

Consistency of ground-motion predictions from the past four decades: Peak ground velocity and displacement, Arias intensity and relative significant duration

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Abstract Due to the limited observational datasets available for the derivation of ground-motion prediction equations (GMPEs) there is always epistemic uncertainty in the estimated median ground motion. Since the quality and quantity of strong-motion datasets is constantly increasing it would be expected that the epistemic uncertainty in ground-motion prediction (related to lack of knowledge and data) is decreasing. This article is a continuation of the study of Douglas (2010) for ground-motion parameters other than peak ground acceleration (PGA) and elastic response spectral acceleration (SA). The epistemic uncertainty in the prediction of peak ground velocity and displacement, Arias intensity and relative significant duration is investigated by plotting predictions from dozens of GMPEs for these parameters against date of publication for three scenarios. In agreement with the previous study, all ground-motion parameters considered show high epistemic uncertainty (often even higher than previously reported for PGA and SA), suggesting that research efforts for the development of GMPEs for these parameters should continue and that it is vital that this uncertainty is accounted for in seismic hazard assessments. The epistemic uncertainty in the prediction of relative significant duration, however, appears to be much lower than any other strong-motion parameter, which suggests that currently available GMPEs for this intensity measure are sufficiently mature.

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1 Introduction

The consistency in predicted peak ground acceleration (PGA) and elastic response spectral acceleration (SA) for 5% damping and a natural period of 1 s was discussed in Douglas (2010). In that article, predicted PGAs and SAs from hundreds of published ground-motion prediction equations (GMPEs) for various earthquake scenarios ($M_w 6$ at 20 km, roughly the best-represented scenario in global strong-motion datasets, and $M_w 7.5$ at 10 km and $M_w 5$ at 10 km, at the edges of most databases used to derive GMPEs) were plotted against their publication dates. The purpose of these plots was to investigate the epistemic uncertainty associated with GMPEs and to test whether this uncertainty is decreasing, which would be expected given the accumulation of new data and knowledge and improvements in regression techniques, for example. The scatter in predictions shown on such plots is a rough measure of epistemic uncertainty because, in the absence of such uncertainty, predictions of the median ground motion for a certain scenario should tend to a single value. The plots of Douglas (2010) showed that even though epistemic uncertainty seems to be reducing slightly (predictions from different models are slowly converging), there is still considerable uncertainty in estimated PGAs and SAs even for scenarios that are well represented in strong-motion databanks, and much higher uncertainties for poorly-sampled scenarios (specifically large earthquakes at short distances).

The purpose of this short article is to extend the analysis of Douglas (2010) to strong-motion parameters other than PGA and SA, which are useful for some aspects of engineering seismology and earthquake engineering. The four non-PGA/SA strong-motion parameters with most associated GMPEs are considered here, namely: peak ground velocity (PGV), peak ground displacement (PGD), Arias intensity (AI) (Arias, 1970) and relative significant duration (RSD) (Trifunac and Brady, 1975b). In contrast to PGA and SA, there are far fewer GMPEs published for these parameters but there are still sufficient to enable some conclusions on their predictability to be drawn. Unlike for PGA and SA, my search for GMPEs for the prediction of these other parameters only started recently and hence it is more likely that the collection of non-PGA/SA models considered here are less complete than given

in Douglas (2011) for PGA and SA. However, a thorough literature search was conducted and various reviews were studied (e.g. Bommer and Martínez-Pereira, 1999; Bommer and Alarcón, 2006; Travararou et al, 2003; Tromans, 2004). Therefore, it is unlikely that many models are missing. Table 1 lists the considered GMPEs and gives, when possible (some of the original references could not be consulted and some authors do not provide the necessary information), their main characteristics.

In the next section, graphs are presented for the four considered strong-motion parameters and the same three earthquake scenarios as in Douglas (2010). To facilitate comparisons with the results of Douglas (2010) the same scenarios are considered here except that separate plots are not made for broad geographical or tectonic regions [western North America; Europe, the Mediterranean and the Middle East; stable continental regions; and Japan (subduction zones)]. The dependence of PGV, PGD, AI and RSD on tectonic regime is less well studied than for PGA and SA because the vast majority of GMPEs for these parameters are derived for shallow crustal earthquakes in active regions (see Table 1). It is likely that this lack of consideration of tectonic regime will slightly increase the scatter in the following plots. The same graph format is used to facilitate comparisons with the previous graphs for PGA and SA. For example, the ratio of the upper and lower limits of the abscissa, displaying the strong-motion parameter, is 25 and a logarithmic axis is used. As before those studies that were published in peer-reviewed international journals and give basic details of the datasets used for their derivation [criteria 2 and 3 of (Cotton et al, 2006)] and which are not being extrapolated far outside their magnitude-distance range of applicability are indicated. Because this study makes the same choices and considers the same scenarios as Douglas (2010), only brief details are given here. The interested reader is referred to the previous article for more information.

The differences between the aleatory variabilities (σ) associated with GMPEs for the different parameters are not discussed here. Table IV of Travararou et al (2003) presents such a comparison for PGA, SA(0.5 s), AI and RSD predicted by a family of GMPEs derived using a similar database, functional form and regression technique. This table shows that the aleatory variabilities for each of these parameters are similar, except for the GMPE for AI, which has a much higher σ suggesting that AI is more intrinsically variable.

2 Comparing ground-motion predictions

Models have been adjusted to, where possible: moment magnitude (M_w), distance to the surface projection of the rupture (Joyner-Boore distance) (r_{jb}), vertical-dipping strike-slip faulting and the geometric mean of the two horizontal components. These adjustments were made using the approaches of Bommer et al (2005) using: for PGV and PGD, style-of-faulting and component definition factors of Campbell and Bozorgnia (2007) and for AI, style-of-faulting and component definition factors of Stafford et al (2009)¹. For the conversion to M_w from surface-wave magnitude (M_s) the equation of Ambraseys and Free (1997) was used. Local magnitude (M_L), and other magnitude scales, were assumed equal to M_w . Harmonization of models is not always possible due to a lack of information in many of the original references on, for example, definition of horizontal component and magnitude scale. This means that the predictions could be in error by roughly 20% but this will not alter the overall trends, which are the focus of this article (the reader should not seek to over-interpret details in the graphs). The size of the rupture plane and other additional parameters needed to evaluate some of the models have been computed using the methods given in Chapter 7 of Campbell and Bozorgnia (2007). To compute the epicentral and hypocentral distances the hypocentre is assumed to be at one end of the fault at a depth of 10km and the site half way along the fault. Some authors seek to model epistemic uncertainty in ground-motion prediction by proposing more than one set of GMPEs, e.g. by providing coefficients for different functional forms (e.g. Stafford et al, 2009). Predictions from each of these variant GMPEs are included here.

Because it is roughly the best-represented scenario in global strong-motion datasets the first scenario considered is a M_w6 strike-slip earthquake at $r_{jb} = 20$ km on a site classified as NEHRP class C (Eurocode 8 class B) ($V_{s,30} = 490$ m/s). If epistemic uncertainty in the prediction of ground motion is decreasing then it should be visible for this scenario since it is where available observations are most abundant and hence GMPEs should be the best constrained. The other two scenarios considered are: $M_w7.5$ strike-slip earthquake at $r_{jb} = 10$ km, for which there are still few available data, and M_w5 strike-slip earthquake at $r_{jb} = 10$ km, which is at the lower edge of most datasets used for the derivation of GMPEs, for

¹ Kempton and Stewart (2006) and Bommer et al (2009) find that style-of-faulting does not have a statistically significant effect on RSD. Factors to convert between different component definitions of RSD are not available so no adjustment was attempted.

the same site conditions. It is expected that epistemic uncertainty (and hence scatter in the predictions) will be higher for these two scenarios compared to $M_w 6$ at $r_{jb} = 20$ km due to the lack of observations and uncertainty over near-source magnitude-scaling, for example. The following sections present the results for the four parameters in turn. As a measure of the dispersion in the median predictions the standard deviation of the common (base 10) logarithm of median estimates for each five-year interval are computed, although because of the limited number of GMPEs this statistic is quite unstable.

As for the analysis shown in Douglas (2010) the median ground motion for the considered scenario obtained from a large (over 13,000 records from over 2,500 events) strong-motion database [the data from the Internet Site for European Strong-motion Data (ISESD) (Ambraseys et al, 2004) with the addition of many accelerograms from western North America and elsewhere] is plotted at all dates. The median should track the predictions, since similar databases were used to derive the GMPEs published up to that date, and the variability in the median should also show a reduction, since more data are being used to compute the averages. The variabilities of the medians are computed here by dividing the standard deviation by \sqrt{n} , where n is the number of records used to compute the standard deviation. The medians and their variabilities were computed by considering the available records within $0.5 - M_w$ units and 10 km of the scenario of interest and excluding a consideration of local site conditions and style of faulting. It could be argued that these bins are too broad and that a consideration of local site effects should have been made. However, given the limited data available, particularly for $M_w > 7$, narrow bins would lead to statistics based on few records from only a handful of earthquakes. The median ground motions computed from averaging data within broad bins should not be strongly affected by the width of the bins but the variabilities of these medians may be slightly overestimated. The uniform filtering applied to the strong-motion databank used here (bandpass filtering with cut-offs of 0.25 and 25 Hz) means that the PGV and, especially, PGD observations obtained from this databank are likely to be incorrect. The averages of these PGV and PGD observations, however, are added for completeness. AI and RSD from these records, however, are likely to be little affected by the uniform filtering.

2.1 Peak ground velocity

Because of its various uses in earthquake engineering (Bommer and Alarcón, 2006) and its simplicity, following PGA and SA, PGV is the best served by GMPEs and 96 models were identified and programmed, many of which also provide coefficients for the prediction of PGA and SA. The predicted PGVs and median PGVs from the strong-motion databank for the three considered scenarios are shown in Figure 1 (some predicted PGVs are off the top or bottom of these figures, often because the GMPEs are being extrapolated far outside their range of applicability). These figures show that the dispersion in predicted PGVs from different GMPEs is large (the ratio between the smallest and largest predictions is greater than ten) and that this scatter is not obviously reducing with time (even when considering only models passing basic quality-control criteria), particularly near to large earthquakes. The standard deviation of the common logarithm of median estimates for each five-year interval are around 0.2 for M_w6 at $r_{jb} = 20\text{km}$ and M_w5 at $r_{jb} = 10\text{km}$ and around 0.3 for $M_w7.5$ at $r_{jb} = 10\text{km}$. Also roughly constant are the average PGV predicted by the models over time. The median observed PGVs are similar to those predicted by the GMPEs although lower for the $M_w7.5$ scenario. A similar conclusion was also noted by Douglas (2010) for PGA and SA(1s) for large earthquakes, which was related to a number of recent large earthquakes (e.g. Chi-Chi 1999; Kocaeli 1999; Denali 2002) showing lower than expected ground motions (e.g. Ellsworth et al, 2004).

[Fig. 1 about here.]

