Empirical-Stochastic Ground-Motion Prediction for Eastern North America

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Abstract An alternative approach based on a hybrid-empirical model is utilized to predict the ground-motion relationship for eastern North America (ENA). In this approach, a stochastic model is first used to derive modification factors from the ground motions in western North America (WNA) to the ground motions in ENA. The ground-motion parameters are then estimated to develop an empirical attenuation relationship for ENA using empirical ground-motion relationships from WNA. We develop an empirical-stochastic source model for both regions to obtain ground motions at different magnitude–distance range of interest. At short distances ($R \le 30$ km) and large magnitudes ($M_{\rm w} \ge 6.4$), an equivalent point-source model is carried out to consider the effect of finite-fault modeling on the ground-motion parameters. Source focal depth and Brune stress drop are assumed to be magnitude dependent. We choose three well-defined empirical attenuation relationships for WNA to compare the empirical ground-motion processes between the two regions. A composite functional attenuation form is defined, and, in turn, a nonlinear regression analysis is performed by using a genetic algorithm (GA) for a wide range of magnitudes and distances to develop an empirical attenuation relationship from the stochastic groundmotion estimates in ENA. The empirical-stochastic attenuation relationship for horizontal peak ground acceleration and spectral acceleration are applicable to earthquakes of $M_{\rm w}$ 5.0–8.2 at distances of up to 1000 km. The resulting attenuation model developed in this study is compared with those used in the 2002 national seismic hazard maps, derived in the 2003 Electric Power Research Institute studies and recorded in ENA. The comparison of the results to the other attenuation functions and the available ENA data show a reasonable agreement for the ENA ground motions.

Introduction

In engineering applications, researchers tend to study the wave attenuation and hazard issues for seismically active regions where ground-motion recordings are abundant. In such areas of high seismicity, there are several mathematical models that relate a given ground-motion parameter (e.g., peak ground acceleration, PGA) to several seismological parameters of an earthquake, such as earthquake magnitude, source-to-site distance, style of faulting, and local site conditions (Abrahamson and Silva, 1997; Sadigh et al., 1997; Campbell, 1997). For example, in western North America (WNA), there are sufficient ground-motion data to perform a statistical fitting procedure for the purpose of developing an attenuation relationship in a seismic hazard analysis. It has been recognized that the attenuation of wave transmission in such regions can be reliably estimated from calculations based on extensive ground-motion data recorded in the region.

One may question how attenuation relationships may be developed for the stable continental regions where groundmotion data are incomplete in the magnitude and distance ranges. For instance, there are insufficient ground-motion data to provide a complete database for developing an empirical attenuation relationship in the eastern North America (ENA) region. In recent years, as there has been a remarkable economic growth in ENA, the need to properly evaluate the attenuation of ground motions and seismic risk of this region is apparent.

Because the quantity of useable ground-motion data in ENA is inadequate, attenuation characteristics can be formulated using the seismological data. It is possible to derive simple seismological models that can be first used to describe how ground-motion scales with earthquake source size and source-to-site distance. The ground-motion amplitude spectra for earthquakes are then predicted to reproduce successfully the sparse earthquakes in the magnitude–distance range for engineering purposes. However, a concern exists about the accuracy of such an approach and the nature of the seismic source radiation. The use of a seismological model with a stochastic approach simultaneously may predict ground-motion amplitudes for earthquakes in a lowseismic region (Toro *et al.*, 1997; Atkinson and Boore, 1998; Atkinson and Silva, 2000; Beresnev and Atkinson, 2002; Boore, 2003).

In areas such as WNA where ground-motion recordings and seismological models are well defined, the uncertainties in models and parameters are appropriately small, but the prediction of ground motions has great uncertainty. If we assume that the ground-motion characteristics in ENA are equivalent to those observed in WNA, the ground-motion modeling of WNA can be used to improve ground-motion relationships for ENA and other regions with few groundmotion data and high uncertainties. This assumption leads to an alternative approach based on the modification factors to convert the WNA ground motions to the equivalent ENA ground motions (Atkinson, 2001; Campbell, 2003). In this approach, a stochastic source model is first used to derive modification factors from WNA to ENA motions. The ground-motion parameters are then estimated to develop an attenuation relationship for ENA by using empirical groundmotion relations from WNA.

Atkinson (2001) presented an alternative stochastic attenuation relationship in ENA based on simple modifications to California ground-motion relationships to account for differences in the crustal properties between California and ENA. The modification factors were independent of the source models. Campbell (2003) proposed a hybridempirical method based on a point-source stochastic model and a constant Brune stress drop of 100 bars for WNA at all magnitudes to estimate ground motions in the ENA region. However, Atkinson and Silva (1997) suggested a stochastic finite-fault model to match the seismic data obtained from the large fault ruptures in WNA. They point out that when a point-source model is used to predict the ground-motion amplitudes in WNA, the Brune stress drop should be reduced with increasing magnitude. Atkinson and Boore (1995) suggested a double-corner source model for ENA to represent the source spectra at the near-source distances. Thus, the point-source model for large magnitudes is the first constraint in the hybrid-empirical method applied in the 2003 Campbell attenuation relationship. The differences in Brune stress drop between WNA and ENA is the second significant factor that should be addressed in the development of an attenuation relationship in ENA. The constant value of Brune stress drop (100 bars) for large magnitudes in WNA (Campbell, 2003) leads to underestimating the modification factors between the two regions and, in turn, underpredicts the ground motions for large magnitudes at near-source distances. The third factor is the near-source amplitude saturation which describes the effects of focal depth on amplitudes at short distances. Consideration of these additional factors in the hybrid-empirical method provides a useful framework for improving the 2003 Campbell attenuation relationship in ENA. Thus, we used the hybrid-empirical method proposed by Campbell (2003) to develop an alternative ground-motion relationship in ENA. The method is more fully implemented than in Campbell (2003) to account

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for discrepancy in the type of sources, Brune stress drops, and focal depths in both regions. The proposed approach in this study is based on a stochastic source model, which combines the main advantages of the both point-source and finite-fault modeling approaches.

The objective of this article is to improve the 2003 Campbell attenuation relationship for ENA, using an empirical-stochastic source model and the modification factors based on seismological models in the WNA and the ENA regions. We utilize the stochastic point-source model for both regions to obtain ground motions at different magnitude–distance ranges of interest. At short distances ($R \le 30$ km) and large magnitudes ($M_w \ge 6.4$), an equivalent pointsource model (double-corner source model) is used to consider the effect of finite-fault modeling on the peak-groundmotion parameters. We choose three well-defined empirical attenuation relationships (Abrahamson and Silva, 1997; Sadigh et al., 1997; Campbell, 1997) for WNA to compute the ground-motion processes in the ENA region. We define a functional attenuation form and perform a nonlinear regression analysis for a wide range of magnitudes and distances to develop an empirical attenuation relationship from the stochastic ground-motion estimates in ENA. A genetic algorithm is used to determine the best estimate of the attenuation coefficients in this relation.

