SITE RESPONSE STUDIES FOR PURPOSE OF REVISING NEHRP SEISMIC PROVISIONS

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ABSTRACT

A strong-motion database was compiled for California earthquakes of surface-wave magnitudes, $M_s \geq 6$, occurring from 1933 through 1992. The database consisted of horizontal peak ground acceleration and 5 percent damped response spectra of accelerograms recorded on four different local geologies: bedrock (class A); soft rock or stiff soil (class B); medium stiff soil (class C); and, soft soil (class D). The results of regression analysis of the database within each of these site classes were used to derive a set of site-dependent spectral amplification factors for oscillator periods between 0.1 and 4.0 sec and ground acceleration levels between 0.1 and 0.4 g. The amplification factors at 0.3 and 1.0 sec periods are generally similar to those recommended during the 1992 NCEER Site Response Workshop.

INTRODUCTION

The National Center for Earthquake Engineering Research (NCEER) held a workshop on site response in November 1992 (Martin, 1994). The primary objectives of the workshop were to develop revised site categories, site coefficients, and site-dependent spectra for inclusion in the 1994 National Earthquake Hazards Reduction Program (NEHRP) seismic provisions. The results of recent and ongoing research by several engineers and seismologists who attended the workshop provided valuable information for making the revisions. In reviewing this research, which was largely based on numerical model analysis using the computer program SHAKE (Schnabel et al., 1972) and on empirical studies of 1989 Loma Prieta earthquake data, it was discovered that a study of site response, using the wealth of strong-motion data recorded during the last 60 years, was not being conducted. This study was performed by the authors to compliment the results of the research completed to date and to provide to the revision process the necessary empirical component, which was currently lacking or underdeveloped.

The site-response parameters appearing in the 1991 NEHRP provisions were based mostly on the site-dependent spectra developed by Seed, et al. (1974) and Mohraz (1976), who used strong-motion data recorded through 1971. The abundant strong-motion accelerogram data recorded since the 1971 San Fernando earthquake offered the opportunity to improve the existing knowledge on site response gained since the Seed and Mohraz studies by conducting more thorough statistical studies of the strong-motion data.

The specific objectives of these statistical studies were to develop a set of site coefficients or amplification factors (F_a and F_v), site-dependent spectra, and the associated site classifications for use in updating the NEHRP seismic provisions (Building Seismic Safety Council, 1991). The databases, analyses, and results of these studies are summarized in the remaining sections of this paper.

DATABASES

Two databases were compiled: (1) geotechnical, geophysical and geological data for strong-motion stations, and (2) horizontal peak ground acceleration (PGA) and 5 percent damped pseudovelocity (PSV) response spectra of accelerograms recorded during central and southern California earthquakes of $M_s \geq 6.0$. Based on the local site data, four site classifications (A,B,C,D) were selected that were similar to those of Boore et al. (1993) and those recommended during the 1992 NCEER Site-Response Workshop (Martin, 1994). Abridged definitions of these site classes are as follows: A– rock, $\bar{V}_s \geq 2500$ fps; B– soft rock or stiff soil, $1200 \leq \bar{V}_s < 2500$ fps; C– medium stiff soils, $600 \leq \bar{V}_s < 1200$ fps; D– soft clay, $\bar{V}_s < 600$ fps, where $\bar{V}_s$ = average shear-wave velocity in the upper 100 feet of soil or rock.

After carefully searching the strong-motion and local geologic databases, a total of 238 records from 16 earthquakes were selected. With few exceptions, the data were recorded in small buildings up to three stories in height or in instrument shelters. The 238 records were distributed among the earthquakes and site classifications as shown in Table 1. Data from several $M_s > 6$ California earthquakes were not included. For example, accelerograms recorded in the Eureka-Ferndale area of Northern California were excluded because of the possible association of the causative earthquake with the southern Cascadia Subduction Zone, which represents a different tectonic environment than found in central and southern California. Accelerograms from the 1980 Mammoth Lakes sequence were excluded because this active volcanic region is atypical of the geological/tectonic regions of California where most of the accelerograms have been recorded. Accelerograms from the 1992 Big Bear earthquake were not available during the time the database was compiled.

A complete listing of the database used in the analysis will be provided in our final SMIP report to be submitted in June 1994. In addition to the information in Table 1, this listing will include: station name, location and type of structure recording ground motion; closest distance (R) from station to fault rupture of causative earthquake; PGA values for both horizontal and vertical components; site class; and, references for the information.

Plots of the M_s–R distribution for the data within each site class in Table 1 are shown in Figure 1. Note that most of the data in each site class fall within the $M_s = 6 - 7.25$ and $R = 10 - 80$ km ranges.

Table 1. Number of Accelerograms Used in Analysis

Date	Earthquake Name	M_S	Type[1]	Soil Classification A	B	C	D
1933.03.11	Long Beach	6.2	S		1	1	
1940.05.19	Imperial Valley	7.1	S			1	
1952.07.21	Kern County	7.7	R		3	1	
1966.06.28	Central California	6.1	S	1	3	3	
1966.08.07	Baja	6.3	S			1	
1968.04.09	Borrego Mountain	6.7	S		2	5	
1971.02.09	San Fernando	6.5	R	6	13	8	
1979.10.15	Imperial Valley	6.8	S	1	1	23	3
1981.04.26	Westmorland	6.0	S	1	1	2	2
1983.05.02	Coalinga	6.7	R	1	13	6	
1984.04.24	Morgan Hill	6.1	S	1	7	6	4
1986.07.08	Palm Springs	6.0	S	4	3	4	
1986.07.21	Chalfant Valley	6.2	S	1			
1987.10.01	Whittier	6.1	R	3	14	13	
1989.10.17	Loma Prieta	7.1	S	11	20	18	7
1992.06.28	Landers	7.6	S	3	7	9	
	Total			33	88	101	16

[1] *Note:* S = *strike slip;* R = *reverse*

ANALYSES

The numbers and distributions of accelerogram records in Table 1 suggested that the appropriate analysis procedure was to (1) conduct separate weighted nonlinear regressions of the more abundant class B and class C databases, and (2) compute factors to convert (i) class B response spectra to class A response spectra, and (ii) class C response to spectra to class D response spectra.