2.2 Peak ground displacement

Because of the difficulty in obtaining reliable PGDs from analogue (and even digital) accelerograms and the limited use of PGD in earthquake engineering, there are only 19 published GMPEs for PGD, which are typically associated with GMPEs for PGV. Although of limited use in most fields of earthquake engineering, the robust prediction of PGD would help constrain the long-period ($> 2\text{s}$) response spectral displacements because these must converge to PGD at very long periods (Faccioli et al, 2004). The predictions from the GMPEs for the three considered scenarios are shown in Figure 2. These graphs show the large dispersion in predictions of PGD, especially near to large earthquakes. This dispersion is probably due in large part to the difficulty in recovering reliable displacement traces from

strong-motion records because of their high sensitivity to processing (e.g. low-cut filtering) (e.g. Paolucci et al, 2008). The observed PGDs match the predictions reasonably well for the smaller magnitudes but they are considerably lower for the $M_w 7.5$ earthquake, which is probably since the application of a low-cut filter with a corner frequency of 0.25 Hz is likely to lead to significant loss of the true long-period energy from such large events.

[Fig. 2 about here.]

2.3 Arias intensity

As noted by, for example, Travararou et al (2003), AI has a number of uses in earthquake engineering, particularly for slope stability analysis and liquefaction assessment. These uses have motivated the development of, at least, 33 GMPEs, including variants, for AI. Some of these GMPEs only give the value of the integral and not the complete expression for AI; for these the constant $\pi/2g$ was included when plotted. The predictions from these 33 models and the median observed AI for the three scenarios are plotted in Figure 3. The standard deviations of the median predicted AIs are around 0.4 for $M_w 5$ at $r_{jb} = 10$ km, around 0.3 for $M_w 6$ at $r_{jb} = 20$ km and around 0.2 for $M_w 7.5$ at $r_{jb} = 10$ km. This implies that the epistemic uncertainty in the prediction of median AI for larger earthquakes is lower than that for smaller events, which is counterintuitive since there are far fewer available records for this scenario. Two possible reasons for this observation are that regional differences in AI, modelled within local GMPEs, are stronger for smaller events, and that current GMPE developers for AI have concentrated their efforts on the prediction of AI from large earthquakes. AI was not considered by the NGA developers (Power et al, 2008) and, therefore, there is perhaps a requirement to develop a new generation of models for the prediction of this parameter; there have been some recent attempts in this direction (e.g. Foulser-Piggott and Stafford, 2012).

[Fig. 3 about here.]

2.4 Relative significant duration

As noted by Bommer and Martínez-Pereira (1999), many dozens of definitions of strong-motion duration have been proposed, which give widely ranging values. The definition of

duration that is most commonly used in earthquake engineering (and consequently for which there are most GMPEs available) is the relative significant duration originally defined by Trifunac and Brady (1975b) as the interval between 5 and 95% of the total Arias intensity. Despite its various uses (e.g. Kempton and Stewart, 2006), e.g. in liquefaction evaluation, only 15 GMPEs have been identified in the literature for the prediction of this parameter. Figure 4 present the history of the predictions from these 15 models and the median observed RSDs for the three scenarios. The epistemic uncertainty in the prediction of median RSD is much lower than for the other ground-motion parameters considered here (the standard deviation of the median predicted RSDs in the past five year is less than 0.1 even for large earthquakes). This suggests that, either: a) epistemic uncertainty in the prediction of this parameter is being under represented by the different models (because they often use similar databases and functional forms) or b) this parameter is easier to predict than the other intensity measures. The widths of the confidence limits for the median observed RSD are narrower than the confidence limits for PGV, PGD and AI [and those for PGA and SA(1s) shown in Douglas (2010)], which hints that the epistemic uncertainty in the prediction of RSD is truly lower than for these other parameters. This could be because the physics underlying the relative duration characteristics of earthquake shaking (e.g. rupture time and wave dispersion and scattering) are perhaps easier to capture in a simple functional form compared with the physics explaining strong-motion amplitudes, measured by the other parameters.

[Fig. 4 about here.]

3 Conclusions

There have been recent studies (e.g. Baker, 2007) applying vector-valued probabilistic seismic hazard assessment (VPSHA) (Bazzurro and Cornell, 2002) for the joint prediction of pairs of parameters other than PGA and SA. Recently, Gehl et al (2011) present a method for the derivation of structural fragility functions of more than one intensity measure, which could be coupled with VPSHA for vector-valued risk evaluation. For this type of study the relative uncertainties in the prediction of each parameter are important. This article suggests that the epistemic uncertainties in the prediction of PGV, PGD and AI are higher even than those evidenced by Douglas (2010) for PGA and SA. For PGV and AI, this larger uncertainty is probably principally due to lesser research effort having been made in the development

of GMPEs for such parameters compared to PGA and SA. Although both parameters have recently been the subject of various articles, e.g. the NGA developers also developed models for the prediction of PGV. The instability in PGD predictions is due to both lack of research interest in the development of GMPEs for this parameter, because of limited engineering applications, but also because PGD is inherently difficult to recover from strong-motion records due to its sensitivity to low-cut filtering (e.g. Boore and Atkinson, 2008). The epistemic uncertainty in the prediction of RSD, on the other hand, seems to be lower than that associated with the prediction of any of the other parameters, which could encourage more consideration of this parameter within earthquake hazard and risk assessments for which it has various engineering applications.

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References

- Abrahamson N, 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, Silva W (2009) Errata for “Summary of the Abrahamson and Silva NGA ground-motion relations” by Abrahamson, N. A. and W. J. Silva. Published on PEER NGA website
- Abrahamson NA, Shedlock KM (1997) Overview. *Seismological Research Letters* 68(1):9–23
- Abrahamson NA, Silva WJ (1996) Empirical ground motion models. Tech. rep., report to Brookhaven National Laboratory. Cited in Stewart et al (2001).
- Abrahamson NA, Youngs RR (1992) A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America* 82(1):505–510
- Akkar S, Bommer JJ (2007) Prediction of elastic displacement response spectra in Europe and the Middle East. *Earthquake Engineering and Structural Dynamics* 36(10):1275–1301, DOI 10.1002/eqe.679

-
- Akkar S, Bommer JJ (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, Çağnan Z (2010) A local ground-motion predictive model for Turkey and its comparison with other regional and global ground-motion models. *Bulletin of the Seismological Society of America* 100(6):2978–2995
- Al-Qaryouti MY (2008) Attenuation relations of peak ground acceleration and velocity in the Southern Dead Sea Transform region. *Arabian Journal of Geosciences* 1(2):111–117
- Alavi AH, Gandomi AH, Modaresnezhad M, Mousavi M (2011) New ground-motion prediction equations using multi expression programming. *Journal of Earthquake Engineering* 15:511–536, DOI 10.1080/13632469.2010.526752
- Alavi B, Krawinkler H (2000) Consideration of near-fault ground motion effects in seismic design. In: *Proceedings of Twelfth World Conference on Earthquake Engineering*
- Ambraseys NN, Free MW (1997) Surface-wave magnitude calibration for European region earthquakes. *Journal of Earthquake Engineering* 1(1):1–22
- Ambraseys NN, 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
- Arias A (1970) A measure of earthquake intensity. In: Hansen R (ed) *Seismic Design for Nuclear Power Plants*, The M.I.T. Press, pp 438–483
- Atkinson GM (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 GM, Boore DM (1997a) Some comparisons between recent ground-motion relations. *Seismological Research Letters* 68(1)
- Atkinson GM, Boore DM (1997b) Stochastic point-source modeling of ground motions in the Cascadia region. *Seismological Research Letters* 68(1):74–85
- Atkinson GM, Boore DM (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 GM, Boore DM (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

-
- Baker JW (2007) Correlation of ground motion intensity parameters used for predicting structural and geotechnical response. In: Kanda, Takada, Furuta (eds) *Applications of Statistics and Probability in Civil Engineering*, Taylor & Francis Group, London
- Bazzurro P, Cornell CA (2002) Vector-valued probabilistic seismic hazard analysis (VPSHA). In: *Proceedings of 7th U.S. National Conference on Earthquake Engineering*, paper No. 61
- Beyer K, Bommer JJ (2006) Relationships between median values and between aleatory variabilities for different definitions of the horizontal component of motion. *Bulletin of the Seismological Society of America* 96(4A):1512–1522, DOI 10.1785/0120050210
- Bindi D, Luzi L, Pacor F, Franceshina G, Castro RR (2006) Ground-motion predictions from empirical attenuation relationships versus recorded data: The case of the 1997-1998 Umbria-Marche, central Italy, strong-motion data set. *Bulletin of the Seismological Society of America* 96(3):984–1002, DOI 10.1785/0120050102
- Bindi D, Parolai S, Grosser H, Milkereit C, Durukal E (2007) Empirical ground-motion prediction equations for northwestern Turkey using the aftershocks of the 1999 Kocaeli earthquake. *Geophysical Research Letters* 34(L08305), DOI 10.1029/2007GL029222
- Bindi D, Luzi L, Pacor F (2009a) Interevent and interstation variability computed for the Italian Accelerometric Archive (ITACA). *Bulletin of the Seismological Society of America* 99(4):2471–2488, DOI 10.1785/0120080209
- Bindi D, Luzi L, Pacor F, Sabetta F, Massa M (2009b) Towards a new reference ground motion prediction equation for Italy: Update of the Sabetta-Pugliese (1996). *Bulletin of Earthquake Engineering* 7(3):591–608, DOI 10.1007/s10518-009-9107-8
- Bindi D, Luzi L, Massa M, Pacor F (2010) Horizontal and vertical ground motion prediction equations derived from the Italian Accelerometric Archive (ITACA). *Bulletin of Earthquake Engineering* 8(5):1209–1230, DOI 10.1007/s10518-009-9130-9
- Boatwright J, Bundock H, Luetgert J, Seekins L, Gee L, Lombard P (2003) The dependence of PGA and PGV on distance and magnitude inferred from northern California ShakeMap data. *Bulletin of the Seismological Society of America* 93(5):2043–2055
- Bommer JJ, Alarcón JE (2006) The prediction and use of peak ground velocity. *Journal of Earthquake Engineering* 10(1):1–31
- Bommer JJ, Martínez-Pereira A (1999) The effective duration of earthquake strong motion. *Journal of Earthquake Engineering* 3(2):127–172

- Bommer JJ, Elnashai AS, Weir AG (2000) Compatible acceleration and displacement spectra for seismic design codes. In: Proceedings of Twelfth World Conference on Earthquake Engineering, paper no. 207
- Bommer JJ, Scherbaum F, Bungum H, Cotton F, Sabetta F, Abrahamson NA (2005) On the use of logic trees for ground-motion prediction equations in seismic-hazard analysis. *Bulletin of the Seismological Society of America* 95(2):377–389, DOI 10.1785/0120040073
- Bommer JJ, Stafford PJ, Alarcón JE (2009) Empirical equations for the prediction of the significant, bracketed, and uniform duration of earthquake ground motion. *Bulletin of the Seismological Society of America* 99(6):3217–3233, DOI 10.1785/0120080298
- Boore DM, Atkinson GM (2007) Boore-Atkinson NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters. PEER Report 2007/01, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley
- Boore DM, Atkinson GM (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
- Boore DM, Watson-Lamprey J, Abrahamson NA (2006) Orientation-independent measures of ground motion. *Bulletin of the Seismological Society of America* 96(4A):1502–1511, DOI 10.1785/0120050209
- Bragato PL, Slejko D (2005) Empirical ground-motion attenuation relations for the eastern Alps in the magnitude range 2.5–6.3. *Bulletin of the Seismological Society of America* 95(1):252–276, DOI 10.1785/0120030231
- Bray JD, Rodriguez-Marek A (2004) Characterization of forward-directivity ground motions in the near-fault region. *Soil Dynamics and Earthquake Engineering* 24(11):815–828, DOI 10.1016/j.soildyn.2004.05.001
- Campbell KW (1990) Empirical prediction of near-source soil and soft-rock ground motion for the Diablo Canyon power plant site, San Luis Obispo county, California. Tech. rep., Dames & Moore, Evergreen, Colorado, prepared for Lawrence Livermore National Laboratory. Not seen. Reported in Idriss (1993).
- Campbell KW (1997) Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters* 68(1):154–179

