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DEVELOPMENT OF SEMI-EMPIRICAL ATTENUATION RELATIONSHIPS FOR THE CEUS

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Abstract

Attenuation relations are used to estimate strong ground motion for most engineering applications. Where strong-motion recordings are abundant, these relations are developed empirically. Where recordings are limited, they are developed theoretically or from seismic intensity. The theoretical method has become the preferred method for estimating strong ground motion in these latter regions when there is good seismological data. However, there is a large degree of uncertainty in calculating absolute values of ground motion using the theoretical method. As an alternative, I propose a hybrid empirical method that uses the ratio of theoretical ground-motion estimates to adjust empirical attenuation relations from one region for use in another. By using empirical models the method taps into the vast amount of observational data and expertise that has been used to develop empirical attenuation relations in high-seismicity regions such as the western United States. I present a formal mathematical framework for the method and apply it to the development of a semi-empirical attenuation relation for peak ground acceleration and pseudoacceleration response spectra in the eastern United States using empirical attenuation relations from the western United States. The application accounts for differences in stress drop, source properties, crustal attenuation, regional crustal structure, and generic-rock site profiles between the two regions. The resulting attenuation relation is considered most appropriate for estimating ground motion on ENA hard rock for earthquakes with $M_W \geq 5.0$ and $r_{rup} \leq 70$ km; however, it has been theoretically constrained at larger distances so that it can be used in more general engineering applications including probabilistic seismic hazard analysis.

Introduction

Attenuation relations, also known as ground motion relations, are traditionally used to estimate strong ground motion for site-specific and regional seismic hazard analyses. The attenuation relation is a simple mathematical model that relates a ground-motion parameter to earthquake magnitude, source-to-site distance, and other seismological parameters, such as style of faulting and local site conditions (Campbell, 2002). The most commonly predicted ground-motion parameters are peak ground acceleration (PGA), peak ground velocity (PGV), and pseudoabsolute response spectral acceleration (PSA). In areas such as western North America (WNA) and Japan where strong-motion recordings are abundant, these attenuation relations are developed empirically. However, in many regions of the world, including eastern North America (ENA), there are not enough recordings to develop reliable empirical attenuation relations. In these latter regions it has been traditional to predict quantitative ground-motion parameters from qualitative measures of ground shaking, such as Modified Mercalli Intensity (MMI) or Medvedev-Spooner-Karnik (MSK) intensity, using what I will refer to as the intensity method. The intensity method is applied by estimating seismic intensity from an attenuation relation then estimating the ground-motion parameter of interest using a relationship between ground-motion and intensity (e.g., Trifunac and Lee, 1989, 1992; Wald *et al.*, 1999).

When the number of strong-motion recordings are limited but good seismological data are available, it is possible to derive simple seismological models that can be used to describe how ground motion scales with earthquake source size and distance from the source. This concept lead McGuire and Hanks (1980) and Hanks and McGuire (1981) to propose a new stochastic method, later generalized by Boore (1983), that could be used to estimate ground motion from simple seismological models. Because of its success and simplicity, the stochastic method is now widely used to predict ground motion in many regions of the world where the number of strong-motion recordings is limited (see Boore, 2002 for a comprehensive list of these applications and a summary of the stochastic method). One such region is ENA (e.g., Atkinson and Boore, 1995, 1997; Frankel *et al.*, 1996; Toro *et al.*, 1997). With the improvement of computers it has become possible to use more sophisticated numerical methods for simulating strong ground motion based on empirical or theoretical source functions and two-and three-dimensional wave propagation theory (e.g., Bolt, 1987; Somerville, 1993; Anderson, 2002). However, I am aware of only one attempt to develop a generalized attenuation relation using such methods (Somerville *et al.*, 2001).

The stochastic method is admittedly powerful but attenuation relations that have been developed using this method lack many of the important ground-motion characteristics that are inherent in empirical attenuation relations. One of the more important characteristics is near-source effects. Furthermore, attenuation relations developed by different investigators using the stochastic method lack an unbiased representation of epistemic variability (uncertainty in scientific knowledge) because of their reliance on a single method. A complete estimate of epistemic variability is an important aspect of the deterministic and probabilistic estimation of design ground motion, especially for critical facilities, and should be included in the estimation of ground motion (Budnitz *et al.*, 1997). The reliance of most ground motion models on a single theoretical method for estimating ground motion in ENA led me to propose an alternative method that does not depend so strongly on theoretical models. This hybrid empirical method uses theoretically based adjustment factors to estimate ground motions in a region where the number of strong-motion recordings is limited, which I call the target region, from ground-motion estimates in a region where good empirical attenuation relations exist, which I call the host region. These adjustment factors are developed from the ratio of the theoretical ground-motion estimates in each region, so they rely only indirectly on the particular method used to derive the estimates. The adjustment factors account for the *differences* in the source, path, and site characteristics between the host and target regions.

In this paper I develop the mathematical basis for the hybrid empirical method and use it to develop PGA and PSA attenuation relations for ENA using empirical attenuation relations developed from WNA strong-motion recordings. These new semi-empirical attenuation relations are shown to be similar to those developed using the stochastic method, but because of their reliance on well-constrained empirical attenuation relations, they add a degree of reliability, especially in the near-source region, that cannot be obtained from the stochastic method alone.

Background

Campbell (1981) introduced a simple procedure that he used to develop a PGA attenuation relation for ENA as an alternative to the intensity method that was the standard at the time (see Campbell, 1986 for a review of the intensity method.) He used theoretical adjustment factors based on simple seismological models to account for differences in anelastic attenuation and regional magnitude measures between WNA and ENA. This was the first application of what would later be called the hybrid empirical method. A year later Campbell (1982) used the same method to develop a PGA attenuation relation for Utah. Campbell (1987, 2000a) applied a more sophisticated version of the hybrid empirical method to develop PGA and PGV attenuation relations for northcentral Utah that took into account theoretical differences in the effects of the stress regime, faulting mechanism, anelastic attenuation, and local site conditions between California, the host region, and Utah. He used these attenuation relations to estimate a near-source response spectrum and its epistemic variability for a postulated large earthquake on the Wasatch fault in the vicinity of Salt Lake City using the spectral shapes recommended by Newmark and Hall (1982).

The refinement of the hybrid empirical method began in the early 1990's when, at the request of the U.S. Nuclear Regulatory Commission (USNRC), it was applied to the development of alternative PSA attenuation relations for use in the probabilistic risk assessments for two nuclear facilities in WNA then under review by the USNRC. The USNRC staff wanted to use these hybrid empirical relations to supplement the purely theoretical models that the utilities were using to estimate the expected ground motion at these facilities. Based on its success in these studies, the method was selected as one of several used in the Senior Seismic Hazard Analysis Committee (SSHAC) Project (Budnitz *et al.*, 1997), the Yucca Mountain High-Level Radioactive Waste Repository Project (Abrahamson and Becker, 1997; Stepp *et al*, 2001), and the Trial Implementation Project (Savy *et al.*, 1999) to develop alternative ground-motion models for PGA, PGV and PSA to use as inputs to probabilistic seismic hazard analysis (PSHA). For these applications the hybrid empirical method took into account differences in stress drop, magnitude measures, faulting mechanism, anelastic attenuation, crustal velocity structure, and local site conditions between WNA, the host region, and ENA and southwestern Nevada, the two target regions.

The first formal mathematical framework of the model was published as part of the Yucca Mtn. Project (Abrahamson and Becker, 1997) and later in a 1999 Nuclear Energy Agency workshop (Campbell, 2001), which included an example application to ENA. Atkinson and Boore (1998) evaluated the hybrid empirical method and independently concluded that ground-motion relations for California could be reliably modified to predict strong ground motion in ENA from future large earthquakes. Atkinson (2001) and Abrahamson and Silva (2001) later applied the method to produce ground-motion estimates for ENA.

Mathematical Framework

The application of the hybrid empirical method requires the following steps: (1) selection of the host and target regions, (2) calculation of empirical ground-motion estimates for the host region, (3) calculation of theoretical adjustment factors between the host and target regions, (4) calculation of hybrid empirical ground-motion estimates for the target region, and (5) development of an attenuation relation for the target region.

The host region should have one or more empirical attenuation relations that can be used to estimate the ground-motion parameters of interest. Both regions should have one or more seismological models that can be used to characterize their regional source spectra, regional crustal velocity structure, wave propagation characteristics, and local site characteristics. Empirical ground-motion estimates should be derived for a suite of ground-motion parameters, magnitudes, distances, and other seismological parameters of interest. The theoretical ground-motion estimates needed to derive the adjustment factors can be computed using any appropriate ground-motion simulation method. However, the relatively simple stochastic method should be adequate for most applications.

One of the strengths of the hybrid empirical method is its ability to easily provide estimates of both aleatory and epistemic variability in the estimated ground motions. Aleatory variability is the inherent randomness in the estimated ground-motion parameter. This randomness is the result of unknown or unmodeled characteristics of the underlying physical process. Epistemic variability is the lack of scientific knowledge in, or the difference in opinion regarding, the equations, algorithms, and parameters that are used to model this physical process. In the mathematical formulation given below, I use a lognormal distribution to describe the aleatory and epistemic variability in the ground-motion predictions and a Gaussian distribution to describe the epistemic variability in the aleatory variability. Following the convention of Benjamin and Cornell (1970), I refer to the mean of the natural logarithm of the ground-motion parameter as its median value. In all cases the standard deviations are given in terms of the natural logarithm of ground motion.

The median hybrid empirical ground-motion estimate for the target region can be calculated from the equation

$$\hat{y}_t(\theta) = \exp\left(\sum_{i=1}^{n} w_i(\theta) \ln y_{t,i}(\theta)\right) \tag{1}$$

where

$$y_{t,i}(\theta) = \hat{F}(\theta) y_{h,i}(\theta) \tag{2}$$

In the above equations the subscripts t and h refer to the target and host regions, respectively; the subscript i refers to the ith empirical attenuation relation; n is the total number of empirical attenuation relations; θ is an array of seismological parameters used to derive the individual ground-motion estimates; $\hat{F}(\theta)$ is the median value of the theoretical adjustment factor; $w_i(\theta)$ are weights whose sum must equal unity; $y_{t,i}(\theta)$ are hybrid empirical ground-motion estimates for the target region; and $y_{h,i}(\theta)$ are empirical ground-motion estimates for the host region (e.g., from an attenuation relation). As many attenuation relations as possible should be used to estimate $y_{h,i}(\theta)$ in order to obtain a reasonable estimate of epistemic variability. The array of seismological parameters that are included in the ground-motion prediction should take into account the distribution of magnitude, distance, faulting mechanism, local site characteristics, and any other seismological parameters that will eventually be used in the development of the ground-motion estimates for the target region. Usually the weights are assigned to an individual attenuation relation without regard to the values of θ. However, by making the weights a function of θ, I have allowed for the more general application where these weights can vary as a function of the value of these seismological parameters.

