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Proposal for Modifying the Site Coefficients in the NEHRP Provisions

William B. Joyner and David M. Boore
U.S. Geological Survey

INTRODUCTION

The basis for the 1994 and 1997 NEHRP site coefficients was laid at a workshop at the University of Southern California in November 1992. Sites were divided into four classes on the basis of the average shear-wave velocity to 30 m (V_{30}). These classes are currently designated by the letters B, C, D, and E. For each class the short-period spectral response is amplified by a factor F_a and the long-period response by a factor F_v. Both F_a and F_v may depend on the ground-motion level expected on the reference site class (Class B), given by A_a and A_v in NEHRP94 and by S_s and S_l in NEHRP97. For all classes the values of F_a and F_v chosen at the workshop for $A_a = A_v = 0.1\ g$ were based on Loma Prieta strong-motion data recorded at sites where V_{30} was known from downhole surveys (Borcherdt, 1992, 1994). For Class E the values of F_a and F_v for A_a and A_v greater than 0.1 g were estimated from equivalent-linear and nonlinear simulations by Dobry et al. (1992) and Seed et al. (1992). Values of F_a and F_v for Classes C and D at ground-motion levels corresponding to A_a and A_v greater than 0.1 g were determined with the aid of the equation (Borcherdt, 1992, 1994)

$$\begin{aligned} F_a &= \left(\frac{V_{ref}}{V}\right)^{m_a}, \\ F_v &= \left(\frac{V_{ref}}{V}\right)^{m_v}, \end{aligned} \qquad (1)$$

or, equivalently,

$$\begin{aligned}\log F_a &= m_a(\log V_{ref} - \log V),\\ \log F_v &= m_v(\log V_{ref} - \log V),\end{aligned} \tag{2}$$

where V is the average V_{30} for a given site class and V_{ref} is the average V_{30} for the reference site condition, usually taken as Class B. The values of F_a and F_v determined for Class E for A_a and A_v greater than 0.1 g were used in equation (2) to obtain values of m_a and m_v for A_a and A_v greater than 0.1 g. The resulting values of m_a and m_v were then used in equation (2) to obtain F_a and F_v for Classes C and D at ground-motion levels corresponding to A_a and A_v greater than 0.1 g. Since 1992 there have been three independent analyses of strong-motion data showing that the method described above for evaluating F_v for the soft rock and firm soil of Classes C and D gives excessive nonlinearity. These analyses also provide the basis for correcting the F_v values for Classes C and D, as proposed in this report. The strong-motion data on which these analyses are based include essentially no Class E sites at high levels of motion and so have nothing new to say about F_v values for Class E. This proposal makes no recommendations concerning Class E.

ANALYSIS BY CROUSE (1995)

Crouse (1995) used a strong-motion data set from western North America with sites assigned to Classes B through E. He developed independent attenuation relationships for peak horizontal acceleration and spectral response for Classes C and D in terms of surface-wave magnitude, distance and style of faulting. There were too few data in either Class B or Class E for the development of independent attenuation relationships, so he determined by least squares a scaling factor to predict values for Class B sites from the Class C relationship and another factor to predict values for Class E sites from the Class D relationship. He then determined F_a and F_v values for each site class for peak horizontal acceleration values of 0.1, 0.2, 0.3, and 0.4 g by selecting three magnitude values (6.5, 7.0, and 7.5), finding the distance at which the relationship yielded the desired peak acceleration for Class B, forming the appropriate ratios of predicted ground motion for the other site classes at that distance, and averaging the ratios over the three magnitude values. The resulting values of

