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The estimation of ground shaking caused by earthquakes

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ABSTRACT: In the last decade, large increases in the database of motions recorded within 100 km of large earthquakes has greatly improved our ability to estimate the mean value of various ground motion parameters (such as peak acceleration, peak velocity, and response spectra), especially for earthquakes less than magnitude 7. For larger earthquakes the database is sparse, especially at close distances to the fault. Estimates of motions within this critical region of magnitude–distance space can be made using extrapolations of the empirically-based regression equations. Theoretical predictions, verified against existing data, can also be useful. The most promising theoretical model for predicting the high-frequency motions of interest to engineers blends the traditional engineering description of ground acceleration, as being made up of random motion, together with seismological models of radiation and propagation of energy from the seismic source. Predictions using two previously published equations for estimating response spectra, one based on empirical analysis of data recorded before 1981 and the other using the theoretical model just described, are in good agreement with the motions recorded at the two stations closest to the recent Nahanni, Northwest Territories earthquake (23 December 1985, M=6.8).

1 INTRODUCTION

Estimation of the ground motions produced by earthquakes have many uses, ranging from the specification of a time series for response calculations of an engineered structure at a particular site to predictions of peak motions needed in the construction of earthquake hazard maps covering broad geographic areas. In some cases the estimations can be based on empirical analyses of existing data; when this is not possible, theoretical models must be used as the basis for the predictions. In this paper, I will give short discussions of both the empirical and theoretical methods for predicting strong motion that I and my colleagues have been developing over the last several years. The paper is not intended to be a comprehensive review of the literature on the subject, relying, as it does, so heavily on my own research (see Campbell, 1985, for another review of empirical estimation of ground motion and Joyner, 1987, for a general review of strong-motion seismology). In spite of this, however, I believe that the majority of the important topics are covered here. Much of this paper is taken from a few of my earlier papers (in particular, Boore and Joyner, 1982, and Boore, 1987). New to this paper, however, is a discussion of the comparison between the response spectra computed from the December 23, 1985, Nahanni, Northwest Territories earthquake and published theoretically and empirically based predictions of the motions.

2 EMPIRICAL PREDICTION

The existing recordings of ground motions within several hundred kilometers of the earthquake source can be used in several ways to predict ground motions for engineering design and seismic hazard planning. The most straightforward use occurs when recordings are available in magnitude and distance ranges for which the design motions must be specified. This is sometimes referred to as site specific prediction. Recordings are generally lacking close to large earthquakes, however, and thus design motions for such cases must be based on extrapolations of the data. This is commonly done by using regression analysis to fit a mathematical function involving distance and magnitude to the existing data, and then using this function to make predictions. The determination of the empirical prediction equations is the subject of this section (see Boore and Joyner, 1982, for a more complete discussion). Because they represent the average value of ground motions for a specified magnitude and distance, the empirically-derived prediction equations are also useful in checking theoretical predictions if care is made to make comparisons in the range of magnitudes and distances for which the empirical functions are constrained by the data.

2.1 Choice of Variables

Empirical predictions are generally based on a mathematical function connecting response variables, such as peak acceleration, velocity, or oscillator response, with explanatory variables, the most common of which are distance and magnitude. Unfortunately, definitions of distance and magnitude are not standard, and thus care must be used in comparing predictions made by various authors. Because the fault rupture occurs over an extended surface, a variety of possible distance definitions are possible. My colleague William Joyner and I have adopted as our measure the clos-

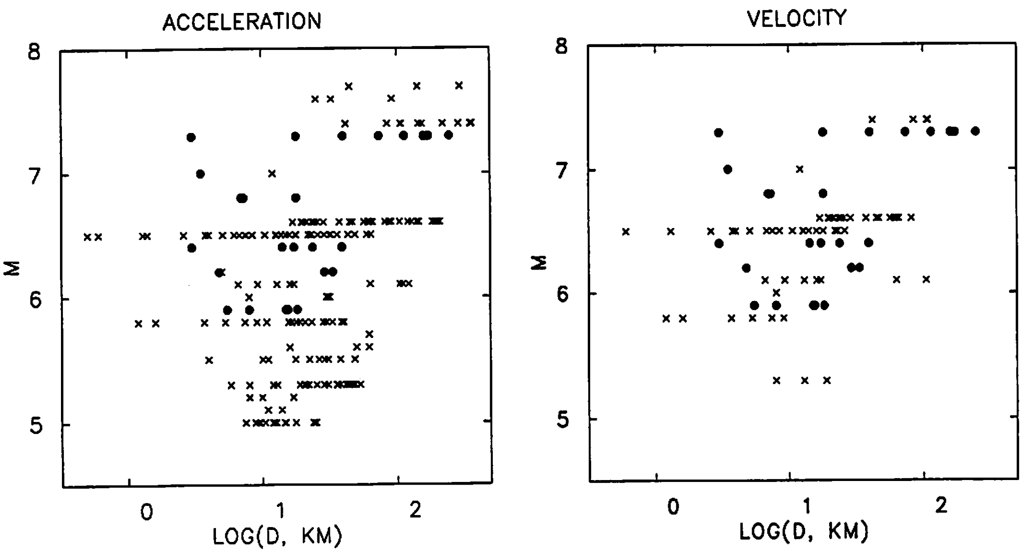

Figure 1. Distribution in magnitude and distance of peak horizontal velocity. The x's show the data used by Joyner and Boore (1981) and the closed circles are a small sample of other data, including Tabas, Iran (M=7.3), and Nahanni, Northwest Territories (M=6.8). Not shown here are the many new data collected for earthquakes of magnitude less than 6.0.

