Compilation and critical review of GMPEs for the GEM-PEER Global GMPEs Project

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SUMMARY:
Ground-motion prediction equations (GMPEs) relate a ground-motion parameter (e.g. peak ground acceleration, PGA) to a set of explanatory variables describing the source, wave propagation path and site conditions. In the past five decades many hundreds of GMPEs for the prediction of PGA and linear elastic response spectral ordinates have been published. We discuss the pre-selection of GMPEs undertaken within the framework of the GEM-PEER Global GMPEs Project. The pre-selection criteria adopted were consistent with the current state-of-the-art in ground-motion characterization and sought to retain only the most robust GMPEs. Consideration of broad tectonic regionalization (e.g. shallow crustal seismicity in tectonically-active areas, stable continental regions and subduction zones) was made but it was assumed (based on previous studies) that strong regional differences were not present within these tectonic classes. In total about thirty GMPEs were pre-selected for closer inspection and testing to obtain a final set of ground-motion models.

Keywords: ground motion prediction equations, attenuation relations, Global Earthquake Model, seismic hazard assessment, tectonic regionalization.

1. INTRODUCTION

As discussed in the other articles in this proceedings on the GEM Global GMPEs project (http://peer.berkeley.edu/globalgmpe/) (Akkar et al., 2012; Stewart et al., 2012a), the goal of this two-year initiative is to provide to the Global Earthquake Model (GEM) a set of ground-motion models with worldwide applicability and based on a consensus view of dozens of international experts. These models should enable the prediction of peak ground acceleration (PGA) and linear elastic (pseudo-)spectral acceleration (PSA) for: the structural period range of main engineering interest; magnitudes from the lower limit generally considered in seismic hazard assessments (typical M_w 5) up to the largest earthquakes possible (roughly M_w 9.5 for subduction events); the source-to-site distances from the closest possible distance (i.e. 0km, right next to the rupture) to the farthest distance considered important in hazard assessments (possibly 1 000km in stable continental regions). The focus of this project is on the selection (and possible adjustment) of pre-existing already-parameterized ground-motion prediction equations (GMPEs) and not on the development of new models. This focus means that Task 2 of the project (the subject of this paper) concerning the pre-selection from the hundreds of available models to obtain a more manageable number for closer examination and testing within Task 3 (the subject of the companion article by Stewart et al., 2012b) is a key step.

Since the publication of the first ground-motion model in the form of an equation with magnitude and source-to-site distance by Esteva and Rosenblueth (1964), the number of GMPEs has increased dramatically and over a dozen new studies are published every year (Figure 1). This high publication rate has been driven by, for example: increased recording (through lower-cost digital instruments and denser networks) and availability of strong-motion data [through online open-access databases, such as the Internet Site for European Strong-motion Data (Ambraseys et al., 2004)], more journals and conferences publishing engineering seismology research, and large-scale initiatives, such as the Next Generation Attenuation (NGA) project (Powers et al., 2008). The latest compendium of published GMPEs by Douglas (2011) lists the characteristics of 289 empirical GMPEs for the prediction of PGA and 188 empirical models for the prediction of elastic response spectral ordinates. In addition, this report lists many dozens of simulation-based models to estimate these parameters.

