation models are used for the host region WNA.
- Soft- and hard-rock site conditions, earlier proposed by Boore and Joyner (1997), are considered.

Toro et al. (1997) – TOEA97

Functional form:

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

$$R_M = \sqrt{R_{jb}^2 + C_7^2}$$

whereY is spectral acceleration or peak ground acceleration in g up to 2 s.

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, M_W (the model proposed for use in GEM1) and M_{LG}) .
- Uncertainties in model parameters, as well as those associated to the ground motion model are considered.

EQUATIONS FOR SUBDUCTION ZONES

Most of the notes given after the functional form of each model are extracted from Douglas (either 2004, or 2006, or 2008). It is 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. Atkinson & Macias, 2009).

Atkinson and Boore (2003) – ATBO03

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 cms^{-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. S_C = 0, S_D = 0 and S_E = 0
  C = NEHRP site class C, 360 < $V_{s,30}$ < 760 ms^{-1}. S_C = 1, S_D = 0 and S_E = 0
  D = NEHRP site class D, 180 < $V_{s,30}$ < 360 ms−1. S_D = 1, S_C = 0 and S_E = 0
  E = NEHRP site class E, $V_{s,30}$ < 180 ms^{-1}. S_E = 1, S_C = 0 and S_D = 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.

Atkinson and Macias (2009) – ATMA09

Developed specifically for great interface events of the Cascadia subduction zone.

Functional form:

$$\log Y = C_0 + C_1 \log R + C_3 R + C_3 (M_W - 8) + C_4 (M_W - 8)^2$$

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

$$h = M_W^2 - 3.1 M_W - 14.55$$

where *Y* is *PSA* in cms^{-2} up to 10 s.

Notes:

- Based on simulations of earthquakes with M_W between 7.5 and 9.

- Applicable for rock sites with reference velocity $V_{s,30}$ = 760 ms^{-1} (NEHRP B/C boundary).

Garcia et al. (2005) – GAEA05
Functional form:

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

where *Y* is either *PGA* or *PSA* up to 5 s in cms^{-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 M_W<5.0 and *R*>400 *km*.
- All data from intra-slab earthquakes.

Zhao et al. (2006) – ZAEA06
Functional form:

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

Notes:

- Use five site classes (*T* is natural period of site):
- Hard rock, NEHRP site class A, $V_{s,30}$>1100 ms-1. 93 records. Use CH. SC I
- Rock, NEHRP site classes A+B, 600 < $V_{s,30}$ ≤ 1100 ms-1, T < 0.2 s. 1494 records. Use C1. SC II
- Hard soil, NEHRP site class C, 300 < $V_{s,30}$≤ 600 ms-1, 0.2 ≤ T < 0.4 s. 1551 records. Use C2. SC III
- Medium soil, NEHRP site class D, 200 < $V_{s,30}$ ≤ 300 ms-1, 0.4 ≤ T < 0.6 s. 629 records. Use C3. SC IV
- Soft soil, NEHRP site classes E+F, $V_{s,30}$ ≤ 200 ms-1, T ≥ 0.6 s. 989 records. Use C4. Site class unknown for 63 records.

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

Classify events into three source types: crustal, interface (use S_I) and slab (use S_S and S_{SL}).

Also into four mechanisms using rake angle of ±45^{o} as limit between dip-slip and strike-slip earthquakes except for a few events where bounds slightly modified: reverse (use F_R if also crustal event), strike-slip, normal and unknown.

Kanno et al. (2006) – KAEA06
See next section

McVerry et al. (2006) – MVEA06
See next Section

Youngs et al. (1997) –YOEA97

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 metre 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 20m 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.

EQUATIONS FOR ACTIVE REGIONS WITH SHALLOW CRUSTAL SEISMICITY

The following GMPEs have been selected:

- Akkar and Bommer (2007b): based on data from Europe and neighbouring regions;
- Boore and Atkinson (2008): of the NGA group, based on global data (mainly from California and Taiwan, Chi-Chi 1999);
- Campbell and Bozorgnia (2008): as above;
- Cauzzi and Faccioli (2008): based on global data, mainly from Japan;
- Chiou and Youngs (2008): of the NGA group, based on global data (mainly from California and Taiwan, Chi-Chi 1999);
- Kanno et al. (2006): based on Japanese data with some WNA data to constrain near-source predictions;
- McVerry et al. (2006): derived by adapting previous models to New Zealand data.

Note that:

- the well-known GMPE of Abrahamson and Silva (2008) is not included in the selection for GEM1 because it was considered to be too complex for GEM1 applications;
- the recent GMPE 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.

Also listed below are some local GMPEs developed for specific countries, which include: Bindi et al. (2009) for Italy, Danciu and Tselentis (2007) for Greece, Douglas et al. (2006) for Southern Spain, and Kalkan and Gulkan (2004, 2005) for Turkey.

Akkar and Bommer (2007b) – AKBO07

Functional form:

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

where y is either *PGA* in cms^{-2} or displacement spectum ordinate *DRS*(T;*z*) in cm up to 4 s.

Notes:

- Use three site categories: soft soil $S_S = 1$, $S_A = 0$, stiff soil $S_A = 1$, $S_S = 0$, rock $S_S = 0$, $S_A = 0$.
- Use three faulting mechanism categories: Normal $F_N = 1$, $F_R = 0$. Strike-slip $F_N = 0$, $F_R = 0$. Reverse $F_R = 1$, $F_N = 0$.
- Provide *DRS(T)* prediction for 2, 5, 10, 20 and 30% damping. Choose displacement because of aimed use of equations for displacement-based design.
- Due to jagged appearance of predicted response spectra, particularly at long periods where different data was used for each period, apply negative exponential smoothing.
- Find that coefficients b_7 - b_{10} weakly dependent on damping ratio so present these coefficients for 2 and 5% damping (combined), 10% and 20 and 30% damping (combined).

