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Recent Trends in Ground Motion and Spectral Response Relations for North America

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Recent ground motion relations which predict *pga*, *pgv* and *psrv* for rock sites in ENA are based on a stochastic model whose parameters are indicated by seismological studies of earthquake source and attenuation processes. The validity of the model is verified by application to WNA. The choice of model parameters is validated by comparison of model predictions with ground motion data for ENA. For any magnitude, near-source ENA ground motions are enriched in high frequencies relative to WNA motions. This causes eastern *pga* values, and *psrv* values for frequencies greater than 10 Hz, to be greater than their western counterparts. For *psrv* at frequencies less than 10 Hz, median near-source ground motions in ENA are roughly comparable to those in WNA. Eastern ground motion characteristics have important implications for seismic hazard. High frequency structures in many parts of ENA face a hazard comparable to that in many active areas of California, whereas the hazard for low-frequency structures on rock sites in ENA is relatively modest.

INTRODUCTION

Ground motion relations are a key element in seismic hazard evaluations. They provide the important mathematical link between the occurrence of earthquakes and the resulting site ground motions which an engineered structure must be able to withstand. The ground motion may be described by a simple measure of its amplitude, such as the peak ground acceleration (*pga*) or velocity (*pgv*), or a frequency-dependent measure such as response spectra (typically the pseudo-relative velocity, *psrv*). Response spectra are particularly useful for engineering design applications, since they are the input parameters for widely-used methods of dynamic analysis. Until recently, however, *pga* was more often used to describe the ground motion, partly due to the widespread availability of applicable ground motion relations. Response spectra for design purposes were then constructed based on empirical correlations between *pga* and spectral amplitudes. It is now recognized that this procedure is inadequate (Joyner and Boore, 1982; Boore and Atkinson, 1987) and can lead to

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major errors in spectral shapes and amplitudes at intermediate to long periods.

The ground motion parameter of interest is almost always predicted as a function of earthquake magnitude, distance, and sometimes site condition. Relations generally predict the horizontal component of ground motion since this is the most critical for the majority of engineered structures.

Most ground motion relations have been obtained by empirical analysis. In western North America (WNA), the analyses were based on regression of recorded strong ground motions. Until the late 1970's, such data were rather limited. Consequently ground motion predictions tended to vary significantly according to the time and method of their development (see Idriss, 1979 for a review of these early predictive relations). Since then, however, the ground motion database for California has improved greatly, although there are still significant shortcomings for large ($M > 7$) earthquakes at close ($r < 50$ km) distances. As a result of the improved database, empirical ground motion relations for WNA have 'stabilized,' and there is reasonable agreement among different investigators (see Joyner and Boore, 1988 for a review of recent relations). Reliable empirical ground motion relations for *pga*, *pgv* and *psrv* in WNA are available for rock and soil sites (*e.g.*, Joyner and Boore, 1981; 1982; Campbell, 1981a; Sadigh *et al.*, 1986; Idriss, 1987).

In eastern North America (ENA), the development of empirical ground motion relations has been hampered by the lack of a strong motion database. It was necessary to resort to other, less direct, data sources, such as observed Modified Mercalli Intensity (MMI) distributions for historical earthquakes, or inference from other comparable regions for which there are more strong motion data (*e.g.*, Milne and Davenport, 1969; Nuttli and Herrmann, 1978; Hasegawa *et al.*, 1981; Campbell, 1981b).

There have recently been improvements in the ground motion database for ENA. At the same time, there have been significant advances in understanding the physical basis for observed ground motions. These factors have led to advances in developing ENA relations.

The advances have followed the work of Hanks and McGuire (1981), who showed that observed *pga* in WNA is successfully predicted by a simple theoretical model. The model is stochastic, and under it ground motion is treated as band-limited finite-duration white Gaussian noise, with amplitude spectra given by a simple seismological model of the source. Boore (1983) and McGuire *et al.* (1984) showed that the stochastic model also predicts *pgv* and *psrv* in WNA.

Success of the stochastic model in predicting WNA motions led to its application to ENA. Atkinson (1984) showed that the model predicts observed ENA values of *pga* and *pgv* from moderate (M ~5) earthquakes. Boore and Atkinson (1987a) and Toro and McGuire (1987) extended the model to prediction of ENA *psrv* levels.

The purpose of this paper is to review the recent ground motion relations developed for ENA and compare them to predictions for WNA. Comparisons with available data are also made. The stochastic model is used as a unifying framework to illustrate the effects of differences in eastern and western ground motion propagation.

REVIEW OF STOCHASTIC MODEL

The Fourier amplitude spectrum of ground motion for a site at some distance r (hypocentral or closest distance to ruptured area) from an earthquake can be represented by the following general form (Boore and Atkinson, 1987a):

$$FA(f) = C\,S(f)\,D(f)\,I(f) \tag{1}$$

The elements of the equation are summarized below; for a more complete description (and for parameter values) the reader is referred to Boore and Atkinson (1987a).

C is a scaling factor accounting for the effects of geometric spreading, and the product of a number of physical constants (specifically, the average radiation pattern for shear waves, free surface effects, the partition of a vector into horizontal components, and density and shear velocity in the source region). Inserting representative values (*cgs* units) for the physical constants in ENA (Boore and Atkinson, 1987a),

$$C = 5.4 \times 10^{-19}/r \tag{2}$$

$S(f)$ specifies the source function as a function of frequency, and is given by

$$S(f) = M_0/[1 + (f/f_0)^2] \tag{3}$$

where M_0 is the seismic moment and f_0 is the corner frequency of the spectrum. The characteristic shape of the source spectrum is that, for displacement, it is flat for frequencies below the corner frequency; above f_0 spectral amplitudes decay as the inverse-square of frequency.

$D(f)$ is a diminution function that models frequency-dependent anelastic attenuation of waves. It is given by

$$D(f) = \exp[-\pi\, f\, r/Q(f)\,\beta]\, P(f, f_m) \tag{4}$$

where Q is the frequency-dependent quality factor that describes the anelastic attenuation, β is shear wave velocity, and $P(f, f_m)$ is a high-cut filter formulated in such a way as to rapidly reduce amplitudes for all frequencies above a high frequency cutoff, f_m.

