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# Procedures for Selecting Earthquake Ground Motions at Rock Sites

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# PROCEDURES FOR SELECTING EARTHQUAKE GROUND MOTIONS AT ROCK SITES

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## INTRODUCTION

There are several procedures that can be used to select earthquake ground motions at a rock site. These procedures include: (i) utilization of motions previously recorded at rock sites during similar size earthquakes and at distances comparable to those under consideration; (ii) estimation of a target spectrum and then selection of natural time histories whose spectral ordinates are comparable to those of the target spectrum for the period range of interest; (iii) estimation of a target spectrum and then generation of a synthetic time history whose spectral ordinates provide a reasonable envelope to those of the target spectrum; or (iv) use of simulation techniques starting with the source and propagating the appropriate wave forms to generate a suite of time histories that can then be used to represent the earthquake ground motions at the rock site of interest.

Procedure number (i) is difficult to utilize at most locations because the number of recorded motions is not extensive enough to cover a sufficiently wide range of possibilities. There are several ways in which procedure number (iv) has been implemented. A significant amount of research and calibration of this procedure has been conducted in the past few years and the procedure has a wide range of applicability.

For the purpose for which NIST plans to use the procedures outlined in this report, only procedures number (ii) and number (iii) are covered herein. Estimation of the target spectrum is based on currently available empirically derived attenuation relationships.

## ESTIMATION OF TARGET SPECTRUM AT 5 PERCENT DAMPING

To estimate the spectral ordinates at a rock site for an earthquake having a given size (magnitude) and occurring at a specified distance from the site, available attenuation relationships are used. These relationships, which have been developed based on available recorded data and typically are for a spectral damping of 5%, provide estimates of the median spectral ordinates and a measure of the dispersion about the median.

Four currently available relationships are summarized in Appendix A to this report. These relationships are those derived by Campbell (1990), Geomatrix (1991), Idriss (1991) and Joyner & Boore (1988). The equations to be used in conjunction with each relationship together with the description and the numerical values of the coefficients pertinent to that relationship are also given in the Appendix.

## ESTIMATION OF TARGET SPECTRUM AT OTHER SPECTRAL DAMPING RATIOS

As noted above and in Appendix A, the equations listed in Appendix A are for a spectral damping ratio of 5%. Attenuation relationships at other damping ratios have not usually been derived. Instead, a factor to adjust from 5% damping to other damping ratios is used. For example, Newmark and Hall (1981) provided the following relationships for the median spectral amplification factors (SAF):

| Region | Approximate Range of Periods, T - seconds | Spectrum Amplification Factor (SAF) | SAF Normalized with respect to $\beta = 5\%$ |
|---|---|---|---|
| Acceleration | $0.125 \leq T < 0.3$ to 0.4 | 3.21 - 0.68 $Ln(\beta)$ | 1.517 - 0.321 $Ln(\beta)$ |
| Velocity | 0.3 to $0.4 \leq T < 1.5$ to 3 | 2.31 - 0.41 $Ln(\beta)$ | 1.400 - 0.248 $Ln(\beta)$ |
| Displacement | $T \geq 1.5$ to 3 | 1.82 - 0.27 $Ln(\beta)$ | 1.314 - 0.195 $Ln(\beta)$ |

*Note: The approximate range of periods listed above depends on the values selected for peak particle acceleration, velocity and displacement.*

For example, the spectral ordinates shown in Fig. 1 are for peak particle acceleration of 1 g, v/a ratio of 75 cm/sec/g and a value of $ad/v^2$ of 4; the resulting range of periods is as follows:

| | |
|---|---|
| Acceleration Region: | $0.125 \leq T < 0.35$ to 0.4 |
| Velocity Region: | 0.35 to $0.4 \leq T < 1.5$ to 1.7 |
| Displacement Region: | $T \geq 1.5$ to 1.7 |

The values of v/a = 75 and $ad/v^2 = 4$ were selected to represent motions at a rock site generated by a nearby earthquake having a magnitude of about 6½ to 7½.

Recordings from the San Fernando (SF) and the Imperial Valley (IV) earthquakes were also used to derive adjustment factors normalized with respect to 5 percent spectral damping. Expressions similar to those utilized by Newmark and Hall (1981) were used to derive the parameters for two sets of expressions. One set relates spectral values at damping ratios less than 5 percent to spectral values at damping of 5 percent and the other set for spectral damping ratios higher than 5 percent. Thus,

$$Ratio = a_1 - b_1 Ln(\beta) \quad \text{for } \beta \leq 5\%, \text{ and}$$

$$Ratio = a_2 - b_2 Ln(\beta) \quad \text{for } \beta \geq 5\%.$$

The values of the parameters $a_1$, $b_1$, $a_2$ and $b_2$ for a selected number of periods are listed below:

| Period - sec | $a_1$ | $b_1$ | $a_2$ | $b_2$ |
|---|---|---|---|---|
| 0.03 | 1 | 0 | 1 | 0 |
| 0.05 | 1.1142 | 0.0709 | 1.083 | 0.0505 |
| 0.075 | 1.3513 | 0.2183 | 1.2902 | 0.1803 |
| 0.1 | 1.4918 | 0.3056 | 1.4179 | 0.2597 |
| 0.15 | 1.5796 | 0.3601 | 1.4992 | 0.3102 |
| 0.2 | 1.6148 | 0.382 | 1.534 | 0.3318 |
| 0.25 | 1.6148 | 0.382 | 1.534 | 0.3318 |
| 0.3 | 1.6148 | 0.382 | 1.534 | 0.3318 |
| 0.35 | 1.606 | 0.3765 | 1.5224 | 0.3246 |
| 0.4 | 1.5972 | 0.3711 | 1.5108 | 0.3174 |
| 0.5 | 1.5796 | 0.3605 | 1.4992 | 0.3102 |
| 0.6 | 1.5445 | 0.3383 | 1.4876 | 0.303 |
| 0.7 | 1.5269 | 0.3274 | 1.4876 | 0.303 |
| 0.8 | 1.5094 | 0.3165 | 1.476 | 0.2958 |
| 0.9 | 1.4918 | 0.3056 | 1.469 | 0.2914 |
| 1 | 1.4742 | 0.2947 | 1.4644 | 0.2885 |
| 1.5 | 1.4391 | 0.2728 | 1.4644 | 0.2885 |
| 2 | 1.4216 | 0.2619 | 1.4644 | 0.2885 |
| 3 | 1.404 | 0.251 | 1.4644 | 0.2885 |
| 4 | 1.404 | 0.251 | 1.4644 | 0.2885 |
| 5 | 1.404 | 0.251 | 1.4644 | 0.2885 |

*Note: The values of the parameters $a_1$, $b_1$, $a_2$ and $b_2$ given above are reported up to the fourth decimal point to provide smooth curves for the calculated spectral ratios; this degree of precision does not imply any increase in accuracy.*

Values of the spectral ordinates for damping ratios of 2, 4, 7 and 10% divided by those for a damping ratio of 5% are presented in Fig. 2 using the above equations and the corresponding values of the parameters $a_1$, $b_1$, $a_2$ and $b_2$. Also shown in Fig. 2 are the values using the expressions proposed by Newmark and Hall for a peak acceleration of 1 g, v/a = 75 cm/sec/g and $ad/v^2 = 4$. The results shown in Fig. 2 indicate that the relationships proposed by Newmark and Hall and the expressions based on recorded data from IV and SF earthquakes provide comparable results. Therefore, either set of equations can be used for obtaining target spectra at damping ratios other than 5 percent.

## SELECTION OF NATURAL TIME HISTORIES

As noted above, either natural time histories or a synthetic time history can be used to represent the target spectrum. If these time histories are to be used in conjunction with a nonlinear analysis, then natural time histories would be preferable. Time histories recorded during several earthquakes were provided to NIST and have been used by NIST to establish a library of recorded time histories and has archived their spectral ordinates so that they can be compared to the target spectrum.

When using natural time histories, it is suggested that at least three time histories, and possibly as many as seven, be used in the analyses. NIST has already developed a computer program that allows instantaneous interaction by the user to apply a scalar multiplier to the time history so that its spectral values are more comparable to the target spectrum over a desired period range. An example of this selection process is provided later in this report.

## GENERATION OF SYNTHETIC TIME HISTORIES

NIST has been provided with the computer program RASCAL, which modifies the Fourier amplitudes of a given time history so that the response spectrum of the modified time history provides a reasonable estimate of the target spectrum. The program was developed by Silva and Lee (1987); details regarding the procedures used, a computer program listing and a user's guide are included in the publication by Silva and Lee. An example of a time history generated using this program is provided later in this report.

## EXAMPLES

Two examples completed by NIST of the time history methods described above are provided in this report. The first example illustrates simple amplitude scaling of a recorded accelerogram to arrive at a scaled accelerogram whose response spectrum is closer to the target response spectrum in the period range of interest to the structure (or soil-structure system) being evaluated. The second example illustrates generating a synthetic accelerogram using the program RASCAL.

The target median and median$\pm\sigma$ (in which $\sigma$ is the standard error term designated as $\varepsilon$ in Appendix A) spectral ordinates at a rock site generated by a magnitude 7 earthquake occurring at a distance of 15 km from the site.

For both examples, the E-W component of the motion recorded at Griffith Park during the 1971 San Fernando Earthquake was used as the starting accelerogram.

**Amplitude Scaling:** Figures 3 and 4 illustrate this method of directly using a recorded accelerogram. The original un-scaled time history of recorded motion is shown in the upper part of Fig. 3 and its spectrum is plotted together with the target spectrum and target $\pm$ $\sigma$ are shown in the lower part of the figure. Figure 4 shows the scaled time history (scaled by a factor of 1.9) and the resulting spectral ordinates in comparison with the target spectrum and target $\pm$ $\sigma$. The scaling factor is selected to provide a time history whose spectral ordinates in the period range of interest are close to those judged appropriate for the evaluation under consideration. Thus, the scaled time history shown in Fig. 4 would provide an appropriate accelerogram for analysis when the target is the median spectrum, although it may be somewhat conservative in the period range of about 0.2 to 0.3 sec and about 0.8 to 1.2 sec. (Note that had the target been the median $+ \sigma$, then a different scaling factor would have been necessary). Normally, 3 to 7 recorded accelerograms are selected and each is adjusted so that the full period range of interest is covered by the selected scaled accelerograms. The soil-structure system of interest is then subjected to each scaled accelerogram separately to evaluate the performance of the structure.

**Synthetic Time History:** Figure 5 shows the results of using this method of generating a synthetic time history whose spectrum is a reasonable fit to a selected target spectrum. The program RASCAL is used for this purpose starting with a selected recorded accelerogram; the accelerogram shown in Fig. 3 was used for this example.

## ACKNOWLEDGMENTS

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The writer gratefully acknowledges the support of NIST and thanks Dr. Yokel for his support and Dr. Taylor for his active participation and input to this part of the studies.