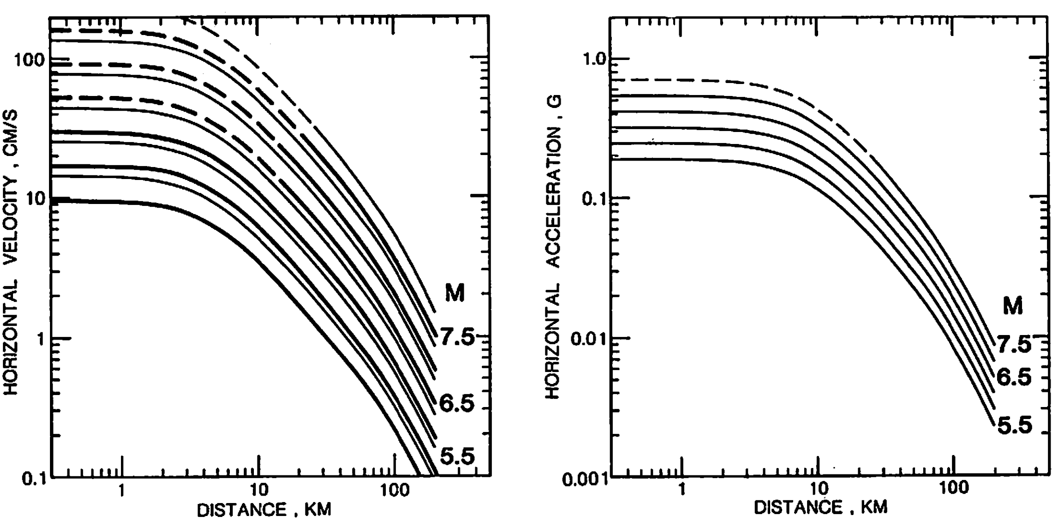

Figure 2. Peak horizontal acceleration and velocity from empirical analysis of randomly chosen horizontal components. Light lines: soil sites; heavy lines: rock sites. Curves are dashed where not constrained by data. (from Joyner and Fumal, 1985).

est distance from the site to the surface projection of the fault rupture. We have used this definition with the goal of prediction in mind: in future earthquakes it is unlikely that the hypocenter or high stress zones will be known beforehand, and thus distance measures based on such things as center of energy release or the point of rupture initiation will be ot little use, even they may lead to reduced scatter in analyzing existing data.

Many measures of magnitude are available, according to the type of wave and its period. A number of people seem to prefer magnitude measures based on motions with periods close to those of interest in engineering. The problem with this, however, is that the explanatory variable (magnitude) and the response variable (the ground motion parameter) are virtually the same quantity. A more sensible magnitude is the moment magnitude (Hanks and Kanamori, 1979), which is defined by the seismic moment by the relation:

$$M = 2/3 \log M_0 - 10.7 \quad (1)$$

where M_0 is the seismic moment in dyne-cm. Because of the definition of moment in terms of overall fault area (A) and fault slip (D) according to

$$M_0 = \mu DA, \quad (2)$$

where μ is the rigidity of the earth in the vicinity of the source, moment magnitude has a clear physical meaning as a measure of the size of an earthquake. Furthermore, geologic investigations can be of some use in predicting the possible moment magnitudes of future earthquakes.

Other explanatory variables are sometimes used in regression analysis; these can include variables to represent the geologic conditions at the recording sites, the tectonic environment (for example, thrust vrs. strike-slip faulting), the type of structure in which the recording was made, and the fault geometry (used to account for directivity). All of these can be shown to influence the response, but the most commonly used variable is the one used to quantify the influence of geologic conditions.

2.2 The Regression Model

The following equation is the one most commonly used in regression analysis:

$$\log Y = c_0 + c_M M - c_D D(M) - c_L D \log D(M) + c_S S + c_P P \quad (3)$$

where Y is the response variable, D is the distance measure, S is a geologic variable (taken by Joyner and Boore, 1981, to be 0 for rock and 1 for soil), P is the uncertainty in the prediction (0 and 1 for 50 and 84 percentile values, respectively, assuming a lognormal distribution for Y), and the c's are coefficients to be determined. The distance may be a function of magnitude; a physically motivated equation that allows this is

$$D(M) = [d^2 + (h_1 e^{h_2(M-6)})^2]^{1/2} \quad (4)$$

where d is the shortest distance to the surface projection of the fault.

The determination of the regression coefficients is easily done using standard least-squares techniques. Some care should be given in the weighting and selection of the data, however, to avoid biases in the result. For example, beyond some distance for any earthquake some accelerographs will not be triggered; readings from those that do will bias the results to large values and should not be included in the regression analysis. It is often the case that a few earthquakes are particularly well-recorded over a range of distances; these events should exert a strong influence on the distance attenuation coefficients c_D and $c_L D$, but they say little about the scaling with source size (as given by c_M). It is therefore natural to separate the regression into two parts. In the first part, the attenuation coefficients are determined, irrespective of earthquake magnitude. In effect, the data from all earthquakes are merged to determine the best attenuation function. The translation factor for each earthquake required to merge the data is regressed against earthquake magnitude in the second regression in order to determine the magnitude scaling.

2.3 Selected Results

The regression method discussed above has been applied to strong motion recordings obtained in western North America. The magnitude and distance distributions of the data used for peak acceleration and peak velocity estimations are shown in Figure 1. The x's are the points used by William Joyner and myself in our predictions of peak acceleration and velocity (Joyner and Boore, 1981) and pseudo relative velocity response spectra (Joyner and Boore, 1982). The closed circles are a representative sampling of data that have become available since then (including the Nahanni, Northwest Territories event, with a magnitude of 6.8). Several points can be made with this figure, the most important of which is that there is a clear lack of data close to large earthquakes, although the increasing number of strong motion instruments placed close to faults throughout the world offers the hope that data will be collected in this critical region of magnitude-distance space. Another point to be made from the figure is that more data are generally available for acceleration than for velocity and response spectra (whose data have a magnitude-distance distribution similar to that of peak velocity) , particularly for smaller earthquakes and larger distances. This is because peak accelerations can be read directly from analog accelerograph recordings; no digitization is needed (unless the records contain unusually high frequencies, in which case a correction for instrument response must be made).

Predictions of peak acceleration and velocity from analysis of many strong motion data from western North America (primarily California) are shown in Figure 2. The predictions used the data set indicated by x's in Figure 1; my colleague William Joyner and I are now in the process of repeating the analysis using a more complete data set. Judging from Figure 1 and some preliminary results, the new analysis is most likely to change our previous ground-motion estimates at close distances to large earthquakes, especially for peak velocity (and response spectra). Note that the curves for both acceleration and velocity have similar shapes beyond about 20 km , although the frequency content of the two measures of ground shaking are quite different. This implies that the effective attenuation parameter Q is frequency dependent (e.g., Boore, 1984, Fig.

