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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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Keywords Strong-motion data · Ground-motion prediction equations (GMPEs) · Epistemic uncertainty · Peak ground velocity · Peak ground displacement · Arias intensity · Relative significant duration

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; Travasarou 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 (sigma) associated with GMPEs for the different parameters are not discussed here. Table IV of Travasarou 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 sigma 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 10 km 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 $r_{jb} = 20\,\mathrm{km}$ on a site classified as NEHRP class C (Eurocode 8 class B) ($V_{s,30} = 490\,\mathrm{m/s}$). 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 $r_{jb} = 10\,\mathrm{km}$, for which there are still few available data, and M_w5 strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$, which is at the lower edge of most datasets used for the derivation of GMPEs, for

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[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 $r_{jb} = 20\,\mathrm{km}$ 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 $10\,\mathrm{km}$ 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(1 s) 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 $0.25\,\mathrm{Hz}$ 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, Travasarou et al (2003), AI has a number of uses in earthquake engineering, particularly for slope stability analysis and liquefaction assessment. These uses have motived 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 $\pi/2\mathrm{g}$ 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 $r_{jb} = 10\,\mathrm{km}$, around 0.3 for $M_w 6$ at $r_{jb} = 20\,\mathrm{km}$ and around 0.2 for $M_w 7.5$ at $r_{jb} = 10\,\mathrm{km}$. 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(1 s) 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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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_{bLg}	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)

	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 staged 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

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[2] Note only valid for $R \geq 20\,\mathrm{km}$

[3] Note only valid for $R \leq 200\,\mathrm{km}$

[4] 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_{bLg}	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 otherwise	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}	I	B	O	A	PGV, PGD

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[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 earthquakes, r_{hypo} otherwise	I	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

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[7] Total number of components does not need to be multiplied by two

[8] State equations should not be used for distances $> 100\,\text{km}$

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	$hypo$	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 simulated	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 simulated	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

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[9] Equations stated to be for distances up to 100 km

[10] 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 otherwise	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 ×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 & I	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 ×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

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[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	Travasarou 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} otherwise	1	G[18]	1M	B	PGV

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[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 200 km.

[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 (shallow) & 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

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[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	Simulation approach			5.3	6.8	M_w	20*	60*	r_{rup}	1	G	1	A	PGV
85	Atkinson (2008)	E. N. America	Referenced-empirical approach			4.3	7.6	M_w	10*	1000*	r_{jb}	C	I50	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	I50	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	I50	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	I50	1M	A (N, R, S, HW)	PGV, PGD

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[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 ($m_b(Lg)$)	5*	100*	r_{hypo}	1	U	1	A	PGV
95	Snæbjörnsson 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

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[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 0 km.

[33] Believe that model valid to 200 km.

[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	I50	1M	A (N, R, S, HW, AS)	PGV ×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×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	I50	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

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[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_s3.2.

[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	Rupakhety 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

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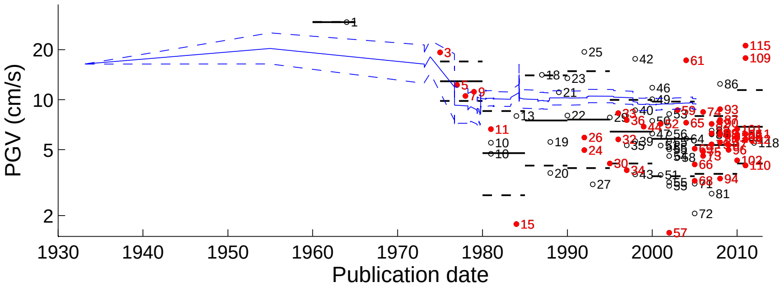
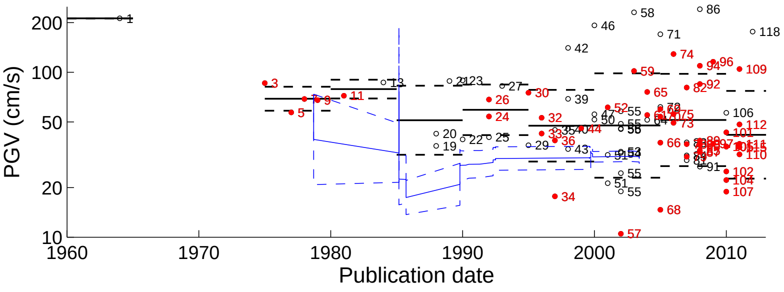
[38] Believe that model can be used to 8.0.

[39] Recommend that model is not used for distances ≥ 200 km.