-
- Campbell KW (2000) Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters* 71(3):352–354
- Campbell KW (2001) Erratum: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra. *Seismological Research Letters* 72(4):474
- Campbell KW, Bozorgnia Y (1994) Near-source attenuation of peak horizontal acceleration from worldwide accelerograms recorded from 1957 to 1993. In: *Proceedings of the Fifth U.S. National Conference on Earthquake Engineering*, vol III, pp 283–292
- Campbell KW, Bozorgnia Y (2007) Campbell-Bozorgnia NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters. PEER Report 2007/02, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley
- Campbell KW, Bozorgnia Y (2008a) Empirical ground motion model for shallow crustal earthquakes in active tectonic environments developed for the NGA project. In: *Proceedings of Fourteenth World Conference on Earthquake Engineering*, paper no. 03-02-0004
- Campbell KW, Bozorgnia Y (2008b) 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 10s. *Earthquake Spectra* 24(1):139–171, DOI 10.1193/1.2857546
- Campbell KW, Duke CM (1974a) Bedrock intensity attenuation and site factors from San Fernando earthquake records. *Bulletin of the Seismological Society of America* 64(1):173–185
- Campbell KW, Duke CM (1974b) A reply. *Bulletin of the Seismological Society of America* 64(6):2009–2010
- Chapman MC (1999) On the use of elastic input energy for seismic hazard analysis. *Earthquake Spectra* 15(4):607–635
- Chiou B, Youngs R, Abrahamson N, Addo K (2010) Ground-motion attenuation model for small-to-moderate shallow crustal earthquakes in California and its implications on regionalization of ground-motion prediction models. *Earthquake Spectra* 26(4):907–926, DOI 10.1193/1.3479930

-
- Chiou BSJ, Youngs RR (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
- Convertito V, De Matteis R, Romeo A, Zollo A, Iannaccone G (2007) A strong motion attenuation relation for early-warning application in the Campania region (southern Apennines). In: Gasparini P, Manfredi G, Zschau J (eds) *Earthquake Early Warning Systems*, Springer
- Cornell CA, Banon H, Shakal AF (1979) Seismic motion and response prediction alternatives. *Earthquake Engineering and Structural Dynamics* 7(4):295–315
- Cotton F, Scherbaum F, Bommer JJ, 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
- Danciu L, Tselentis GA (2007a) Engineering ground-motion parameters attenuation relationships for Greece. *Bulletin of the Seismological Society of America* 97(1B):162–183, DOI 10.1785/0120040087
- Danciu L, Tselentis GA (2007b) Engineering ground-motion parameters attenuation relationships for Greece. In: *Proceedings of the International Symposium on Seismic Risk Reduction: The JICA Technical Cooperation Project in Romania*, pp 327–334, paper ID 26
- Dobry R, Idriss IM, Ng E (1978) Duration characteristics of horizontal components of strong-motion earthquake records. *Bulletin of the Seismological Society of America* 68(5):1487–1520
- Douglas J (2010) Consistency of ground-motion predictions from the past four decades. *Bulletin of Earthquake Engineering* 8(6):1515–1526, DOI 10.1007/s10518-010-9195-5
- Douglas J (2011) Ground-motion prediction equations 1964–2010. Final report RP-59356-FR, BRGM, Orléans, France, URL <http://www.brgm.fr/publication/rechRapportSP.jsp>
- Ellsworth WL, Celebi M, Evans JR, Jensen EG, Kayen R, Metz MC, Nyman DJ, Roddick JW, Spudich P, Stephens CD (2004) Near-field ground motion of the 2002 Denali Fault, Alaska, earthquake recorded at Pump Station 10. *Earthquake Spectra* 20(3):597–615, DOI 10.1193/1.1778172
- Emolo A, Convertito V, Cantore L (2011) Ground-motion predictive equations for low-magnitude earthquakes in the Campania-Lucania area, southern Italy. *Journal of Geophysics and Engineering* 8:46–60, DOI 10.1088/1742-2132/8/1/007

-
- Esteva L, Rosenblueth E (1964) Espectros de temblores a distancias moderadas y grandes. *Boletin Sociedad Mexicana de Ingenieria Sismica* 2:1–18, in Spanish.
- Faccioli E (1983) Measures of strong ground motion derived from a stochastic source model. *Soil Dynamics and Earthquake Engineering* 2(3):135–149
- Faccioli F, Paolucci R, Rey J (2004) Displacement spectra for long periods. *Earthquake Spectra* 20(2):347–376
- Foulser-Piggott R, Stafford PJ (2012) A predictive model for Arias intensity at multiple sites and consideration of spatial correlations. *Earthquake Engineering and Structural Dynamics* 41(3):431–451, DOI 10.1002/eqe.1137
- Frisenda M, Massa M, Spallarossa D, Ferretti G, Eva C (2005) Attenuation relationships for low magnitude earthquakes using standard seismometric records. *Journal of Earthquake Engineering* 9(1):23–40
- Frohlich C, Apperson KD (1992) Earthquake focal mechanisms, moment tensors, and the consistency of seismic activity near plate boundaries. *Tectonics* 11(2):279–296
- Fukushima S, Hayashi T, Yashiro H (2007) Seismic hazard analysis based on the joint probability density function of PGA and PGV. In: *Transactions, SMiRT 19*, paper # M03/1
- García D, Singh SK, Herráiz M, Ordaz M, Pacheco JF (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
- Gaull BA (1988) Attenuation of strong ground motion in space and time in southwest Western Australia. In: *Proceedings of Ninth World Conference on Earthquake Engineering*, vol II, pp 361–366
- Gaull BA, Michael-Leiba MO, Rynn JMW (1990) Probabilistic earthquake risk maps of Australia. *Australian Journal of Earth Sciences* 37:169–187, not seen. Cited in Musson and Cecić (2002).
- Gehl P, Seyedi DM, Douglas J (2011) Vector-valued fragility functions for seismic risk evaluation. *Bulletin of Earthquake Engineering* Submitted
- Ghanat S (2011) Duration characteristics of the mean horizontal component of shallow crustal earthquake records in active tectonic regions. PhD thesis, Arizona State University, USA
- Ghodrati Amiri G, Mahdavian A, Dana FM (2007a) Attenuation relationships for Iran. *Journal of Earthquake Engineering* 11(4):469–492, DOI 10.1080/13632460601034049

-
- Ghodrati Amiri G, Mahdavian A, Dana FM (2007b) Response on the Discussion of 'Attenuation relationships for Iran'. *Journal of Earthquake Engineering* 11(6):1036–1037, DOI 10.1080/13632460701647476
- Ghodrati Amiri G, Khorasani M, Mirza Hessabi M, Razavian Amrei SA (2010) Ground-motion prediction equations of spectral ordinates and Arias intensity for Iran. *Journal of Earthquake Engineering* 14(1):1–29, DOI 10.1080/13632460902988984
- Gregor N, Bolt B (1997) Peak strong motion attenuation relations for horizontal and vertical ground displacements. *Journal of Earthquake Engineering* 1(2):275–292
- Gregor N, Silva W, Darragh B (2002) Development of attenuation relations for peak particle velocity and displacement. A pearl report to pg&e/cec/caltrans., Pacific Engineering and Analysis, El Cerrito, U.S.A., URL http://www.pacificengineering.org/rpts_page1.shtml
- Hasegawa HS, Basham PW, Berry MJ (1981) Attenuation relations for strong seismic ground motion in Canada. *Bulletin of the Seismological Society of America* 71(6):1943–1962
- Hernandez B, Cotton F (2000) Empirical determination of the ground shaking duration due to an earthquake using strong motion accelerograms for engineering applications. In: *Proceedings of Twelfth World Conference on Earthquake Engineering*, paper no. 2254/4/A
- Huo JR (1989) The characteristics of near field strong earthquake ground motion. PhD thesis, Institute of Engineering and Mechanics, China Seismological Bureau, China, in Chinese
- Hwang H, Lin CK, Yeh YT, Cheng SN, Chen KC (2004) Attenuation relations of Arias intensity based on the Chi-Chi Taiwan earthquake data. *Soil Dynamics and Earthquake Engineering* 24:509–517
- Idriss IM (1978) Characteristics of earthquake ground motions. In: *Proceedings of the ASCE Geotechnical Engineering Division Speciality Conference: Earthquake Engineering and Soil Dynamics*, vol III, pp 1151–1265
- Idriss IM (1993) Procedures for selecting earthquake ground motions at rock sites. Tech. Rep. NIST GCR 93-625, National Institute of Standards and Technology
- Iervolino I, Giorgio M, Galasso C, Manfredi G (2010) Conditional hazard maps for secondary intensity measures. *Bulletin of the Seismological Society of America* 100(6):3312–3319, DOI 10.1785/0120090383
- Jibson RW (1987) Summary of research on the effects of topographic amplification of earthquakes shaking on slope stability. Open-File Report 87-268, US Geological Survey,

Menlo Park, California, USA

- Jin X, Kang LC, Ou YP (2008) Ground motion attenuation relation for small to moderate earthquakes in Fujian region, China. *Acta Seismologica Sinica* 21(3):283–295, DOI 10.1007/s11589-008-0283-4
- Joyner WB, Boore DM (1981) Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bulletin of the Seismological Society of America* 71(6):2011–2038
- Joyner WB, Boore DM (1988) Measurement, characterization, and prediction of strong ground motion. In: *Proceedings of Earthquake Engineering & Soil Dynamics II, Geotechnical Division, ASCE*, pp 43–102
- Joyner WB, Boore DM (1993) Methods for regression analysis of strong-motion data. *Bulletin of the Seismological Society of America* 83(2):469–487
- Joyner WB, Fumal TE (1984) Use of measured shear-wave velocity for predicting geologic site effects on strong ground motion. In: *Proceedings of Eighth World Conference on Earthquake Engineering, vol II*, pp 777–783
- Joyner WB, Fumal TE (1985) Predictive mapping of earthquake ground motion. In: *Evaluating Earthquake Hazards in the Los Angeles Region — An Earth Science Perspective*, no. 1360 in U.S. Geological Survey Professional Paper, United States Government Printing Office, Washington, pp 203–220
- Kamiyama M (1984) Effects of subsoil conditions and other factors on the duration of earthquake ground shakings. In: *Proceedings of Eighth World Conference on Earthquake Engineering, vol II*, pp 793–800
- Kamiyama M (1995) An attenuation model for the peak values of strong ground motions with emphasis on local soil effects. In: *Proceedings of the First International Conference on Earthquake Geotechnical Engineering, vol 1*, pp 579–585
- Kamiyama M, O'Rourke M, Flores-Berrones R (1992) A semi-empirical analysis of strong-motion peaks in terms of seismic source, propagation path and local site conditions. *Tech. Rep. NCEER-92-0023*, National Center for Earthquake Engineering Research
- 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
- Kawashima K, Aizawa K, Takahashi K (1984) Attenuation of peak ground motion and absolute acceleration response spectra. In: *Proceedings of Eighth World Conference on Earth-*