2). Also note the difference in spacing between the curves: the peak velocity is a more sensitive function of moment magnitude than is peak acceleration. As I will show later, this is in agreement with a commonly used seismological model of spectral radiation.

Although peak acceleration is widely used to specify design motions (often to scale a fixed spectral shape), many engineers and seismologists deplore this and urge that response spectra be specified directly. With the increasing amount of digitized data it is now possible to accomplish this, using the same procedures used for the derivation of predictive equations for peak acceleration. Figure 3 shows an example, in which response spectra for a range of magnitude and site geology are shown for a fixed distance. The dashed curves are not constrained by data (and thus emphasize the crucial need for more data close to large earthquakes). Note that the shape of the curves is strongly magnitude dependent, in contradiction to the assumption underlying the commonly used method of deriving design motions by scaling a fixed spectral shape.

3 THEORETICAL PREDICTION

As with the empirical prediction of ground motion, there are many uses for theoretical predictions, both in seismology and in engineering. Theoretical predictions can be used to specify a suite of time series for use in dynamic structural analysis, they can provide estimates of ground motion parameters in geographic regions or portions of magnitude-distance space lacking observations, and they can be used as an essential part of understanding the physics of earthquake sources and wave propagation. Much effort in seismology has been devoted to deterministic simulations of ground motion from specified faults in laterally uniform geologic materials whose properties are a function of depth. Although these simulations can be useful in predicting low frequency motions, they are generally not relevant for simulations of high frequency motions: not only does the cost of doing the simulations increase dramatically with frequency, but the basic model assumptions are invalid. Engineers, on the other hand, usually use a purely stochastic approach in deriving time series for design purposes. The parameters that control the duration, frequency content, and amplitude of these motions are taken from empirical analyses of the existing data. Because of this, however, the usual stochastic techniques share the same problems as do the empirical techniques in predicting motions for situations in which no data exist.

Recently a hybrid approach has been developed that assumes random ground motion with properties determined from seismological models of the source and the wave propagation (Hanks and McGuire, 1981; McGuire and Hanks, 1980; Boore, 1983; McGuire et al, 1984; Boore, 1986a). This new method does not have the limitations of the methods just discussed. The basic idea of the method is a simple one: the ground motion is represented by windowed and filtered white noise, with the average spectral content and the duration over which the motion lasts being determined by a seismological description of seismic radiation that depends on source size.

3.1 Spectral Content

The spectrum at a distance r from an earthquake can be written as a cascade of a number of filters. A common description of the spectrum at a site is:

$$R(f) = CS(f)A(f)D(f)I(f) \qquad (5)$$

In the above equation, C stands for a frequency-independent scaling factor that depends on elastic moduli, fault orientation, and distance, S is the source spectrum, commonly given by the equation

$$S(f) = M_0/[1 + (f/f_0)^2], \qquad (6)$$

where M_0 is the seismic moment and f_0 is the corner frequency, and $A(f)$, $D(f)$, and $I(f)$ are amplification, diminution, and instrument filters, discussed below.

The amplification factor $A(f)$ can be given in a variety of ways. Probably most familiar is the frequency-dependent transfer function that results from wave propagation in a stack of layers with a strong impedance contrast at the base of the stack (e.g., Boore and Joyner, 1984a). There is another source of amplification, however, that may be more generally important, since it will operate even in the absence of strong impedance contrasts. The factor C is usually derived for homogeneous materials, but in general both ρ and β will decrease toward the earth's surface. Conservation of energy for waves traveling through materials with decreasing velocity requires an increase in wave amplitude as the wave speed slows down. Thus as seismic waves approach the earth's surface, they are amplified by gradual decreases in seismic impedance. This amplification can be greater than a factor of two for typical California rock recordings, and increases with frequency (Boore, 1986a). The correction needed to account for propagation from average crustal depths up to the surface can be approximated by multiplying the estimate of spectral amplitude by $\sqrt{\rho_0\beta_0/\rho_r\beta_r}$, where the subscripts 0 and r refer to density (ρ) and shear velocity (β) in average crustal material and near the receiver, respectively. The frequency dependence of the correction arises through an interpretation of the receiver properties as being determined by an average of the point properties to a depth equal to a quarter of a wavelength (Joyner and Fumal, 1984).

The diminution factor $D(f)$ accounts for the loss of high-frequency energy, either through wave propagation or as a fundamental property of the source radiation not accounted for in equation (6). The following is a convenient form for the diminution factor $D(f)$

$$D(f) = \exp(-\pi f r/Q(f)\beta)P(f, fm), \qquad (7)$$

where Q is a frequency dependent attenuation function and P is a high-cut filter of arbitrary shape. For high frequencies, a number of studies have found that Q is a strongly increasing function of frequency. The values of Q are generally higher in eastern North America than in western North America (Singh and Herrmann, 1983), implying that ground motions will decay less rapidly in eastern North America. The difference, however, is most noticeable beyond about 100 km (Boore and Atkinson, 1987), by which time the geometrical spreading of the