The regression model that was ultimately selected was

$$\ln Y = a + bM + d \ln\left(R + c_1 \exp\{c_2 M\}\right) + eF$$

where: Y is the ground-motion parameter (i.e., PGA or PSV); M is surface-wave magnitude; R is closest distance from the site to the fault rupture in km; F is a binary fault-type parameter (1 for reverse earthquakes and 0 for strike-slip earthquakes) and a, b, c_1, c_2, d, and e are the regression coefficients. The weighting scheme for the regression of each database was a modified form of one used by Campbell (1990), who defined distance intervals and gave the recordings from each earthquake within each interval the same total weight. In our weighing scheme, both magnitude and distance intervals were defined and the recordings within each magnitude-distance interval pair were given the same total weight. The magni-

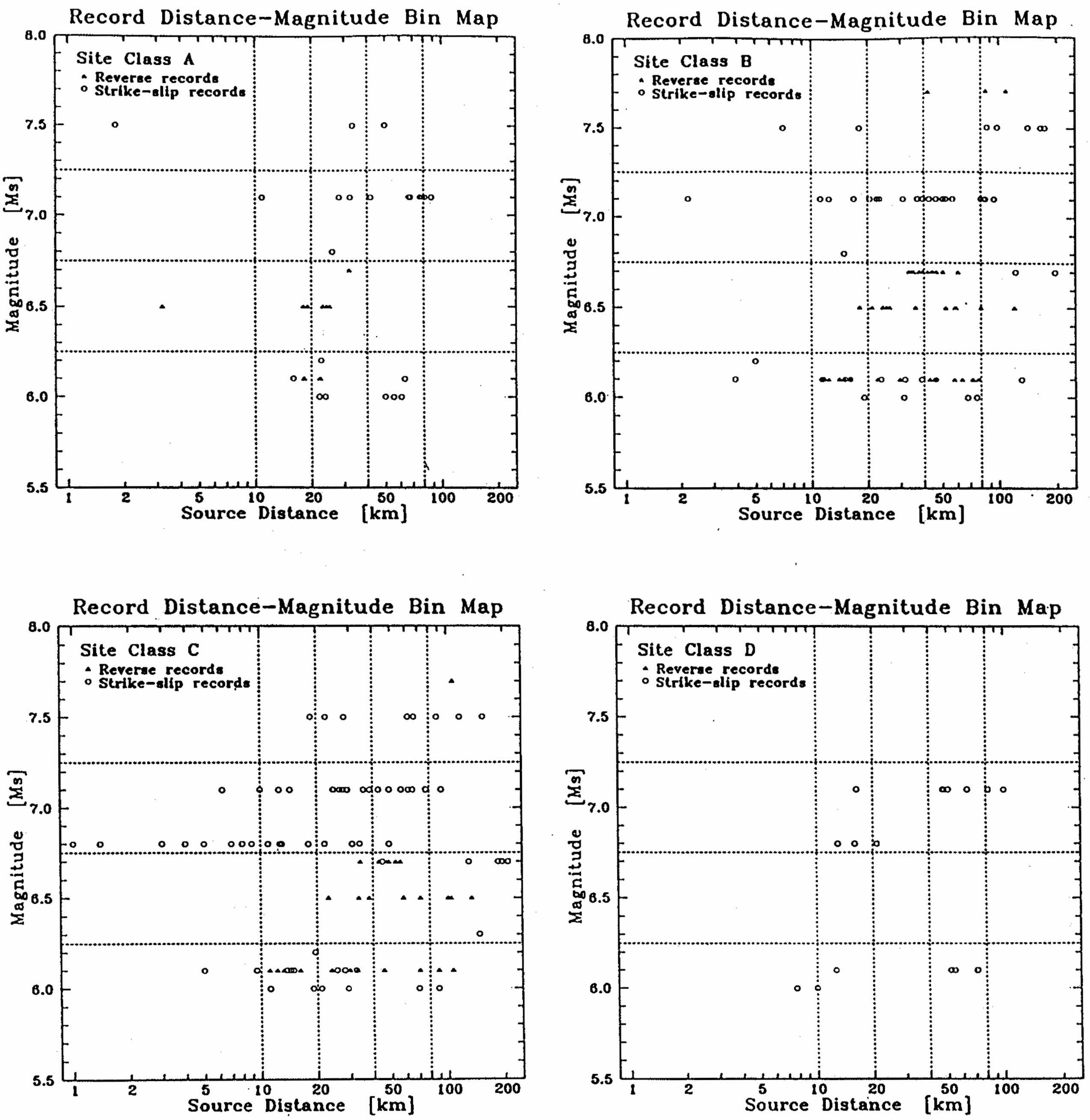


Figure 1. Distribution of Strong-Motion Data

tude–distance intervals are indicated with dashed lines in Figure 1. The geometric mean of both horizontal component values for each record was used in the regression analysis.