The median value of the adjustment factor can be calculated from the equation

$$\hat{F}(\theta) = \exp\left(\sum_{i=1}^{m}\sum_{j=1}^{n_i} \ln\left[\frac{w(\phi_{t,i,j}) Y_t(\theta, \phi_{t,i,j})}{Y_h(\theta, \phi_h)}\right]\right) \tag{3}$$

where $\phi_{t,i,j}$ is the jth value of the ith seismological parameter used to derive the theoretical estimates of ground motion for the target region, excluding those included in the parameter set θ, $w(\phi_{t,i,j})$ is the weight assigned to the parameter value $\phi_{t,i,j}$; ϕ_h is the array of seismological parameters used to derive the theoretical estimates of ground motion for the host region; m is the total number of seismological parameters in the target region; n_i is the total number values used to define the variability in the ith seismological parameter in the target region; $Y_t(\theta, \phi_{t,i,j})$ is the value of theoretical ground motion in the target region associated with the parameter set θ and the parameter value $\phi_{t,i,j}$; $Y_h(\theta, \phi_h)$ is the value of theoretical ground motion in the host region associated with the parameter sets θ and ϕ_h; and

$$\sum_{j=1}^{n_i} w(\phi_{t,i,j}) = 1 \tag{4}$$

In the above equations the index j accounts for epistemic variability in the median value of ground motion due to variability in ϕ_t. Stress drop and crustal attenuation are typical examples of parameters that would be included in the parameter sets ϕ_t and ϕ_h. The parameter set ϕ_h is not considered to have any significant epistemic variability in the mathematical formulation given above, since it will usually be calibrated from strong-motion recordings. The theoretical ground-motion estimates for a given seismological parameter $\phi_{t,i}$ are calculated differently depending on its assumed distribution and how this distribution is sampled. Usually $\phi_{t,i}$ will be defined by a discrete set of values or models (defined by the index j in the above equations) along with their corresponding weights as is done in a PSHA logic tree. This is true even for continuous variables as long as they can be defined by a finite set of values. If the number of alternative values becomes very large, then $\phi_{t,i}$ can be sampled by Monte Carlo simulation, in which case its distribution (usually assumed to be lognormal), mean value, and standard deviation will need to be defined.

The mean aleatory variability in $\ln \breve{y}_t(\theta)$ can be calculated from the equation

$$\bar{\sigma}_t(\theta) = \sum_{i=1}^{n} w_{t,i}(\theta)\,\sigma_{t,i}(\theta) \tag{5}$$

where $\sigma_{t,i}(\theta)$ is the aleatory standard deviation of $\ln y_{t,i}(\theta)$ given by

$$\sigma_{t,i}(\theta) = \sqrt{\sigma_{h,i}^2(\theta) + \Delta\sigma_{h,i}^2}\,. \tag{6}$$

In this latter equation $\sigma_{h,i}(\theta)$ is the aleatory standard deviation of $\ln y_{h,i}(\theta)$, $\Delta\sigma_{h,i}$ is the additional aleatory variability in $\ln y_{h,i}(\theta)$ that results from excluding one or more empirically modeled seismological parameters in its estimation. A modeled seismological parameter that would contribute to additional aleatory variability is one that is included in the attenuation relation, for example faulting mechanism, but which is not used in deriving the empirical estimates of ground motion. This distinction will become clearer in the example application of the method later in the paper.

The epistemic variability in $\ln \breve{y}_t(\theta)$ can be calculated from the equation

$$\tau_{t,y}(\theta) = \sqrt{\tau_F^2(\theta) + \sum_{i=1}^{n} w_{t,i}(\theta)\left(\ln y_{t,i}(\theta) - \ln \breve{y}_t(\theta)\right)^2} \tag{7}$$

where $\tau_F(\theta)$ is the epistemic standard deviation of $\ln \breve{F}(\theta)$. This later standard deviation should account for any uncertainty in $\breve{F}(\theta)$ that is not accounted for in the aleatory standard deviation defined in Equation (5). It can be calculated from the equation

$$\tau_F(\theta) = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{n_i} w(\phi_{t,i,j})\left[\ln\left(\frac{Y_t(\theta,\phi_{t,i,j})}{Y_h(\theta,\phi_h)}\right) - \ln \breve{F}(\theta)\right]^2} \tag{8}$$

where all of the variables are defined in Equation (3). The total variability in an individual estimate of $\ln \breve{y}_t(\theta)$ can be estimated by taking the square root of the sum of the squares of its epistemic and aleatory standard deviations, or

$$\sigma_{t,tot} = \sqrt{\bar{\sigma}_t^2 + \tau_{t,y}^2} \tag{9}$$

Although rarely used except for analyses involving high-risk facilities, the epistemic standard deviation of $\bar{\sigma}_t(\theta)$ can be calculated from the equation

$$\tau_{t,\sigma}(\theta) = \sqrt{\sum_{i=1}^{n} w_{t,i}(\theta)\left(\sigma_{t,i}^2(\theta) - \bar{\sigma}_t(\theta)\right)^2} \tag{10}$$

Example Application to Eastern North America

I have used the hybrid empirical method presented in the previous section to develop PGA and PSA attenuation relations for ENA hard rock using the general approach adopted for the Trial Implementation Project (Savy *et al.*, 1999). For the target region I selected the region of ENA that Toro *et al.* (1997) defined as the Midcontinent. It includes the region of North America bounded on the west by the Rocky Mountains and on the south by the Gulf Coast. ENA is a good candidate for the method because it has been well studied seismologically. I selected WNA as the host region because of the large number of reliable empirical attenuation relations that are available for this region and because it too has been well studied seismologically. As defined for this application, WNA represents the shallow crustal region of North America located west of the Sierra Nevada and Cascade Mountains. Most of the strong-motion recordings in this region come from California, although many of the empirical attenuation relations developed for this region include worldwide recordings from similar tectonic environments.

I selected four empirical attenuation relations to estimate empirical ground motions in WNA, which I designate $y_{wna,i}(\theta)$, and their aleatory standard deviations, which I designate $\sigma_{wna,i}(\theta)$. Note that the generic subscript *h* for the host region has been replaced by the subscript *wna* to designate WNA as the host region. Similarly, the subscript *t* has been replaced by the subscript *ena* to designate ENA as the target region. The four attenuation relations are from Abrahamson and Silva (1997), Campbell (1997), Sadigh *et al.* (1997), and Campbell and Bozorgnia (2000). All of these investigators are recognized experts in empirical ground-motion modeling and collectively represent a wide range of differing opinions regarding the mathematical forms, databases, and regression techniques that are used to develop empirical attenuation relations. The Boore *et al.* (1997) attenuation relation was not used in this study because it was found to give unrealistic hybrid empirical ground-motion estimates due to its unrealistic functional form. Had the Boore *et al.* (1997) attenuation relation been used, it would have been necessary to compute empirical ground motions for a large number of different fault geometries in order to relate the distance measure used in that relation to those used in the other relations.

The empirical ground-motion parameters were defined as the geometric mean of the two horizontal components (referred to as the average horizontal component) of PGA and 5%-damped PSA at natural periods ranging from 0.02 to 4.0 sec. PGA was assumed to represent the value of PSA at the 0.01-sec period. For those attenuation relations that did not provide spectral values at the shorter periods, I estimated these values using interpolation factors derived from those relations that did. Estimates for such short periods are necessary to accommodate the expected peak in the ENA hard-rock acceleration response spectra. Moment magnitude M_W and the fault-distance measures r_{rup} and r_{seis} were the only seismological parameters that were included as variables in deriving the empirical estimates. These parameters made up the seismological parameter set θ. All empirical estimates were defined in terms of r_{rup} so that this parameter could be used to define distance in the development of the hybrid empirical ground-motion estimates. I considered the ground-motion variability from all other seismological parameters to be aleatory, since in most applications these parameters will not be known or their affect on ground motion will not necessarily the same in ENA as in WNA.

All of the empirical attenuation relations use M_W to define magnitude so no adjustment for differences in magnitude measures was necessary. Abrahamson and Silva (1997) and Sadigh *et al.* (1997) use r_{rup} to define distance so no adjustment in distance measures was necessary for these two relations. The closest distance to seismogenic fault rupture r_{seis} used by Campbell (1997) and Campbell and Bozorgnia (2000) was easily related to r_{rup} by setting it to 3 km for $r_{rup} < 3$ km (Campbell, 2000b). Abrahamson and Shedlock (1997) discuss the differences between these two distance measures. Empirical ground-motion estimates were made for moment magnitudes ranging from 5.0 to 8.2 in increments of 0.2 and for rupture distances equal to 1, 2, 3, 5, 7, 10, 20, 30, 40, 50, 70, 100, 130, 200, 300, 500, 700 and 1000 km.

All of the attenuation relations were evaluated for local site conditions defined as WNA generic rock by Boore and Joyner (1997). I assumed that the rock categories defined by Abrahamson and Silva (1997) and Sadigh *et al.* (1997) represented generic rock so no correction was necessary for these two relations. I evaluated the Campbell (1997) attenuation relation for generic rock by setting $S_{SR} = 1$, $S_{HR} = 0$, and $D = 1$ km as recommended by Campbell (2000b). I evaluated the Campbell and Bozorgnia (2000) relation for generic rock by setting $S_{SR} = 0.5$, $S_{HR} = 0.5$, and $S_{PS} = 0$ as suggested by these authors. All of the attenuation relations were evaluated for a random faulting mechanism. This was accomplished by setting $F_{RV} = 0.25$ and $F_{TH} = 0.25$ in the Campbell and Bozorgnia (2000) relation as suggested by these authors and by setting $F = 0.5$ in all of the other relations.