$I(f)$ is a filter used to shape the spectrum to correspond to the particular ground motion measure of interest. If, for example, response spectra are to be computed, I

is the response of an oscillator to ground displacement. For ground motion parameters, I is simply

$$I(f) = (2\pi f)^p \tag{5}$$

where $p = 0$ for displacement, 1 for velocity, or 2 for acceleration.

The net effect of the terms of Equation (1), for sites near an earthquake source, is a spectrum which (for displacement) has a constant value at low frequencies. The value of the low frequency level is determined by the seismic moment. For frequencies between f_0 and f_m, the displacement spectrum decreases with f^2. Above f_m amplitudes quickly diminish towards zero.

The spectrum of ground motion diminishes with distance from the source as a result of geometric spreading and anelastic attenuation. Geometric spreading reduces the entire spectrum, whereas anelastic attenuation and scattering combine to alter its shape by reducing high frequencies more rapidly with distance than lower frequencies.

The stochastic model uses Parseval's theorem to relate spectral amplitudes, as given above, to root-mean-square (*rms*) amplitudes in the time domain. Equations from random-process theory are then used to obtain expected values of peak amplitudes from the *rms* amplitudes. For details of the derivation the reader is referred to Hanks and McGuire (1981) and Boore (1983).

An alternative method of using the spectra of Equation (1) to derive ground motions has been formulated by Boore (1983). It is based on time domain simulations, and produces equivalent results to the random process approach (Boore, 1983; Boore and Atkinson, 1987a).

The important unknown variables in the above equations are M_0, f_0, and r. M_0 is directly related to moment magnitude M, since by definition (Hanks and Kanamori, 1979):

$$M = 2/3 \log M_0 - 10.7 \tag{7}$$

The ground motion equations can thus be reduced to functions of magnitude and distance only, by a relationship between M_0 and f_0, which is referred to as a source scaling relation.

In WNA, and many other parts of the world, it has generally been observed that source scaling can be characterized by

$$f_0 \sim (\sigma/M_0)^{1/3} \tag{8}$$

where σ is a stress parameter. Because the high frequency level of the spectrum scales as $M_0 f_0^2$ (see Equation 3), the stress parameter effectively controls the level of the ground motion curves at high frequencies. It has been observed that σ is approximately constant in WNA, with a value of 100 bars as given by Hanks and McGuire (1981) or 50 bars as given by Boore (1986); Boore's value is lower because his model takes account of near surface amplification, which is about a factor of two in California.

Source scaling relations for ENA have been a controversial topic. Some studies (Somerville *et al.*, 1987; Boore and Atkinson, 1987a) support a constant stress model, with a value of σ of approximately 100 bars. However, it has also been proposed that stress increases with moment in ENA (Nuttli, 1983; Nuttli *et al.*, 1987; Chael, 1987; Chun *et al.*, 1989). This issue has yet to be fully resolved. However, it appears that a constant stress of 100 bars does an adequate job of predicting observed ENA spectral levels. It was therefore adopted for the ground motion predictions of the stochastic model.

The above equations can be used to calculate pga, pgv or $psrv(f)$, knowing just moment magnitude and distance. For convenience in application, the same model can also be used to compute a relationship between moment magnitude and more commonly reported magnitudes such as Nuttli magnitude m_N, as described by Boore and Atkinson (1987a). All that is required is appropriate definition of the filter function $I(f)$ of Equation (1).

By repeated applications of the computations, a predicted 'data set' of ground motions for various magnitudes and distances can be generated. Regression analysis of this simulated data set can then provide simple equations for ground motions as a function of M and r, for use in engineering analyses. Relations obtained for ENA by this method are presented later in the paper.

REVIEW OF GROUND MOTION RELATIONS FOR WNA

An extensive technical review of ground motion relations for WNA (and also ENA) has been prepared by Joyner and Boore (1988). They show that there is now general agreement on western ground motion relations among different investigators. This is perhaps not surprising, given the range of magnitude and distance spanned by available ground motion data, as shown in Figure 1. Figures 2 to 4 show typical WNA ground motion relations, all derived by empirical analysis.

The predictions of empirical relations have been compared to those made theoretically by the stochastic model, by Hanks and McGuire (1981), Boore (1983), and McGuire *et al.* (1984). The key parameter choices made by these authors for the theoretical predictions for WNA are a constant stress parameter of 100 bars, and a high frequency cut-off (f_m) of 15 Hz. Each study concludes that there is good agreement between theoretical and empirical predictions, as illustrated in Figures 5 and 6. The good agreement suggests that the stochastic model can make reliable predictions of median ground motion levels, and tends to validate the parameter values