- quake Engineering, vol II, pp 257–264
- Kawashima K, Aizawa K, Takahashi K (1986) Attenuation of peak ground acceleration, velocity and displacement based on multiple regression analysis of Japanese strong motion records. *Earthquake Engineering and Structural Dynamics* 14(2):199–215
- Kayen RE, Mitchell JK (1997) Assessment of liquefaction potential during earthquakes by Arias intensity. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 123(12):1162–1175, not seen
- Kempton JJ, Stewart JP (2006) Prediction equations for significant duration of earthquake ground motions considering site and near-source effects. *Earthquake Spectra* 22(4):985–1013, DOI 10.1193/1.2358175
- Lee CT, Hsieh BS, Sung CH, Lin PS (2012) Regional Arias intensity attenuation relationship for Taiwan considering V_{S30} . *Bulletin of the Seismological Society of America* 102(1):129–142, DOI 10.1785/0120100268
- Lee J (2009) Engineering characterization of earthquake ground motions. PhD thesis, University of Michigan, USA
- Lee VW, Trifunac MD, Todorovska MI, Novikova EI (1995) Empirical equations describing attenuation of peak of strong ground motion, in terms of magnitude, distance, path effects and site conditions. Tech. Rep. CE 95-02, Department of Civil Engineering, University of Southern California, Los Angeles, California, U.S.A.
- Liang J, Hao H, Gaull BA, Sinadinovski C (2008) Estimation of strong ground motions in southwest Western Australia with a combined Green's function and stochastic approach. *Journal of Earthquake Engineering* 12(3):382–405
- Lin, Lee (2004) Unknown. Original reference not seen. Cited in 'Attenuation Relationship of Arias Intensity for Taiwan' by Hsieh, P.-S. (2007)
- Liu KS, Tsai YB (2005) Attenuation relationships of peak ground acceleration and velocity for crustal earthquakes in Taiwan. *Bulletin of the Seismological Society of America* 95(3):1045–1058, DOI 10.1785/0120040162
- Margaris B, Papazachos C, Papaioannou C, Theodulidis N, Kalogeras I, Skarlatoudis A (2002a) Ground motion attenuation relations for shallow earthquakes in Greece. In: *Proceedings of the XXVIII General Assembly of the European Seismological Commission (ESC)*
- Margaris B, Papazachos C, Papaioannou C, Theodulidis N, Kalogeras I, Skarlatoudis A (2002b) Ground motion attenuation relations for shallow earthquakes in Greece. In: Pro-

-
- ceedings of Twelfth European Conference on Earthquake Engineering, paper reference 385
- Massa M, Morasca P, Moratto L, Marzorati S, Costa G, Spallarossa D (2008) Empirical ground-motion prediction equations for northern Italy using weak- and strong-motion amplitudes, frequency content, and duration parameters. *Bulletin of the Seismological Society of America* 98(3):1319–1342, DOI 10.1785/0120070164
- McGarr A, Fletcher JB (2005) Development of ground-motion prediction equations relevant to shallow mining-induced seismicity in the Trail Mountain area, Emery County, Utah. *Bulletin of the Seismological Society of America* 95(1):31–47, DOI 10.1785/0120040046
- McGuire RK (1977) Seismic design spectra and mapping procedures using hazard analysis based directly on oscillator response. *Earthquake Engineering and Structural Dynamics* 5:211–234
- McGuire RK (1978) Seismic ground motion parameter relations. *Journal of The Geotechnical Engineering Division, ASCE* 104(GT4):481–490
- McGuire RK, Barnhard TP (1979) The usefulness of ground motion duration in prediction of severity of seismic shaking. In: *Proceedings of the Second U.S. National Conference on Earthquake Engineering*, pp 713–722
- Megawati K (2007) Hybrid simulations of ground motions from local earthquakes affecting Hong Kong. *Bulletin of the Seismological Society of America* 97(4):1293–1307, DOI 10.1785/0120060129
- Megawati K, Pan TC (2010) Ground-motion attenuation relationship for the Sumatran megathrust earthquakes. *Earthquake Engineering and Structural Dynamics* 39:827–845, DOI 10.1002/eqe.967
- Megawati K, Pan TC, Koketsu K (2003) Response spectral attenuation relationships for Singapore and the Malay peninsula due to distant Sumatran-fault earthquakes. *Earthquake Engineering and Structural Dynamics* 32(14):2241–2265
- Megawati K, Pan TC, Koketsu K (2005) Response spectral attenuation relationships for Sumatran-subduction earthquakes and the seismic hazard implications to Singapore and Kuala Lumpur. *Soil Dynamics and Earthquake Engineering* 25(1):11–25
- Mezcua J, García Blanco RM, Rueda J (2008) On the strong ground motion attenuation in Spain. *Bulletin of the Seismological Society of America* 98(3):1343–1353, DOI 10.1785/0120070169

-
- Midorikawa S (1993) Preliminary analysis for attenuation of ground velocity on stiff site. In: Proceedings of the International Workshop on Strong Motion Data, vol 2, pp 39–48, not seen
- Midorikawa S, Ohtake Y (2004) Variance of peak ground acceleration and velocity in attenuation relationships. In: Proceedings of Thirteenth World Conference on Earthquake Engineering, paper no. 0325
- Molas GL, Yamazaki F (1995) Attenuation of earthquake ground motion in Japan including deep focus events. *Bulletin of the Seismological Society of America* 85(5):1343–1358
- Musson RMW, Cecić I (2002) Macroseismology. In: Lee WHK, Kanamori H, Jennings PC, Kisslinger C (eds) *International Handbook of Earthquake and Engineering Seismology*, vol 81A, Academic Press, San Diego, USA, chap 49, pp 807–822
- Nguyen LM, Lin TL, Wu YM, Huang BS, Chang CH, Huang WG, Le TS, Nguyen QC, Dinh VT (2012) The first peak ground motion attenuation relationships for north of Vietnam. *Journal of Asian Earth Sciences* 43(1):241–253, DOI 10.1016/j.jseaes.2011.09.012
- Niazi M, Bozorgnia Y (1991) Behaviour of near-source peak horizontal and vertical ground motions over SMART-1 array, Taiwan. *Bulletin of the Seismological Society of America* 81(3):715–732
- Nuttli OW, Herrmann RB (1987) Ground motion relations for eastern North American earthquakes. In: Proceedings of the Third International Conference on Soil Dynamics & Earthquake Engineering, vol II, pp 231–241
- Ohno S, Ohta T, Ikeura T, Takemura M (1993) Revision of attenuation formula considering the effect of fault size to evaluate strong motion spectra in near field. *Tectonophysics* 218:69–81
- Ólafsson S, Sigbjörnsson R (1999) A theoretical attenuation model for earthquake-induced ground motion. *Journal of Earthquake Engineering* 3(3):287–315
- Paciello A, Rinaldis D, Romeo R (2000) Incorporating ground motion parameters related to earthquake damage into seismic hazard analysis. In: Proceedings of the Sixth International Conference on Seismic Zonation, pp 321–326
- Pankow KL, Pechmann JC (2004) The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. *Bulletin of the Seismological Society of America* 94(1):341–348
- Pankow KL, Pechmann JC (2006) Erratum: The SEA99 ground-motion predictive relations for extensional tectonic regimes: Revisions and a new peak ground velocity relation. Bul-

-
- letin of the Seismological Society of America 96(1):364, DOI 10.1785/0120050184
- Paolucci R, Rovelli A, Faccioli E, Cauzzi C, Finazzi D, Vanini M, Di Alessandro C, Calderoni G (2008) On the reliability of long period spectral ordinates from digital accelerograms. *Earthquake Engineering and Structural Dynamics* 37(5):697–710
- Pousse G, Bonilla LF, Cotton F, Margerin L (2006) Non stationary stochastic simulation of strong ground motion time histories including natural variability: Application to the K-net Japanese database. *Bulletin of the Seismological Society of America* 96(6):2103–2117, DOI 10.1785/0120050134
- 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
- Rajabi AM, Khamsehchiyan M, Mahdaviifar MR, Del Gaudio V (2010) Attenuation relation of Arias intensity for Zagros Mountains region (Iran). *Soil Dynamics and Earthquake Engineering* 30:110–118, DOI 10.1016/j.soildyn.2009.09.008
- Rinaldis D, Berardi R, Theodulidis N, Margaris B (1998) Empirical predictive models based on a joint Italian & Greek strong-motion database: I, peak ground acceleration and velocity. In: *Proceedings of Eleventh European Conference on Earthquake Engineering*
- Rupakhety R, Sigurdsson SU, Papageorgiou AS, Sigbjörnsson R (2011) Quantification of ground-motion parameters and response spectra in the near-fault region. *Bulletin of Earthquake Engineering* 9:893–930, DOI 10.1007/s10518-011-9255-5
- Sabetta F, Pugliese A (1996) Estimation of response spectra and simulation of nonstationary earthquake ground motions. *Bulletin of the Seismological Society of America* 86(2):337–352
- Sadigh RK, Egan JA (1998) Updated relationships for horizontal peak ground velocity and peak ground displacement for shallow crustal earthquakes. In: *Proceedings of the Sixth U.S. National Conference on Earthquake Engineering*
- Sarma SK, Srbulov M (1998) A uniform estimation of some basic ground motion parameters. *Journal of Earthquake Engineering* 2(2):267–287
- Si H, Midorikawa S (1999) New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition. *Journal of Structural and Construction Engineering*, AIJ 523:63–70, in Japanese with English abstract. Not seen.
- Si H, Midorikawa S (2000) New attenuation relations for peak ground acceleration and velocity considering effects of fault type and site condition. In: *Proceedings of Twelfth World Conference on Earthquake Engineering*, paper No. 0532

