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# THE PREDICTION AND USE OF PEAK GROUND VELOCITY

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Peak ground velocity (PGV) has received much less attention in the technical literature than more widely-used parameters such as peak ground acceleration (PGA) and response spectral ordinates. However, there are many examples of the use of PGV in engineering seismology and earthquake engineering, including as a parameter from which to estimate macroseismic intensity and structural damage. PGV is also employed in some methods for the assessment of liquefaction potential and, because of its relationship to ground strains, in the seismic design and assessment of buried pipelines. One of the most important uses of PGV has been in the construction of elastic response spectra. There are relatively few predictive equations for PGV, compared to those for PGA and spectral ordinates, but 25 such equations are reviewed and summarised. The issue of scaling PGV from response spectral ordinates is explored and it is shown that the common practice of scaling PGV from spectral accelerations at 1.0 second should not be continued because the ratio of the two quantities is highly variable. A more stable relationship exists between PGV and the spectral acceleration at 0.5 second response period; however, it is clearly preferable to estimate peak velocities directly and PGV equations should be derived together with equations for spectral ordinates in the same way as PGA.

*Keywords*: Peak ground velocity; peak ground acceleration; spectral acceleration; response spectra.

## 1. Introduction

Despite the widespread acceptance that it has little geophysical significance and is of limited value for earthquake engineering, peak ground acceleration (PGA) remains the most commonly used ground-motion parameter. In large part this is due to the fact that most earthquake-resistant design is based on the response spectrum of acceleration and PGA corresponds to the spectral ordinate at zero period. The predominance of the response spectrum method in seismic design has led to the publication of a large number of predictive equations for PGA and spectral ordinates of acceleration [Douglas, 2003]. In recent years the increasing interest in

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spectral displacements has led to the development of some equations for their prediction, either as over-damped elastic ordinates [e.g. Bommer and Elnashai, 1999] or inelastic ordinates [e.g. Lawson and Krawinkler, 1995; Borzi *et al.*, 2001], but these are very few. The number of available predictive equations for other strong-motion parameters is also small, with very few for Arias intensity [e.g. Travasarou *et al.*, 2003; Hwang *et al.*, 2004b] and the number of cycles of motion [e.g. Hancock and Bommer, 2005], and a somewhat greater but still limited number for strong-motion duration [e.g. Bommer and Martínez-Pereira, 1999].

This paper deals specifically with peak ground velocity (PGV), first reviewing its many applications in engineering seismology, which range from use as an indicator of damage potential of ground shaking and an indicator of ground strain for the seismic analysis of buried pipelines, to a measure of the frequency content of the motion and a parameter for the construction of elastic response spectra for seismic design. Despite these many applications of PGV in engineering, there are comparatively few equations available for the prediction of this parameter from future earthquakes. The third section of this paper provides an overview of published equations for the prediction of PGV, effectively as a complement to the review of equations for PGA and spectral acceleration by Douglas [2003].

One consequence of the relative scarcity of predictive equations for PGV is that peak velocity is sometimes inferred from the response spectral acceleration at a response period of 1.0 s. This practice is shown to have no rigorous technical basis but rather has arisen through an unintended combination of two independent aspects of representing earthquake actions for engineering design. The fourth section of the paper explores this presumed relationship between PGV and spectral acceleration at 1.0 s, using empirical equations, stochastic simulations and an extensive strong-motion database, and shows that it is highly variable.

## 2. The Use of PGV in Earthquake Engineering

This section provides an overview of the varied uses of PGV in earthquake engineering applications.

### 2.1. *PGV as a damage potential indicator*

One way that PGV has been used as an indirect indicator of damage potential is through correlations with intensity. Trifunac and Brady [1975] derived empirical correlations between PGV and MMI, but the regressions were performed on intensity so that the resulting equations could be used to estimate PGV. Other studies have regressed intensity observations against recorded PGV values to obtain relationships for estimating MMI from PGV [e.g. Wu *et al.*, 2003]. Wald *et al.* [1999a] derive such relationships using both PGA and PGV, and concluded that the latter is more suitable for higher values of intensity whereas PGA correlates well with lower ($<$ VII) intensities. These correlations are used in the generation of 'shake maps' [Wald *et al.*, 1999b]. Kaka and Atkinson [2004] derived new relationships in order to generate 'shake maps' for eastern North America, for which they found the Wald *et al.* [1999a] equations to be unsuitable because of the different nature of ground motions — specifically much higher frequency content — in this stable continental region. The Kaka and Atkinson [2004] equation uses PGV to estimate MMI for both high and low values of intensity. Gerstenberger *et al.* [2005] have also proposed correlations that use PGV for all values of MMI and dispense with PGA altogether.

Fajfar *et al.* [1990] defined a parameter to measure the potential of earthquake ground motions to cause damage in structures of intermediate periods of vibration; the parameter is the product of PGV and the significant duration to the power of 0.25.

Peak ground velocity has also been used to derive vulnerability functions, such as those derived using damage data from the 1995 Hyogo-ken Nanbu earthquake in Japan by Miyakoshi *et al.* [1998] and by Yamazaki and Murao [2000]. Morii and Hayashi [2003] identified PGV as the best parameter for indicating potential earthquake damage in wooden structures.

Akkar and Özen [2005] explored the influence of PGV on inelastic demand of SDOF oscillators using 60 accelerograms obtained at soil sites in the near-source region of earthquakes of moderate-to-large magnitude. Their study considered spectral acceleration, PGA, PGV and the ratio PGV/PGA as ground-motion measures and examined their correlations with inelastic deformation demands in simple oscillators. The best results, in terms of consistently high correlation coefficients between the ground-motion parameter and the inelastic deformations across the period range 0 to 4 seconds, were obtained for PGV. On this basis Akkar and Özen [2005] recommend the use of PGV "*as a stable candidate for ground motion intensity measure in simplified seismic assessment methods*".

The ratio of PGA to PGV, which has been proposed as a measure of the frequency content of the ground motion (see Sec. 2.4), was found to be correlated to some degree with induced damage to inelastic SDOF oscillators subjected to earthquake excitation by Zhu *et al.* [1987, 1988]. The usefulness of the ratio was also affirmed by Sucuoğlu *et al.* [1998] who concluded that intermediate period structures were more vulnerable to damage under ground motions with either long durations (significant duration more than 10 s) or PGV/PGA ratios greater than 0.1, with PGV measured in cm/s and PGA in cm/s$^2$.

Peak ground velocity has also been selected to characterise the seismic hazard due to induced seismicity [van Eck *et al.*, 2005; Bommer *et al.*, 2005b]. In both cases, PGV was chosen because of its simplicity — for prediction and for real-time monitoring — combined with the fact that it avoids the problem of overestimating the hazard associated with non-destructive motions with high PGA values generated by small magnitude, shallow-focus earthquakes.

The usefulness of any ground-motion parameter defined to serve as an indicator of damage potential is enhanced by the definition of threshold values for that parameter. Martínez-Pereira and Bommer [1998] used correlations with macroseismic intensities to identify lower bounds on various ground-motion parameters as necessary (but not sufficient) conditions for damage to be expected in engineered structures (MMI $\geq$ VIII) and for PGV this was determined as 20 cm/s. This value is consistent with the value at which the fragility curves for moderate damage to engineered structures in Japan depart from zero [Miyakoshi *et al.* 1998; Yamazaki and Murao, 2000]. Bommer *et al.* [2005b] defined a much lower threshold (6 cm/s) for the control of risk due to induced seismicity in Central America because of the very high vulnerability of the exposed *adobe* (sun-dried clay brick) houses.

Estimates of the largest values of PGV that could be generated, all published in the 1960s, were in the range from 120 to 150 cm/s [Bommer *et al.*, 2004]. There are now several records that have exceeded 100 cm/s [Bray and Rodriguez-Marek, 2004], the first of these being the famous Pacoima Dam record of the 1971 San Fernando earthquake. The largest estimate of PGV was proposed by Esteva [1970] who suggested 300 cm/s to represent near-source saturation of PGV. The largest recorded PGV, from the TCU068 station accelerogram of the Chi-Chi earthquake, is just below this limit; if the vector combination of the horizontal components is considered then the recorded PGV value is actually slightly higher.

### 2.2. *Seismic analysis of buried pipelines*

One of the most important uses of PGV in earthquake engineering is in the seismic analysis of buried pipelines. This is the result of peak horizontal strain in the soil due to the passage of seismic waves being proportional to the horizontal PGV [Newmark, 1967; Newmark and Rosenblueth, 1971; St. John and Zahrah, 1987]. Peak ground velocity has been used to produce maps of peak soil strain due to earthquakes [e.g. Todorovska and Trifunac, 1996].

Many empirical studies have found good correlations between pipeline damage in earthquakes — generally characterised by number of repairs per kilometre of pipeline — and peak ground velocity [e.g. O'Rourke and Ayala, 1993; Eidinger *et al.*, 1995; Isoyama *et al.*, 2000; O'Rourke *et al.*, 2001; Davis and Bardet, 2000]. One exception to this trend is the studies of the 1999 Chi-Chi, Taiwan, earthquake, for which both Chen *et al.* [2002] and Hwang *et al.* [2004a] found that PGV was the parameter that had the poorest correlation with the pipeline damage, the former study concluding that PGA was the optimal parameter and the latter study identifying Arias intensity as the best damage predictor.

Based on general acceptance of good empirical correlations between pipeline damage and PGV, fragility relationships for buried pipelines in terms of peak ground velocity have been included in the manuals of the American Lifelines Alliance [ALA, 2001] and in HAZUS [FEMA, 2003].

### 2.3. *Assessment of liquefaction potential*

The assessment of liquefaction potential in saturated cohesionless soils is composed of two elements: Evaluation of the susceptibility of the soil to liquefaction and a measure of the capacity of the ground shaking to trigger liquefaction. The latter has generally been represented by the combination of PGA and a measure of the number of effective cycles of ground motion [e.g. Green and Terri, 2005] but other approaches have also been proposed, some of which involve the use of PGV.

Trifunac [1995] derived several empirical relationships for liquefaction potential using different measures of the ground-motion energy, one of these being the product of duration and the square of PGV. Kostadinov and Towhata [2002] propose a method to assess liquefaction in real-time for remedial measures to be taken to protect pipelines in liquefiable materials, as a more economical alternative to soil improvement over great lengths of buried pipelines. The indicators for the onset of liquefaction are thresholds on the horizontal frequency content of the surface motion and the horizontal PGV at the surface. The utility of PGV thresholds to indicate the potential for the onset of liquefaction is confirmed by Orense [2005] who develops a method for assessing liquefaction potential using both PGA and PGV, arguing that the use of PGA alone neglects the effects of the frequency content of the ground motion and makes the analysis susceptible to high-frequency, low-energy spikes of acceleration.