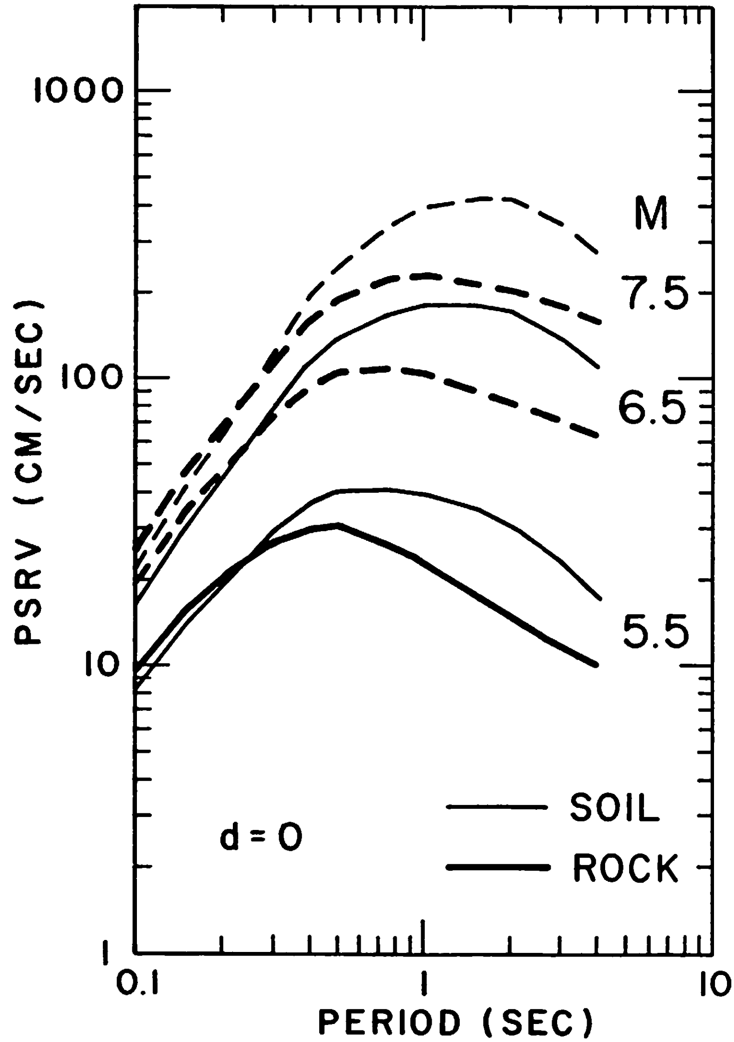

Figure 3. Predicted pseudo-velocity response spectra for 5 percent damping at rock sites (heavy line) and soil sites (light line) for zero distance, for larger of peaks on the two horizontal components. Curves are dashed where not constrained by data.

energy has reduced the motion to relatively undamaging levels. The high-cut filter P is needed to account for the general observation that acceleration spectra often show an abrupt depletion of high frequency energy above some frequency f_m (Hanks, 1982, who uses the term f_{max} rather than f_m as I have done). There is currently some controversy regarding the origin of this energy depletion. On one hand, it could be an inherent property of the source radiation not accounted for in the spectral description given in equation (6), and on the other hand it could be due to near-site attenuation in the upper kilometer or so of the ray path. In either case, f_m plays an important role in determining the level of the high-frequency ground motions. For small distances or large Q, most of the attenuation in the filter $D(f)$ is due to the factor P.

Finally, the filter $I(f)$ is used to shape the spectrum so that the predicted motions correspond to the particular ground motion measure of interest. For example, if response spectra or Richter magnitude are to be computed, I is the response of an oscillator of frequency f_r and damping η to ground displacement, and if peak velocity or peak acceleration are the quantities of interest, then $I(f)$ is simply given by $2\pi f$ or $(2\pi f)^2$, respectively.

The long-period level of the spectrum is (by definition) determined by the seismic moment of the event. The consequent features of the amplitude spectrum for acceleration are that it increases as f^2 (where f is frequency) for frequencies below the source corner frequency f_0, then is constant for frequencies above f_0 until a cut-off frequency f_m is approached. Amplitudes decay rapidly for frequencies above f_m. Anelastic attenuation acts as a filter on this source spectrum shape, reducing high frequencies more rapidly with distance than lower frequencies. At large distances this causes the 'flat' portion of the spectrum to slope significantly, and obscures the corner frequency (Boore, 1986b). The spectral shape described by the series of equations above captures most of the salient features concerning the shape of earthquake spectra, but by themselves the equations are not useful for prediction since I have not yet specified how the various parameters depend on earthquake size. This is the subject of source scaling, which is discussed in the next section.

3.2 Source-spectral Scaling

At close distances, where the whole path attenuation is of little importance, the shape of the spectrum is governed by two corners — f_0 and f_m. The spectral amplitudes for $f < f_0$ scale as seismic moment M_0, and the level of the portion of the spectra between the corners is proportional to $M_0 f_0^2$. In order to predict ground motions for any particular size earthquake, it is necessary to express the corner frequencies as functions of seismic moment. This is a crucial step in the method, especially for high-frequency motions, which are controlled by the part of the spectrum whose amplitude depends on corner frequency squared. A number of studies have found that very simple relations between the corner frequencies and moment lead to predictions that are in excellent agreement with many measures of strong ground motion (McGuire and Hanks, 1980; Hanks and McGuire, 1981; Boore, 1983; Atkinson, 1984; Hanks and Boore, 1984; McGuire et al, 1984; Boore, 1986a, 1986b; Boore and Atkinson, 1987). In these studies,

$$f_m = constant \quad (8)$$

and

$$f_0 = 4.9 \times 10^6 \beta (\Delta\sigma / M_0)^{1/3} \quad (9)$$

where β and M_0 have units of km/s and dyne-cm, respectively, and $\Delta\sigma$ is a scaling parameter with the dimensions of stress (in bars). The studies referred to above found that choosing a constant value for $\Delta\sigma$ leads to predictions in good agreement with the data; the specific value required to fit the data may depend on tectonic region, as well as details in the modeling, including the values used for the radiation pattern, the vector partition of motion, the value of f_m, and the presence or absence of site amplification. The use of a constant $\Delta\sigma$ leads to a prediction model in which the scaling of motions with earthquake size depends on only one parameter: seismic moment.

Other scaling laws have been proposed. For example, Nuttli (1983)'s scaling for mid-plate earthquakes has the corner frequency proportional to moment to the inverse quarter power, rather than inverse cube root as in equation (9). The implication is that the stress parameter increases with source size, and therefore the ground motions are more sensitive to moment than for the constant stress model. Boore and Atkinson (1987) show that predictions made with this scaling relation do not match the relatively sparse data recorded close to mid-plate earthquakes (Figure 4).

3.3 Predicting Peak Motions

All of the discussion above is directed to specifying the spectrum at a given distance and moment magnitude; how is this converted to estimates of peak motion, a quantity of particular importance to engineers? There are two paths available to do this. One uses time domain, Monte Carlo simulation, and the other uses random process theory (RPT). The former method is useful in applications demanding time series and is subject to fewer assumptions than is the RPT. On the other hand, it is much more costly than RPT to predict the peak motion.