F_a and F_v for site Classes B through D are given in Tables 1 and 2 along with the results of the other analyses explained below, the proposed revised values, and the values from NEHRP97. The F_a values ascribed to Crouse (1995) in Table 1 are for a period of 0.3 sec; the F_v values ascribed to Crouse (1995) in Table 2 are averages over periods of 1.0, 2.0, and 3.0 sec (Crouse, 1995, Table 7). The F_v values for Classes C and D show essentially no nonlinearity. That result does not mean that there is no nonlinearity in Classes C and D relative to Class B, because the Class B ground-motion values are constrained in the analysis to be a constant multiple of the Class C values (though Crouse [1995] states that examination of the residuals showed no obvious dependence of the scaling factor on peak acceleration). What it does indicate is that there is essentially no nonlinearity in Class D relative to Class C. At all ground motion levels the Class D F_v values for Crouse (1995) are less than the results of the other analyses explained below. A possible partial explanation is suggested by the fact that Crouse (1995) classified three sites, Gilroy # 4, El Centro # 2, and Calipatria Fire Station as Class E sites, whereas Boore et al. (1993) classified the same sites as Class D sites using the same basic data. Boore et al. (1993) classified entirely on the basis of V_{30} whereas Crouse (1995) followed the definition recommended by the 1992 workshop which put sites into Class E either if they had a V_{30} less than 180 m/sec *or* if the profile contained more than 3 m of soft to medium stiff clay. The workshop definition is also used in NEHRP97, though there are some, including us, who believe it should be reconsidered. If Crouse (1995) classified as E sites some sites that would qualify on the basis of V_{30} as D sites, his F_v values for Class D might be biased lower as a result. Crouse's (1995) data set included no sites at high levels of motion that would qualify as Class E sites on the basis of V_{30} alone, so no values for Class E ascribed to Crouse (1995) are included in Tables 1 and 2.

ANALYSIS BY BOORE ET AL. (1994; BOORE, UNPUBLISHED, 1998)

The problem encountered by Crouse (1995), too few data points in Class B and Class E for the development of independent attenuation relationnships, can be avoided by dividing the strong-motion data into two classes, rock and soil. Boore and Joyner (1997) determined average values of V_{30} for rock and soil sites equal to 620 and 310 m/sec, respectively, from more than 200 downhole shear-wave velocity surveys. To facilitate the analysis we derive here a modified set of equations to describe nonlinear site response. We start with an equation analogous to equation (2)

$$\log S - \log S_0 = m(\log V_{ref} - \log V), \tag{3}$$

where S is the response value at a site where $V_{30} = V$, S_0 is the pseudoacceleration response value at a site where $V_{30} = V_{ref}$, the reference velocity, and m is given by the equation

$$m = c_1 + c_2 \log S_0, \tag{4}$$

where c_1 and c_2 are constants chosen to fit strong-motion data. The values of c_1 and c_2 depend upon the reference velocity chosen. Nonlinearity is introduced by way of equation (4). To change the reference velocity from V_{ref} to another value V'_{ref}, as illustrated in Figure 1, we substitute into equation (3) to obtain

$$\log S_0 = \log S'_0 - m(\log V_{ref} - \log V'_{ref}), \tag{5}$$

where S'_0 is the response value at a site where the velocity is V'_{ref}. Substituting from equation (5) into equation (4), rearranging, and solving for m gives

$$m = \frac{c_1 + c_2 \log S'_0}{1 + c_2(\log V_{ref} - \log V'_{ref})}. \tag{6}$$

If we define

$$\begin{aligned} c'_1 &= \frac{c_1}{1 + c_2(\log V_{ref} - \log V'_{ref})}, \\ c'_2 &= \frac{c_2}{1 + c_2(\log V_{ref} - \log V'_{ref})}, \end{aligned} \tag{7}$$

then equation (6) can be written

$$m = c'_1 + c'_2 \log S'_0, \tag{8}$$

which is analogous to equation (4).

Boore et al. (1994) used a strong-motion data set from shallow earthquakes in western North America to develop attenuation relationships for peak horizontal acceleration and spectral response. The relationships can be rewritten so that the site-effects term is in the form,

$$\log S_{pred} - \log S_0 = -b_V(\log V_{ref} - \log V), \tag{9}$$

where S_{pred} is the response value predicted by the attenuation relationships, V_{ref} is 620 m/sec, the average value at rock sites, and b_V is given by Boore *et al.* (1994) as a function of period. The term is independent of ground-motion level. Boore (unpublished, 1998), however, has regressed the residuals to the Boore et al. (1994) relationship at rock sites and soil sites (average $V_{30} = 310$ m/sec) separately against the predicted pseudovelocity response on rock. The resulting equation is

