Empirical Near Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra

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ABSTRACT

A consistent set of empirical attenuation relationships is presented for predicting free-field horizontal and vertical components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute acceleration response spectra (PSA). The relationships were derived from attenuation relationships previously developed by the author from 1990 through 1994. The relationships were combined in such a way as to emphasize the strengths and minimize the weaknesses of each. The new attenuation relationships are considered to be appropriate for predicting free-field amplitudes of horizontal and vertical components of strong ground motion from worldwide earthquakes of moment magnitude (M_W) ≥ 5 and sites with distances to seismogenic rupture (R_{SEIS}) ≤ 60 km in active tectonic regions.

INTRODUCTION

The development of design ground motions is a critical part of the seismic design of engineered structures. Methods commonly used to develop these ground motions include: (1) seismic zoning maps, (2) site-specific deterministic analyses, and (3) site-specific probabilistic seismic hazard analyses (*e.g.*, Campbell, 1992a). All of these methods require a strong-motion attenuation relationship to estimate earthquake ground motions from simple parameters characterizing the earthquake source, the propagation path between the earthquake source and the site, and the geologic conditions beneath the site. See Campbell (1985) for a general discussion of attenuation relationships and their parameters.

Design ground motions are often controlled by a hypothesized occurrence of a large earthquake on a nearby fault. Therefore, it is important that the seismological model or attenuation relationship used to predict these design ground motions specifically addresses this requirement. This study describes a set of empirical attenuation relationships that were specifically developed to predict horizontal and vertical components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute acceleration response spectra (PSA) in the near-source region of moderate-to-large earthquakes.

The attenuation relationships presented in this paper represent a compendium and synthesis of near-source attenuation relationships previously developed by the author (*e.g.*, Campbell, 1981, 1987, 1989a, 1990, 1992a, 1993; Campbell and Bozorgnia, 1994a). The 1989 and 1990 studies provided the only coherent set of attenuation relationships for both the horizontal and vertical components of PGA, PGV, and PSA—the 1989 study for soil sites and the 1990 study for both soil and soft rock sites. In 1993, these studies were extended to include hard rock recordings, but only for the horizontal components of PGA and PSA. In the 1994 study, the attenuation relationship for the horizontal component of PGA underwent a major revision with the addition of recordings on soil, soft rock, and hard rock from significant worldwide earthquakes that occurred from 1987 to 1992, and from selected worldwide earthquakes that occurred prior to 1987.

Recommended Ground Motion Models

Engineering applications require ground motion predictions for all strong motion parameters and local site conditions. Therefore, it is desirable to have a single coherent set of near-source attenuation relationships. With this in mind, the attenuation relationships of Campbell (1990, 1993) and Campbell and Bozorgnia (1994a) were combined in such a way as to incorporate the strengths and minimize the weaknesses of each. As described later in the paper, the relationship for the horizontal component of PGA was developed from the study of Campbell and Bozorgnia (1994a); the relationships for the horizontal components of PGV and PSA were developed from the studies of Campbell (1990, 1992b) for soil and soft rock and from Campbell (1993) for hard rock; and the relationships for the vertical components of

PGA, PGV, and PSA were developed from the study of Campbell (1990).

MODEL PARAMETERS

Strong Motion Parameters

The strong-motion parameters of interest in this study include the horizontal and vertical components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute acceleration response spectra (PSA), hereafter referred to as spectral acceleration. The horizontal and vertical components of PGA are denoted A_H and A_V, the horizontal and vertical components of PGV are denoted V_H and V_V, and the horizontal and vertical components of PSA are denoted SA_H and SA_V, respectively. The horizontal ground motion parameters, defined as the geometric mean (*i.e.*, the mean of the logarithm) of the peaks of the two horizontal components, are approximately 12% and 17% less than the largest horizontal component of PGA and PGV, respectively (Campbell, 1981; Joyner and Fumal, 1984). For PSA, the relationship between the geometric mean and the peak is a function of the oscillator period (*e.g.*, see Boore *et al.*, 1993).

Earthquake Magnitude (M)

Moment magnitude (M_W) was used to define earthquake magnitude in the study by Campbell and Bozorgnia (1994a). The use of moment magnitude avoids the "saturation" of the more traditional band-limited magnitude measures at large seismic moments and, therefore, is considered to be a better measure of the true size of an earthquake (*e.g.*, Bolt, 1993)

Earlier studies (*e.g.*, Campbell, 1989a, 1990, 1992b, 1993) used surface-wave magnitude (M_S) to define earthquake magnitude for earthquakes with $M_S \geq 6$ and local magnitude (M_L) to define earthquake magnitude for earthquakes with $M_S < 6$. A comparison of magnitude scales presented by Heaton *et al.* (1986) indicates that M_L is approximately equal to M_W for $M_L < 6.5$ (see also Bakun, 1984; Hanks and Boore, 1984) and that M_S is approximately equal to M_W for M_S ranging from 6.0 to 8.0. Thus, the magnitude measures used in these earlier studies are consistent with M_W over the range of magnitudes of engineering interest and the magnitude measure used in the attenuation relationships recommended in this study can be considered to be M_W for all intents and purposes.

Source-to-Site Distance (R_{SEIS})

Source-to-site distance is defined as the shortest distance between the recording site and the presumed zone of seismogenic rupture on the fault. Implicit in this definition is the assumption that fault rupture within the softer sediments and within the upper 2 to 4 km of the fault zone is primarily non-seismogenic (Marone and Scholz, 1988). Therefore, this shallow rupture is not believed to contribute significantly to recorded ground motions at oscillator periods of engineering interest. The seismogenic part of the rupture zone was estimated from several types of information, including the mapped surface trace of the fault rupture, the spatial distribution of aftershocks, the inversion of strong motion and teleseismic recordings, regional crustal velocity profiles, and regional geodetic and geologic data.

Other distance measures that have been proposed for use in empirical attenuation relationships include the shortest distance between the recording site and the observed or inferred rupture on the fault, even if this rupture is within the softer sediments (*e.g.*, Campbell, 1981; Idriss, 1991a,b; Sadigh *et al.*, 1993; Abrahamson and Silva, 1995, 1996), and the shortest distance between the recording site and the horizontal projection of the rupture zone on the surface of the earth (*e.g.*, Joyner and Boore, 1981; Boore *et al.*, 1993, 1994).

Shakal and Bernreuter (1981) recommended that the source-to-site distance should be measured from the recording site to the closest asperity—that part of the fault rupture that releases the greatest amount of radiated energy. They suggested that ground motion predictions made using attenuation relationships that use distance measures based on the closest-distance to the fault rupture will "at best be accurate and at worst may significantly under-predict ground-motion levels." Although their proposed distance measure is admittedly more seismologically based than the closest-distance measures proposed by other investigators, their statement regarding the bias in these distance measures is true only if the relationships are developed in terms of a closest-distance measure, then applied in terms of the distance to the closest asperity. Because it is not known in advance where the true source of the strongest ground motion will come from, it is not feasible to make ground-motion predictions in terms of the distance measure recommended by Shakal and Bernreuter. On the other hand, R_{SEIS} has a reasonable seismological basis, can be reliably and easily determined for most significant earthquakes, and can be easily defined for a hypothetical design earthquake. If correctly applied, it appropriately accounts for uncertainty in the location of the actual source of the strongest recorded ground motions by including it as random variability.

Unlike the distance measures defined by Campbell (1981), Sadigh *et al.* (1986, 1993), Idriss (1991a,b), Abrahamson and Silva (1995, 1996), and Shakal and Bernreuter (1981), R_{SEIS} avoids ambiguities associated with identifying and predicting the location of asperities for large earthquakes and the shallowest extent of rupture for moderate-size earthquakes, which are often accompanied by limited surface cracking but no clear identification of surface rupture. Also, Anderson and Luco (1983) have found from theoretical ground motion modeling studies that R_{SEIS} is analytically superior to the distance measure proposed by Joyner and Boore (1981) and later used by Boore *et al.* (1993, 1994) for characterizing the attenuation of ground motion from dipping faults.

By definition, R_{SEIS} cannot be less than the depth to the top of the seismogenic part of the earth's crust. Based on

TABLE 1
Recommended Minimum Values for the Average Value of d_{SEIS}
(H_{TOP} = 3 km, H_{BOT} = 15 km)

Magnitude (M_W)	Rupture Width (W, km)	d_{SEIS} (km)		
		$\alpha = 30°$	$\alpha = 45°$	$\alpha = 90°$
5.00	3.2	8.0	7.6	7.1
5.25	4.2	7.8	7.3	6.7
5.50	5.6	7.6	7.0	6.2
5.75	7.5	7.3	6.6	5.6
6.00	10.0	7.0	6.1	4.9
6.25	13.3	6.6	5.5	4.1
6.50	17.8	6.1	4.8	3.1
6.75	23.7	5.5	4.0	3.0
7.00	31.6	4.8	3.0	3.0

observations by Marone and Scholz (1988), this depth should be no shallower than about 2 to 4 km. It can, however, be greater than this range. For example, in the Imperial Valley of California, the depth to the seismogenic portion of the crust has been determined to be at least 5 km from accurate hypocenter determinations and from the inferred principal zone of rupture during the 1979 (M_W = 6.5) Imperial Valley earthquake (Doser and Kanamori, 1986). If no other information is available, an estimate of the average depth to the top of the seismogenic rupture zone for a hypothetical earthquake can be derived by assuming that its expected rupture zone is equally likely to occur anywhere within the seismogenic part of the fault zone. This can be calculated from:

when $d_{SEIS} \geq H_{TOP}$

$$d_{SEIS} = \frac{1}{2}\left[H_{BOT} - H_{TOP} - W\sin(\alpha)\right]H_{TOP} + \frac{1}{2}[\cdot\ \cdot] \quad (1)$$

otherwise

$$d_{SEIS} = H_{TOP}$$

where d_{SEIS} is the average depth to the top of the seismogenic rupture zone, H_{TOP} and H_{BOT} are the depth to the top and bottom of the seismogenic part of the crust, α is the dip of the fault plane, and W is the expected width (down-dip dimension) of the fault rupture. Rupture width can be estimated from moment magnitude from the following relationship (Wells and Coppersmith, 1994),

$$W = -1.01 + 0.32M_W \quad (2)$$

for W in kilometers. Table 1 gives expected minimum values of d_{SEIS} for several values of M_W and α and for depths to the top and bottom of the seismogenic crust typical of California, *i.e.*, H_{TOP} = 3 km and H_{BOT} = 15 km. Values of d_{SEIS} greater than these should not be used unless supported by the specific geometry of the fault plane or the depth and thickness of the seismogenic crust.

Style of Faulting (F)

Style of faulting, or fault type, is defined by the index variable F, where F = 0 for strike-slip faulting and F = 1 for reverse, thrust, reverse-oblique, and thrust-oblique faulting. Reverse faulting is distinguished from thrust faulting by the value of the dip angle of the fault plane, with reverse faulting having a dip angle greater than or equal to 45°. To be consistent with the way F was determined in this study, strike-slip faulting is defined as an event whose absolute value of the slip direction (rake) is no more than 22.5° from horizontal as measured along the fault plane. A rake of 0° represents left-lateral strike-slip faulting, 180° represents right-lateral strike-slip faulting, 90° represents reverse or thrust faulting, and –90° represents normal faulting.

Based on theoretical and empirical studies, McGarr (1984) concluded that normal-faulting earthquakes located in extensional stress regimes are associated with lower ground motions than either strike-slip or reverse-faulting earthquakes located in compressional stress regimes. However, Westaway and Smith (1989) and Spudich *et al.* (1995) have found that attenuation relationships developed from primarily California and other western United States strike-slip and reverse-faulting earthquakes provide a reasonable estimate of PGA from normal-faulting earthquakes located worldwide. A similar result was found from an analysis of strong ground motions from the 1992 Little Skull Mountain, Nevada, normal-faulting earthquake by Hofmann and Ibrahim (1994).

