A Study of the Potential Use of an Energy Based Motion Parameter for Probabilistic Determination of Scenario Earthquakes

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Investigations Undertaken

The study examines the use of the elastic input-energy spectrum in probabilistic hazard analysis. Energy-based prediction models may have application for identification of scenario events, because they include the effects of both amplitude and duration of motion in terms of the work done on an oscillator. The study develops regression models for predicting the elastic input-energy spectrum using strong motion data from western U.S. earthquakes. The regression results are compared with models for *PSV* response spectra derived from the same data set, using identical processing procedures. Similar regression models are used for *PSV* spectra and equivalent velocity spectra derived from the elastic absolute input-energy spectra. The energy-based models exhibit stronger dependence upon earthquake magnitude, and less attenuation with distance, compared to the *PSV* models. The study assesses the effect these differences have on probabilistic seismic hazard estimates with regard to the definition of events (magnitude and distance) contributing significantly to hazard for specified return periods.

Results

Data Collection:

Strong motion recordings from 23 earthquakes in western North America have been used for analysis. The sources include the collection compiled on CD-ROM by the NOAA National Geophysical Data Center, and data available via the Internet from the California Division of Mines and Geology, the U.S. Geological Survey Strong Motion Instrumentation Program, and the Department of Civil Engineering, University of Southern California. In most cases, processed data (acceleration recordings) were available. In cases where only unprocessed data were available, the data were interpolated to equal sample intervals, bandpass filtered and corrected for instrument response. The distance metric, as well as the site classification scheme, are as defined by Boore et al., (1993). Figure 1 indicates the distribution of data, in terms of moment magnitude and distance.

Motion Parameters:

The parameters of interest are the elastic pseudo-relative velocity response, *PSV*, and the absolute input energy for an elastic oscillator, E_a. From Uang and Bertero (1990),

$$E_a = \int m (\ddot{x} + \ddot{x}_g) \dot{x}_g \, dt.$$

Here x is the relative displacement of the oscillator mass with respect to the ground, and x_g is the ground displacement. We define *Vea* as the maximum value of $(2Ea/m)^{1/2}$ occurring during the shaking episode.

Regression Analysis:

The following regression model (Boore et al., 1993) is very successful in modeling the *PSV* and *Vea* data sets:

$$Log\ Y = a + b(M-6) + c(M-6)^2 + d \log (R^2 + h^2)^{1/2} + e\, G_1 + f\, G_2 + e.$$

Here, *Y* is the response variable (geometric mean of the two horizontal components for *PSV* and *Vea) M* is moment magnitude, *R* is the horizontal distance to the nearest surface projection of the fault rupture, and G_1 and G_2 are indicator variables for site classifications B and C (e.g., G_1=1 for class B sites, 0 otherwise). The unknowns *a,b,c,d,h,e,f* and estimates of random error ε are determined using the two-step regression procedure of Joyner and Boore (1993, 1994).

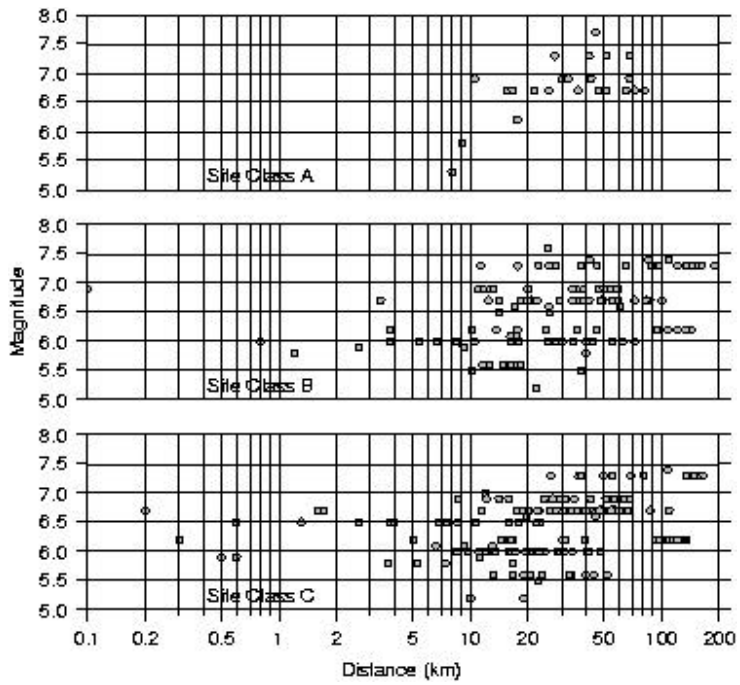

Figure 1: Distribution of data for regression analysis.