-
- Silva W, Gregor N, Darragh R (2002) Development of regional hard rock attenuation relations for central and eastern North America. Tech. rep., Pacific Engineering and Analysis
- Singh RP, Aman A, Prasad YJJ (1996) Attenuation relations for strong seismic ground motion in the Himalayan region. *Pure and Applied Geophysics* 147(1):161–180
- Snæbjörnsson JT, Sigbjörnsson R (2008) The duration characteristics of earthquake ground motions. In: *Proceedings of Fourteenth World Conference on Earthquake Engineering*
- Somerville PG (1998) Development of an improved representation of near fault ground motions. In: *Proceedings of the SMIP98 Seminar on Utilization of Strong Motion Data*, pp 1–20
- Stafford PJ, Berrill JB, Pettinga JR (2009) New predictive equations for Arias intensity from crustal earthquakes in New Zealand. *Journal of Seismology* 13(1):31–52, DOI 10.1007/s10950-008-9114-2
- Stewart JP, Chiou SJ, Bray JD, Graves RW, Somerville PG, Abrahamson NA (2001) Ground motion evaluation procedures for performance-based design. PEER Report 2001/09, Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley, USA
- Theodulidis N, Lekidis V, Margaris B, Papazachos C, Papaioannou C, Dimitriou P (1998) Seismic hazard assessment and design spectra for the Kozani-Grevena region (Greece) after the earthquake of May 13, 1995. *Journal of Geodynamics* 26(2–4):375–391
- Theodulidis NP, Papazachos BC (1992) Dependence of strong ground motion on magnitude-distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, peak horizontal acceleration, velocity and displacement. *Soil Dynamics and Earthquake Engineering* 11:387–402
- Toro GR, Silva WJ (2001) Scenario earthquakes for Saint Louis, MO, and Memphis, TN, and seismic hazard maps for the central United States region including the effect of site conditions. Tech. rep., research supported by the U.S. Geological Survey (USGS), under award number 1434-HQ-97-GR-02981
- Travasarou T, Bray JD, Abrahamson NA (2003) Empirical attenuation relationship for Arias intensity. *Earthquake Engineering and Structural Dynamics* 32:1133–1155, DOI 10.1002/eqe.270
- Trifunac MD (1976) Preliminary analysis of the peaks of strong earthquake ground motion – dependence of peaks on earthquake magnitude, epicentral distance, and recording site conditions. *Bulletin of the Seismological Society of America* 66(1):189–219

-
- Trifunac MD, Brady AG (1975a) On the correlation of peak acceleration of strong motion with earthquake magnitude, epicentral distance and site conditions. In: Proceedings of the U.S. National Conference on Earthquake Engineering, pp 43–52
- Trifunac MD, Brady AG (1975b) A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America* 65(3):581–626
- Trifunac MD, Brady AG (1976) Correlations of peak acceleration, velocity and displacement with earthquake magnitude, distance and site conditions. *Earthquake Engineering and Structural Dynamics* 4(5):455–471
- Tromans I (2004) Behaviour of buried water supply pipelines in earthquake zones. PhD thesis, University of London
- Tromans IJ, Bommer JJ (2002) The attenuation of strong-motion peaks in Europe. In: Proceedings of Twelfth European Conference on Earthquake Engineering, paper no. 394
- Wald DJ, Worden BC, Quitoriano V, Pankow KL (2005) ShakeMap® manual. Technical Manual, users guide, and software guide Version 1.0, USGS Techniques and Methods 12-A1, URL <http://pubs.usgs.gov/tm/2005/12A01/>
- Wilson RC (1993) Relation of Arias intensity to magnitude and distance in California. Open-File Report 93-556, US Geological Survey, Menlo Park, California, USA
- Wilson RC, Keefer DK (1985) Predicting areal limits of earthquake-induced landsliding. In: Professional Paper, 1360, US Geological Survey, pp 317–345
- Wu YM, Shin TC, Chang CH (2001) Near real-time mapping of peak ground acceleration and peak ground velocity following a strong earthquake. *Bulletin of the Seismological Society of America* 91(5):1218–1228
- Yaghmaei-Sabegh S, Shoghian Z, Sheikh MN (2012) A new model for the prediction of earthquake ground-motion duration in Iran. *Natural Hazards* DOI 10.1007/s11069-011-9990-6, in press
- Zonno G, Montaldo V (2002) Analysis of strong ground motions to evaluate regional attenuation relationships. *Annals of Geophysics* 45(3–4):439–454

A GMPEs considered here

- H Number of horizontal records (if both horizontal components are used then multiply by two to get total number)
- V Number of vertical components
- E Number of earthquakes
- M_{\min} Magnitude of smallest earthquake
- M_{\max} Magnitude of largest earthquake
- M scale Magnitude scale (scales in brackets refer to those scales which the main M values were sometimes converted from, or used without conversion, when no data existed), where:
- m_b Body-wave magnitude
 - M_{CL} Coda length magnitude
 - M_D Duration magnitude
 - M_{JMA} Japanese Meteorological Agency magnitude
 - M_L Local magnitude
 - M_{pLg} Magnitude calculated using Lg amplitudes on short-period vertical seismographs
 - M_s Surface-wave magnitude
 - M_w Moment magnitude
- r_{\min} Shortest source-to-site distance
- r_{\max} Longest source-to-site distance
- r scale Distance metric, where (when available the *de facto* standard abbreviations of Abrahamson and Shedlock (1997) are used):
- 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_q Equivalent hypocentral distance (EHD) (Ohno et al, 1993)
 - r_{rup} Distance to rupture plane
 - r_{seis} Distance to seismogenic rupture plane (assumes near-surface rupture in sediments is non-seismogenic) (Campbell, 1997)
 - r_{slip} Distance to point of highest slip
- S Number of different site conditions modelled, where:
- C Continuous classification
 - I Individual classification for each site
- C Use of the two horizontal components of each accelerogram [see Beyer and Bommer (2006)], where:
- A Arithmetic mean
 - B Both components
 - C Randomly chosen component
 - G Geometric mean
- I50 GMrotI50 (Boore et al, 2006).
- L Larger component
 - L3 Larger component amongst three components (including vertical)

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- M Mean (not stated what type)
 - N Fault normal
 - O Randomly oriented component
 - R Resolved component
 - T Transverse (SH) component
 - U Unknown
 - R Regression method used, where:
 - 1 Ordinary one-stage
 - 1M Maximum likelihood one-stage or random-effects (Abrahamson and Youngs, 1992; Joyner and Boore, 1993)
 - 1WM Weighted maximum-likelihood one-stage
 - 2 Two-stage (Joyner and Boore, 1981)
 - 2M Maximum likelihood two-stage (Joyner and Boore, 1993)
 - 2W Two-stage with second stage weighted as described in Joyner and Boore (1988)
 - O Other (see section referring to study)
 - U Unknown (often probably ordinary one-stage regression)
 - M Source mechanisms (and tectonic type) of earthquakes (letters in brackets refer to those mechanism that are separately modelled), where:
 - A All (this is assumed if no information is given in the reference)
 - AS Aftershock
 - B Interslab
 - C Shallow crustal
 - F Interface
 - HW Hanging wall
 - I Intraplate
 - M Mining-induced
 - N Normal
 - O Oblique or odd (Frohlich and Apperson, 1992)
 - R Reverse
 - Rake Rake angle explicitly given
 - S Strike-slip
 - T Thrust
 - U Unspecified

'+' refers to extra records from outside region used to supplement data. (...) refer either to magnitudes of supplementing records or to those used for part of analysis. * means information is approximate because either read from graph or found in another way.

Table 1: Characteristics of GMPEs considered here

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
1	Esteva and Rosenblueth (1964)	W. USA	46*	-	U	U	U	U	15*	450*	r_{hypo}	1	U	U	A	PGV
2	Campbell and Duke (1974a,b)	W. USA	Hybrid approach			M_S	4.5	U	10	47	r_{hypo}	5	A	O	A	AI
3	Trifunac and Brady (1975a), Trifunac (1976) & Trifunac and Brady (1976)	W. USA	181	181	57	3.8	7.7	Mostly M_L	6 ^{2*}	400 ^{3*}	r_{epi}	3	B	O	A	PGV, PGD
4	Trifunac and Brady (1975b)	W. USA	188	188	48	3.8	7.7	Mostly M_L	6*	400*	r_{epi}	3	B	O	A	AI, RSD
5	McGuire (1977)	W. USA	34	-	22	5.3	7.6	M_L	14	125	r_{hypo}	1	B	U	A	PGV, PGD
6	Dobry et al (1978)	W. USA	84	-	14	4.7	7.6	M_L	0.1	130	r_{rup}	2	B	1	A	RSD
7	McGuire (1978)	W. USA	70	-	17+*	4.5*	7.7	U ⁴	11*	210*	r_{hypo}	2	B	U	A	PGV, PGD
8	McGuire and Barnhard (1979)	W. USA	50	-	U	U	U	U	U	U	r_{rup} (r_{epi} for some)	2	B	1	A	RSD
9	Cornell et al (1979)	W. USA	70	-	U	U	U	M_L	U	U	r_{hypo}	1	C	U	A	PGV, PGD
10	Hasegawa et al (1981)	E. & W. Canada	Hybrid approach			4*	7.6*	U	5*	400*	r_{hypo}	1	U	O	A	PGV × 2
11	Joyner and Boore (1981)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	2	L	2	A	PGV
12	Faccioli (1983)	Worldwide	Hybrid approach			4.7	7.7	M_w	4*	95*	r_{hypo}	C	R	O	A	AI
13	Joyner and Fumal (1984) and Joyner and Fumal (1985)	W. N. America	182	-	23	5.0	7.7	M_w (M_L)	0.5	370	r_{jb}	C	L	2	A	PGV
14	Kamiyama (1984)	Japan	192	-	U	4.1	7.9	M_{JMA}	10	310	r_{epi}	I	B	1	A	RSD
15	Kawashima et al (1984) & Kawashima et al (1986)	Japan	197	-	90	5.0	7.9	M_{JMA}	5*	550*	r_{epi}	3	R	1	A	PGV, PGD
16	Wilson and Keefer (1985)	W. USA	30	-	20	5.0	7.4	M_w	6	130	r_{jb}	1	A	1	A	AI

continued on next page

² Note only valid for $R \geq 20$ km³ Note only valid for $R \leq 200$ km⁴ Idriss (1978) finds magnitudes to be mixture of M_L , m_b and M_S .