There were only two normal-faulting earthquakes included in the current database used to determine the coefficient of F—the 1935 (M_L = 5.5) Helena, Montana earthquake and the 1975 (M_W = 6.0) Oroville, California

TABLE 2
Comparison of Site Classifications

Borcherdt Site Class	Boore *et al.* Site Class	Sadigh, Idriss & Abrahamson Site Class	Campbell Site Class
SC-Ib	A	Rock	Hard Rock
SC-II	B	Rock	Soft Rock
SC-III	C	Soil	Firm Soil
SC-IV	D	Soft Soil	Soft Soil
—			Shallow Soil

earthquake. Therefore, there is no statistical basis in this study for concluding whether strong ground motions from normal-faulting earthquakes are different from those of other types of earthquakes. However, considering the recent empirical results cited above, it is recommended that normal-faulting earthquakes be assigned a value of F halfway between that of strike-slip and reverse-faulting earthquakes, or $F = 0.5$, until more definitive studies become available.

Local Site Conditions (S_{SR} and S_{HR})

Local site conditions are defined by the index variables S_{SR} and S_{HR}; where $S_{SR} = S_{HR} = 0$ for alluvium or firm soil; $S_{SR} = 1$ and $S_{HR} = 0$ for soft rock; and $S_{SR} = 0$ and $S_{HR} = 1$ for hard rock. Alluvium and firm soil is defined as firm or stiff Quaternary deposits with depths greater than 10 m. Soft rock is defined as primarily Tertiary sedimentary deposits and soft volcanic deposits (*e.g.*, ash deposits). Hard rock is defined as primarily Cretaceous and older sedimentary deposits, metamorphic rock, crystalline rock, and hard volcanic deposits (*e.g.*, basalt). The approximate relationship between the site classifications defined above and similar classifications defined in terms of shear-wave velocity (*e.g.*, Boore *et al.*, 1993; Borcherdt, 1994) and simpler soil and rock site classifications (*e.g.*, Sadigh *et al.*, 1986, 1993; Idriss, 1991a,b; Abrahamson and Silva, 1995, 1996) are given in Table 2.

Depth to Basement Rock (D)

Long-period site response is modeled by depth to basement rock. The importance of this parameter has been noted by several investigators (*e.g.*, see the list of references in Campbell, 1990). It has been explicitly included in empirical attenuation relationships developed by Trifunac and Lee (1978, 1979) and Campbell (1987, 1989a, 1990, 1991a, 1992b, 1993). For shallow sediments, D is defined as the depth to the top of Cretaceous or older deposits. For deep sediments, D is determined from crustal velocity profiles where basement is defined as crystalline basement rock or sedimentary deposits having a P-wave velocity of least 5 km/sec or a shear-wave velocity of at least 3 km/sec. These high-velocity sediments are typically referred to as "seismic basement" by geophysicists. They are typically underlain by deposits characterized by a low velocity gradient and a relatively small velocity impedance.

When direct estimates of D are not available, this depth can be inferred from gravity and aeromagnetic data, from stratigraphic sequences, and from extrapolation of bedrock slopes. For the majority of sites in the database compiled for this study (*e.g.*, the Los Angeles Basin), basement was identified as the top of crystalline or metamorphic rock. However, in some cases (*e.g.*, parts of the Livermore Basin in central California), deposits representing seismic basement were identified within the sedimentary sequence.

Soil-Structure Interaction Parameters (K_i)

Because recordings from embedded and tall buildings were included in the database for PGV and PSA, it was necessary to remove soil-structure interaction (SSI) effects by including the index parameters K_i in the analyses involving these strong motion parameters. These SSI parameters were defined as $K_1 = 1$ and $K_2 = K_3 = 0$ for embedded buildings 3 to 11 stories high; $K_1 = 0$, $K_2 = 1$, and $K_3 = 0$ for embedded buildings greater than 11 stories high; $K_1 = K_2 = 0$ and $K_3 = 1$ for ground-level buildings greater than 2 stories high; and $K_1 = K_2 = K_3 = 0$ for all other recording sites (Campbell, 1989a, 1990). Because the recommended attenuation relationships developed in this study are for free-field sites, these parameters have not been explicitly included in these relationships. They are presented as a means of understanding the definition of "free-field" in these earlier studies.

STRONG MOTION DATABASE

A description of the strong motion database is given in Table 3. Table 4 gives a listing of the earthquakes and the number of recordings for each of the strong motion parameters. The recordings were restricted to near-source distances to minimize the influence of regional differences in crustal attenuation and to avoid the complex propagation effects that have been observed at longer distances during, for example, the 1987 ($M_W = 6.1$) Whittier Narrows, the 1989 ($M_W = 6.9$) Loma Prieta, and the 1992 ($M_W = 7.3$) Landers, California earthquakes (Campbell, 1988, 1991c; Campbell and Bozorgnia, 1994b). Recordings from small earthquakes were restricted to shorter distances than large earthquakes, depending on the magnitude and style of faulting of the

TABLE 3
Ground Motion Database Characteristics

Description	PGA	PGV and PSA
Dates	1957–1993	1933–1987
No. of Recordings	645 (Horizontal); 225 (Vertical)	226 (Horizontal); 173 (Vertical)
No. of Earthquakes	47 (Horizontal); 26 (Vertical)	30 (Horizontal); 22 (Vertical)
Component	Mean of horizontal components Vertical component	Mean of horizontal components; Vertical component
Magn ıde Measure	M_W	M_S for $M_S < 6$; M_L for $M_S \geq 6$
Magnitude Range	4.7–8.0 (Horizontal); 4.7–8.1 (Vertical)	4.7–8.1
Distance Measure	Closest distance to seismogenic rupture (R_{SEIS})	Closest distance to seismogenic rupture (R_{SEIS})
Distance Range (km)	3.0–60.0	3.0–30.0 for $M < 6.25$; 3.0–50.0 for $M \geq 6.25$
Local Site Conditions	Firm Soil > 10m deep; Soft and Hard Rock	Firm Soil > 10m deep; Soft and Hard Rock
Style of Faulting	Strike Slip; Reverse and Thrust	Strike Slip; Reverse and Thrust
Depth of Rupture (km)	Upper crust (< 25 km)	Upper crust (< 25 km)
Recordings Excluded	Basement of buildings; > 2 stories (Soil & Soft Rock); > 5 stories (Hard Rock); Toe and base of dams; Base of bridge columns	Toe and base of dams
Regions	Active tectonic regions; Worldwide	Active tectonic regions; Worldwide

TABLE 4
Earthquakes Used in the Analysis

Earthquake	Year	M	Fault Type	Number of Recordings			
				A_H	A_V	V_H SA_H	V_V SA_V
Long Beach, CA	1933	6.2	Strike Slip	0	3	3	3
Helena, MT	1935	5.5	Normal	0	0	1	0
Imperial Valley, CA	1940	7.2	Strike Slip	0	1	1	1
Kern County, CA	1952	7.8	Reverse Oblique	0	1	1	1
Daly City, CA	1957	5.4	Reverse Oblique	1	4	4	4
Parkfield, CA	1966	6.1	Strike Slip	4	4	4	4
Borrego Mtn., CA	1968	6.8	Strike Slip	0	1	1	1
Koyna, India	1967	6.3	Strike Slip	1	0	1	0
Lytle Creek, CA	1970	5.3	Reverse	6	5	6	4

TABLE 4 (Continued)
Earthquakes Used in the Analysis

Earthquake	Year	M	Fault Type	Number of Recordings			
				A_H	A_V	V_H SA_H	V_V SA_V
San Fernando, CA	1971	6.6	Reverse	12	55	60	55
Sitka, AK	1972	7.7	Strike Slip	1	0	1	0
Stone Canyon, CA	1972	4.7	Strike Slip	3	2	2	2
Managua, Nicaragua	1972	6.2	Strike Slip	1	1	1	1
Point Mugu, CA	1973	5.6	Reverse	1	1	0	0
Hollister, CA	1974	5.1	Strike Slip	1	2	2	2
Oroville, CA	1975	6.0	Normal	4	0	1	0
Kalapana, HI	1975	7.1	Thrust	0	0	1	0
Gazli, Uzbekistan	1976	6.8	Reverse	1	1	1	1
Caldiran, Turkey	1976	7.3	Strike Slip	1	0	0	0
Mesa de Andrade, Mexico	1976	5.6	Strike Slip	2	0	0	0
Santa Barbara, CA	1978	6.0	Thrust	3	6	4	4
Tabas, Iran	1978	7.4	Thrust	3	3	3	3
Bishop, CA	1978	5.8	Strike Slip	4	1	0	0
Malibu, CA	1979	5.0	Reverse	1	3	0	0
St. Elias, AK	1979	7.6	Thrust	1	1	2	1
Coyote Lake, CA	1979	5.8	Strike Slip	17	8	10	8
Imperial Valley, CA	1979	6.5	Strike Slip	43	41	43	38
Livermore, CA #1	1980	5.8	Strike Slip	7	0	0	0
Livermore, CA #2	1980	5.4	Strike Slip	6	0	0	0
Westmorland, CA	1981	6.0	Strike Slip	22	0	0	0
Morgan Hill, CA	1984	6.2	Strike Slip	40	25	29	24
Valparaiso, Chile	1985	8.0	Thrust	3	2	4	2
Michoacan, Mexico	1985	8.1	Thrust	0	1	1	1
Zihuatanejo, Mexico	1985	7.6	Thrust	3	0	3	0
Nahanni, Canada	1985	6.8	Thrust	3	0	2	0
N. Palm Springs, CA	1986	6.1	Strike Slip	35	14	16	4
Chalfant Valley, CA	1986	6.3	Strike Slip	14	6	10	0
Whittier Narrows, CA #1	1987	6.1	Thrust	74	33	48	9
Whittier Narrows, CA #2	1987	5.3	Reverse Oblique	37	0	0	0
Elmore Ranch, CA	1987	6.2	Strike Slip	25	0	0	0
Superstition Hills, CA	1987	6.6	Strike Slip	31	0	0	0
Spitak, Armenia	1988	6.8	Reverse Oblique	1	0	0	0
Pasadena, CA	1988	5.0	Strike Slip	8	0	0	0
Loma Prieta, CA	1989	6.9	Reverse Oblique	51	0	0	0
Malibu, CA	1989	5.0	Thrust	3	0	0	0
Manjil, Iran	1990	7.4	Strike Slip	4	0	0	0
Upland, CA	1990	5.6	Strike Slip	34	0	0	0

TABLE 4 (Continued)
Earthquakes Used in the Analysis

Earthquake	Year	M	Fault Type	Number of Recordings			
				A_H	A_V	V_H SA_H	V_V SA_V
Sierra Madre, CA	1991	5.6	Reverse	61	0	0	0
Landers, CA	1992	7.4	Strike Slip	18	0	0	0
Big Bear, CA	1992	6.6	Strike Slip	22	0	0	0
Joshua Tree, CA	1992	6.2	Strike Slip	13	0	0	0
Petrolia, CA #1	1992	7.1	Thrust	13	0	0	0
Petrolia, CA #2	1992	7.0	Strike Slip	5	0	0	0
Erzincan, Turkey	1992	6.7	Strike Slip	1	0	0	0

earthquake and the geology of the recording site, in order to mitigate the bias associated with non-triggering instruments. The magnitudes were restricted to about $M_W \geq 5$ to emphasize those ground motions of greatest engineering interest and to limit the analyses to the more reliable, well-studied earthquakes.