Boore and Atkinson (2008) – BOAT08

Functional form:

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

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

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

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

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

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

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

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

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

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

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

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

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

Notes:

- Characterise sites using V_{S30}. Believe equations applicable for $180 \leq V_{S30} \leq 1300\mathrm{ms}^{-1}$. Bulk of data from NEHRP C and D sites (soft rock and firm soil) and very few data from A sites (hard rock).
- Focal depths between 2 and $31\mathrm{km}$ with most $< 20\mathrm{km}$.
- Use three faulting mechanism categories using P and T axes: SS Strike-slip. Plunges of T and P axes $< 40^\circ$. 35 earthquakes. Dips between 55 and 90°. $4.3 \leq M \leq 7.9$. $\mathrm{SS} = 1$, $\mathrm{U} = 0$, $\mathrm{NS} = 0$, $\mathrm{RS} = 0$ - RS Reverse. Plunge of T axis $> 40^\circ$. 12 earthquakes. Dips between 12 and 70°. $5.6 \leq M \leq 7.6$. $\mathrm{RS} = 1$, $\mathrm{U} = 0$, $\mathrm{SS} = 0$, $\mathrm{NS} = 0$ - NS Normal. Plunge of P axis $> 40^\circ$. 11 earthquakes. Dips between 30 and 70°. $5.3 \leq M \leq 6.9$. $\mathrm{NS} = 1$, $\mathrm{U} = 0$, $\mathrm{SS} = 0$, $\mathrm{RS} = 0$.

- Exclude singly-recorded earthquakes .

- Use estimated R_{JB}s for earthquakes with unknown fault geometries.

- Lack of data at close distances for small earthquakes.

- Three events (1987 Whittier Narrows, 1994 Northridge and 1999 Chi-Chi) contribute large proportion of records (7%, 10% and 24%).

- 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 $1\mathrm{s}$, slight decrease at $2\mathrm{s}$ and a rapid fall off in number of records for periods $> 2\mathrm{s}$.

- For long periods very few records for small earthquakes ($M < 6.5$) at any distance so magnitude scaling at long periods poorly determined for small events. This has been found to lead to physically unsound long period DRS trends in PSHAs of low seismicity regions (Faccioli and Villani 2009).

- No data from normal-faulting events for $10\mathrm{s}$ so assume ratio of motions for normal and unspecified faults is same as for $7.5\mathrm{s}$.

- Chi-Chi data major controlling factor for predictions for periods $> 5\mathrm{s}$ even for small events.

Campbell and Bozorgnia (2008) – CABO08

Functional form:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where Y is either *PGA* in g, *PGV* in cms^{-2}, *PGD* in cm or *PSA(T;5%)* in g. $\sigma_{\ln Y_B} = (\sigma^2_{\ln Y} - \sigma^2_{\ln AF})^{1/2}$ 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_{S30}. Account for nonlinear effects using A_{1100}, median estimated PGA on reference rock outcrop ($V_{S30} = 1100\mathrm{ms}^{-1}$) in g. Believe model applicable for $V_{S30} = 150\text{-}1500\mathrm{ms}^{-1}$.

- Use depth to $2.5\mathrm{kms}^{-1}$ shear-wave velocity horizon (basin or sediment depth) in km, $Z_{2.5}$. Note high correlation between V_{S30} and $Z_{2.5}$. Provide relationships for predicting $Z_{2.5}$ based on other site parameters. Believe model applicable for $Z_{2.5} = 0\text{-}10\mathrm{km}$.

- Use three faulting mechanism categories based on rake angle, λ: Reverse and reverse-oblique. $30 < \lambda < 150^\circ$. 17 earthquakes. $F_{RV} = 1$ and $F_{NM} = 0$ - Normal and normal-oblique. $-150 < \lambda < -30^\circ$. 11 earthquakes. $F_{NM} = 1$ and $F_{RV} = 0$ - Strike-slip. All other rake angles. 36 earthquakes. $F_{RV} = 0$ and $F_{NM} = 0$.

- Use data from PEER Next Generation Attenuation (NGA) Flatfile.

- Include depth to top of coseismic rupture plane, Z_{TOR}, which find important for reverse-faulting events. Believe model applicable for $Z_{TOR} = 0\text{-}15\mathrm{km}$; for default options on the Z_{TOR} values, the following table can be used (Harmsen and Zeng 2008), well suited for logic trees in PSHAs.

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 $\delta = 15\text{-}90^\circ$.

- If *PSA* < *PGA* for $T \le 0.25$s then set *PSA* equal to *PGA*, to be consistent with definition of *PSA* (occurs for large distances and small magnitudes).

- Due to cut-off frequencies used number of records available for periods $> 4\text{-}5$s falls off significantly. Majority of earthquakes at long periods are for $6.5 \le M \le 7.9$ 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.