The aleatory standard deviation was increased for those attenuation relations in which some of the seismological parameters were treated as random variables. Adjustments were made for the sediment depth term D in the Campbell (1997) attenuation relation and for the faulting mechanism terms in all of the attenuation relations. No adjustment was made for the hanging-wall term in the Abrahamson and Silva (1997) attenuation relation, since this term affects such a small number of recordings that it does not have a measurable impact on the aleatory variability. This hanging-wall factor was set to zero (no hanging-wall effect) for this study. The additional aleatory variability terms are given in Table 1.

Based on its success in modeling a wide range of ground motions (Boore, 2002), I selected the stochastic method together with a single corner frequency, ω-square source spectrum to estimate the median theoretical ground-motion parameters $Y_{wna}(\theta,\phi_{wna})$ and $Y_{ena}(\theta,\phi_{ena})$. I used the computer program SMSIM developed by Boore (1996) to perform the calculations. Atkinson and Boore (1995, 1997), Frankel *et al.* (1996), and Toro *et al.* (1997) used this same method to develop theoretical attenuation relations for ENA. However, Atkinson and Boore used a double corner frequency instead of a single corner frequency source spectrum in their calculations. I developed stochastic ground motions for the same values of M_W and r_{rup} that I used to develop the empirical ground-motion estimates.

The stochastic method is based on the principals of band-limited white noise and random vibration theory. The salient features of this method are summarized below for completeness. A more thorough description can be found in Boore (2002). Using notation proposed by Boore (2002), the total Fourier amplitude spectrum of displacement $Y(M_0,R,f)$ can be broken down into the contributions from the earthquake source *E*, the propagation path *P*, the site *G*, and the instrument or type of motion *I*, giving

$$Y(M_0,R,f)=E(M_0,f)P(R,f)G(f)I(f) \tag{11}$$

where *f* is frequency, *R* is distance, and M_0 is seismic moment. Seismic moment is related to moment magnitude by the relationship (Hanks and Kanamori, 1979)

$$M_W=\frac{2}{3}\log M_0-10.7 \tag{12}$$

where M_0 is seismic moment in dyne-cm.

The source term is given by the relationship

$$E(M_0,f)=C\,M_0\,S(M_0,f) \tag{13}$$

where $S(M_0,f)$ is the source displacement spectrum and the constant *C* is given by the expression

$$C=\langle R_{\Theta\Phi}\rangle VF/(4\pi\rho_s\beta_s^3 R_0) \tag{14}$$

where $\langle R_{\Theta\Phi}\rangle=0.55$ is the radiation pattern for shear waves averaged over the focal sphere, $V=1/\sqrt{2}$ is the partition of the total shear-wave energy into its two horizontal components, $F=2$ is the effect of the free surface, ρ_s and β_s are the density and shear-wave velocity in the vicinity of the earthquake source, and $R_0=1$ km is a reference distance. The source displacement spectrum for a single corner frequency, ω-square source model is given by the equation (Brune, 1970, 1971)

$$S(M_0, f) = \frac{1}{1+(f/f_0)^2} \tag{15}$$

where the corner frequency f_0 in Hz is given by the expression

$$f_0 = 4.9\times10^6 \beta_s (\Delta\sigma/M_0)^{1/3} \tag{16}$$

where $\Delta\sigma$ is stress drop in bars, β_s is shear-wave velocity in km/sec, and M_0 is seismic moment in dyne-cm.

For this study the path term was calculated by multiplying a point-source geometric attenuation term $Z(R)$ by a crustal damping term, giving

$$P(R, f) = Z(R)\exp\left(\frac{-\pi f R}{Q(f)c_Q}\right) \tag{17}$$

where the quality factor $Q(f)$ is anelastic attenuation and scattering within the crust and $c_Q = \beta_s$ is the seismic velocity used in the determination of $Q(f)$. The geometric attenuation term is modeled as a piecewise continuous function of distance as demonstrated in Table 2.

The site term is conveniently separated into its amplification and diminution components, giving

$$G(f) = A(f)D(f) \tag{18}$$

where, for this study, the amplification term was calculated by the quarter-wavelength method (Joyner *et al.*, 1981; Boore and Joyner, 1991) as defined by the equation

$$A(f) = \sqrt{\frac{\rho_s\beta_s}{\bar{\rho}(f)\bar{\beta}(f)}} \tag{19}$$

where

$$\bar{\rho}(f) = \frac{1}{z(f)}\int_0^{z(f)} \rho(z)dz, \tag{20}$$

$$\bar{\beta}(f) = z(f)\left[\int_0^{z(f)} (1/\beta(z))\,dz\right]^{-1}, \tag{21}$$

and

$$z(f) = \frac{\bar{\beta}(f)}{4f}. \tag{22}$$

In the above equations $\bar{\rho}(f)$ and $\bar{\beta}(f)$ are the average density and shear-wave velocity to a depth of a quarter-wavelength for a wave of frequency f. Because of the interdependence of $\bar{\beta}(f)$ and $z(f)$, these two parameters must be calculated by iteration.

For this study the attenuation term was calculated using the Kappa filter (Anderson and Hough, 1984)

$$D(f) = \exp(-\pi\kappa_0 f) \tag{23}$$

where κ_0 (kappa) is a parameter that represents the attenuation of ground motion in the upper few kilometers of the site profile.

The ground motion and instrument response term depends on the desired ground-motion parameter. The calculation of PGA requires the estimation of the Fourier amplitude spectrum of ground acceleration. The calculation of PSA requires the estimation of the Fourier amplitude spectrum of pseudoacceleration response. The response term for ground acceleration is given by the equation

$$I(f) = (2\pi f)^2 \tag{24}$$

whereas the equivalent response term for pseudoacceleration is given by the equation

$$I(f) = \frac{(2\pi f f_r)^2}{[(f^2 - f_r^2)^2 - (2 f f_r \varsigma)^2]^{1/2}} \tag{25}$$

where f_r and ζ are the undamped natural frequency and the critical damping ratio of a single-degree-of-freedom system.

Given the appropriate form for $I(f)$, the expected value of PGA and 5%-damped PSA was calculated from $Y(M_0, R, f)$ using random vibration theory. According to Cartwright and Longuet-Higgins (1956), the peak of a random function can be calculated from its root-mean-square (RMS) value by the approximate expression (valid for large N_z)

$$\frac{y_{max}}{y_{rms}} = \sqrt{2\ln N_z} + \left(\frac{0.5772}{\sqrt{2\ln N_z}}\right) \tag{26}$$

where N_z is the number of zero crossings in the time domain. A more accurate form of this equation used in SMSIM is given by the integral

$$\frac{y_{max}}{y_{rms}} = 2\int_0^\infty \left(1 - [1 - \xi\exp(-z^2)]N_e\right) dz \tag{27}$$

where $\xi = N_z/N_e$ and N_e is the number of extrema in the time domain. From Parseval's Theorem, y_{rms} can be calculated from the integral

$$y_{rms} = \left[\frac{1}{T_{rms}} \int_0^{\infty} |Y(M_0, R, f)|^2 \, df \right]^{1/2} \tag{28}$$

where T_{rms} is the equivalent RMS duration. One of the critical elements of the above relation is the appropriate selection of T_{rms}. This is particularly critical for long periods and small-magnitude earthquakes where the natural period can be longer than the duration of the time series. Methods for estimating T_{rms} that take into account the period of the oscillator are discussed by Boore and Joyner (1984), Liu and Pezeshk (1999), and Boore (2002). According to D. Boore (personal communication, 2001), SMSIM uses the method proposed by Boore and Joyner (1984)

$$T_{rms} = T_{gm} + T_0 \left(\frac{\gamma^3}{\gamma^3 + \frac{1}{3}} \right) \tag{29}$$

where $\gamma = T_{gm}/T_0$, the ground motion duration is given by $T_{gm} = T_s + T_p$ where T_s is the duration due to the source and T_p is the duration due to the path (Table 2), and the oscillator duration is given by $T_0 = 1/(2\pi f_r \zeta)$.

The key to the calculation of theoretical ground motion is the selection of an appropriate set of seismological parameters. For this study representative seismological parameters for WNA (principally California), with the exception of $\Delta\sigma$ and κ_0, were adopted from the seismological model of Atkinson and Silva (2000). This model uses the geometric and path attenuation terms of Raoof *et al.* (1999) and the WNA generic rock crustal velocity and amplification model of Boore and Joyner (1997). I chose to use $\Delta\sigma = 100$ bars and $\kappa_0 = 0.04$ sec to estimate stress drop and kappa based on my independent interpretation of the comparison of stochastically generated response spectra with spectra predicted by several empirical attenuation relations given in Boore and Joyner (1997). Boore and Joyner concluded from this comparison that the values $\Delta\sigma = 70$ bars and $\kappa_0 = 0.035$ sec were reasonably consistent with the empirical spectra predicted from the Boore *et al.* (1997) attenuation relation. Atkinson and Silva (2000) used the values $\Delta\sigma = 80$ bars and $\kappa_0 = 0.03$ sec based on their comparison of the empirical spectra predicted from the Abrahamson and Silva (1997) attenuation relation with the spectra predicted from a finite-fault stochastic simulation model. Representative median values of the seismological parameters for ENA were taken from Atkinson and Boore (1998), except for β_s and $\Delta\sigma$, which were taken from Frankel *et al.* (1996). This model uses the ENA hard rock crustal velocity and amplification model of Boore and Joyner (1997). The selected WNA and ENA seismological parameters are summarized in Tables 2 to 4.

I assumed that the epistemic variability in the theoretical ground-motion estimates for WNA were negligible since the seismological parameters derived for this region are well constrained by strong-motion recordings. This assumption was confirmed at least partially by comparing several empirical response spectra evaluated for $M_W = 5.0$ and $r_{rup} = 10$ km with the theoretical WNA ground-motion estimates calculated from the seismological parameters given in Tables 2 to 4. This comparison is given in Figure 1. In contrast, many of the seismological parameters in ENA were estimated theoretically or from ground-motion recordings for small magnitudes and large distances leading to significant epistemic variability in the calculated ground motion. Following the approach used in the Trial Implementation Project (Savy *et al.*, 1999), I included epistemic variability in the median values of $\Delta\sigma$, $Q(f)$ and κ_0 using alternative values recommended in EPRI (1993) and Toro *et al.* (1997), although I used slightly different weights for these alternatives. I considered the uncertainty in all of the other seismological parameters to be aleatory and, therefore, included as part of the WNA aleatory standard deviation. This is a departure from EPRI (1993) and Toro *et al.* (1997) who assumed that only the variability in the median value of stress drop was epistemic. This brings up the difficulty in trying to separate uncertainty into its aleatory and epistemic components. I have based my definition of aleatory variability on that used for the Yucca Mountain and Trial Implementation Projects. This definition could change in the future as research in this area progresses. Example values of the ENA/WNA adjustment factors for $M_W = 6.5$ and $R = 10$ km showing their sensitivity to $\Delta\sigma$ and κ_0 are given in Tables 5 and 6.