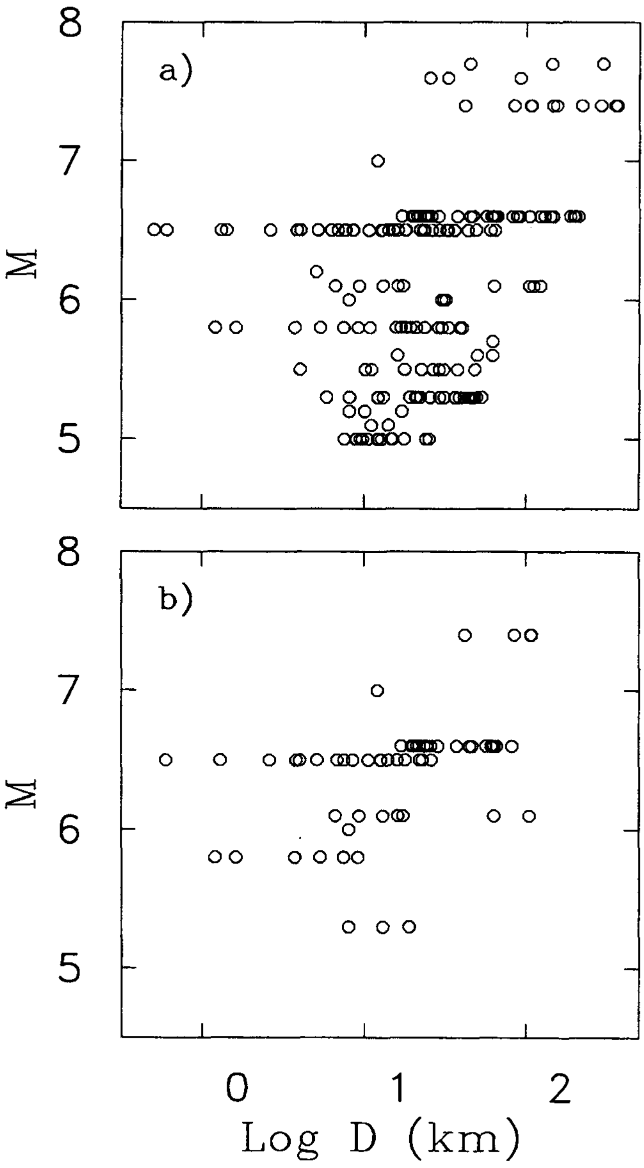

Figure 1 – Distribution in magnitude and distance of the strong motion data used by Joyner and Boore (1981) to develop predictive relationships for (a) *pga* and (b) *pgv* and *psrv*, for WNA.

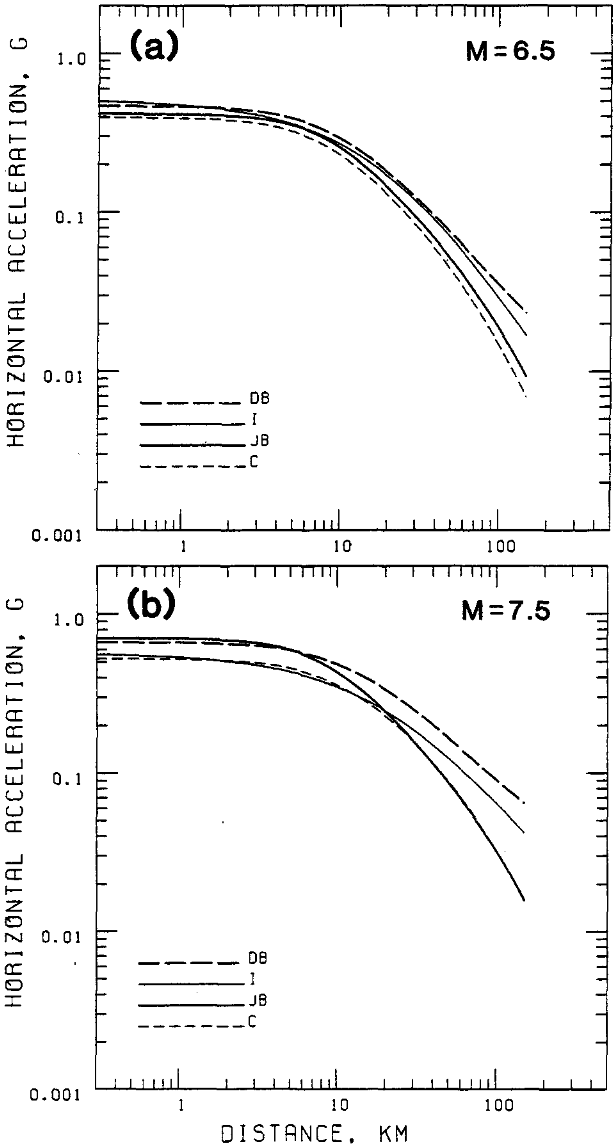

Figure 2 – Comparison of different relationships for *pga* at M 6.5 (a) and 7.5 (b), in WNA. DB, from Donovan and Bornstein (1978); I, from Idriss (1987) for deep soil sites; JB, from Joyner and Boore (1982); C, from Campbell (1988). After Joyner and Boore (1988).

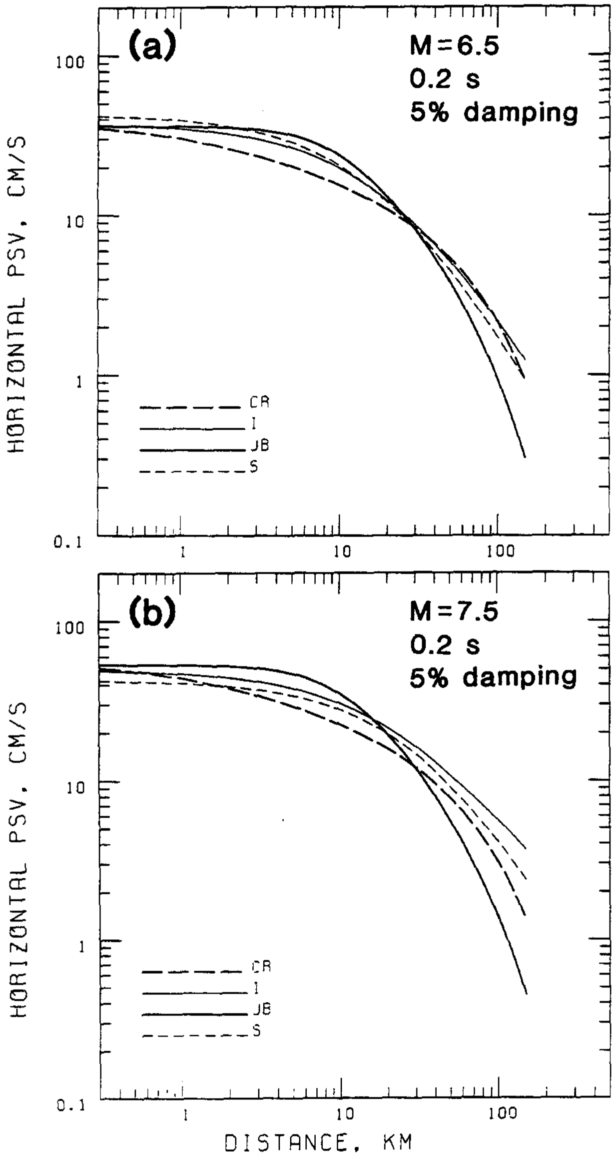

Figure 3 – Comparison of different relationships for 0.2 s *psrv* at 5% damping for M 6.5 (a) and 7.5 (b), in WNA. CR, from Crouse (1987) for deep soil sites; I, from Idriss (1987) for deep soil sites; JB, from Joyner and Boore (1982) for soil sites; S, from Sadigh *et al.* (1986). After Joyner and Boore (1988).