### 2.4. *Scaling of response spectra*

The use of PGV to construct elastic response spectra for design dates back to Newmark *et al.* [1973]. The method, summarised by Newmark and Hall [1982], requires estimation of PGA, PGV and the peak ground displacement (PGD) at the site, although it allows for the latter two quantities to be scaled directly from PGA rather than being independently estimated. The spectrum is then constructed, on tripartite logarithmic axes, by multiplying the three peak ground-motion parameters by factors related to the proportion of critical damping of the required spectrum (Fig. 1); scaling factors were provided for median and 84-percentile values of the spectral ordinates. The product of the scaling factors with PGD, PGV and PGA then defined three lines on the tripartite plot that are considered as the displacement-, velocity- and acceleration-sensitive portions of the response spectrum; the corner periods between these sections are defined by the intersection of these three lines, and the linear decay of the acceleration-sensitive branch to intercept the value of PGA at a response frequency of 33 Hz.

The concept of acceleration- and velocity-sensitive branches of the response spectrum has been explicitly taken up in the definition of elastic design spectra in some seismic design codes. For example, the 1984 Colombian code presented maps of coefficients related to acceleration ($A_a$) and to velocity ($A_v$) and used these to construct the short- and intermediate-period sections of the response spectrum [IAEE, 1996]. The 1985 edition of the Canadian seismic design code was even more

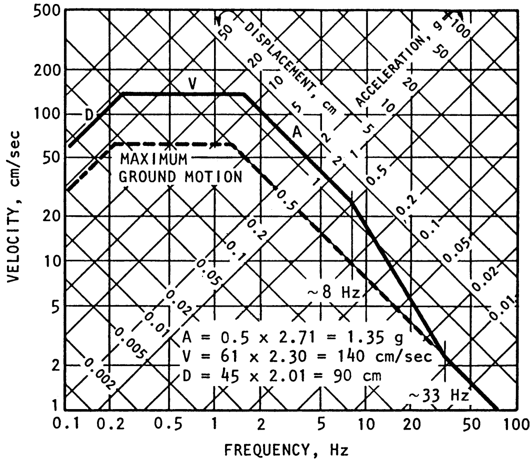


Fig. 1. Construction of tripartite response spectrum (84th percentile level) using peak ground-motion parameters and damping-dependent amplification factors [Newmark and Hall, 1982].

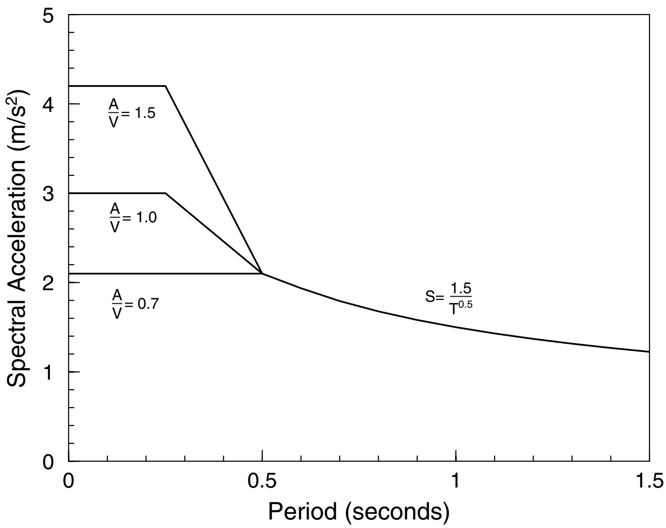


Fig. 2. Acceleration response spectra from the 1995 Canadian seismic code, for a mapped PGV of 1 m/s. A/V represents the ratio of the mapped values of coefficients $Z_a$ and $Z_v$, related to PGA and PGV respectively, from the hazard maps presented in the code.

explicit and presented maps of PGA and PGV [Basham *et al.*, 1985], anchoring the medium-period part of the response spectrum to PGV and then constructing the short-period spectral ordinates as a function of the PGA/PGV ratio (Fig. 2).

Researchers in Canada [e.g. Tso *et al.*, 1992] have carried out extensive studies on the PGA/PGV ratio and its significance, particularly in terms of a measure of the frequency content of the ground motion.

Bommer *et al.* [2000] proposed a method for constructing compatible acceleration and displacement spectra for seismic design codes, based on two corner periods: The first defines the end of the constant acceleration plateau and, adapting the procedure of Newmark *et al.* [1973], is calculated from the ratio PGV/PGA; the second corner period defines the start of the constant displacement plateau and this is calculated from the ratio PGD/PGV.

Peak ground velocity has also been considered as a parameter for scaling strong-motion accelerograms to be used in nonlinear structural analysis, particularly for structures with higher natural periods of vibration [e.g. Kappos and Kyriakakis, 2000]. Japanese regulations for the seismic design of tall buildings specify analysis of the structures under the action of acceleration records scaled to different values of PGV depending on the level of design [e.g. Fitzpatrick, 1992].

## 3. Predictive Equations for PGV

A list of ground-motion prediction equations for PGV is presented in Table 1, together with the main characteristics of the relations in terms of the definitions employed for the basic parameters and the ranges of magnitude and distance covered by the datasets employed for their derivation. The list is almost definitely not exhaustive but represents those equations that the authors have been able to retrieve from the literature; however, even taking into account that a few equations will have been omitted, it is clear that equations for this parameter are far less abundant than those for PGA.

In the remainder of this section, following a brief consideration of some of the issues related to retrieving PGV from strong-motion recordings, the equations are briefly discussed, grouped in geographical regions. The equations themselves are not presented, partly because of space limitations but mainly to avoid their use without reference to the original publications in which they appeared: It is vitally important to be aware of any limitations associated with the application of a particular equation and any assumptions made in its derivation.

Direct comparisons of ground motions estimated from predictive equations are generally complicated by the fact that there are often differences in the definitions used for the predicted parameters and the independent variables [e.g. Bommer *et al.*, 2005a]. For two of the regions for which there are a number of equations, graphical comparisons are made after making adjustments for any incompatibilities.

### 3.1. *PGV from strong-motions accelerograms*

Peak ground velocity is defined simply as the largest absolute amplitude in a time history of the ground velocity, which is generally obtained from integration of the acceleration record. Accelerograms, especially those obtained from analogue instruments, generally require processing to compensate for the long-period noise that is encountered in the digitised record. The low-period cut-off selected for the filter has

Table 1. Characteristics of equations for the prediction of peak ground velocity (PGV).

| Study | Geographical coverage | No. of records, earthquakes | C | $M_{min}$, $M_{max}$ | M | $R_{min}$, $R_{max}$ (km) | R | Site Classes |
|---|---|---|---|---|---|---|---|---|
| Trifunac and Brady (1976) | Western USA | 187, 57 | B | 3.0, 7.7 | $M_L$ | 20, 200 | $R_{epi}$ | 3 |
| McGuire (1978) | Western USA | 70, > 30 | B | 5.0, 7.7 | $M_L$ | 11, 210 | $R_{hyp}$ | 2 |
| Joyner and Boore (1981) | Western North America | 62, 10 | L | 5.0, 7.7 | $M_W$ | 1, 109 | $R_{jb}$ | 2 |
| Kawashima *et al.* (1986) | Japan | 197, 90 | M | 5.0, 7.9 | $M_{JMA}$ | < 500 | $R_{epi}$ | 3 |
| Gaull (1988) | S.W. of western Australia | > 21, 16 | U | 2.0, 6.3 | $M_L$ | < 200 | $R_{epi}$ | 2 |
| Kamiyama *et al.* (1992) | Japan | 357, 82 | B | 4.1, 7.9 | $M_{JMA}$ | 3, 413 | $R_{hyp}$ | S |
| Theodulidis and Papazachos (1992) | Primarily Greece | 61, 40 | U | 4.5, 7.5 | $M_s$ | < 35 | $R_{epi}$ | 2 |
| Atkinson and Boore (1995)+ | Eastern North America | U, 22 | R | 4.0, 7.0 | $M_W$ | 10, 500 | $R_{hyp}$ | 2 |
| Molas and Yamazaki (1995) | Japan | 2166, 387 | L | 4.1, 7.8 | $M_{JMA}$ | < 1000 | $R_{rup}$ | S |
| Sabetta and Pugliese (1996) | Italy | 95, 17 | L | 4.6, 6.8 | $M_s$, $M_L$ | < 100 | $R_{epi}$, $R_{jb}$ | 3 |
| Atkinson and Boore (1997)+ | Primarily West Canada | > 1000, > 68 | R | 3.7, 6.7 | $M_W$ | 10, 400 | $R_{hyp}$ | 2 |
| Campbell (1997) | Worldwide Primarily California | 226, 30 | G | 4.7, 8.1 | $M_W$ | 3, 50 | $R_{seis}$ | 3 |
| Rinaldis *et al.* (1998) | Italy and Greece | 310, U | U | 4.5, 7.0 | $M_s$, $M_W$ | 7, 138 | $R_{epi}$ | 2 |
| Sadigh and Egan (1998) | Primarily California | 960, 51 | G | 3.8, 7.4 | $M_W$ | 0, 100 | $R_{rup}$ | 2 |
| Si and Midorikawa (2000) | Japan | 394, 21 | L | 5.8, 8.3 | $M_W$ | < 300 | $R_{rup}$, $R_{hyp}$ | 1 |
| Gregor *et al.* (2002) | Worldwide Primarily California | 993, 143 | U | 4.4, 7.6 | $M_W$ | 0.1, 267 | $R_{rup}$ | 2 |

Table 1. (*Continued*)

| Study | Geographical coverage | No. of records, earthquakes | C | $M_{min}$, $M_{max}$ | M | $R_{min}$, $R_{max}$ (km) | R | Site Classes |
|---|---|---|---|---|---|---|---|---|
| Margaris *et al.* (2002) | Greece | 474,142 | B | 4.5, 7.0 | $M_W$ | 1, 150 | $R_{epi}$ | 3 |
| Shabestari and Yamazaki (2002) | Taiwan | 95, 1 | A | 7.6 | $M_W$ | U | $R_{seis}$ | 2 |
| Tromans and Bommer (2002) | Europe | 249, 51 | L | 5.5, 7.9 | $M_s$ | 1, 359 | $R_{jb}$ | 3 |
| Sigh *et al.* (2003)$^+$ | India | U, 5 | U | 5.7, 7.6 | $M_W$ | 23, 2437 | U | 1 |
| Bray and Rodriguez-Marek (2004) | Worldwide | 54, 13 | F | 6.1, 7.6 | $M_W$ | $< 20$ | $R_{rup}$ | 2 |
| Hao and Gaull (2004) $^+$ | S.W. of western Australia | 10, 5 | U | 4.1, 6.2 | $M_L$ | 6, 96 | $R_{hyp}$ | 1 |
| Midorikawa and Ohtake (2004) | Japan | 1980, 33 | L | 5.5, 8.3 | $M_W$ | $< 300$ | $R_{rup}$ | 2 |
| Pankow and Pechmann (2004) | Worldwide | 124, 39 | G | 5.0, 7.7 | $M_W$ | 0, 100 | $R_{jb}$ | 2 |
| Frisenda *et al.* (2005) | Northwestern Italy | $> 14000$, U | U | 0.03, 5.1 | $M_L$ | 0, 200 | $R_{hyp}$ | 2 |

*Notes*: $^+$ Stochastic model. U — unknown. **C:** Use of the horizontal components of each record: A — arithmetic mean; B — both components; F — fault-normal component; G — geometric mean; L — largest component; M — maximum vector value; R — random component. **M:** Magnitude scale used: $M_{JMA}$ — Japanese Meteorological Agency magnitude; $M_L$ — local magnitude; $M_s$ — surface wave magnitude; $M_W$ — moment magnitude. **R:** Source-to-site distance definition [see Abrahamson and Shedlock, 1997]: $R_{epi}$ — epicentral distance; $R_{hyp}$ — hypocentral distance; $R_{jb}$ — closest horizontal distance to the fault rupture projection on the surface; $R_{seis}$ — closest distance to the presumed zone of seismogenic rupture on the fault; $R_{rup}$ — closest distance to rupture surface; **Site class:** Number of site classifications used; S — individual classification for each recording station.

a large influence on the resulting value of PGV [e.g. Tromans and Bommer, 2002]. Douglas [2002a] compared the values of PGV obtained from near-source recordings processed using filters and a baseline correction technique that retains permanent displacements associated with the fault slip, concluding that filtering with long-period cut-offs of the order of 5 to 10 s will lead to underestimation of PGV from larger (M $>$ 6.5) earthquakes. For analogue recordings from small-to-moderate magnitude earthquakes, filter parameters may be chosen that result in cut-off frequencies greater than the theoretical corner frequency, implying that application of the filter will then remove significant parts of the signal [Boore and Bommer, 2005]. The general conclusion therefore is that PGV values obtained from analogue accelerograms of small-to-moderate magnitude earthquakes or recorded at short source-to-site distances are likely to be underestimated if these records have been filtered.