The resulting attenuation model developed in this study is compared with those used in the 2002 national seismic hazard maps (Frankel *et al.*, 2002; Frankel, 2004) and derived in the Electric Power Research Institute (EPRI) studies (EPRI, 2003). The proposed model is also compared with available ENA data for 1.0 and 0.2-sec periods to test our attenuation relationships.

Stochastic Model of Rock Motions

The stochastic source method assumes that ground motion can be modeled as band-limited Gaussian white noise (BLWN) and the peak amplitude approximated using random vibration theory (RVT) (Hanks and McGuire, 1981; Boore, 1983). This method assumes that the seismic shear-wave energy represented by the Fourier amplitude spectrum is band limited by the source-corner frequency (f_c) at low frequencies and by the site-corner frequency (f_{max}), or the spectral decay parameter (κ) at high frequencies.

In this study, an empirical-stochastic source approach is used to generate ground motions at the soft- and hard-rock sites in the WNA and the ENA regions, respectively. A brief overview of the seismological models is given in the following sections.

Fourier Amplitude Spectrum (FAS)

A point-source stochastic model in the frequency domain assumes that the total Fourier amplitude spectrum of displacement, $Y(M_0, R, f)$, for horizontal ground motions due to shear waves may be modeled as (Boore, 2003)

$$Y(M_0, R, f) = E(M_0, f)D(R, f)P(f),$$
(1)

where M_0 is the seismic moment (dyne cm), R is the distance (km), and f is the frequency (Hz). $E(M_0, f)$ is the point-source spectrum term, D(R, f) is a diminution factor accounting for anelastic attenuation, and P(f) is a low-pass filter to model the decrease of Fourier amplitude spectra at high frequencies.

The seismological parameters are discussed in more detail in the following sections.

Earthquake Source Model

The most commonly used earthquake source model is based on the Brune's spectrum (Brune, 1970, 1971). The basic seismological model of a ground acceleration spectrum has a simple ω^2 shape, where ω is angular frequency (Brune, 1970, 1971). This model assumes that the earthquake source is modeled as a circular fault source and the ground acceleration spectrum from this simplified source has a ω^{-2} decay for frequencies below a source-corner frequency (f_c) and a flat level for frequencies greater than source-corner frequency and less than site-corner frequency (f_{max}). The amplitude spectrum level begins to drop faster at higher frequencies beyond the site-corner frequency. The choices of source and site-corner frequencies depend mainly on the earthquake size and the site condition, respectively.

The point-source spectrum model is defined as

$$E(M_0, f) = CM_0 S(M_0, f),$$
(2)

where *C* is the frequency-independent scaling factor and $S(M_0, f)$ is the source displacement spectrum. The constant *C* is defined as

$$C = \frac{\Re VF}{4\pi\rho_s \beta_s^3 R_0}, \tag{3}$$

where $\Re = 0.55$ is the scaling parameter to account for the average shear-wave radiation pattern, F = 2 is the freesurface amplification, $V = 1/\sqrt{2}$ is the partition of total shear-wave energy onto two horizontal components, ρ_s and β_s are the mass density and the shear-wave velocity in the vicinity of the earthquake source, and $R_0 = 1$ km is a reference distance. Boore (2000) suggests the use of $\rho_s = 2.8$ g/cm³ and $\beta_s = 3.5$ km/sec for WNA, and $\rho_s = 2.8$ g/cm³ and $\beta_s = 3.6$ km/sec for ENA. These regional physical constants were used in this study as input to the stochastic simulation models.

At near-source distances and large magnitudes, the ground acceleration spectrum becomes much more sensitive to the details of fault location and its exact configuration. For instance, matching the predicted and the measured spectral amplitudes at low-to-intermediate frequencies ($\sim 0.1-2$ Hz) indicates that the shape of the Fourier spectrum of the near-field motions should have two corner frequencies in-

stead of a single-corner frequency (Atkinson and Boore, 1995; Atkinson and Silva, 2000). The equivalent spectrum shape of model is flat for frequencies greater than the second corner, goes as ω^{-1} between the corners, and decays as ω^{-2} for the low frequencies. The corner frequencies are a function of moment magnitude. As the fault length increases, the corner frequencies move to lower frequencies. The observed discrepancy between the single-corner source model and the empirical data could be the reason for considering the effects of finite-fault source at short distances.

Atkinson and Silva (2000) and Atkinson and Boore (1995) have proposed a generalized form of source spectrum that provides a better fit to the empirical spectral shapes in both the WNA and the ENA regions. A double-corner frequency source model for displacement spectrum is expressed as

$$S(M_0, f) = \left[\frac{1-\varepsilon}{1+\left(\frac{f}{f_a}\right)^2} + \frac{\varepsilon}{1+\left(\frac{f}{f_b}\right)^2}\right], \quad (4)$$

where in the case of $M_w \ge 4$, the lower (f_a) and the higher (f_b) corner frequencies for earthquakes in ENA are given by (Atkinson and Boore, 1995):

$$\log f_a = 2.41 - 0.533M_w$$

$$\log f_b = 1.43 - 0.188M_w$$
 (5)

$$\log \varepsilon = 2.52 - 0.637M_w$$

In the case of $M_w \ge 4.8$, the lower (f_a) and the higher (f_b) corner frequencies for earthquakes in WNA are given by (Atkinson and Silva, 2000):

$$\log f_a = 2.181 - 0.496M_w$$

$$\log f_b = 2.410 - 0.408M_w$$
 (6)

$$\log \varepsilon = 0.605 - 0.255M_w$$

The parameter (ε) is a relative weighting parameter whose value lies between 0 and 1 (where, for $\varepsilon = 1$, the doublecorner frequency model is identical with a single-corner frequency model). According to the stochastic modeling of California proposed by Atkinson and Silva (2000), the double-corner source model and finite-fault stochastic model will generate the same median ground motion. Thus, both the single- and double-corner source models are utilized in this study to provide a representation of the epistemic uncertainty in ground-motion prediction at rock site in the region.

The source spectrum depends on two key parameters: (1) the size of the earthquake given by the seismic moment and (2) the energy released during the earthquake defined by the Brune stress drop. The seismic moment (M_0) defines the size of the earthquake based on the product of the rigidity modulus (μ), the area of fault rupture (A), and the average

slip along the fault rupture (D). Moment magnitude (M_w) is related to M_0 by the Hanks and Kanamori's relationship (1979). In general, the Brune stress drop ($\Delta \sigma$) is computed from the high-frequency energy of the Fourier amplitude spectra of measured earthquakes (Atkinson and Silva, 1997). Many researchers believe that the stress drops of earthquakes are higher in the ENA region than in the WNA region. They found that the median stress drop of earthquakes vary from 100 to 200 bars in ENA and 50 to 120 bars in WNA (EPRI, 1993; Boore and Joyner, 1997; Atkinson and Silva, 1997; Toro et al., 1997). The higher corner frequency that is proportional to stress drop would increase the amplitude levels at higher frequencies. In ENA, we included the median values of stress drops recommended in previous studies (Campbell, 2003) by different weights for each of the alternative values (see Table 4). The value of stress drop may be used as a fitting parameter to adjust the source spectrum model to adequately model observed ground motions that may not fit a single-corner source model. Hence, the empiricalstochastic source simulation can be performed to predict the ground-motion parameters for magnitudes and distances established from both the single- and the double-corner source modeling.