I calculated the median hybrid empirical ground-motion estimates for ENA by multiplying the median WNA empirical ground-motion estimates by the median ENA/WNA theoretical adjustment factors for each of the magnitudes, distances, and ground-motion parameters defined previously. I used as the hybrid empirical estimate of the aleatory standard deviation of ground motion the mean adjusted aleatory standard deviation from the empirical ground-motion estimates, consistent with the methodology used in the Yucca Mountain and Trial Implementation Projects. I assumed that the distance measure used in the theoretical calculations was generally consistent with the distance measure r_{rup} for purposes of deriving the adjustment factors.

One important limitation in the empirical ground-motion estimates, and therefore the hybrid empirical estimates, is their invalidity beyond distances of 70 to 100 km. Because of the lower rate of attenuation in ENA, ground motions of engineering significance can occur to distances of several hundred kilometers in this region. Therefore, the range of validity of the hybrid empirical estimates was extended out to 1000 km by using the theoretical ENA ground-motion estimates to define the rate of attenuation beyond 70 km where it is relatively safe to assume that near-source attenuation effects are negligible.

I used regression analysis together with ordinary least squares to develop a semi-empirical attenuation relation for ENA from the individual hybrid empirical ground-motion estimates. The functional form of the relationship was developed from trial and error using functional forms proposed in previous empirical studies. I used a similar approach to develop a relationship for the aleatory standard deviation. The resulting attenuation relation is given by the equation

$$\ln Y = c_1 + c_2 M_W + c_3(8.5 - M_W)^2 + c_4 \ln[f_1(M_W, r_{rup})] + f_2(r_{rup}) + (c_9 + c_{10} M_W) r_{rup} \tag{30}$$

where

$$f_1(M_W, r_{rup}) = \sqrt{r_{rup}^2 + [c_5 \exp(c_6 M_W)]^2}\ , \tag{31}$$

$$f_2(r_{rup}) = \begin{cases} 0 & \text{for } r_{rup} \le r_1 \\ c_7(\ln r_{rup} - \ln r_1) & \text{for } r_{rup} > r_1\ , \\ c_8(\ln r_{rup} - \ln r_2) & \text{for } r_{rup} > r_2 \end{cases} \tag{32}$$

and Y is the geometric mean of the two horizontal components of PGA or PSA in g, M_W is moment magnitude, r_{rup} is closest distance to fault rupture in km, $r_1 = 70$ km, and $r_2 = 130$ km.

The relationship for the aleatory standard deviation of ground motion is given by the equation

$$\sigma_{\ln Y} = \begin{cases} c_{11} + c_{12} M_W & \text{for } M_W < M_1 \\ c_{13} & \text{for } M_W \ge M_1 \end{cases} \tag{33}$$

where $M_1 = 7.16$.

The regression coefficients c_1 through c_{13} are listed in Table 7. Figure 2 shows the magnitude and distance dependence of PGA and PSA at periods of 0.2, 1.0 and 3.0 sec that is predicted by the attenuation relations give by Equation (30) along with the individual hybrid empirical ground-motion estimates used to develop this relation. Figure 3 shows a similar comparison of the 5%-damped PSA response spectra. These figures show that the error involved in fitting Equation (30) to the hybrid empirical estimates is very small and does not contribute measurably to the aleatory standard deviation. Equations for the epistemic standard deviations in $\ln Y$ and $\sigma_{\ln Y}$ were not formally evaluated in this study. These parameters are typically only used for high-level PSHA analyses, and even then they are likely to be evaluated by a panel of experts. For ENA I would recommend using multiple attenuation relations to evaluate the epistemic standard deviations in the predicted value of ground motion and aleatory variability. In other regions where multiple attenuation relations do not exist, one can use the mathematical framework presented in the previous section to formally evaluate these standard deviations.

Several previous models have been proposed to estimate ground-motion parameters in ENA. Figure 4 compares the magnitude and distance scaling characteristics of PGA and 5%-damped pseudoacceleration at 1 sec that are predicted by the semi-empirical attenuation relation developed in this study for $M_W = 5.5$ and 7.5 with the scaling characteristics predicted by the alternative hybrid empirical models developed by Atkinson (2001) and Abrahamson and Silva

(2001). Figure 5 gives a similar comparison of 5%-damped pseudoacceleration response spectra for $r_{rup} = 10$ km. Since Atkinson (2001) only developed a model for the adjustment factors, I have applied her adjustment factors to the empirical ground-motion estimates developed in this study. Figures 6 and 7 give similar comparisons of the hybrid empirical ground motions predicted from the semi-empirical attenuation relation developed in this study with those predicted from the theoretical attenuation relations developed by Atkinson and Boore (1995, 1997), Frankel *et al.* (1996), Toro *et al.* (1997), Savy *et al.* (1999), and Somerville *et al.* (2001). For simplicity, all of these comparisons are made assuming a vertical fault. The assumed point-source (hypocentral) depth for the Atkinson and Boore and Frankel *et al.* relations was taken as 6 km for $M_W = 5.5$ and 12 km for $M_W = 7.5$ as recommended by Atkinson (2001) based on an evaluation by Atkinson and Silva (2000). Assuming these point-source depths represent the center of the rupture plane, the remaining distance measures needed for the comparisons were evaluated assuming a depth to the top of the rupture plane of 3.2 km for $M_W = 5.5$ and 0 km for $M_W = 7.5$ based on the rupture width versus magnitude relation given in Wells and Coppersmith (1994). The comparisons given in Figures 4 to 7 would be different, and possibly considerable different, if other assumptions regarding the fault geometry and the point-source and rupture depths had been used, because of the inherent differences in the distance measures. A full evaluation of these differences is beyond the scope of this paper.

The specific assumptions used in making the comparisons in Figures 4 to 7 prevent me from making general conclusions regarding the various ground-motion models. However, some differences are striking enough to warrant discussion. Figure 4 demonstrates an important aspect of the hybrid empirical model mentioned earlier. The rise in the Atkinson (2001) ground-motion estimates with distance at distances beyond 50 to 400 km, the exact value depending on the particular ground-motion parameter and magnitude value, is caused by the unrealistic attenuation rate predicted by the empirical attenuation relations at these distances. Atkinson noted this same phenomenon and recommended that her adjustment factors not be used at such large distances. I have purposely extended the plots to large distances to emphasize this point. This same phenomenon is also seen in the Abrahamson and Silva (2001) hybrid empirical model at large distances, only to a much lesser degree. This latter model is based on the empirical WNA attenuation relation of Abrahamson and Silva (1997). These differences are not visible in the response spectral comparisons in Figure 5 because of the small distance, although this figures does show that there is a considerable variation at short periods.

The comparisons of the theoretical estimates in Figures 6 and 7 indicates that there are differences in these models that reach a factor of five or more. I believe that it is important to include this large degree of epistemic variability in making ground-motion estimates in ENA. The semi-empirical attenuation relation developed in this study predicts the highest ground motion at $M_W = 5.5$ and $r_{rup} < 10$ km, which I believe is due to the relatively shallow depth to fault rupture (3.2 km) that used in the comparisons. This is consistent with the behavior of the empirical attenuation relations and, in my opinion, is appropriate for such a shallow source.

Because of the high-rate of attenuation predicted by the hybrid empirical model, a deeper source would likely reduce the hybrid empirical estimates relative to the other models. The Somerville *et al.* (2001) attenuation relation predicts the lowest ground motion for $M_W = 5.5$ especially at the shorter distances, which is likely due to a greater overall average depth of the assumed source. Since this relation, like that of Toro *et al.* (1997), uses the closest distance to the surface projection of fault rupture r_{jb} as its distance measure, its predicted value is independent of source depth. So as source depth increases, predictions from those relations that are based on fault or hypocentral distance will be reduced relative to the Somerville *et al.* and Toro *et al.* relations. The Atkinson and Boore (1995, 1997) attenuation relation predicts relatively low 1-sec PSA values consistent with its use of a double corner frequency source model. Differences among the various ground-motion models are smaller at $M_W = 7.5$, for which differences in the treatment of source depth are less important because of the relatively large rupture area. This strong dependence on source depth demonstrates the importance of including epistemic variability in source depth when estimating ground motion from attenuation relations using different distance measures.

Discussion

There are several inherent strengths in the hybrid empirical method that make it a viable alternative to the more traditional theoretical method used to estimate ground motion in areas, such as ENA, where there is a limited number of strong-motion recordings. The first strength is that it relies on empirical attenuation relations that are well constrained by strong-motion recordings over the range of magnitudes and distances of greatest engineering interest. As a result, the magnitude- and distance-scaling characteristics predicted by the method, at least in the near-source region, are strongly founded on observations rather than theoretical assumptions. This aspect of the method is particularly important for ground-motion estimates close to large-magnitude earthquakes that are strongly influenced by the complexities of fault geometry and rupture characteristics. More complex seismological models could be used to better predict these near-source effects, but it would take a considerable computational effort to produce ground-motion estimates that account for the wide range in period, magnitude, distance, source geometry, stress drop, regional attenuation and crustal structure, local site characteristics, and other seismological parameters that are necessary to develop such regional attenuation relations (e.g., Somerville *et al.*, 2001). Besides, these more complex models require many more assumptions than the simpler model used here.

A second strength in the hybrid empirical method is its use of relative differences in theoretical estimates of ground motion between the host and target regions to derive the adjustment factors needed to apply empirical attenuation relations to the target region. This avoids the additional and often unmodeled uncertainty that is inherent in calculating absolute values of ground motion using the theoretical method. A third strength of the hybrid empirical method is its ability to provide explicitly in a straightforward manner estimates of aleatory variability (randomness) and epistemic variability (lack of scientific knowledge) in the predicted ground motions for the target region.

