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RECENT DEVELOPMENTS IN EARTHQUAKE GROUND MOTION ESTIMATION

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ABSTRACT

Analysis of strong-motion data shows that the long-period site-response coefficients in the building code need modification to eliminate nonlinearity for the soft rock and firm soils of NEHRP Site Classes C and D. Strong-motion data from new, high-resolution digital instruments will enable improvements to be made in code and design values for periods of 4 sec and longer.

Nonlinear Site Coefficients for Building Codes

The basis for the 1994 and 1997 NEHRP site coefficients, which are now part of the 2000 edition of the International Building Code (IBC), was laid at a workshop at the University of Southern California in November 1992. Sites were divided into four classes depending on the average shear-wave velocity to 30 m (V_{30}). These classes are currently designated by the letters B, C, D, and E, and a Class A has been added for very hard rock. 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 at the reference site class (Class B), given by A_a and A_v in NEHRP94 and by S_s and S_l in NEHRP97 and IBC 2000. 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 greater than 0.1 g were determined with the aid of the equation (Borcherdt, 1992, 1994)

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

where V is the average V_{30} for a given site class and V_{ref} is the average V_{30} for the reference site usually taken as Class B. The values of F_a and F_v determined for Class E for A_a and A_v greater

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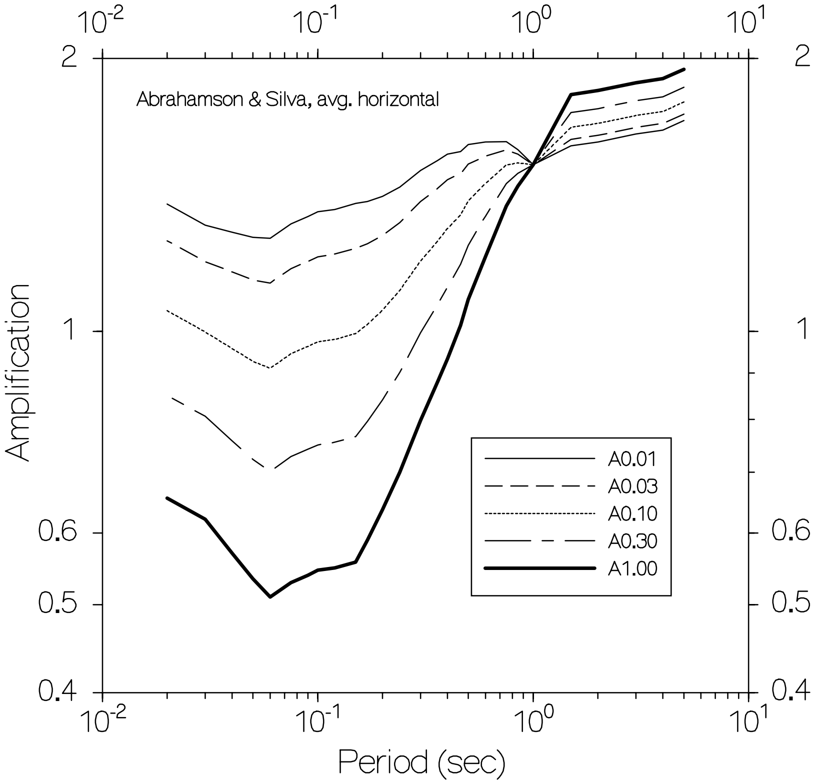

Figure 1. Amplification at deep-soil sites relative to rock and shallow-soil sites for the attenuation relationship of Abrahamson and Silva (1997) for various values (A) of predicted peak horizontal acceleration on rock and shallow soil.

than 0.1 *g* were used in equation (1) 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 (1) 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 a number of 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. In this paper we obtain F_a and F_v for Classes A, B, C, and D for a range of ground-motion values directly from regression analysis of strong-motion data. There are insufficient strong-motion data at high ground-motion levels to obtain F_a or F_v values for Class E.

Crouse (1995) analyzed a strong-motion data set from western North America with sites assigned to Classes B through E. His F_v values (Crouse, 1995, Table 7) show essentially no nonlinearity in Class D relative to Class C. There were insufficient data to check for nonlinearity in Classes C and D relative to Class B. An analysis of strong-motion data from the 1994 Northridge, California, earthquake, by Borcherdt (1996) showed essentially no dependence of F_a or F_v for either Class C or Class D on the ground-motion level on rock. Abrahamson and Silva (1997) developed attenuation relationships for peak horizontal acceleration and spectral response based on 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