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
17	Jibson (1987)	W. USA	31	-	21	5.0	7.4	M_w	6	130	r_{jb}	1	A	1	A	AI
18	Nuttli and Herrmann (1987)	E. N. America	Simulation approach			U	U	m_{hLg}	U	U	r_{hypo}	1	G	1	A	PGV
19	K.W. Campbell (1988) ⁵	Worldwide	U	-	U	≥ 5	U	M_L for $M < 6.0$ and M_S other- wise	U	<50	r_{seis}	2	M	U	A (S, R)	PGV
20	Gaull (1988)	S.W. W. Australia	25+	-	12+	2.6	6.9	M_L	2.5	175	r_{hypo}	1	U	O	A	PGV
21	Huo (1989)	S. China	U	-	U	U	U	U	U	U	U	1	G	1	A	PGV
22	Campbell (1990)	Unknown	U	-	U	U	U	M_L for $M < 6,$ M_S for $M \geq 6$	U	U	r_{seis}	1	U	U	A	PGV
23	Gaull et al (1990)	SE Australia	Hybrid approach			U	U	U	U	U	r_{hypo}	1	U	O	A	PGV
24	Niazi and Bozorgnia (1991)	SMART-1 array, Taiwan	236	234	12	3.6	7.8	M_L (M_D) for $M_L < 6.6,$ else M_S	3.1 ⁶	119.7 ⁶	r_{hypo}	1	M	2W	A	PGV, PGD
25	Kamiyama et al (1992) & Kamiyama (1995)	Japan	357	-	82	4.1	7.9	M_{JMA}	3.4	413.3	r_{hypo}	1	B	O	A	PGV, PGD

*continued on next page*⁵ Reported in Joyner and Boore (1988).⁶ Distance to centre of array

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
26	Theodulidis and Papazachos (1992)	Greece+16 foreign	105+16 ⁷	-	36+4	4.5 (7.2)	7.0 (7.5)	M_S , M_W , M_{JMA}	1 (48)	128 (236)	r_{epi}	2	B	O	A	PGV, PGD
27	Midorikawa (1993)	Japan	U	-	U	6.5	7.8	M_W	U	U	r_{rup}	1	U	1	A	PGV
28	Wilson (1993)	W. USA	Hybrid approach			5.3	7.5	M_W	3*	100*	r_{jb}	1	G	O	A	AI
29	Lee et al (1995)	W. N. America	1926	1926	297	1.7	7.7	Usually M_L for $M \leq$ 6.5 and M_S for $M >$ 6.5	2	200+	r_{hypo}	9, 3 × C	U	1	A	PGV, PGD
30	Molas and Yamazaki (1995)	Japan	2166	-	387	4.1*	7.8*	M_{JMA}	8*	1000*	r_{rup} for 2 earth- quakes, r_{hypo} other- wise	1	L	O	A	PGV
31	Abrahamson and Silva (1996)	California with some others	U	U	U	4.7	7.4	M_W	0.1	220*	r_{rup}	2	G	1M	A	RSD
32	Sabetta and Pugliese (1996)	Italy	95	95	17	4.6	6.8	M_S if M_L & $M_S \geq$ 5.5 else M_L	1.5, 1.5	179, 180 ⁸	Both r_{jb} & r_{epi}	3	L	1	A	PGV, AI
33	Singh et al (1996)	Himalayas	86	-	5	5.7	7.2	m_b	33.15	340.97	r_{hypo}	1	U	1	A	PGV
34	Atkinson and Boore (1997a)	E. N. America	Simulation approach			4.0	7.0	M_W	10	500	r_{hypo}	2	G	O	A	PGV

*continued on next page*⁷ Total number of components does not need to be multiplied by two⁸ State equations should not be used for distances > 100km

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
35	Atkinson and Boore (1997b)	Cascadia	Simulation approach			3.7	6.7	M_w	10	400	r_{hypo}	2	G	O	A	PGV
36	Campbell (1997), Campbell (2000), Campbell (2001) & Campbell and Bozorgnia (1994)	Worldwide	645	225	H:47, V:26	4.7	H:8.0, V:8.1	M_w	3	60	r_{seis}	3	G	1	A(S,R,N)	PGV
37	Gregor and Bolt (1997)	California	110	110	12	5.4	7.2	M_w	6*	200*	r_{slip}	2	T, V	1	R, S	PGD
38	Kayen and Mitchell (1997)	W. USA	66	-	U	U	U	M_w	1*	100*	r_{rup}	3	G	1	A	AI
39	Rinaldis et al (1998)	Italy & Greece	137*	-	24*	4.5	7	M_S or M_w	7	138	r_{epi}	2	U	O	A (N,ST)	PGV
40	Sadigh and Egan (1998)	California with 4 foreign	960+4	-	119+2	3.8	7.4	M_w	0.1	305 ⁹	r_{rup} for some, r_{hypo} for small ones	2	G	U	A(R,SN)	PGV, PGD
41	Sarma and Srbulov (1998)	Worldwide	690 ¹⁰	-	113	3.9	7.7	M_S (U)	0	197	r_{jb} , r_{epi}	2	B	1	A	AI
42	Somerville (1998)	15 mainly W. USA+12 sim- ulated	27	-	13	6.2	7.5	M_w	0.1	10	r_{rup}	1	N	1	A	PGV
43	Theodulidis et al (1998)	Kozani-Grevena (Greece)	232 ¹¹	-	U	3.1	6.6	M_w	1	140*	r_{epi}	1	B	1	A	PGV
44	Chapman (1999)	W. N. America	304	-	23	5.0	7.7	M_w	0.1	189.4	r_{jb}	3	G	2M	A	PGV
45	Ólafsson and Sigbjörnsson (1999)	Iceland	88 ¹²	-	17	4.0	5.9	M_w	2	112	r_{epi}	1	B	1	A	RSD
46	Alavi and Krawinkler (2000)	15 mainly W. USA+12 sim- ulated	27	-	13	6.2	7.5	M_w	0.1	10	r_{rup}	1	N	1	A	PGV
47	Bommer et al (2000)	Europe & Middle East	183	-	43	5.5	7.9	M_S	3	260	r_{jb}	3	L	1	A	PGV, PGD

*continued on next page*⁹ Equations stated to be for distances up to 100km¹⁰ Total number of components do not need to be multiplied by two.¹¹ Total number of components do not need to be multiplied by two.¹² Total number of components do not need to be multiplied by two.

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
48	Hernandez and Cotton (2000)	Italy & California	272 ¹³	-	40*	3.2	7.4	M_L for $M < 6$, M_S other- wise	1	109	r_{rup}	2	B	1	A	RSD
49	Paciello et al (2000)	Greece & Italy	115	-	18	4.5	U	M_W or M_S	U	U	r_{epi}	2	B	1	A (N)	PGV, PGD, AI
50	Si and Midorikawa (1999, 2000)	Japan	856	-	21	5.8	8.3	M_W	0*	280*	Both r_q & r_{rup}	2	L	O	A	PGV
51	Toro and Silva (2001)	Central USA	Simulation approach			5.5	7.5	M_W	1	400	r_{jb}	1	G	1	A	PGV $\times 2$
52	Wu et al (2001)	Taiwan	1941	-	60	4.8	7.6	M_W (M_L)	0.05*	400*	r_{rup} (r_{epi} for some)	1 & 1	U	U	A	PGV
53	Gregor et al (2002)	Shallow crustal worldwide (mainly California)	993	993	68	4.4	7.4	M_W	0.1	267.3	r_{rup}	2	U	1M	A (S, R/O, T)	PGV, PGD
54	Margaris et al (2002a) & Margaris et al (2002b)	Greece	744	-	142	4.5	7.0	M_W	1	150	r_{epi}	3	B	O	A	PGV, PGD
55	Silva et al (2002)	Cen. and E. N. America	Simulation approach			4.5	8.5	M_W	1	400	r_{jb}	1	G	1	A	PGV $\times 5$
56	Tromans and Bommer (2002)	Europe	249	-	51	5.5	7.9	M_S	1	359	r_{jb}	3	L	2	A	PGV, PGD
57	Zonno and Montaldo (2002)	Umbria-Marche	161	-	15	4.5	5.9	M_L	2*	100*	r_{epi}	2	L	2	N, O	PGV, AI
58	Megawati et al (2003)	Sumatran interface	Simulation approach			4.0	8.0	M_W	174	1379	r_{rup}	1	G	1	F	PGV

*continued on next page*¹³ Total number of components do not need to be multiplied by two.

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
59	Boatwright et al (2003)	N. California	4028	-	104	3.3	7.1	Mainly M_w , M_L for some	1*	370*	r_{hypo}	4	U	O	A	PGV
60	Travasrou et al (2003)	Mainly W. USA	1208	-	75	4.7	7.6	M_w	0.1*	200*	r_{rup}	3	A	1M	A (N, R)	AI
61	Bray and Rodriguez-Marek (2004)	Worldwide	54	-	13	6.1	7.6	M_w	0.1	17.6	M_{rup}	2	N	1M	A	PGV
62	Hwang et al (2004)	Chi-Chi (Taiwan)	221 ¹⁴	-	4	6.2	7.7	M_w	U	U	r_{jb}	1	A	2M	A	AI
63	Lin and Lee (2004)	Taiwan	U	-	41	U	U	U	U	U	r_{rup}	1	U	1	A	AI
64	Midorikawa and Ohtake (2004)	Japan	3335	-	33	5.5	8.3	M_w	0*	300*	r_{rup}	2	L	1	A (C, B, F)	PGV
65	Pankow and Pechmann (2004) and Pankow and Pechmann (2006)	Worldwide extensional regimes	142	-	39	5.1	7.2	M_w	0	99.4	r_{jb}	2	G, O	1M	NS	PGV
66	Bragato and Slejko (2005)	E Alps (45.6–46.8°N & 12– 14°E)	1402	3168	240	2.5	6.3	M_L	0	130	r_{jb} & r_{epi}	1	R	O	A	PGV, AI
67	Frisenda et al (2005)	NW Italy	6899 ¹⁵	-	>1152	0.0*	5.1 ¹⁶	M_L	0	300 ¹⁷	r_{hypo}	2	B	1	A	PGV
68	García et al (2005)	Central Mexico	277	277	16	5.2	7.4	M_w	4*	400*	r_{rup} for $M_w >$ 6.5, r_{hypo} other- wise	1	G ¹⁸	1M	B	PGV

*continued on next page*¹⁴ Three other equations for site classes B, D and E.¹⁵ Authors state in text that 'more than 14 000' values were used but their Table 1 gives 2×6899 .¹⁶ State equations valid to 4.5.¹⁷ State equations valid up to 200km.¹⁸ Call it 'quadratic mean', which is assumed to be geometric mean.

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
69	Liu and Tsai (2005)	Taiwan	7907	7907	51	4.05	7.10	M_w (M_L)	5*	300*	r_{hypo}	1	M	2M	A	PGV
70	McGarr and Fletcher (2005)	Central Utah coal-mining areas	72	-	12	0.98	4.2	M_w (M_{CL})	0.5*	10*	r_{hypo}	2	L	2M	M	PGV
71	Megawati et al (2005)	Sumatran interface	Simulation approach			4.5	8.0	M_w	150	1500	r_{rup}	1	G	1	F	PGV
72	Wald et al (2005)	California	U	-	U	U	5.3*	M_w	U	U	r_{jb}	1	L	U	A	PGV
73	Atkinson and Boore (2006)	E. N. America	Simulation approach			3.5	8.0	M_w	1	1000	r_{rup}	1	G	1	A	PGV
74	Bindi et al (2006)	Umbria-Marche	239	-	45	4.0	5.9	M_L	1*	100*	r_{epi} & r_{hypo}	4	L	1M	NS	PGV
75	Kanno et al (2006)	Japan+some foreign	3392+377 (shal- low) & 8150 (deep)	-	73+10 & 111	5.0* (6.1) & 5.5*	8.2* (7.4) & 8.0*	M_w (M_{JMA})	1* (1.5*) & 30*	450* (350*) & 450*	r_{rup} (r_{hypo} for some)	C	R	2M	A	PGV
76	Kempton and Stewart (2006)	Worldwide shallow crustal	1559	-	73	5.0*	7.6*	M_w	0*	200*	r_{rup}	C	G	1M	A	RSD
77	Pousse et al (2006)	Japan	9390 ¹⁹	-	U	4.1	7.3	(M_w)	5*	250*	r_{hypo} (r_{rup} for some)	5	B	2M	A	AI, RSD
78	Akkar and Bommer (2007)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	r_{jb}	3	G	1WM	A (N, S, R)	PGV
79	Ghodrati Amiri et al (2007a) & Ghodrati Amiri et al (2007b)	Alborz and central Iran ²⁰	200*	200*	50*	4.5*	7.3*	M_S (m_b)	5*	400*	r_{hypo}	2	L	1	A	PGV
80	Bindi et al (2007)	NW Turkey	4047	4047	528	0.5	5.9	M_L ²¹	5*	200*	r_{hypo} ²²	2	L	1M	A	PGV
81	Convertito et al (2007)	Campania, Italy	Mainly simulated with some natural			5	7	M_w	5	150	r_{epi}	1	G	1	A	PGV

*continued on next page*¹⁹ Does not need to be multiplied by two.²⁰ Also develop models for the Zagros region of Iran using about 100 records.²¹ Also derive model using M_w .²² Also derive model using r_{epi} .