The application of the hybrid empirical method requires reliable seismological parameters for the host and target regions. Therefore, it might not be possible to apply the method in some regions. An underlying assumption in the method is that the near-source characteristics captured in empirical attenuation relations from the host region (e.g., California) are similar to those expected in the target region; that is, that such near-source characteristics can be considered regionally invariant. If this is not the case then the methodology will not give reliable estimates of ground motion in the near-source region. One possible reason why empirically based near-source ground-motion characteristics would not be transferable to another region is if they include the effects of soil nonlinearity that is not taken into account in the calculation of the theoretical adjustment factors. Soil nonlinearity will only be important if the selected empirical attenuation relations are developed from soil rather than rock recordings. It is for this very reason that empirical attenuation relations appropriate for rock were used to derive the ENA estimates presented in this paper. If a hybrid empirical estimate of ground motion on a different site condition is needed, the ENA hard-rock estimates provided by the attenuation relation developed in this paper will need to be modified for the desired site conditions using empirical or theoretical site factors.

There are several potential limitations in the hybrid empirical method, at least as it has been applied in this paper, that the user should be aware of. The first limitation is that it assumes that a point source, single corner frequency, ω-square source spectrum (Brune, 1970, 1971) is valid for predicting theoretical ground-motion ratios between WNA and ENA. Atkinson and Silva (2000) proposed a double corner frequency source spectrum for California that they believe is more consistent with the strong-motion recordings in that region. Many other investigators (see compilation in Atkinson and Boore, 1998) have proposed double corner source spectra for ENA. For example, Atkinson and Boore (1995, 1997) used a double corner source spectrum to develop a theoretical attenuation relation for ENA using the stochastic method. Actually, it might not matter whether a single corner or a double corner source spectrum, or whether a point source or a finite source model, is used to compute theoretical ground-motion *ratios*, as long as the same type of model is valid in both the target and host regions. This hypothesis will be tested in a future study.

It is interesting to note that Atkinson and Silva (1997) found that their empirical source spectrum for California was similar to that for ENA at low-frequencies when differences in crustal properties were taken into account. This implies that the two regions might have similar source spectra at these frequencies. They further found that the ENA source spectrum appears to have enhanced high-frequency amplitudes as compared to that in California, at least for ENA hard-rock sites, which they suggested was consistent with known differences in stress drop between the two regions. Therefore, differences in source spectra, aside from those caused by differences in stress drop, which were accounted for in the application presented in this paper, might not be important in the development of theoretical adjustment factors between WNA and ENA.

Atkinson (2001) goes one step further and gives evidence to suggest that there is little, if any, difference in the apparent source radiation from ENA and California earthquakes of a given moment magnitude at both high and low frequencies. For example, she cites a comparison of MMI data in WNA and ENA by Hanks and Johnston (1992) as suggesting that near-source damage levels, and by inference ground-motion levels, are similar in the two regions for the same moment magnitude. However, Hanks and Johnston conclude that the MMI data, especially at the intensity VII level, are extremely limited and are not in themselves sufficient to rule out a factor of two higher stress drop in ENA. Bollinger *et al.* (1993) performed a similar study and concluded that the scatter in the MMI data was indeed large but that, in their opinion, it did support a factor of two higher stress drop in ENA. Atkinson and Boore (1998) used the stochastic method to modify the empirical California source model of Atkinson and Silva (1997) for differences in crustal properties and generic rock characteristics between California and ENA and found that this modified model matched the ENA strong-motion data almost as well as the theoretically derived Atkinson and Boore (1995, 1997) attenuation relation and better than many of the other theoretical attenuation relations that have been developed for ENA. Beresnev and Atkinson (1999, 2001) performed finite-fault stochastic simulations of well-recorded moderate-to-large earthquakes in both California and ENA and suggested that the observed difference in ground motion between the two regions is caused by regional differences in crustal properties and anelastic attenuation. If Atkinson's (2001) hypothesis is correct, it would corroborate my use of the same source-spectral shape in WNA and ENA, aside from the issue of whether the single corner or the double corner version of this shape is important. The significance of Atkinson's hypothesis will be addressed in a future study.

A second limitation in the hybrid empirical method is that it can only provide reliable estimates of ground motion out to distances of 70 to 100 km because of the limitation in the empirical strong-motion database. Therefore, it must rely on theoretical ground-motion estimates to extrapolate the hybrid empirical estimates beyond these distances where, for example, crustal reflections off the Moho and other significant crustal reflectors have been observed to be important in both California (e.g., Somerville and Yoshimura, 1990; Campbell, 1991) and ENA (Burger *et al.*, 1987; Atkinson and Mereu, 1992; Atkinson and Boore, 1995). Luckily, near-source effects are no longer important at these distances and the approach of extrapolating the hybrid empirical ground-motion estimates to larger distances using the theoretically derived attenuation rates proposed in this study should be reasonably valid.

Conclusions

The application of the hybrid empirical method presented in this paper indicates that it is a viable alternative to the more traditional intensity and theoretical methods that are presently used to develop ground-motion models in regions where there are a limited number of strong-motion recordings. It is especially useful for estimating strong ground motion near large-magnitude earthquakes. It has recently gained credibility amongst seismologists as an alternative method for estimating ground motion in ENA by evidence of its use by a panel of ground-motion experts in the SSHAC (Budnitz *et al.*, 1997), Trial Implementation (Savy *et al.*, 1999), and Yucca Mountain (Stepp *et al.*, 2001) Projects, as well as its use by Atkinson (2001) and Abrahamson and Silva (2001) to develop independent hybrid empirical ground-motion estimates for ENA. I believe that the method is now mature enough to be used to develop alternative attenuation relations in regions where good seismological models are available. I specifically suggest that the semi-empirical ENA hard-rock attenuation relation developed in this study using the hybrid empirical method is a viable alternative ground motion model for this region.

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Table 1
Additional Aleatory Uncertainty Due to Randomness in Sediment Depth and Faulting Mechanism

Period (s)	Additional Aleatory Uncertainty, $\Delta\sigma_{wna}$		
	Faulting Mechanism	Sediment Depth	Total
0.01	0.10	0	0.100
0.02	0.10	0	0.100
0.03	0.10	0	0.100
0.05	0.10	0	0.100
0.075	0.10	0	0.100
0.10	0.10	0	0.100
0.15	0.10	0	0.100
0.20	0.09	0	0.090
0.30	0.08	0	0.080
0.50	0.07	0.043	0.082
0.75	0.06	0.064	0.088
1.0	0.05	0.099	0.111
1.5	0.03	0.125	0.129
2.0	0.02	0.144	0.145
3.0	0	0.149	0.149
4.0	0	0.182	0.182

Table 2

Seismological Parameters Used with the Stochastic Method

Parameter	Western North America (WNA)	Eastern North America (ENA)
Source spectrum	ω-square, point source	ω-square, point source
Stress drop, $\Delta\sigma$ (bars)	100	105 (0.05)[a], 125 (0.25) 150 (0.40), 180 (0.25) 215 (0.05)
Geometric attenuation	R^{-1}; $R < 40$ km $R^{-0.5}$; $R \geq 40$ km	R^{-1}; $R < 70$ km R^{0}; $70 \leq R < 130$ km $R^{-0.5}$; $R \geq 130$ km
Source duration, T_s (sec)	$1/f_0$	$1/(2f_0)$
Path duration, T_p (sec)	$R^{0.05}$	R^{0}; $R \leq 10$ km $R^{0.16}$; $10 < R \leq 70$ km $R^{-0.03}$; $70 < R \leq 130$ km $R^{0.04}$; $R > 130$ km
Path attenuation, Q	$180f^{0.45}$	$400f^{0.4}$ (0.3), $680f^{0.36}$ (0.4) $1000f^{0.3}$ (0.3)
Shear velocity, β_s (km/s)	3.5	3.6
Density, ρ_s (gm/cc)	2.8	2.8
Site attenuation, κ_0 (sec)	0.04	0.003 (0.3), 0.006 (0.4) 0.012 (0.3)
Site amplification method[b]	Quarter–wavelength	Quarter–wavelength
Local site profile[c] (30-m velocity)	WNA generic rock (620 m/s)	ENA hard rock (2,800 m/sec)

[a] Where multiple values are used weights are given in parentheses

[b] Site amplification terms are given in Table 4

[c] Crustal velocity models are given in Table 2

Table 3

Properties of Theoretical Local Site Profiles

Western North America (WNA)			Eastern North America (ENA)		
Depth, z (km)	Velocity, β (km/sec)[a]	Density, ρ (gm/cc)	Depth, z (km)	Velocity, β (km/sec)[a]	Density, ρ (gm/cc)
≤ 0.001	0.245	2.495	0	2.768	2.731
0.001–0.03	$2.206z^{0.272}$	—[b]	0.05	2.808	2.735
0.03–0.19	$3.542z^{0.407}$	—[b]	0.10	2.847	2.739
0.19–4.00	$2.505z^{0.199}$	—[b]	0.15	2.885	2.742
4.00–8.00	$2.927z^{0.086}$	—[b]	0.20	2.922	2.746
≥ 8.00	3.500	2.800	0.25	2.958	2.749
			0.30	2.993	2.752
			0.35	3.026	2.756
			0.40	3.059	2.759
			0.45	3.091	2.762
			0.50	3.122	2.765
			0.55	3.151	2.767
			0.60	3.180	2.770
			0.65	3.208	2.773
			0.70	3.234	2.775
			0.75	3.260	2.778
			0.75–2.20	$3.324z^{0.067}$	—[b]
			2.20–8.00	$3.447z^{0.0209}$	—[b]
			≥ 8.00	3.6	2.809

[a] Average shear-wave velocity in upper 30 m is 620 m/sec for WNA and 2,800 m/sec for ENA

[b] $\rho = 2.5 + 0.09375(\beta - 0.3)$ gm/cc

Table 4
Theoretical Site Amplification Factors

Western North America (WNA)			Eastern North America (ENA)		
Frequency, f (Hz)	Amplification, $A(f)$ [a]	Site Term, $G(f)$ [b]	Frequency, f (Hz)	Amplification, $A(f)$ [a]	Site Term, $G(f)$ [b]
0.01	1.00	1.00	0.01	1.00	1.00
0.09	1.10	1.09	0.10	1.02	1.02
0.16	1.18	1.16	0.20	1.03	1.03
0.51	1.42	1.33	0.30	1.05	1.04
0.84	1.58	1.42	0.50	1.07	1.06
1.25	1.74	1.49	0.90	1.09	1.07
2.26	2.06	1.55	1.25	1.11	1.08
3.17	2.25	1.51	1.80	1.12	1.08
6.05	2.58	1.21	3.00	1.13	1.07
16.60	3.13	0.39	5.30	1.14	1.03
61.20	4.00	0.00	8.00	1.15	0.99
			14.00	1.15	0.88
			30.00	1.15	0.65
			60.00	1.15	0.37
			100.00	1.15	0.17