The nonlinear regressions on the class B and class C databases were performed using the BMDP Statistical Software program, 3R, (Dixon, 1986). Constraints involving the coefficients, b, d, c_1, and c_2, were introduced to ensure that Y was an increasing function of M for all $R \geq 0$. The coefficients, a, b, c_1, c_2, d, and e, and standard error, $\sigma_{\ell n Y}$ from the regressions are listed in Table 2. Plots of PGA and PSV ($T = 1$ sec) attenuation curves for M = 6.0, 6.5, 7.0 and 7.5 strike-slip earthquakes are shown in Figure 2. These PGA and PSV figures are typical of the attenuation observed at short and long periods, respectively, where it can be seen that (1) the attenuation is slower for class C sites, and (2) the attenuation becomes slower with the increasing oscillator period, T.

Values of the coefficient, e, in Table 2 were used to plot the ratio of reverse to strike-slip ground motion versus T (Figure 3) for class B and class C sites. The results for both site classes are similar in the sense that the ratios for $T < 1.0$ sec are generally greater that those for $T > 1.0$ sec, but the absolute values are different for the most part. Small values of $|e|$ (i.e., ratios ~ 1.0) were found statistically to not be significantly different from zero, but the general inconsistency in the class B and class C values makes it difficult to attach any significance of fault type on the level of ground motion from the results of this analysis.

The class B and class C regression equations were scaled to fit the class A and class D ground motion data. Specifically, the least-squares method was used to compute a factor k_1 such that $Y_A = k_1\ Y_B$. Similarly, a factor k_2 was computed such that $Y_D = k_2\ Y_C$. In these expressions, Y_i denotes ground-motion parameters for site class i. The k_1 and k_2 values were computed as a function of T and the median values are listed in Table 3. The possible dependence of k_i with the acceleration level was not obvious based on a visual examination of the residuals from the regressions. Plots of the median k_1 and k_2 values (including the ± 1σ limits) versus T are shown in the upper and lower frames, respectively, of Figure 4. As expected from a visual examination of the results, the k_i are not significantly different from 1.0 at the 95th percentile confidence level for the shorter periods (i.e., $T \leq 0.15$ sec for k_1 and $T \leq 0.50$ sec for k_2). Values of k_1 significantly less than 1.0 at longer periods are consistent with results of Boore et al. (1993) who show that longer period motions on rock sites are substantially less than those on soil sites. Similarly, values of k_2 significantly greater than 1.0 at longer periods are consistent with Borcherdt's (1994) results for the 1989 Loma Prieta earthquake data, which showed that longer period motion on the soft soils were greater than those on the stiff soil.

AMPLIFICATION FACTORS AND RESPONSE SPECTRA

The PGA and PSV equations for site classes A, B, C and D were then used to generate amplification factors, F_a and F_v , analogous to those originally recommended during the 1992 NCEER workshop. The workshop values of F_a and F_v were primarily derived from the results of SHAKE computer analyses of soil profiles representative of the different site classes and to a lesser extent from empirical studies of the 1989 Loma Prieta earthquake ground motions (Borcherdt, 1994); these values were

Table 2. Results of Regression Analyses

$$\ln Y^{\alpha,T} = a^{\alpha,T} + b^{\alpha,T}M + d^{\alpha,T}\ln\left(R + c_1^{\alpha,T}exp\{c_2^{\alpha,T}M\}\right) + e^{\alpha,T}F$$

Site Class B

Ground-Motion Parameter, $Y^{B,T}$	Period T [sec]	Predictor Equation Parameters						
		$a^{B,T}$	$b^{B,T}$	$c_1^{B,T}$	$c_2^{B,T}$	$d^{B,T}$	$e^{B,T}$	$\sigma_{\ln Y}^{B,T}$
PGA	...	−2.342699	1.091713	0.413033	0.623255	−1.751631	0.087940	0.427787
PSV(T, ξ=5%)	0.04	−0.472585	1.036917	0.387669	0.612898	−1.691826	0.108989	0.413926
⋮	0.10	7.571783	1.625135	4.612965	0.454664	−3.574364	0.033013	0.467394
⋮	0.15	9.070027	1.601903	5.449227	0.434297	−3.688497	−0.014652	0.490720
⋮	0.20	7.408577	1.468556	3.775168	0.464040	−3.164719	0.043634	0.472181
⋮	0.30	1.194880	1.086794	0.166050	0.706093	−1.539165	0.128310	0.467039
⋮	0.40	0.887084	1.026752	0.083872	0.757907	−1.354721	0.154355	0.495514
⋮	0.50	0.711154	1.055968	0.060623	0.788026	−1.340017	0.153348	0.509970
⋮	0.60	−0.070871	1.025031	0.048384	0.742853	−1.104581	0.187939	0.529652
⋮	0.80	−0.410607	0.936184	0.002278	1.044000	−0.896728	0.330569	0.577221
⋮	1.00	−1.829222	1.457603	0.008444	1.144165	−1.273945	0.112767	0.592915
⋮	1.50	−2.206094	1.262859	0.001634	1.287978	−0.922951	0.032286	0.595854
⋮	2.00	−3.886444	1.509735	0.000269	1.590216	−0.949390	0.014204	0.561973
⋮	3.00	−5.067456	1.651407	0.000080	1.807710	−0.907890	−0.135754	0.602980
PSV(T, ξ=5%)	4.00	−5.707326	1.745192	0.000070	1.844360	−0.914570	−0.245670	0.633340