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
82	Danciu and Tselentis (2007a) & Danciu and Tselentis (2007b)	Greece	335	-	151	4.5	6.9	M_w	0*	136	r_{epi}	3	A	1M	A (ST, N)	PGV, PGD, AI
83	Fukushima et al (2007)	Japan	8615	-	158	5.0	6.8	M_{JMA}	18.1	448.4	r_{rup}	1	R	1	A	PGV
84	Megawati (2007)	Hong Kong				5.3	6.8	M_w	20*	60*	r_{rup}	1	G	1	A	PGV
85	Atkinson (2008)	E. N. America				4.3	7.6	M_w	10*	1000*	r_{jb}	C	150	O	A (N, R, S, U)	PGV
86	Al-Qaryouti (2008)	Dead Sea area	26	-	19	4.0	6.2	M_L	5.8	330.6	r_{epi}	1	U	2	A	PGV
87	Abrahamson and Silva (2008) & Abrahamson and Silva (2009)	Worldwide shallow crustal	2754	-	135	4.27 ²³	7.9 ²⁴	M_w	0.06*	200*	r_{rup}	C	150	1M	A (N, R, S, HW)	PGV
88	Boore and Atkinson (2007) & Boore and Atkinson (2008)	Worldwide shallow crustal	1574	-	58	4.27 ²⁵	7.90 ²⁶	M_w	0	280 ²⁷	r_{jb}	C	150	2M	A (N, R, S, U)	PGV
89	Campbell and Bozorgnia (2007), Campbell and Bozorgnia (2008b) & Campbell and Bozorgnia (2008a)	Worldwide shallow crustal	1561	-	64	4.27 ²⁸	7.90 ²⁹	M_w	0.07	199.27	r_{rup}	C	150	1M	A (N, R, S, HW)	PGV, PGD

continued on next page

²³ Recommend that model is not extrapolated below 5 due to lack of data.

²⁴ Believe that model can be reliably extrapolated to 8.5.

²⁵ Recommend that model is not extrapolated below 5 due to lack of data.

²⁶ Believe that model can be used to 8.0.

²⁷ Recommend that model is not used for distances ≥ 200 km.

²⁸ Believe that model can be extrapolated down to 4.0.

²⁹ Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
90	Chiou and Youngs (2008)	Worldwide shallow crustal	1950	-	125	4.265 ³⁰	7.90 ³¹	M_w	0.2* ³²	70* ³³	r_{rup}	C	I50	1M	A (N, R, S, HW, AS)	PGV
91	Jin et al (2008)	Fujian (China)	1974	1974	94	2.8	4.9	M_L	13	462	r_{epi}	1	U	O	A	PGV
92	Liang et al (2008)	SW W. Australia	Simulation approach			4.0	7.0	M_L	10	200	r_{epi}	1	G	1	A	PGV
93	Massa et al (2008)	Northern Italy	306	306	82	3.5 & 4.0	6.3 & 6.5	M_w (M_L) & M_L	1*	100*	r_{epi}	3	L	1M	A	PGV
94	Mezcua et al (2008)	Spain	250	-	149	3.1	5.3	M_w ($m_b(L_g)$)	5*	100*	r_{hypo}	1	U	1	A	PGV
95	Snabjörnsson and Sigbjörnsson (2008)	Europe & Middle East	71	-	13	5.0*	7.6*	M_w	0*	100*	r_{jb}	1	U	1	SS	RSD
96	Bindi et al (2009a)	Italy	241	241	27	4.8	6.9	M_w	0	190	r_{jb} (r_{epi} for small)	3	L, G	1M	A (N, S, R)	PGV
97	Bindi et al (2009b)	Italy	235	-	27	4.6	6.9	M_w (M_L)	0	183	r_{jb} , r_{epi}	3	L	1M	A	PGV
98	Bommer et al (2009)	Worldwide shallow crustal	2406	-	114	4.8	7.9	M_w	1.5*	100*	r_{rup}	C	B	O	A	RSD
99	Lee (2009)	W. USA ³⁴	324	324	49	5.0	7.6	M_w	0.1	199.1	r_{rup}	2	A	1M	A	AI×2, RSD×2
100	Stafford et al (2009)	New Zealand + foreign	144+241 & 144+200	-	23+41	5.08	7.51	M_w	0.07	300	r_{jb} & r_{rup}	3	L, O, G, A	1M	A (S/N, R)	AI×4

*continued on next page*³⁰ Believe that model can be extrapolated down to 4.0.³¹ Believe that model can be extrapolated up to 8.5 for strike-slip faulting and 8.0 for reverse faulting.³² Believe that model valid to 0km.³³ Believe that model valid to 200km.³⁴ Also model for Central USA using 14 records and 296 scaled records

Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
101	Akkar and Bommer (2010)	Europe & Middle East	532	-	131	5.0	7.6	M_w	0	99	r_{jb}	3	G	1M	A (N, S, R)	PGV
102	Akkar and Çağnan (2010)	Turkey	433	-	137	5.0	7.6	M_w	0*	200*	r_{jb}	C	G	1M	A (N, S, R)	PGV
103	Ghodrati Amiri et al (2010)	Alborz and central Iran ³⁵	416	-	189	3.2 ³⁶	7.7	M_s (m_b)	5*	400*	r_{hypo}	2	L	1M	A	AI
104	Bindi et al (2010)	Italy	561	561	107	4.0	6.9	M_w	1*	100*	r_{jb} , r_{epi}	3	L	1M	A	PGV
105	Chiou et al (2010) ³⁷	S & N California	15684	-	U	3*	6*	M_w	5*	200*	r_{rup}	C	150	1M	A (N, R, S, HW, AS)	PGV $\times 2$
106	Iervolino et al (2010)	Italy	95	-	17	4.6	6.8	M_s if M_L & $M_s \geq$ 5.5 else M_L	1.5, 1.5	179, 180	r_{jb} & r_{epi}	3	L	1	A	PGV, AI
107	Megawati and Pan (2010)	Sumatran interface	Simulation approach			5	9	M_w	300*	1200*	r_E	1	G	1	F	PGV
108	Rajabi et al (2010)	Zagros, Iran	37	-	35	4.1	7.0	M_w	5	150	r_{epi}	1, 3 & 4	L	1	A	AI $\times 5$
109	Atkinson (2008) modified by Atkinson and Boore (2011)	E. N. America	Referenced-empirical approach			4.3	7.6	M_w	10*	1000*	r_{jb}	C	150	O	A (N, R, S, U)	PGV
110	Atkinson and Boore (2006) modified by Atkinson and Boore (2011)	E. N. America	Simulation approach			3.5	8.0	M_w	1	1000	r_{rup}	1	G	1	A	PGV

*continued on next page*³⁵ Also develop models for the Zagros region of Iran using 309 records from 190 earthquakes.³⁶ State that only use data with $M_s \geq 4$ but one earthquake in their Appendix A has $M_s 3.2$.³⁷ Adjustment of GMPE of Chiou and Youngs (2008) for $M_w < 6$

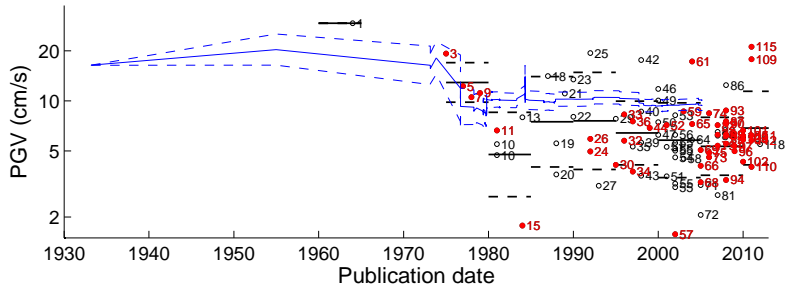
Table 1: *continued*

No.	Reference	Area	H	V	E	M_{\min}	M_{\max}	M scale	r_{\min}	r_{\max}	r scale	S	C	R	M	IM
111	Boore and Atkinson (2007) & Boore and Atkinson (2008) modified by Atkinson and Boore (2011)	Worldwide shallow crustal	1574	-	58	4.27	7.90 ³⁸	M_w	0	280 ³⁹	r_{jb}	C	I50	2M	A (N, R, S, U)	PGV
112	Alavi et al (2011)	Worldwide shallow crustal	2252	-	U	5.1*	7.9*	M_w	0.2*	350*	r_{rup}	C	U	O	A (Rake)	PGV, PGD
113	Emolo et al (2011)	Campania-Lucania, Italy	875	-	123	1.5	3.2	M_L	3	100*	r_{hypo}	2	L	1	A	PGV
114	Ghanat (2011)	Worldwide shallow crustal	2690	-	129	4.8	7.9	M_w	0.2*	200*	r_{rup}	C	G	1M	A	RSD
115	Rupakhty et al (2011)	Worldwide shallow crustal	93	-	29	5.56	7.6	M_w	0	74.16	r_{jb}	1	N	1M	A	PGV
116	Foulser-Piggott and Stafford (2012)	Worldwide shallow crustal	2406	-	114	4.79	7.9	M_w	0.07	100	r_{rup}	C	A	1M	A (S/N, R)	AI
117	Lee et al (2012)	Taiwan	6570	-	62	3.93	7.62	M_w	0.3	205	r_{rup}	C	A	1M	A (S, N, R)	AI
118	Nguyen et al (2012)	Vietnam	330	-	53	1.6	4.6	M_L	5*	500*	r_{epi}	1	L3	1	A	PGV
119	Yaghmaei-Sabegh et al (2012)	Iran	286	-	141	3.7	7.7	M_w	0.6	294	r_{rup}	4	G	1	A	RSD

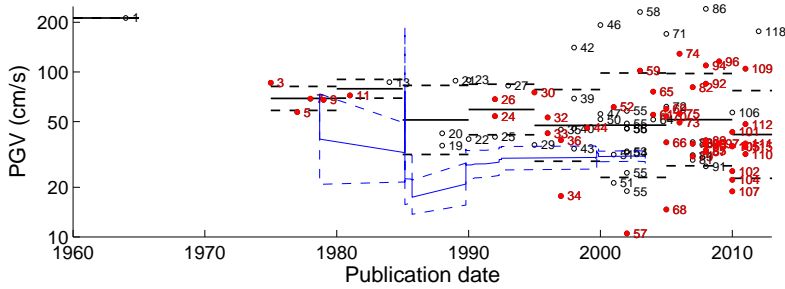
³⁸ Believe that model can be used to 8.0.³⁹ Recommend that model is not used for distances ≥ 200 km.