$$\log S_{obs} - \log S_{pred} = b_1 + b_2 \log PSV_0, \tag{10}$$

where PSV_0 is the pseudovelocity response on rock in cm/sec. Converting to pseudoacceleration response in g gives

$$\log S_{obs} - \log S_{pred} = b_1 + b_2 \left(\log S_0 - \log \left[\frac{2\pi}{980T} \right] \right), \tag{11}$$

where T is the period in sec. The regression coefficients are given in Table 3, and the slopes of the regression, b_{2r} for rock and b_{2s} for soil, and their standard errors are shown in Figure 2, plotted against period. The difference in slope between rock and soil sites is clearly significant statistically for 0.2 sec period and clearly not significant at 1.0 sec period. In other words, Figure 2 shows significant nonlinearity for 0.2 sec period, but not for 1.0 sec. The values of b_{2r} for short periods are relatively large and positive because the attenuation relationship from which the residuals were calculated forced a constant difference between rock and soil sites, independent of ground motion level. In the original attenuation relationship, nonlinearity was accommodated through the distance and magnitude coefficients. Since there are many more soil sites than rock sites, the original relationship fit the soil sites better than the rock sites. Soil nonlinearity relative to rock, therefore, results in rock-site residuals that increase strongly with amplitude (large positive b_{2r}) and soil-site residuals that decrease weakly with amplitude (small negative b_{2s}). The results of the regression can be used to correct equation (9) for nonlinearity. The corrected equation is the equivalent of equation (3) with an m value of

$$m = -b_v + \frac{b_{1s} - b_{1r}}{\log 620 - \log 310} + \frac{b_{2s} - b_{2r}}{\log 620 - \log 310} \left(\log S_0 - \log \left[\frac{2\pi}{980T} \right] \right). \qquad (12)$$

The value of c_2 for use in equations (4) and (6) is the coefficient of the S_0 term,

$$c_2 = \frac{b_{2s} - b_{2r}}{\log 620 - \log 310}. \qquad (13)$$

Equation (12) was applied at 0.2 sec period to determine a set of m_a values corresponding to a reference velocity of 620 m/sec. We corrected the values to a reference velocity of 1068 m/s, the geometric mean of the class boundaries for Class B, using equation (6). The corrected values are given in Table 4. The m_v values in Table 4 are simply $-b_V$, because there was no statistically significant nonlinearity at 1.0 sec (Figure 2). Applying the values in Table 4 with equation (2) and the velocity values in Table 5, gives the F_a and F_v values ascribed in Tables 1 and 2 to Boore et al. (1994; Boore unpublished, 1998). The velocity values ascribed to the site classes in Table 5 are simply the geometric means of the values at the class boundaries.

All the data in the Boore et al. (1994) data set were used in the determination of nonlinearity, but, since the 1.0 sec response was linear, the m_v value depends only on the coefficient b_V, which was determined entirely by data at sites where V_{30} was known from downhole shear-wave velocity surveys. For that reason the F_v values ascribed in Table 2 to Boore *et al.* (1994; Boore, unpublished, 1998) should be given more weight than the values ascribed to Crouse (1995) or Abrahamson and Silva (1997).

ANALYSIS BY ABRAHAMSON AND SILVA (1997)

Abrahamson and Silva (1995) used a world-wide data set of "strong ground motions from shallow crustal events in active tectonic regions, excluding subduction events." They divided the data into two site classes, a deep soil class with soil thickness greater than 20 m and a "rock" class with less than 20 m of soil over rock. This is a somewhat different definition of a rock site from that used by Joyner and Boore (1997), who included only sites with less than 5 m of soil over rock. The attenuation relationships for acceleration and spectral response derived by Abrahamson and Silva (1995) contain a soil amplification term that depends explicitly on the acceleration level on "rock" (PGA_{rock}),