units of PGA: [PGA] = *g*; *units of PSV:* [PSV] = cm/sec

Site Class C

Ground-Motion Parameter, $Y^{C,T}$	Period T [sec]	Predictor Equation Parameters						
		$a^{C,T}$	$b^{C,T}$	$c_1^{C,T}$	$c_2^{C,T}$	$d^{C,T}$	$e^{C,T}$	$\sigma_{\ln Y}^{C,T}$
PGA	...	−2.353903	0.838847	0.305134	0.640249	−1.310188	−0.051707	0.416639
PSV(T, ξ=5%)	0.04	−0.316018	0.775418	0.317517	0.607199	−1.277041	−0.010872	0.424616
⋮	0.10	4.844192	0.668470	4.045981	0.352728	−1.850579	−0.091919	0.453879
⋮	0.15	12.359194	1.064481	16.158960	0.310128	−3.432391	−0.231488	0.435481
⋮	0.20	6.529981	1.249258	4.378859	0.443090	−2.635199	−0.041310	0.474415
⋮	0.30	2.043062	0.838572	0.884282	0.454604	−1.285166	0.055896	0.496294
⋮	0.40	−0.449217	1.103279	0.015008	0.978334	−1.127712	0.227447	0.478698
⋮	0.50	−1.079692	1.198570	0.006383	1.092807	−1.096781	0.193853	0.468321
⋮	0.60	−1.495757	1.172313	0.001802	1.232590	−0.951097	0.159078	0.498147
⋮	0.80	−3.567871	1.612229	0.000749	1.487888	−1.083569	0.049774	0.558253
⋮	1.00	−7.286583	2.563514	0.000557	1.716614	−1.493355	−0.102444	0.569552
⋮	1.50	−6.200445	2.052788	0.000123	1.790362	−1.146577	−0.127769	0.545691
⋮	2.00	−5.888256	1.974398	0.000155	1.748081	−1.129466	−0.279244	0.564984
⋮	3.00	−6.088140	1.944268	0.000130	1.714319	−1.134134	−0.155093	0.692397
PSV(T, ξ=5%)	4.00	−7.441490	2.122133	0.000092	1.779805	−1.119420	−0.107566	0.745120

units of PGA: [PGA] = *g*; *units of PSV:* [PSV] = cm/sec

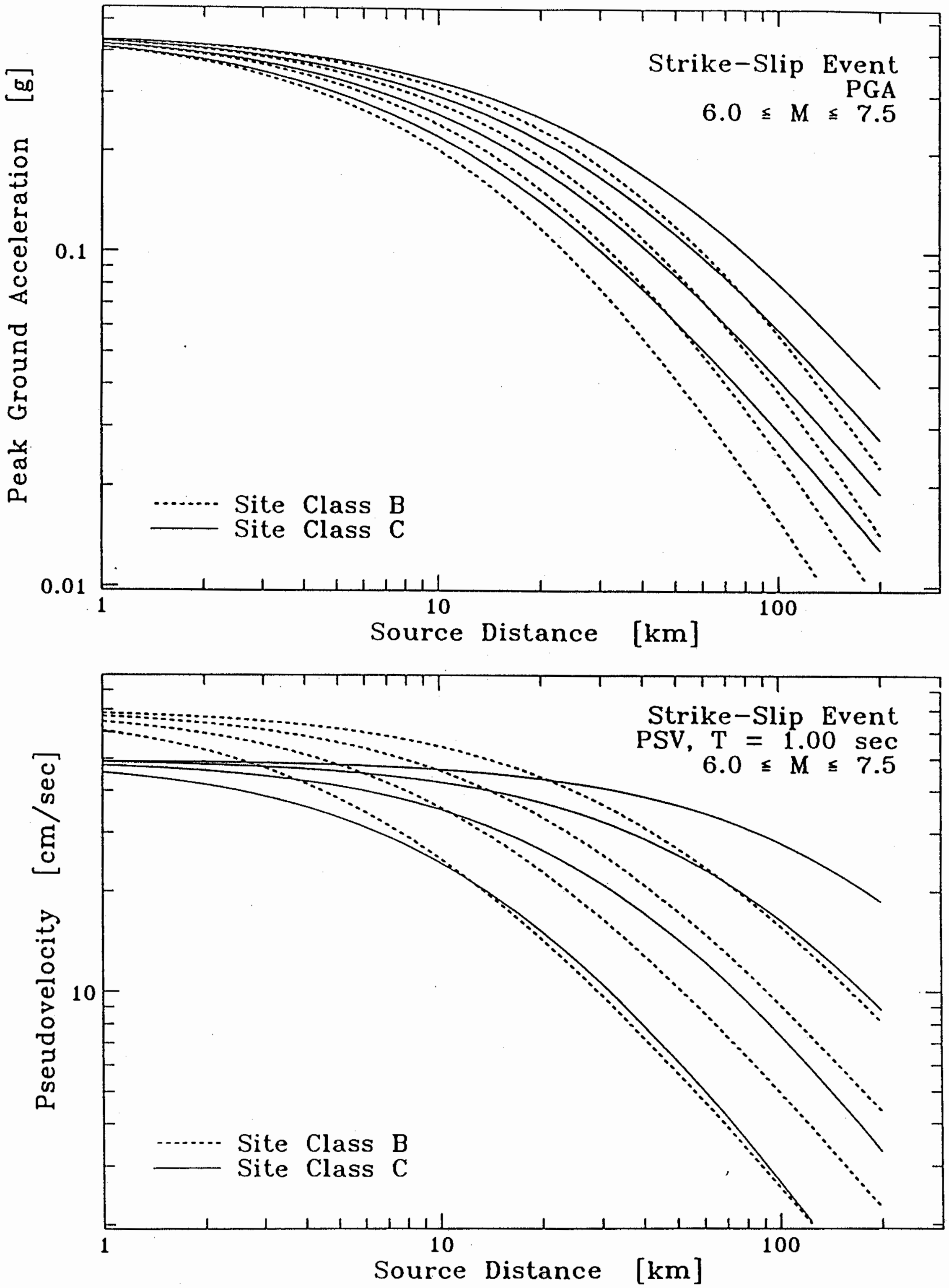


Figure 2. Median PGA and PSV (*T* = 1 sec) Attenuation Curves for *M* = 6.0, 6.5, 7.0, and 7.5 Strike-Slip Events