Previous analyses have indicated that embedded and large structures can have accelerations significantly less than those at free-field sites (*e.g.*, Campbell, 1987, 1989a,b). However, these recordings were included in the 1990 and 1993 studies because there were too few free-field values of PGV and PSA with which to perform a reliable statistical analysis. Because of the larger database, Campbell and Bozorgnia (1994a) excluded those recordings which were believed to be adversely affected by soil-structure interaction (Table 3). Although excluded by Boore *et al.* (1993, 1994), recordings from dam abutments were included because such sites comprise a significant number of the rock recordings in the database and, due to their stiff foundation conditions, are expected to be only minimally affected by the presence of the dam. Although not addressed in this study, some of these abutment recordings could be affected by local topography.

Recordings on shallow soil and soft soil were excluded from the database based on previous analyses that showed that these sites have accelerations significantly higher than those on deeper, firmer soil (*e.g.*, Campbell, 1987, 1988, 1989b, 1991c). Shallow soil is defined as Quaternary deposits with depths less than 10 m. Soft soil is defined as soft to very soft clay (*e.g.*, San Francisco Bay Mud) and loose to very loose granular soils (*e.g.*, hydraulic fill).

Earthquakes were included only if they had seismogenic rupture within the shallow crust (depths less than about 25 km) in order to avoid the potential differences in attenuation characteristics and tectonic stresses associated with deeper earthquakes (*e.g.*, Youngs *et al.*, 1988). Several large, shallow subduction interface earthquakes were included in the database based on previous studies that found that these events had source characteristics and near-source ground motions similar to those of shallow crustal earthquakes (*e.g.*, Boore, 1986; Youngs *et al.*, 1988).

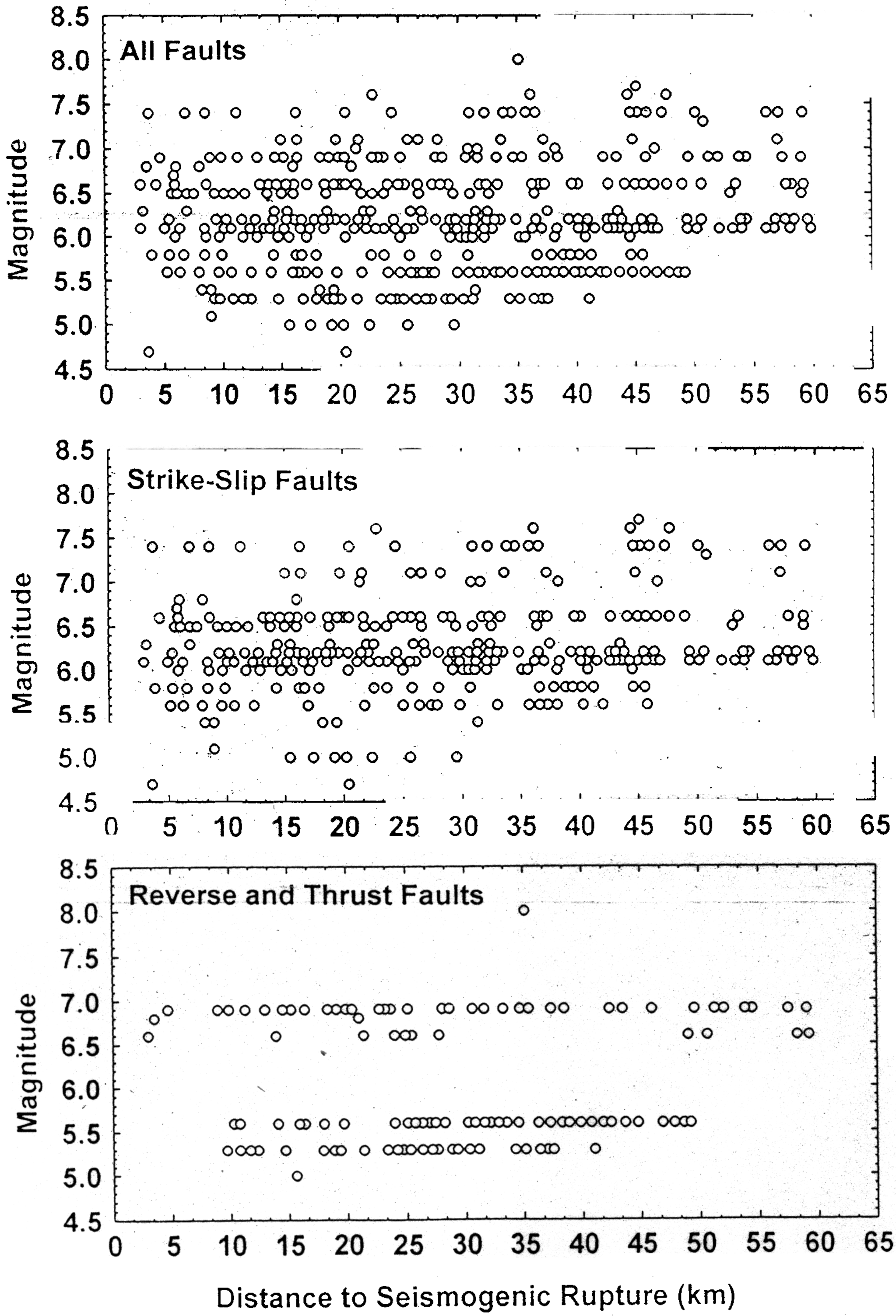
HORIZONTAL ATTENUATION RELATIONSHIPS

Peak Ground Acceleration

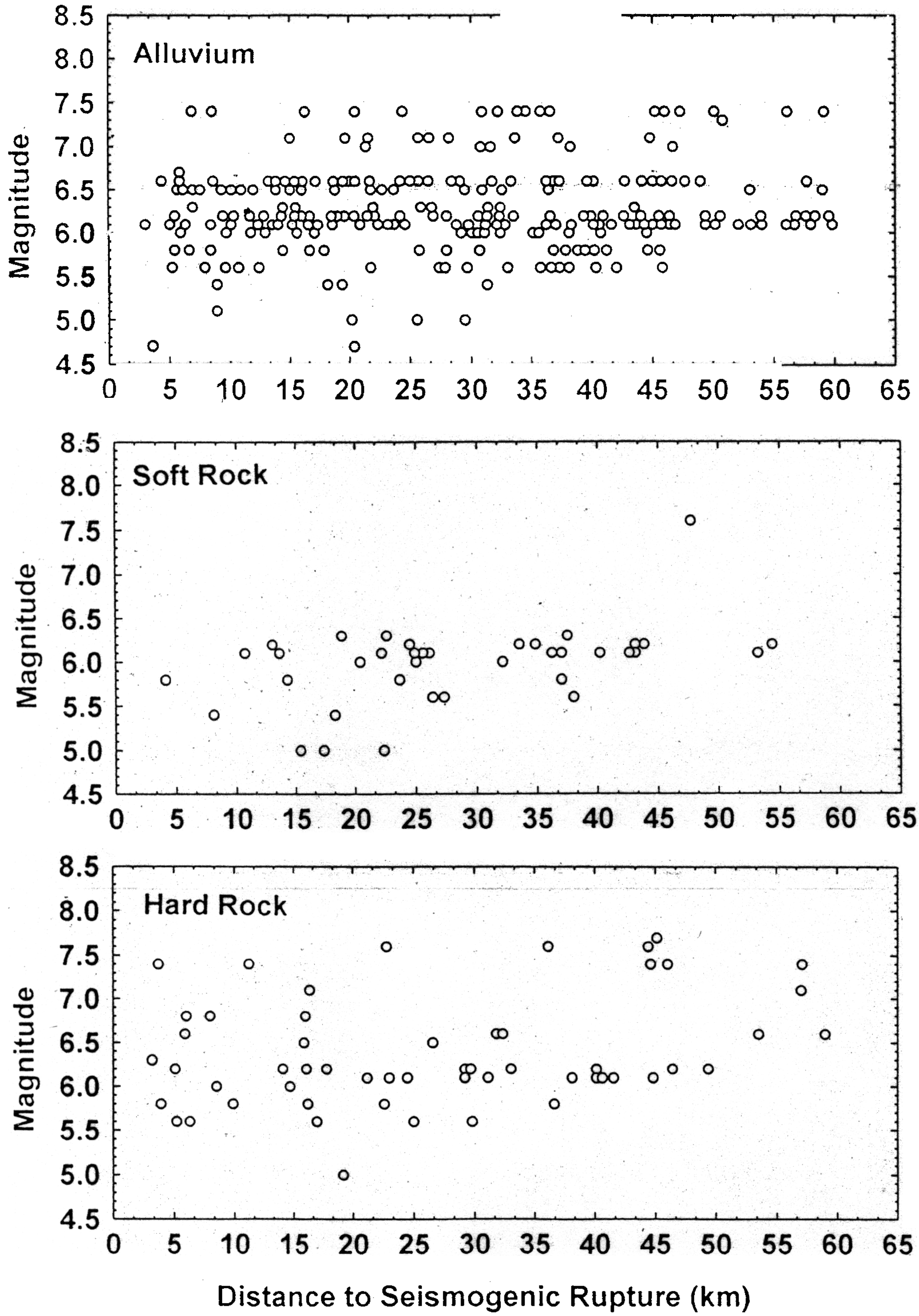
The attenuation relationship developed by Campbell and Bozorgnia (1994a) is recommended for predicting A_H. The coefficients in this relationship were determined from an unweighted generalized nonlinear least-squares regression analysis. The distribution of the recordings with respect to magnitude and distance plotted by style of faulting and local site conditions is shown in Figures 1 through 3.

To avoid the bias associated with non-triggering instruments, the analysis was done in two stages. In the first stage, all selected recordings were used to determine the regression coefficients. The resulting attenuation relationship was then used to compute the predicted value of A_H as a function of magnitude, distance, style of faulting, and local site conditions. A distance threshold was then selected for each value of magnitude, style of faulting, and local site condition such that the 16th-percentile estimate of A_H was equal to $0.02g$. This threshold value of A_H was chosen because it corresponds approximately to a peak vertical acceleration of $0.01g$, the nominal trigger threshold of modern strong motion accelerographs. In stage 2, recordings not meeting the calculated distance thresholds were removed from the database and the regression analysis was repeated. Ideally, this process should be repeated until the distance thresholds become stable. However, a repeat of stage 1 indicated that there would be little gained in repeating the two-stage analysis.