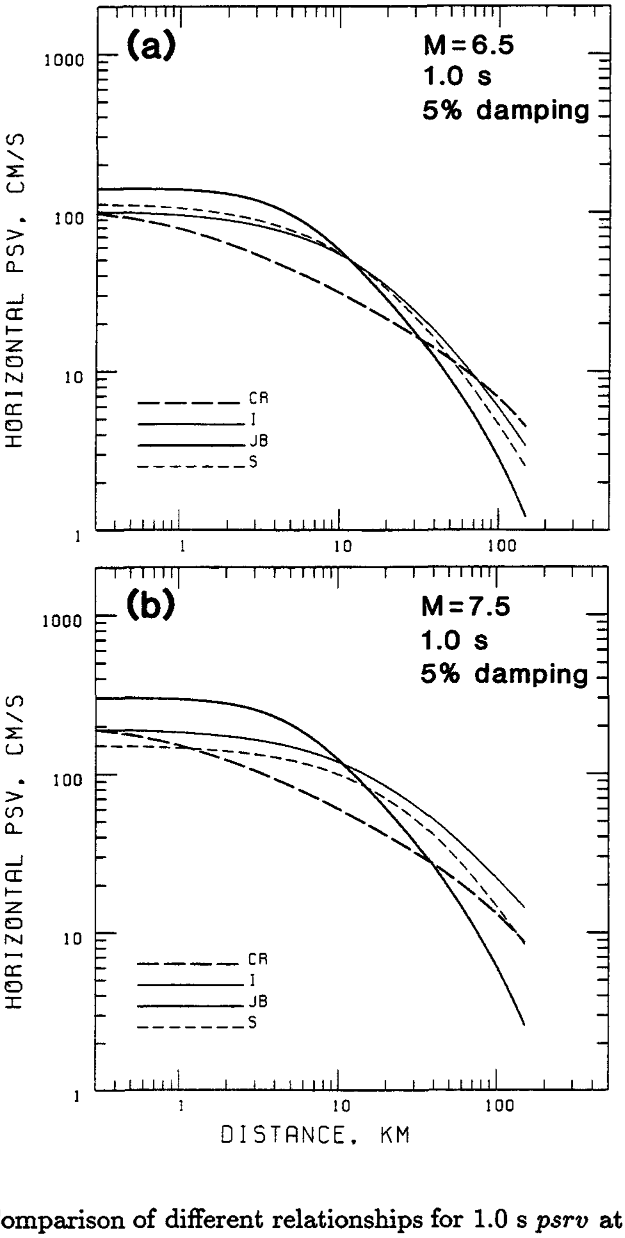

Figure 4 – Comparison of different relationships for 1.0 s *psrv* at 5% damping for M 6.5 (a) and 7.5 (b), in WNA. Curves as defined for Figure 3. After Joyner and Boore (1988).