A floppy disk containing the source listing of the program RASCAL was made available by Dr. Walter Silva of Pacific Engineering & Analysis, El Cerrito, California. His cooperation in making this listing readily available is gratefully acknowledged

Drs. K. Sadigh, F. Makdisi, C-Y. Chang and R. Youngs and Mr. M. S. Power of Geomatrix Consultants, provided early editions of the equations representing the attenuation relationship listed as Geomatrix (1991) in this report. Dr. Makdisi provided updated distance and site information regarding many of the recordings used by the writer in checking his attenuation relationships. The writer is grateful for their cooperation and timely input.

The writer was a consultant to PG&E in their ground motion studies for Diablo Canyon Nuclear Plant. Ground motion evaluations were completed as part of these studies by PG&E, by Geomatrix Consultants, by Dr. Norm Abrahamson and by Woodward-Clyde Consultants for PG&E under the direction of Mr. Lloyd Cluff, Mr. Frank Brady and Dr. Y. B. Tsai of PG&E. Dr. K. Campbell conducted similar studies for the U. S. Nuclear Regulatory Commission. The insight gained from these studies was extremely valuable and facilitated the preparation and completion of this report.

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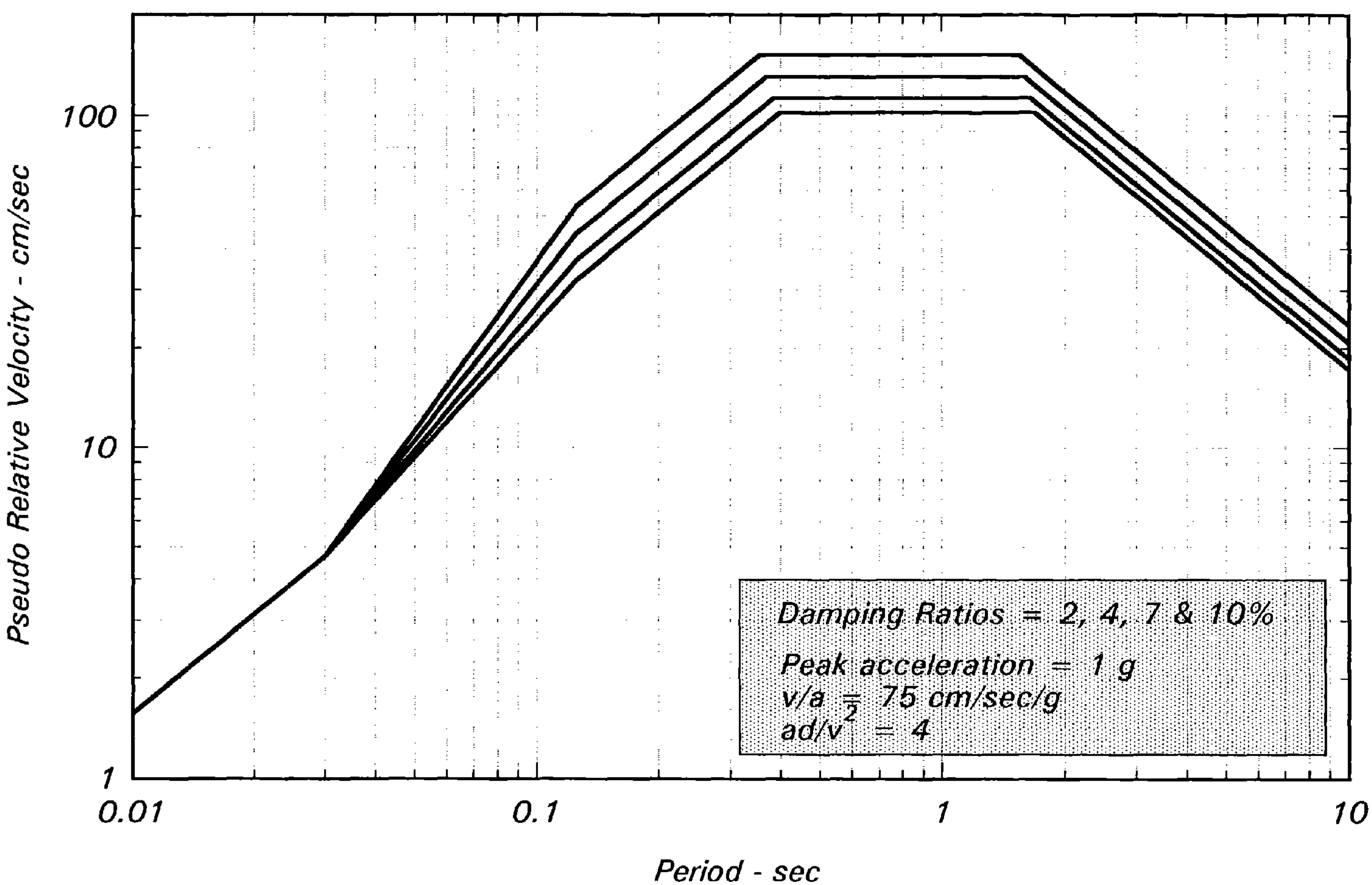


*Fig. 1 Spectral Shapes Using Relationships Proposed by Newmark & Hall (1981)*

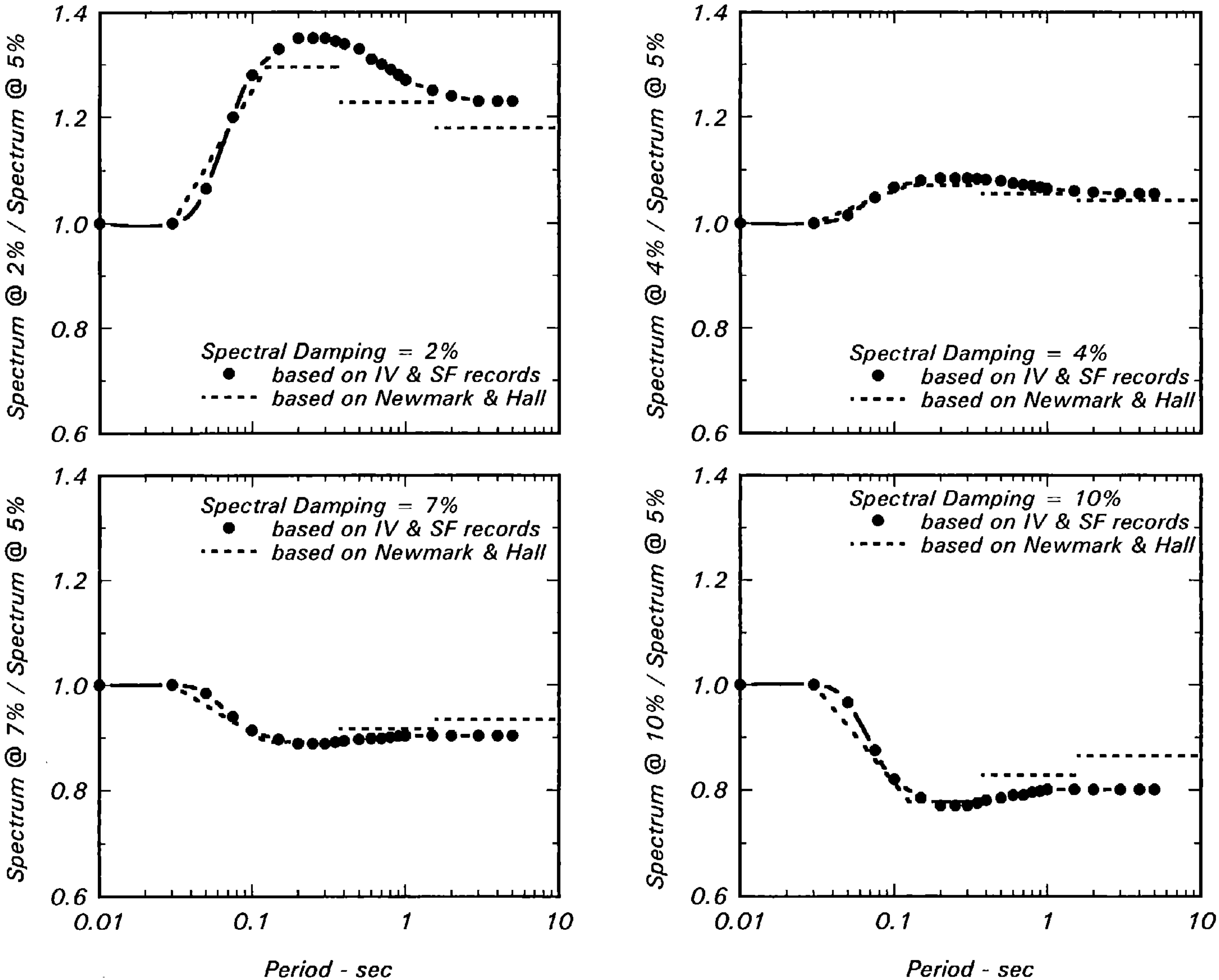


*Fig. 2 Variations of Spectral Ordinates with Spectral Damping*

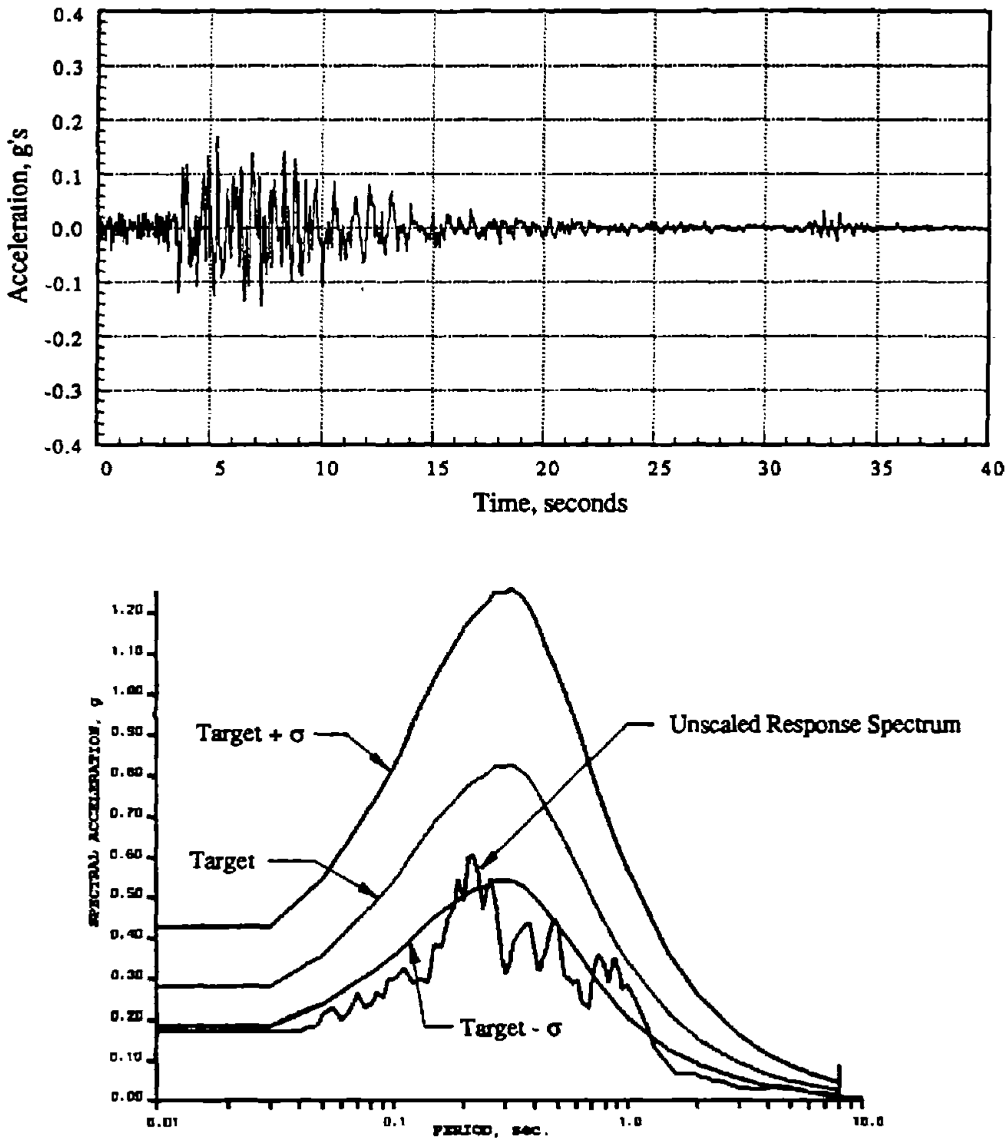


*Fig. 3 Accelerogram and Spectrum for the E-W Component of Motion Recorded at Griffith Park during the 1971 San Fernando Earthquake*