In passing it may be noted that in addition to deriving PGV directly from the integration of accelerograms, methods have been developed to estimate peak ground velocities from records obtained on Wood-Anderson seismographs [Boore, 1980] and from seismoscope recordings [Boore, 1984].

### 3.2. *Equations for western North America*

Table 1 shows that there are surprisingly few PGV prediction equations for western North America, despite the abundance of strong-motion records from the region and the large number of predictive equations developed for PGA and for response spectral ordinates. The early equations of Trifunac and Brady [1976], McGuire [1978] and Joyner and Boore [1981] would probably now be considered to be obsolete because of their age. Campbell [1997] included PGV together with his equations for PGA and spectral accelerations, one of the few studies to do so in a special issue of *Seismological Research Letters* dedicated to ground-motion prediction equations, mainly for North America. The equation was derived specifically for near-source application, with an upper limit of 50 km on distance. The PGV equation of Campbell [1997] is rather complex, including style-of-faulting and site classification, and a distance metric (measured from the closest point on the fault rupture below the non-seismogenic uppermost layer of the crust) that has not been adopted by other studies.

Sadigh and Egan [1998] developed an equation for PGV from the dataset used by Sadigh *et al.* [1997] for predicting response spectral ordinates; the dataset is dominated by recordings from California with a few other records from large magnitude, shallow crustal events such as Gazli (former USSR) and Tabas (Iran). The equations are applicable for distances up to 100 km and include style-of-faulting and site classification as predictive parameters. The other equation that has been derived for PGV in western North America is that of Gregor *et al.* [2002], which was intended to estimate values of PGV and PGD in western North America conditional on estimates of PGA. The database employed is dominated by recordings from western North America, but includes a few records from other regions including Italy, Iran, Taiwan (SMART array) and Turkey. Additionally, the database was supplemented by near-source recordings from the 1999 Chi-Chi, Kocaeli and Duzce earthquakes, processed using baseline techniques to preserve the static component of the fault slip, which will have prevented underestimation of PGV by filtering, as noted by Douglas [2002a].

The equation of Campbell [1997] is applicable only up to 50 km, the equation of Sadigh and Egan [1998] was published in the proceedings of a conference and the equation of Gregor *et al.* [2002] was presented in a private consultancy report. This situation may explain why Field *et al.* [2005] mapped PGV in Los Angeles by scaling the values from spectral acceleration rather than using direct predictions of peak velocity, as discussed further in Sec. 4.1.

### 3.3. *Equations from Europe and the Middle East*

Predictive equations derived from the extensive strong-motion database covering Europe, the Mediterranean and Middle Eastern regions for spectral accelerations have included PGA but not PGV [Ambraseys *et al.*, 1996, 2005]. Tromans and Bommer [2002] used a database from this region to derive compatible equations for PGA, PGV and PGD as functions of magnitude, distance and site classification. Other studies have derived PGV equations for specific countries, mainly Greece and Italy, including a recent equation by Frisenda *et al.* [2005] that is based on recordings from small magnitude ($M_L < 5.2$) earthquakes in northwest Italy.

Figure 3 presents comparisons of the PGV (larger horizontal component) predictions on rock from four European equations as functions of Joyner-Boore ($R_{jb}$) distance and surface-wave magnitudes of $M_s$ 5.5 and 7.0. Component conversions

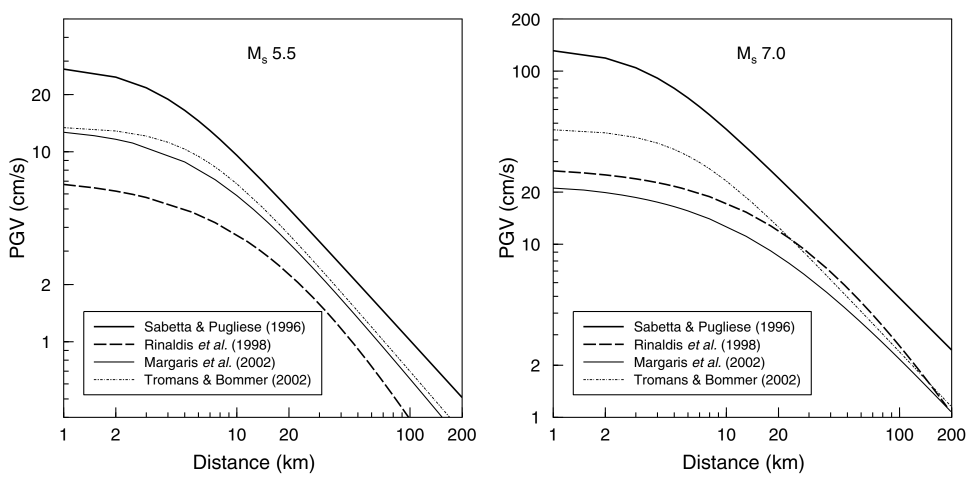


Fig. 3. Comparisons of predicted PGV values for rock sites from European equations.

are applied following Bommer *et al.* [2005a], using the 0.5 s spectral ordinate as a surrogate for PGV (see Sec. 4) and magnitude conversions using Ambraseys and Free [1997]. For the equations based on epicentral distance ($R_{epi}$) the conversion from $R_{jb}$ is performed using the median values, as suggested by Bommer *et al.* [2005a], from the normal distributions presented in the study of Scherbaum *et al.* [2004]. The Rinaldis *et al.* [1998] equation requires the specification of the style-of-faulting, for which reverse and strike-slip (as opposed to normal) was selected.

There are clearly very large differences amongst the predicted PGV values, which in part may be a result of the approximations that the various conversions for parameter compatibility represent; for example, the correlations of Scherbaum *et al.* [2004] are based on randomly distributed receivers, whereas this is generally not the case for the distribution of recordings within the datasets used to derive equations. Two of the most notable features of the comparisons in Fig. 3 are the comparatively high values predicted by Sabetta and Pugliese [1996] and the very low velocities predicted by Rinaldis *et al.* [1998] for $M_s$ 5.5. On the latter point, it may be noted that this equation, published in conference proceedings, has some notable features that possibly militate against its reliability, such as the fact that it predicts slightly higher values of PGV for normal faulting events than for other mechanisms. This equation also has a magnitude scaling coefficient for PGV, which for $\log_{10}(\text{PGV})$ would be equal to 0.58, which is higher than the values in all the other equations in Fig. 3. With regards to the apparently very high predicted velocity from the equation of Sabetta and Pugliese [1996], this might be the result of the record processing since the low-frequency cut-off filters used for that study were at longer periods than those used in the other studies, such as Tromans and Bommer [2002]. As noted in Sec. 3.1, it is highly likely that the rather severe cut-offs applied by Tromans and Bommer [2002] led to an underestimation of PGV; it may be the case therefore that the Sabetta and Pugliese [1996] curves appear to be high only because the others are low as a result of the filter parameters used in processing the mainly analogue records. Another point worthy of note is that the largest differences between Sabetta and Pugliese [1996] and the other equations is for short ($< 10$ km) distances, for which the former equation is poorly constrained, particularly for magnitudes greater than 6.

### 3.4. *Equations from Japan*

A number of equations for PGV have been derived from the extensive strong-motion databases of Japan, which includes both crustal earthquakes and subduction earthquakes with focal depth down to about 120 km; deeper events are recorded but the equations are generally limited to this depth. Predicted peak velocities from three of these are compared graphically in Fig. 4.

Both Molas and Yamazaki [1995] and Midorikawa and Ohtake [2004] present equations for different ranges of focal depth and the equations applicable to events of depth less than 30 km are used. Si and Midorikawa [2000] and Midorikawa and

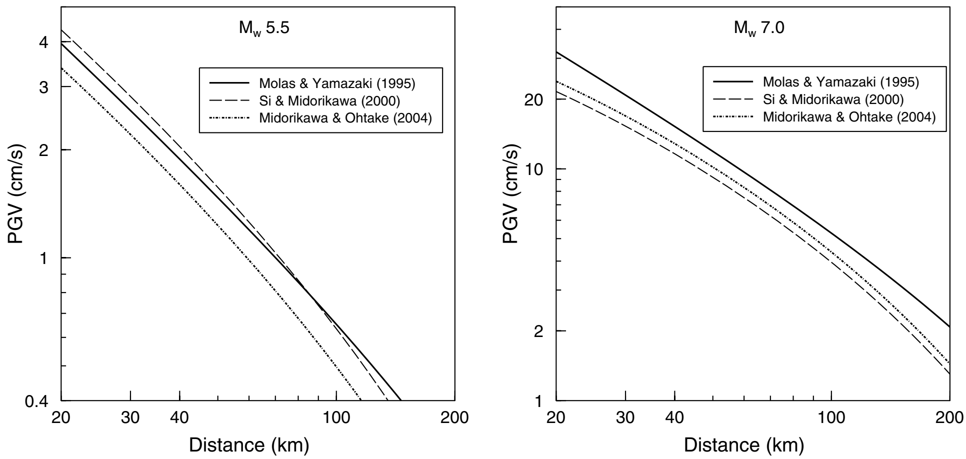


Fig. 4. Comparisons of predicted PGV values for rock sites from Japanese equations.

Ohtake [2004] include a coefficient that varies for crustal, interface and in-slab earthquakes, and these are set to interface, for which a focal depth of 20 km is selected. All three equations use the larger horizontal component of motion and the $R_{rup}$ distance definition; the only adjustment required is for Molas and Yamazaki [1995], for which $M_w$ values are converted to $M_{JMA}$ via the relationship of Fukushima [1996].

The equations show general agreement, which in view of the commonality of the databases employed and the use of the same parameter definitions, is perhaps not surprising.

### 3.5. *Equations from stable continental regions*

Two of the equations listed in Table 1 are for the southwest of western Australia, the first an empirical relationship based on a small database of earthquake recordings in which the largest magnitude was $M_L$ 6.3, while the lowest magnitude is 2.0 [Gaull, 1988]. A subsequent study used stochastic simulations adjusted to match the previous equation rather than producing a new one [Hao and Gaull, 2004].