Cauzzi and Faccioli (2008) – CAFA08

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 y is either *PGA* in ms^{-2} or *DRS(T;z)* 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. $V_{s,30} \geq 800\mathrm{ms}^{-1}$, $S_B = S_C = S_D = 0$ - Stiff ground. $360 \leq V_{s,30} < 800\mathrm{ms}^{-1}$. $S_B = 1$, $S_C = S_D = 0$, $180 \leq V_{s,30} < 360\mathrm{ms}^{-1}$. $S_C = 1$, $S_B = S_D = 0$ - Very soft ground. $V_{s,30} < 180\mathrm{ms}^{-1}$. $S_D = 1$, $S_B = S_C = 0$.
- Use mechanism classification scheme of Boore & Atkinson (2007) based on plunges of P-, T- and B-axes: Normal 16 earthquakes. $5 \leq M_w \leq 6.9$ - Strike-slip 32 earthquakes. $5 \leq M_w \leq 7.2$ - Reverse 12 earthquakes. $5.3 \leq M_w \leq 6.6$.
- 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 $10\mathrm{s}$ are obtainable. Include 9 analogue records from 1980 Irpinia ($M_w 6.9$) earthquake after careful scrutiny of long-period characteristics.
- Use 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 $22\mathrm{km}$. Exclude earthquakes with focal depth $> 22\mathrm{km}$ 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 $800\mathrm{ms}^{-1}$. 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.

Chiou and Youngs (2008) – CHYO08

Functional form:

$$\ln(y) = \ln(y_{ref}) + \phi_1 \min\left[\ln\left(\frac{V_{S30}}{1130}\right), 0\right] \quad + \phi_2\{\mathrm{e}^{\phi_3[\min(V_{S30},1130)-360]} - \mathrm{e}^{\phi_3(1130-360)}\}\ln\left(\frac{y_{ref}\mathrm{e}^{\eta} + \phi_4}{\phi_4}\right)$$

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

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

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

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

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

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

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

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

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

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

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

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

where y is either *PGA* in g, *PGV* in cms-2 or *PSA(T)* up to 10 s. σ_T is the total variance for $\ln(y)$ and is approximate based on the Taylor series expansion of the sum of the inter-event and intra-event variances. σ_{NL_0} is the equation for σ evaluated for $\eta = 0$.

Notes:

- Characterise sites using V_{S30}. $F_{Inferred}=1$ if V_{S30} inferred from geology and 0 otherwise. $F_{Measured}=1$ if V_{S30} is measured and 0 otherwise. Believe model applicable for $150 \le V_{S30} \le 1500\mathrm{ms}^{-1}$.

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

- Focal depths less than $20\mathrm{km}$ and $Z_{TOR} \le 15\mathrm{km}$. 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. $\mathrm{AS}=1$ if event aftershock and 0 otherwise. Use of AS = 0 is recommended for GEM1, since seismic hazard assessments are mainly performed for mainshocks.

- Choose reference site V_{S30} to be $1130\mathrm{ms}^{-1}$ because expected that no significant nonlinear site response at that velocity and very few records with $V_{S30} > 1100\mathrm{ms}^{-1}$ in NGA database. Functional form adopted for nonlinear site response able to present previous models from empirical and simulation studies.

Kanno et al. (2006) – KAEA06

Functional form:

$$\begin{cases} \log y = a_1 M_W + b_1 X - \log(X + d_1 10^{0.5M_W}) + c_1 & Depth \le 30km \\ \log y = a_2 M_W + b_2 X - \log X + c_2 & Depth > 30km \end{cases}$$

where *y* either PGA or PSA in cms^{-2} up to 3 s.

Notes:

- Focal depths, *D*, for shallow events between 0 *km* and 30 *km* and for deep events between 30 *km* and about 180 *km*;
- Use V_{s30} to characterise site effects through a correction formula.
- Introduce correction terms for site effects and regional anomalies.
- Originally collect 91731 records from 4967 Japanese earthquakes.
- Include foreign near-source data (from California and Turkey, which are compressional regimes similar to Japan) because insufficient from Japan.
- 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. It is suggested to not use this correction in GEM1 for simplicity in coding of the PSHA.

McVerry et al. (2006) – MVEA06

Functional form for crustal earthquakes:

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

Functional form subduction earthquakes:

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

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 r_{VOL} is length in km of source-to-site path in volcanic zone and $F_{HW}(M;r)$ is hanging wall factor.

Notes:

- Use site classes (combine A and B together and do not use data from E). Categories based on classes in existing New Zealand Loadings Standard but modified following statistical analysis.
  - A Strong rock.
  - B Rock
  - C, d_C=1, d_D=0 shallow soil sites
  - D, d_D=1, d_C=0 deep or soft soil sites
  - E Very soft soil sites.
- Classify earthquakes in three categories:

crustal (earthquakes occurring in the shallow crust of overlying Australian plate), segregated into:

Strike-slip -33£l£33^{O}, 147£l£180^{O} or -180£l£-147^{O} where l is the rake. *CN*=0, *CR*=0.

Normal -146£l£-34^{O}. *CN*=-1, *CR*=0.

Oblique-reverse 33£l£66^{O} or 124£l£146^{O}. *CR*=0.5, *CN*=0.

Reverse 67£l£123^{O}. *CR*=1, *CN*=0.

Interface (earthquake occurring on the interface between Pacific and Australian plates with H_C<50 *km*). *SI*=1, *DS*=0.

Slab (earthquakes occurring in slab source zone within the subducted Pacific plate). *SI*=0, *DS*=1 (for deep slab events).

- State that models apply for $5.25 \leq M_W \leq 7.5$ and for distances $\leq 400\,km$, which is roughly range covered by data.
- Note possible problems in applying model for $H_C > 150\,km$ therefore suggest H_C is fixed to $150\,km$ if applying model to deeper earthquakes.
- Note possible problems in applying model for $M_W < 5.25$.

Additional models for specific regions

In addition, the following regional models are of interest for particular areas:

Bindi et al. (2009) – BIEA09 for Italy

Functional form:

$$\log_{10} Y = a + b_1(M_W - M_{\mathrm{ref}}) + b_2(M_W - M_{\mathrm{ref}})^2 + (c_1 + c_2(M_W - M_{\mathrm{ref}}))\log_{10}\sqrt{(R^2 + h^2)} + e_i S_i + f_j F_j$$

where is either *PGA(cm/s^2), PGV(cm/s)* or 5%-damped *SA(cm/s^2)* up to 2 s. Coefficients available for Joyner-Boore, r_{jb}, and epicentral distance, r_{epi}. Use three site classes, see Sabetta and Pugliese (1996). Style-of-faulting not included in the final model.