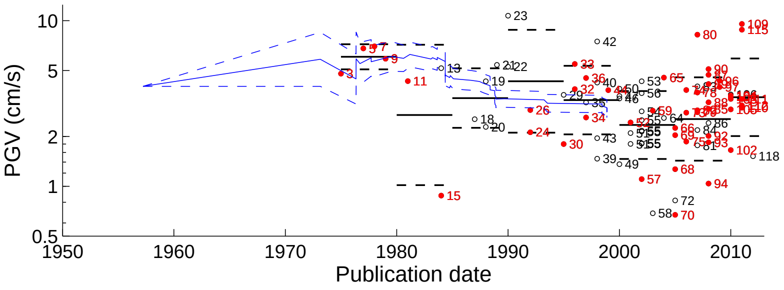
List of Figures



(a) For a $M_w 6$ strike-slip earthquake at $r_{jb} = 20\,\mathrm{km}$. Up until the end of 2005, 253 records from 56 earthquakes were used to compute the average observed PGV.

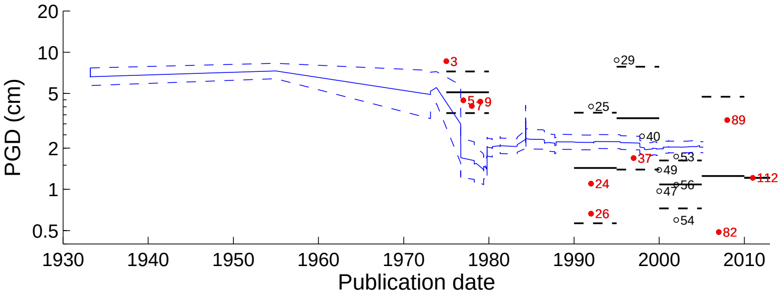


(b) For a $M_w 7.5$ strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$. Up until the end of 2003, 129 records from 15 earthquakes were used to compute the average observed PGV. The vertical blue line in 1985 is caused by many number of records from the same date (the Chile earthquake of 3rd March 1985)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

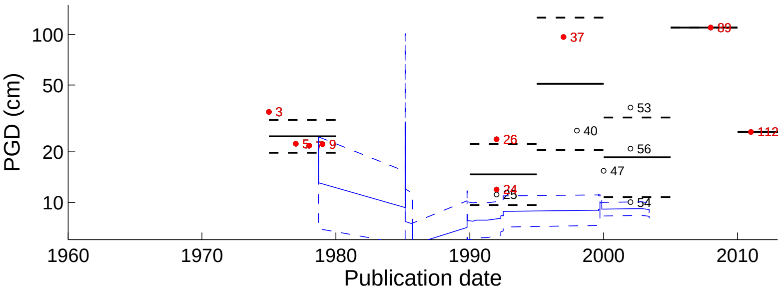


(c) For a $M_w 5$ strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$. Up until the end of 1998, 51 records from 30 earthquakes were used to compute the average observed PGV.

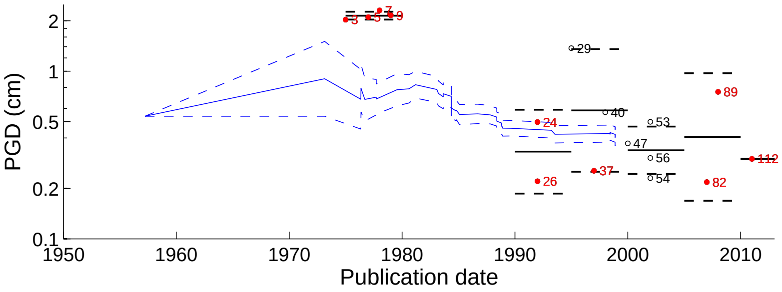
Fig. 1 Predicted PGV at a NEHRP C site against publication date for 96 models published in the literature. Filled red circles indicate models published in peer-reviewed journals, for which basic information on the used dataset is available and which are not being extrapolated far outside their range 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 $r_{jb} = 20\,\mathrm{km}$.

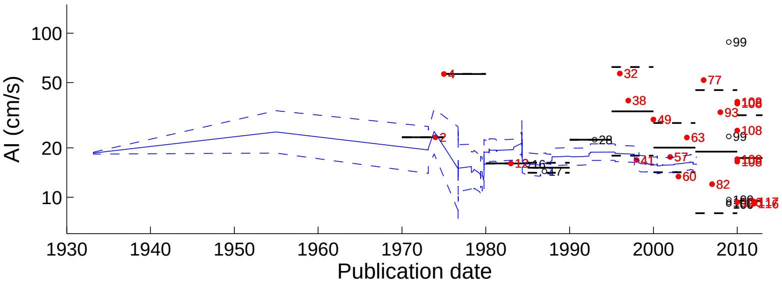


(b) For a $M_w 7.5$ strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$.