$$f_5 = a_{10} + a_{11} \ln(PGA_{rock} + c_5). \tag{14}$$

Values of soil amplification are plotted against period in Figure 3 for selected values of acceleration on rock. We use the Joyner and Boore (1997) values of V_{30} for rock and soil along with equation (14) to obtain m_a and m_v for the Abrahamson and Silva (1997) relationships corresponding to different values of PGA_{rock}, recognizing that the m_a and m_v obtained will be underestimates, particularly at short periods, because of the difference in definition of rock sites. The relationship for 0.2 sec was used for m_a, and the relationship for 1.0 sec was used for m_v. Since a_{11} is zero for 1.0 sec, there is no nonlinearity for m_v. The values of m_a for $PGA_{rock} = 0.1$ and 0.4, assumed to correspond to 0.2 sec response values of 0.25 and 1.0, were used in equation (4) to solve for c_1 and c_2. Equation (4) was then used to compute a new set of m_a values, which did not differ from the original set by more than 0.01. The resulting m_a values correspond to a reference velocity of 620 m/sec. We corrected the values to a reference velocity of 1068 m/s, corresponding to the geometric mean of the class boundaries for Class B, using equation (6). The corrected values are given in Table 6. Equation (2) with m_a and m_v values from Table 6 and V and V_{ref} values from Table 5 provides the F_a and F_v values ascribed to Abrahamson and Silva (1997) in Tables 1 and 2. As should be expected from the different definitions of rock, the Abrahamson and Silva (1997) F_a values are smaller than the others.

CONCLUSION

The F_a and F_v values computed on the basis of the analyses by Crouse (1995), Abrahamson and Silva (1997), and Boore et al. (1994, Boore; unpublished, 1998) given in Tables 1 and 2 are in relatively good agreement, except that the Class C and D F_a values for Abrahamson and Silva (1997) are somewhat lower than the others, probably because they were computed using the Boore and Joyner (1997) values for V_{30} for rock and soil, despite the difference in definition of rock and soil between Abrahamson and Silva (1997) and Boore and Joyner (1997). We believe these results are a satisfactory basis for revising the NEHRP site coefficients.

The proposed F_a values in Table 1 are virtually identical to the NEHRP97 values. The Class D F_a values for Crouse (1995) show less nonlinearity than the NEHRP97 values. In that respect they are similar to the results of Borcherdt (1996), who found no nonlinearity of site Classes C and D in the 1994 Northridge earthquake relative to class B sites. The analyses of Abrahamson and Silva (1997) and Boore et al. (1994; Boore, unpublished, 1998), however, show somewhat more nonlinearity in F_a than NEHRP97. Consequently, the values proposed for F_a in Table 1 are similar to the NEHRP97 values.

The important differences between the values proposed here and the NEHRP97 values are for F_v. The analyses of Crouse (1995), Abrahamson and Silva (1997), and Boore et al. (1994; Boore, unpublished, 1998) all show essentially no nonlinearity of F_v values for site classes C and D. These findings are in agreement with the results of Borcherdt (1996) for the Northridge earthquake and results by Dobry (oral comm., 1998). The proposed values for F_v in Table 2, therefore, show no nonlinearity.

The F_a and F_v values in Tables 1 and 2 are based on assumed values of 1.0 for Class B. The V_{30} for Class B, however, from the geometric mean of the class boundaries, is 1068 m/sec, whereas the ground-motion maps made by Frankel's group at the USGS, which are the basis for NEHRP97, were made for an assumed V_{30} of 760 m/sec. This inconsistency could be resolved by modifying the ground-motion maps or by correcting the F_a and F_v values to a reference velocity of 760 m/sec with the aid of equations (2), (4), and (6). We believe that the second course would be easier and lead to less confusion and misunderstanding. Tables 7 and 8 show the proposed set of F_a and F_v coefficients, respectively, for a reference velocity of 1068 m/sec, and Tables 9 and 10 show the coefficients for a reference velocity of 760 m/sec.