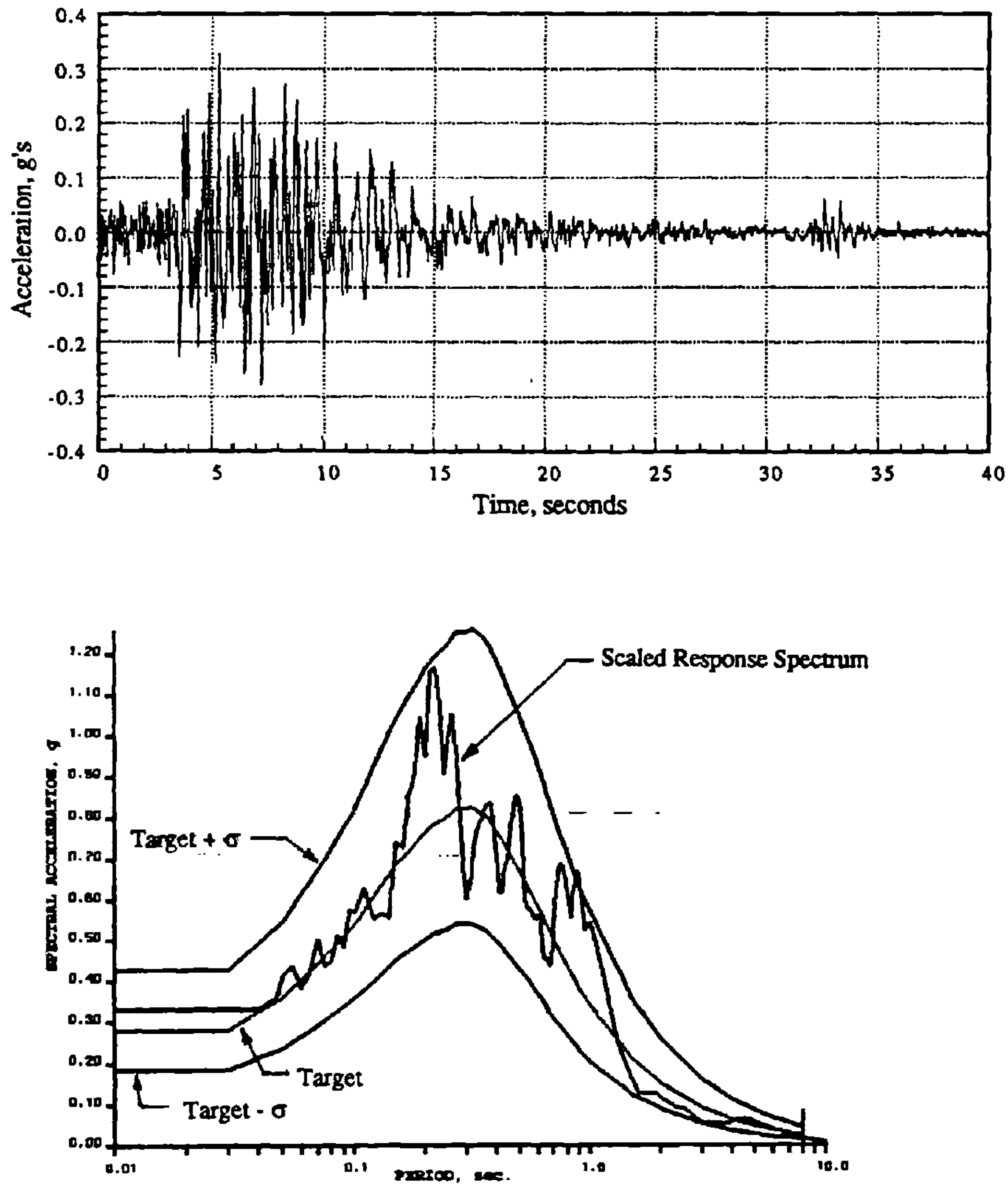


*Fig. 4 Recorded Accelerogram Scaled by a Factor of 1.9 to Provide Spectrum that is a Reasonable Fit to Target Spectrum*

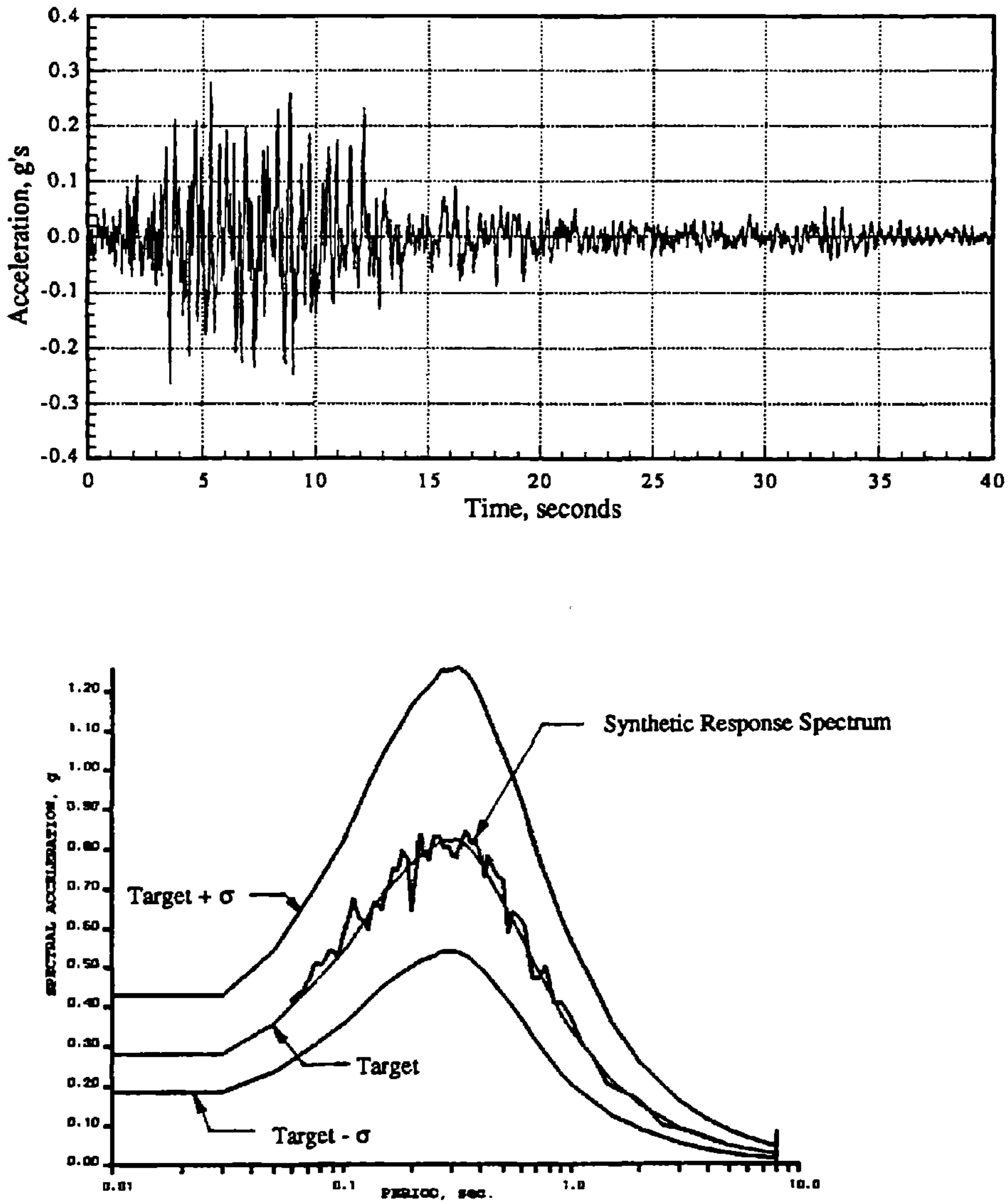


*Fig. 5 Synthetic Accelerogram, Generated Using Program RASCAL, Whose Spectrum is a Reasonable Envelope of the Target Spectrum*

# APPENDIX A

# EMPIRICALLY-DERIVED ATTENUATION RELATIONSHIPS

## INTRODUCTION

Several attenuation relationships have been derived over the past few years using recorded earthquake ground motions. These relationships typically relate a given earthquake ground motion parameter (eg, peak acceleration, spectral acceleration .. etc) to the factors which are considered to affect these parameters such as source, path and local site conditions. Earthquake magnitude is usually used to represent the source, distance to represent the path and some relationships include and some do not include the effects of local site conditions. All available relationships use a log-normal distribution to represent these ground motion parameters.

Many attenuation relationships have been derived over the past four decades. Initially, most relationships were for peak accelerations and spectral ordinates were estimated using normalized spectral shapes. As more recordings from recent earthquakes became available, attenuation relationships for peak accelerations as well as spectral ordinates were derived. At present, there are several available relationships, some of which were derived specifically for rock sites.

The following relationships for horizontal earthquake ground motions at rock sites are summarized in this appendix for possible use by NIST:

1. Joyner and Boore (1981, 1988)
2. Campbell (1990)
3. Geomatrix (1991)
4. Idriss (1991)

## RELATIONSHIP BY JOYNER AND BOORE (1981, 1988)

Joyner and Boore derived attenuation relationships for peak horizontal acceleration, peak horizontal velocity and for horizontal pseudo relative spectral velocities. Their relationships were first published in 1981 and were summarized in their paper in 1988.