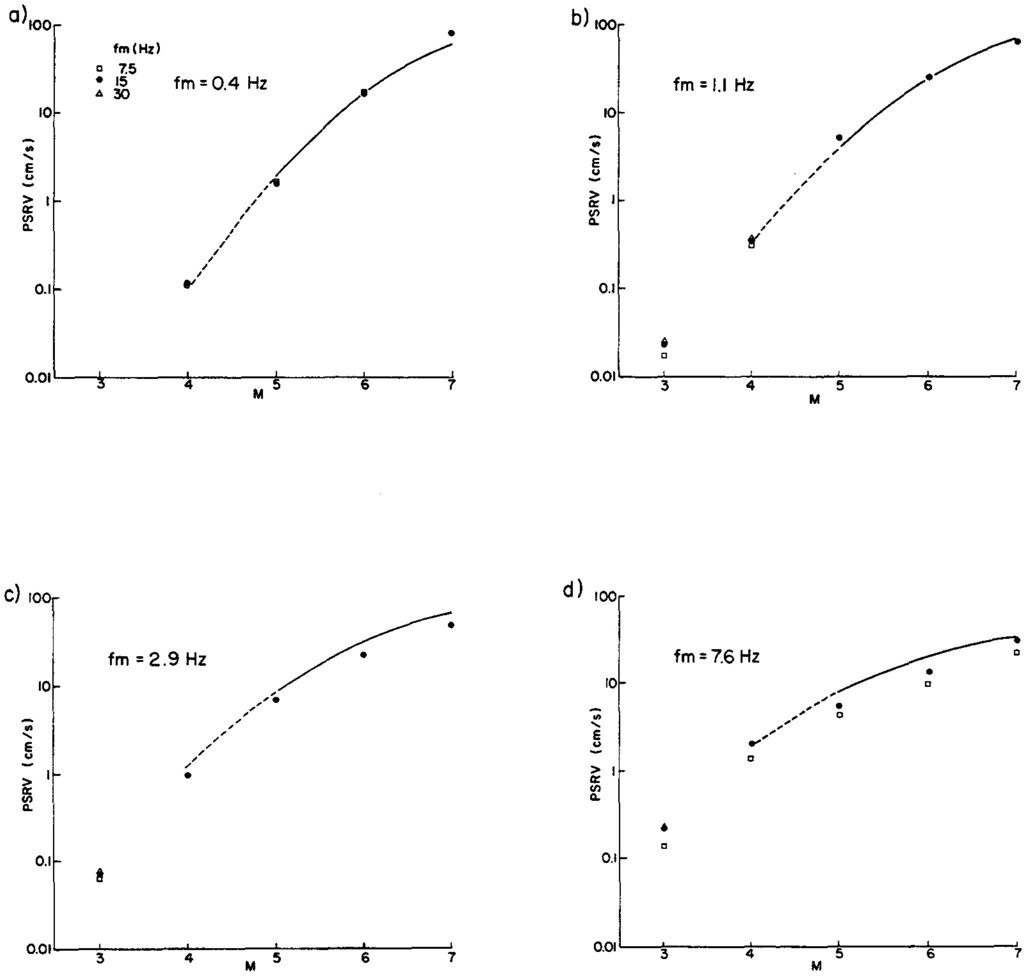

Figure 5 – Comparison of predicted *psrv* in WNA from the stochastic model (symbols) with empirical equations of Joyner and Boore (1982) (curves). Symbols are from simulations with three values of f_m. When missing from plot, open symbols are indistinguishable from solid circles. After Boore (1983).

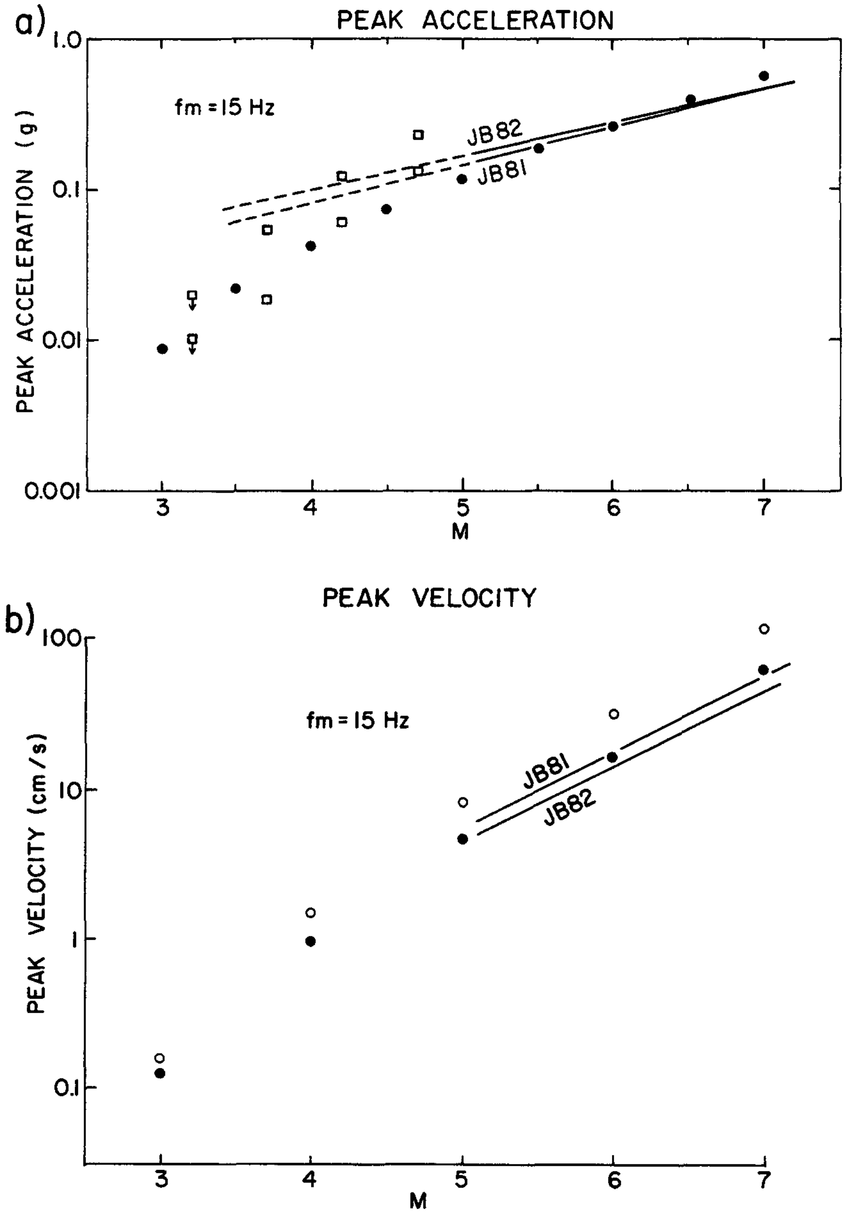

Figure 6 – Comparison of predicted *pga* and *pgv* in WNA from the stochastic model (circles) with empirical equations of Joyner and Boore (1981; 1982) (curves, dashed where not defined by data). Open squares show data from rock (upper points) and soil (lower points) sites from the 1975 Oroville, California earthquake. After Boore (1983).

used for WNA.

Typical ground motion relations for WNA are given in Table 1, which gives the constants of the equation

$$\begin{aligned}\log y = \;& a + b(M-6) + c(M-6)^2 + d\log r + k\,r + s \\ & 5.0 < M < 7.7 \qquad (9) \\ & r = (r_0^2 + h^2)^{0.5}\end{aligned}$$

where M is moment magnitude, r_0 is the shortest distance (km) from the recording site to the vertical projection of the earthquake fault rupture on the surface of the earth, and s is a site correction for soil sites (sites with 5 m or more of soil). The ground motion parameter y corresponds to the average horizontal component of motion. For *psrv* damping is 5% of critical. The relations of this table were obtained empirically (Joyner and Boore, 1982). Due to the agreement indicated on Figures 5 and 6, they may also be considered representative of stochastic model predictions for WNA crustal conditions, with $\sigma = 100$ bars and $f_m = 15$ Hz.

TABLE 1

Parameters in the predictive equations of Joyner and Boore (1982) for the randomly oriented horizontal component of *psrv* (cm/s) at 5% damping (see Equation 9), for WNA. Parameters are also given for *pga* (g) and *pgv* (cm/s) in WNA.