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TABLE 1 F_a for $V_{ref} = 1068$ m/sec

S_s (g)	0.25	0.5	0.75	1.0
B	1.0	1.0	1.0	1.0
C Boore *et al.* (1994; Boore, unpublished, 1998)	1.20	1.04	0.96	0.90
Abrahamson and Silva (1997)	1.05	0.92	0.86	0.81
Crouse (1995)	1.3	1.3	1.3	1.3
C Proposed	1.3	1.2	1.1	1.0
C NEHRP97	1.2	1.2	1.1	1.0
D Boore *et al.* (1994; Boore, unpublished, 1998)	1.45	1.09	0.92	0.82
Abrahamson and Silva (1997)	1.11	0.85	0.74	0.66
Crouse (1995)	1.6	1.5	1.4	1.3
D Proposed	1.6	1.4	1.2	1.1
D NEHRP97	1.6	1.4	1.2	1.1
E NEHRP97	2.5	1.7	1.2	0.9

TABLE 2 F_v for $V_{ref} = 1068$ m/sec

S_l (g)	0.1	0.2	0.3	0.4
B	1.0	1.0	1.0	1.0
C Boore *et al.* (1994; Boore, unpublished, 1998)	1.65	1.65	1.65	1.65
Abrahamson and Silva (1997)	1.55	1.55	1.55	1.55
Crouse (1995, Table 7)	1.7	1.7	1.7	1.7
C Proposed	1.6	1.6	1.6	1.6
C NEHRP97	1.7	1.6	1.5	1.4
D Boore *et al.* (1994; Boore, unpublished, 1998)	2.72	2.72	2.72	2.72
Abrahamson and Silva (1997)	2.40	2.40	2.40	2.40
Crouse (1995, Table 7)	2.0	2.0	1.9	1.9
D Proposed	2.5	2.5	2.5	2.5
D NEHRP97	2.4	2.0	1.8	1.6
E NEHRP97	3.5	3.2	2.8	2.4

TABLE 3 Coefficients for Rock and Soil Residuals to the Boore *et al.* (1994) Attenuation Relationship Regressed Against the Predicted Value for Rock

Coefficient	b_{1r}	b_{2r}	b_{1s}	b_{2s}
0.2 sec Period	-0.1110	0.1159	0.1052	-0.1219

TABLE 4 Values of m_a and m_v for a Reference Velocity of 1068 m/sec from the Analysis of Boore *et al.* (1994; Boore, unpublished, 1998)

S_s (g)	0.25	0.5	0.75	1.0
m_a	0.26	0.06	-0.06	-0.14
S_l (g)	0.1	0.2	0.3	0.4
m_v	0.70	0.70	0.70	0.70

TABLE 5 V_{30} for Site Classes B, C, and D (see text)

Class	B	C	D
V_{30} (m/sec)	1068	523	255

TABLE 6 Values of m_a and m_v for a Reference Velocity of 1068 m/sec from the Analysis of Abrahamson and Silva (1997)

S_s (g)	0.25	0.5	0.75	1.0
m_a	0.07	-0.11	-0.22	-0.29
S_l (g)	0.1	0.2	0.3	0.4
m_v	0.61	0.61	0.61	0.61