Filter Function of the Transfer Media

The loss of wave energy within a geological medium is calculated by multiplying a point-source geometrical attenuation factor by a deep crustal damping factor. The geometrical attenuation factor is modeled by using the distance parameter and depends mainly on the regional thickness of the earth crust.

In the ENA region, the geometric attenuation of seismic waves is given by three-part expression (Atkinson and Boore, 1995). The spherical spreading of body waves results in an R^{-1} amplitudes decay within a 70 km distance range. Beyond 70 km, the direct shear waves are superimposed by waves reflected from the Moho discontinuity and offset any decay in the amplitude of seismic waves between 70 and 130 km. The cylindrical spreading of surface waves results in an $R^{-0.5}$ amplitudes decay beyond 130 km. In the WNA region, the geometrical attenuation is modeled by a spherical spreading of R^{-1} to a distance of 40 km and a cylindrical spreading of $R^{-0.5}$ beyond 40 km (Raoof *et al.*, 1999).

The amplitude of ground motion is proportional to the factor $\exp(-\gamma R)$, where *R* is distance and γ is the coefficient of anelastic attenuation, given by

$$\gamma = \frac{\pi f}{Q\beta}.$$
 (7)

The quality factor, Q(f), models anelastic attenuation and scattering within the deep crustal structure. The qualityfactor model used in this study is considered as a function of frequency for both the WNA and the ENA regions. The quality factor is inversely proportional to the damping. The regional Q(f) factor seems to be higher in ENA than in WNA. The refitted results of 1500 seismograms from 100 small and moderate earthquakes and associated uncertainties in ENA show that the quality factor can be modeled as the median of seismic wave attenuation with the lower and the upper uncertainty levels (EPRI, 1993; Atkinson and Boore, 1995).

$$Q_{s(\text{upperlevel})} = 1000 f^{0.30}$$

$$Q_{s(\text{medianlevel})} = 680 f^{0.36}$$

$$Q_{s(\text{lowerlevel})} = 400 f^{0.40}$$
(8)

In the WNA region, the ground-motion attenuation associated with this spreading model is represented by a frequency-dependent regional quality factor (Raoof *et al.*, 1999) given by function

$$Q_s = 180 f^{0.45} \tag{9}$$

Anelastic attenuation in ENA and WNA are then given by $\exp(-\gamma_{\text{ENA}}R)$, where $\gamma_{\text{ENA}} = 0.00122f^{0.64}$ (when the median level of quality factor in equations (8) is considered), and $\exp(-\gamma_{\text{WNA}}R)$, where $\gamma_{\text{WNA}} = 0.00499f^{0.55}$, respectively.

Filter Function of the Local Site Conditions

Anderson and Hough (1984) proposed a low-pass filter based on the spectral decay parameter (κ) that produces a near-surface attenuation of high-frequency energy. The κ filter (shallow crustal damping) is defined as the highfrequency slope of the Fourier amplitude spectra plots. Anderson and Hough (1984) found κ approaching a constant value near the epicenter of a seismic event and assumed it depended on the subsurface geology. At longer distances from the source, κ increases slightly due to path effects associated with wave propagation in the crust and quality factor.

In the WNA region, the value of κ is in the order of about 0.02–0.04 sec (Anderson and Hough, 1984). The κ value of 0.04 is adopted for the hard-rock site in WNA. The value of κ decreases to 0.006 sec in the ENA region (Silva and Darragh, 1995), because the high-frequency contents of ground motions in the ENA region are more abundant than those in the WNA region. The κ values used in this study (see Table 4) are similar to the values considered by Campbell (2003).

The crustal model defines the shear-wave velocity and density as a function of depth. Boore and Joyner (1997) have shown that the average value of shear velocity (\bar{V}_s) in the upper 30 m for generic rock sites in WNA is estimated to be about 620 m/sec. They have estimated that the shear-wave velocity at source depths in ENA is 3.6 km/sec and the average shear-wave velocity in the upper 30 m is about 2900 m/sec. The final shear-wave velocity models for generic softand hard-rock sites are listed in Tables 1 and 2. In this study, the results of Joyner and Boore (1997) including the generic

 Table 1

 Characteristic Shear-Wave Velocity Profile for Generic Soft-Rock Sites in WNA (Source: Boore and Joyner, 1997)

Depth, km	Velocity, km/sec	Density, g/cm ³
$z \le 0.001$	0.245	2.495
$0.001 < z \le 0.03$	$2.206z^{0.272}$	*
$0.03 < z \le 0.19$	$3.542z^{0.407}$	*
$0.19 < z \le 4.00$	$2.505z^{0.199}$	*
$4.00 < z \le 8.00$	$2.927z^{0.086}$	*
≥ 8.00	3.500	2.800

*Estimated by equation (10).

 Table 2

 Characteristic Shear-Wave Velocity Profile for Generic Hard-Rock Sites in ENA (Source: Boore and Joyner, 1997)

Depth, km	Velocity, km/sec	Density, g/cm ³
0.00	2.768	2.731
0.05	2.808	2.735
0.10	2.847	2.739
0.15	2.885	2.742
0.20	2.922	2.746
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
$0.75 < z \le 2.20$	$3.324z^{0.067}$	*
$2.20 < z \le 8.00$	$3.447z^{0.0209}$	*
≥ 8.00	3.600	2.800

*Estimated by equation (10).

shear-wave velocity profiles are used to define the parameters of the local site profiles in WNA and ENA.

The density (ρ in g/cm³) is given as a function of shearwave velocity (β in kilometers per second) by the following simple relation (Campbell, 2003):

$$\rho(z) = 2.5 + 0.09375[\beta(z) - 0.3].$$
(10)

When seismic waves travel through the previouslymentioned crustal models, the amplitude, frequency content, and duration of ground surface motions change. The extent of these changes depends mainly on the geometry and material properties of the subsurface conditions. Boore and Joyner (1997) provide site-amplification factors, A(f) from the shear-wave velocity profiles in both WNA and ENA as a function of frequencies. The site-amplification factors have been computed by using the quarter-wavelength approximation method (Joyner *et al.*, 1981). In this method, amplification at a specific frequency (or wavelength) is given by the square root of the ratio between the seismic impedance (product of shear-wave velocity and density) at the site averaged over a depth equal to one quarter of the wavelength and the seismic impedance at the source. Table 3 lists amplifications versus frequencies for the soft- and the hard-rock sites proposed by Boore and Joyner (1997). Amplification factors at other frequencies are obtained by interpolation, assuming a linear dependence between log-frequency and log-amplification.