The time domain method, discussed in detail in Boore (1983), is very simple: Gaussian white noise is generated with a random number generator. This noise is windowed with either a shaping function or a box car whose duration is related to the source corner frequency (close to faults, the duration is given by the inverse of f_0, and farther away an additional term involving distance might be added to account for the spreading out of the source energy due to scattering and wave propagation effects; see Herrmann, 1985). The amplitude of the window is chosen such that the mean level of the white spectrum is unity. Filtering is then performed in the frequency domain by multiplying the spectrum of the windowed white noise by the spectral shape given by the equations in the previous two sections. Fourier transformation back to the time domain then yields the desired time series. Peak motions are then obtained, and the whole process is repeated with a different seed for the random number generator. Between 20 and 100 simulations is usually sufficient to derive a good estimate of the peak motion. The spectrum of any one realization of the process will not match the target spectrum, but the spectrum averaged over the whole suite of simulations will (Figure 5). The time series for one realization for two magnitudes are shown in Figure 6; in the computer program used to generate these motions, only one input parameter (magnitude) needed to be changed to produce the motions from the different earthquakes.

The order of windowing and filtering described above is important if the desired spectral shape is to be preserved. As Safak and Boore (1987) have shown, the usual engineering method of filtering a random time series and then windowing will produce biases in the low frequency part of the resulting spectrum (Figure 7).

The random process theory provides a very convenient and powerful means to estimate peak motions from a description of the spectra. A detailed discussion of the applicable theory, largely taken from Cartwright and Longuet-Higgins (1956), is contained in Boore (1983) and Boore and Joyner (1984b). Random process theory can be used to derive a relation between the root-mean-square and the peak motion of a stochastic series. In its simplest form, good for a large number of extrema N, this relation is

$$\frac{a_{max}}{a_{rms}} = [2\ln(N)]^{1/2} \quad (10)$$

The number of extrema is related to the specified duration and the dominant frequency. Fortunately, both the dominant frequency and a_{rms} are given by simple formulas involving integrals of the radiated spectra.

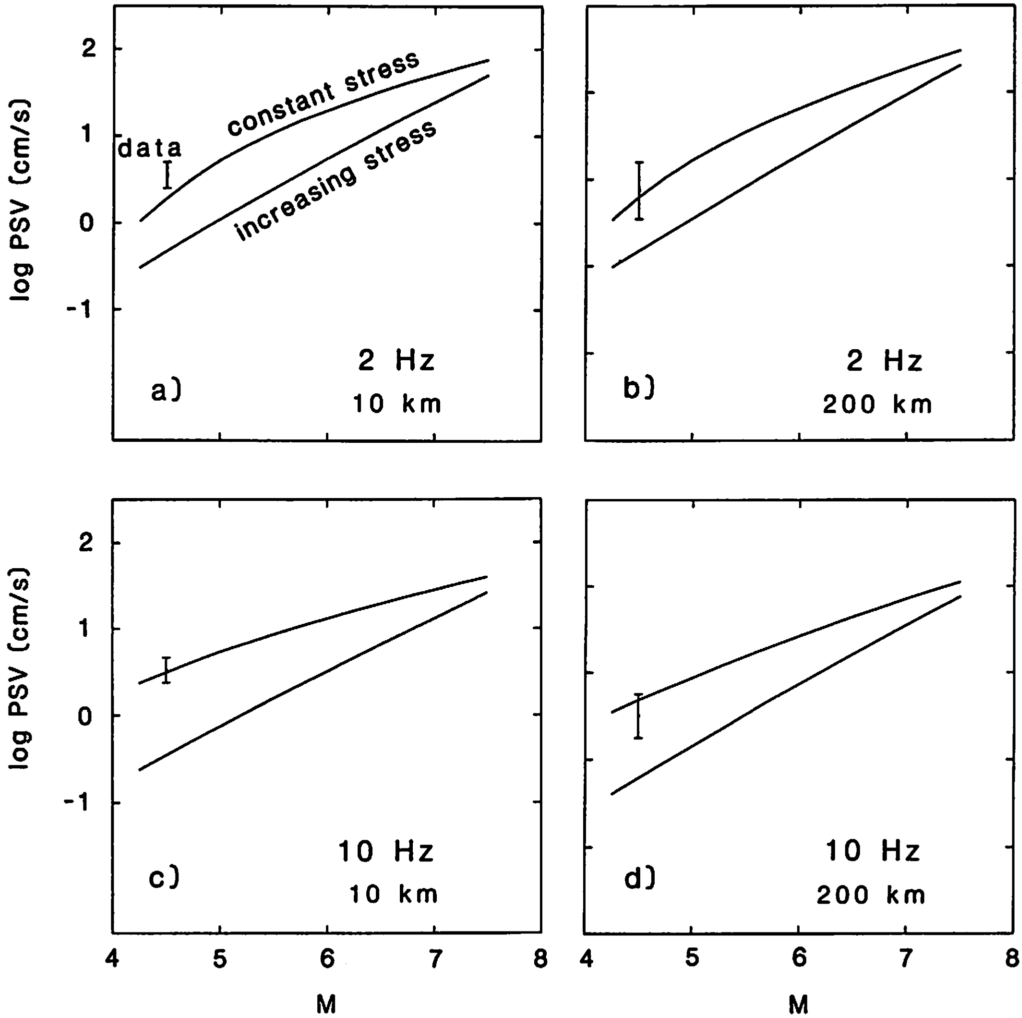

Figure 4. Predicted dependence of 5 percent damped pseudo-velocity response spectra (PSV) on moment magnitude (M) for oscillator frequencies of 2 and 10 Hz and distances of 10 and 200 km. The theoretical predictions for Nuttli's scaling and the 100 bar models are given by the curves labeled *increasing stress* and *constant stress*, respectively. (from Boore and Atkinson, 1987).

3.4 Examples of Predictions

A suite of spectra derived from equation (5) are shown in Figure 8. Some general conclusions can be drawn without complex calculations, simply from the spectral shapes and the spacing between the spectra: for large earthquakes, the peak velocity will be a stronger function of seismic moment (or, equivalently, moment magnitude) than will peak acceleration. In contrast, the moment dependence of both peak acceleration and peak velocity will be identical for small earthquakes and will have a stronger dependence on moment than do either a_p and v_p for large earthquakes. These conclusions are based on the low and high frequency limits of the spectra and are useful for a general understanding of what to expect in the way of ground motion scaling with source size. Detailed predictions of motions for arbitrary size events can be made by using both time domain simulation and random process theory.