The study by Singh *et al.* [2003] developed a stochastic model to estimate the peak velocities from the 2001 Bhuj earthquake in India and it is therefore not an equation of general applicability for seismic hazard analysis.

Atkinson and Boore [1995] used the stochastic method to develop a predictive equation for PGV in eastern North America (ENA). The interesting feature of this study is the high ratio of PGA to PGV obtained from their equations, which is entirely consistent with the very high frequency content of ground motions in this region, the result of high stress drops and very hard ($V_s \sim 2{,}500$ km/s) rock site conditions. This is, as far as the authors have been able to identify, the only generally applicable PGV equation for a stable continental region (SCR). An important question then arises as to whether or not it might be applicable in other SCRs;

direct comparisons are hampered by many differences, but graphical comparison (not shown here) of the attenuation curves for ENA and for Australia, using the equations described above, suggests that these two regions have quite distinct characteristics, with more rapid attenuation in ENA. This is very limited evidence but it does suggest that caution should be exercised in applying equations from one SCR to another.

### 3.6. *Other equations*

Three other equations listed in Table 1 deserve brief commentary. The first of these is the study by Pankow and Pechmann [2004], who used the database of Spudich *et al.* [1999] for extensional tectonic regions to derive equations for PGV, noting that whilst PGV is required for applications such as estimating damages and Modified Mercalli intensities (see Sec. 2.1), few PGV equations have been published.

The two other equations in Table 1 are concerned specifically with the predictions of ground motions in the near-source region of strong earthquakes. Shabestari and Yamazaki [2002] derived equations for the records from the 1999 Chi-Chi earthquake in Taiwan, with separate relationships for recordings from the footwall and hanging wall regions. The equations are specific to this earthquake and therefore independent of magnitude and of limited applicability in general seismic hazard analysis. Using the directivity model of Somerville *et al.* [1997], Shabestari and Yamazaki [2002] then developed predictive models that include forward rupture directivity effects and polarization of the ground motion in the fault-normal and fault-parallel directions; however, these directivity-dependent models are only developed for response spectral ordinates, and not for PGV. Bray and Rodriguez-Marek [2004], on the other hand, developed equations specifically for PGV in the near-source region. For this purpose, they compiled a database of 54 accelerograms from around the world, recorded within 20 km of seismic fault ruptures (or within 15 km for events with $M_w < 6.5$), generated by 13 earthquakes. For each record they identified PGV, the period of the velocity pulse and the number of pulses, and produced predictive relationships for each of these parameters.

## 4. Scaling PGV from Response Spectral Ordinates

The relative scarcity of predictive equations for PGV has often led to this parameter being inferred from response spectral ordinates. In this section we explore the development of this practice and then demonstrate that a widely used assumption — that PGV is stably correlated with the spectral ordinate at 1 second — is not valid. This is followed by exploratory analyses, using published equations, stochastic simulations and a large strong-motion database, to identify the response period at which there is a relatively stable relationship between spectral acceleration and peak ground velocity. Throughout this section, the spectral ordinates with 5% of critical damping are considered.

### 4.1. *PGV and the spectral acceleration at 1 second*

Engineering seismology is a young science and much is owed to the great pioneers who made fundamentally important contributions to the subject, often in the areas of ground motion and structural response at the same time, in the 1970s. However, facing the need in those early days to provide viable engineering solutions with limited data, a number of simple formulations were put forward, often with limited technical basis, and these have subsequently remained as key elements of engineering practice until challenged by new and quantitative research. Clear examples of this kind of unsubstantiated rule-of-thumb in earthquake engineering include the 2/3 ratio for vertical-to-horizontal motion, which has now been demonstrated to be invalid in most circumstances [Bozorgnia and Campbell, 2004], and the 475-year return period that at one point was the universal basis for defining acceptable seismic risk in standard constructions [Bommer and Pinho, 2005]. We believe that the concept of scaling PGV from the 1-second response spectral ordinate is another example of earthquake engineering 'folklore'.

As noted in Sec. 3.2, Field *et al.* [2005] mapped PGV in Los Angeles as part of loss estimation for an earthquake on the Puente Hills blind thrust, noting that "*the maps for peak ground velocity (PGV) are simply the results for 1-second SA multiplied by the scalar conversion factor given by Newmark and Hall (1982)*". This approach is in fact embodied in HAZUS [FEMA, 2003], which Field *et al.* [2005] use for their loss estimations, where a relationship is given whereby PGV can be calculated from the pseudo-spectral velocity (PSV) at a period of 1 s divided by a factor of 1.65, attributed again to Newmark and Hall [1982]. This same equation is also cited by Pankow and Pechmann [2004], who state that "*due to the lack of recent PGV predictive relations, this Newmark and Hall method is gaining popularity*". The idea that PGV and the response spectral ordinate at a period of 1 second are closely related is widespread: Heidebrecht [1995], discussing the introduction of PGA and PGV maps into the 1985 seismic code from Canada, explains that "*the map of peak horizontal velocity was added to depict strong ground motion at a period of approximately 1 s because peak horizontal acceleration depicts ground motion only at low periods, i.e. approximately 0.2 s*".

By definition the zero-period spectral acceleration must be equal to PGA and the two quantities are found to converge at periods between 0.01 and 0.03 s depending on the type of motion; the periods that actually control the peak acceleration can be much longer. Similarly, the long-period spectral displacement ordinates must eventually converge to PGD, albeit that there is considerable uncertainty about the period at which this occurs. Therefore, it is common to refer to different portions of the response spectrum as being sensitive to the peak acceleration, velocity and displacement of the ground motion. Sucuoğlu and Erberik [1998] concluded that "*peak velocity completely governs the spectral response in the long period range*" and most studies concur in describing the spectral ordinates at intermediate periods as being controlled by velocity, which is entirely consistent with the methodology proposed by Newmark and Hall [1982] to construct the response spectrum. However, in the context of this paper the issue is not scaling spectral ordinates up from PGV but the inverse process of inferring PGV from response spectral ordinates. The key point here is that Newmark *et al.* [1973] and Newmark and Hall [1982] never mentioned the 1-second spectral ordinate as having any specific property. In the Newmark and Hall [1982] method the corner periods of the response spectrum are found from the intersection of the branches scaled up from PGA, PGV and PGD; in the example shown in Fig. 1, the velocity-controlled portion of the spectrum is in the range from 0.256 to 1.64 Hz (0.6 to 3.9 s period) and the 1-second ordinate happens to be within this range.

Our investigation of the historical development of the scaling relationship now embodied in HAZUS suggests that it came about as the result of merging two separate and independent lines of work, without it ever being the intention of the groups developing either of the two parts to suggest a direct relationship between PGV and PSV(1.0). On the one hand, there was the scaling of intermediate-period spectral ordinates from PGV, proposed by Newmark and his co-workers. On the other hand, there was the practice of mapping seismic hazard in terms of the spectral acceleration at 1.0 second. This was first proposed by Algermissen and Leyendecker [1992], who produced hazard maps for the US in terms of 5% damped spectral accelerations at response periods of 0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0 and 4.0 seconds. However, for code applications they concluded that only two response periods should be used "*since it would be impractical to provide maps for each of the 12 spectral ordinates*". The selected periods were 0.3 s and 1.0 s, although no specific reasons were stated for this choice; it may be assumed, however, that at least part of the reasoning was related to the fact that the ordinate at 0.3 s will nearly always lie within the constant acceleration plateau, whereas the 1.0 s ordinate, which is a round number, will nearly always lie beyond the plateau in the descending acceleration branch. The suggestion of Algermissen and Leyendecker [1992] has been widely accepted [e.g. Frankel *et al.*, 2000] but it is important to note that Algermissen and Leyendecker [1992] made no assertions regarding the relationship between PGV and the 1.0-second spectral ordinate. However, the presentation of hazard in terms of 1.0-second spectral ordinates and the proportionality between spectral ordinates at intermediate periods and PGV have been combined in earthquake engineering in the form of a relationship that was never proposed by Newmark and Hall [1982] or by Algermissen and Leyendecker [1992].

The concept — or myth — of direct proportionality between PGV and the spectral ordinate at 1.0 s has been reinforced by some quantitative studies. Figure 5 shows the average spectra of four groups of accelerograms from a very heterogeneous database of 35 records, after scaling each accelerogram to a PGV of 50 cm/s [Sucuoğlu and Erberik, 1998]. However, the dispersion of the spectral ordinates within each group is not reported and it is also not clear if the groupings of the accelerograms has any seismological rationale.

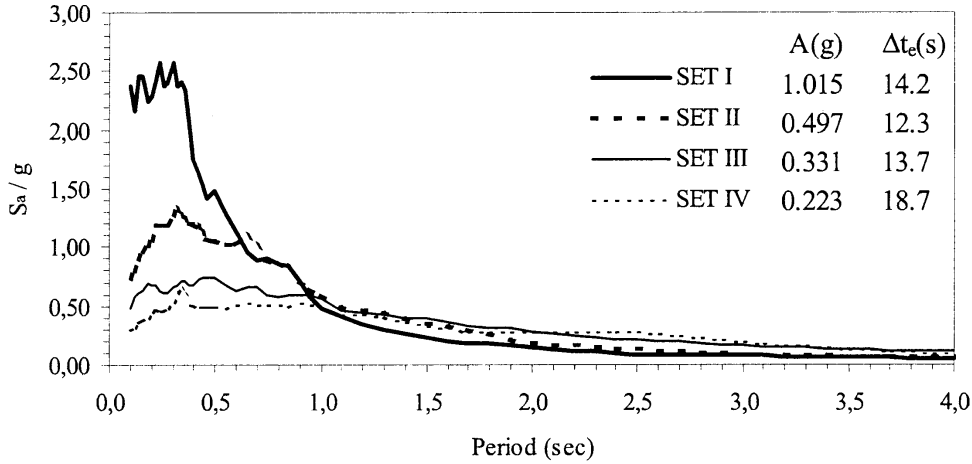


Fig. 5. Average spectra of records scaled to PGV = 50 cm/s [Sucuoğlu and Erberik, 1998].

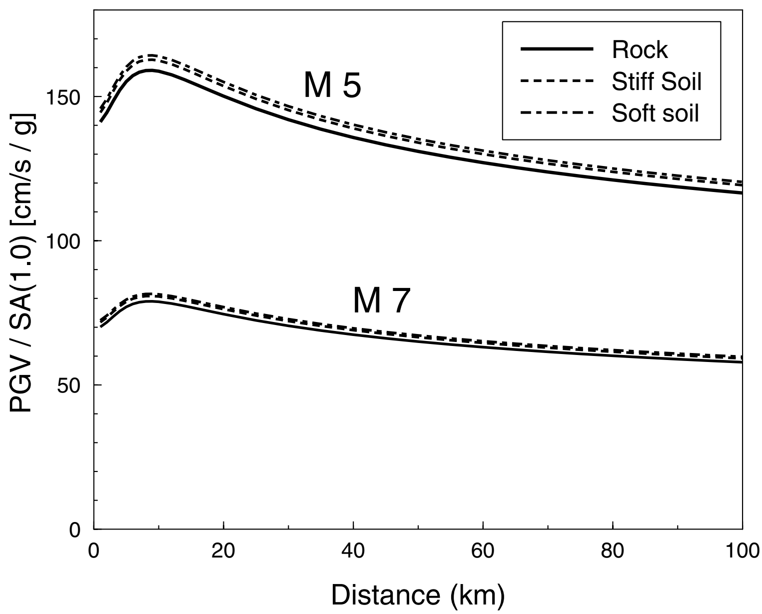


Fig. 6. Ratios of PGV to spectral acceleration at 1.0 s inferred from median values obtained from the predictive relationships of Tromans and Bommer [2002] and Ambraseys *et al.* [1996].