Table 1. F_a for V_{ref} = 1068 m/sec

Site Class	$S_s < 0.25$	0.50	0.75	0.10	> 1.25 *g*
A (This paper)	0.82	0.87	0.91	0.97	1.01
(IBC 2000)	0.8	0.8	0.8	0.8	0.8
B (This paper)	1.00	1.00	1.00	1.00	1.00
(IBC 2000)	1.0	1.0	1.0	1.0	1.0
C (This paper)	1.23	1.16	1.10	1.04	0.99
(IBC 2000)	1.2	1.2	1.1	1.0	1.0
D (This paper)	1.51	1.35	1.20	1.07	0.97
(IBC 2000)	1.6	1.4	1.2	1.1	1.0

Table 2. F_v for V_{ref} = 1068 m/sec

Site Class	$S_l < 0.1$	0.2	0.3	0.4	> 0.5 *g*
A (This paper)	0.57	0.57	0.57	0.57	0.57
(IBC 2000)	0.8	0.8	0.8	0.8	0.8
B (This paper)	1.00	1.00	1.00	1.00	1.00
(IBC 2000)	1.0	1.0	1.0	1.0	1.0
C (This paper)	1.80	1.80	1.80	1.80	1.80
(IBC 2000)	1.7	1.6	1.5	1.4	1.3
D (This paper)	3.24	3.24	3.24	3.24	3.24
(IBC 2000)	2.4	2.0	1.8	1.6	1.5

deep-soil class with soil thickness greater than 20 m and a rock and shallow-soil class with less than 20 m of soil over rock. The attenuation relationships contain a soil-amplification term that depends explicitly on the acceleration level on rock and shallow soil. As illustrated in Figure 1, that soil-amplification term shows substantial nonlinearity at short periods, but no nonlinearity at one second.

In order to develop a set of F_a and F_v values from strong-motion data, we took the data set used by Boore *et al.* (1997) with sites assigned to Classes B through E and repeated the regression with a site-response term of the form

$$(a_6 + a_7 PSV_{ref}) \log(V / V_{ref}) \qquad (2)$$

where V is the average V_{30} for the site class, V_{ref} is the average V_{30} for the reference site condition, PSV_{ref} is the predicted response value for the reference site condition, and a_6 and a_7 are coefficients determined in the regression. Equation (2) enables us to compute values of F_a and F_v for each site class for different levels of S_s and S_l. Equation (2) can also be used to convert the values from one reference site velocity to another. Values of F_a and F_v for a Class B reference (V_{30} =1068 m/sec) obtained from equation (2) are compared in Tables 1 and 2 with the values given in IBC 2000 (the current code). The F_a values are quite similar, but the F_v values obtained from equation (2) are significantly different from those in IBC 2000 and do not show any nonlinearity. These results along with the results of earlier analyses call for changes in the

Table 3. F_a for V_{ref} = 760 m/sec

Site Class	$S_s < 0.25$	0.50	0.75	1.00	> 1.25 *g*
A (This paper)	0.74	0.80	0.87	0.94	1.02
B (This paper)	0.90	0.93	0.95	0.98	1.01
C (This paper)	1.12	1.08	1.05	1.02	0.99
D (This paper)	1.38	1.27	1.16	1.07	0.98

Table 4. F_v for V_{ref} =760 m/sec

Site Class	$S_l < 0.1$	0.2	0.3	0.4	> 0.5 *g*
A (This paper)	0.43	0.43	0.43	0.43	0.43
B (This paper)	0.76	0.76	0.76	0.76	0.76
C (This paper)	1.36	1.36	1.36	1.36	1.36
D (This paper)	2.45	2.45	2.45	2.45	2.45

code values. Equation (2) is based on a data set that does not include any data from the Northridge earthquake, but the results are generally similar to those of Abrahamson and Silva (1997) whose data set did include Northridge data.

The National Seismic Hazard Maps (Frankel *et al.*, 2000), which the ground-motion maps in the code are based on, use attenuation relationships with a reference site velocity of 760 m/sec rather than 1068 m/sec. To minimize confusion it would be preferable to continue use of 760 m/sec as the map reference velocity and adjust F_a and F_v in the code to match. Tables 2 and 3 give the values computed from equation (3) for a reference velocity of 760 m/sec.

Very Long Period Ground Motions from High-Resolution Digital Instruments

Most existing strong-motion data were recorded by analog instruments. The output is filtered to remove long-period noise, and the result is unreliable for computing response spectra at periods longer, typically, than about 4 sec. For many engineering purposes this situation poses no problem, but there are structures, some of them very important, with periods longer than 4 sec. Indeed, there have been proposals to add a branch of the seismic response coefficient curve that decreases as the square of the period above a Newmark-type “corner period” fixed at 4 sec. The problem with these proposals is that the corner period increases with magnitude. The 4 sec value may be approximately correct for earthquakes of magnitudes near 6.5, but will be too small generally for earthquakes of magnitude greater than 7.0. Until recently, there were insufficient reliable strong-motion data to address this problem directly.