A comparison of predicted and observed peak acceleration and peak velocity is shown in Figure 9, with f_m as a parameter. The observed values are based on the comprehensive regression work of Joyner and Boore (1981, 1982), which used earthquakes greater than moment magnitude

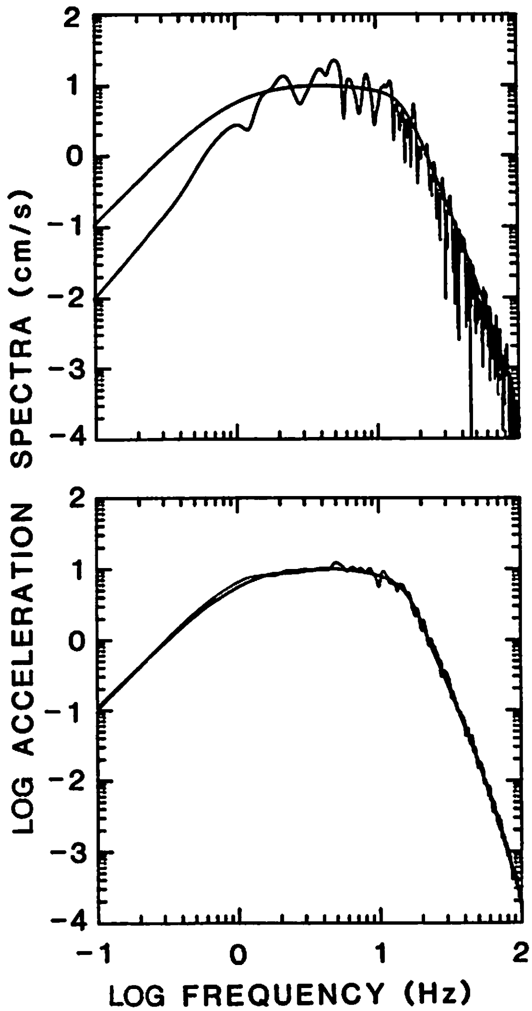

Figure 5. Fourier amplitude spectrum of ground acceleration at 10 km from a magnitude 5 earthquake. (Top) *smooth curve*: given spectra; *jagged curve*: spectra for one realization of the simulation process. (Bottom) as above, but averaged over 20 simulations (the averaged spectrum is the square root of the arithmetic mean of the energy density spectrum). (from Boore, 1983).

5. As seen in the figure, the simple constant stress parameter model gives predictions that are in good agreement with the observations. As expected, the effect of f_m is seen to be most important for motions that contain high frequencies (peak accelerations from small earthquakes). It is likely that one of the major differences in high-frequency ground motions in eastern and western North America may be due to differences in f_m: for rock sites in the Mirimichi region, f_m is probably greater than 50 Hz, whereas in California, f_m is closer to 10 - 15 Hz at rock sites.

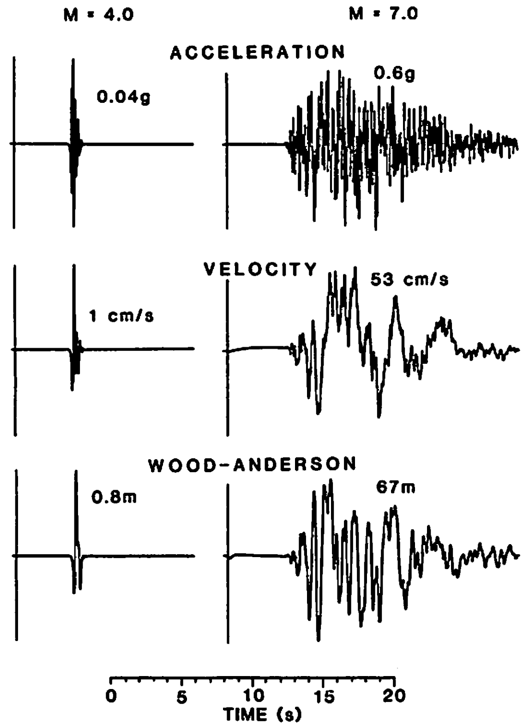

Figure 6. Time series for magnitude 4 and 7 earthquakes. Peak motions are the average of peaks from 20 such time series. A low-cut filter with a cutoff frequency of 0.10 Hz has been applied to the velocity trace. (from Boore, 1983).

The predicted values of the peak response of various oscillators are in good agreement with the data. Boore (1983, 1986a) discusses such a comparison for pseudo-relative velocity spectra and short-period response for P-waves at teleseismic distances, and Figure 10 shows comparisons for the output of a Wood-Anderson seismograph (used in determining M_L). Note that the motions are being predicted for a range of almost 12 orders of magnitude in seismic moment, with good agreement with the data over this enormous range of earthquake size.

As a final example, Figure 11 shows observed and predicted response spectra for two sites within 10 km of the December 23, 1985 Nahanni, Northwest Territories earthquake (M 6.8). The response spectra for both sites have been computed for the first 7 secs of the record, in order to exclude the contribution from a large but inexplicable burst of energy late in the record from site 1 (this energy is not present at site 2, which is situated 11 km from site 1 and, like site 1, is situated at the northern end of the rupture zone of the earthquake). The predictions have been made from the empirical results, largely using California strong-motion records (Joyner and Boore, 1982), and from the theoretically-based predictions of Boore and Atkinson (1987) for ground motions in eastern North America, who used the theoretical method outline in this paper. For the latter predictions, two distances