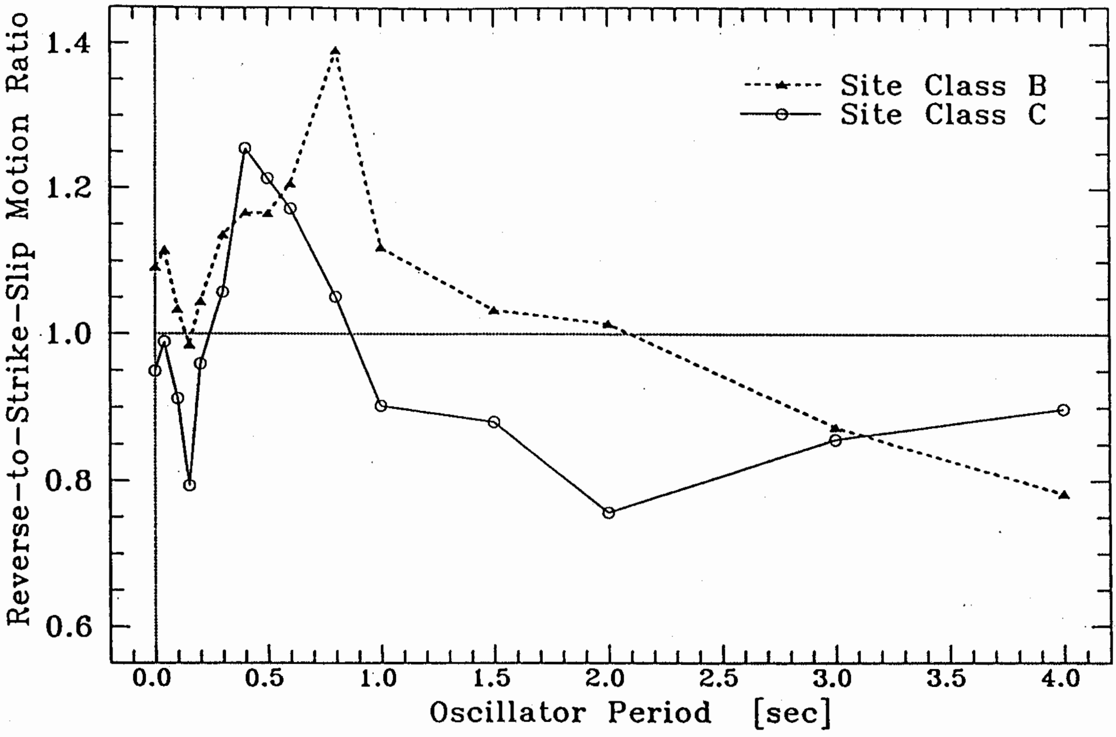


Figure 3. Ratio of Reverse to Strike-Slip Earthquake Ground Motion

Table 3. Regression Results for k_1 and k_2

$$Y^{A,T} = k_1^T \, Y^{B,T}$$
$$Y^{D,T} = k_2^T \, Y^{C,T}$$

Ground-Motion Parameter, $Y^{\alpha,T}$	Period T [sec]	k_1^T	k_2^T
PGA	...	0.998638	1.200678
PSV(T, ξ=5%)	0.04	1.023352	1.135611
⋮	0.10	1.144851	0.951057
⋮	0.15	0.952255	0.872571
⋮	0.20	0.817204	0.939360
⋮	0.30	0.753139	1.261232
⋮	0.40	0.719723	1.204849
⋮	0.50	0.620631	1.293272
⋮	0.60	0.600028	1.598795
⋮	0.80	0.629231	1.490827
⋮	1.00	0.572224	1.428036
⋮	1.50	0.529423	1.425156
⋮	2.00	0.578300	1.352620
⋮	3.00	0.589383	1.408488
PSV(T, ξ=5%)	4.00	0.632419	1.300720