The equations derived by Joyner and Boore are the following:

$$Log(Y) = a + b(M-6) + c(M-6)^2 + dLog(r) + kr + s + \varepsilon$$

$$r^2 = r_o^2 + h^2$$

in which:

- Log base 10 logarithm;
- Y = ground motion parameter (peak acceleration, velocity ... );
- M = earthquake magnitude ( moment magnitude);
- $r_O$ = shortest distance from the site to the vertical projection of the earthquake fault rupture on the surface of the earth, in km;
- s = parameter representing site correction for soil sites; for rock sites s = 0 and for soil sites the value of s is as given in the attached table;
- ε = standard error term (base 10 logarithm);

The coefficients a, b, c, d, k, s and h were determined by Joyner and Boore from a regression analysis. The values of these coefficients obtained by Joyner & Boore for the average of the two horizontal components of peak acceleration, a, peak velocity, v, and for pseudo relative spectral velocity, PRV (for 12 periods at spectral damping of 5%), are given in Table A-1. Note that the pseudo absolute acceleration, PAA, can be obtained from pseudo relative velocity using the following equation:

$$PAA = \omega PRV / 981 \quad \text{or,} \quad PAA = 2\pi PRV / (981T)$$

in which PAA is in g's, PRV is in cm/sec, ω is circular frequency in radians per second and T is period in seconds.

## RELATIONSHIP BY CAMPBELL (1990)

Campbell (1990) derived attenuation relationships for peak horizontal acceleration and for horizontal pseudo-relative velocity at firm soil sites and at soft rock sites. The following equation was derived by Campbell:

$$Ln(Y) = a + bM + dLn[R + c_1 exp(c_2 M)] + eF + F_1 tanh[f_2(M + f_3)]$$
$$+ g_1 tanh(g_2 D) + h_1 K_1 + h_2 K_2 + h_3 K_3 + \varepsilon$$

in which:

- *Ln:* natural logarithm
- *exp:* exponential function
- *tanh:* hyperbolic tangent function; *tanh*(x) = [*exp*(x) - *exp*(-x)]/[*exp*(x) + *exp*(-x)]
- *Y* = ground motion parameter (peak acceleration, a, pseudo relative spectral velocity, PRV, at 5% damping);
- *M* = earthquake magnitude ( $M_L$ for $M < 6$ and $M_S$ for $M \geq 6$);
- *R* = distance to seismogenic rupture in km;

$F$ = parameter representing style of faulting; $F = 0$ for strike slip faults and $F = 1$ for reverse faults;
$D$ = depth to basement rock (sediment depth) in km;
$K_i$ = parameter representing building effects; $K_1 = 1$ for embedded buildings three to 11 stories; $K_2 = 1$ for embedded buildings with more than 11 stories; $K_3 = 1$ for non-embedded buildings greater than two stories in height; $K_1 = K_2 = K_3 = 0$ for all other sites;
$\varepsilon$ = standard error term (natural logarithm)

The coefficients obtained by Campbell for the horizontal components of peak acceleration, a, and for pseudo relative velocity, PRV (for 15 periods at a spectral damping of 5%) are given in Table A-2. Values of PAA can be obtained from PRV as noted above.

## RELATIONSHIP BY GEOMATRIX (1991)

Geomatrix (1991) updated the attenuation relationships published by Sadigh (1988) and by Tsai et al (1990) incorporating the recorded data from the Loma Prieta earthquake and extending the equations for periods up to 7.5 seconds. The following equation was derived for rock sites:

$$Ln(Y) = c_1 + c_2 M + c_3(8.5 - M)^{2.5} + c_4 Ln[R + exp(c_5 + c_6 M)]$$
$$+ c_7 Ln(R + 2) + \varepsilon$$

in which:

*Ln:* natural logarithm
*exp:* exponential function
$Y$ = ground motion parameter;
$M$ = earthquake magnitude ( moment magnitude);
$R$ = closest distance to the fault rupture surface in km;
$\varepsilon$ = standard error term (natural logarithm)

Values of $c1$ ... $c7$ and $\varepsilon$ for peak horizontal acceleration and for pseudo absolute horizontal spectral acceleration (for 21 periods at 5% spectral damping) are given in Table A-3. The above equation using the values of $c1$ ... $c7$ listed in Table A-3 are for motions generated on strike slip faults. For reverse/thrust faults and for oblique faulting, factors of 1.2 and 1.09, respectively, are suggested by Geomatrix.

## RELATIONSHIP BY IDRISS (1991)

As part of this study Idriss derived, in equation format, the relationships he had published in 1985 and 1987 (Idriss 1985; 1987) in discrete equation format for peak accelerations and in chart format for spectral ordinates. He also incorporated recordings from recent earthquakes. The distribution of magnitude and distance of available strong motion data recorded at rock sites used by Idriss to check the derived expressions are shown in Fig. A-1. The magnitude range is from 4.6 to 7.4 and the distance range is from one to 100 km as shown in the figure. The available data included 572 individual horizontal components.

The equation derived for rock sites is the following:

$$Ln(Y) = [\alpha_o + exp(\alpha_1 + \alpha_2 M)] + [\beta_o - exp(\beta_1 + \beta_2 M)] Ln(R + 20)$$
$$+ 0.2F + \varepsilon$$

in which:

*Ln:* natural logarithm
*exp:* exponential function
Y = ground motion parameter;
M = earthquake magnitude; for M less than 6, local magnitude, $M_L$, is used and for M equal to or greater than 6, surface wave magnitude, $M_S$, is used. Thus, in essence, M represents moment magnitude, $M_w$
R = closest distance to the source in km; however, for small magnitude earthquakes (say M less than 6), the hypocentral distance is used.
F = style of faulting factor; F = 0 for a strike slip fault; F = 1 for a reverse fault and F = 0.5 for an oblique source.
$\varepsilon$ = standard error term (natural logarithm)

Values of $\alpha_o$ .. $\beta_2$ and $\varepsilon$ are given in Table A-4 for peak horizontal acceleration and for pseudo absolute horizontal spectral acceleration for 22 periods at 5% spectral damping.

The residuals (for peak horizontal acceleration) using the above equation are shown in Fig. A-2. As can been seen, the average residual is almost zero over the entire distance range. The trend with distance is reasonable for distances up to about 60 km; beyond a distance of about 60 km, the above relationships would underestimate the recorded values.

## COMPARISON OF COMPUTED MOTIONS USING THESE ATTENUATION RELATIONSHIPS

Spectral ordinates at the four sites shown in Fig. A-3 were calculated using four of the attenuation relationships given in this Appendix. Sites R1 and R2 are adjacent to a reverse fault as shown in the upper part of Fig. A-3 while Sites S1 and S2 are adjacent to a strike slip fault as shown in the lower part of the figure. The distance from the source for each site applicable to each attenuation relationship are listed below:

| Site | Distance (in km) to Site Applicable to Attenuation Relationship by | | | |
|---|---|---|---|---|
| | Joyner & Boore | Campbell | Geomatrix | Idriss |
| $R_1$ | 0 | 4.1 | 3.4 | 3.4 |
| $R_2$ | 40 | 40.4 | 40 | 40 |
| $S_1$ | 10 | 10.5 | 10 | 10 |
| $S_2$ | 30 | 30 | 30 | 30 |

The seismogenic zone was assumed to be at a depth of 3 km and the depth to basement rock was assumed to be at 0 km for Campbell's (1990) relationships.

The median and the 84th percentile spectral ordinates calculated for a magnitude 6.5 earthquake occurring on the reverse fault are presented in Fig. A-4 for Site $R_1$ and in Fig. A-5 for Site $R_2$. The median and the 84th percentile spectral ordinates calculated for a magnitude 7.5 earthquake occurring on the strike slip fault are presented in Fig. A-6 for Site $S_1$ and in Fig. A-7 for Site $S_2$.

For all cases, the median values calculated by these attenuation relationships are reasonably close and the 84th percentile values are comparable. Probably more agreement could be obtained for other magnitudes and other distances. Similarly, less agreement could be obtained for still other distances and other magnitudes.

The results presented in Figs. A-4 through A-7, however, indicate that reasonable estimates of spectral ordinates at a rock site can be obtained using these attenuation relationships. It is generally advisable that as many of these (and future modifications to these) attenuation relationships as possible be used to select earthquake ground motions at a rock site.

Table A-1
Equations Derived by Joyner & Boore (1988)
for Spectral Ordinates

$$Log(Y) = a + b(M-6) + c(M-6)^2 + dLog(r) + kr + s + \varepsilon$$
$$and\ r^2 = r_o^2 + h^2$$

Log is base 10 logarithm;
Y = ground motion parameter (peak acceleration, velocity, spectral ordinate at 5% damping ... );
M = earthquake magnitude ( moment magnitude);
$r_o$ = shortest distance from the site to the vertical projection of the earthquake fault rupture on the surface of the earth, in km;
s = parameter representing site correction for soil sites; for rock sites s = 0 and for soil sites the value of s is as given below;
ε = standard error term (base 10 logarithm);

| Parameter, Y | Period sec | a | b | c | d | h | k | s | ε |
|---|---|---|---|---|---|---|---|---|---|
| a in g's | - | 0.43 | 0.23 | 0 | -1 | 8 | -0.0027 | 0 | 0.28 |
| v in cm/sec | - | 2.09 | 0.49 | 0 | -1 | 4 | -0.0026 | 0.17 | 0.33 |
| PRV | 0.1 | 2.16 | 0.25 | -0.06 | -1 | 11.3 | -0.0073 | -0.02 | 0.28 |
| in cm/sec | 0.15 | 2.40 | 0.30 | -0.08 | -1 | 10.8 | -0.0067 | -0.02 | 0.28 |
| | 0.2 | 2.46 | 0.35 | -0.09 | -1 | 9.6 | -0.0063 | -0.01 | 0.28 |
| | 0.3 | 2.47 | 0.42 | -0.11 | -1 | 6.9 | -0.0058 | 0.04 | 0.28 |
| | 0.4 | 2.44 | 0.47 | -0.13 | -1 | 5.7 | -0.0054 | 0.10 | 0.31 |
| | 0.5 | 2.41 | 0.52 | -0.14 | -1 | 5.1 | -0.0051 | 0.14 | 0.33 |
| | 0.75 | 2.34 | 0.60 | -0.16 | -1 | 4.8 | -0.0045 | 0.23 | 0.33 |
| | 1 | 2.28 | 0.67 | -0.17 | -1 | 4.7 | -0.0039 | 0.27 | 0.33 |
| | 1.5 | 2.19 | 0.74 | -0.19 | -1 | 4.7 | -0.0026 | 0.31 | 0.33 |
| | 2 | 2.12 | 0.79 | -0.20 | -1 | 4.7 | -0.0015 | 0.32 | 0.33 |
| | 3 | 2.02 | 0.85 | -0.22 | -0.98 | 4.7 | 0 | 0.32 | 0.33 |
| | 4 | 1.96 | 0.88 | -0.24 | -0.95 | 4.7 | 0 | 0.29 | 0.33 |

*Note*: the pseudo absolute acceleration, PAA, can be obtained from pseudo relative velocity using the following equation:

$$PAA = \omega PRV/981 \qquad \text{or} \qquad PAA = 2\pi PRV/(981T)$$

in which *PAA* is in g's, *PRV* is in cm/sec, ω is circular frequency in radians per second and *T* is period in seconds.