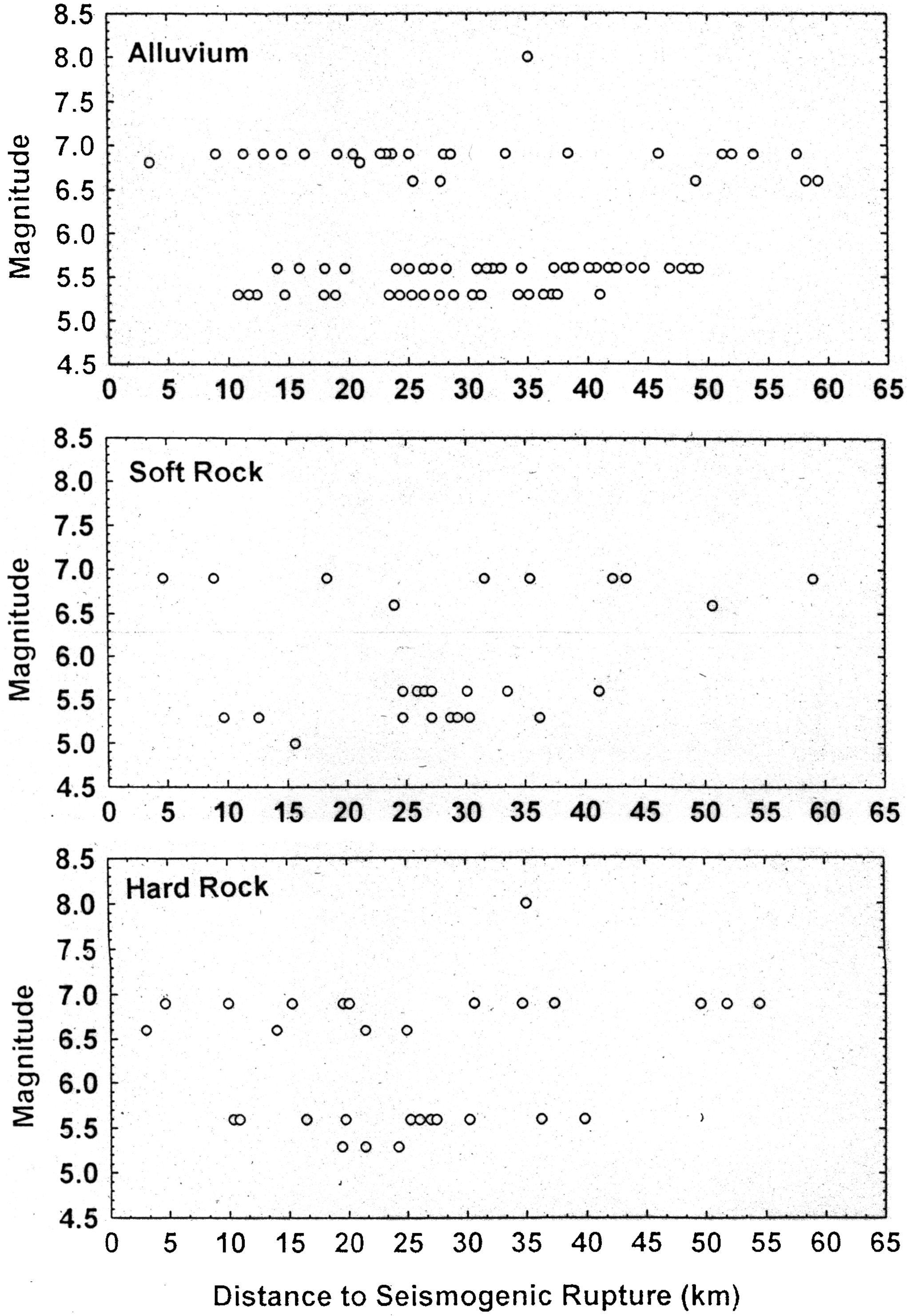
The final attenuation relationship is given by the expression



▲ **Figure 1.** The distribution of recordings in the PGA database of Campbell and Bozorgnia (1994a) plotted as a function of magnitude, distance, and style of faulting.



▲ **Figure 2.** The distribution of recordings in the PGA database of Campbell and Bozorgnia (1994a) plotted as a function of magnitude, distance, and local site conditions for strike-slip earthquakes.



▲ **Figure 3.** The distribution of recordings in the PGA database of Campbell and Bozorgnia (1994a) plotted as a function of magnitude, distance, and local site conditions for reverse and thrust earthquakes.

$$\ln(A_H) = -3.512 + 0.904M - 1.328\ln\sqrt{R_{SEIS}^2 + \left[0.149\exp(0.647M)\right]^2} + \left[1.125 - 0.112\ln(R_{SEIS}) - 0.0957M\right]F + \left[0.440 - 0.171\ln(R_{SEIS})\right]S_{SR} + \left[0.405 - 0.222\ln(R_{SEIS})\right]S_{HR} + \varepsilon \quad (3)$$

where A_H has units of g (g = 981 cm/sec^2), ε is a random error term with a mean of zero and a standard deviation equal to the standard error of estimate of $\ln(A_H)$, and all other parameters are defined in the previous section.

Some studies have found that the dispersion in the predicted value of PGA is dependent on earthquake magnitude (*e.g.*, Sadigh *et al.*. 1986, 1993; Idriss, 1991a,b; Abrahamson and Silva , 1995, 1996), whereas others have found it to be a function of PGA (*e.g.*, Donovan and Bornstein, 1978). Campbell and Bozorgnia (1994a) investigated both of these hypotheses by plotting the running value of the standard error of estimate of $\ln(A_H)$ as a function of mean earthquake magnitude and mean predicted value of $\ln(A_H)$ and fitting a simple equation to these observations using the method of least squares. The running values were calculated using 30 observations. The resulting relationship between σ, the standard error of estimate of $\ln(A_H)$, and $\ln(A_H)$ is given by:

$$\begin{aligned} &\text{when } A_H < 0.068g \\ &\quad \sigma = 0.55 \\ &\text{when } 0.068g \le A_H \le 0.21g \\ &\quad \sigma = 0.173 - 0.140\ln(A_H) \\ &\text{when } A_H > 0.21g \\ &\quad \sigma = 0.39 \end{aligned} \quad (4)$$

The relationship relating σ to M is given by the expression

$$\begin{aligned} &\text{when } M < 7.4 \\ &\quad \sigma = 0.889 - 0.0691M \\ &\text{when } M \ge 7.4 \\ &\quad \sigma = 0.38 \end{aligned} \quad (5)$$

Equation (4) is more statistically robust than Equation (5) with an r-squared value of 0.89 (*i.e.*, 89 percent of the variance is explained by the model) and a standard error of estimate of 0.021. By comparison, Equation (5) has an r-squared value of 0.56 and a standard error of estimate of 0.044.

The statistical robustness of the results are demonstrated in Figures 4 through 7. These figures show plots of the normalized residuals—the observed value minus the predicted value of $\ln(A_H)$ divided by the standard error of estimate of $\ln(A_H)$—as a function of source-to-site distance and magnitude. The plots are segregated by style of faulting and local soil conditions.

Peak Ground Velocity and Spectral Acceleration

The recommended attenuation relationships for the horizontal components of PGV and PSA were developed by combining the relationships of Campbell (1990) and Campbell (1993). The coefficients in these relationships were determined from a weighted generalized nonlinear least-squares regression analysis. Weights were used to reduce the potential bias in distance and site location. The bias in distance results from the vastly different numbers of recordings between earthquakes. To reduce this bias, recordings from a given earthquake that fell within a specified distance interval were assigned the same weight as those recordings from other earthquakes that fell within the same distance interval. The potential bias in site location results from the virtually identical source, path, and site effects that are common to recordings obtained at the same location during the same earthquake. To reduce this bias, recordings from a given earthquake that occurred at the same site location were given the same cumulative weight as a single recording at that distance. Ten distance intervals of equal logarithmic increments between 0 and 56.6 km were used to establish the weights.

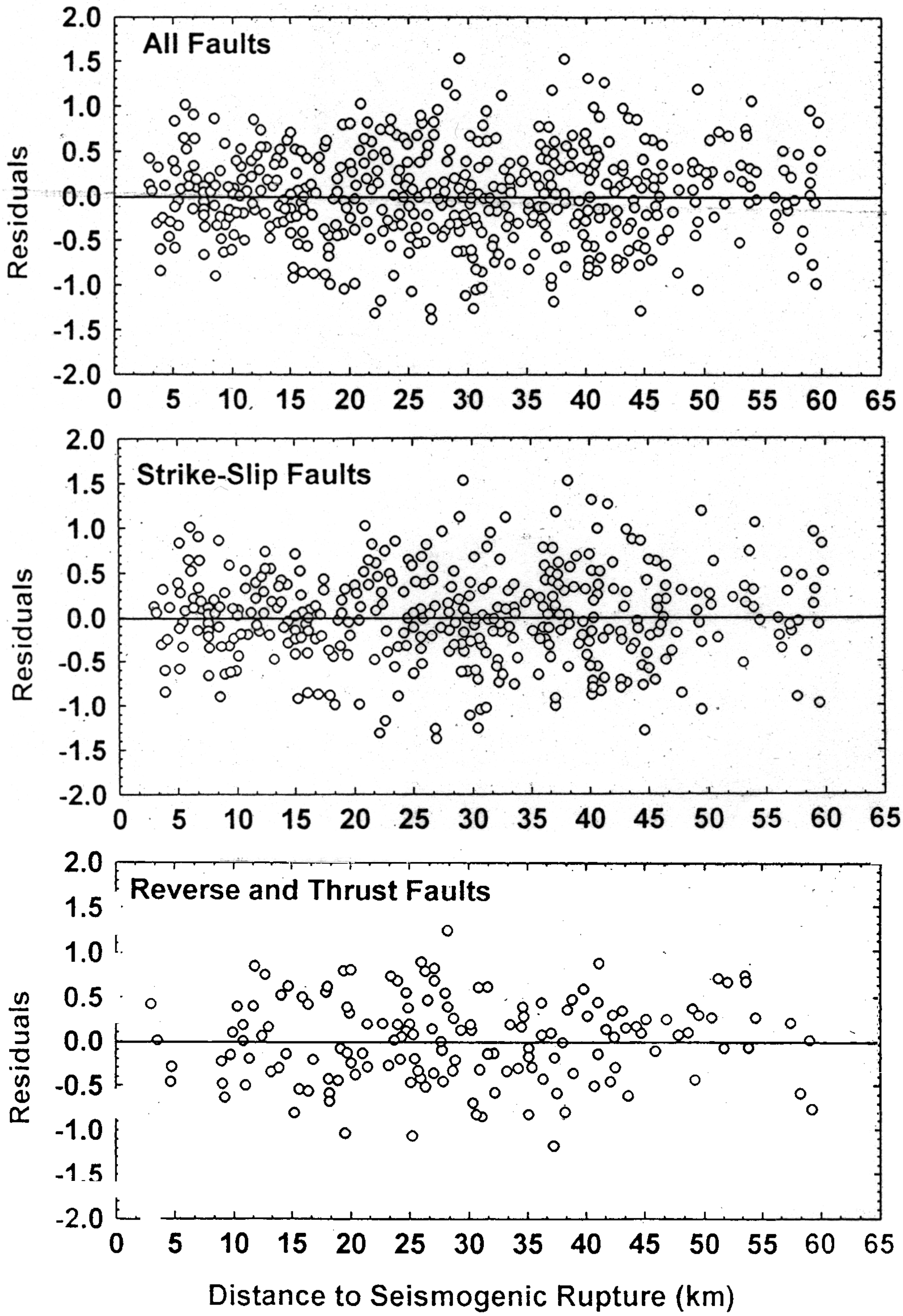
The weight of each recording was computed from the following expression:

$$w_i = \frac{N}{N_i}\sum\frac{1}{N} \quad (6)$$

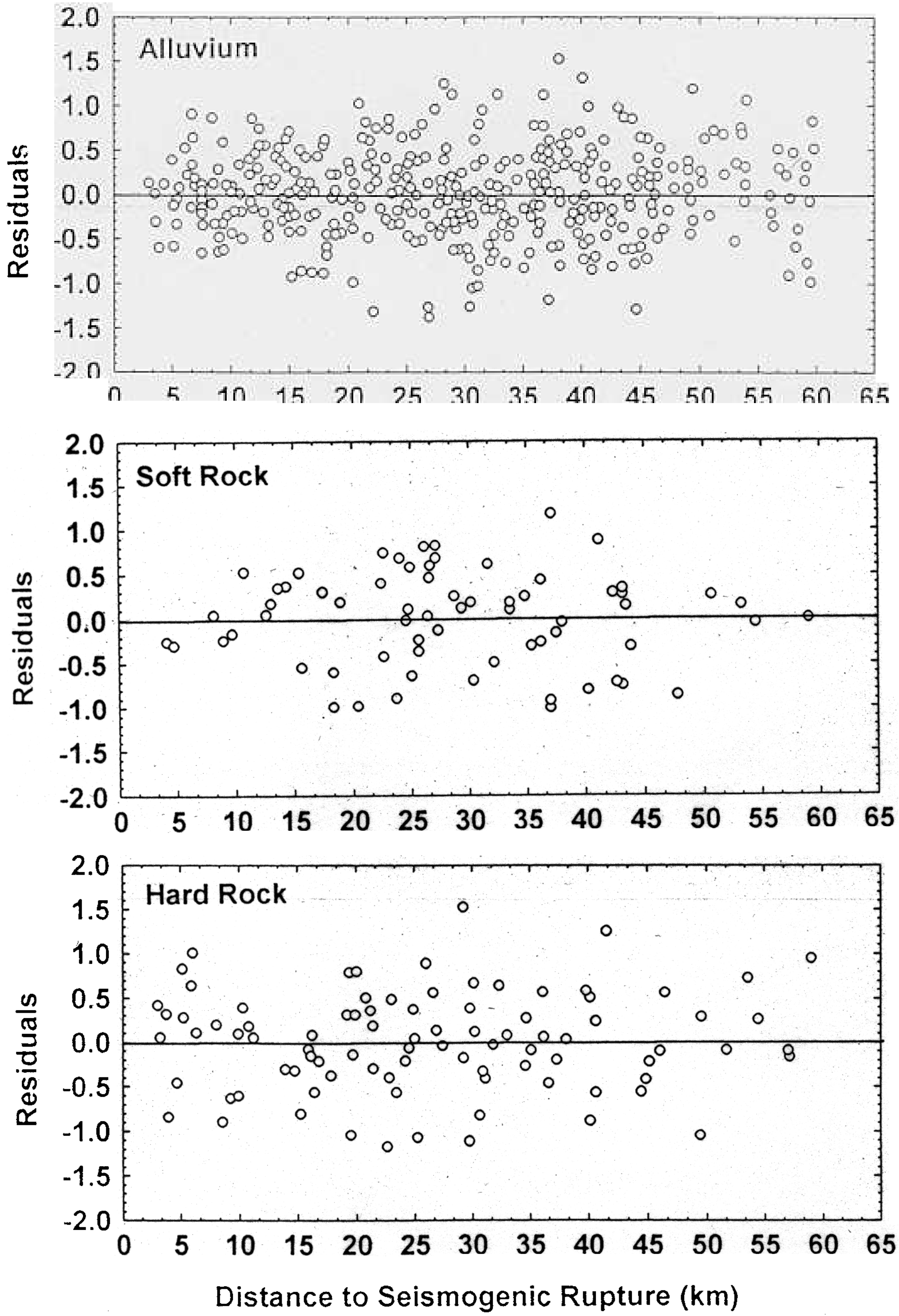
where i is the index representing the recording; $N_i = N_{i,1}\,N_{i,2}$; $N_{i,1}$ is the number of recordings from the same earthquake and distance interval as the ith recording; $N_{i,2}$ is the number of recordings from the same earthquake and site location as the ith recording; and N is the total number of recordings. The above expression has been normalized such that the sum of the weights equals N, a constraint required in order to maintain the correct number of degrees of freedom and, thus, the correct weighted value of the standard error of estimate.

Other investigators have proposed different statistical methods to compensate for the potential bias associated with the uneven distribution of recordings between earthquakes. The two most notable are the two-step regression procedure proposed by Joyner and Boore (1981) and Boore *et al.* (1993), and the random-effects regression procedure proposed by Brillinger and Preisler (1984) and Abrahamson and Youngs (1992) and later applied by Campbell (1991d) and Abrahamson and Silva (1995, 1996).

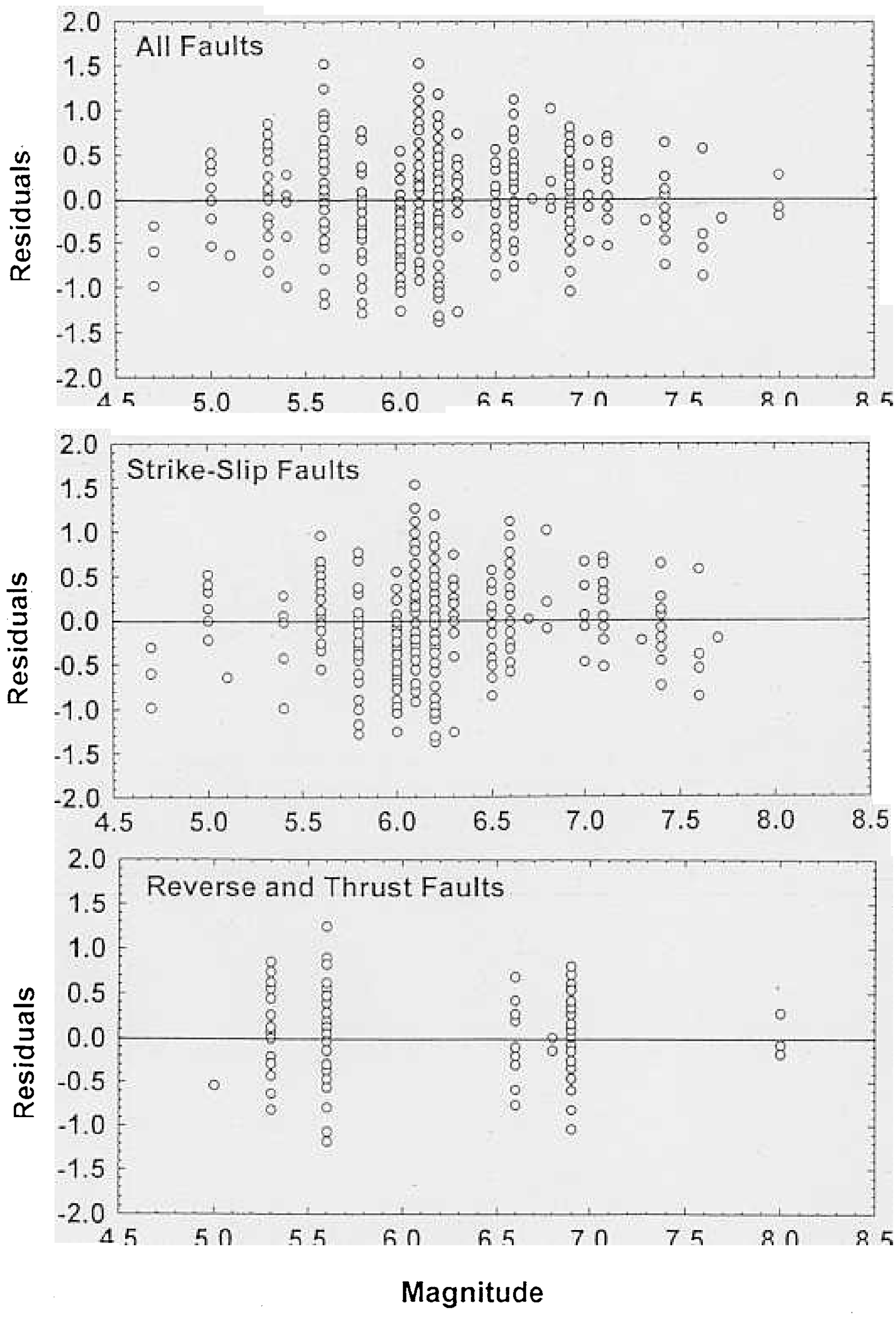
After correctly weighting the second stage of their two-stage regression analysis, Joyner and Boore (1993) found that the two-stage and random-effects approaches gave similar results. TERA Corporation (1982) found that both a single and two-stage regression analysis of the Joyner and Boore (1981) database gave virtually identical results. Campbell



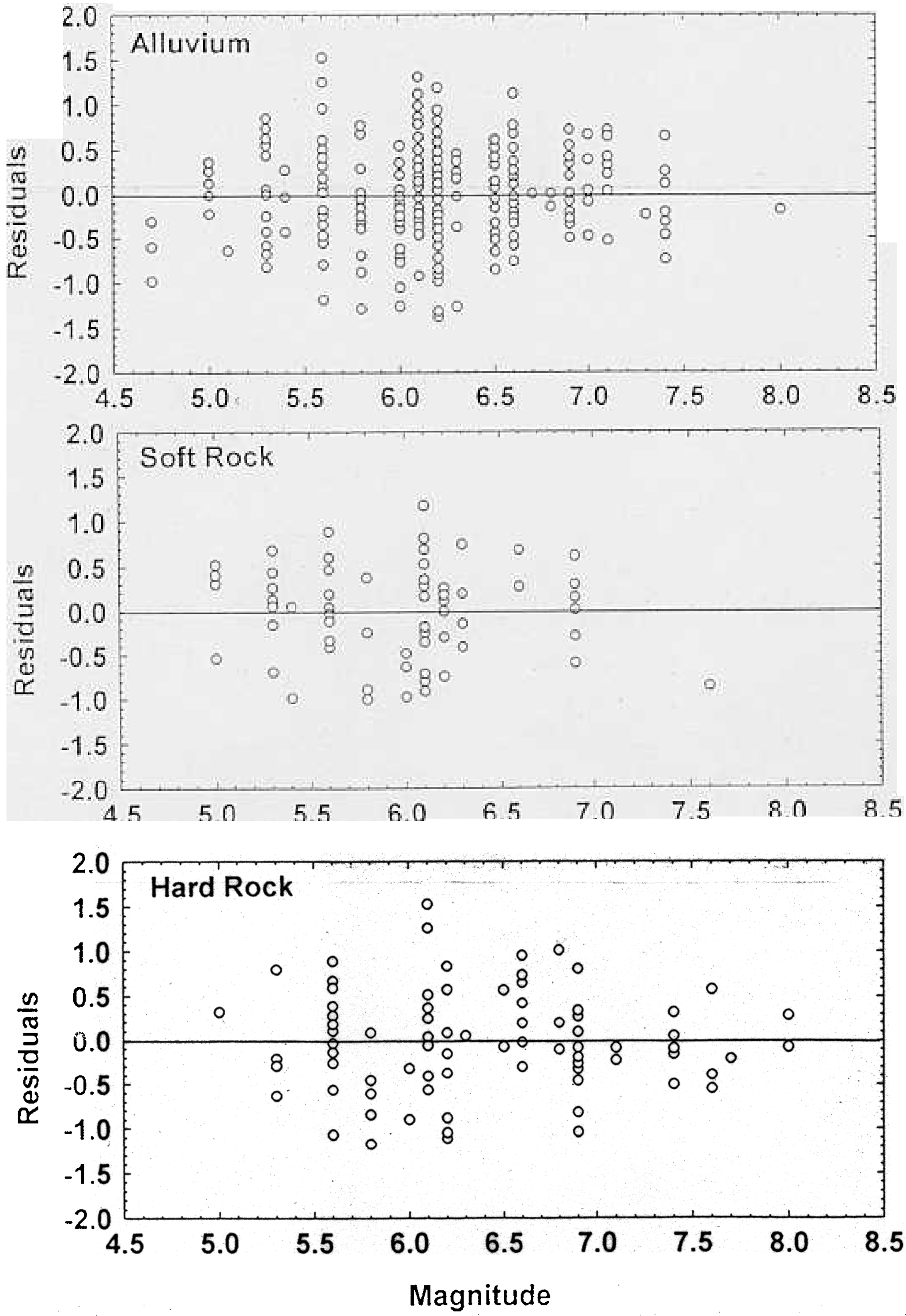
▲ **Figure 4.** The distribution of residuals in the PGA analysis of Campbell and Bozorgnia (1994a) plotted as a function of distance and style of faulting.