units of PGA: g; *units of PSV:* cm/sec

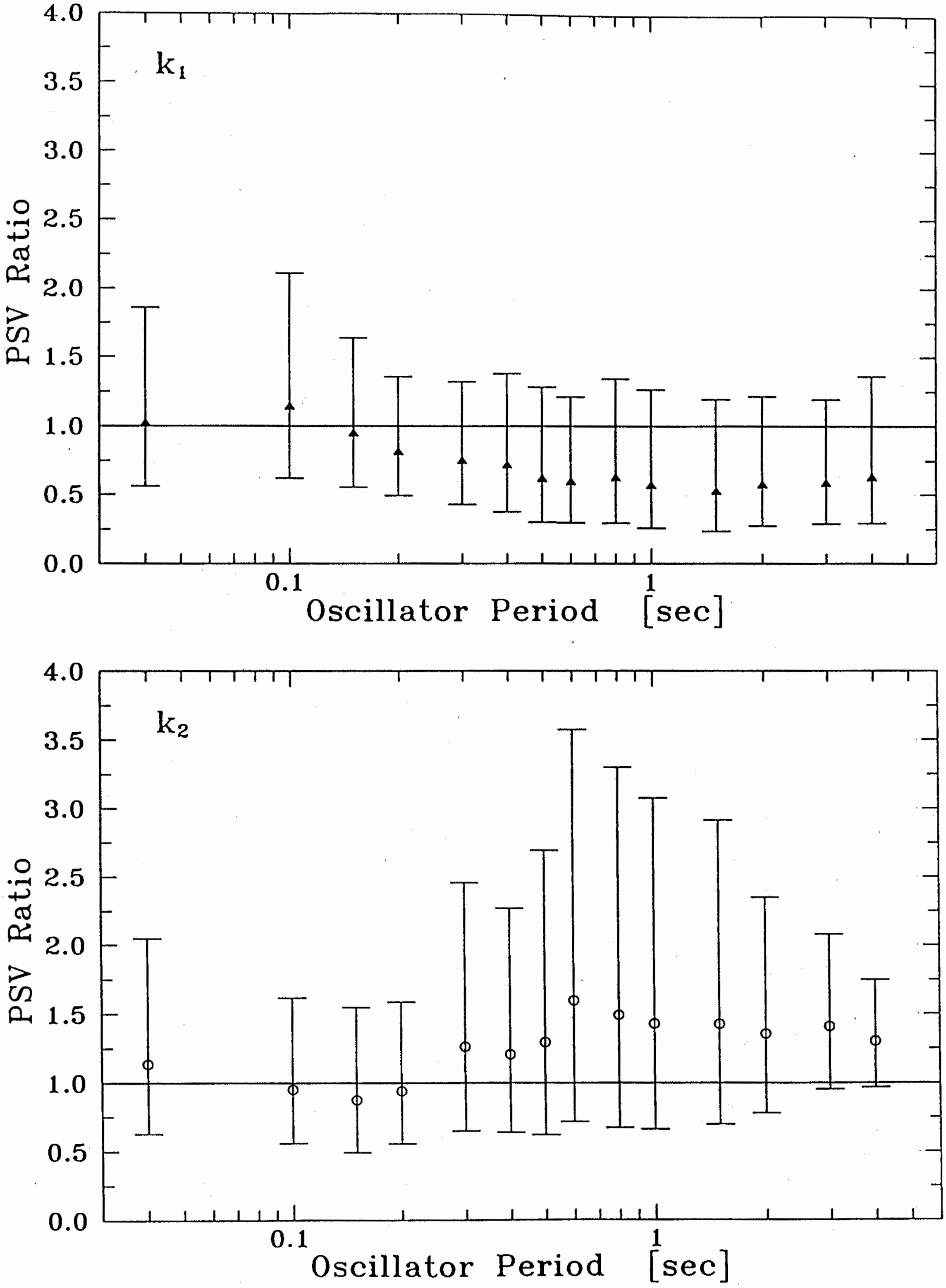


Figure 4. Median Values and ± 1 Sigma Limits of k_1 and k_2

functions of the ground acceleration level (0.1 g, 0.2 g, 0.3 g, 0.4 g, and 0.5 g). The F_a values from the present study were derived from similar rock-site acceleration levels (median PGA_A = 0.1 g, 0.2 g, 0.3 g, and 0.4 g) by computing the ratio PSV_i / PSV_A (where i = site classes B, C, and D) at period T = 0.3 sec for selected magnitude–distance combinations that yielded the proper acceleration values. Specifically, for each acceleration level PGA_A, three magnitude values (M = 6.5, 7.0, and 7.5) and three acceleration values (PGA_A and $PGA_A \pm 0.05$ g) were considered; for each magnitude, the value of R required to yield each of the three acceleration values was computed. Thus, for a given acceleration level, nine (M, R) ordered pairs were used to compute nine values of PSV_i / PSV_A, which in turn were averaged to obtain the value of F_a for a given site class i. In this manner, values of F_a were determined at each acceleration level for site classes i = B, C, and D.

The F_v values were computed in a similar manner using the PSV (T = 1 sec) predictions. The strong-motion data were insufficient to estimate factors for PGA = 0.5 g. Our computed F_a and F_v factors are summarized in Table 4; the adjacent values in parentheses are the recommendations from the 1992 NCEER workshop (Martin, 1994).

Table 4. Amplification Factors, F_a and F_v

Site Class	Acceleration Level 0.1 g	0.2 g	0.3 g	0.4 g
	Amplification Factor, F_a, at T = 0.3 sec			
A	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)
B	1.3 (1.2)	1.3 (1.2)	1.3 (1.1)	1.3 (1.0)
C	1.6 (1.6)	1.5 (1.4)	1.4 (1.2)	1.3 (1.1)
D	2.1 (2.25)	1.9 (1.65)	1.8 (1.2)	1.7 (0.9)
	Amplification Factor, F_v, at T = 1.0 sec			
A	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)
B	1.8 (1.7)	1.8 (1.6)	1.8 (1.5)	1.8 (1.4)
C	2.3 (2.4)	1.7 (2.0)	1.4 (1.8)	1.2 (1.6)
D	3.2 (3.5)	2.5 (3.2)	2.1 (2.8)	1.8 (2.4)

Note: Values in ( ) are from the 1992 NCEER Workshop (Martin, 1994)