Table A-2
Equations Derived by Campbell (1990)
for Spectral Ordinates at Firm Soil Sites and at Soft Rock Sites

$$Ln(Y) = a + bM + dLn[R + c_1 \exp(c_2 M)] + eF + f_1 \tanh[f_2(M + f_3)]$$
$$+ g_1 \tanh(g_2 D) + h_1 K_1 + h_2 K_2 + h_3 K_3 + \varepsilon$$

| | |
|---|---|
| *Ln:* | natural logarithm |
| *exp:* | exponential function |
| *tanh:* | hyperbolic tangent function; *tanh*(x) = [*exp*(x) - *exp*(-x)]/[*exp*(x) + *exp*(-x)] |
| $Y$ = | ground motion parameter (peak acceleration, a, peak velocity, v, and pseudo relative spectral velocity, PRV, at 5% damping); |
| $M$ = | earthquake magnitude ( $M_L$ for $M < 6$ and $M_S$ for $M \geq 6$); |
| $R$ = | distance to seismogenic rupture in km; |
| $F$ = | parameter representing style of faulting; $F = 0$ for strike slip faults and $F = 1$ for reverse faults; |
| $D$ = | depth to basement rock (sediment depth) in km; |
| $K_i$ = | parameter representing building effects; $K_1 = 1$ for embedded buildings three to 11 stories; $K_2 = 1$ for embedded buildings with more than 11 stories; $K_3 = 1$ for non embedded buildings greater than two stories in height; $K_1 = K_2 = K_3 = 0$ for all other sites; |
| $\varepsilon$ = | standard error term (natural logarithm); |

*Note:* the pseudo absolute spectral acceleration, PAA, can be obtained from pseudo relative spectral velocity, PRV, using the following equations:

$$PAA = \omega PRV / 981 \quad \text{or} \quad PAA = 2\pi PRV / (981T)$$

in which PAA is in g's, PRV is in cm/sec, $\omega$ is circular frequency in radians per second and T is period in seconds.

Table A-2 (Cont'd)
Equations Derived by Campbell (1990)
for Spectral Ordinates at Firm Soil Sites and at Soft Rock Sites

| Parameter, Y | Period sec | a | b | $c_1$ | $c_2$ | d | e | $f_1$ | $f_2$ | $f_3$ | $g_1$ | $g_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a in g's | - | -2.245 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| v in cm/sec | - | -1.765 | 1.38 | 0.0203 | 0.958 | -1.44 | 0.101 | - | - | - | 0.529 | 0.471 |
| PRV in cm/sec | 0.04 | -0.402 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.05 | -0.141 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.075 | 0.489 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.1 | 0.987 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.15 | 1.625 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.2 | 1.988 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.3 | 2.370 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | - | - | - | - | - |
| | 0.4 | 2.153 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 0.514 | 0.659 | -4.7 | - | - |
| | 0.5 | 2.086 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 0.738 | 0.659 | -4.7 | - | - |
| | 0.75 | 1.802 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 1.23 | 0.659 | -4.7 | - | - |
| | 1 | 1.398 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 1.59 | 0.659 | -4.7 | 0.183 | 0.574 |
| | 1.5 | 0.795 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 1.98 | 0.659 | -4.7 | 0.488 | 0.574 |
| | 2 | 0.411 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 2.23 | 0.659 | -4.7 | 0.634 | 0.574 |
| | 3 | -0.140 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 2.39 | 0.659 | -4.7 | 0.836 | 0.574 |
| | 4 | -0.188 | 1.09 | 0.361 | 0.576 | -1.89 | 0.218 | 2.03 | 0.659 | -4.7 | 1.170 | 0.574 |

Table A-2 (Cont'd)
Equations Derived by Campbell (1990)
for Spectral Ordinates at Firm Soil Sites and at Soft Rock Sites

| Parameter, Y | Period sec | $h_1$ | $h_2$ | $h_3$ | ε $M \leq 6.1$ | ε $M \geq 6.2$ | ε $M \geq 4.7$ |
|---|---|---|---|---|---|---|---|
| a in g's | - | -0.137 | -0.403 | - | 0.517 | 0.387 | 0.450 |
| v in cm/sec | - | 0.093 | - | 0.219 | 0.567 | 0.403 | 0.454 |
| PRV in cm/sec | 0.04 | -0.137 | -0.403 | - | 0.716 | 0.387 | 0.491 |
| | 0.05 | -0.137 | -0.403 | - | 0.631 | 0.492 | 0.532 |
| | 0.075 | -0.137 | -0.403 | - | 0.703 | 0.430 | 0.528 |
| | 0.1 | -0.137 | -0.403 | - | 0.703 | 0.427 | 0.526 |
| | 0.15 | -0.137 | -0.403 | - | 0.754 | 0.440 | 0.555 |
| | 0.2 | -0.137 | -0.403 | - | 0.722 | 0.421 | 0.532 |
| | 0.3 | -0.137 | -0.403 | - | 0.597 | 0.382 | 0.456 |
| | 0.4 | -0.137 | -0.403 | - | 0.671 | 0.342 | 0.464 |
| | 0.5 | -0.137 | -0.403 | - | 0.722 | 0.330 | 0.483 |
| | 0.75 | -0.137 | -0.403 | - | 0.776 | 0.420 | 0.548 |
| | 1 | -0.137 | -0.130 | - | 0.751 | 0.426 | 0.532 |
| | 1.5 | -0.137 | 0.118 | - | 0.687 | 0.478 | 0.530 |
| | 2 | -0.137 | 0.091 | - | 0.591 | 0.496 | 0.505 |
| | 3 | 0.312 | 0.430 | 0.794 | 0.628 | 0.520 | 0.520 |
| | 4 | 0.394 | 0.515 | 0.892 | 0.647 | 0.532 | 0.535 |

Table A-3
Equations Derived By Geomatrix (1991)
for Spectral Ordinates at Rock Sites

$$Ln(Y) = c_1 + c_2 M + c_3(8.5 - M)^{2.5} + c_4 Ln[R + exp(c_5 + c_6 M)]$$
$$+ c_7 Ln(R + 2) + \varepsilon$$

*Ln:* natural logarithm
*exp:* exponential function
*Y* = ground motion parameter (peak acceleration, a in g's, and pseudo absolute spectral acceleration, PAA in g's, at 5% damping);
*M* = earthquake magnitude ( moment magnitude);
*R* = closest distance to the fault rupture surface in km;
ε = standard error term (natural logarithm)

***For Magnitude, M < 6½***

$c_2 = 1.0$ $c_5 = 1.29649$ $c_6 = 0.25$

| Period - sec | $c_1$ | $c_3$ | $c_4$ | $c_7$ | Standard Error Term, ε |
|---|---|---|---|---|---|
| a | -0.624 | 0 | -2.100 | 0 | 1.39 - 0.14*M |
| 0.05 | -0.090 | 0.006 | -2.128 | -0.082 | 1.39 - 0.14*M |
| 0.07 | 0.110 | 0.006 | -2.128 | -0.082 | 1.40 - 0.14*M |
| 0.09 | 0.212 | 0.006 | -2.140 | -0.052 | 1.40 - 0.14*M |
| 0.10 | 0.275 | 0.006 | -2.148 | -0.041 | 1.41 - 0.14*M |
| 0.12 | 0.348 | 0.005 | -2.162 | -0.014 | 1.41 - 0.14*M |
| 0.14 | 0.307 | 0.004 | -2.144 | 0 | 1.42 - 0.14*M |
| 0.15 | 0.285 | 0.002 | -2.130 | 0 | 1.42 - 0.14*M |
| 0.17 | 0.239 | 0 | -2.110 | 0 | 1.42 - 0.14*M |
| 0.20 | 0.153 | -0.004 | -2.080 | 0 | 1.43 - 0.14*M |
| 0.24 | 0.060 | -0.011 | -2.053 | 0 | 1.44 - 0.14*M |
| 0.30 | -0.057 | -0.017 | -2.028 | 0 | 1.45 - 0.14*M |
| 0.4 | -0.298 | -0.028 | -1.990 | 0 | 1.48 - 0.14*M |
| 0.5 | -0.588 | -0.040 | -1.945 | 0 | 1.50 - 0.14*M |
| 0.75 | -1.208 | -0.050 | -1.865 | 0 | 1.52 - 0.14*M |
| 1 | -1.705 | -0.055 | -1.800 | 0 | 1.53 - 0.14*M |
| 1.5 | -2.407 | -0.065 | -1.725 | 0 | 1.53 - 0.14*M |
| 2 | -2.945 | -0.070 | -1.670 | 0 | 1.53 - 0.14*M |
| 3 | -3.700 | -0.080 | -1.615 | 0 | 1.53 - 0.14*M |
| 4 | -4.230 | -0.100 | -1.570 | 0 | 1.53 - 0.14*M |
| 5 | -4.714 | -0.100 | -1.540 | 0 | 1.53 - 0.14*M |
| 7.5 | -5.530 | -0.110 | -1.510 | 0 | 1.53 - 0.14*M |

Table A-3 (Cont'd)
Equations Derived By Geomatrix (1991)
for Spectral Ordinates at Rock Sites

***For Magnitude, M ≥ 6½***

$c_2 = 1.1$ $c_5 = -0.48451$ $c_6 = 0.524$

| Period - sec | $c_1$ | $c_3$ | $c_4$ | $c_7$ | Standard Error Term, ε, M < 7¼ | Standard Error Term, ε, M ≥ 7¼ |
|---|---|---|---|---|---|---|
| a | -1.274 | 0 | -2.100 | 0 | 1.39 - 0.14*M | 0.38 |
| 0.05 | -0.740 | 0.006 | -2.128 | -0.082 | 1.39 - 0.14*M | 0.38 |
| 0.07 | -0.540 | 0.006 | -2.128 | -0.082 | 1.40 - 0.14*M | 0.39 |
| 0.09 | -0.438 | 0.006 | -2.140 | -0.052 | 1.40 - 0.14*M | 0.39 |
| 0.10 | -0.375 | 0.006 | -2.148 | -0.041 | 1.41 - 0.14*M | 0.40 |
| 0.12 | -0.302 | 0.005 | -2.162 | -0.014 | 1.41 - 0.14*M | 0.40 |
| 0.14 | -0.343 | 0.004 | -2.144 | 0 | 1.42 - 0.14*M | 0.41 |
| 0.15 | -0.365 | 0.002 | -2.130 | 0 | 1.42 - 0.14*M | 0.41 |
| 0.17 | -0.411 | 0 | -2.110 | 0 | 1.42 - 0.14*M | 0.41 |
| 0.20 | -0.497 | -0.004 | -2.080 | 0 | 1.43 - 0.14*M | 0.42 |
| 0.24 | -0.590 | -0.011 | -2.053 | 0 | 1.44 - 0.14*M | 0.43 |
| 0.30 | -0.707 | -0.017 | -2.028 | 0 | 1.45 - 0.14*M | 0.44 |
| 0.4 | -0.948 | -0.028 | -1.990 | 0 | 1.48 - 0.14*M | 0.47 |
| 0.5 | -1.238 | -0.040 | -1.945 | 0 | 1.50 - 0.14*M | 0.49 |
| 0.75 | -1.858 | -0.050 | -1.865 | 0 | 1.52 - 0.14*M | 0.51 |
| 1 | -2.355 | -0.055 | -1.800 | 0 | 1.53 - 0.14*M | 0.52 |
| 1.5 | -3.057 | -0.065 | -1.725 | 0 | 1.53 - 0.14*M | 0.52 |
| 2 | -3.595 | -0.070 | -1.670 | 0 | 1.53 - 0.14*M | 0.52 |
| 3 | -4.350 | -0.080 | -1.610 | 0 | 1.53 - 0.14*M | 0.52 |
| 4 | -4.880 | -0.100 | -1.570 | 0 | 1.53 - 0.14*M | 0.52 |
| 5 | -5.364 | -0.100 | -1.540 | 0 | 1.53 - 0.14*M | 0.52 |
| 7.5 | -6.180 | -0.110 | -1.510 | 0 | 1.53 - 0.14*M | 0.52 |

*Note*: The above equation using the values of $c_1 \ldots c_7$ listed in this table are intended for motions generated on strike slip faults. For reverse/thrust faults and for oblique faulting, factors of 1.2 and 1.09, respectively, are suggested by Geomatrix.