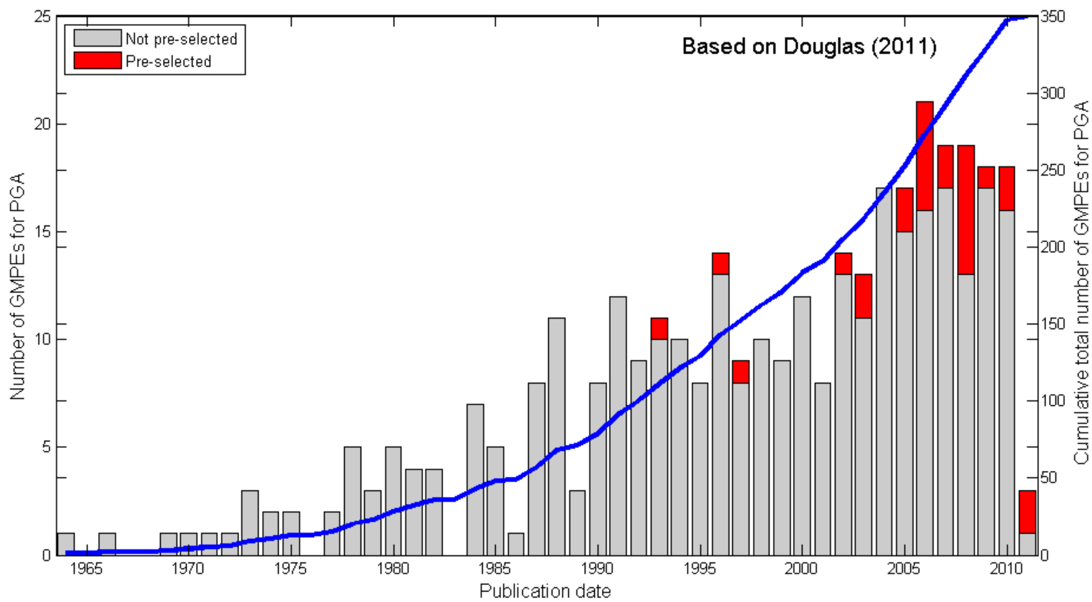


Figure 1. Number of published GMPEs per year (histogram) and cumulatively since 1964 (blue line).

This abundance of models, however, creates a difficulty. On one hand, it is feasible from a practical point of view to carefully consider only a small fraction (less than 10%) of all available GMPEs in any project but, on the other hand, predictions of the median ground motions from the available GMPEs show a large (and not noticeably narrowing) dispersion (Figure 2), which needs to be considered since it demonstrates high epistemic uncertainty in ground-motion prediction. Consequently, a set of objective selection criteria need to be applied to the list of available models to pre-select GMPEs that are the most appropriate for the aims of a given project. For ease of application, these criteria should only require examination of the original references and should not involve numerical evaluation or testing of models against data, which can only be performed for a dozen models at most. These criteria were discussed by the experts comprising the Task 2 working group (the authors of this paper) and subsequently applied by the working group to the lists of models given in Douglas (2011). The discussion process was conducted through a series of conference calls and email exchange in order to obtain a consensus view, which was also objective so it can be supported by the wider community (within the GEM Global GMPEs project and beyond). The working group benefitted from the experience gained in GMPEs pre-selection for the projects: PEGASOS (Cotton et al., 2006), SHARE (Douglas, 2009), GEM1 (Douglas et al., 2009) and PEGASOS Refinement (Bommer et al., 2010).

Because a GMPE excluded during this stage could not be subsequently re-instated, care was taken to avoid applying criteria that are too strict at this step. About thirty GMPEs were finally pre-selected within Task 2, from the models summarized in Douglas (2011), for closer inspection and testing during Task 3 to obtain a final set of ground-motion models. This subsequent winnowing process is described in the companion paper by Stewart et al. (2012b).