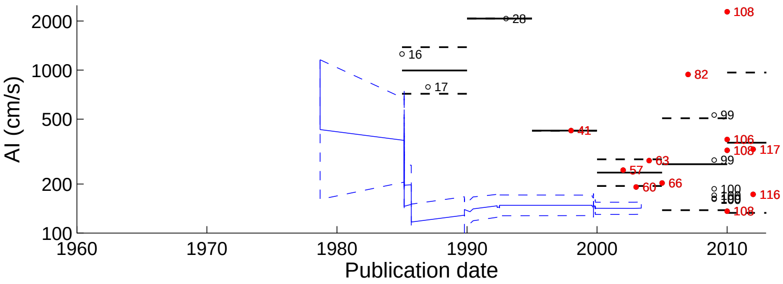


(c) For a $M_w 5$ strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$.

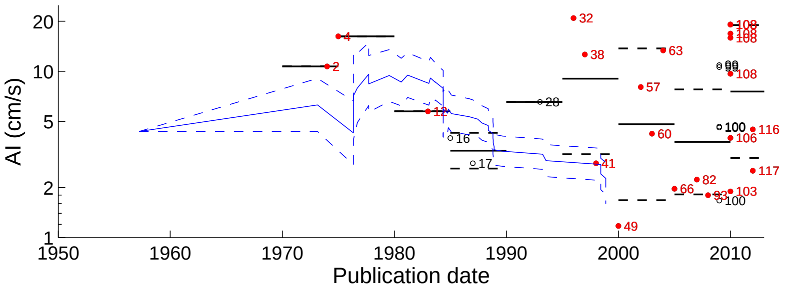
Fig. 2 Like Figure 1 but for PGD (19 models).



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

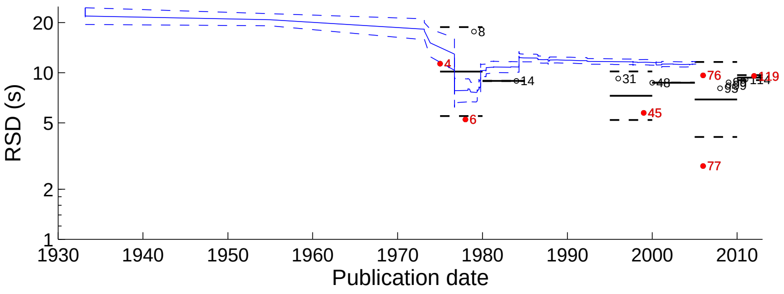


(b) For a $M_w 7.5$ strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$.

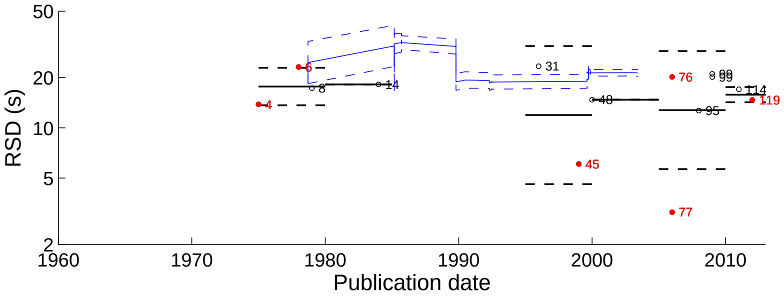


(c) For a $M_w 5$ strike-slip earthquake at $r_{jb} = 10\,\mathrm{km}$.

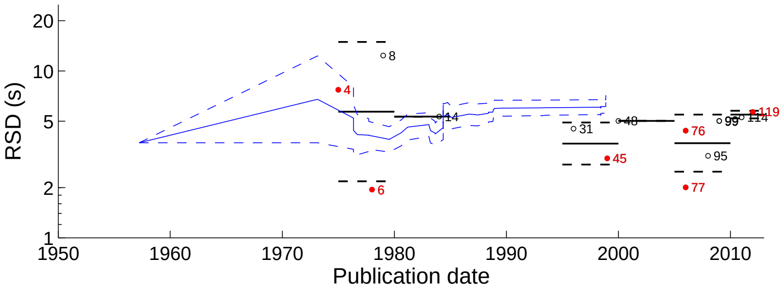
Fig. 3 Like Figure 1 but for AI (33 models).



(a) For a M_w6 strike-slip earthquake at $r_{jb} = 20$ km.



(b) For a M_w7.5 strike-slip earthquake at $r_{jb} = 10$ km.



(c) For a M_w5 strike-slip earthquake at $r_{jb} = 10$ km.

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