To provide an indication of the differences in site-dependent spectra, response spectra for site classes A, B, C, and D were computed for several values of M and R. A typical example is shown in Figure 5 for an M = 7.0 strike-slip event at R = 10 km. In this figure the differences in the spectra, which are representative of the 0.3 g acceleration level, are fairly consistent with the differences in the F_a and F_v values in Table 4. Note that at T = 1.0 sec, the spectral acceleration for site class C is less than the spectral acceleration for site class B , which is consistent with the F_v values for 0.3 g in Table 4 for

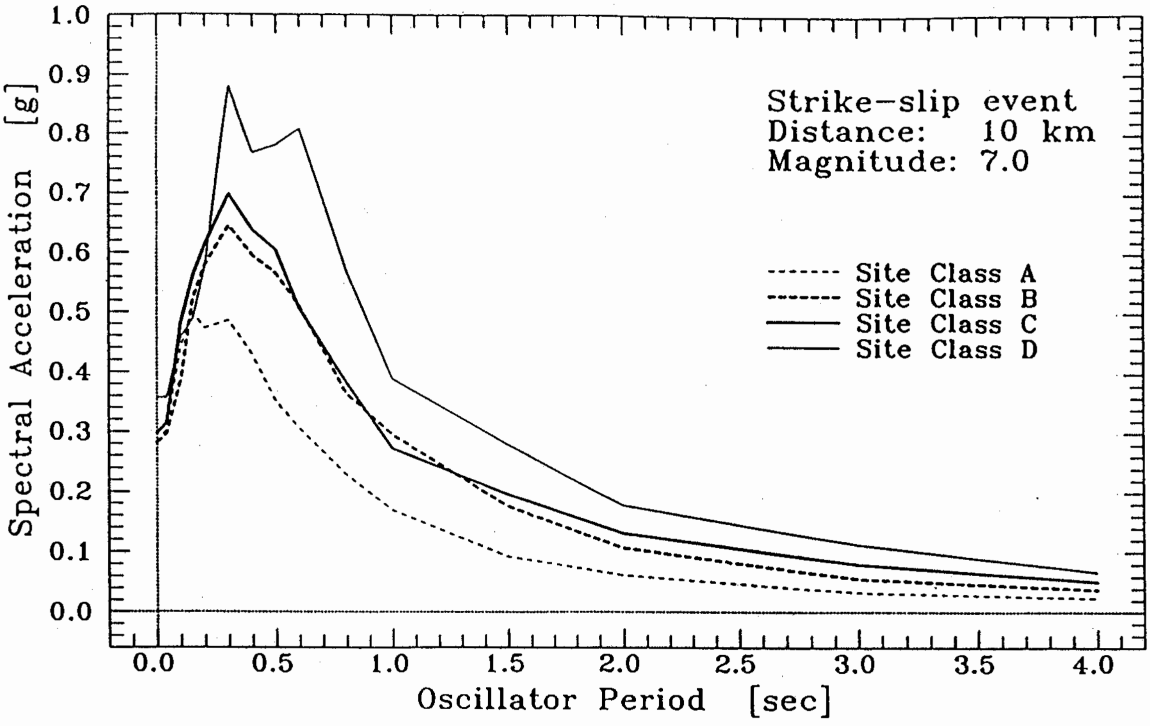
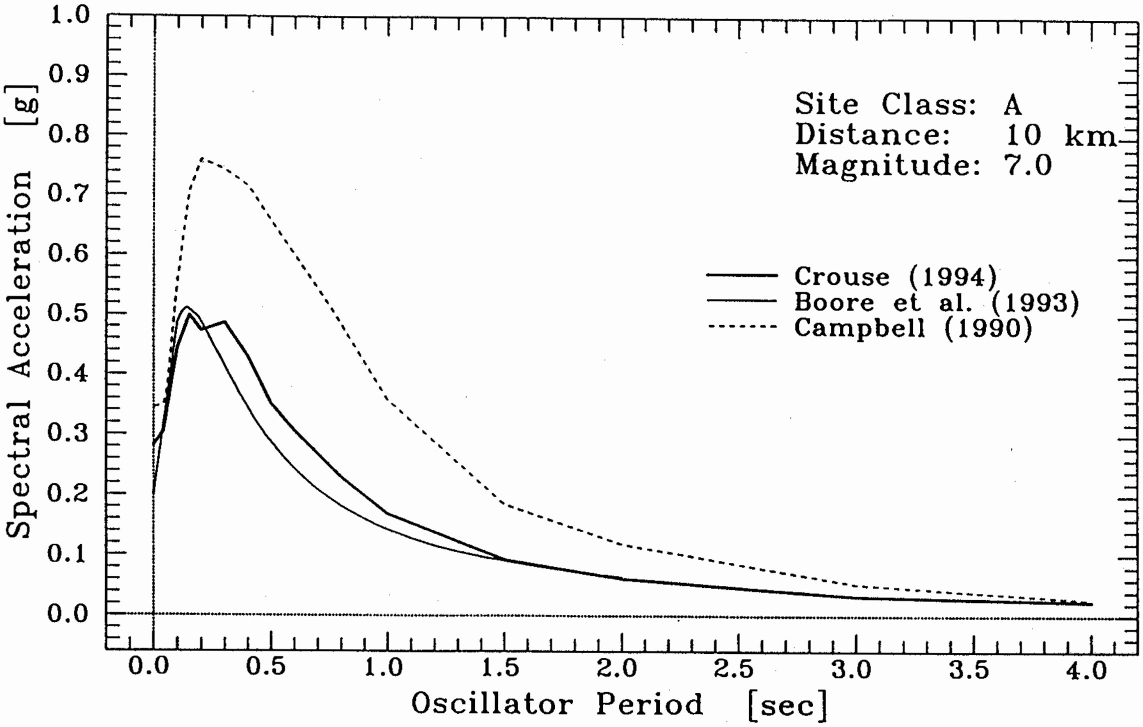