Outline of the Random Vibration Theory for Extreme Values

The stochastic source model provides the average shape and amplitude level of earthquakes for a wide range of magnitudes and distances (Hanks and McGuire, 1981; Boore, 2003). First, the stochastic model is used to generate an acceleration time history as a Gaussian white noise. The Fourier amplitude spectrum of time history is then combined with the seismological model of ground motion to obtain desired spectrum shape at the near-source distance, as a function of earthquake size. RVT is finally used to determine maximum ground-motion parameters such as PGA and SA for developing the attenuation relationships. Thus, the process of developing site- and region-specific attenuation relationships involves exercising the stochastic compositesource model for a suite of magnitudes and distances and then regressing on the predicted ground motion. Regionaland site-specific elements are introduced through the selection of appropriate model parameters and their uncertainties. For example, epistemic uncertainty about the median ground-motion regression is estimated through multiple ground-motion estimates at each magnitude and distance based on random model parameters.

RVT is used to estimate peak ground motion parameters including PGA and peak spectral acceleration (SA_{max}) from root mean square (rms) parameters (Silva, 1992). The maximum acceleration or peak ground acceleration (a_{max} , PGA) from equation (1) is obtained by the Cartwright and Longuet-Higgins (1956) approach using the maxima of a random function. This approach assumes that the phases of a random function are random and uniformly distributed between 0 and 2π . The peak of a random function can be calculated from its rms value by the ratio of y_{max} to y_{rms} as the following functional form:

$$\frac{y_{\text{max}}}{y_{\text{rms}}} = 2 \int_{0}^{\infty} \left\{ 1 - (1 - \xi \exp(-z^2)^{N_e} \right\} dz$$
$$\approx \sqrt{2 \ln N_z} + \left(\frac{0.5572}{\sqrt{2 \ln N_z}} \right), \quad (11)$$

where $\xi = N_z/N_e$, N_z and N_e are the number of zero crossings and the number of extrema in the time domain. Parseval's theorem relates the total energy in the frequency domain to the total energy in the time domain. Thus, the $y_{\rm rms}$ is defined as function

 Table 3

 Theoretical Site-Amplification Factors for Two Different

 Subsurface Conditions (Source: Boore and Joyner, 1997)

Soft-Rock S	ites (WNA)	Hard-Rock S	Sites (ENA)					
Frequency, Hz	Amplification	Frequency, Hz	Amplification					
0.01	1.00	0.01	1.00					
0.09	1.10	0.10	1.02					
0.16	1.18	0.20	1.03					
0.51	1.42	0.30	1.05					
0.84	1.58	0.50	1.07					
1.25	1.74	0.90	1.09					
2.26	2.06	1.25	1.11					
3.17	2.25	1.80	1.12					
6.05	2.58	3.00	1.13					
16.60	3.13	5.30	1.14					
61.20	4.00	8.00 1.15						
		14.00	1.15					

 Table 4

 Alternative Seismological Parameters Used with the Stochastic Method in WNA and ENA*

Parameters	WNA	ENA
Source spectrum model	SCPS	SCPS
	DCPS	DCPS
Stress drop (bars)	120-90 (SCPS)	105 (0.05), [†] 125 (0.25),
	90-60 (DCPS)	150 (0.40), 180 (0.25),
Quality factor	180f ^{0.45}	$\begin{array}{c} 215 \ (0.05) \\ 400 f^{0.40} \ (0.3),^{\dagger} \\ 622 \ 60 \ 36 \ 60 \ 1) \end{array}$
Карра	0.04	$\begin{array}{c} 680f^{0.30} (0.4), \\ 1000f^{0.30} (0.3) \\ 0.003 (0.3),^{\dagger} 0.006 (0.4), \end{array}$
		0.012 (0.3)

*WNA, western North America; ENA, eastern North America; SCPS, single-corner point source; DCPS, double-corner point source.

[†]Weighting factors. After Campbell (2003).

$$y_{\rm rms} = \left[\frac{1}{T_{\rm rms}}\int_{0}^{\infty} |Y(M_0, R, f)|^2 df\right]^{1/2},$$
 (12)

where $T_{\rm rms}$ is the equivalent rms duration and is estimated as follows (Boore and Joyner, 1984; Liu and Pezeshk, 1999)

$$T_{\rm rms} = T_{\rm gm} + T_0 \left(\frac{\gamma^3}{\gamma^3 + 1/3} \right),$$
 (13)

where $\gamma = T_{\rm gm}/T_0$ The ground-motion duration is given by $T_{\rm gm} = T_s + T_p$, in which T_s is the duration of source, and T_p is the duration of path. The source duration can be defined as the time for the fault rupturing and is proportional to the inverse of the corner frequency (Hanks and McGuire, 1981). The path duration depends on the epicentral distance and is estimated based on the method proposed by Atkinson and Boore (1995). In the WNA region, a simplified representation of ground-motion duration is adopted as follows:

$$T_{\rm gm} = \frac{1}{f_c} + 0.05R,$$
 (14)

whereas the ground-motion duration in the ENA region can be represented by the following model:

$$T_{\rm gm} = \frac{1}{2f_a} + bR,$$
 (15)

where f_c is the corner frequency, f_a is the lower corner frequency for earthquakes in ENA, and *b* represents the slope of the path duration. The slope (*b*) is zero for R < 10 km, 0.16 for $10 \le R \le 70$ km, -0.03 for $70 < R \le 130$ km, and 0.04 for 130 < R < 1000 km (Atkinson and Boore, 1995).

The oscillator duration (T_0) is given by

$$T_0 = \frac{1}{2\pi} f_r \,\xi, \tag{16}$$

where f_r and ξ are the undamped natural frequency and 5% of critical damping ratio of a single-degree-of-freedom system, respectively.

Independent Seismic Parameters

Dependent seismic parameters for the earthquake source model include Brune stress drop, quality-factor model (deep crustal damping), kappa (shallow crustal damping), a crustal model, and a shallow profile at the site. Independent seismic parameters are magnitudes (M) and distances (R), which are selected to cover the appropriate ranges in M and R in the hazard analyses. Many different scales can be used to define magnitude and distance. In this study, 5%-damped pseudoacceleration for frequencies of 0.25-100 Hz and PGA are simulated for moment magnitudes ranging from 5.0 to 8.2, in 0.2 magnitude-unit increments, and for rupture distances (closest distance to the rupture plane) equal to 1, 2, 3, 5, 10, 20, 30, 40, 50, 100, 130, 200, 300, 500, and 1000 km. The effective distance is a function of focal depth and, in turn, the earthquake size (Atkinson and Silva, 2000). We perform the double-corner source simulation for source focal depths that increase with magnitudes. In this study, we used a focal depth of 4.5 km for M_w 5.0 and of about 15 km for M_w 8.2 as they were proposed by Atkinson and Silva (2000). It reflects that seismic waves, whose wavelengths are much smaller than the earthquake source rupture, do not increase in amplitude as the earthquake size and energy release increase. The variation of focal depth would affect the shape of the attenuation curves at near-source distances. Thus, we would observe the effect of amplitude saturation (a constant amplitude value as distance is decreased) in the plot of empirical attenuation relationship in ENA.