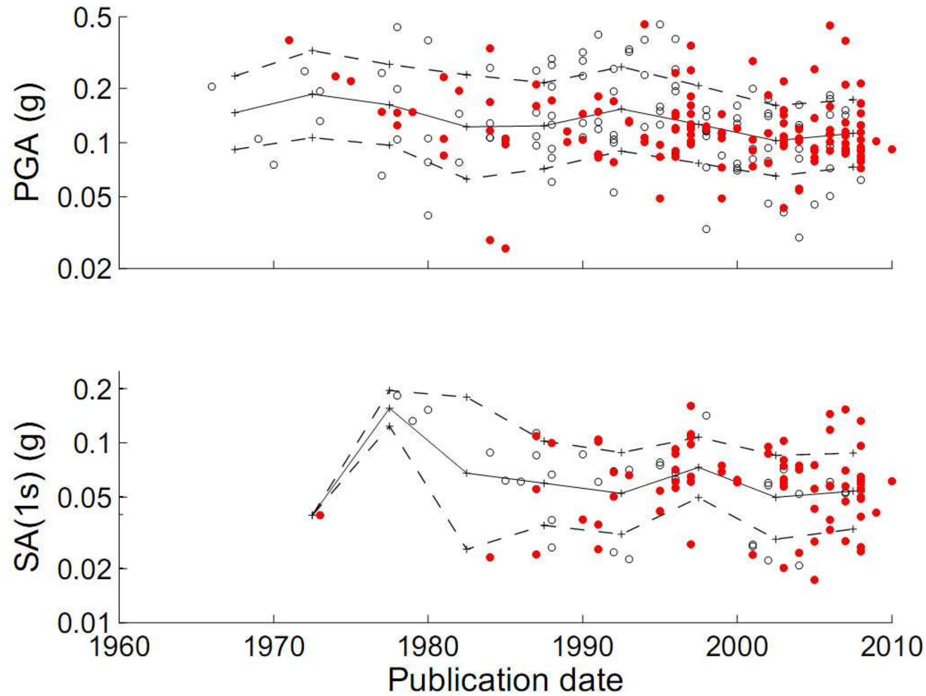


Figure 2. Predicted PGA and SA(1 s) (unfilled black circles) for a M_w6 strike-slip earthquake at 20 km on a NEHRP C site against publication date for over 250 models published in the literature. Filled red circles indicate models published in peer-reviewed journals and for which basic information on the used dataset is available. Also shown are the median PGA and SA(1 s) within five-year intervals (black line) and the median ±1 standard deviation (dashed black lines) based on averaging predictions. From Douglas (2010).

2. PRE-SELECTION CRITERIA

The purpose of this section is to present the final pre-selection criteria for all the seismotectonic regimes present on Earth. Consideration of broad tectonic regionalization (e.g. shallow crustal seismicity in active areas, stable continental regions and subduction zones) was made but it was assumed (based on previous studies) that strong regional differences were not present within these tectonic classes, although we retained a suite of models within each class to account for epistemic uncertainty. We considered these broad tectonic regimes when pre-selecting GMPEs:

- 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.

The pre-selection criteria adopted in this study are consistent with the companion paper (Akkar et al., 2012), which describes and suggests predictive parameters to use in ground-motion modeling and their appropriate values.

As discussed above, 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). It should be noted that these criteria have been updated by Bommer et al. (2010) to make them more objective and stronger. It was decided, however, that for pre-selection the Bommer et al. (2010) proposals would be too strict. The seven exclusion criteria applied to the compilation (both empirical and simulation-based GMPEs) of Douglas (2011) are:

1. the model is from a clearly irrelevant tectonic regime;
2. the model is not published in an international peer-reviewed journal;
3. the documentation of model and its underlying dataset is insufficient;
4. the model has been superseded by more recent publications;
5. the frequency range of the model is not appropriate for engineering application;
6. the model has an inappropriate functional form; and
7. 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, and a few other special cases where it was felt that a model that failed this criterion was potentially interesting for further study within Task 3. 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 are 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, is 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 modeling 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 to at least 100km are rejected since this is the focus of seismic hazard assessments in GEM. The choices here reflect the decision from Task 1a to reject models that would require more than a 0.5 unit extrapolation of the maximum M_w for which the GMPEs were derived. 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, we 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 stochastic models without fitted functional forms were 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. Non-parametric models (e.g. those represented by neural networks) were not considered because of the difficulty in using them in practice and because of doubts over their extrapolation outside the range of data. Overall the aim was to retain between five and ten models per tectonic type for further examination.

3. PRE-SELECTED MODELS

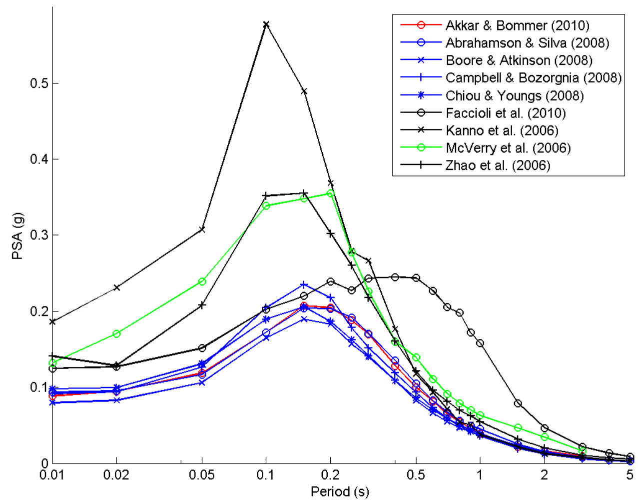
Table 3.1 lists the models pre-selected in Task 2 for the three main seismotectonic regimes. Details on the pre-selection procedure and the pre-selected models are given in the report by Douglas et al. (2011). It should be noted that this pre-selection was performed in April 2011. During the duration of the GEM Global GMPEs project many new GMPEs will be published (by considering the publication rate shown in Figure 1) but it is not planned within the project to repeat this pre-selection to account for these new models. This exclusion of the most recent GMPEs is an inherent limitation of all seismic hazard assessments.