Danciu and Tselentis (2007) – DATS07 for Greece

Functional form

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

Notes:

- Use three site classes: B Rock, $V_{s,30} > 800\mathrm{ms}^{-1}$. $S = 0$. 75 records. C Stiff soil, $360 \le V_s \le 665\mathrm{ms}^{-1}$. $S = 1$. 197 records. D Soft soil, $200 \le V_s \le 360\mathrm{ms}^{-1}$. $S = 2$. 63 records.
- Use three style-of-faulting categories: Thrust $F = 1$. Strike-slip $F = 1$. Normal $F = 0$,
- Use epicentral distance because most earthquakes are offshore and those that are onshore do not display evidence of surface faulting and, therefore, cannot use a fault-based distance measure.
- Data from large events recorded at intermediate and long distances and small events at small distances. Correlation coefficient between magnitude and distance is 0.64.
- Also derive equations for other strong-motion parameters, e.g. Arias intensity.

Douglas et al. (2006) – DAEA06 for Southern Spain

Functional form:

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

where

$$\begin{aligned} f_1(M_w) &= c_2 M_w + c_3(8.5 - M_w)^2 \\ f_2(M_w, d_{jb}) &= c_4 \ln R + (c_5 + c_6 M_w) d_{jb}, \\ R &= \sqrt{d_{jb}^2 + [c_7 \exp(c_8 M_w)]^2} \end{aligned}$$

and

$$\begin{aligned} f_3(d_{jb}) &= 0 && \text{for } d_{jb} \leq r_1 \\ f_3(d_{jb}) &= c_9(\ln d_{jb} - \ln r_1) && \text{for } d_{jb} > r_1 \end{aligned},$$

where $r_1 = 40\,\mathrm{km}$.

Notes:

- Use a recently published composite approach. Seven empirical ground-motion relations employed. The different relations are first adjusted to convert the differing choices of independent parameters to a single one. After these transformations, which include the scatter introduced, were performed, 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. Finally 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 (see above).

Kalkan and Gulkan (2004 and 2005) – KAGU04 for Turkey

Functional form:

$$\ln Y = b_1 + b_2(M-6) + b_3(M-6)^2 + b_5 \ln r + b_V \ln(V_S/V_A)$$

$$r = (r_{cl}^2 + h^2)^{1/2}$$

where Y is the ground motion parameter (peak ground acceleration [PGA] or pseudospectral acceleration [PSA] in g), M is the (moment) magnitude; r_{cl} is the closest horizontal distance (or Joyner-Boore distance) from the station to a site of interest in km; V_S is the characteristic shear-wave velocity for the station in m/s.

- Use three site classes: Rock, average V_S=700 ms^{-1}, 23 records. Soil, average V_S=400 ms^{-1}, 41 records. Soft soil, average V_S=200 ms^{-1}, 48 records. Use V_S measurements where available (10 stations, 22 records) but mainly classify using approximate methods. Note that correspondence between average V_S values for each site class and more widely accepted soil categories is tenuous.
- Focal depths from 0 to 111.0 *km*.
- Use only records from earthquakes with $M_w \geq 4$ to include only more reliably recorded events. Data reasonably well distributed w.r.t. M and d for d<100 *km.*

Note that a number of recent regional models fail the selection criteria of Cotton et al. (2006) since they use local magnitude, M_L, and/or they are derived for a limited magnitude ranges.

It is instructive to visually represent the ground motions predicted by the proposed GMPEs at representative magnitudes. Fig. 1 shows such a comparison for a single type of tectonic region (active tectonic regions in this case) for PGA. The predictions at the median and at the 16- and 84-percentile levels are displayed, so that one can grasp the epistemic uncertainty and the aleatory variability present. To make the representation homogeneous with respect to the distance metrics used in the different GMPEs, the plots are drawn for a vertical strike-slip fault reaching the surface (so that r_{jb} = $r_{\rm rup}$). To transform the hypocentral distance r_{hypo} used in CAFA08 into r_{rup}, a very recent correlation based on nearly 3000 data points was used, namely: r_{hypo} (km) = 2.122 + 0.991 r_{rup} + 0.0160 exp (0.982 M_w), with σ_R = 6.92 km (Faccioli et al 2009).