Table A-4
Equations Derived By Idriss (1991) for Spectral Ordinates at Rock Sites

$$Ln(Y) = [\alpha_o + exp(\alpha_1 + \alpha_2 M)] + [\beta_o - exp(\beta_1 + \beta_2 M)] Ln(R+20) + 0.2F + \varepsilon$$

*Ln:* natural logarithm
*exp:* exponential function
Y = ground motion parameter (peak horizontal acceleration, a in g's, and pseudo absolute spectral acceleration, PAA in g's, at 5% damping)
M = local magnitude, $M_L$, for $M \leq 6$ and surface wave magnitude, $M_S$ for $M > 6$. Thus, in essence, M represents moment magnitude, $M_W$
R = closest distance to the source in km; however, for $M \leq 6$ the hypocentral distance is used.
F = style of faulting factor; F = 0 for a strike slip fault; F = 1 for a reverse fault and F = 0.5 for an oblique source.
$\varepsilon$ = standard error term

***For Magnitude, $M \leq 6$***

$\beta_1 = 1.602$ and $\beta_2 = -0.142$

| Period - sec | $\alpha_o$ | $\alpha_1$ | $\alpha_2$ | $\beta_o$ | Standard Error Term, $\varepsilon$ |
|---|---|---|---|---|---|
| a | -0.150 | 2.261 | -0.083 | 0 | 1.39 - 0.14*M |
| 0.03 | -0.150 | 2.261 | -0.083 | 0 | 1.39 - 0.14*M |
| 0.05 | -0.278 | 2.365 | -0.092 | 0.066 | 1.39 - 0.14*M |
| 0.075 | -0.308 | 2.334 | -0.081 | 0.070 | 1.39 - 0.14*M |
| 0.10 | -0.318 | 2.319 | -0.075 | 0.072 | 1.41 - 0.14*M |
| 0.11 | -0.328 | 2.294 | -0.070 | 0.073 | 1.42 - 0.14*M |
| 0.13 | -0.338 | 2.255 | -0.062 | 0.075 | 1.42 - 0.14*M |
| 0.15 | -0.348 | 2.219 | -0.055 | 0.076 | 1.42 - 0.14*M |
| 0.20 | -0.358 | 2.146 | -0.042 | 0.078 | 1.42 - 0.14*M |
| 0.25 | -0.429 | 2.073 | -0.030 | 0.080 | 1.44 - 0.14*M |
| 0.30 | -0.486 | 2.010 | -0.020 | 0.082 | 1.44 - 0.14*M |
| 0.35 | -0.535 | 1.977 | -0.016 | 0.087 | 1.44 - 0.14*M |
| 0.4 | -0.577 | 1.921 | -0.009 | 0.092 | 1.44 - 0.14*M |
| 0.5 | -0.648 | 1.818 | 0.003 | 0.099 | 1.46 - 0.14*M |
| 0.6 | -0.705 | 1.704 | 0.017 | 0.105 | 1.46 - 0.14*M |
| 0.7 | -0.754 | 1.644 | 0.022 | 0.111 | 1.48 - 0.14*M |
| 0.8 | -0.796 | 1.593 | 0.025 | 0.115 | 1.48 - 0.14*M |
| 0.9 | -0.834 | 1.482 | 0.039 | 0.119 | 1.48 - 0.14*M |
| 1 | -0.867 | 1.432 | 0.043 | 0.123 | 1.48 - 0.14*M |
| 1.5 | -0.970 | 1.072 | 0.084 | 0.136 | 1.48 - 0.14*M |
| 2 | -1.046 | 0.762 | 0.121 | 0.146 | 1.52 - 0.14*M |
| 3 | -1.143 | 0.194 | 0.191 | 0.160 | 1.52 - 0.14*M |
| 4 | -1.177 | -0.466 | 0.280 | 0.169 | 1.52 - 0.14*M |
| 5 | -1.214 | -1.361 | 0.410 | 0.177 | 1.52 - 0.14*M |

Table A-4 (Cont'd)
Equations Derived By Idriss (1991) for Spectral Ordinates at Rock Sites

***For Magnitude, M > 6***

$\beta_1 = 2.475$ and $\beta_2 = -0.286$

| Period sec | $\alpha_o$ | $\alpha_1$ | $\alpha_2$ | $\beta_o$ | Standard Error Term, ε, M < 7¼ | Standard Error Term, ε, M ≥ 7¼ |
|---|---|---|---|---|---|---|
| a | -0.050 | 3.477 | -0.284 | 0 | 1.39-0.14*M | 0.38 |
| 0.03 | -0.050 | 3.477 | -0.284 | 0 | 1.39-0.14*M | 0.38 |
| 0.05 | -0.278 | 3.426 | -0.269 | 0.066 | 1.39-0.14*M | 0.38 |
| 0.075 | -0.308 | 3.359 | -0.252 | 0.070 | 1.39-0.14*M | 0.38 |
| 0.10 | -0.318 | 3.327 | -0.243 | 0.072 | 1.41-0.14*M | 0.41 |
| 0.11 | -0.328 | 3.289 | -0.236 | 0.073 | 1.42-0.14*M | 0.41 |
| 0.13 | -0.338 | 3.233 | -0.225 | 0.075 | 1.42-0.14*M | 0.41 |
| 0.15 | -0.348 | 3.185 | -0.216 | 0.076 | 1.42-0.14*M | 0.41 |
| 0.20 | -0.358 | 3.100 | -0.201 | 0.078 | 1.42-0.14*M | 0.41 |
| 0.25 | -0.429 | 3.034 | -0.190 | 0.080 | 1.44-0.14*M | 0.43 |
| 0.30 | -0.486 | 2.982 | -0.182 | 0.082 | 1.44-0.14*M | 0.43 |
| 0.35 | -0.535 | 2.943 | -0.177 | 0.087 | 1.44-0.14*M | 0.43 |
| 0.4 | -0.577 | 2.906 | -0.173 | 0.092 | 1.44-0.14*M | 0.43 |
| 0.5 | -0.648 | 2.850 | -0.169 | 0.099 | 1.46-0.14*M | 0.45 |
| 0.6 | -0.705 | 2.803 | -0.166 | 0.105 | 1.46-0.14*M | 0.45 |
| 0.7 | -0.754 | 2.765 | -0.165 | 0.111 | 1.48-0.14*M | 0.47 |
| 0.8 | -0.796 | 2.728 | -0.164 | 0.115 | 1.48-0.14*M | 0.47 |
| 0.9 | -0.834 | 2.694 | -0.163 | 0.119 | 1.48-0.14*M | 0.47 |
| 1 | -0.867 | 2.662 | -0.162 | 0.123 | 1.48-0.14*M | 0.47 |
| 1.5 | -0.970 | 2.536 | -0.160 | 0.136 | 1.48-0.14*M | 0.47 |
| 2 | -1.046 | 2.447 | -0.160 | 0.146 | 1.52-0.14*M | 0.51 |
| 3 | -1.143 | 2.295 | -0.159 | 0.160 | 1.52-0.14*M | 0.51 |
| 4 | -1.177 | 2.169 | -0.159 | 0.169 | 1.52-0.14*M | 0.51 |
| 5 | -1.214 | 2.042 | -0.157 | 0.177 | 1.52-0.14*M | 0.51 |

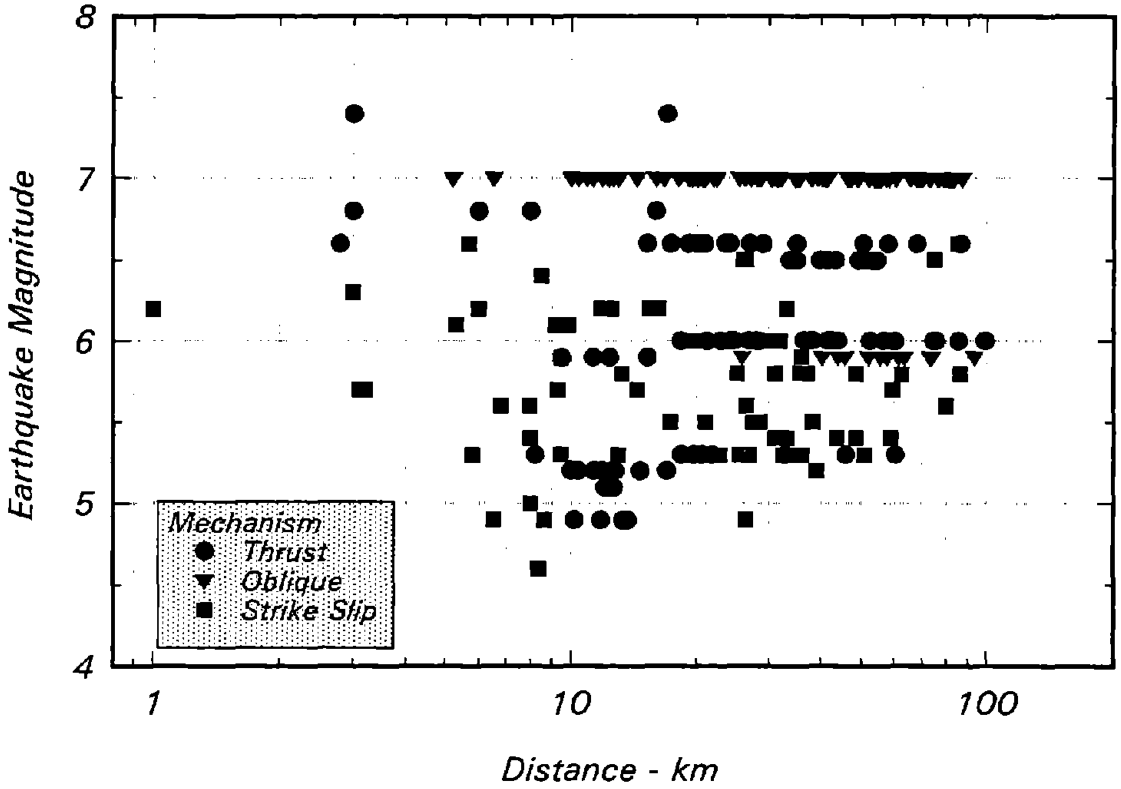


*Fig. A-1 Distribution of Magnitude and Distance of Available Strong Motion Data Recorded at Rock Sites*