As an example of the dispersion in the predicted response spectra from the pre-selected GMPEs, Figure 3 shows spectra estimated using the three sets of GMPEs for three of the scenarios considered by Douglas (2010), although for rock rather than stiff soil conditions. These scenarios are roughly in the barycentre of available strong-motion data and, consequently, the differences amongst the predicted spectra should be lowest here. The differences amongst the spectra will probably be greater closer to the source and for larger earthquakes because of a lack of data to constrain the models and a lack of knowledge on how earthquake shaking scales with magnitude and distance. These comparisons show that even after careful pre-selection of models based on data from the best-observed regions (e.g. California and Japan) there is still much epistemic uncertainty in the prediction of earthquake response spectra. It will be the challenge of Task 3 of the GEM Global GMPEs project to propose a reduced set of ground-motion models that capture this epistemic uncertainty but without overestimating it. The interested reader is referred to the companion paper by Stewart et al. (2012) on how this challenge is being faced for subduction zones.

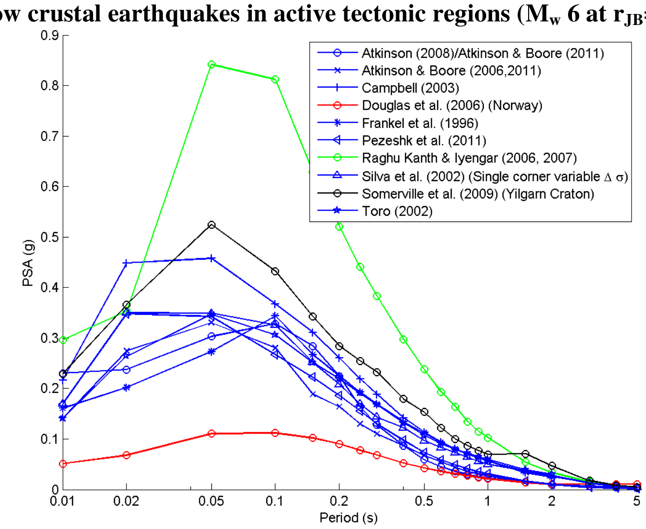
Very few GMPEs have been published for the remaining seismotectonic regimes [volcanic zones; areas of deep focus non-subduction earthquakes, such as Vrancea (Romania); and areas where the travel paths are mainly through oceanic crust, such as coastal Portugal] and the majority of these do not pass the pre-selection criteria. Therefore, within Task 3 it is planned to propose that models finally selected for the other three regimes are adjusted to make them applicable for the prediction of ground motions in these special areas. It is admitted that this work-around is not an optimal solution but we prefer proposing a suite of robust models to account for high epistemic uncertainty rather than choosing a single local (and potentially poorly-constrained) model for each regime that gives the false impression of low uncertainty.

Table 3.1 List of pre-selected models in Task 2 of the GEM – PEER Global GMPEs project