Frequency	a	b	c	h	d	k	s
0.25	1.96	0.88	−0.24	4.7	−0.95	0.0	0.29
0.5	2.12	0.79	−0.20	4.7	−1.0	−.0015	0.32
1.0	2.28	0.67	−0.17	4.7	−1.0	−.0039	0.27
2.0	2.41	0.52	−0.14	5.1	−1.0	−.0051	0.14
5.0	2.46	0.35	−0.09	9.6	−1.0	−.0063	−0.01
10.0	2.16	0.25	−0.06	11.3	−1.0	−.0073	−0.02
pga	0.43	0.23	0.0	8.0	−1.0	−.0027	0.0
pgv	2.09	0.49	0.0	4.0	−1.0	−.0026	0.17

REVIEW OF GROUND MOTION RELATIONS FOR ENA

Development of reliable ground motion relations for ENA has advanced significantly in the past 5 years, due to improvements in the empirical database, studies of relevant source parameters, and application of the stochastic model to provide a predictive framework. Until 5 years ago, the ground motion database for ENA consisted almost entirely of qualitative observations, such as maps of MMI from historical earthquakes. At present, the database contains about a hundred quantitative recordings for M 4 to 5 ½ earthquakes at distances of 10 to 1000 km. Recordings from the recent M 6 earthquake at Saguenay, Quebec (obtained after this paper was written) will further increase the database. The records include peak ground accelerations, velocities, and response spectra. Most records were obtained on rock sites, during recent moderate earthquakes in New Brunswick, New Hampshire, New York, Ontario and Ohio. For some of these events there are strong motion recordings at distances close to the earthquake source (Weichert *et al.*, 1982; Chang, 1983; Borcherdt, 1986), while other events were recorded by digital seismographic networks at distances of 100 to 1000 km (Atkinson, 1985).

Ground motion data show that ENA earthquakes have more energy at high frequencies than do western events, as manifested by higher f_m values. Western earthquakes exhibit a high frequency cut-off of approximately 10 to 15 Hz (Hanks, 1982; Boore, 1983; Joyner, personal communication, 1988), whereas corresponding eastern values are about 40 Hz or greater (Atkinson, 1984). This difference may be attributed to smaller near-surface attenuation at the recording site (Hanks, 1982); alternatively, it could be due to a difference in source characteristics (Papageorgiou and Aki, 1981). Because *pga* values increase with increasing high frequency content, higher *pga* values are observed in ENA than in WNA, for records at the same magnitude and distance (Atkinson, 1984). This was not known prior to the recording of ENA earthquakes at near-source distances.

The quantitative database also shows that eastern ground motions decay more slowly with distance than do their western counterparts. This corroborates earlier MMI observations, which indicated that eastern earthquakes are felt at very large distances. The slower eastern attenuation is attributed to the relatively stable and unfractured crust.

The available ground motion data have been well-matched by the predictions of the stochastic model (Atkinson, 1984; Boore and Atkinson, 1987a; Toro and McGuire 1987). This provides reasonable confidence in ENA ground motion relations for moderate events on rock sites. The validity of model predictions for large magnitude earthquakes is still subject to debate concerning the underlying seismic source model.

The debate over source model concerns the value of the stress parameter for ENA, and whether it increases with increasing earthquake magnitude. Current relations assume a constant stress parameter of 100 bars for ENA (Atkinson, 1984; Boore and Atkinson, 1987a; Toro and McGuire, 1987). Nuttli *et al.* (1987) propose a stress parameter that increases with magnitude, from approximately 60 bars for a M 5 earthquake, to 160 bars for M 7. Nuttli *et al.*'s *slope* for the increase of stress with magnitude is supported by Chael (1987) and Chun *et al.* (1989), although their work provides no information concerning values for the stress parameter. The Nuttli *et al.* (1987) relation is a weaker function of magnitude than an earlier proposal by Nuttli (1983), which featured a stress parameter which increased from approximately 10 bars at M 5 to 60 bars at M 7. Existing data are not sufficient to resolve the source scaling issue, and thus ground motion relations may be revised in the future as the source properties of ENA events become better understood.

Boore and Atkinson's (1987a) predictions of the stochastic model for the random horizontal component of ground motion, on rock sites in ENA, are shown in Figure 7, and compared to applicable ground motion data in Figure 8. Regression analyses have been used to obtain convenient equations for the ground motion predictions of Figure 7. Boore and Atkinson (1987a) used a polynomial equation, with up to 8 constants, to fit model predictions accurately. For many engineering applications, however, it is more convenient to have relations in a simpler functional form, comparable to Table 1 for example. Regression analyses of ENA predictions have also been performed, using the two-step procedure of Joyner and Boore (1981), to obtain equations of the following functional form:

$$\begin{aligned} \log y = {} & a + b(M-6) + c(M-6)^2 - \log r + k\,r \\ & 4.5 < M < 7.5 \\ & 10 < r < 400 \text{ km} \end{aligned} \tag{10}$$

The resulting predictive equations are given in Table 2, where M may be either moment magnitude (Table 2a) or Nuttli magnitude (Table 2b). The equations apply to the random horizontal component of motion, on rock sites. For *psrv*, damping is 5% of critical. These predictions differ somewhat from those of Boore and Atkinson (1987a) in that the attenuation with distance is based on regression results from the ENA seismographic data of Figure 8 (see Atkinson, 1989), as opposed to an assumed attenuation rate based on literature review.