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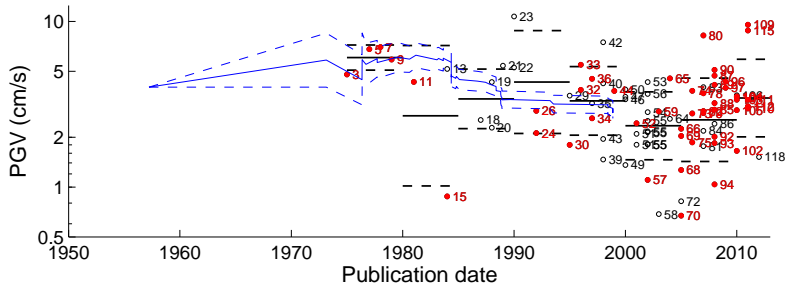
1	Predicted PGV at a NEHRP C site against publication date for 96 models published in the literature. Filled red circles indicate models published in peer-reviewed journals, for which basic information on the used dataset is available and which are not being extrapolated far outside their range of applicability. Numbers correspond to those given in Table 1. Also shown is the median PGV within five-year intervals (black line) and the median ± 1 standard deviation (dashed black lines) based on averaging predictions. Finally indicated is the median PGV (solid blue line) and its 16th and 84th confidence limits (dashed blue line) based on averaging records up until that date (see text for details). Note that the selection criteria and the fact that the database used to compute these averages has not been recently updated mean that the blue lines end before 2012.	38
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(a) For a M_w 6 strike-slip earthquake at $r_{jb} = 20$ km. Up until the end of 2005, 253 records from 56 earthquakes were used to compute the average observed PGV.

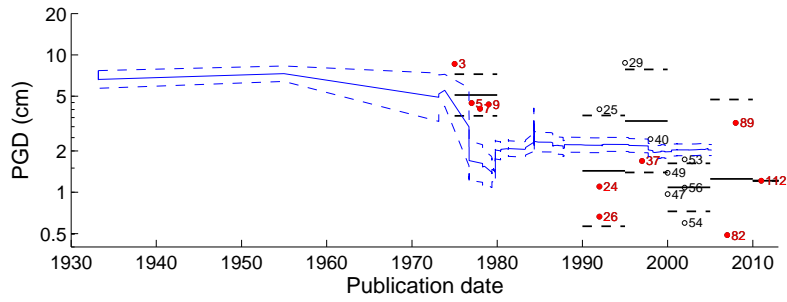


(b) For a M_w 7.5 strike-slip earthquake at $r_{jb} = 10$ km. Up until the end of 2003, 129 records from 15 earthquakes were used to compute the average observed PGV. The vertical blue line in 1985 is caused by many number of records from the same date (the Chile earthquake of 3rd March 1985) that significantly change the average computed up to that time.

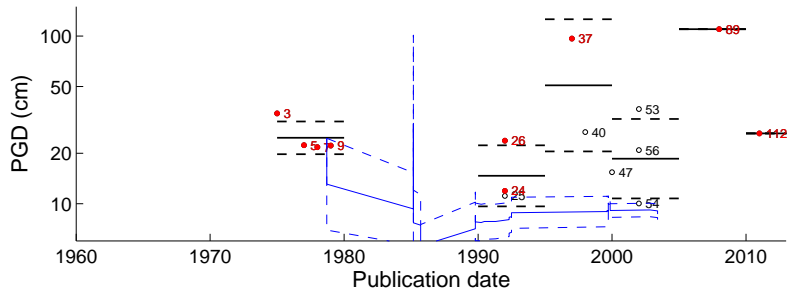


(c) For a M_w 5 strike-slip earthquake at $r_{jb} = 10$ km. Up until the end of 1998, 51 records from 30 earthquakes were used to compute the average observed PGV.

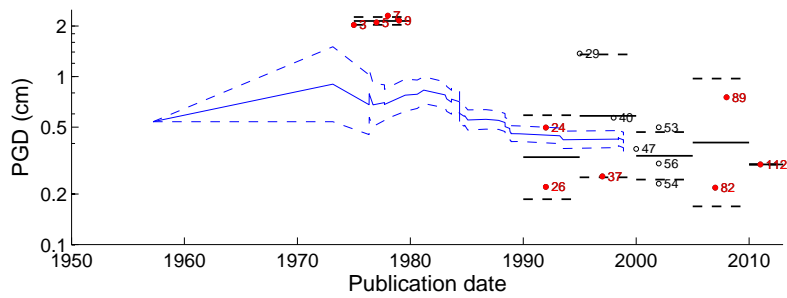
Fig. 1 Predicted PGV at a NEHRP C site against publication date for 96 models published in the literature. Filled red circles indicate models published in peer-reviewed journals, for which basic information on the used dataset is available and which are not being extrapolated far outside their range of applicability. Numbers correspond to those given in Table 1. Also shown is the median PGV within five-year intervals (black line) and the median ± 1 standard deviation (dashed black lines) based on averaging predictions. Finally indicated is the median PGV (solid blue line) and its 16th and 84th confidence limits (dashed blue line) based on averaging records up until that date (see text for details). Note that the selection criteria and the fact that the database used to compute these averages has not been recently updated mean that the blue lines end before 2012.



(a) For a M_w 6 strike-slip earthquake at $r_{jb} = 20$ km.

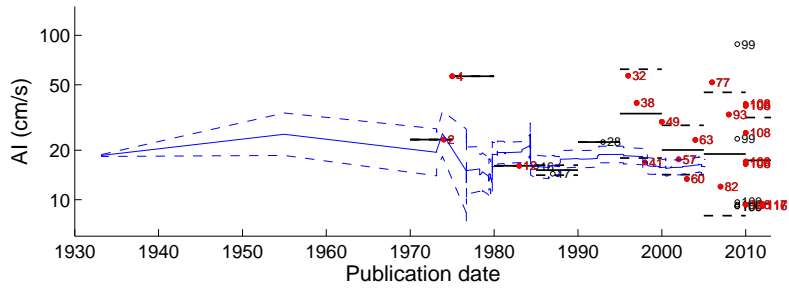


(b) For a M_w 7.5 strike-slip earthquake at $r_{jb} = 10$ km.

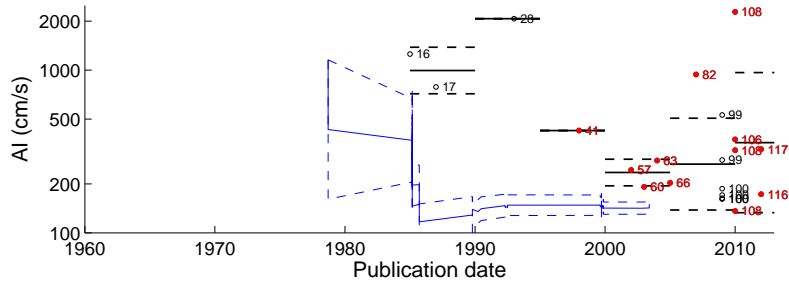


(c) For a M_w 5 strike-slip earthquake at $r_{jb} = 10$ km.

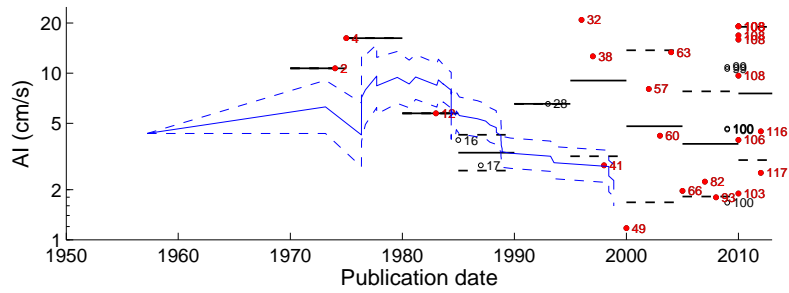
Fig. 2 Like Figure 1 but for PGD (19 models).



(a) For a M_w 6 strike-slip earthquake at $r_{jb} = 20$ km.

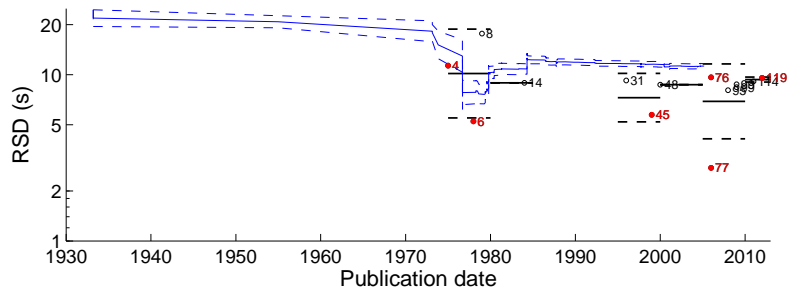


(b) For a M_w 7.5 strike-slip earthquake at $r_{jb} = 10$ km.

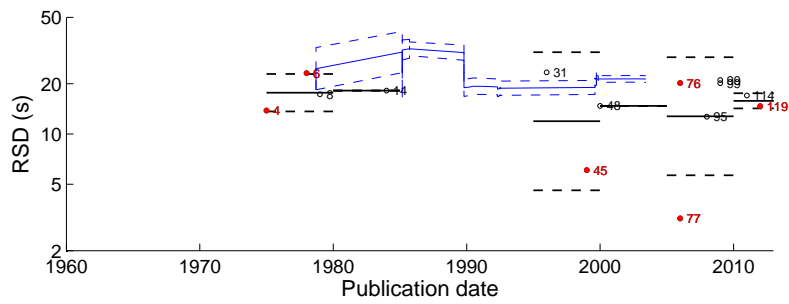


(c) For a M_w 5 strike-slip earthquake at $r_{jb} = 10$ km.

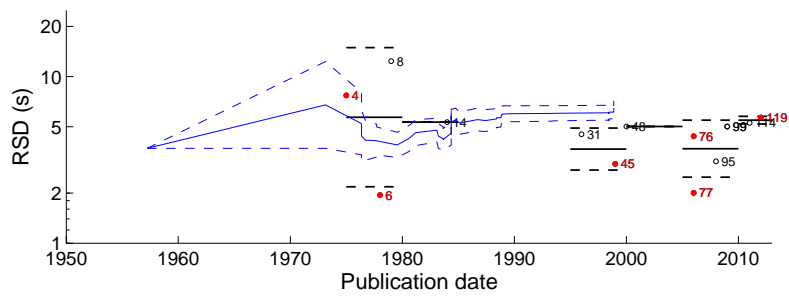
Fig. 3 Like Figure 1 but for AI (33 models).



(a) For a M_w 6 strike-slip earthquake at $r_{jb} = 20$ km.



(b) For a M_w 7.5 strike-slip earthquake at $r_{jb} = 10$ km.



(c) For a M_w 5 strike-slip earthquake at $r_{jb} = 10$ km.

Fig. 4 Like Figure 1 but for RSD (14 models).