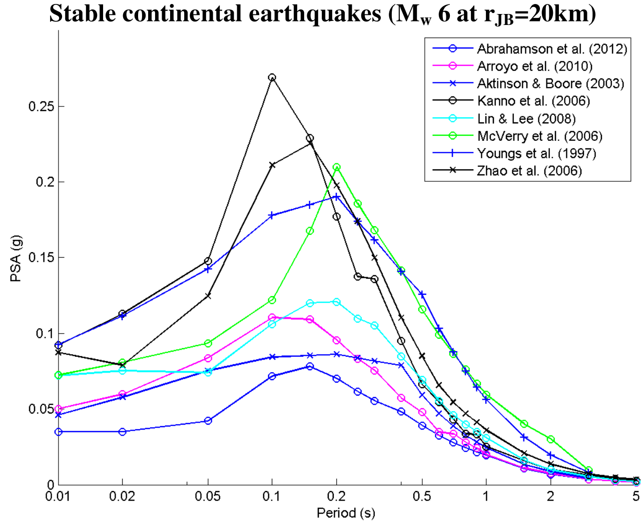
Stable Continental	Atkinson (2008) as modified by Atkinson & Boore (2011): Referenced empirical model for eastern North America
	Atkinson & Boore (2006) as modified by Atkinson & Boore (2011): Extended stochastic model for eastern North America
	Campbell (2003): Hybrid model for eastern North America
	Douglas et al. (2006): Hybrid model for southern Norway
	Frankel et al. (1996) as parameterized by EPRI (2004): Stochastic model for eastern North America
	Pezeshk et al. (2011): Hybrid model for eastern North America
	Raghu Kanth & Iyengar (2006, 2007): Peninsular India
	Silva et al. (2002): Stochastic model for eastern North America
	Somerville et al. (2009): Simulation-based models for Australia
	Toro et al. (1997), originally published in EPRI (1993), modified by Toro (2002): Stochastic model for eastern North America
Subduction	Abrahamson et al. (2012): Worldwide
	Arroyo et al. (2010): Interface model for Mexico (complementary to Garcia et al., 2005))
	Atkinson & Boore (2003): Worldwide
	Garcia et al. (2005): Intraslab model for Mexico (complementary to Arroyo et al., 2010)
	Kanno et al. (2006): Japan
	Lin & Lee (2008): Taiwan
	McVerry et al. (2006): New Zealand
	Youngs et al. (1997): Worldwide
	Zhao et al. (2006) with modifications by Zhao (2010): Japan
Shallow crustal in tectonically active regions	Abrahamson & Silva (2008): NGA model using worldwide data
	Akkar & Bommer (2010): Model using Mediterranean and Middle Eastern data
	Boore & Atkinson (2008) as modified by Atkinson & Boore (2011): NGA model using worldwide data
	Campbell & Bozorgnia (2008) : NGA model using worldwide data
	Cauzzi & Faccioli (2008) as updated by Faccioli et al. (2010): Model using worldwide data (mainly Japanese)
	Chiou & 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



Shallow crustal earthquakes in active tectonic regions (M_w 6 at r_{JB}=20km)



Stable continental earthquakes (M_w 6 at r_{JB}=20km)



Subduction interface earthquakes (Mw 6.5 at r_{rup}=50km)

Figure 3. Predicted elastic pseudo-acceleration response spectra from for a rock site for (top): a strike-slip shallow crustal earthquake of Mw 6 at a distance to the surface projection of the rupture of 20km, (middle): an Mw 6 earthquake in a stable continential region at a distance to the surface projection of the rupture of 20km, and (bottom): an Mw 6.5 interface earthquake in a subduction zone at a rupture distance of 50km.