$Y_{\rm ENA}/Y_{\rm WNA}$ Theoretical Modification Factors

The ratio of $Y_{\rm ENA}/Y_{\rm WNA}$ for ground-motion amplitudes are first derived to predict the equivalent ENA ground motions from the WNA ground motions. To achieve that, the computer program SMSIM (Boore, 2000) is used to calculate stochastic simulation of ground-motion amplitudes in WNA and ENA. If the amplitudes are estimated to be similar in the two regions for events of the same moment magnitude, there appears to be little difference in the path and the source model from the ENA and WNA earthquakes. In such a case, the empirical attenuation relationships in WNA can be utilized to predict the equivalent ground motions in ENA. Otherwise, the median amplitude ratio for each of the magnitudes, distances, and ground-motion parameters is multiplied by the median WNA empirical ground motions. The median amplitude ratio of ground motions at a certain frequency, magnitude, and distance is given by the following equation:

$$\frac{Y_{\text{ENA}}}{Y_{\text{WNA}}} = \frac{E_{\text{ENA}}(f_c)}{E_{\text{WNA}}(f_c)} \times \frac{A_{\text{ENA}}(f)}{A_{\text{WNA}}(f)} \times \frac{G_{\text{ENA}}(R)}{G_{\text{WNA}}(R)} \times \exp[R(\gamma_{\text{WNA}} - \gamma_{\text{ENA}}) + \pi f(\kappa_{\text{WNA}} - \kappa_{\text{ENA}})].$$
(17)

To incorporate the uncertainties into the calculations, the decision-making process will be formulated as the process of choosing a parameter value from among the available alternative parameter values. Each parameter value is assigned a weighting factor that is interpreted as the probability of that parameter being correct. The sum of the weights associated to a given parameter must be equal to unity. Table 4 lists alternative seismological parameters that influence ground motions in both regions. The degree of preference in alternative source models is expressed by the logic tree weights. Strong and weak preferences are presented by weighting factors of 0.9 and 0.1, respectively. If there is no preference for either model (e.g., attenuation relationships), they are assigned equal weights. Observed differences between the WNA and the ENA motions are within the reasonable range to regional differences in Brune stress drop, crustal properties, and combined effects of amplification and attenuation. These modification factors for each pair of magnitude and distance at a specified frequency are used to convert the WNA to the ENA ground motions. Table 5 shows the variation of modification factors for all magnitudes at a source distance of 10 km. The differences in ground motion between the two source models depend on magnitude and frequency. The single-corner source model shows larger low-frequency motions and smaller high-frequency motions at the large magnitudes ($M_w \ge 6.4$) than the double-corner source model. Thus, for instance, the 2003 Campbell attenuation relationship underestimates the ground motions for large magnitudes at the 0.2-sec period. This constraint (the use of point-source models) would be very significant when the relationship is used to estimate the ground motion from a large earthquake in the New Madrid seismic zone (NMSZ).

Ground Motions in WNA and ENA

Several researchers have developed attenuation relationships in the WNA region where sufficient ground-motion records are available. Abrahamson and Silva (1997) estimated ground motions for shallow crustal earthquakes based on a database of 655 recordings from 58 earthquakes. They used moment magnitude and the closest distance to the rupture plane for developing an attenuation relation at the periods ranging from 0.01 to 5 sec. Sadigh et al. (1997) modeled ground motions for moment magnitudes ranging from 4 to 8 and rupture distances up to 100 km at rock and soil sites based on ground motions from California earthquakes. The earthquakes used in their relation are those that occur on faults within the upper 20-25 km of continental crust. Campbell (1997) predicted ground motions at WNA rock and soil sites and introduced uncertainty in estimating modeling parameters. These three well-defined empirical attenuation relationships, each of which is assigned a relative likelihood 1/3, are used to estimate the WNA ground motions (Y_{WNA}) in equation (17). We have chosen these relationships because of their matching for magnitude-scaling characteristics and the 5%-damped pseudoacceleration values for frequencies of 0.25-100 Hz.

Figure 1a–c shows the comparison between the median ground motions for these three relations with the stochastic ground-motion estimates for moment magnitudes 5.5, 6.5, and 7.5 at a rupture distance of 10 km. The differences among these attenuation relationships in WNA are primarily due to the criteria used to select the recordings and the theo-

Table 5The Theoretical Modification Factors for All Magnitudes at R = 10 km

		Period, sec												
Magnitude	0.02	0.05	0.075	0.1	0.15	0.2	0.3	0.5	0.75	1	1.5	2	3	4
5.0	5.403	3.534	2.243	1.754	1.277	1.044	0.901	0.832	0.751	0.726	0.699	0.708	0.793	0.876
5.4	4.781	3.483	2.231	1.761	1.283	1.098	0.961	0.848	0.809	0.782	0.751	0.735	0.730	0.775
6.0	5.110	3.854	2.583	2.031	1.530	1.325	1.148	1.061	1.014	1.034	0.970	0.937	0.915	0.883
6.4	5.394	4.190	2.798	2.228	1.690	1.493	1.295	1.254	1.186	1.115	1.082	1.066	0.966	0.918
7.0	5.196	4.234	2.815	2.195	1.725	1.470	1.299	1.307	1.310	1.242	1.216	1.188	1.079	1.068
7.4	5.102	4.255	2.865	2.271	1.759	1.582	1.383	1.337	1.341	1.315	1.319	1.285	1.245	1.255
8.0	5.076	4.311	2.999	2.329	1.817	1.584	1.434	1.376	1.387	1.356	1.347	1.372	1.314	1.338



Figure 1. Comparison of 5%-damped acceleration response spectra developed in this study and predicted empirically from the WNA attenuation relationships (a) for M_w 5.5 and stress drops of 100–120 bars, (b) for M_w 6.5 and stress drops of 80–100 bars, (c) for M_w 7.5 and stress drops of 60–100 bars. AS97, Abrahamson and Silva (1997); S97, Sadigh *et al.*, (1997); C97, Campbell (1997). The comparison is for a rupture distance of 10 km and a generic rock site in WNA.

retical assumptions used to develop the models. For example, the use of a constant Brune stress drop of 100 bars in a stochastic simulation model for WNA (Campbell, 2003) is inconsistent with the response spectral shapes empirically derived by others. The Brune stress drop should be decreased from a value of about 120 bars at M_w 5.5 to a value near 60 bars at M_w 7.5. Therefore, we propose in this study a source model developed by using a combination of the double-corner source model and the stochastic point-source model for the large fault ruptures.