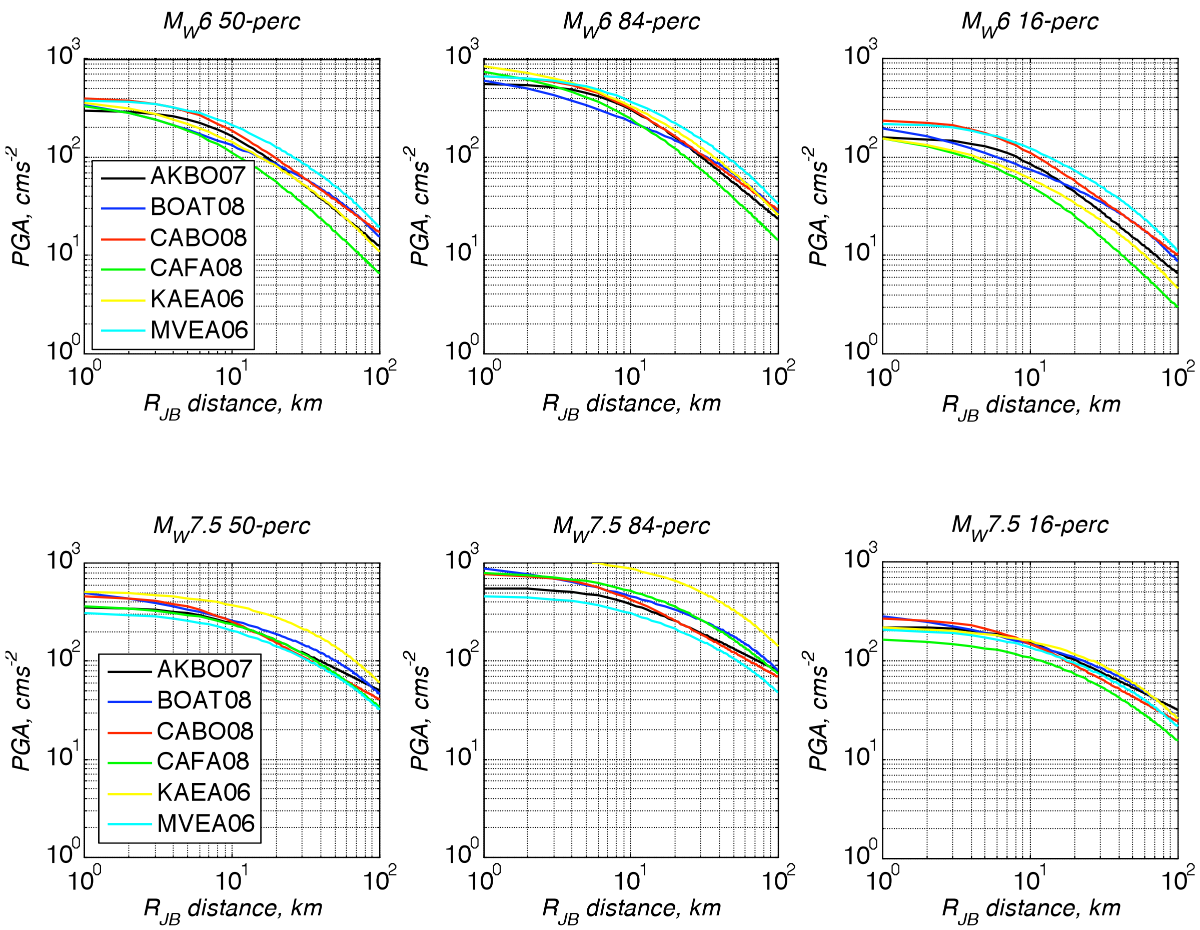

Figure 1 – Distance attenuation of horizontal PGA on rock ($V_{s,30}$= 800 m/s) predicted by the proposed GMPEs for active tectonic regions, at moment magnitudes 6.0 and 7.5. The 50-, 16.0 and 84-percentiles are separately displayed.

It may be noted from Fig. 1 that the spread in the median predictions for both magnitudes is a factor of two, and the same is roughly true for the other percentile levels (except for *M* 7.5 84-perc.)

EQUATIONS FOR VOLCANIC ZONES

Only McVerry et al. (2006) explicitly mentions the prediction of ground motions in volcanic zones and passes the adopted selection criteria. See section on active regions for details of this model. Other regional models for volcanic areas are available, e. g. for volcanic zones of Italy (De Natale et al. 1988) and Hawaii (Munson & Thurber, 1997) .but they are limited to prediction of PGA and/or PGV.

EQUATIONS FOR AREAS OF DEEP FOCUS NON-SUBDUCTION EARTHQUAKES (e.g. VRANCEA – ROMANIA)

Sokolov et al. (2008) – SOEA08

Functional form:

$$\ln Y = a_1 + a_2 M_W - e^{(a_3 + a_4 \ln H)R} + a_5 H$$

where Y is either *PGA* in cms^{-2}, *PGV* in cms^{-1} or *PSA(T)* in cms^{-2} up to 3s. *R* is epicentral distance, km and *H* is the focal depth, km.

Notes:

- The coefficients of the equations are available from V. Sokolov and are not given in the article.
- Found a good agreement with the observed data and clear azimuth (or region) dependence of the ground motion parameters of Vrancea earthquakes.
- Lack of site coefficients (the model does not strictly satisfy criterion 6).

6. Weights to be assigned to the different GMPEs, ranking for GEM1 applications, and extrapolation

Since the selected GMPEs will not be tested against observations in GEM1, previous studies must be relied upon to assign weights. Thus, if a certain model has been shown to give good predictions in previous studies then that is a useful indication for assigning a high weight (e. g. Douglas and Mohais, 2009).

In principle, unless there are pressing reasons for assigning different weights to different geographical regions, the weights associated to the selected GMPEs for each tectonic regime will remain the same for all geographical areas classified as the same regime. For example, if we select three GMPEs for active tectonic regimes and assign 0.4, 0.3 and 0.3 weights to them, for all areas classified as active tectonic regimes these models retain these weights. An exception to this general rule are areas where local models are available, e.g. Turkey, New Zealand and Japan, where such models may be assigned more weight.

Our recommendation is to assign equal weights to each of the ‘global’ models for the three main regimes, i.e.: AT08, ATBO06, CA03, TP05 and TOEA97 for SCRs each with 0.2 weight; ATBO03, KAEA06 and YOEA97 for subduction each with 0.33 weight; AKBO07, BOAT08, CABO08, CAFA08 and CHYO08 for active regimes each with 0.2 weight, and then modify this for regions with local models or where we have evidence that one model does not work well (e.g. Lesser Antilles where ATBO03 seems not to give good predictions, as shown by Douglas & Mohais, 2009). For volcanic regions it is suggested to include MVEA06 just as an additional local model to the active regimes set and giving it a 0.2 weight. Similarly for Vrancea (and other similar regions) it is suggested that the SOEA08 model be included just as an additional model in the subduction regimes set. Giving 100% weight to either of these models for their zone is not justified since this would not account for the large epistemic uncertainty.