The new generation of high-resolution digital strong-motion instruments now widely deployed is providing data reliable to much longer periods than before. Boore (1999) processed digital records (Lee, *et al.*, 1999) from the 1999 Chi-Chi, Taiwan, earthquake (moment magnitude 7.6) and found that for periods shorter than about 20 sec the response spectra were insensitive to the method of baseline correction. Figure 2 shows the horizontal pseudovelocity spectra for a sample of six records from the Chi-Chi earthquake. Figure 3 gives a corresponding display for the 1999 Hector Mine, California, earthquake (moment magnitude 7.1). The corner periods evident on Figures 2 and 3 are typically much larger than 4 sec. We plan to use these new data to develop attenuation relationships for very long-period response spectra, or perhaps for maximum response displacement. Such attenuation relationships would permit maps of response to be made that could be used to incorporate long-period response properly into codes.

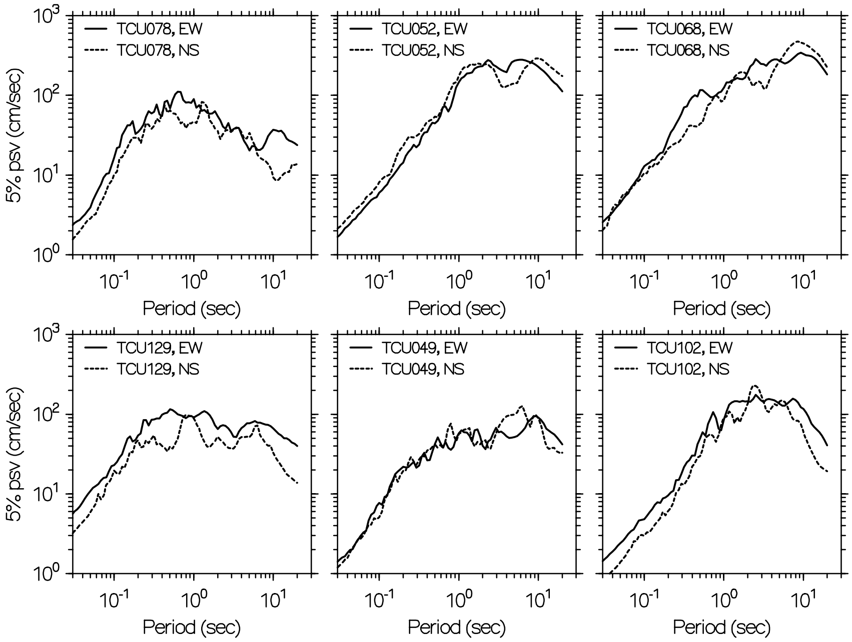

Figure 2. Horizontal pseudovelocity spectra from the Chi-Chi, Taiwan, earthquake.

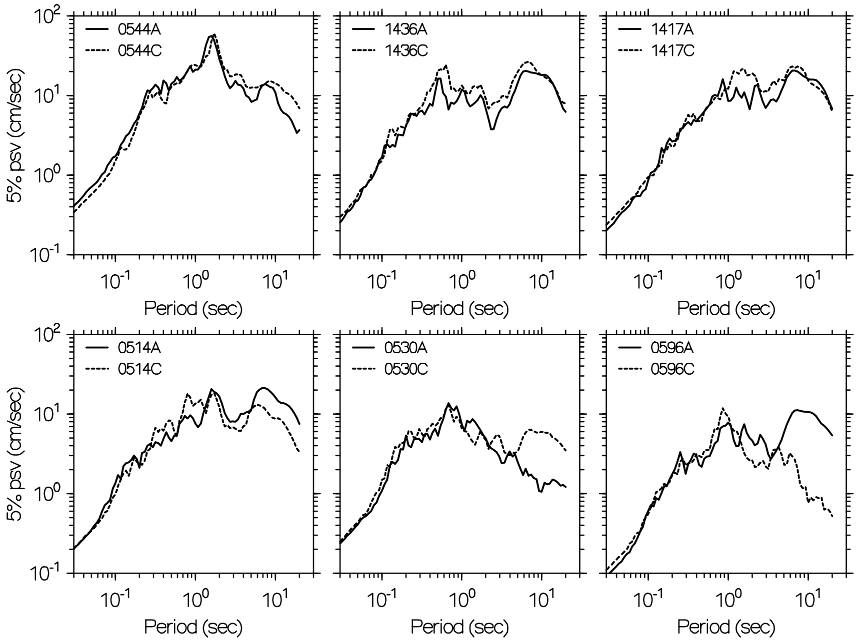

Figure 3. Horizontal pseudovelocity spectra from the Hector Mine, California, earthquake.

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