[a] Amplification excluding the effects of κ_0. Amplification at other frequencies are obtained by interpolation assuming a linear dependence between log frequency and log amplification

[b] Amplification including the effects of $\kappa_0 = 0.04$ sec in WNA and $\kappa_0 = 0.006$ sec in ENA

Table 5

Theoretical Adjustment Factors Showing the Effect of κ_0 and $\Delta\sigma$

Period (sec)	Adjustment Factor for $M_W = 6.5$, $R = 10$ km				
	$\kappa_0 = 0.003$	$\kappa_0 = 0.006$			$\kappa_0 = 0.012$
	$\Delta\sigma = 150$	$\Delta\sigma = 105$	$\Delta\sigma = 150$	$\Delta\sigma = 215$	$\Delta\sigma = 150$
0.01	3.005	1.701	2.261	3.018	1.568
0.02	7.652	3.767	5.040	6.731	2.470
0.03	6.631	3.730	4.964	6.623	2.895
0.05	4.127	2.599	3.453	4.598	2.444
0.075	2.556	1.709	2.266	3.012	1.789
0.10	1.921	1.324	1.754	2.327	1.466
0.15	1.424	1.015	1.340	1.772	1.187
0.20	1.232	0.893	1.176	1.550	1.073
0.30	1.081	0.800	1.048	1.373	0.986
0.50	1.015	0.768	0.997	1.292	0.960
0.75	1.009	0.777	0.997	1.277	0.973
1.0	1.002	0.783	0.994	1.257	0.976
1.5	0.991	0.795	0.987	1.217	0.977
2.0	0.978	0.804	0.977	1.176	0.972
3.0	0.939	0.805	0.941	1.088	0.942
4.0	0.919	0.809	0.921	1.041	0.924

Note: κ_0 is in sec, $\Delta\sigma$ is in bars

Table 6

Regression Coefficients

T (s)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}
0.01	0.0305	0.633	-0.0427	-1.591	0.683	0.416	1.140	-0.873	-0.00428	0.000483	1.030	-0.0860	0.414
0.02	1.3535	0.630	-0.0404	-1.787	1.020	0.363	0.851	-0.715	-0.00388	0.000497	1.030	-0.0860	0.414
0.03	1.1860	0.622	-0.0362	-1.691	0.922	0.376	0.759	-0.922	-0.00367	0.000501	1.030	-0.0860	0.414
0.05	0.3736	0.616	-0.0353	-1.469	0.630	0.423	0.771	-1.239	-0.00378	0.000500	1.042	-0.0838	0.443
0.075	-0.0395	0.615	-0.0353	-1.383	0.491	0.463	0.955	-1.349	-0.00421	0.000486	1.052	-0.0838	0.453
0.10	-0.1475	0.613	-0.0353	-1.369	0.484	0.467	1.096	-1.284	-0.00454	0.000460	1.059	-0.0838	0.460
0.15	-0.1901	0.616	-0.0478	-1.368	0.461	0.478	1.239	-1.079	-0.00473	0.000393	1.068	-0.0838	0.469
0.20	-0.4328	0.617	-0.0586	-1.320	0.399	0.493	1.250	-0.928	-0.00460	0.000337	1.077	-0.0838	0.478
0.30	-0.6906	0.609	-0.0786	-1.280	0.349	0.502	1.241	-0.753	-0.00414	0.000263	1.081	-0.0838	0.482
0.50	-0.5907	0.534	-0.1379	-1.216	0.318	0.503	1.166	-0.606	-0.00341	0.000194	1.098	-0.0824	0.508
0.75	-0.5429	0.480	-0.1806	-1.184	0.304	0.504	1.110	-0.526	-0.00288	0.000160	1.105	-0.0806	0.528
1.0	-0.6104	0.451	-0.2090	-1.158	0.299	0.503	1.067	-0.482	-0.00255	0.000141	1.110	-0.0793	0.543
1.5	-0.9666	0.441	-0.2405	-1.135	0.304	0.500	1.029	-0.438	-0.00213	0.000119	1.099	-0.0771	0.547
2.0	-1.4306	0.459	-0.2552	-1.124	0.310	0.499	1.015	-0.417	-0.00187	0.000103	1.093	-0.0758	0.551
3.0	-2.2331	0.492	-0.2646	-1.121	0.310	0.499	1.014	-0.393	-0.00154	0.000084	1.090	-0.0737	0.562
4.0	-2.7975	0.507	-0.2738	-1.119	0.294	0.506	1.018	-0.386	-0.00135	0.000074	1.092	-0.0722	0.575

Figure Captions

1. A comparison of 5%-damped pseudoacceleration response spectra predicted from WNA empirical attenuation relations with theoretical response spectra predicted from the point-source, ω-square stochastic model used in this study with $\Delta\sigma = 100$ bars, $\kappa_0 = 0.04$ sec, and a WNA generic-rock site profile. The comparison is made for $M_W = 5.0$ and $r_{rup} = 10$ km.

2. Individual estimates of ground motion on ENA hard rock predicted using the hybrid empirical method developed in this study (solid circles) compared to the ground motion predicted from the semi-empirical attenuation relation developed from these estimates (lines): (a) peak ground acceleration, (b) spectral acceleration at 0.2 sec, (c) spectral acceleration at 1.0 sec, (d) spectral acceleration at 3.0 sec.

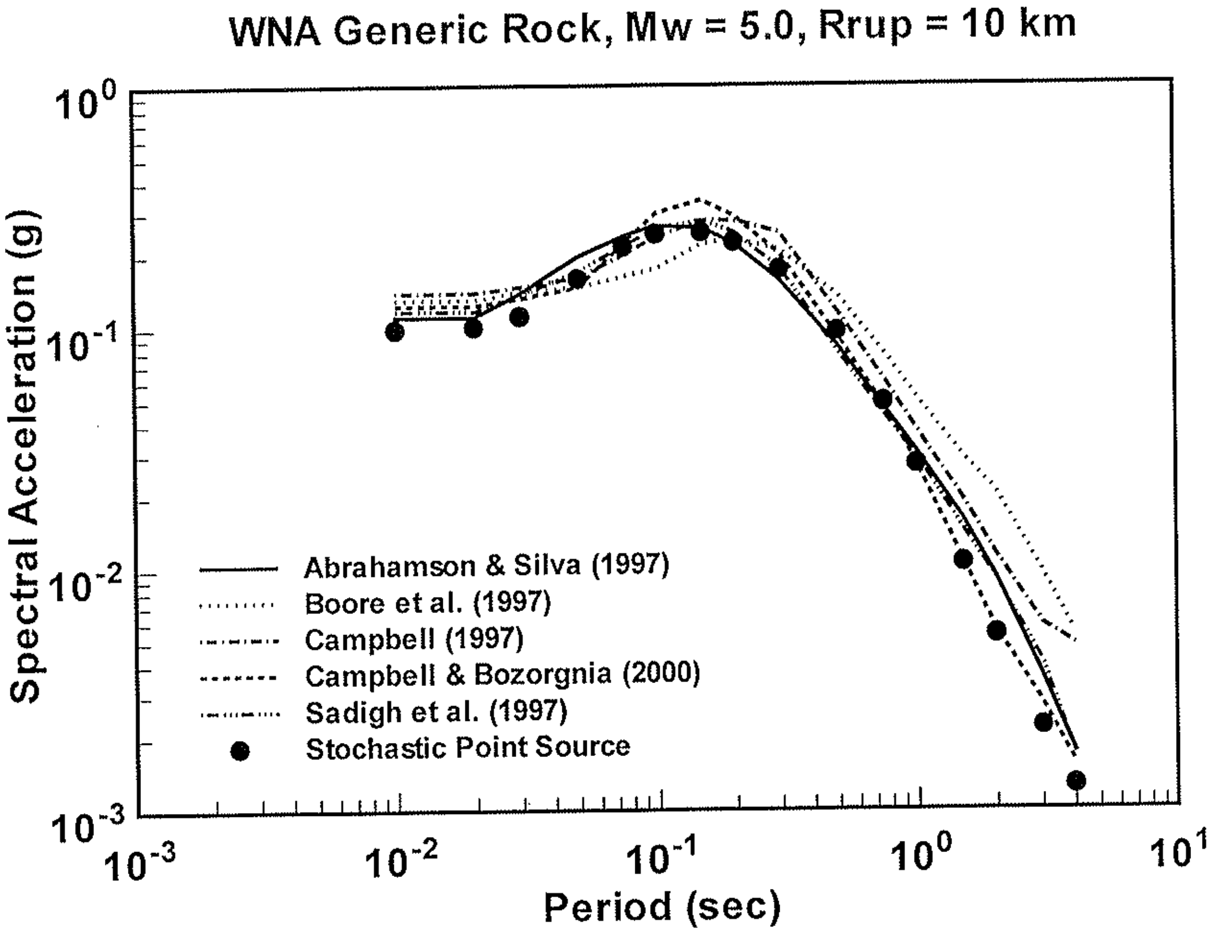
3. Individual estimates of 5%-damped pseudoacceleration response spectra on ENA hard rock predicted using the hybrid empirical method developed in this study (solid circles) compared to the ground motion predicted from the semi- empirical attenuation relation developed from these estimates (lines): (a) rupture distance of 3 km, (b) rupture distance of 30 km.