As a support to the recommendation of assigning equal weights to the selected active crustal GMPEs, the following remarks by Allen and Wald (2009) seem appropriate: "The observation that the Europe and Middle Eastern and NGA GMPEs all perform well against an independent dataset of global ground motions (including extensive ground-motion data from Japan) suggests that regionalization of ground-motion attenuation in shallow active tectonic crust may not be significant, at least for earthquakes of magnitude $M_w \geq 5.0$. This seems to be particularly apparent at shorter distance ranges (for example, R<100–150 km). We do expect that regional crustal structure will affect ground-motion attenuation at larger distances. However, this first-order assessment of GMPEs developed for different regions and evaluated against global data, suggests there is little difference between the physical characteristics of ground-motion attenuation from each of the regions where the models are derived".

For subduction zones, based on the indications by Allen and Wald (2009, p. 12), a lower weight should probably be assigned to ATBO03 with respect to KAEA06 and YOEA97.
On the other hand, due the small amount of strong motion data available for SCRs, the residuals analysis carried out by Allen and Wald does not result in a clear indication of some GMPE performing significantly better than the others.

For use within a logic tree approach that accommodates only a reduced set of GMPEs, as foreseen in GEM1 applications, the following preferences are indicated, based on our opinion and experience:

- Stable continental regions (SCRs): No.1 Toro et al. (1997) and No.2 Atkinson & Boore (2006);
- Subduction zones: No. 1 Youngs et al. (1997) and No. 2 Zhao et al. (2006);
- Active tectonic regions: No. 1 Boore & Atkinson (2008) (restricted to periods T < 3s in regions with M < 6.5) and No. 2 Cauzzi & Faccioli (2008) (restricted to $R \geq 15$ km and M < 7.5).

Finally, if the target magnitude M is outside the range in which a GMPE is assumed to be valid, we consider that half a unit extrapolation is acceptable. Beyond that limit, we suggest capping the magnitude to M_{max}+0.5 (where M_{max} is the upper magnitude used to derive of the GMPE). The authors of some of the selected GMPEs give specific suggestions on dealing with the upper magnitude limit, see Douglas (2004, 2006, 2008). We note, however, that the extrapolation of GMPEs is still a research topic, see Bommer et al. (2007).

7. $V_{s,30}$ values on rock to be associated to the selected weighted GMPEs

For some of the selected equations, only a range of S-wave velocities is known for the rock class, a range that moreover will often be a nominal one rather than based on actual measurements encompassed by the data. To overcome the subjectivity of site classifications some studies have used ground properties measured directly underneath the accelerograph station. The most commonly used parameter obtained from the measurements is the weighted, near-surface shear-wave velocity $V_{s,30}$. Table 2 summarizes the definitions of rock used by the selected GMPEs, the estimated $V_{s,30}$ associated to each rock definition, and additional information on the determination of $V_{s,30}$.

Using Table 2, a mean $V_{s,30}$ of the proposed weighted models of about 800 m/s has been estimated, for subduction and active tectonic regions. The mean $V_{s,30}$ value for SCRs is estimated to be around 2800 m/s.

Table 2 – Characterization of rock used by the selected GMPEs, with associated $V_{s,30}$ values

Reference	Definition	Comments
Atkinson (2008)	$V_{s,30}$ = 760 m/s	Observed data from very hard rock sites adjusted to NEHRP B/C boundary
Atkinson and Boore (2006)	Only $V_{s,30}$= 2800 m/s	
Campbell (2003)	Only $V_{s,30}$= 2800 m/s	
Douglas et al. (2006)	Southern Spain: only $V_{s,30}$= 2000 m/s Southern Norway: only $V_{s,30}$= 2800 m/s	
Tavakoli and Pezeshk (2005)	Only $V_{s,30}$= 2800 m/s	
Toro et al. (1997)	Only $V_{s,30}$= 2800 m/s	
Atkinson and Boore (2003)	$V_{s,30}$ ≥ 760 m/s	$V_{s,30}$ generally measured
Atkinson and Macias (2009)	$V_{s,30}$ ≥ 760 m/s	
Garcia et al. (2005)	$V_{s,30}$ ≥ 760 m/s	
Zhao et al. (2006)	600 ≤ $V_{s,30}$ ≤ 1100 m/s or $V_{s,30}$ > 1100 m/s	$V_{s,30}$ generally measured
Kanno et al. (2006)	$V_{s,30}$ explicit	$V_{s,30}$ generally measured
Mc Verry et al. (2006)	$V_{s,30}$ > 360 m/s (complex definition)	$V_{s,30}$ often estimated
Youngs et al. (1997)	$V_{s,30}$ ≥ 760 m/s	
Akkar and Bommer (2007)	$V_{s,30}$ ≥ 750 m/s	$V_{s,30}$ often estimated
Boore and Atkinson (2008)	$V_{s,30}$ explicit	$V_{s,30}$ often measured. Lack of data for $V_{s,30}$ > 1000 m/s
Campbell and Bozorgnia (2008)	$V_{s,30}$ explicit	$V_{s,30}$ often measured. Lack of data for $V_{s,30}$ > 1000 m/s
Cauzzi and Faccioli (2008)	$V_{s,30}$ ≥ 800 m/s	$V_{s,30}$ generally (85% of cases) measured
Chiou and Youngs (2008)	$V_{s,30}$ explicit	$V_{s,30}$ often measured. Lack of data for Vs,30 > 1000 m/s
Cotton et al. (2008)	$V_{s,30}$ > 800 m/s	$V_{s,30}$ always measured
Bindi et al. (2009)	Rock outcrops or deposits < 5 m thick	Site classifications based on recent studies
Danciu and Tselentis (2007)	$V_{s,30}$ > 800 m/s	$V_{s,30}$ often estimated
Kalkan and Gülkan (2004b and 2005)	Average $V_{s,30}$ = 700 m/s	Many Turkish sites have recently been reclassified (Akkar et al., 2009)
Sokolov et al. (2008)	Lack of site coefficients	