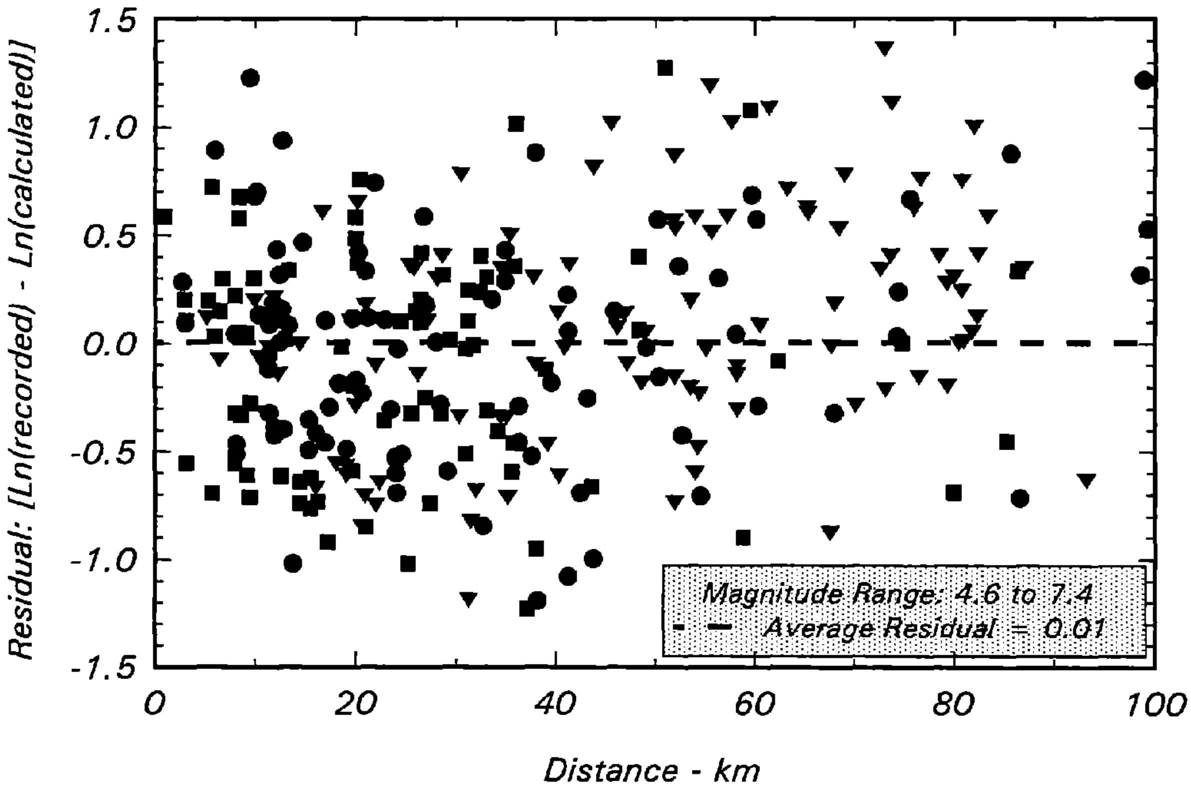


*Fig. A-2 Residuals Calculated Using Attenuation Relationship by Idriss (1991) for Horizontal Accelerations at Rock Sites*

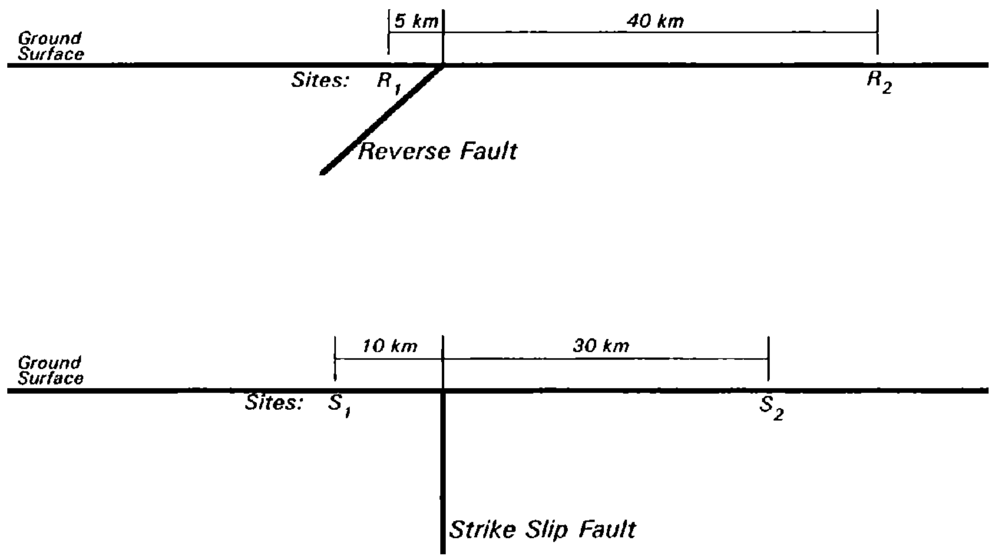


*Fig. A-3 Locations of Sites and Faults Used in Sample Calculations*

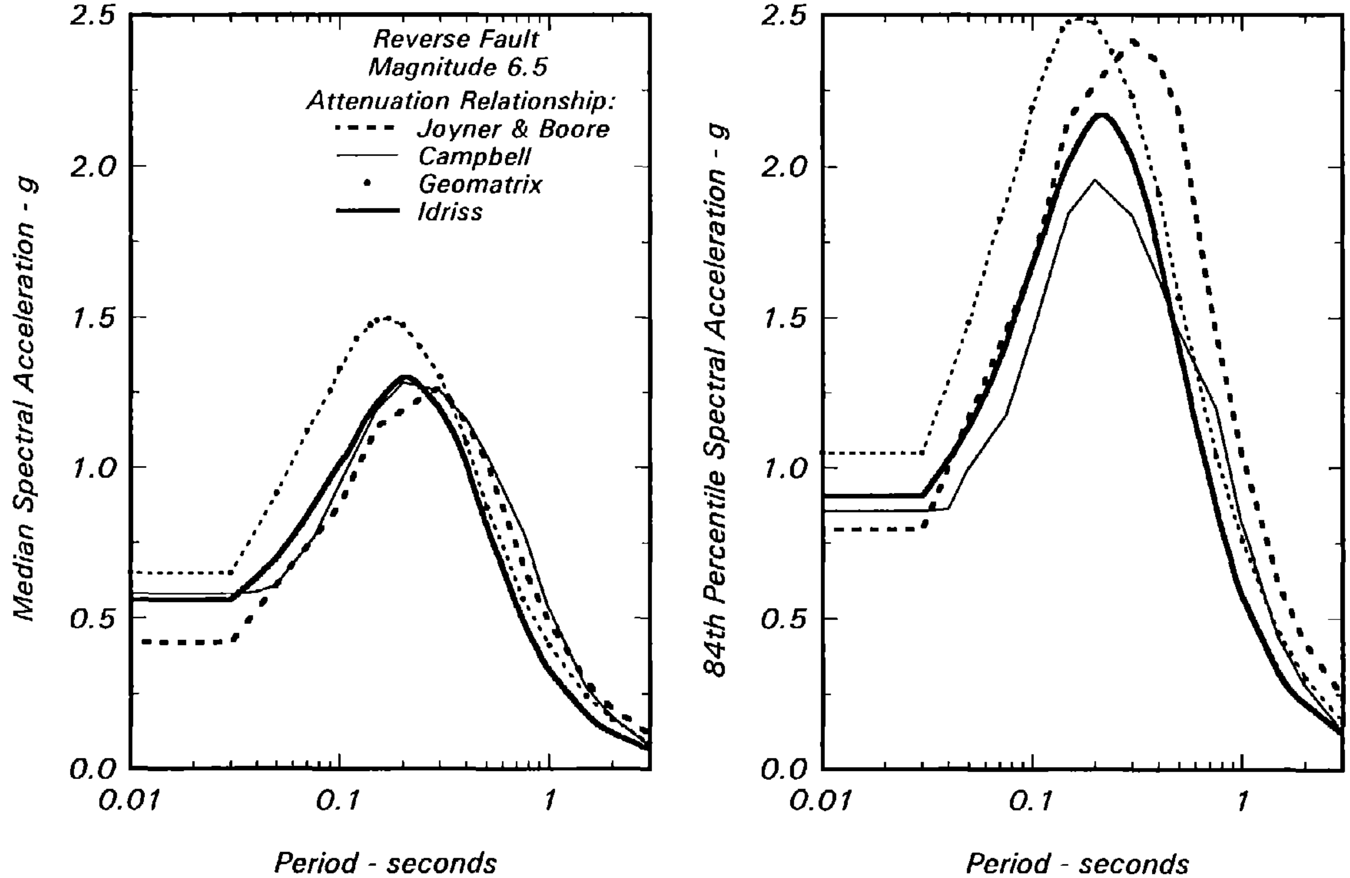


*Fig. A-4 Comparison of Median and 84th Percentile Spectral Ordinates at Site $R_1$ Using the Four Attenuation Relationships Presented in Appendix A*