▲ **Figure 5.** The distribution of residuals in the PGA analysis of Campbell and Bozorgnia (1994a) plotted as a function of distance and local site conditions.



▲ **Figure 6.** The distribution of residuals in the PGA analysis of Campbell and Bozorgnia (1994a) plotted as a function of magnitude and style of faulting.



▲ **Figure 7.** The distribution of residuals in the PGA analysis of Campbell and Bozorgnia (1994a) plotted as a function of magnitude and local site conditions.

(1991d), using the same database as Campbell (1990), found that a random-effects analysis resulted in predicted strong-motion parameters that were generally within about 10% of those given by the traditional variance-weighted model used by Campbell (1990). Larger differences at oscillator periods of 0.5 sec and longer were attributed to differences in magnitude and depth-to-basement-rock scaling characteristics, which were determined independently of period. In contrast, Campbell (1990) used period-independent scaling characteristics for these parameters. Differences among the three regression procedures are sufficiently small for the robust databases available for the western United States that one method is not preferred over the other based on differences in regression results alone.

The regression analysis of PSA was considerably more complicated than the analyses of PGA and PGV. An attempt to perform a direct regression on ln(PSA) led to an unacceptably large period-to-period variability in the regression coefficients and in the resulting predicted response spectra (*e.g.*, see Campbell, 1991d). This variability is believed to have been caused by three factors: (1) the relatively large number of independent variables included in the attenuation relationship, (2) the relatively small number of available recordings, and (3) the period-to-period variability in the number of recordings and associated earthquakes.

When confronted with similar variability, Joyner and Boore (1982), Joyner and Fumal (1984), and Boore *et al.* (1993) smoothed the regression coefficients to obtain well-behaved predicted response spectra. However, Campbell (1990, 1993) noted several unique factors that made this type of approach virtually impossible. First, some of the regression coefficients were found to be strongly correlated with one another, making it difficult to smooth them without many iterations. Second, the nonlinearity and relatively large number of coefficients in these attenuation relationships made each iteration extremely time consuming.

Therefore, instead of attempting to smooth the regression coefficients, the analyses were simplified by performing the regression on the logarithm of the spectral ratio, ln(PSA/PGA), rather than directly on ln(PSA). This approach has been adopted by many previous investigators (*e.g.*, Newmark and Hall, 1982; Sadigh, 1983, Sadigh *et al.*, 1986, 1993; also see references in Campbell, 1985 and Joyner and Boore, 1988). Besides giving more stable results, the analysis of the spectral ratio has several advantages that makes it suitable for developing spectral attenuation relationships: (1) it simplifies the analysis by reducing the number of coefficients to be evaluated, (2) it minimizes the impact of the period-to-period variability in the number of recordings and associated earthquakes, and (3) it can be used with a PGA attenuation relationship based on a significantly larger number of recordings than those used to develop the relationships for the spectral ratios.

The prediction of spectral ordinates from spectral ratio has been recently criticized by Joyner and Boore (1988) and Bender and Campbell (1989). The major criticism concerns the use of peak acceleration to scale a fixed spectral shape, which neglects observed differences in the period-dependence of PSA on magnitude, source-to-site distance, and local site conditions. This criticism was avoided by allowing the spectral ratio to scale freely with all of the independent variables discussed in the previous section.

Even with the simpler analysis on spectral ratio, there were too many regression coefficients to ensure convergence of the nonlinear algorithms. Therefore, it was necessary to perform the analysis in several steps, with each step used to evaluate a different set of independent variables, until all of the regression coefficients were determined. With each successive step, the observed values were detrended using the regression coefficients determined in all of the previous steps and the resulting residuals were inspected to revalidate the appropriateness of the previous coefficients. The procedure is similar to a stepwise regression analysis. The order in which the coefficients were determined was selected based on the significance of the observed trends. Before each step, the detrended residuals of the previous step were plotted and analyzed to identify trends and suggest appropriate functional forms for the next step. The steps involved the following analyses in the order indicated: (1) scaling with magnitude, (2) scaling with depth to basement rock, (3) scaling with local site conditions (Campbell, 1993 only), and (4) scaling with soil-structure interaction parameters. There was no statistically significant dependence of the spectral ratio on source-to-site distance or style of faulting, although the Campbell (1993) study included a distance-scaling term based on a theoretical model of anelastic attenuation developed by Campbell (1991b).

After the final step was completed, weighted residuals were calculated directly in terms of ln(PSA) and were plotted against magnitude, source-to-site distance, depth-to-basement rock, and local site conditions to ensure that there were no significant trends with respect to these variables. These residuals were also used to develop standard errors of estimate for ln(PSA) as a function of magnitude and oscillator period.

In order to combine the strengths and minimize the weaknesses of the Campbell (1990, 1993) studies, after considerable review and comparison, the recommended attenuation relationship for the spectral ratio was developed as indicated below:

- Scaling characteristics with respect to magnitude (M) were taken from Campbell (1990),
- Scaling characteristics with respect to distance (R_{SEIS}) were taken from Campbell (1993),
- Scaling characteristics with respect to depth to basement rock (D) for firm soil and for $D \geq 1$ km were taken from Campbell (1993) and were normalized to have the amplitude of the spectral ratio given by Campbell (1990) at $D = 5$ km,
- Scaling characteristics with respect to depth to basement rock (D) for soft rock and for $D \geq 1$ km were taken from Campbell (1993) and were normalized to the amplitude

of the spectral ratio given by Campbell (1993) at $D = 5$ km and long periods,

- The amplitude of the spectral ratio at $D = 0$ km (hard rock) was taken from Campbell (1993),
- The amplitude of the spectral ratio for soft rock at short periods was taken to be halfway between the amplitudes for hard rock and for firm soil for $D < 1$ km, and
- The transition between the logarithm of the spectral ratios at $D = 0$ and at $D = 1$ km was assumed to be a linear function of D.

Recommended Attenuation Relationships. In order to take advantage of the updated attenuation relationship for A_H developed by Campbell and Bozorgnia (1994a), the recommended attenuation relationships for V_H and SA_H were developed by first normalizing by A_H, then multiplying these normalized values by the value of A_H from the Campbell and Bozorgnia (1994a) study. The resulting attenuation relationship for V_H is given by the expression

$$\begin{aligned}\ln(V_H) = {} & \ln(A_H) + 0.26 + 0.29M \\ & -1.44\ln[R_{SEIS} + 0.0203\exp(0.958M)] \\ & +1.89\ln[R_{SEIS} + 0.361\exp(0.576M)] \\ & +(0.0001 - 0.000565M)R_{SEIS} - 0.12F \\ & -0.15S_{SR} - 0.30S_{SR} \\ & +0.75\tanh(0.51D)(1 - S_{HR}) + f_V(D) + \varepsilon\end{aligned} \tag{7}$$

where

when $D \geq 1$ km

$$f_V(D) = 0$$

when $D < 1$ km

$$f_V(D) = -0.30(1 - S_{HR})(1 - D) - 0.15(1 - D)S_{SR}$$

The attenuation relationship for SA_H is given by the expression

$$\begin{aligned}\ln(SA_H) = {} & \ln(A_H) + c_1 + c_2\tanh[c_3(M - 4.7)] \\ & +(c_4 + c_5M)R_{SEIS} + 0.5c_6S_{SR} + c_6S_{HR} \\ & +c_7\tanh(c_8D)(1 - S_{HR}) + f_{SA}(D) + \varepsilon\end{aligned} \tag{8}$$

where

when $D \geq 1$ km

$$f_{SA}(D) = 0$$

when $D < 1$ km

$$f_{SA}(D) = c_6(1 - S_{HR})(1 - D) + 0.5c_6(1 - D)S_{SR}$$

In all of the above relationships, V_H has units of cm/sec; S_{AH} has units of g; A_H is the mean horizontal component of PGA from Equation (3); and all other variables are defined in Equation (3) or in the section *Model Parameters*. The regression coefficients for Equation (8) are summarized in Table 5.

Consistent with the way Equations (7) and (8) were developed, the square of the standard errors associated with these relationships were developed by adding the difference

TABLE 5
Regression Coefficients For SA_H
Note: SA_H has units of g

Period (sec)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8
0.05	0.05	0	0	−0.0011	0.000055	0.20	0	0
0.075	0.27	0	0	−0.0024	0.000095	0.22	0	0
0.1	0.48	0	0	−0.0024	0.000007	0.14	0	0
0.15	0.72	0	0	−0.0010	−0.00027	−0.02	0	0
0.2	0.79	0	0	0.0011	−0.00053	−0.18	0	0
0.3	0.77	0	0	0.0035	−0.00072	−0.40	0	0
0.5	−0.28	0.74	0.66	0.0068	−0.00100	−0.42	0.25	0.62
0.75	−1.08	1.23	0.66	0.0077	−0.00100	−0.44	0.37	0.62
1.0	−1.79	1.59	0.66	0.0085	−0.00100	−0.38	0.57	0.62
1.5	−2.65	1.98	0.66	0.0094	−0.00100	−0.32	0.72	0.62
2.0	−3.28	2.23	0.66	0.0100	−0.00100	−0.36	0.83	0.62
3.0	−4.07	2.39	0.66	0.0108	−0.00100	−0.22	0.86	0.62
4.0	−4.26	2.03	0.66	0.0112	−0.00100	−0.30	1.05	0.62

between the square of the standard error of the desired strong motion parameter and $\ln(A_H)$ to the square of the standard error of $\ln(A_H)$ from the Campbell and Bozorgnia (1994a) attenuation relationship. The resulting standard errors are given by the following expressions

$$\text{for } V_H \qquad \sigma_H = \sqrt{\sigma^2 + 0.06^2} \tag{9}$$

$$\text{for } SA_H \qquad \sigma_H = \sqrt{\sigma^2 + 0.27^2} \tag{10}$$

where σ is the standard error of estimate of $\ln(A_H)$ from Equations (4) or (5). A single value of σ_H was used for SA_H for all oscillator periods because there was no clear trend in the calculated values for the individual periods.