8. Conclusions

This report has presented the opinions of John Douglas, Ezio Faccioli and Fabrice Cotton on the ground-motion prediction equations and their weights and ranking that should be applied for the SHA component of GEM1. Due to the scope of the project brief and the limited resources available it should be noted that the suggestions on ground-motion models made here are not necessarily those that would be made following a larger project, such that proposed to be undertaken by the same team for GEM. However, we believe that the current document is in keeping with the '80% solution' concept of GEM1.

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MAG Recommendations on Ground Motion Prediction Equations (GMPEs)

Draft Report

Paul Somerville, John Adams, Gottfried Grünthal, Mark Petersen

December 3, 2009

(*replies and comments by John Douglas, Ezio Faccioli, and Carlo Cauzzi, authors of the Douglas et al. (2009) report on GMPEs, are added in green, December 10, 2009)*)

INTRODUCTION

Douglas et al. (2009) prepared a GEM Report entitled "Selection of ground-motion prediction equations for GEM1." At the November 2-4, 2009 Review Meeting, some members of the MAG expressed concern about some of the GMPE's that were suggested for use in GEM1. The MAG concerns on this matter resulted in a MAG review group being formed (Somerville (coordinator) Petersen, Adams, Grünthal) to review recommendations and if necessary suggest supplementary or alternative GMPE's for inclusion in GEM1. This report presents the recommended supplementary GMPE selection criteria, recommended changes in the selected GMPE's following on from those criteria, and other guidance.

Table 1 of the Douglas et al. (2009) report provides a large amount of useful information about the selected GMPE's (see the list of column headings). However, this information was not used in the Selection Criteria provided in Section 6 of the Report. Our recommended supplementary criteria are derived from this information and summarized below.

The selection criteria used by Douglas et al. (2009) are outlined in Section 2 of the report, not Section 6. These criteria were proposed by Cotton et al. (2006) following experience gained in the SSHAC Level 4 PEGASOS project for four Swiss nuclear power plants. The models listed in Table 1 and proposed by Douglas et al. (2009) for use in GEM1 are directly based on these selection criteria as noted in Section 2.

SUPPLEMENTARY CRITERIA FOR SELECTION OF GMPE'S

1. Use models covering the widest ranges of magnitude, distance, and period

The GMPE's must cover the widest ranges of magnitude, distance and period, to avoid the cumbersome requirement to restrict the range of applicability of individual models and thus the need to make corresponding adjustments to the averaging of alternative models, with resulting lack of uniformity in the average values.

We agree with the MAG Subcommittee Recommendations on this point. This is why Criterion 6 used to select the proposed GMPEs is interpreted '*to exclude models that do not use moment magnitude (Mw) (since there are difficulties in converting between other magnitude scales, particularly local magnitude ML, and Mw, 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). The same criterion has been extended to include preferably those models that take style of faulting somehow into account.*' (Douglas et al., 2009).

2. Avoid hypocentral distance models

At sites close to large earthquake ruptures, hypocentral distance can be very much larger (hundreds of km) than distance to the fault, and introduce unnecessary scatter into the relationships. It is essential that the GMPE's accurately address close distances and large earthquakes.
For large earthquake ruptures hypocentral distance can be much larger than distance to the fault and, hence, models using distance metrics that take into account the dimensions of the fault (e.g. Joyner-Boore distance and rupture distance) are preferred. However, for the hypocentral distance to be 'hundreds of km' larger than the distance to the fault one requires earthquakes with Mw around 8 (e.g. Wells & Coppersmith, 1994) since the fault ruptures in smaller events would be less than 100km long. The only selected models that use point-source distance metrics are those of Cauzzi & Faccioli (2008), Danciu & Tselentis (2007) and Sokolov et al. (2008).
Although it does not cover very large earthquakes, a model such as that of C&F (2008), when tested with the Scherbaum et al (2004) tools for residual analysis using data from active tectonic regions not included in their reference dataset, proves to be quite reliable (notably in the European and Mediterranean context). Further, the use of the hypocentral distance can implicitly take into account the depth of the rupture initiation point, as opposed to models using R_{JB}. This is basic for seismic source zone models with associated depth, as well as for gridded (smoothed) seismicity approaches.
For these reasons we feel that models employing hypocentral distance could profitably be retained within the group of selected GMPEs in all active tectoinic regions with Mmax ≤ 7.5. We also note that Sokolov et al. (2008) is the only selected model for the Vrancea-type earthquakes, that control hazard in an extended region of Europe.

3. Use GMPEs that distinguish between different tectonic categories of earthquakes

It is essential that the GMPEs that are selected distinguish between the following four categories of earthquakes: shallow crustal earthquakes in tectonically stable regions; shallow crustal earthquakes in tectonically active regions, subduction interface earthquakes, and in-slab earthquakes; there may be additional special cases such as Volcanic and Vrancea[1]. There is general agreement that the ground motion characteristics of these four categories of earthquakes are different, so only GMPE's that recognize these differences should be used. Douglas et al. (2009) in Section 1 refer to "main seismotectonic regimes" such as "Subduction zones, such as those of the Pacific Rim." It is important to recognize that such a zone has multiple tectonic categories of earthquakes,

[1] Douglas et al. flag a further exception: earthquakes whose waves have to traverse a significant amount of oceanic crust before contributing to onshore hazard. This exception need not be treated separately for GEM1, but must be for GEM. Any GEM1 treatment will likely overestimate the hazard these events contribute

namely crust-tectonic, subduction interface, and in-slab, and they should not be represented by a single category of model such as “subduction zone.”