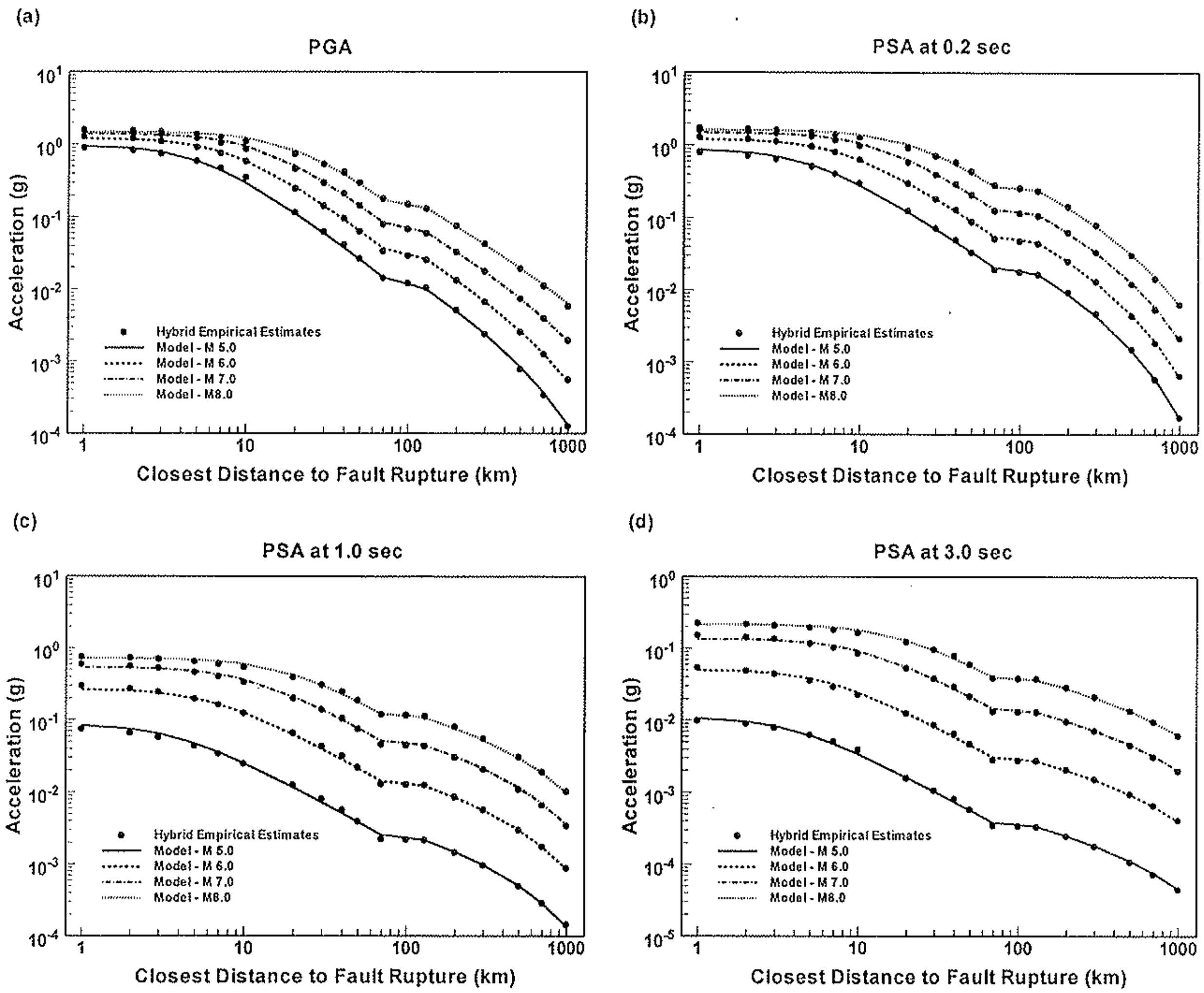
4. A comparison of ground-motion attenuation relations for ENA hard rock predicted using the hybrid empirical method: (a) peak ground acceleration for $M_W = 5.5$, (b) 5%-damped pseudoacceleration at 1.0 s for $M_W = 5.5$, (c) peak ground acceleration for $M_W = 7.5$, (d) 5%-damped pseudoacceleration at 1.0 s for $M_W = 7.5$.

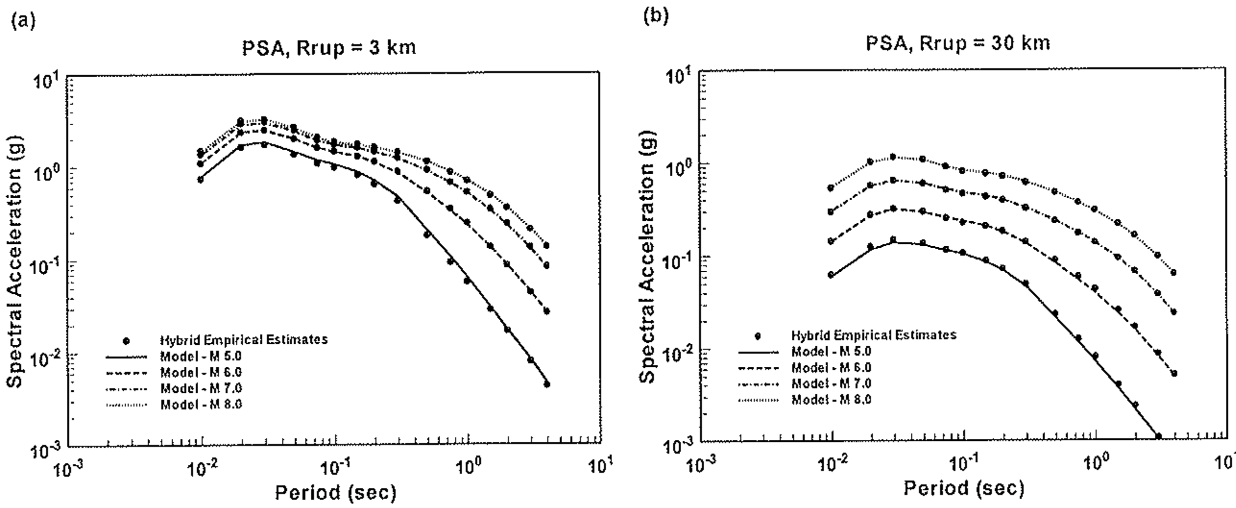
5. A comparison of 5%-damped pseudoacceleration response spectra on ENA hard rock for a rupture distance of 10 km predicted using the hybrid empirical method: (a) $M_W = 5.5$, (b) $M_W = 7.5$.

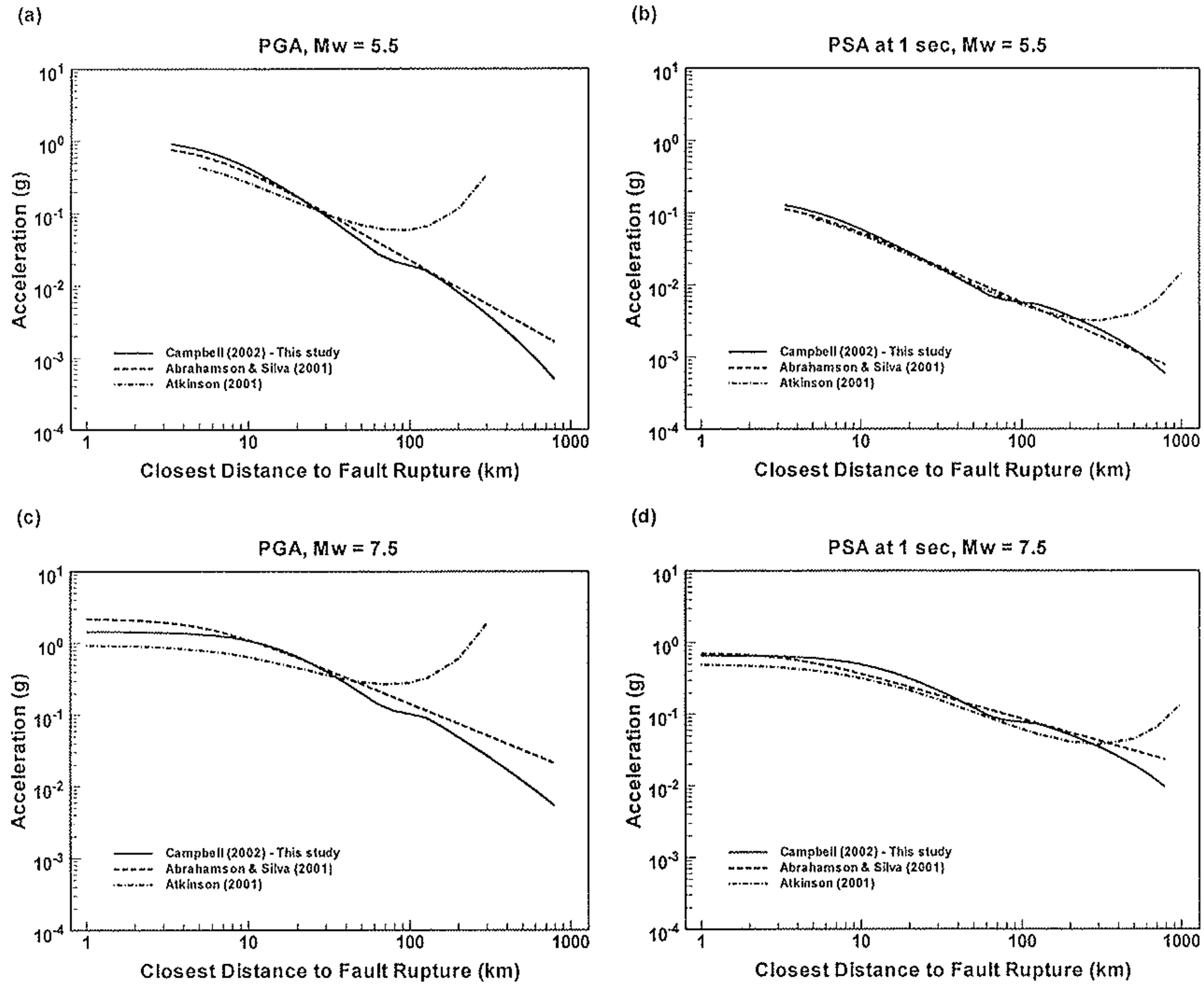
6. A comparison of the semi-attenuation relation for ENA hard rock developed using the hybrid empirical method in this study with attenuation relations developed previously using the theoretical method: (a) peak ground acceleration for $M_W = 5.5$, (b) 5%-damped pseudoacceleration at 1.0 s for $M_W = 5.5$, (c) peak ground acceleration for $M_W = 7.5$, (d) 5%-damped pseudoacceleration at 1.0 s for $M_W = 7.5$.

7. A comparison of the 5%-damped pseudoacceleration response spectra on ENA hard rock for a rupture distance of 10 km predicted from the semi-empirical attenuation relation developed in this study using the hybrid empirical method with spectra predicted from attenuation relations developed previously using the theoretical method: (a) $M_W = 5.5$, (b) $M_W = 7.5$.