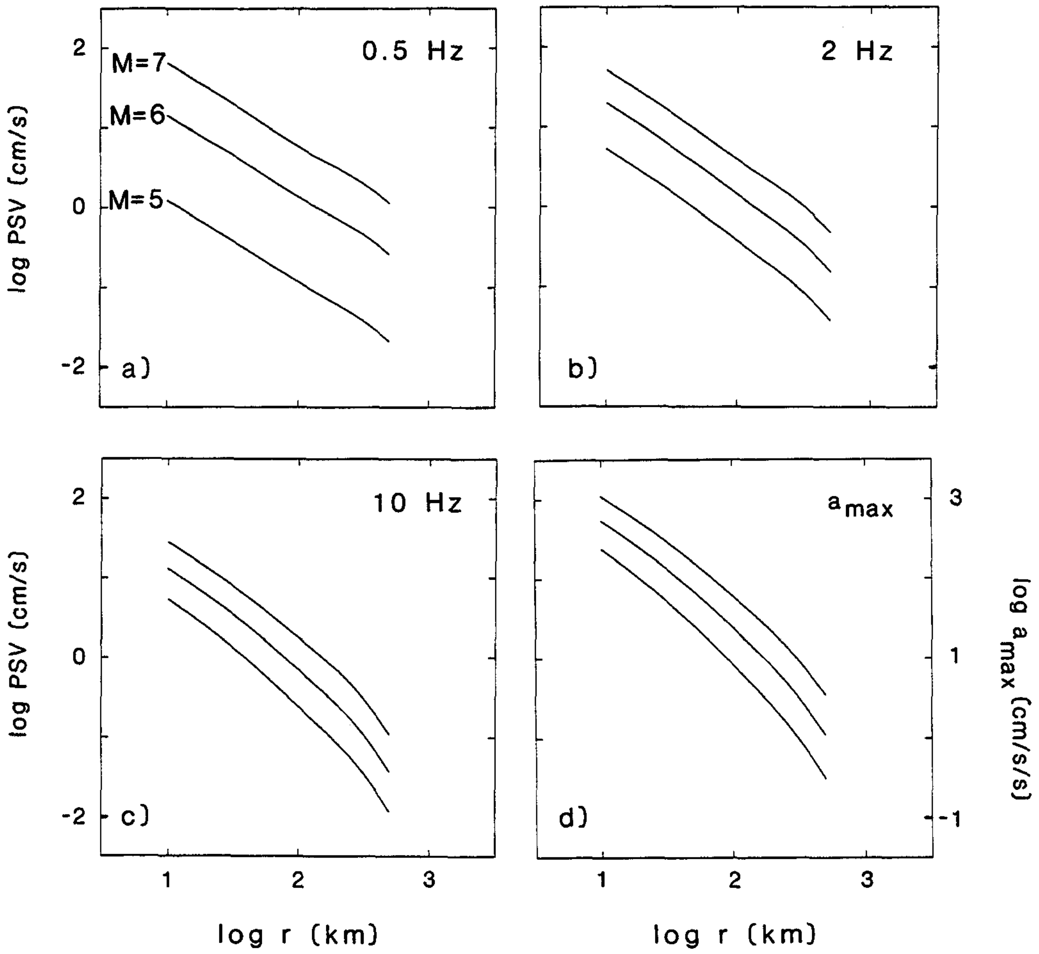

Figure 7 – Predicted ENA ground motion relations for psrv at 0.5 Hz, 2 Hz, 10 Hz, and *pga*, based on the stochastic model, for M 5, 6 and 7. After Boore and Atkinson (1987a).

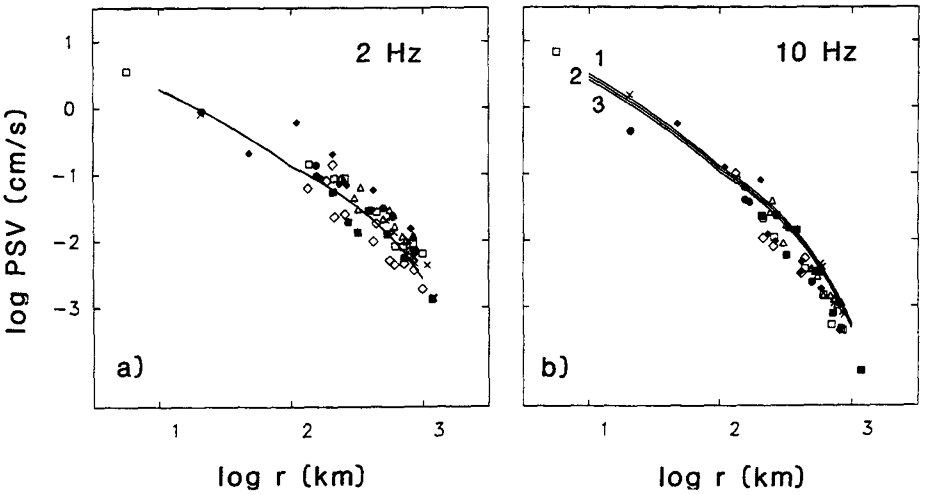

Figure 8 – Comparison of predicted *psrv* from the stochastic model for ENA (curves) with observations from 7 earthquakes (different symbol for each event). Data have been normalized to M 4.5, using theoretical scaling. Three curves for 10 Hz show different forms for f_m. After Boore and Atkinson (1987a).

TABLE 2
Parameters in the predictive equations for the random horizontal component of *psrv* (5% damped), *pga* and *pgv* in ENA (see Equation 10).

Frequency	*a*	*b*	*c*	*k*
a) FOR MOMENT MAGNITUDE				
0.2	1.73	0.96	−0.03	−.00034
0.5	2.16	0.85	−0.18	−.00037
1.0	2.30	0.67	−0.15	−.00064
2.0	2.30	0.53	−0.09	−.00102
5.0	2.21	0.44	−0.04	−.00170
10.0	2.11	0.42	−0.03	−.00250
20.0	1.97	0.41	−0.03	−.00350
pga	3.65	0.42	−0.03	−.00281
pgv	2.16	0.66	−0.03	−.00131
b) FOR NUTTLI MAGNITUDE				
0.2	1.36	1.21	+0.09	−.00034
0.5	1.83	1.17	−0.18	−.00037
1.0	2.04	0.93	−0.16	−.00064
2.0	2.10	0.71	−0.08	−.00102
5.0	2.04	0.58	+0.01	−.00170
10.0	1.95	0.54	+0.01	−.00250
20.0	1.81	0.53	+0.01	−.00350
pga	3.49	0.54	0.0	−.00281
pgv	1.91	0.85	+0.04	−.001131