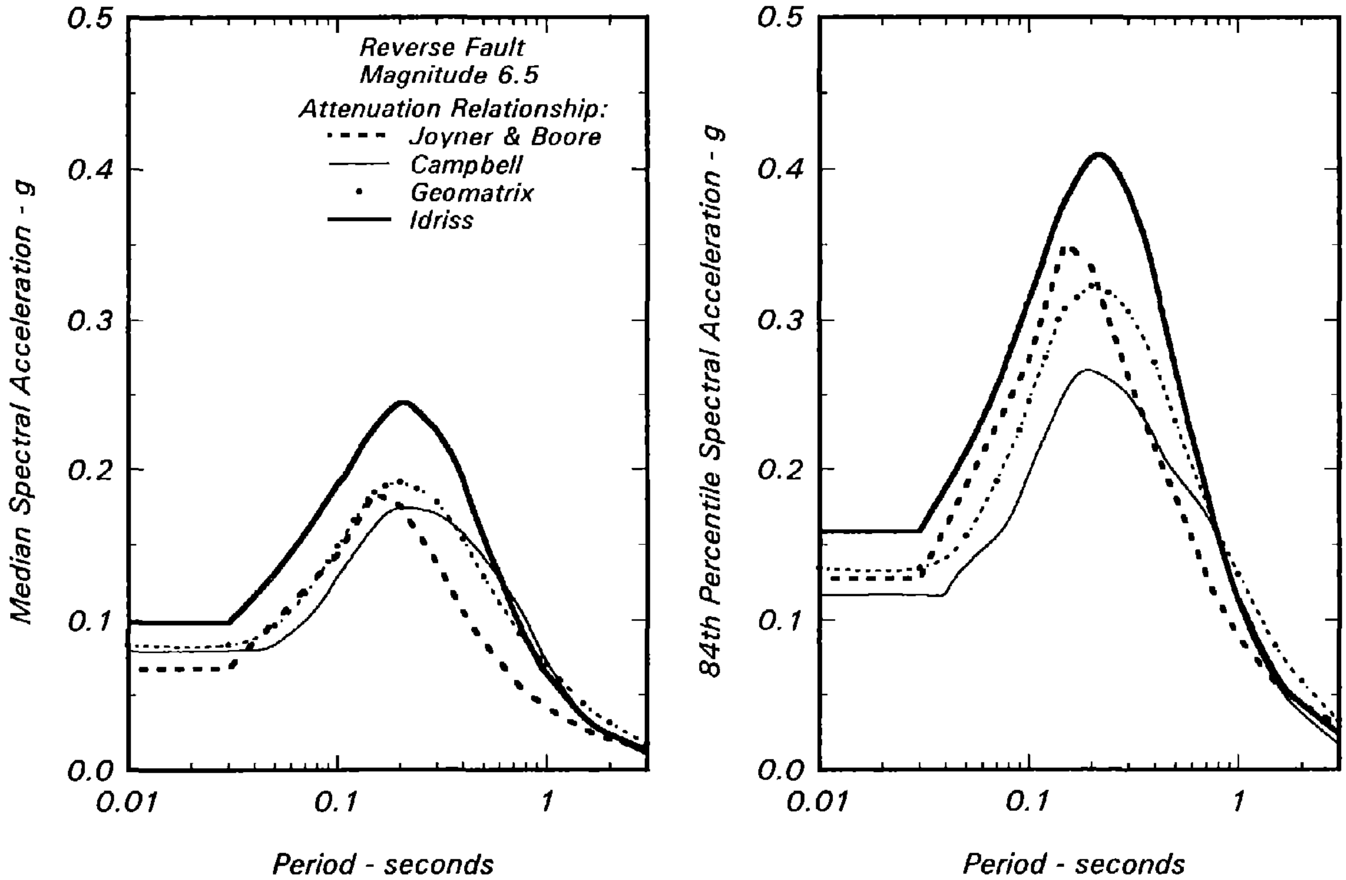


*Fig. A-5 Comparison of Median and 84th Percentile Spectral Ordinates at Site $R_2$ Using the Four Attenuation Relationships Presented in Appendix A*

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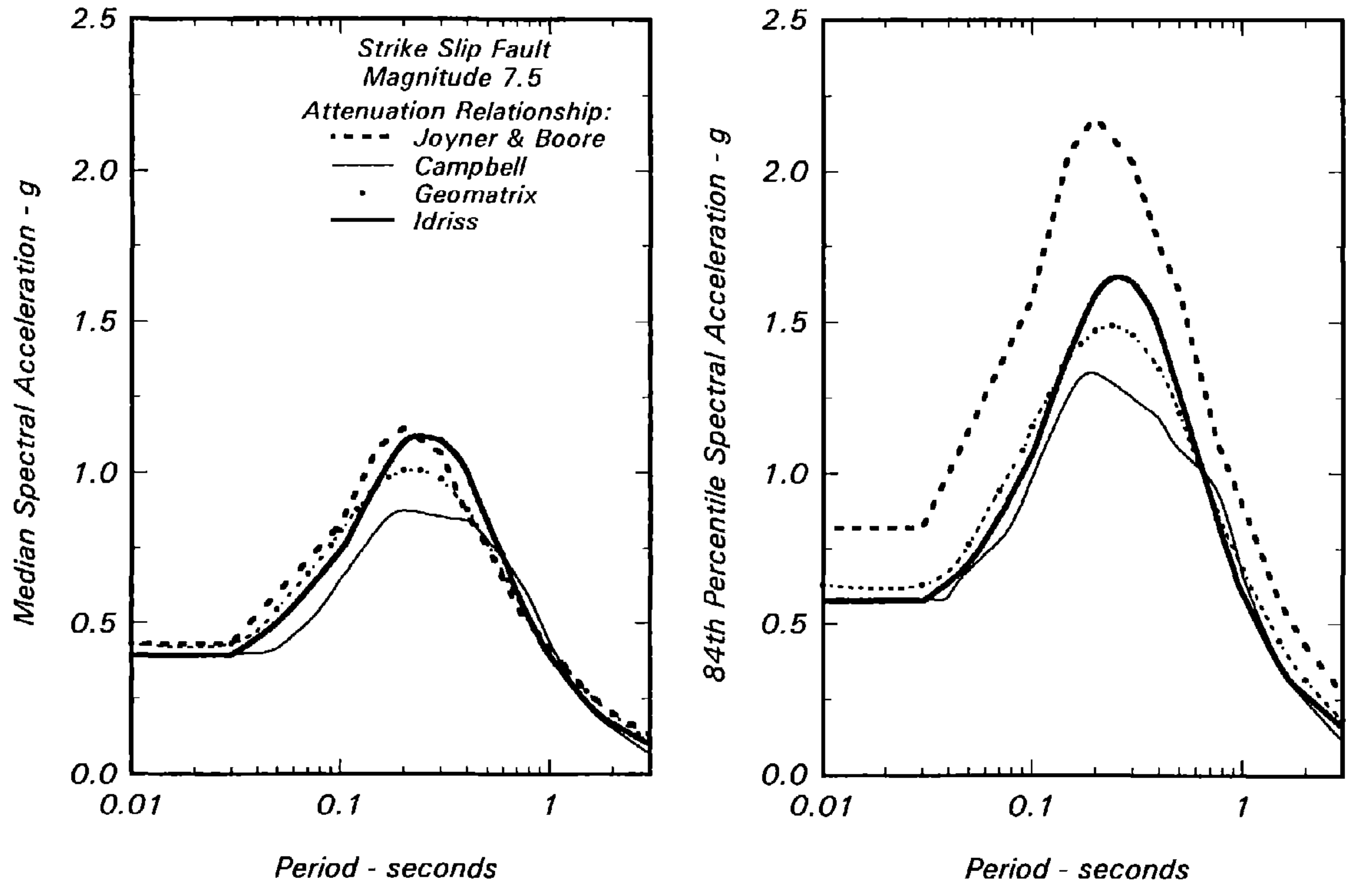


*Fig. A-6 Comparison of Median and 84th Percentile Spectral Ordinates at Site $S_1$ Using the Four Attenuation Relationships Presented in Appendix A*

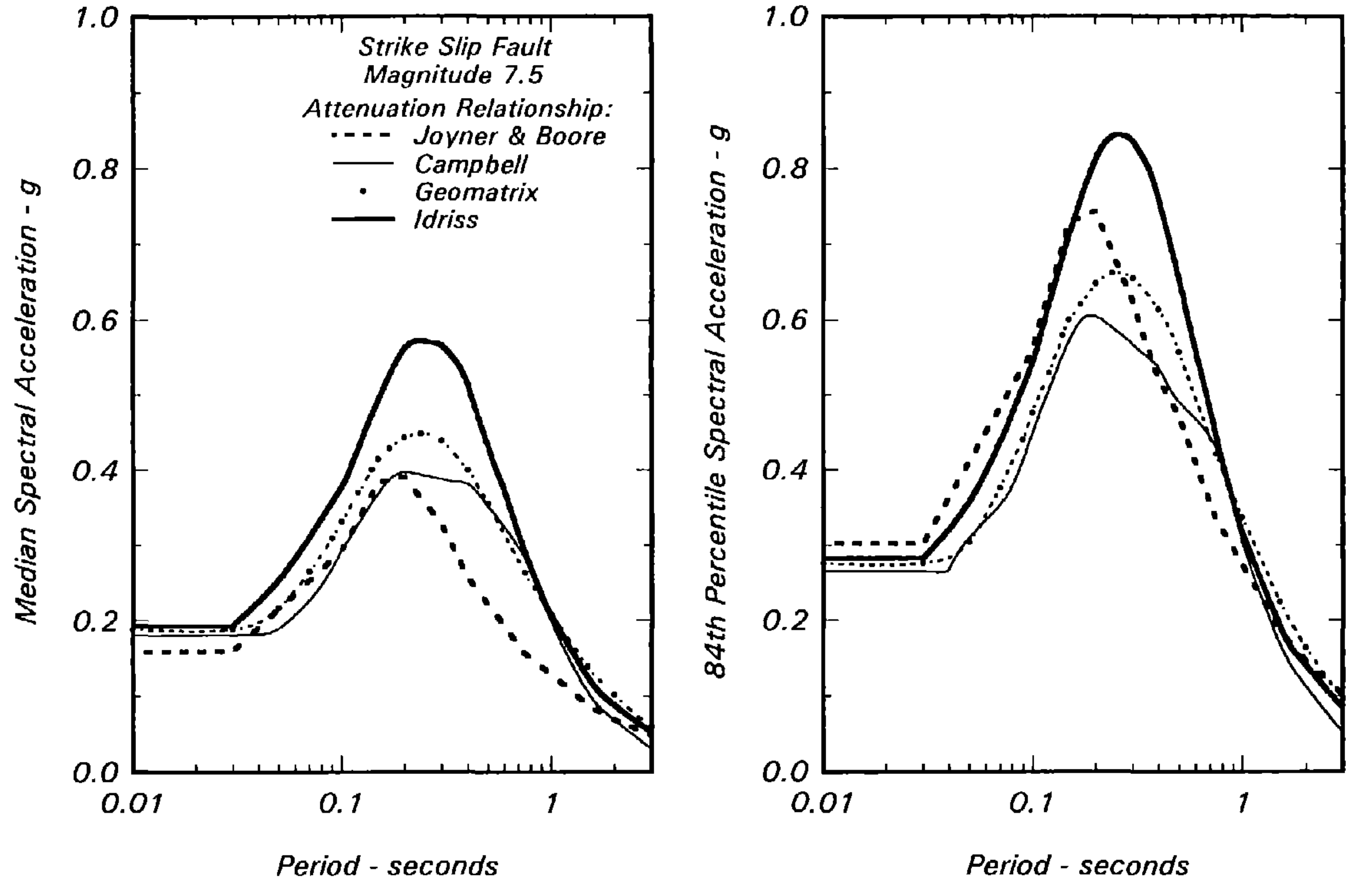


*Fig. A-7 Comparison of Median and 84th Percentile Spectral Ordinates at Site $S_2$ Using the Four Attenuation Relationships Presented in Appendix A*

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ABSTRACT (A 1500-CHARACTER OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, CITE IT HERE. SPELL OUT ACRONYMS ON FIRST REFERENCE.) (CONTINUE ON SEPARATE PAGE, IF NECESSARY.)

To estimate the spectral ordinates at a rock site for an earthquake having a given size (magnitude) and occurring at a specified distance from the site, available attenuation relationships are used. These relationships, which have been developed based on available recorded data and typically are for a spectral damping of 5%, provide estimates of the median spectral ordinates and a measure of the dispersion about the median. Four currently available relationships are summarized in this report. These relationships are those derived by Campbell (1990), Geomatrix (1991), Idriss (1991) and Joyner and Boore (1988). The equations to be used in conjunction with each relationship together with the description and the numerical values of the coefficients pertinent to that relationship are given.

KEY WORDS (MAXIMUM 9 KEY WORDS; 28 CHARACTERS AND SPACES EACH; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES)

acceleration response spectrum; attenuation relationships; earthquake ground motions;

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