To have the best match to data, we utilize the stochastic point-source model for the WNA region to obtain ground motions at different magnitude-distance ranges of interest (Table 4). In the ENA region where there are no response spectra estimated from ground-motion recordings to match the data, the uncertainties in the model parameters should be taken into account. The uncertainty values recommended by EPRI (1993) and Toro et al. (1997) are incorporated into the analysis of the ENA ground motion via a logic-tree approach. The logic tree allows the use of a sequence of assessments for the models and parameters, each of which is assigned as a weighted uncertainty or likelihood (Table 4). At short distances and large magnitudes ($M_{\rm w} \ge 6.4$), the double-corner source model is performed by a weighting factor of 0.9 for both regions to consider the effects of finite-fault modeling on the peak-ground-motion parameters.

Attenuation Relation Developed for ENA

Attenuation relationships estimate ground motion as a function of magnitude and distance. We used a nonlinear least-squares regression to develop the ground-motion relations from the individual stochastic estimates. The composite functional form of this relation was developed by a GA with the functional forms proposed in previous studies (Sa-digh *et al.*, 1997; Abrahamson and Silva, 1997; Campbell, 2003) until there was a sufficient match between the predicted and observed values. These relationships have typically considered the PGA. However, more recent models estimate the spectral acceleration at select periods, in particular, at 0.2 and 1.0 sec because of the use of these periods in the seismic hazard analysis. The resulting ground-motion relation that we have developed for hard-rock sites is given by

$$\ln(Y) = f_1(M_w) + f_2(r_{rup}) + f_3(M_w, r_{rup}), \quad (18)$$

where the first term is needed to provide a better fit to the ground-motion model predictions for all frequencies, and the next two terms represent geometrical spreading and anelastic attenuation of seismic waves caused by material damping and scattering as they propagate through the crust. In these terms, r_{rup} (kilometers) is a rupture distance and defined as the closest distance to the fault rupture.

The magnitude-scaling characteristics are given by a polynomial magnitude function (Sadigh *et al.*, 1997):

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$$f_1(M_w) = C_1 + C_2 M_w + C_3 (8.5 - M_w)^{2.5}.$$
 (19)

The geometric spreading effect in terms of amplitude decay within 70 km, between 70 and 130 km, and beyond 130 km distance ranges, respectively, are given by function:

$$f_2(r_{\rm rup}) = \begin{cases} C_9 \ln(r_{\rm rup} + 4.5) & r_{\rm rup} \le 70 \text{ km} \\ C_{10} \ln\left(\frac{r_{\rm rup}}{70}\right) + C_9 \ln(r_{\rm rup} + 4.5) & 70 < r_{\rm rup} \le 130 \text{ km} \\ C_{11} \ln\left(\frac{r_{\rm rup}}{130}\right) + C_{10} \ln\left(\frac{r_{\rm rup}}{70}\right) + C_9 \ln(r_{\rm rup} + 4.5) & r_{\rm rup} \ge 130 \text{ km} \end{cases}$$

The magnitude-distance scaling characteristics are given by function

$$f_3(M_{\rm w}, r_{\rm rup}) = (C_4 + C_{13}M_{\rm w}) \ln R + (C_8 + C_{12}M_{\rm w})R,$$
 (21)

where the distance measure R includes a magnitude dependence to illustrate the effect of the focal depth on the shape of the attenuation curve which is given by (Campbell and Bozorgnia, 2003).

$$R = \sqrt{r_{\rm rup}^2 + (C_5 \exp[C_6 M_{\rm w} + C_7 (8.5 - M_{\rm w})^{2.5}])^2}.$$
(22)

We have added the parameter C_9 to account for near-source ground motions. The slope of the $\ln R$ term is magnitude dependent as was used by Abrahamson and Silva (1997). The slope of distance R is also magnitude dependent (Campbell, 2003). In these equations, r_{rup} (kilometers) is the closest distance to the fault rupture. We have found the need to develop different coefficients for events larger and smaller than $M_{\rm w}$ 6.4 to account for near-source saturation effects.

The aleatory standard deviation of ln Y is defined as a function of earthquake magnitude and is modeled as follows:

$$\sigma_{\ln Y} = \begin{cases} C_{14} + C_{15}M_{\rm w} & M_{\rm w} < 7.2\\ C_{16} & M_{\rm w} \ge 7.2. \end{cases}$$
(23)

We constructed the magnitude dependence of the standard error using an equally weighted average of the standard deviations from each of the WNA attenuation relations used in this study (Campbell, 2003). The epistemic standard deviations of ground motion in ENA can be derived for the magnitude-distance range of interest.

The regression coefficients C_1 through C_{16} for hard-rock sites at different frequencies are listed in Table 6. We used a GA to determine the unknown coefficients in the relation. The GA process starts with a population of solutions to find a theoretical attenuation curve, then continues by optimizing and fitting the theoretical curve to the stochastic groundmotion data. The final result is the best estimation of the coefficients that fits sufficiently the predicted model to the stochastic model.

$$r_{\rm rup} \le 70 \text{ km}$$

 $70 < r_{\rm rup} \le 130 \text{ km}$ (20)
 $r_{\rm rup} \ge 130 \text{ km}$

The GA focuses on a population of attenuation coefficients, which are created randomly. Coefficients are grouped in variable sets, each of which is called a string and composed of a series of characters that defines a possible solution for the problem. The performance of the variables, as described by the objective function and the constraints, is represented by the fitness of each string. A mathematical expression, called a fitness function, calculates a value for a solution of the objective function. The fitter solution gets the higher value, and the ones that violate the objective function and constraints are penalized. Therefore, like what happens in nature, the fittest and best solutions will survive and get the chance to be a parent of the next generation. In a crossover procedure two selected parents reproduce the next generation. The procedure first divides the selected parent strings into segments and then some of the segments of a parent string are exchanged with corresponding segment of another parent string. The mutation operation guarantees diversity in the generated populations. This is done by flipping (0 to 1 or vice versa) a randomly selected bit in the selected binary string to create a muted string. Mutation prevents a fixed model of solutions from being transferred to the next generation (Holland, 1975; Goldberg, 1989).

The resulting attenuation coefficients are considered to produce an alternative empirical attenuation relationship for ENA that predicts response spectra over the wide range of magnitudes (M_w 5.0–8.2) and rupture distances (r_{rup} 0– 1000). However, the WNA attenuation relationships cannot be reliable at distances greater than 200 km because all of the relationships are truncated at distances of 100-200 km. To estimate the ground motions over the distance of 200 km, we followed the magnitude-scaling model proposed by Campbell (2003). The stochastic ground motions for all magnitudes at a distance of 70 km are considered to correspond to the empirical ground-motion values for the same magnitudes at the same distance. The scaling factors calculated for all magnitudes at a distance of 70 km are used to predict ground motions at the distances of beyond 70 km.