Figure 6 shows ratios of PGV to SA(1.0 s) inferred from the predictive equations of Ambraseys *et al.* [1996] for spectral accelerations and Tromans and Bommer [2002] for peak velocity. The figure demonstrates that the relationship between PGV and the 1.0-second spectral acceleration is highly variable, although these particular equations indicate that the ratio of PGV to SA(1.0) is not sensitive to site classification. The ratio does, however, vary strongly with earthquake magnitude and to a lesser extent with source-to-site distance.

### 4.2. *Empirical equations*

To explore if the tendencies shown in Fig. 6 are consistent, a number of published ground-motion prediction equations are used to calculate the ratios of median PGV to median spectral acceleration over a range of periods for different combinations of magnitude, distance and site classification. In most cases, the equations for spectral ordinates and for PGV are from the same study, and are therefore directly compatible. The exceptions are the equations of Sadigh and Egan [1998] and Sadigh *et al.* [1997] and those of Molas and Yamazaki [1995, 1996], but both these pairs use the same strong-motion database. The other exception is the European equations of Ambraseys *et al.* [1996] and Tromans and Bommer [2002], which use different but strongly overlapping datasets and the same explanatory variables. In terms of the definition of the horizontal component of motion, all the studies use the same definition for PGV and for spectral ordinates, with the exception of Sabetta and Pugliese [1996] who use the component with the larger value of PGA for spectral ordinates and the larger PGV value, which may not always correspond to the same component; however, no adjustment is made for this possible incompatibility.

In these figures lines are drawn connecting the period of 0.5 s to the ratio PGV/SA of 0.05; it can be seen that in nearly all cases the curves, regardless of magnitude, distance and site classification, pass very close to this point. The pattern is remarkably consistent and for some of the equations has also been confirmed for greater distances of 50 and 100 km. The ratio at a period of 1.0 second implied by the scaling factor of Newmark and Hall [1982] for median spectral ordinates is 0.096; although the curves at 1.0 s generally encompass this value, there is considerable scatter about this level.

Other equations in Table 1 were also analysed in the same way but the results are not shown graphically herein because of space limitations; however, the general result — that the ratio of PGV to spectral acceleration at 0.5 s is more stable than the ratio of PGV to SA(1.0 s) — is confirmed in all cases. The Sabetta and Pugliese [1996] equations produce curves that intersect exactly at 0.5 s for all magnitudes, distances and both site classes; in that case, the PGV/SA ratio is approximately equal to 0.04. Very similar results are obtained using the equations of Campbell [1997] for rock motions; for firm soil sites, ratios closer to 0.025 are obtained. The curves obtained using the equations of Atkinson and Boore [1997] for subduction zones also converge at about 0.5 s although they indicate PGV/SA ratios between 0.07 and 0.10. These equations are based mainly on vertical recordings of ground motion converted to equivalent horizontal motions, so the implied ratio needs to be interpreted with some caution. The results obtained using the equations of Pankow and Pechmann [2004], for which PGV/SA ratios close to 0.05 at 0.5 s are obtained for magnitudes $M_w$ 5 and 6, for all distances and site classes, but higher ratios are found for magnitude 7, being about 0.06 on soil sites and 0.075 on rock sites.

Whatever variations in the PGV/SA ratios at 0.5 s are encountered and whatever rationale can be provided for this in terms of the datasets employed to derive the equations, the important observation from Figs. 7–10 is that the PGV/SA ratio is rather stable at 0.5 s and varies significantly at 1.0 s.

For all the curves discussed above, including those that are not shown, the ratios of the highest to the lowest values of the PGV/SA ratios at 0.5 s and 1.0 s are reported in Table 2. The values show that the ratios at 0.5 s are not without appreciable variation but in all but one case the variation at 1.0 s is appreciably greater. The only equation for which this is not the case is Pankow and Pechmann [2004] but it is possible to disregard this result for the simple reason that whilst

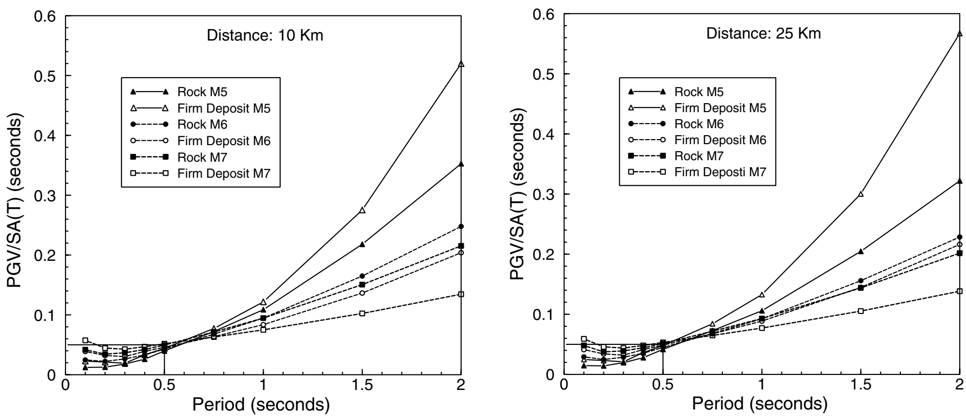


Fig. 7. Relationship between PGV/SA(T) and period, using the Sadigh and Egan [1998] and Sadigh *et al.* [1997] predictive equations.

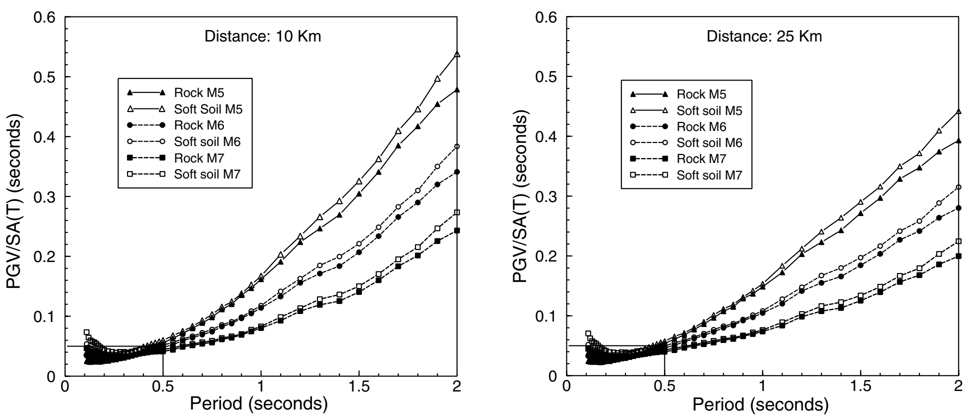


Fig. 8. Relationship between PGV/SA(T) and period, using the Tromans and Bommer [2002] and Ambraseys *et al.* [1996] predictive equations.

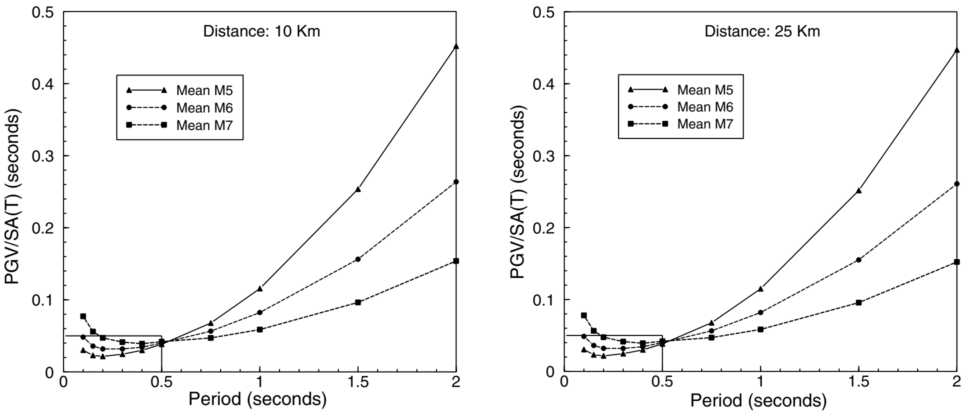


Fig. 9. Relationship between PGV/SA(T) and period, using the Molas and Yamazaki [1995, 1996] predictive equations. This equation has a site coefficient for each recording station; the curves are plotted here for 'average' conditions.

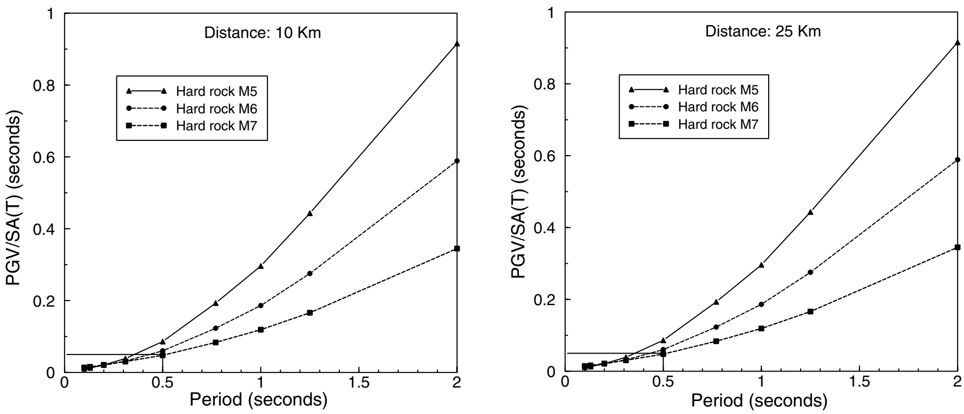


Fig. 10. Relationship between PGV/SA(T) and period, using the Atkinson and Boore [1995] predictive equations.

they derived the magnitude scaling coefficients for spectral ordinates from their data set, the magnitude scaling coefficients for their PGV equation was fixed using the values from Joyner and Boore [1988].