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REFERENCES

Abrahamson, N.A., Silva, W. (2008). Summary of the Abrahamson & Silva NGA ground-motion relations, *Earthquake Spectra*, **24:1**, 67–97, doi: 10.1193/1.2924360.
Abrahamson, N., Gregor, N., Addo, K. (2012). BCHydro ground motion prediction equations for subduction earthquakes, *Earthquake Spectra*, submitted.
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*, **81:2**, 195–206.
Akkar, S., Douglas, J., Di Alessandro, C., Campbell, K., Somerville, P., Cotton, F., Silva, W., Baker, J. (2012), Defining a consistent strategy to model ground-motion parameters for the GEM-PEER Global GMPEs Project, *Proceedings of the Fifteenth World Conference on Earthquake Engineering*.
Ambraseys, N. N., Smit, P., Douglas, J., Margaris, B., Sigbjörnsson, R., Ólafsson, S., Suhadolc, P., Costa, G. (2004). Internet site for European strong-motion data. *Bollettino di Geofisica Teorica ed Applicata*, **45:3**, 113–129.
Arroyo, D., García, D., Ordaz, M., Mora, M.A., Singh, S.K. (2010). Strong ground-motion relations for Mexican interplate earthquakes, *Journal of Seismology*, **14:4**, 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*, **98:3**, 1304–1318, doi: 10.1785/0120070199.
Atkinson, G. M., Boore, D. M. (2003). Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions, *Bulletin of the Seismological Society of America*, **93:4**, 1703–1729.
Atkinson, G. M., Boore, D. M. (2006). Earthquake ground-motion prediction equations for eastern North America, *Bulletin of the Seismological Society of America*, **96:6**, 2181–2205, doi: 10.1785/0120050245.
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*, **101:3**, 1121-1135, doi: 10.1785/0120100270.
Bommer, J. J., Stafford, P. J., Alarcón, J. E. Akkar, S. (2007). The influence of magnitude range on empirical ground-motion prediction. *Bulletin of the Seismological Society of America,* **97:6**, 2152–2170.
Bommer, J.J., Douglas, J., Scherbaum, F., Cotton, F., Bungum, H., Fäh, D. (2010). On the selection of ground-motion prediction equations for seismic hazard analysis, *Seismological Research Letters*, **81:5**, 783–793.
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*, **24:1**, 99–138, doi: 10.1193/1.2830434.
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*, **93**, 1012–1033.
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*, **24:1**, 139–171, doi: 10.1193/1.2857546.
Cauzzi, C., Faccioli, E. (2008). Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records, *Journal of Seismology*, **12:4**, 453–475, doi: 10.1007/s10950-008-9098-y.
Chiou B.S-J., Youngs, R.R. (2008). An NGA model for the average horizontal component of peak ground motion and response spectra, *Earthquake Spectra*, **24:1**, 173–215, doi: 10.1193/1.2894832.
Cotton, F., Scherbaum, F., Bommer, J.J., Bungum, H. (2006). Criteria for selecting and adjusting ground-motion models for specific target regions: Application to central Europe and rock sites, *Journal of Seismology*, **10:2**, 137–156, doi: 10.1007/s10950-005-9006-7.
Crouse, C.B. (1991). Ground-motion attenuation equations for earthquakes on the Cascadia subduction zones, *Earthquake Spectra*, **7:2**, 201–236.
Douglas, J. (2009). Pre-selection of ground-motion prediction equations for WP4 of SHARE, Internal SHARE Report.
Douglas, J. (2010). Consistency of ground-motion predictions from the past four decades, *Bulletin of Earthquake Engineering*, **8**, 1515-1526.
Douglas, J. (2011). Ground-motion prediction equations 1964–2010, *Final report RP-59356-FR (PEER Report 2011/102)*, BRGM, Orléans, France, URL http://www.brgm.fr/publication/rechRapportSP.jsp.