Attenuation curves of the simulated ground motion values for PGA and spectral accelerations at periods of 0.2 and 1.0 sec are shown in Figure 2a-c, respectively. The discrepancy in ground motions between the attenuation model and

	C_{16}	4.09E - 01	4.41E - 01	4.49E - 01	4.56E - 01	4.64E - 01	4.69E - 01	4.79E - 01	5.05E - 01	5.22E - 01	5.37E - 01	5.51E - 01	5.62E - 01	5.73E - 01	5.89E - 01
	C_{15}	-1.11E-01	-1.08E - 01	-1.08E - 01	-1.08E - 01	-1.08E - 01	-1.08E - 01	-1.09E - 01	-1.73E - 01	-1.05E - 01	-1.03E - 01	-9.99E - 02	-9.78E - 02	-9.52E - 02	-9.26E - 02
	C_{14}	1.21E + 00	1.22E + 00	1.22E + 00	1.23E + 00	1.24E + 00	1.24E + 00	1.26E + 00	1.28E + 00	1.28E + 00	1.28E + 00	1.27E + 00	1.26E + 00	1.26E + 00	1.25E + 00
	C_{13}	1.33E - 04	9.30E - 04	7.33E - 04	3.58E - 04	6.84E - 04	6.43E - 04	2.87E – 04	1.46E - 04	5.47E - 04	7.59E - 04	1.66E - 04	3.91E - 04	3.98E - 04	3.59E - 04
ENA	C_{12}	4.32E - 04	5.12E - 04	4.82E - 04	4.11E - 04	3.64E - 04	1.61E - 04	4.32E - 04	2.77E - 04	2.45E - 04	1.17E - 04	2.33E - 04	2.14E - 04	1.16E - 04	1.10E - 04
nuation in E	C_{11}	-9.61E - 01	-9.39 E - 01	-9.16E - 01	-9.13E - 01	$-8.65\mathrm{E}-01$	-9.25E - 01	-9.15E-01	-8.59E - 01	-7.84E - 01	-7.57E - 01	-7.69E - 01	-7.55E - 01	-8.18E - 01	-7.37E-01
nastic Atter	C_{10}	1.41E + 00	9.80 E - 01	1.13E + 00	1.04E + 00	1.51E + 00	1.64E + 00	1.52E + 00	1.59E + 00	1.55E + 00	1.52E + 00	1.71E + 00	1.43E + 00	1.93E + 00	1.69E + 00
rical-Stocha	C,	9.46E - 03	-3.14E - 03	-5.50E - 03	-4.24E-03	$3.93 \mathrm{E} - 03$	-2.02E - 03	6.44E - 03	-2.65 E - 04	-1.19E - 03	$3.30 \mathrm{E} - 03$	2.51E - 03	2.30E - 03	3.58E - 03	-3.34E-03
a New Emp	C_8	$-4.05 \mathrm{E} - 03$	-4.91E - 03	-4.94E - 03	-4.70E - 03	-4.80E - 03	-3.65 E - 03	-5.41E - 03	-3.65 E - 03	-3.37E - 03	$-2.09 \mathrm{E} - 03$	-3.27E-03	-2.14E-03	$-2.03 \mathrm{E} - 03$	-1.72E-03
Developing	\mathbf{C}_7	-2.93E - 05	7.77E - 03	-9.68E - 04	-6.19E-03	$6.60 \mathrm{E} - 03$	2.79E - 03	1.08E - 02	7.89 E - 03	9.53E - 03	-5.84E - 03	8.30E - 03	$2.06\mathrm{E}-02$	1.67E - 02	1.13E - 02
ficients for	C ₆	4.46E - 01	4.54E - 01	$4.60 \mathrm{E} - 01$	4.49 E - 01	4.14E - 01	4.33E - 01	4.68E - 01	4.14E - 01	4.35E - 01	4.24E - 01	4.12E - 01	4.08E - 01	4.37E - 01	4.25E-01
ession Coef	C_5	-6.52E-01	-5.67E - 01	-7.56E - 01	-7.04E - 01	-9.76E - 01	$-8.61 \mathrm{E} - 01$	-4.70E - 01	-8.44E-01	-7.34E - 01	-9.41E - 01	-8.86E - 01	-9.23E-01	-8.98E - 01	$-8.45 \mathrm{E} - 01$
Regr	C_4	-1.81E + 00	-1.63E + 00	-1.71E + 00	-1.52E + 00	-1.73E + 00	-1.68E + 00	-1.42E + 00	-1.55E + 00	-1.48E + 00	-1.49E + 00	-1.45E + 00	-1.44E + 00	-1.65E + 00	-1.46E + 00
	C_3	-4.83E-02	-4.75E-02	-2.93E-02	-4.74E-02	-6.42E - 02	-2.62E - 02	-4.43E-02	-7.89E - 02	-8.30E - 02	-8.59 E - 02	-8.84E - 02	-9.29 E - 02	-1.08E - 01	-1.18E - 01
	C_2	6.23 E - 01	5.33E - 01	7.43E - 01	6.07E - 01	5.01E - 01	8.57E - 01	6.67E - 01	6.11E - 01	6.66E - 01	7.64E - 01	7.94E - 01	8.05E - 01	8.01E - 01	8.17E-01
	C1	1.14E + 00	1.82E + 00	6.83E - 01	8.69 E - 01	2.38E + 00	-5.48E - 01	$-5.13 \mathrm{E} - 01$	2.40E - 01	$-6.79 \mathrm{E} - 01$	-1.55 E + 00	-2.30E + 00	-2.70E + 00	-2.42E + 00	-3.69 E + 00
	T, sec	0.00	0.05	0.08	0.10	0.15	0.20	0.30	0.50	0.75	1.00	1.50	2.00	3.00	4.00

the simulated amplitudes is very small. Thus, the ENA attenuation relationship is sufficiently accurate in the magnitude–distance ranges that are significant to seismic hazard analysis.