WNA Generic Rock, Mw = 5.0, Rrup = 10 km
Spectral Acceleration (g)
Period (sec)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Abrahamson & Silva (1997)
Boore et al. (1997)
Campbell (1997)
Campbell & Bozorgnia (2000)
Sadigh et al. (1997)
Stochastic Point Source


(a)
PGA
Acceleration (g)
Closest Distance to Fault Rupture (km)
Hybrid Empirical Estimates
Model - M 5.0
Model - M 6.0
Model - M 7.0
Model - M8.0
(b)
PSA at 0.2 sec
(c)
PSA at 1.0 sec
(d)
PSA at 3.0 sec


(a)
PSA, Rrup = 3 km
Spectral Acceleration (g)
Period (sec)
Hybrid Empirical Estimates
Model - M 5.0
Model - M 6.0
Model - M 7.0
Model - M 8.0
(b)
PSA, Rrup = 30 km
Spectral Acceleration (g)
Period (sec)
Hybrid Empirical Estimates
Model - M 5.0
Model - M 6.0
Model - M 7.0
Model - M 8.0


(a)
PGA, Mw = 5.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)
(b)
PSA at 1 sec, Mw = 5.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)
(c)
PGA, Mw = 7.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)
(d)
PSA at 1 sec, Mw = 7.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)

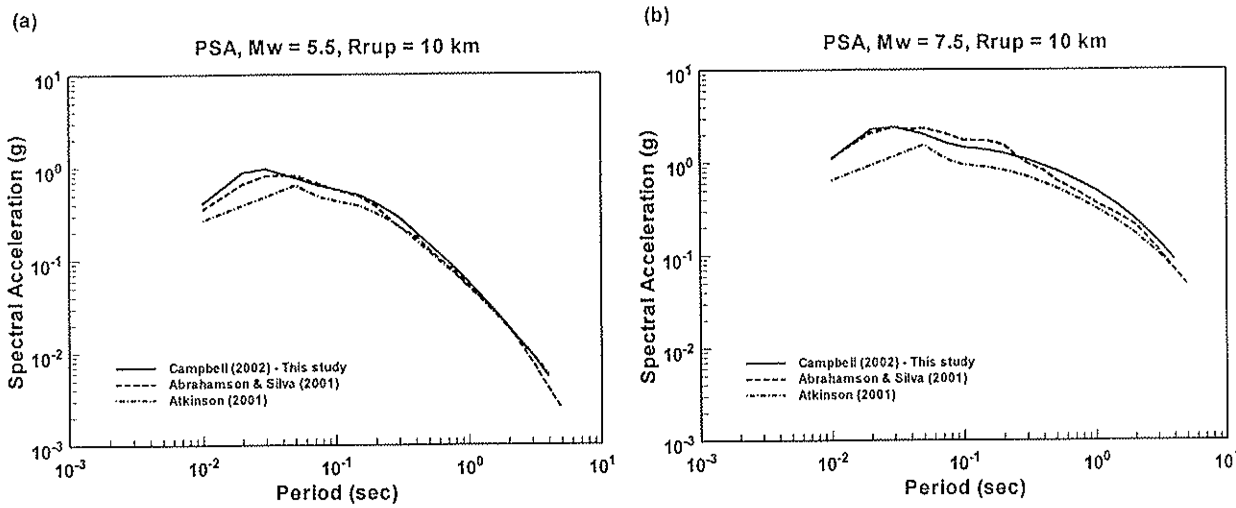
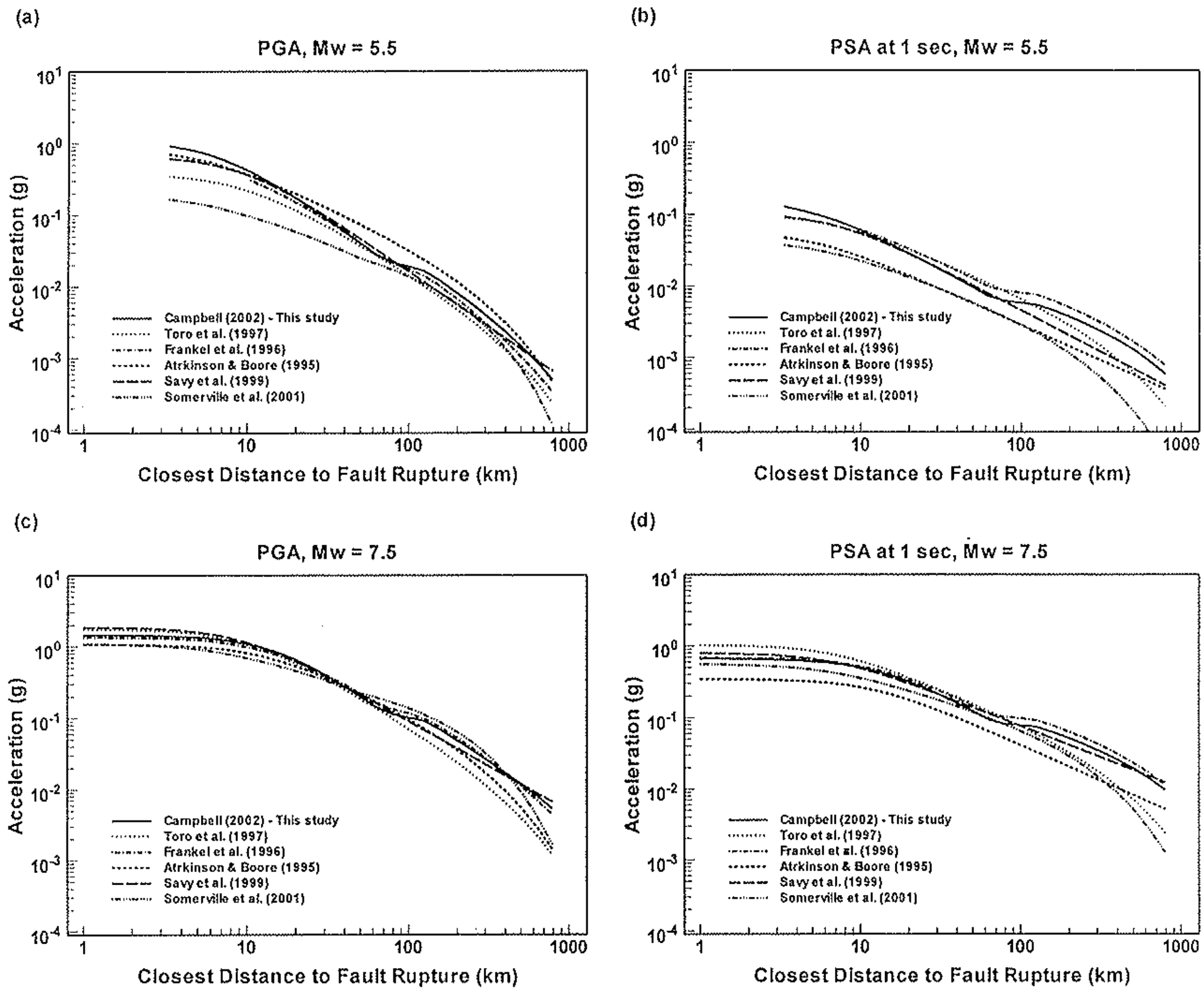
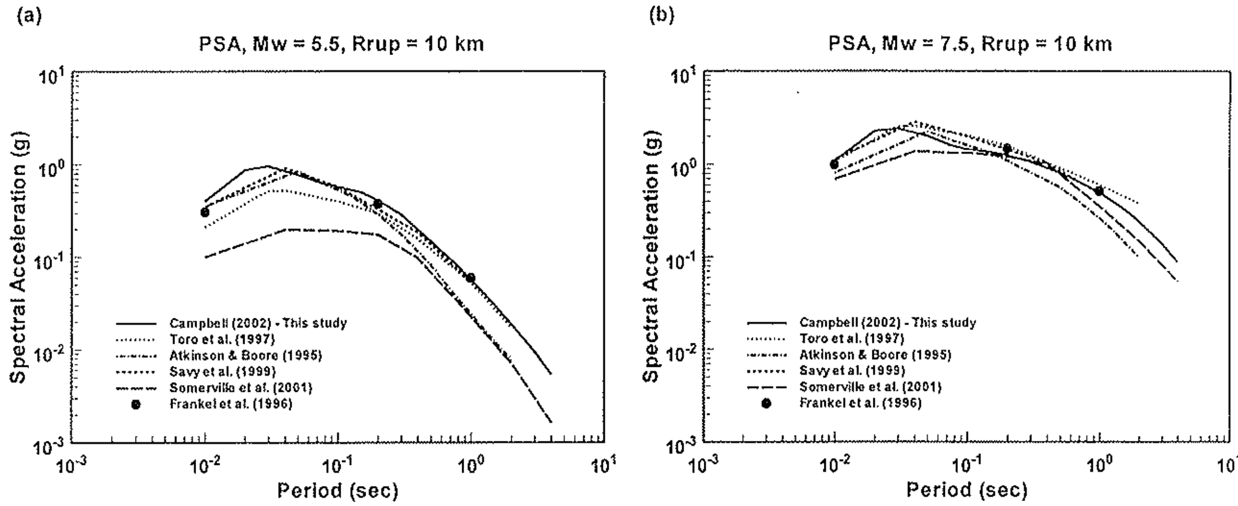

(a)
PSA, Mw = 5.5, Rrup = 10 km
Spectral Acceleration (g)
Period (sec)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)
(b)
PSA, Mw = 7.5, Rrup = 10 km
Spectral Acceleration (g)
Period (sec)
Campbell (2002) - This study
Abrahamson & Silva (2001)
Atkinson (2001)

Figure 6


(a)
PGA, Mw = 5.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Toro et al. (1997)
Frankel et al. (1996)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
(b)
PSA at 1 sec, Mw = 5.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Toro et al. (1997)
Frankel et al. (1996)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
(c)
PGA, Mw = 7.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Toro et al. (1997)
Frankel et al. (1996)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
(d)
PSA at 1 sec, Mw = 7.5
Acceleration (g)
Closest Distance to Fault Rupture (km)
Campbell (2002) - This study
Toro et al. (1997)
Frankel et al. (1996)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)


(a)
PSA, Mw = 5.5, Rrup = 10 km
Spectral Acceleration (g)
Period (sec)
Campbell (2002) - This study
Toro et al. (1997)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
Frankel et al. (1996)
(b)
PSA, Mw = 7.5, Rrup = 10 km
Spectral Acceleration (g)
Period (sec)
Campbell (2002) - This study
Toro et al. (1997)
Atkinson & Boore (1995)
Savy et al. (1999)
Somerville et al. (2001)
Frankel et al. (1996)