In the Matlab database files provided by Douglas et al (2009) many regions (e.g. New Zealand) have multiple types of earthquakes specified and, hence, GMPEs are proposed for each of these types. We agree that the prediction of ground motions in each region should use the correct GMPEs for each tectonic type. Contrary to what seems to be the MAG Subcommittee’s opinion, we did not propose mixing tectonic types within our report.

4 Give preference to GMPE’s that use a continuous representation of site effects, or use a quantitative measure of site conditions e.g. $V_{S,30}$

GMPE’s that use a continuous representation of site effects, or use a quantitative measure of site conditions such as $V_{S,30}$ are preferred over ones that use geological categories or ranges of parameters such as $V_{S,30}$.

We agree that GMPEs that use continuous $V_{s,30}$ in their modeling of site response are, in general, to be preferred. In Douglas et al. (2009) we list a number of such models (mainly from the NGA project), which are the only ones that pass the selection criteria and use continuous $V_{s,30}$. However, to limit our selection just to such models would not have been appropriate since this would lead to an underestimation of the epistemic uncertainty in ground-motion prediction. As a matter of fact, many of these models were derived within a single project (NGA) and for many regions (e.g. Europe) and tectonic types (e.g. subduction zones) there are no available models that use continuous $V_{s,30}$ since $V_{s,30}$ measures are not generally available.

RECOMMENDED CHANGES IN SELECTED GMPE’S

Subduction (ATBO03, KAEA06 and YOEA97 were recommended by Douglas et al.):

Section 6, Paragraph 3: Eliminate Kanno et al. (2006), based on criterion 3, because it separates earthquakes into two depth ranges, 0 – 30 km (including crust and subduction interface) and > 30 km (including subduction interface and in-slab)

Although Kanno et al. (2006) does account for the differences in tectonic type in a simple manner, this model has been shown to provide good predictions in some regions, e.g. Lesser Antilles (Douglas & Mohais, 2009). In addition, it is based on many thousands of records from Japan. Therefore, we believe it is a useful model for GEM1 and should be retained.

Add Zhao et al. (2006) instead of KAEA06 (it is not listed in the selection of three models given in Section 6, paragraph 3 of Douglas et al.; perhaps KAEA06 in that list was intended to mean ZAEA06 there, because ZAEA06 turns up in the reduced set of equations on the second page of section 6).

Details of Zhao et al. (2006) are given in the section on Equations for subduction zones.

Section 6, Paragraph 6: If just two ground motion models are to be used, then we agree with Douglas et al. that they should be KAEA06 and YOEA97 *(the only two left).*

We assume that the authors mean Zhao et al. (2006) especially if they do not think Kanno et al. (2006) should have been selected in the first place.

Crustal Earthquakes in Tectonically Active Regions (AKBO07, BOAT06, CAB08, CAFA08 and CHYO08 were recommended by Douglas et al.):

Eliminate Cauzzi and Faccioli (2008), based on criterion 1 – its applicability is limited to R > 15 km and M < 7.5, and criterion 2 - it uses hypocentral distance. We previously stated some of the reasons in favour of retaining Cauzzi & Faccioli (2008); as a further consideration, we add that it was derived using a large dataset with good site characterization.

If just two ground motion models are to be used, then keep BOAT08 (over full magnitude and distance ranges, notwithstanding its data limitations for M<6.5, T<3, (In view of these limitations we find this recommendation highly questionable) but replace Cauzzi and Faccioli (2008) with Chiou and Youngs (2008), based on the evaluation in Allen and Wald (2009). Chiou and Youngs (2008) is more consistent with criteria 1 and 4 than Akkar and Bommer (2007), because the latter is limited to periods not longer than 4 seconds (as against 10), and uses geological categories (as against continuous $V_{S,30}$) to represent site effects. However, if it is preferred not to use only NGA models in this subset of two models, then use BOAT08 plus Akkar and Bommer (2007).

We do not agree since Boore & Atkinson (2008) and Akkar & Bommer (2007) would probably not capture epistemic uncertainty for the entire global and shallow crustal seismicity since they have been shown (e.g. Stafford et al., 2008) to given similar predictions. Cauzzi & Faccioli (2008) is mainly based on Japanese data and hence it would account for these observations.

OTHER GUIDANCE

1. Use the world stress map project to establish tectonic regime

   We really do not know how this would be done and, besides, are there really serious problems with our classification?

2. Adopt a value for truncation of the number of standard deviations to be used with the GMPE's; this truncation is commonly done at 3 standard deviations.

   We do not believe that this was our job, since that is a seismic hazard modeling issue and it was not included in the brief provided to us by Stefan Wiemer. However, any truncation at less than 3 is not justified by the data (e.g. Strasser et al., 2008). The choice between truncation at 3 or 4 epsilon or no truncation is unlikely to significantly affect the results at return periods less than 1000 years.

3 GEM should produce a seismic hazard map for a single reference ground condition as well as the actual expected shaking given inferred Vs30. The former is valuable for portraying global variations in ground motion levels, and for using an alternative preferred set of site amplifications factors

   This issue of what GEM1 (not GEM) should do with our proposed GMPEs was not in our remit.

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