VERTICAL ATTENUATION RELATIONSHIPS

Only Campbell (1990) included an analysis of the vertical components of strong ground motion. In order to take advantage of the increased reliability of the recommended attenuation relationships for the horizontal components, the recommended attenuation relationships for A_V, V_V and SA_V were developed by taking the ratio of the vertical to the mean horizontal components from the 1990 study and multiplying this ratio by the value of A_H, V_H, or SA_H from the recommended horizontal attenuation relationships. The resulting attenuation relationships are given by the expressions

$$\begin{aligned}\ln(A_V) &= \ln(A_H) - 1.58 - 0.10M \\ &\quad -1.5\ln\left[R_{SEIS} + 0.079\exp(0.661M)\right] \\ &\quad +1.89\ln\left[R_{SEIS} + 0.361\exp(0.576M)\right] \\ &\quad -0.11F + \varepsilon\end{aligned} \tag{11}$$

$$\begin{aligned}\ln(V_V) &= \ln(V_H) - 2.15 + 0.07M \\ &\quad -1.24\ln\left[R_{SEIS} + 0.00394\exp(1.17M)\right] \\ &\quad +1.44\ln\left[R_{SEIS} + 0.0203\exp(0.958M)\right] + 0.10F \\ &\quad +0.46\tanh(2.68D) - 0.53\tanh(0.47D) + \varepsilon\end{aligned} \tag{12}$$

$$\begin{aligned}\ln(SA_V) &= \ln(SA_H) + c_1 - 0.10M \\ &\quad +c_2\tanh\left[0.71(M-4.7)\right] \\ &\quad +c_3\tanh\left[0.66(M-4.7)\right] \\ &\quad -1.50\ln\left[R_{SEIS} + 0.071\exp(0.661M)\right] \\ &\quad +1.89\ln\left[R_{SEIS} + 0.361\exp(0.576M)\right] \\ &\quad -0.11F + c_4\tanh(0.51D) \\ &\quad +c_5\tanh(0.57D) + \varepsilon\end{aligned} \tag{13}$$

TABLE 6
Regression Coefficients for SA_V
Note: SA_V has units of g

Period (sec)	c_1	c_2	c_3	c_4	c_5
0.05	−1.32	0	0	0	0
0.075	−1.21	0	0	0	0
0.1	−1.29	0	0	0	0
0.15	−1.57	0	0	0	0
0.2	−1.73	0	0	0	0
0.3	−1.98	0	0	0	0
0.5	−2.03	0.46	−0.74	0	0
0.75	−1.79	0.67	−1.23	0	0
1.0	−1.82	1.13	−1.59	0.18	−0.18
1.5	−1.81	1.52	−1.98	0.57	−0.49
2.0	−1.65	1.65	−2.23	0.61	−0.63
3.0	−1.31	1.28	−2.39	1.07	−0.84
4.0	−1.35	1.15	−2.03	1.26	−1.17

where A_V and SA_V have units of g; V_V has units of cm/sec; A_H, V_H, and SA_H are the mean horizontal components of PGA, PGV, and PSA from Equations (3), (7) and (8); and all other variables are defined in Equation (3) and in the section *Model Parameters*. The regression coefficients for Equation (13) are summarized in Table 6.

Consistent with the way that Equations (11) through (13) were developed, the square of the standard errors associated with these relationships were developed by adding the difference between the square of the standard errors of the vertical and horizontal components from Campbell (1990) to the square of the standard errors of the recommended horizontal attenuation relationships given by Equations (4) or (5), (9) and (10). The resulting standard errors are given by the following expressions

$$\text{for } A_V \qquad \sigma_V = \sqrt{\sigma^2 + 0.36^2} \tag{14}$$

$$\text{for } V_V \qquad \sigma_V = \sqrt{\sigma_H^2 + 0.30^2} \tag{15}$$

$$\text{for } SA_V, \qquad \sigma_V = \sqrt{\sigma_H^2 + 0.39^2} \tag{16}$$

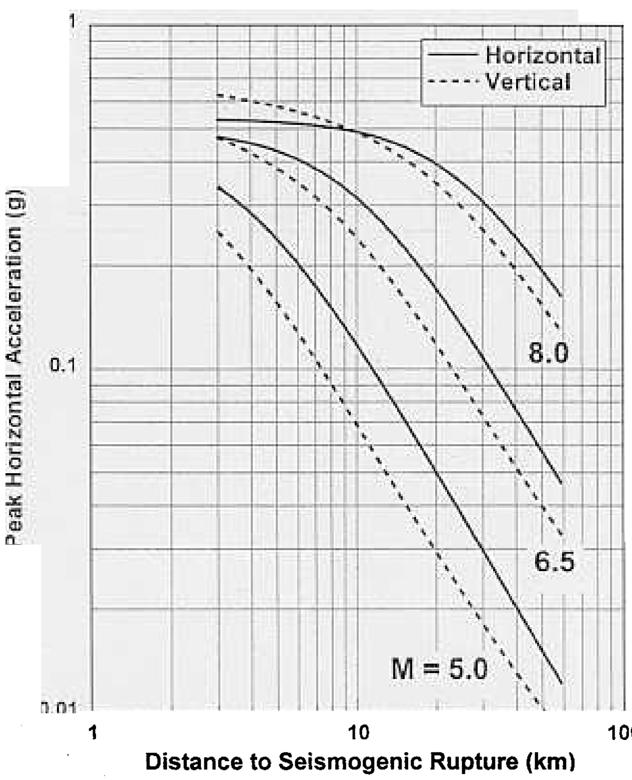
where σ is the standard error of estimate of $\ln(A_H)$ from Equations (4) or (5), and σ_H is the standard error of estimate of $\ln(V_H)$ and $\ln(SA_H)$ from Equations (9) and (10), respectively. A single value of σ_V was used for SA_V for all oscillator periods because there was no clear trend in the calculated values for the individual periods.

DISCUSSION

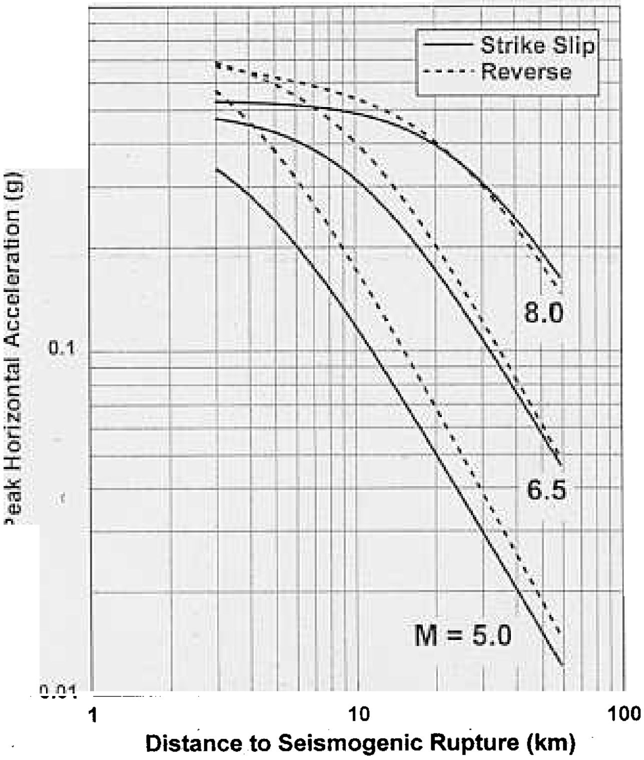
The recommended attenuation relationships presented in this paper were developed by combining the results of three previous studies (Campbell, 1990, 1993; Campbell and Bozorgnia, 1994a) in such a way as to maximize the strengths and to minimize the weaknesses of each. The recommended attenuation relationship for the horizontal component of PGA was taken from the Campbell and Bozorgnia (1994a) study, which included twice the number of earthquakes and triple the number of recordings than the earlier studies. The recommended attenuation relationships for the vertical component of PGA and for the horizontal components of PGV and PSA were developed in terms of the ratio of these parameters with respect to the horizontal component of PGA, then combined with the horizontal component of PGA from the Campbell and Bozorgnia (1994a) study, in order to take advantage of the increased reliability of the 1994 results. The recommended attenuation relationships for the vertical components of PGV and PSA were developed in terms of the ratio of these parameters with respect to their horizontal components, then combined with the horizontal components from the recommended horizontal attenuation relationships in order to take advantage of the increased reliability of these latter relationships.

The results for firm soil and for thick sedimentary deposits were taken from Campbell (1990). The results for hard rock were taken from Campbell (1993). Because neither study adequately modeled soft rock recordings, these sites were assumed to have amplitudes halfway between those of firm soil and hard rock at short periods and consistent with the Campbell (1993) results for soft rock at $D = 5$ km and long periods. Although the approach of combining several attenuation relationships takes advantage of the strengths of each, it unavoidably results in a set of relationships which do not have the same statistical robustness as the individual relationships. However, until a thorough, consistent analysis of PGA, PGV, and PSA can be conducted using an up-to-date strong-motion database, these recommended attenuation relationships can be used to predict near-source ground motions for engineering purposes. The recommended attenuation relationships for PGA are shown in Figures 8 through 10. Predicted PSA spectra are shown in Figures 11 through 16.

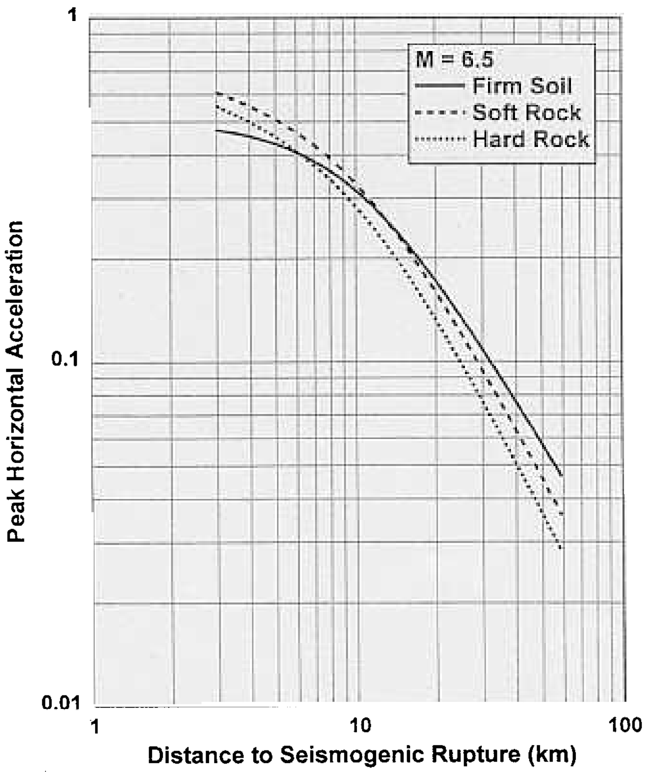
Since the original studies were published, there have been several earthquakes that have produced significant near-source recordings. Notable earthquakes that have occurred since the Campbell and Bozorgnia (1994a) study include the 1994 (M_W = 6.7) Northridge, California and the 1995 (M_W = 6.9) Hyogo-ken Nanbu (Kobe), Japan earthquakes.



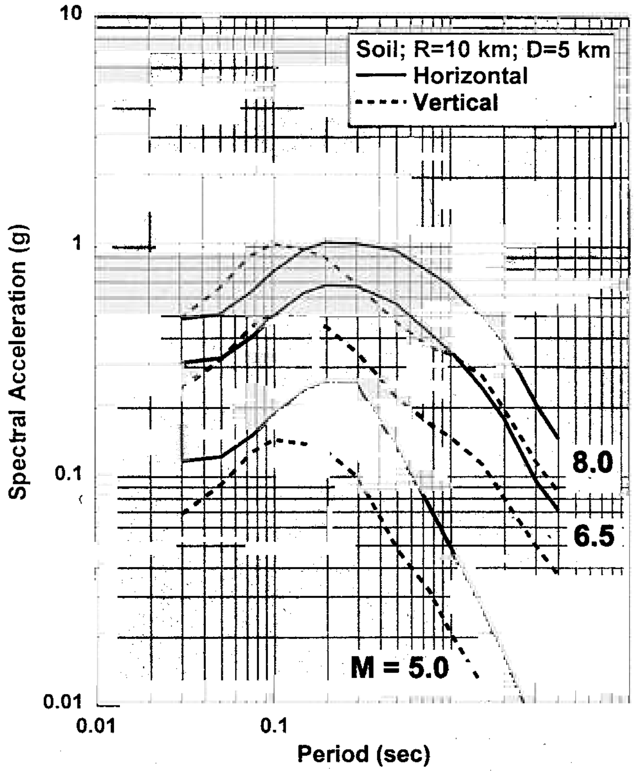
▲ **Figure 8.** Scaling of peak ground acceleration with magnitude, distance, and ground motion component predicted by the attenuation relationship recommended in this study.