TABLE 7 Proposed F_a for $V_{ref} = 1068$ m/sec

S_s (g)	0.25	0.5	0.75	1.0
B	1.0	1.0	1.0	1.0
C	1.3	1.2	1.1	1.0
D	1.6	1.4	1.2	1.0

TABLE 8 Proposed F_v for $V_{ref} = 1068$ m/sec

S_l (g)	0.1	0.2	0.3	0.4
B	1.0	1.0	1.0	1.0
C	1.6	1.6	1.6	1.6
D	2.5	2.5	2.5	2.5

TABLE 9 Proposed F_a for $V_{ref} = 760$ m/sec

S_s (g)	0.25	0.5	0.75	1.0
B	0.9	0.9	1.0	1.0
C	1.1	1.1	1.1	1.0
D	1.5	1.3	1.2	1.1

TABLE 10 Proposed F_v for $V_{ref} = 760$ m/sec

S_l (g)	0.1	0.2	0.3	0.4
B	0.8	0.8	0.8	0.8
C	1.3	1.3	1.3	1.3
D	2.0	2.0	2.0	2.0

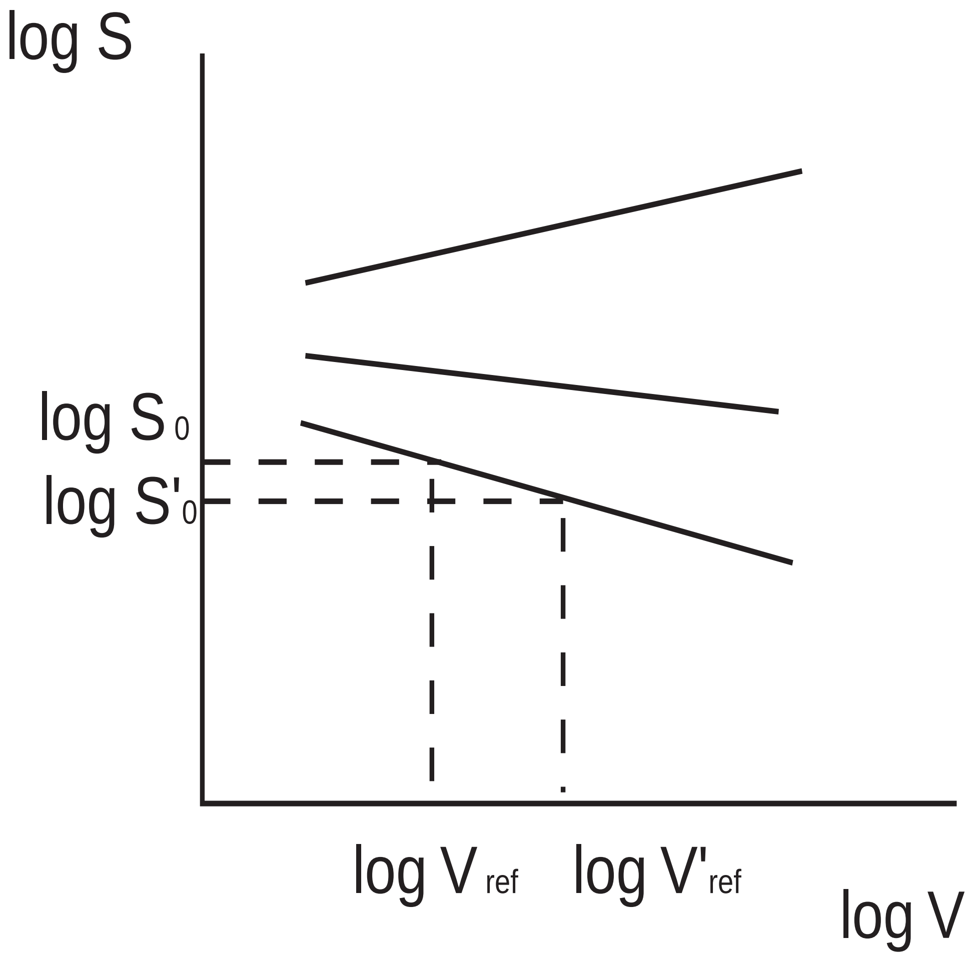

Figure 1. Changing the reference velocity from V_{ref} to V'_{ref}. The response value S'_0 at V'_{ref} corresponds to the value S_0 at V_{ref}. The solid lines show the relationships between $\log S$ and $\log V$ for given values of S_0.