COMPARISON OF ENA AND WNA GROUND MOTION RELATIONS

Model predictions for ENA differ from those for WNA primarily due to differences in f_m values, and anelastic attenuation. Different source properties and crustal constants are also factors. To illustrate the resulting differences in ground motions, Figure 9 compares eastern and western relations for *psrv* at four frequencies. The eastern relations are from Boore and Atkinson (1987a) and the western ones are from Joyner and Boore (1982). For frequencies less than 10 Hz, eastern and western *psrv* values are comparable at near-source distances, although eastern ground motions decay more slowly with distance. This is also true for *pgv* (not shown in figure). The modest differences shown in the figure for the near-source amplitudes for these frequencies are due to a combination of factors. These include real differences in expected levels due to differences in average crustal properties, and random variations introduced into the comparison by using an empirical ground motion relation

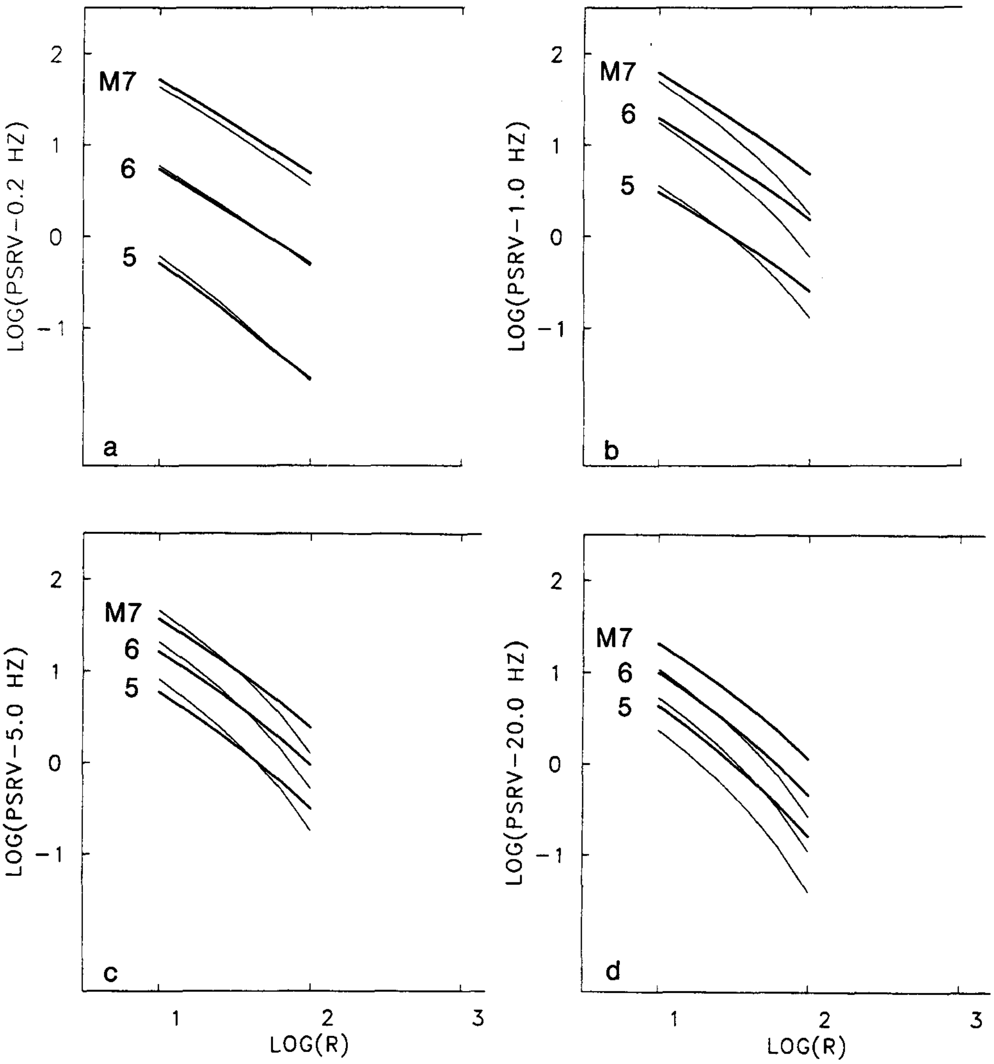

Figure 9 – Comparison of *psrv* for ENA (heavy lines) with WNA (light lines), for M 5, 6 and 7. After Boore and Atkinson (1987b).

for the west.

For frequencies above 10 Hz, the high f_m values in ENA cause *psrv* values to be significantly higher than those for WNA. For the same reason, *pga* values in ENA are also higher than those in WNA (by about a factor of two), for near-source distances (not shown in figure).

Implications for Seismic Hazard

If eastern and western ground motion relations were equivalent, then the lower occurrence rates for eastern earthquakes would imply a lesser seismic hazard, for structures of all natural frequencies. However, ENA response spectra are enriched at high frequencies relative to western events. Consequently, for structures with significant high frequency modes of vibrations (above about 10 Hz), the earthquake hazard may be greater in much of ENA than it is in active areas of California (Atkinson, 1988). In essence, the high f_m values in ENA 'compensate' for the low occurrence rates of events. Thus generalizations about earthquake hazards and structural damage derived from California experience cannot simply be 'transported' to the east on a scaled-down level. The types of structures at risk, and the types of damage to be expected, are potentially different.

Another consequence of differences in eastern and western ground motions concerns the use of *pga* as an index parameter for simplified analysis of earthquake response, or as a basis for scaling a standard spectrum. It has long been known that *pga* itself is not strongly correlated with damage potential. Nevertheless it is still widely used, particularly in geotechnical engineering, due to the large body of empirical data correlating *pga* with field performance. For example, *pga* is used as an empirical index to the expected performance of earth embankments (Seed, 1979) and concrete dams (Tarbox, 1980). Such techniques may be overly conservative when applied to ENA, because the empirical performance data are largely based on western observations. Eastern *pga* values do not necessarily have the same implications for structural response due to the higher frequency content.

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