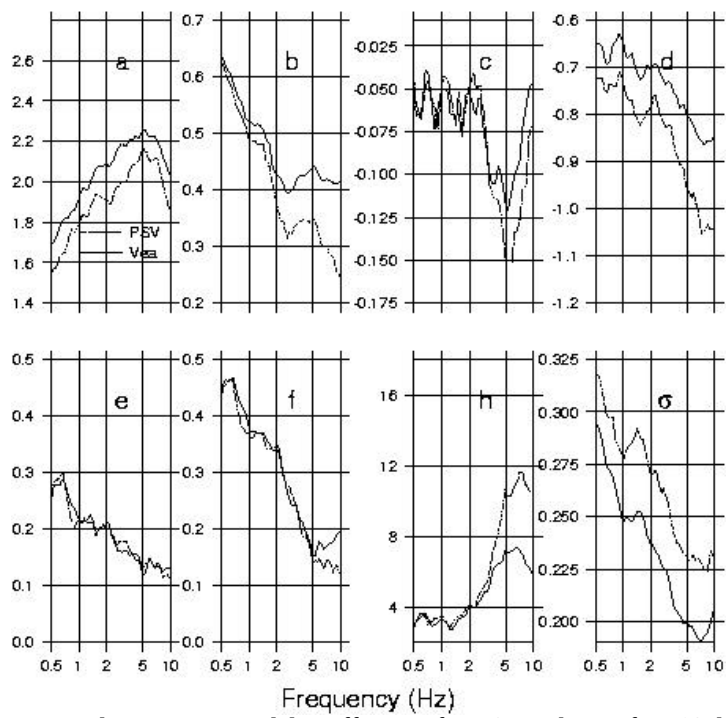

Figure 2: Estimated regression model coefficients for *PSV* and *Vea*, for 5% damping.

Figure 2 shows results of the regression analysis, for 5% damping. The linear magnitude coefficient *b* is larger (more positive) for *Vea* than for *PSV*, at the higher frequencies, as is the distance coefficient *d*. The site class coefficients *e* and *f* are very similar for *Vea* and *PSV*: the effect of site class is most important at the lower oscillator frequencies. The standard deviation of the regression, σ, generally decreases with increasing oscillator frequency. The results just described are much the same for 2% and 10% damped oscillators.

Figure 3 summarizes some important differences between *PSV* and *Vea* by plotting both spectra for several magnitudes at 5 and 50 km distance. At low frequencies (less that approximately 2 Hz) *Vea* and *PSV*

spectra exhibit similar magnitude scaling. At the higher frequencies the *PSV* spectra exhibit near saturation for *M*>6.5, whereas the *Vea* spectra continue to increase with increasing earthquake magnitude.

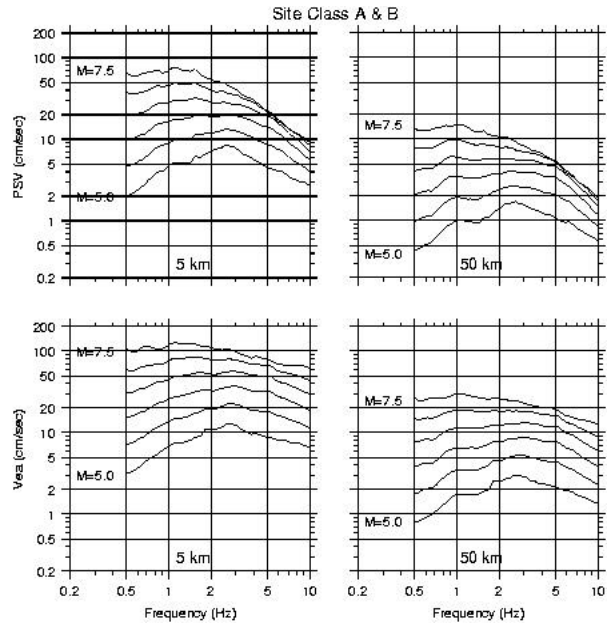

Figure 3: *PSV* (upper) and *Vea* (lower) spectra for site class A and B, combined. Spectra are for 5% damping, and a randomly oriented horizontal component, for 5 and 50 km distances.