Comparison of Results with Other Attenuation Relations for ENA

The results of spectral accelerations calculated for an earthquake of magnitude 7.7 in ENA are compared with the other recent relations. All relations are considered for the ENA hard-rock sites. We concentrate on comparison with the relations developed by the EPRI (2003) and with those used in the 2002 national seismic hazard maps (Frankel et al., 2002). The five attenuation relations incorporated into the 2002 hazard maps include those of Atkinson and Boore (1995), Frankel et al. (1996), Toro et al. (1997), Somerville et al. (2001), and Campbell (2003). The EPRI (2003) represents four different ground-motion models, including single-corner, double-corner, hybrid-empirical, and finitesource, for developing a representation of the median ground motion and its epistemic uncertainty in ENA. For the previously mentioned attenuation models, the PGA values and spectral accelerations at two periods of 0.2 and 1.0 sec are shown in Figures 3 and 4. We have used the average ENA focal depth of 10 km to convert various distances to the horizontal distance. Figure 3a-c compares the ENA attenuation relationship in this study with the relations used in the 2002 hazard maps. Figure 4a-c compares our results with those derived in the 2003 EPRI study. At high frequencies and for PGA, the attenuation relationship developed in this study and the EPRI relations predict similar ground-motion amplitudes for nearly all magnitudes and distances. Note that the 2003 EPRI4 relationship and the 2001 Somerville et al. relationship are identical. The apparent differences in the shape of the attenuation curves come mainly from the mathematical functional form of the relations. The attenuation relationship developed in this study for distances more than 30 km is most consistent with the 1996 Frankel et al. relationship and the 1997 Toro et al. relationship. The 2003 Campbell relationship and the 2001 Somerville et al. relationship for the ENA region underpredict PGA for distances less than 50 km in comparison with the attenuation relationship developed in this study. This underprediction is not evident at the spectral acceleration of 1.0 sec. The 0.2- and 1.0sec spectral accelerations in Figures 3 and 4 indicate that the attenuation relationship developed in this study at nearsource distances is similar to the 2001 Somerville et al. relationship (the 2003 EPRI4 relationship). This relationship is the only finite-source model available in ENA. The calculated spectral accelerations at 1.0 sec for hard-rock sites show that the predicted spectral accelerations are consistent with the all attenuation models, excluding the Atkinson and Boore (1995) and the EPRI2 relationships. The lower values predicted by these two models are due to the source models and the magnitude-scaling characteristics used. For 1.0-sec

Table 6



Figure 2. Empirical-stochastic attenuation relation developed in this study for ENA. The solid lines show the empirical attenuation of Table 5 and the filled circles illustrate the stochastic groundmotion estimates at different distances from the source. (a) Attenuation of peak horizontal acceleration. (b) Spectral horizontal acceleration at 0.2-sec period. (c) Spectral horizontal acceleration at 1.0-sec period. The attenuation relation has been evaluated for magnitudes of M_w 5.0, 6.0, 7.0, and 7.6 at the hard-rock site conditions in ENA.



Figure 3. Comparison of several ENA ground-motion relations used in the 2002 national seismic hazard maps (dashed lines) with the empirical-stochastic attenuation model (solid line) for (a) PGA, (b) 5%-damped response spectral acceleration at 0.2-sec period, and (c) 5%-damped response spectral acceleration at 1.0-sec period. For this comparison, we assumed an M_w 7.7 earthquake with a focal depth of 10 km occurs at a hard-rock site in ENA. AB95, Atkinson and Boore (1995); C03, Campbell (2003); FEA96, Frankel *et al.* (1996); SOEA01, Somerville *et al.* (2001); TEA97, Toro *et al.* (1997).



Figure 4. Comparison of several ENA groundmotion relations derived in the 2003 EPRI study (dashed lines) with the empirical-stochastic attenuation model (solid line) for (a) PGA, (b) 5%-damped response spectral acceleration at 0.2-sec period, and (c) 5%-damped response spectral acceleration at 1.0sec period. For this comparison, we assumed an M_w 7.7 earthquake with a focal depth of 10 km occurs at a hard-rock site in ENA.



Figure 5. Comparison of ground-motion amplitudes developed in this study (solid line) with the observed ground-motion data (circles) in ENA for (a) 5%-damped response spectral acceleration at 0.2-sec period and (b) 5%-damped response spectral acceleration at 1.0-sec period. The observed data show the spectral amplitudes for events of $4.8 < M_w < 5.2$.

spectral acceleration, the values of the attenuation relationship developed in this study for distances less than 30 km is estimated to be lower than the 1996 Frankel *et al.* relationship and the 1997 Toro *et al.* relationship. The variation of focal depth would affect the shape of the attenuation curves (near-source saturation), and, in turn, our ground-motion prediction would tend to have lower values at near-source distances. The 2003 Campbell attenuation model gives lower ground-motion values for large magnitudes at near-source distances than those developed in this study. Despite of the similarity in the magnitude scaling, geometrical and anelastic attenuation characteristics for these two models, the variation of Brune stress drops and source models in WNA would lead to biased ground-motion attenuation in the ENA region. In other words, the theoretical modification factors ($Y_{ENA}/$ Y_{WNA}) in the hybrid-empirical method are sensitive to the values of Brune stress drop used to predict ground motions in WNA, in particular, for large magnitudes. Thus, the 2003 Campbell relationship in ENA would exhibit unrealistic attenuation characteristics for large magnitudes at short distances because of a constant value of 100 bars for the Brune stress drop at all magnitudes.

Comparison of Results with Observed Ground-Motion Data for ENA

The 0.2- and 1.0-sec spectral accelerations are compared with the ENA ground-motion data (Kaka and Atkinson, 2005) at hard-rock sites to test the prediction of groundmotion relationships developed in this study. In Figure 5a and b, the 0.2- and 1.0-sec spectral accelerations for magnitude 5.0 are compared with the recorded ground-motion data. Some instruments recorded only the vertical components, and these data should be converted to an equivalent horizontal component. Kaka and Atkinson (2005) suggested correction factors of 1.13 and 1.36 to be used to convert vertical-component data to the average horizontal-component values for periods of 1.0 and 0.2 sec, respectively. These conversion factors are used in this study to plot the equivalent horizontal components from the vertical data in ENA.

Based on Figure 5a and b, one may conclude that the attenuation relationships developed in this study are in good agreement with the data.

Discussion

The discrepancy between the ENA attenuation models provides a representation of the epistemic uncertainty in ground-motion prediction at the hard-rock sites. These differences are attributed in this study to the use of different source models and parameters. In the probabilistic hazard calculations, for the development of a reliable scenario spectrum at a given site, the different attenuation relationships should be employed with different weighting factors. The degree of preference in the selection of an attenuation relationship depends mainly on how well the seismic source characterizations are defined. The most important differences in defining seismic models and parameters concern the source models and the parameters such as Brune stress drop and kappa. The large difference in ground-motion levels between the single (point) and double-corner source models reflects the large contribution of Brune stress drop variability. Thus, the differences in ground motion between the two source models depend on magnitude and frequency. The single-corner source model shows larger low-frequency motions and smaller high-frequency motions at the large magnitudes $(M_w \ge 6.4)$ than the double-corner source model. Accordingly, at low frequencies the attenuation relationship developed in this study and the finite-source relationship (Somerville et al., 2001) predict equal ground-motion amplitudes at near-source distances, but our results estimates larger amplitudes from large ($M_{\rm w} \ge 6.4$) earthquakes at distances greater than 100 km. These ground-motion amplitudes cover a similar range of values as those of the pointsource attenuation relations for the ENA hard-rock sites. Frankel et al. (1996), Toro et al. (1997), and Campbell (2003) used the point-source stochastic model, whereas Atkinson and Boore (1995) used a double-corner source model to estimate ground-motion amplitudes in ENA. We used an empirical-stochastic source model that is a reliable model to predict ground motion, in particular, for large magnitudes at near-source distances. Another significant difference in parameters is kappa, which affects the high-frequency amplitudes such as the PGA. The kappa variation, which is a function of different rock site conditions, causes different amplification factors in a given site class.

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