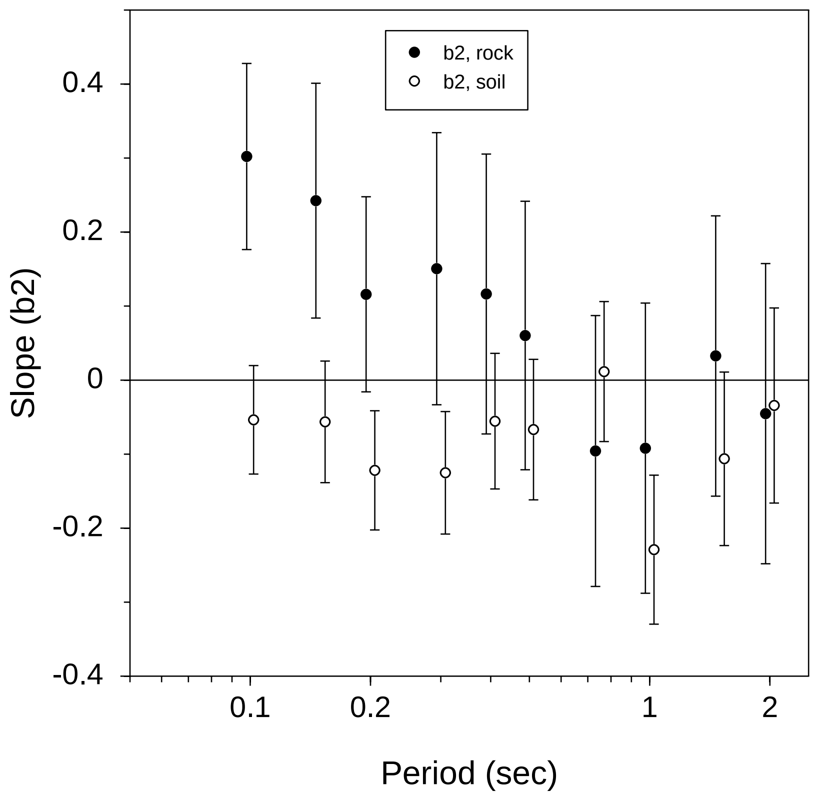

Figure 2. Slopes of the regression of residuals to the Boore et al. (1994) relationship for rock and soil sites against predicted response at rock sites, plotted against period. The bars show the standard errors of the slopes. (Both the rock and soil symbols have been offset horizontally for clarity.)

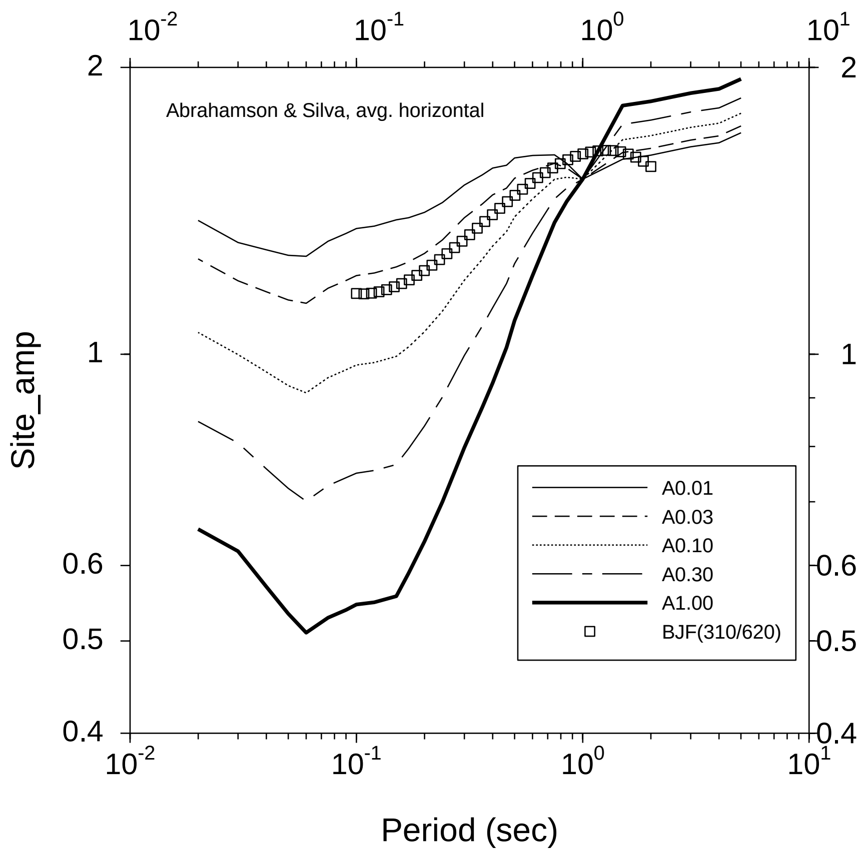

Figure 3. Amplification at deep soil sites relative to rock and shallow soil sites for the attenuation relationship of Abrahamson and Silva (1997) for various values (A) of predicted peak horizontal acceleration on rock and shallow soil. Squares show the amplification at soil sites relative to rock sites, independent of rock acceleration, given by Boore et al. (1994). The squares appear to correspond to a peak acceleration on rock of about 0.04 g, a value much lower than appropriate for an average of the Boore et al. (1994) data set. The discrepancy results from the different definitions of rock and soil.