Implications for Seismic Hazard Assessment:

In the following, we examine differences in the results of simple hazard calculations using the two different motion parameters.

Assume a hazard model wherein the random variables are statistically independent and limited to those appearing in the motion prediction model. For those assumptions, the seismic hazard from a single source can be represented (McGuire 1995) as

$$E(x) = \iiint n\, f_M(m)\, f_R(r)\, f_E(e)\, H[Y(m,r,e) - \log x]\, dm\, dr\, de,$$

where $E(x)$ is the expected rate of exceeding motion parameter value x. The rate of earthquakes in the source is n. The probability densities of the random variables M, r and e are $f_M(m)$, $f_R(r)$ and $f_E(e)$; H is the Heaviside function, and $Y(m,r,e)$ is the motion prediction model.

Let $U(m,r,e\,|x)$ represent the integrand, for a specific value of x. Let $(\underline{m}, \underline{r}, \underline{e})$ define the location of the maximum value of $U(m,r,e\,|x)$. This is the "β-point" (McGuire 1995) and is the modal value of the joint distribution of the random variables for the selected hazard value $E(x)$. A marginal distribution $U'(m,r|x)$ can be obtained by integration of $U(m,r,e\,|x)$ with respect to standardized variable e. Let the maximum value of $U'(m,r|x)$ occur at $(\underline{m}',\underline{r}')$. In general, $\underline{m}$ and $\underline{r}$ are not equivalent to $\underline{m}'$ and $\underline{r}'$.

Results using *Vea* and *PSV* for the general (elemental) model of a point source for earthquakes are shown below. The following recurrence model is used: Log N = 2.8 - 0.8 M. We assume a truncated exponential form for $f_M(m)$, with lower and upper magnitude bounds at M=5.0 and M=7.7, and n = 0.0626 events/year.

Figure 4 shows the marginal density functions $U'(m,r \mid x)$ for several frequencies, for two cases: point sources at 10 and 60 km, and return periods 2500 and 500 years, respectively. As expected from the similarity of magnitude scaling in the regression models, there is little difference in the density functions for the low frequency oscillators (e.g., 0.5 and 1.0 Hz). For 2.0 Hz, $\underline{m}'$ for V_{ea} is approximately 0.2 magnitude units larger than $\underline{m}'$ for *PSV*. This difference increases to approximately 0.6 units for the 6.7 Hz oscillator. Similar differences occur for $\underline{m}$. The modal magnitudes for V_{ea} (either $\underline{m}'$ or $\underline{m}$) are larger than those for *PSV*, and tend to decrease less rapidly (i.e., vary less) with increasing oscillator frequency. In this example, scenarios based on $\underline{m}$ would, in the case of V_{ea}, focus on earthquakes with magnitudes in the relatively narrow range 6.81 to 7.03 for the 60 km, 2500 year scenario, whereas if the calculations are done using *PSV*, a much wider range