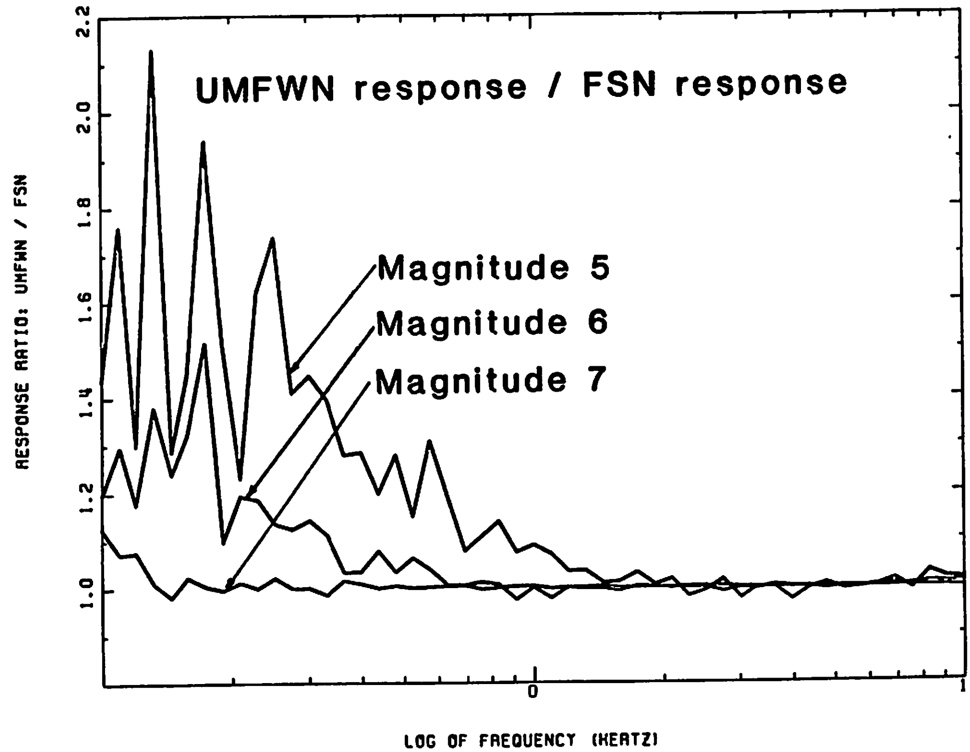

Figure 7. Ratio of pseudo-velocity response spectra due to uniformly modulated filtered white-noise (UMFWN) and filtered shot-noise (FSN) models. The UMFWN is commonly used in engineering and the FSN model is the stochastic model based on a seismological description of the radiated energy. (from Safak and Boore, 1987).

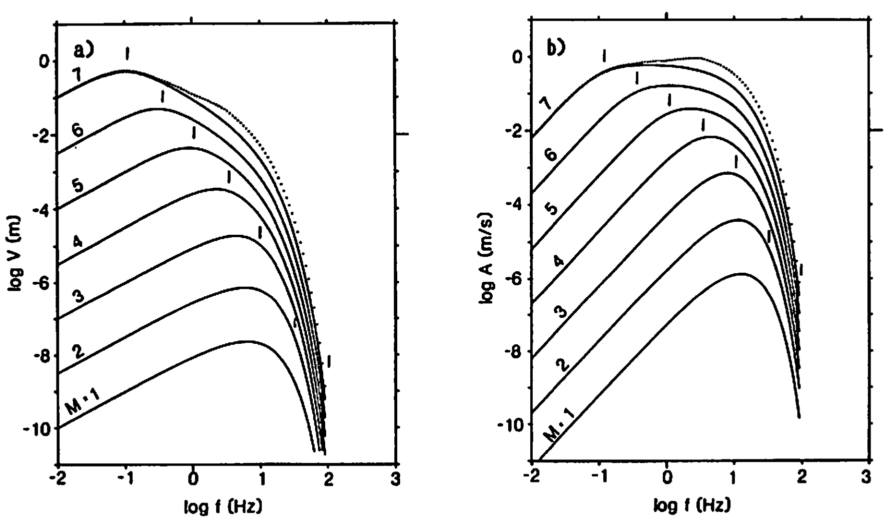

Figure 8. Velocity and acceleration Fourier spectra for a range of moment magnitudes, computed for a distance of 10 km. The vertical bars indicate corner frequencies. Dots show modification of M=7 spectra for amplification factors given in Table 3 in Boore (1986a). (from Boore, 1986b).

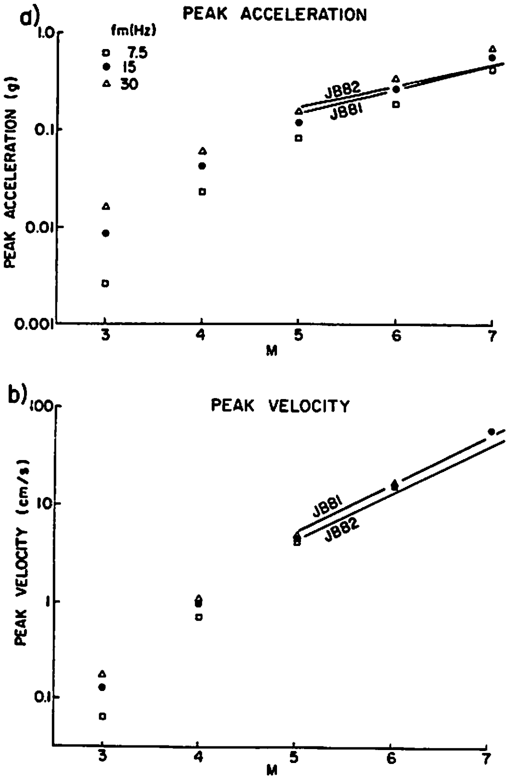

Figure 9. Magnitude scaling of simulated peak ground accelerations and velocities for three values of f_m. The regression curves of Joyner and Boore (1981, 1982) are shown for reference. (from Boore, 1983).

have been used: the distance to the closest point of the rupture surface and the distance to the approximate center of the rupture surface. Both of the distances rely on my estimate of the location of the rupture surface, which I have based on aftershock locations (e.g., Weichert et al, 1986). The predictions are in reasonable accord with the observations, especially in view of the fact that the predictions are intended to be predictions of mean motions; any one observation can be more than a factor of 2 from the mean (the standard deviation of individual observations is close to a factor of 1.8)

4 DISCUSSION

The prediction of motions for use in engineering design must rely both on empirical and theoretical methods. The methods complement on another, for the empirical analyses provide checks on the theory and help determine the necessary parameters. An example of this is in the predictions of ground motions in regions devoid of large earthquakes during this century, for which no instrumental records are available. A good example is eastern North America. Recordings of a few moderate earthquakes suggest that the source scaling follows the constant stress parameter relation in equation (9), and fitting the amplitudes of the data determines the value of $\Delta\sigma$. The theoretical model can then be used to predict values of ground motion for the large earthquakes of most interest to engineering design and seismic hazard evaluation (Atkinson, 1984; Boore and Atkinson, 1987). Of course, the predictions remain just that... predictions. There is no substitute for data, and continuing world-wide efforts should be maintained to record strong motions, particularly close to large earthquakes.