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*, **10:1**, 33–72.
Douglas, J., Faccioli, E., Cotton, F., Cauzzi, C. (2009). Selection of ground-motion prediction equations for GEM1, *GEM Technical Report E1*. URL http://www.globalquakemodel.org/system/files/doc/GEM-TechnicalReport_2010-E1.pdf.
Douglas, J., Cotton, F., Abrahamson, N., Akkar, S., Boore, D.M. and Di Alessandro, C. (2011). Pre-selection of ground-motion prediction equations (Task 2), *PEER GEM – Global GMPEs Task 2 WG*, URL www.nexus.globalquakemodel.org/gem-gmpes/posts/
Electric Power Research Institute (1993). Guidelines for determining design basis ground motions. Palo Alto, Calif: Electric Power Research Institute, vol. 1-5, *EPRI TR-102293*.
Electric Power Research Institute. (2004). CEUS ground motion project final report. *Tech. rept. 1009684*. EPRI, Palo Alto, CA, Dominion Energy, Glen Allen, VA, Entergy Nuclear, Jackson, MS, and Exelon Generation Company, Kennett Square, PA.
Esteva, L., Rosenblueth, E. (1964). Espectros de temblores a distancias moderadas y grandes. *Boletin Sociedad Mexicana de Ingenieria Sesmica*, **2**, 1–18. In Spanish.
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 the University of Tokyo Symposium on Long-Period Ground Motion and Urban Disaster Mitigation*.
Field, E.H. (2000). A modified ground-motion attenuation relationship for southern California that accounts for detailed site classification and a basin-depth effect, *Bulletin of the Seismological Society of America*, **90:6B**, S209–S221.
Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E.V., Dickman, N., Hanson, S., Hopper, M. (1996). National Seismic-Hazard Maps: Documentation June 1996, *Open-File Report 96-532*. U.S. Department of the Interior, U.S. Geological Survey.
Ghasemi, H., Zare, M., Fukushima, Y., Koketsu, K. (2009). An empirical spectral ground-motion model for Iran, *Journal of Seismology*, **13**, 499–515, doi: 10.1007/s10950-008-9143-x.
Garcia, D., Singh, S.K., Herraiz, M., Ordaz, M., Pacheco J.F. (2005). Inslab earthquakes of central Mexico: Peak ground-motion parameters and response spectra, *Bulletin of the Seismological Society of America*, **95:6**, 2272–2282, doi: 10.1785/0120050072.
Hwang, H., Huo, J.-R. (1997). Attenuation relations of ground motion for rock and soil sites in eastern United States, *Soil Dynamics and Earthquake Engineering*, **16:6**, 363–372.
Kanno, T., Narita, A., Morikawa, N., Fujiwara, H., Fukushima, Y. (2006). A new attenuation relation for strong ground motion in Japan based on recorded data, *Bulletin of the Seismological Society of America*, **96:3**, 879–897, doi: 10.1785/0120050138.
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*, **98:1**, 220–240, doi:10.1785/0120060002.
McVerry, G.H., Zhao, J.X., Abrahamson, N.A., Somerville, P.G. (2006). New Zealand acceleration response spectrum attenuation relations for crustal and subduction zone earthquakes, *Bulletin of the New Zealand Society for Earthquake Engineering*, **39:4**, 1–58.
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*, **101:4**, 1859-1870, August 2011, doi: 10.1785/0120100144
Power, M., Chiou, B., Abrahamson, N., Bozorgnia, Y., Shantz, T., Roblee, C. (2008). An overview of the NGA project, *Earthquake Spectra*, **24:1**, 3-21, doi: 10.1193/1.2894833.
Raghu Kanth, S.T.G., Iyengar, R.N. (2006). Seismic hazard estimation for Mumbai city, *Current Science*, **91:11**, 1486–1494.
Raghu Kanth, S.T.G., Iyengar, R.N. (2007). Estimation of seismic spectral acceleration in peninsular India, *Journal of Earth System Science*, **116:3**, 199–214.
Silva, W., Gregor, N., Darragh, R. 2002 (Nov). Development of regional hard rock attenuation relations for central and eastern North America. *Tech. rept. Pacific Engineering and Analysis*.
Somerville, P., Graves, R., Collins, N., Song, S.G., Ni, S., Cummins, P. (2009). Source and ground motion models of Australian earthquakes, *Proceedings of the 2009 Annual Conference of the Australian Earthquake Engineering Society*.
Stewart, J. P., Seyhan, E., Boore, D. M., Campbell, K. W., Erdik, M., Silva, W. J., Di Alessandro, C., Bozorgnia, Y. (2012a), Site Effects in Parametric Ground Motion Models for the GEM-PEER Global GMPEs Project, *Proceedings of the Fifteenth World Conference on Earthquake Engineering.*

Stewart, J. P., Douglas, J., Di Alessandro, C., Abrahamson, N. A., Boore, D. M., Bozorgnia, Y., Campbell, K., Delavaud, E., Erdik, M., Stafford, P. J. (2012b). Selection or derivation of a global set of GMPEs for the GEM-PEER Global GMPEs Project, *Proceedings of the Fifteenth World Conference on Earthquake Engineering*.

Toro, G.R. (2002). Modification of the Toro et al. (1997) attenuation equations for large magnitudes and short distances, *Technical Report, Risk Engineering*.

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*, **68:1**, 41–57.

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

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*, **100:2**, 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, Y. (2006) Attenuation relations of strong ground motion in Japan using site classification based on predominant period, *Bulletin of the Seismological Society of America*, **96:3**, 898–913, doi: 10.1785/0120050122.