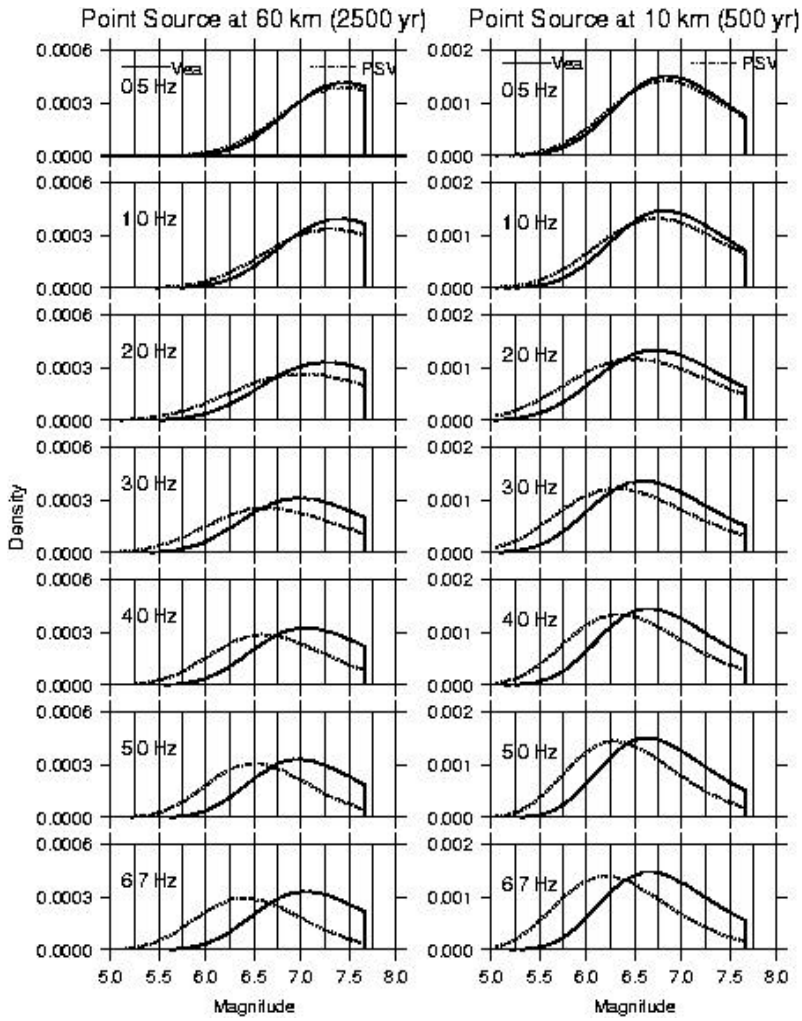

Figure 4. Marginal density functions U' for two examples involving point sources for earthquakes at 60 km (left) and 10 km (right).

of magnitudes (6.27 to 7.08) is indicated for the frequency band 0.5 to 6.67 Hz. Clearly, the choice of motion parameter has a substantial impact upon the perceived source of the seismic hazard. This has implications for the problem of design earthquake selection. In this simple example, use of V_{ea} puts more emphasis upon a scenario involving a larger magnitude shock, than would be the case if *PSV* where used in the hazard calculation.

References Cited:

Boore, D.M., W.B. Joyner and T.E. Fumal (1993), Estimation of response spectra and peak acceleration from western North American earthquakes: an interim report, U.S. Geological Survey Open-File Report 93-509.

Joyner, W.B. and D.M. Boore (1993), Methods for regression analysis of strong-motion data, Bull. Seism. Soc. Am., 83, 469-487.

Joyner, W.B. and D.M. Boore (1994), Errata, Bull. Seism. Soc. Am., 84, 955-956.

McGuire, R. K., (1995), Probabilistic seismic hazard analysis and design earthquakes: Closing the loop, Bull. Seism. Soc. Am., 85, 1275-1284.

Uang, C.-M. and V.V. Bertero (1990), Evaluation of seismic energy in structures, Earthquake Eng. and Struct. Dyn., 19, 77-90.

Related Publications and Reports

Chapman, M.C., K. Zhang and J.A. Snoke (1997), The potential use of an energy-based motion parameter for probabilistic seismic hazard analysis, (abst), Seismological Res. Lett., 69, no. 1, 77.
Chapman, M. C., (1998), An energy-based motion parameter for probabilistic determination of scenario earthquakes, (abst), Seismological Res. Lett., 69, no. 2, 173.

Non-technical Summary

The amplitude and duration of ground motion are important considerations for engineering analysis. However, the duration of shaking is not modeled routinely in probabilistic seismic hazard assessments. Because input energy for an elastic oscillator depends upon the duration as well as the amplitude of motion, energy-based prediction models may have application in the identification of scenario events for dynamic analysis. This study develops models which predict the elastic input energy as a function of magnitude and distance, and assesses the effect these models have on probabilistic seismic hazard estimates, in regard to the definition of events (magnitude and distance) contributing significantly to hazard for specified return periods.

Availability of Data

The results of all regression analyses (regression coefficients) for 40 discrete oscillator frequencies between 0.5 and 10 Hz, for 2%, 5% and 10% damping, are available in electronic form by contacting the first author.