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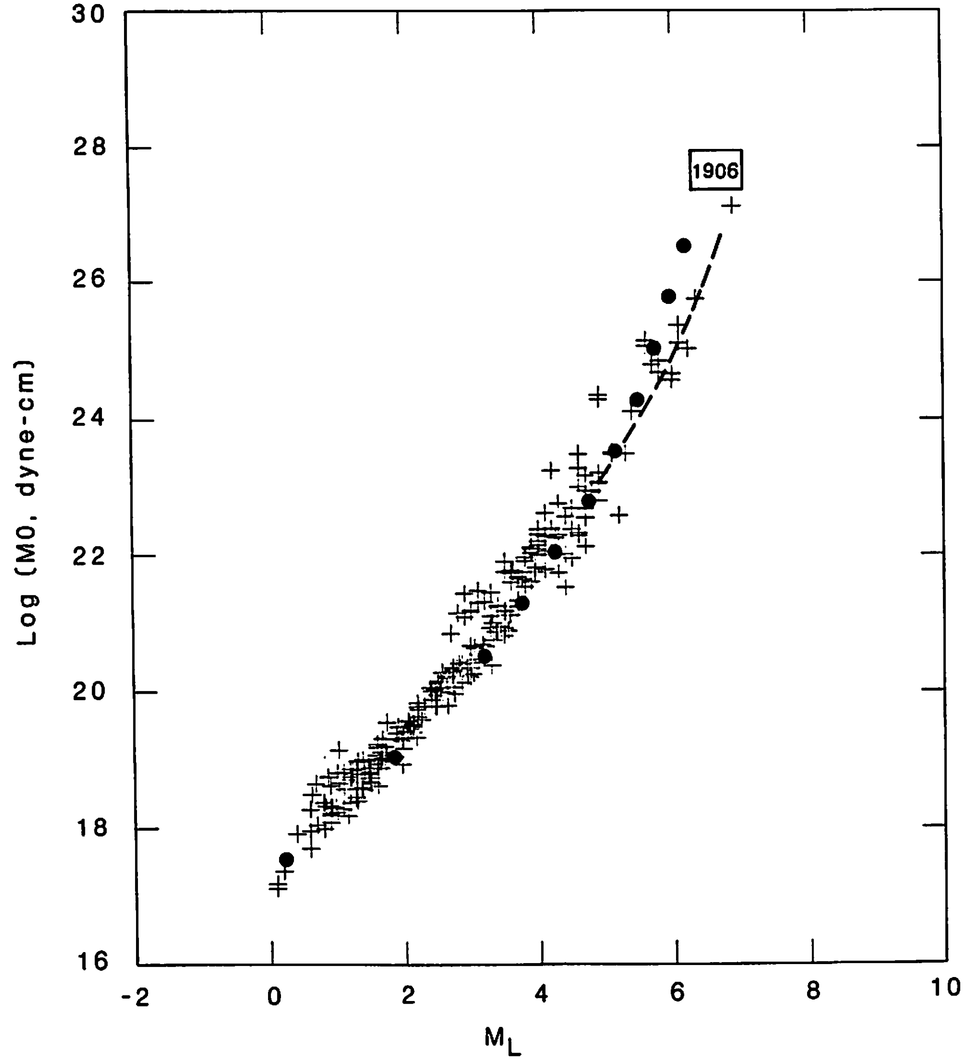

Figure 10. Moment-magnitude data for central California earthquakes (crosses, box for 1906 earthquake) and model calculations after Boore (1983) (solid circles; dashed line for Luco, 1982, correction for difference in near-source and far-source estimates of M_L); see Hanks and Boore (1984) for details.

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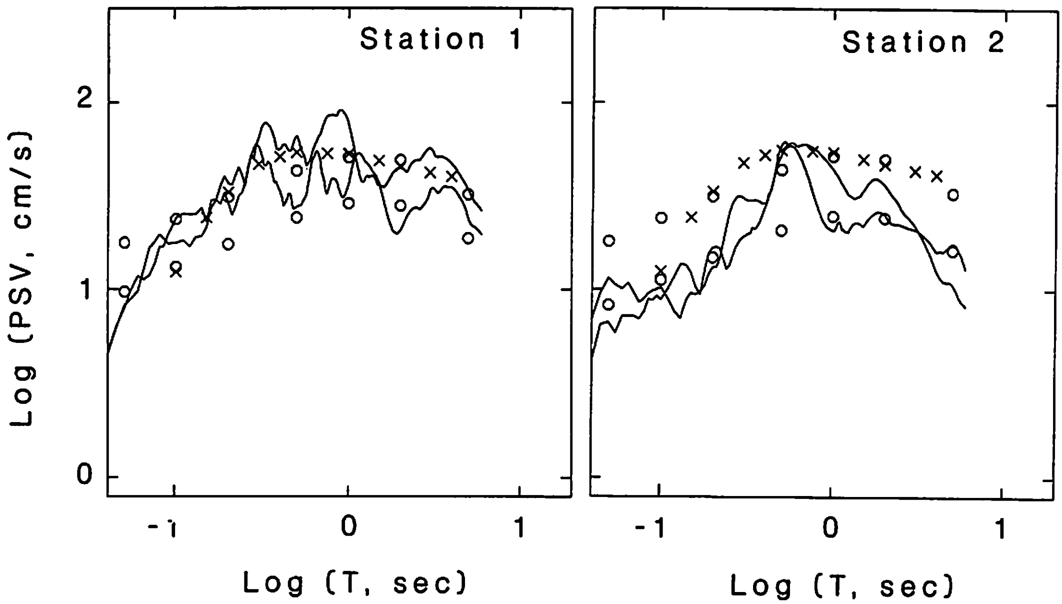

Figure 11. (*lines*) 5-percent damped response spectra calculated from first 7 seconds of horizontal components at sites 1 and 2 recorded during December 23, 1985, Nahanni, Northwest Territories earthquake; (*circles*) theoretical predictions from stochastic model, using equations in Boore and Atkinson (1987) and two estimates of distance to rupture surface; (*x's*) estimates from regression analysis of western North America recordings prior to 1981, from equations in Joyner and Boore (1982).

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