Although response spectral ordinates may be very strongly dependent on distance, the shape of the response spectrum is mainly influenced by earthquake magnitude [e.g. Bommer and Acevedo, 2004]. As a result, the most stable relationship between PGV and spectral ordinates should to be found at those response periods for which the magnitude scaling coefficient is comparable to that in the predictive equation for PGV. Douglas [2002b] determined the theoretical scaling of $\log_{10}(\text{PGV})$ to be equal to 0.375; the values from many of the equations in Table 1 are generally close to or somewhat greater than this value. Table 3 lists values of the magnitude scaling coefficients for PGV, SA(0.5) and SA(1.0) for many

Table 2. Ratios between highest and lowest values of PGV/SA ratio at response periods of 0.5 and 1.0 second.

| | 10 km | | 25 km | |
|---|---|---|---|---|
| Equation | 0.5 s | 1.0 s | 0.5 s | 1.0 s |
| Atkinson and Boore [1995] | 1.80 | 2.49 | 1.80 | 2.49 |
| Molas and Yamazaki [1995, 1996] | 1.09 | 1.98 | 1.09 | 1.98 |
| Sabetta and Pugliese [1996] | 1.05 | 2.18 | 1.05 | 2.18 |
| Atkinson and Boore [1997] | 1.24 | 1.44 | 1.24 | 1.44 |
| Campbell [1997] | 1.64 | 3.08 | 1.71 | 2.96 |
| Sadigh and Egan [1998] and Sadigh *et al.* [1997] | 1.30 | 1.62 | 1.28 | 1.72 |
| Ambraseys *et al.* [1996], Tromans and Bommer [2002] | 1.45 | 2.08 | 1.45 | 2.08 |
| Pankow and Pechmann [2004] | 1.89 | 1.63 | 1.89 | 1.63 |

Table 3. Magnitude-scaling coefficients for PGV and spectral accelerations at 0.5 s and 1.0 s from selected prediction equations.

| | Magnitude scaling coefficient $\log_{10}(Y)$ | | |
|---|---|---|---|
| Equations | PGV | SA(0.5) | SA(1.0) |
| Ambraseys *et al.* [1996] | — | 0.420 | 0.508 |
| Tromans and Bommer [2002] | 0.356 | — | — |
| Sabetta and Pugliese [1996] | 0.455 | 0.455 | 0.570 |
| Molas and Yamazaki [1995] | 0.628 | — | — |
| Molas and Yamazaki [1996] | — | 0.608 | 0.775 |

of the equations in Table 1 (equations for single events and those with quadratic magnitude-dependence are excluded); the magnitude-scaling coefficients of PGV and SA prediction equations generally have similar values at short periods, of the order of 0.5 s or even shorter, whereas the magnitude-scaling coefficients at 1.0 s are generally much larger.

### 4.3. *Stochastic simulations*

In order to explore further the implied PGV/SA(0.5 s) ratios of the order of 0.05 inferred from ground-motion prediction equations, stochastic simulations using the SMSIM software and the standard Californian and ENA models [Boore, 2003a,b] were used to generate PGV and spectral acceleration values. The ratios obtained for the two regions are presented in Fig. 11 in the same way as the figures from the previous section, except that in this case the figures are plotted only up to a period of 1.0 second.

The results indicate that the ratio of 0.05 for the PGV/SA(0.5 s) ratio holds reasonably well in both cases (the vertical scale on these plots is different from that on Figs. 7–10, which makes the curves appear to be more dispersed). The greater stability of the PGV/SA ratio at 0.5 s than 1.0 s is very clear for the case of ENA but much less pronounced for California. However, for the latter case, for which

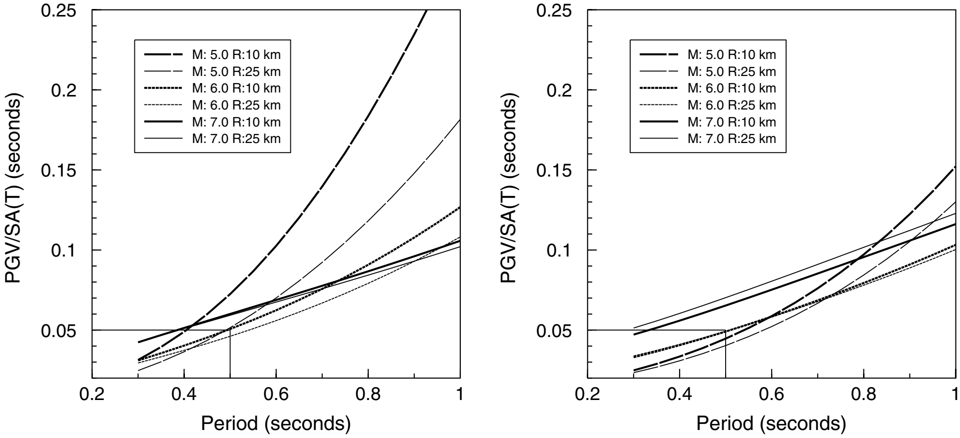


Fig. 11. Ratios of PGV to SA on rock sites for different combinations of magnitude and distance obtained using stochastic simulations and the generic model for eastern North America (*left*) and for coastal California (*right*) following the method of Boore [2003b].

there is abundant strong-motion data, the empirical equations clearly indicate that the relationship between PGV and spectral acceleration is much more stable at 0.5 s than at 1.0 s (Fig. 7).

### 4.4. *Strong-motion data*

The final part of the investigation was to use the strong-motion database of Abrahamson and Silva [1997] to calculate the PGV/SA ratios for each horizontal component and then explore the statistics. Figure 12 shows the ratios calculated for the records; the mean of the residuals at each period is shown by a thick horizontal line and the thin lines indicate ±1 standard deviation. The lower plot shows the ratio of the mean values to the standard deviations.

The first observation that can be made is that the interval representing ±1 standard deviation decreases with increasing period from 0.3 s and then begins to increase again; the minimum value of the standard deviation is encountered at 0.46 s, which is also the period at the which the ratio of the mean to the standard deviation has its maximum value. The standard deviation is only slightly larger (0.030 as opposed to 0.028) at 0.5 s, where the median value of the ratio is 0.058. The dispersion of the data clearly increases with increasing period beyond 0.5 seconds.

An entirely independent earlier study using Canadian seismographic data also concluded that PGV is most closely correlated with pseudo-spectral acceleration (PSA) at 2 Hz [G.M. Atkinson, *personal communication*, 2005].

## 5. Discussion and Conclusions

This paper has presented an overview of the use of PGV in earthquake engineering and provided a summary of published equations for the prediction of this important

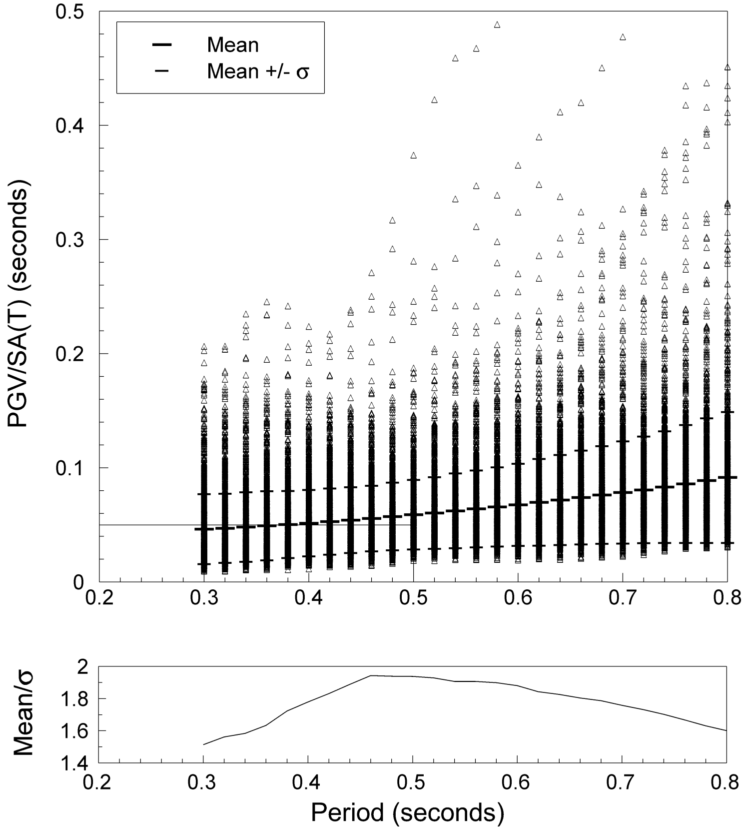


Fig. 12. *Upper*: Ratios of PGV to SA calculated for horizontal components of accelerograms in the Abrahamson and Silva [1997] database. *Lower*: Median values of PGV/SA ratios at each period divided by the standard deviation.

parameter. The number of available equations for predicting PGV is small compared to those available for PGA and response spectral ordinates, which leads to PGV values often being obtained by scaling from the 1-second ordinate of the 5%-damped response spectrum. The assumed direct proportionality between PGV and the 1-second spectral ordinate has been shown to be rather variable (particularly with earthquake magnitude). The assumed relationship between PGV and SA(1.0) was never actually proposed on the basis of focused research but rather arose from the confluence of two independent areas of engineering seismology: the Newmark-Hall procedure for the scaling of the response spectral ordinates from PGV (and not vice versa) and the decision to map hazard in terms of short- and long-period response spectral ordinates, with a value of 1.0 s being chosen — more or less arbitrarily — for the latter. We recommend that the practice of estimating PGV by dividing the 5%-damped PSV ordinate at 1.0 s by a factor of 1.65, which is currently embedded within HAZUS, should be discontinued.

On the basis of the investigations carried out in this paper using published ground-motion prediction equations, stochastic simulations and a large strong-motion database, we propose that if it is necessary to infer PGV values from response spectral ordinates, then the following approximate relationship should be employed in preference to the practice of scaling PGV from the 1.0-second spectral ordinate:

$$PGV(\text{cm/s}) = \frac{SA[0.5](\text{cm/s}^2)}{20}. \tag{1}$$

The method of Newmark and Hall [1982] for constructing the response spectrum applies a scaling factor of 1.65 to PGV to estimate median values of PSV, which implies a relationship very similar to Eq. (1) except that the denominator would be about 20.7. However, as can be noted from Fig. 1, the constant spectral velocity portion of the tripartite spectrum obtained following the Newmark and Hall [1982] procedure will often start at a period greater than 0.5 seconds.

Equation (1) should definitely not be used for engineering projects close to active geological faults where near-source directivity effects may be expected; in such situations we recommend the use of the equations of Bray and Rodriguez-Marek [2004].

Equation (1) is clearly an approximation that has considerable associated uncertainty, which should strictly be propagated to the estimated value of PGV. However, if the response spectrum to which it is applied has been determined from a probabilistic seismic hazard analysis (PSHA) taking full account of the aleatory variability in the ground-motion prediction equation, the propagation of uncertainty may be neglected. The reason for this is that the standard deviation associated with equations for predicting PGV are consistently smaller than those associated with the prediction of the 0.5-second spectral ordinate (Table 4). Therefore, the higher sigma values in the prediction of SA should at least partially account for the uncertainty in the PGV-SA conversion that is not being propagated.