Figure 5. Median Site-Dependent Response Spectra for 5% Damping

classes B and C. However, in Figure 5 the class C spectra are larger than the class B spectra at $T > 1.0$ sec, which is intuitively expected and which was consistently observed in the spectra computed at other (M, R) values. Because the F_v values proposed in the 1992 NCEER workshop were intended to represent the amplification over the intermediate period (constant spectral velocity) range of the spectrum, some revisions to the values in Table 4 are required. Factors of F_v at other periods between 0.8 and 4.0 sec will be presented in our final SMIP report and used to develop our final recommendations.

Site-dependent response spectra estimated with the equations developed in this study were compared with spectra estimated from the attenuation equations recently published by Boore et al. (1993) and Campbell (1990). An example is shown in Figure 6 for the $M = 7.0$ strike-slip event at $R = 10$ km; the top and bottom plots show the spectra predicted for class A and class C sites, respectively. In an attempt to simulate site class A using Campbell's equations, the depth-to-basement-rock parameter (D) in his equations was set equal to zero; to simulate site class C, D was set equal to 5 km. The differences among the spectra in Figure 6 are expected given the differences in databases, regression equations and analyses, and parameter definitions such as magnitude and distance. For example, for site class A, the Crouse and Boore et al. spectra are similar and both are significantly lower than Campbell's spectrum. The much larger Campbell spectrum is believed to be primarily the result of his rock database, which he defines as soft rock. Most of these soft rock data would fall into the site class B category rather than into site class A. Thus, Campbell's (1990) equations are not recommended for class A sites. Precise reasons for the differences in the class C spectra are less obvious, and further analysis would be required to explain them, which was outside the scope of this study.



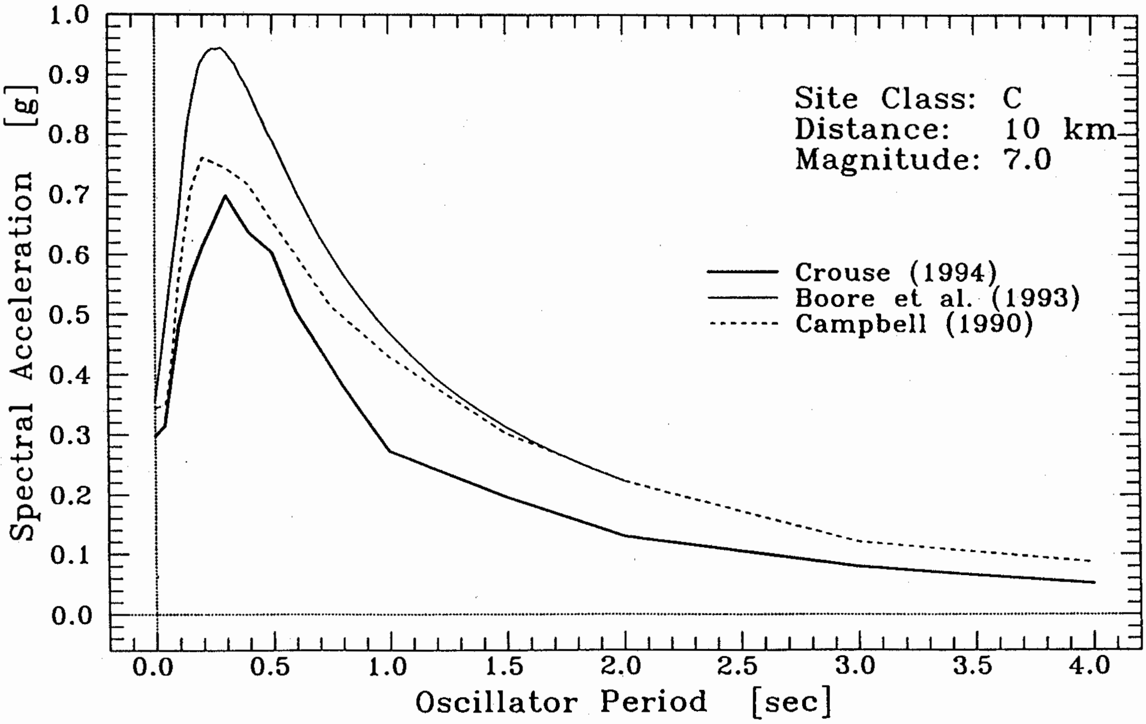


Figure 6. Comparison of 5% Damped Median Response Spectra for Magnitude 7.0 Strike-Slip Earthquake

CONCLUSIONS

The results of this study provide estimates of the spectral amplification due to differences in local geology. The amount and distribution of the strong-motion data suggest that the results are more reliable for ground acceleration levels of approximately 0.1 to 0.3 g for class A, B, and C sites. These acceleration levels roughly correspond to the $M = 6 - 7.25$ and $R = 10 - 80$ km ranges where there is a reasonable amount of data. The results for 0.4 g and for class D sites at all acceleration levels are more uncertain. As a final note, the equations presented herein were developed to estimate site amplification factors and were not developed for seismic hazard analyses. The authors caution potential users of these equations for such analyses, especially for near-field conditions ($R < 10$ km), where the database used to derive the equations is recognized as being limited.

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