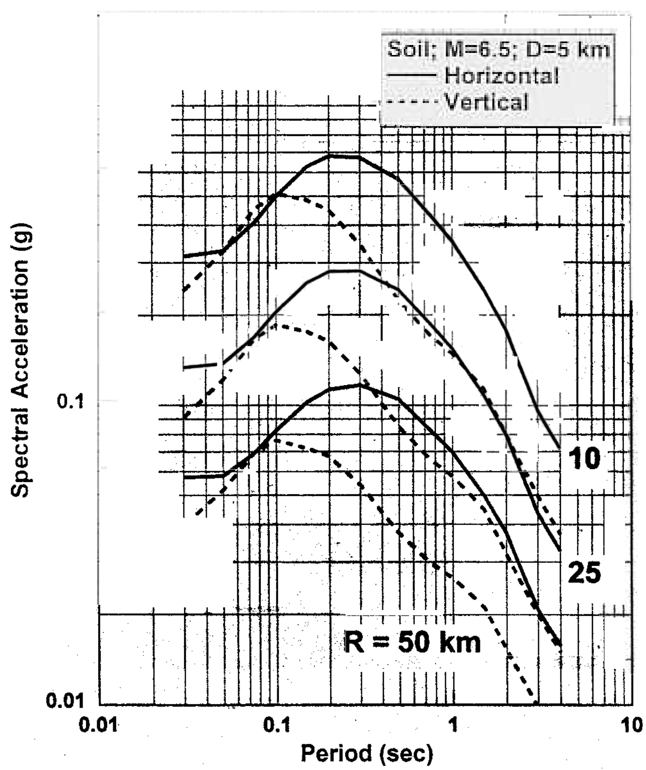
▲ **Figure 9.** Scaling of peak ground acceleration with magnitude, distance, and style of faulting from the attenuation relationship recommended in this study.



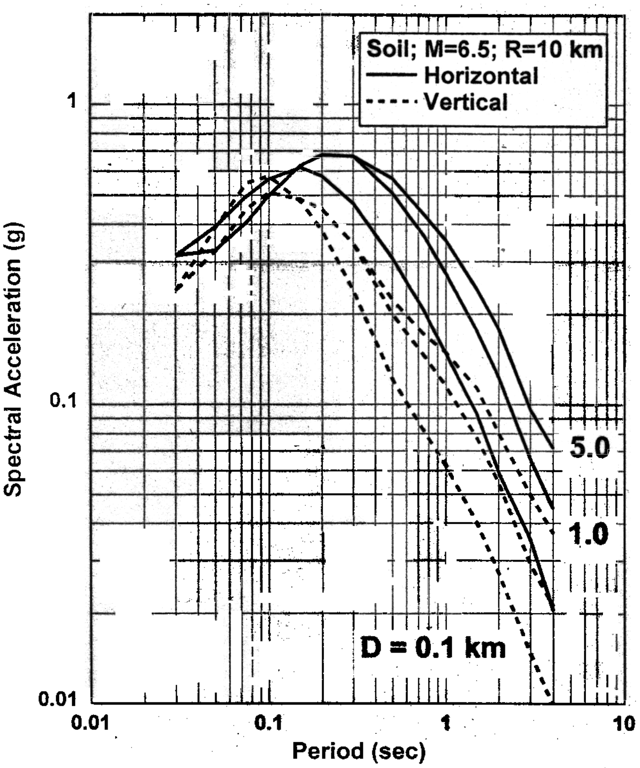
▲ **Figure 10.** Scaling of peak ground acceleration with distance and local site conditions from the attenuation relationship recommended in this study.



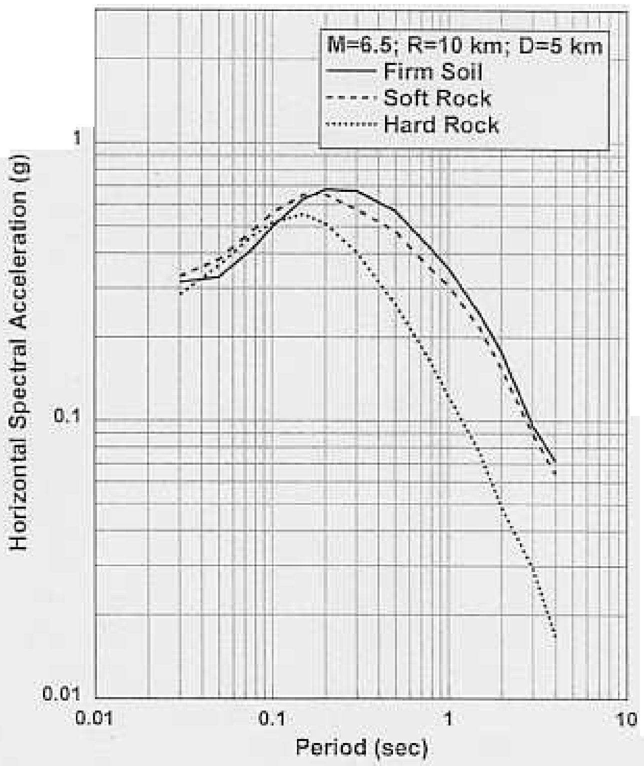
▲ **Figure 11.** Scaling of 5% damped pseudo-absolute acceleration with magnitude and ground motion component from the attenuation relationship recommended in this study.



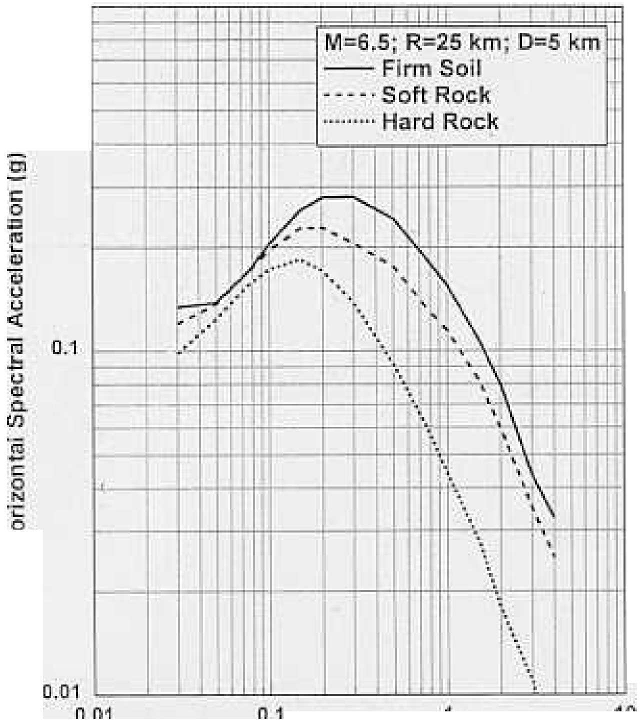
▲ **Figure 12.** Scaling of 5% damped pseudo-absolute acceleration with distance and ground motion component from the attenuation relationship recommended in this study.



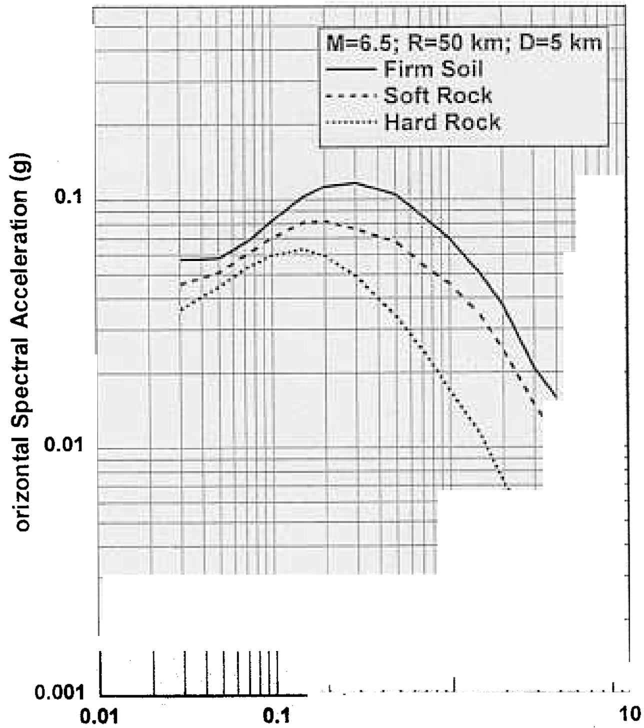
▲ **Figure 13.** Scaling of 5% damped pseudo-absolute acceleration with depth to basement rock and ground motion component from the attenuation relationship recommended in this study.



▲ **Figure 14.** Scaling of horizontal 5% damped pseudo-absolute acceleration with local site conditions at a distance of 10 km from the attenuation relationship recommended in this study.



▲ **Figure 15.** Scaling of horizontal 5% damped pseudo-absolute acceleration with local site conditions at a distance of 25 km from the ıttenuation relationship recommended in this study.



▲ **Figure 16.** Scaling of horizontal 5% damped pseudo-absolute acceleration with local site conditions at a distance of 50 km from the attenuation relationship recommended in this study.

Additional notable earthquakes that have occurred since the Campbell (1990, 1993) studies include the 1989 ($M_W = 6.9$) Loma Prieta, California, the 1992 ($M_W = 7.3$) Landers, California, and the 1992 ($M_W = 7.1$) Petrolia, California earthquakes.

Other than the Northridge earthquake, the earthquakes noted above have been shown to have near-source amplitudes relatively consistent with those predicted from previously published attenuation relationships (*e.g.*, Campbell, 1991c; Campbell and Bozorgnia, 1994b; EQE International, 1995; Geomatrix Consultants, 1995). The Northridge earthquake is unique among these earthquakes in that its near-source accelerations were approximately 50% higher than those predicted from previous attenuation relationships (Campbell, 1995). A similar result was found for the 1987 ($M_W = 6.1$) Whittier Narrows, California earthquake (Campbell, 1988), another relatively deep blind thrust-faulting earthquake. These results indicate that, taken as a whole, the new recordings are not expected to result in significant changes to the near-source attenuation relationships recommended in this paper. However, it is possible that relatively deep blind thrust faults could systematically produce ground motions that are roughly 50% higher than those from shallower blind and surface faults with the same style of faulting, but additional recordings will be required to confirm this hypothesis.

Only one earthquake in the database—the 1985 ($M_W = 6.8$) Nahanni, Canada earthquake—can arguably be considered to have occurred in a stable continental region (SCR), similar to eastern North America. The earthquake occurred along the eastern front of the Rocky Mountains in a region considered to be a transition zone between the North American SCR and the more seismically active and tectonically deformed region of western North America. Therefore, there is no statistical basis for determining whether the attenuation relationships presented in this paper can be used to estimate ground motions in the near-source region of SCR earthquakes.

Earthquakes from stable continental regions have been shown to have higher near-source ground motions than those from more tectonically active regions due primarily to differences in stress drop (*e.g.*, EPRI, 1993a,b). Therefore, it is possible that ground motions from earthquakes with similar stress drops in stable continental and active tectonic regions might also be similar, unless, of course, there are systematic differences in source scaling relations between the two regions (*e.g.*, Atkinson, 1993; Atkinson and Boore, 1995). In any case, the author has proposed a relatively simple technique based on stochastic simulation/random vibration procedures that can be used to modify empirical attenuation relationships, such as those presented in this paper, for use in stable continental regions (Campbell, 1994). These modified empirical attenuation relationships serve as an alternative to the more conventional attenuation relationships developed for these regions using theoretical ground motion models.

CONCLUSIONS

The recommended attenuation relationships presented in this paper are considered to be appropriate for predicting free-field amplitudes of horizontal and vertical components of peak ground acceleration, peak ground velocity, and 5% damped pseudo-absolute acceleration response spectra from worldwide earthquakes of $M_W \geq 5$ and sites with $R_{SEIS} \leq$ 60 km in active tectonic regions. ■

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