We have presented Eq. (1) with some reluctance since although it is an improvement on current practice it is clearly preferable to estimate PGV directly from

Table 4. Standard deviations in predictive equations for PGV and SA (0.5 s); in all cases, the values are expressed for prediction of the $\log_{10}$ value of the ground-motion parameter.

| | Standard Deviation, $\sigma[\log_{10}(\text{Y})]$ | |
|---|---|---|
| Equations | PGV | SA(0.5) |
| Ambraseys *et al.* [1996] | — | 0.32 |
| Tromans and Bommer [2002] | 0.28 | — |
| Sabetta and Pugliese [1996] | 0.215 | 0.279 |
| Campbell [1997] $M_w$ 6.5 | 0.192 | 0.224 |
| Molas and Yamazaki [1995] | 0.236 | — |
| Molas and Yamazaki [1996] | — | 0.266 |

equations derived specifically for this purpose. Therefore we recommend the use of Eq. (1) only when there is no option but to infer PGV from spectral ordinates and in such cases this equation should be used in preference to the scaling of PGV from the 1-second ordinate of the 5%-damped response spectrum. In the same way that it is standard practice to include an equation for PGA as part of studies to derive equations for the prediction of response spectral ordinates, we would urge all strong-motion modellers to also include an equation for PGV as standard, notwithstanding the additional burden that this imposes in terms of record processing.

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## References

Abrahamson, N. A. and Shedlock, K. M. [1997] "Overview," *Seismological Research Letters* **68**(1), 9–23.

Abrahamson, N. A. and Silva, W. J. [1997] "Empirical response spectra attenuation relations for shallow crustal earthquakes," *Seismological Research Letters* **68**(1), 94–127.

Akkar, S. and Özen, Ö. [2005] "Effect of peak ground velocity on deformation demands for SDOF systems," *Earthquake Engineering & Structural Dynamics* (in press).

ALA [2001] *Seismic Fragility Formulations for Water Systems*, American Lifelines Association, *http://www.americanlifelinesalliance.org*.

Algermissen, S. T. and Leyendecker, E. V. [1992] "A technique for uniform hazard spectra estimation in the US," *Proceedings of the Tenth World Conference on Earthquake Engineering*, Madrid **1**, 391–397.

Ambraseys, N. N. and Free, M. W. [1997] "Surface-wave magnitude calibration for European region earthquakes," *Journal of Earthquake Engineering* **1**(1), 1–22.

Ambraseys, N. N., Douglas, J., Sarma, S. K. and Smit, P. M. [2005] "Equations for the estimation of strong ground motions from shallow crustal earthquake using data from Europe and the Middle East: Horizontal peak ground acceleration and spectral acceleration," *Bulletin of Earthquake Engineering* **3**(1), 1–53.

Ambraseys, N. N., Simpson, K. A. and Bommer, J. J. [1996] "Prediction of horizontal response spectra in Europe," *Earthquake Engineering and Structural Dynamics* **25**, 371–400.

Atkinson, G. M. and Boore, D. M. [1995] "Ground-motion relations for eastern North America," *Bulletin of the Seismological Society of America* **85**(1), 17–30.

Atkinson, G. M. and Boore, D. M. [1997] "Stochastic point-source modelling of ground motions in the Cascadian region," *Seismological Research Letters* **68**(1), 74–85.

Basham, P. W., Weichert, D. H., Anglin, F. M. and Berry, M. J. [1985] "New probabilistic strong ground motion maps of Canada," *Bulletin of the Seismological Society of America* **75**, 563–595.

Bommer, J. J. and Acevedo, A. B. [2004] "The use of real earthquake accelerograms as input to dynamic analysis," *Journal of Earthquake Engineering* **8**(1), 43–91.

Bommer, J. J. and Elnashai, A. S. [1999] "Displacement spectra for seismic design," *Journal of Earthquake Engineering,* **3**(1), 1–32.

Bommer, J. J. and Martinez-Pereira, A. [1999] "The effective duration of earthquake strong motion," *Journal of Earthquake Engineering*, **3**(2), 127–172.

Bommer, J. J. and Pinho, R. [2005] "Adapting earthquake actions in Eurocode 8 for performance-based seismic design," *Earthquake Engineering & Structural Dynamics* (in press).

Bommer, J. J., Abrahamson, N. A., Strasser, F. O., Pecker, A., Bard, P.-Y., Bungum, H., Cotton, F., Fäh, D., Sabetta, F., Scherbaum, F. and Studer, J. [2004] "The challenge of defining the upper limits on earthquake ground motions," *Seismological Research Letters* **70**(1), 82–95.

Bommer, J. J., Elnashai, A. S. and Weir, A. G. [2000] "Compatible acceleration and displacement spectra for seismic design codes," *Proceedings of the Twelfth World Conference on Earthquake Engineering*, Auckland, Paper No. 207.

Bommer, J. J., Scherbaum, F., Bungum, H., Cotton, F., Sabetta, F. and Abrahamson, N. A. [2005a] "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.

Bommer, J. J., Oates, S., Cepeda, J. M., Lindholm, C., Bird, J., Torres, R., Marroquín, G. and Rivas, J. [2005b] "Control of hazard due to seismicity induced by a hot fractured rock geothermal project," Submitted to *Engineering Geology.*

Boore, D. M. [1980] "On the attenuation of peak velocity," *Proceedings of the Seventh World Conference on Earthquake Engineering*, Istanbul **2**, 577–584.

Boore, D. M. [1984] "Use of seismoscope records to determine $M_L$ and peak velocities," *Bulletin of the Seismological Society of America* **74**(1), 315–324.

Boore, D. M. [2003a] "Simulation of ground motion using the stochastic method," *Pure and Applied Geophysics* **160**, 635–676.

Boore, D. M. [2003b] "SMSIM — Fortran programs for simulating ground motions from earthquakes. Version 2.0 — A revision of OFR 96-08," *A modified version of OFR 00–509, describing the program as February 09, 2003 [version 2.20]*, US Geological Survey.

Boore, D. M. and Bommer, J. J. [2005] "Processing of strong-motion accelerograms: Needs, options and consequences," *Soil Dynamics & Earthquake Engineering* **25**(2), 93–115.

Borzi, B., Calvi, G. M., Elnashai, A. S., Faccioli, E. and Bommer, J. J. [2001] "Inelastic spectra for displacement-based seismic design," *Soil Dynamics and Earthquake Engineering* **21**(1), 47–61.

Bozorgnia, Y. and Campbell, K. W. [2004] "The vertical-to-horizontal response spectral ratio and tentative procedures for developing simplified V/H and vertical design spectra," *Journal of Earthquake Engineering* **8**(2), 175–207.

Bray, J. D. and Rodriguez-Marek, A. [2004] "Characterization of forward-directivity ground motions in the near-fault region," *Soil Dynamics and Earthquake Engineering* **24**, 815–828.

Campbell, K. W. [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.

Chen, W. W., Shih, B., Chen, Y., Hung, J. and Hwang, H. H. [2002] "Seismic response of natural gas and water pipelines in the Ji-Ji earthquake," *Soil Dynamics and Earthquake Engineering* **22**(9), 1209–1214.

Davis, C. A. and Bardet, J. P. [2000] "Responses of buried corrugated metal pipes to earthquakes," *Journal of Geotechnical and Geoenvironmental Engineering* **126**(1), 28–39.

Douglas, J. [2002a] "On the recovery of peak ground velocity and peak ground displacement from strong-motion records," *Proceedings of the Twelfth European Conference on Earthquake Engineering*, London, Paper No. 18.

Douglas, J. [2002b] "Note on scaling of peak ground acceleration and peak ground velocity with magnitude," *Geophysical Journal International* **148**, 336–339.

Douglas, J. [2003] "Earthquake ground motion estimation using strong-motion records: A review of equations for the estimation of peak ground accelerations and response spectral ordinates," *Earth–Science Reviews* **61**, 43–104.

Eidiger, J., Maison, B., Lee, D. and Lau, B. [1995] "East Bay Municipal District water distribution damage in 1989 Loma Prieta earthquake," *Proceedings of the Fourth US Conference on Lifeline Earthquake Engineering*, ASCE, TCLEE, Monograph **6**, 240–247.

Esteva, L. [1970] "Seismic risk and seismic design," In: *Seismic Design for Nuclear Power Plants*, MIT Press, Cambridge, Massachusetts, pp. 142–182.

Fajfar, P., Vidic, T. and Fischinger, M. [1990] "A measure of earthquake motion capacity to damage medium-period structures," *Soil Dynamics & Earthquake Engineering* **9**, 236–242.

FEMA [2003] Hazus-MH, FEMA's software program for estimating potential losses from disasters, *http://www.fema.gov/hazus*.

Field, E. H., Seligson, H. A., Gupta, N., Gupta, V., Jordan, T. H. and Campbell, K. W. [2005] "Loss estimates for a puente hills blind-thrust earthquake in Los Angeles, California," *Earthquake Spectra* **21**(2), 329–338.

Fitzpatrick, A. J. [1992] "Structural design of Century Tower, Tokyo," *The Structural Engineer* **70**(18), 313–317.

Frankel, A. D., Mueller, C. S., Barnhard, T. P., Leyendcker, E. V., Wesson, R. L., Harmsen, S. C., Klein, F. W., Perkins, D. M., Dickman, N. C , Hanson, S. L. and Hopper, M. G. [2000] "USGS national seismic hazard maps," *Earthquake Spectra* **16**(1), 1–19.

Frisenda, M., Massa, M., Spallarossa, D., Ferretti, G. and Eva, C. [2005] "Attenuation relationships for low magnitude earthquakes using standard seismometric records," *Journal of Earthquake Engineering* **9**(1), 23–40.

Fukushima, Y. [1996] "Scaling relations for strong ground motion prediction models," *Bulletin of the Seismological Society of America* **86**(2), 329–336.

Gaull, B. A. [1988] "Attenuation of strong ground motion in space and time in South Western Australia," *Proceedings of Ninth World Conference on Earthquake Engineering*, Tokyo **II**, 361–366.

Gerstenberger, M. C., Warden, C. B. and Wald, D. J. [2005] "Relationship between ground-motion parameters and Modified Mercalli Intensity from community Internet intensities [abstract]," *Seismological Research Letters* **76**(2), 232.

Green, R. A. and Terri, G. A. [2005] "Number of equivalent cycles concept for liquefaction evaluations — revisited," *Journal of Geotechnical and Geoenvironmental Engineering* **131**(4), 477–488.

Gregor, N., Silva, W. and Darragh, B. [2002] "Development of attenuation relations for peak particle velocity and displacement," *Pearl Report to PG&E/CEC/Caltrans — Pacific Engineering and Analysis, http://www.pacificengineering.org/rpts page1.shtml.*

Hancock, J. and Bommer, J. J. [2005] "The effective number of cycles of earthquake ground motion," *Earthquake Engineering and Structural Dynamics* **34**, 637–664.

Hao, H. and Gaull, B. A. [2004] "Prediction of seismic ground motion in Perth Western Australia for engineering application," *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Paper No. 1892.

Heidebrecht, A. C. [1995] "Insights and challenges associated with determining seismic design forces in a loading code," *Bulletin of the New Zealand National Society for Earthquake Engineering* **28**(3), 224–246.

Hwang, H., Chiu, Y., Chen, W. and Shih, B. [2004a] "Analysis of damage to steel gas pipelines caused by ground shaking effects during the Chi-Chi, Taiwan, earthquake," *Earthquake Spectra* **20**(4), 1095–1110.

Hwang, H., Lin, C. K., Yeh, Y. T., Chang, S. N. and Chen, K. C. [2004b] "Attenuation relations of Arias intensity based on the Chi-Chi Taiwan earthquake data," *Soil Dynamics & Earthquake Engineering* **24**(7), 509–517.

IAEE [1996] "Regulations for Seismic Design: A world list — 1996," *International Association for Earthquake Engineering*, Tokyo, Japan.

Isoyama, R., Ishida, E., Yune, K. and Shirozu, T. [2000] "Seismic damage estimation procedure for water supply pipelines," *Proceedings of the Twelfth World Conference on Earthquake Engineering*, Auckland, Paper No. 1762.

Joyner, W. B. and Boore, D. M. [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, W. B. and Boore, D. M. [1988] "Measurement, characterization, and prediction of strong ground motion," In: *Earthquake Engineering & Soil Dynamics II: Recent Advances in Ground-Motion Evaluation*, J. L. Von Thun (ed.) ASCE Geotechnical Special Publication 20, American Society of Civil Engineers, New York, p. 595.

Kaka, S. I. and Atkinson, G. M. [2004] "Relationships between instrumental ground-motion parameters and Modified Mercalli Intensity in eastern North America," *Bulletin of the Seismological Society of America* **94**(5), 1728–1736.

Kamiyama, M., O'Rourke, M. J. and Flores-Berrones, R. [1992] "A semi-empirical analysis of strong-motion peaks in terms of seismic source, propagation path and local site conditions," *Technical Report NCEER-92-0023*, NCEER, Buffalo, New York.

Kappos, A. J. and Kyriakakis, P. [2000]. "A re-evaluation of scaling techniques for natural records," *Soil Dynamics & Earthquake Engineering* **20**, 111–123.

Kawashima, K., Aizawa, K. and Takahashi, K. [1986] "Attenuation of peak ground acceleration, velocity and displacements based on multiple regression analysis of Japanese strong motion records," *Earthquake Engineering and Structural Dynamics* **14**, 199–215.

Kostadinov, M. V. and Towhata, I. [2002] "Assessment of liquefaction-inducing peak ground velocity and frequency of horizontal ground shaking at onset of phenomenon," *Soil Dynamics and Earthquake Engineering* **22**(4), 309–322.

Lawson, R. S. and Krawlinker, H. [1995] "Cumulative damage potential of seismic ground motion," *Proceedings of the Tenth European Conference of Earthquake Engineering*, Vienna **2**, 1079–1086.

Margaris, B., Papazachos, C., Papaioannou, Ch., Theodulidis, N., Kalogeras, I. and Skarlatoudis, A. [2002] "Ground motion attenuation relations for shallow earthquakes in Greece," *Proceedings of the 12th European Conference on Earthquake Engineering*, London, Paper No. 385.

Martínez-Pereira, A. and Bommer, J. J. [1998] "What is the near field?" In: *Seismic Design Practice into the Next Century*, E. Booth (ed.), Balkema, pp. 245–252.

McGuire, R. K. [1978] "Seismic ground motion parameter relations," *Journal of the Geotechnical Division ASCE* **104**(4), 481–490.

Midorikawa, S. and Ohtake, Y. [2004] "Variance of peak ground acceleration and velocity in attenuation relationships," *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Paper No. 325.

Miyakoshi, J., Hayashi, Y., Tamura, K. and Fukuwa, N. [1998] "Damage ratio functions for buildings using damage data of the Hyogo-ken Nanbu earthquake," *Proceedings of the 7th International Conference on Structural Safety and Reliability [ICOSSAR'97]*, Kyoto, pp. 349–362.

Molas, G. L. and 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.

Molas, G. L. and Yamazaki, F. [1996] "Attenuation of response spectra in Japan using new JMA records," *Bulletin of Earthquake Resistant Structures* **29**, 115–128.

Morii, T. and Hayashi, Y. [2003] "Effect of characteristics of incident ground motion and ground motion amplification in surface soil on wood houses response," *Journal of Structural and Construction Engineering* **568**, 75–82 [In Japanese].

Newmark, N. M. [1967] "Problems in wave propagation in soil and rocks," *Proceedings of the International Symposium on Wave Propagation and Dynamic Properties of Earth Materials*, University of New Mexico Press, pp. 7–26.

Newmark, N. M. and Hall, W. J. [1982] "Earthquake spectra and design," *Earth quake Engineering Research Institute*, El Cerrito, California.

Newmark, N. M. and Rosenbleuth, E. [1971] *Fundamentals of Earthquake Engineering*, Prentice-Hall, Inc.

Newmark, N. M., Blume, J. A. and Kapur, K. K. [1973] "Seismic design spectra for nuclear power plants," *Journal of Power Division ASCE* **99**(PO2), 287–303.

Orense, R. P. [2005] "Assessment of liquefaction potential based on peak ground motion parameters," *Soil Dynamics and Earthquake Engineering* **25**, 225–240.

O'Rourke, M. J. and Ayala, G. [1993] "Pipeline damage due to wave propagation," *Journal of Geotechnical Engineering* **119**(9), 1490–1498.

O'Rourke, M. J., Stewart, H. E. and Jeon, S. S. [2001] "Geotechnical aspects of lifeline engineering," *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering* **149**(1), 13–26.

Pankow, K. L. and Pechmann, J. C. [2004] "The SEA99 ground-motion predictive relations and new peak ground velocity relation," *Bulletin of the Seismological Society of America* **94**(1), 341–348.

Rinaldis, D., Berardi, R., Theodulidis, N. and Margaris, B. [1998] "Empirical predictive models based on a joint Italian and Greek strong-ground motion database: I, peak ground acceleration and velocity," *Proceedings of the 11th European Conference on Earthquake Engineering*, A. A. Balkema, Rotterdam.

Sabetta, F. and 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, R. K. and Egan, J. A. [1998] "Updated relationships for horizontal peak ground velocity and peak ground displacements for shallow crustal earthquakes," *Proceedings of the Sixth US National Conference on Earthquake Engineering*, Seattle, Paper No. 317.

Sadigh, K., Chang, C. Y., Egan, J. A., Makdisi, F. and Youngs, R. R. [1997] "Attenuation relationships for shallow crustal earthquakes based on California strong motion data," *Seismological Research Letters* **68**(1), 180–189.

Scherbaum, F., Schmedes, J. and Cotton, F. [2004] "On the conversion of source-to-site distance measures for extended earthquake source models," *Bulletin of the Seismological Society of America* **94**(3), 1053–1069.

Shabestari, K. T. and Yamazaki, F. [2002] "Attenuation relationships of the ground motion parameters considering directivity effects in the 1999 Chi-Chi, Taiwan earthquake," *Proceedings of the 7th US National Conference on Earthquake Engineering*, Boston.

Si, H. and Midorikawa, S. [2000] "New attenuation relations for peak ground acceleration and velocity considering effects of fault type and site condition," *Proceedings of the 12th World Conference on Earthquake Engineering*, Auckland, Paper No. 532.

Singh, S. K., Gansl, B. K., Bhattacharya, S. N., Pacheco, J. F., Dattatrayam, R. S., Ordaz, M., Kamal, G. S. and Hough, S. E. [2003] "Estimation of ground motion for Bhuj (26 January 2001; Mw 7.6) and for future earthquakes in India," *Bulletin of Seismological Society of America* **93**(1), 353–370.

Somerville, P. G., Smith, N. F. and Graves, R. W. [1997] "Modification of empirical strong ground motion attenuation relations to include the amplitude and duration effects of rupture directivity," *Seismological Research Letters* **68**(1), 199–222.

Spudich, P., Joyner, W. B., Lindh, A. G., Boore, D. M., Margaris, B. M. and Fletcher, J. B. [1999] "SEA99: a revised ground motion prediction relation for use in extensional tectonic regimes," *Bulletin of Seismological Society of America* **89**(5), 1156–1170.

St. John, C. M. and Zahrah, T. F. [1987] "Aseismic design of underground structures," *Tunneling and Underground Space Technology* **2**(2), 165–197.

Sucuoğlu, H. and Erberik, A. [1998] "Influence of ground motion intensity parameters on elastic response spectra," *Proceedings of the 11th European Conference on Earthquake Engineering*, Rotterdam, CD-ROM.

Sucuoğlu, H., Yücemen, S., Gezer, A. and Erberik, A. [1998] "Statistical evaluation of the damage potential of earthquake ground motions," *Structural Safety* **20**, 357–378.

Theodulidis, N. P. and Papazachos, B. C. [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.

Todorovska, M. I. and Trifunac, M. D. [1996] "Hazard mapping of normalized peak strain in soils during earthquakes: Microzonation of a metropolitan area," *Soil Dynamics & Earthquake Engineering* **15**, 321–329.

Travasarou, T., Bray, J. D. and Abrahamson, N. A. [2003] "Empirical attenuation for Arias intensity," *Earthquake Engineering & Structural Dynamics* **32**(7), 1133–1155.

Trifunac, M. D. [1995] "Empirical criteria for liquefaction in sands via standard penetration tests and seismic wave energy," *Soil Dynamics & Earthquake Engineering* **14**(6), 419–426.

Trifunac, M. D. and Brady, A. G. [1975] "On the correlation of seismic intensity scales with the peaks of recorded strong ground motion," *Bulletin of the Seismological Society of America* **65**(1), 139–162.

Trifunac, M. D. and Brady, A. G. [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. J. and Bommer, J. J. [2002] "The attenuation of strong-motion peaks in Europe," *Proceedings of the Twelfth European Conference on Earthquake Engineering*, London, Paper 394.

Tso, W. K., Zhu, T. J. and Heidebrecht, A. C. [1992] "Engineering implication of ground motion A/V ratios," *Soil Dynamics and Earthquake Engineering* **11**, 133–144.

van Eck, T., Goutbeek, F., Haak, H. and Dost, B. [2005] "Seismic hazard due to small shallow induced earthquakes in The Netherlands," Submitted to *Engineering Geology.*

Wald, D. J., Quitoriano, V., Heaton, T. H. and Kanamori, H. [1999a] "Relationships between peak ground acceleration, peak ground velocity, and Modified Mercalli intensity in California," *Earthquake Spectra* **15**(3), 557–564.

Wald, D. J., Quitoriano, V., Heaton, T. H., Kanamori, H., Scrivner, C. W. and Worden, C. B. [1999b] "TriNet "ShakeMaps": Rapid generation of peak ground motion and intensity maps for earthquakes in southern California," *Earthquake Spectra* **15**(3), 537–555.

Wu, Y., Teng, T., Shin, T. and Hsiao, N. [2003] "Relationship between peak ground acceleration, peak ground velocity, and intensity in Taiwan," *Bulletin of the Seismological Society of America* **93**(1), 386–396.

Yamazaki, F. and Murao, O. [2000] "Vulnerability functions for Japanese buildings based on damage data from the 1995 Kobe earthquake," In: *Implications of Recent Earthquakes on Seismic Risk*, A. S. Elnashai and S. Antoniou (eds.), Imperial College Press, pp. 91–102.

Zhu, T. J., Tso, W. K. and Heidebrecht, A. C. [1987] "Ductility demand on structures designed based on NBCC 1985 base shear specifications," *Proceedings of the Fifth Canadian Conference on Earthquake Engineering*, pp. 275–283.

Zhu, T. J., Tso, W. K. and Heidebrecht, A. C. [1988] "Effect of peak ground A/V ratio on structural damage," *Journal of Structural Engineering* **114**(5), 1019–1037.