USE OF MEASURED SHEAR-WAVE VELOCITY
FOR PREDICTING GEOLOGIC SITE EFFECTS ON
STRONG GROUND MOTION

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SUMMARY

We present here estimates of the site effects on strong ground motion as functions of local shear-wave velocity. The estimates are made for peak horizontal acceleration, velocity, and response spectra at 5 percent damping. The method makes use of the ground-motion predictive equations of Joyner and Boore (Ref. 1, 2, 3) and down-hole shear velocity measurements made to depths generally equal to or greater than 30 m at 33 of the strong motion sites where data used in deriving the predictive equations were recorded. The method and results are presented briefly here; a fuller discussion will be published elsewhere.

INTRODUCTION

There is a basis in traditional seismological theory (Ref. 4, 5) for the use of local shear-wave velocity in estimating the site effect on ground motion amplitude. If we neglect losses due to reflection, scattering, and anelastic attenuation, the energy along a tube of rays is constant and the amplitude is inversely proportional to the square root of the product of the density and the propagation velocity. (This product is commonly referred to as the seismic impedance.) If we include a correction for the change in cross-sectional area of the ray tube due to refraction in a medium where velocity is a function of depth, the amplitude of ground motion is proportional to

$$(\cos i)^{-1/2} (\rho V)^{-1/2}$$

where ρ is the density, V the propagation velocity and i is the angle of incidence measured from the vertical. The variations in density are relatively small and tend to correlate with the shear velocity. Because of the tendency for propagation velocity to increase with depth, incidence angles are small near the surface and the factor in $\cos i$ can be neglected. Thus amplitude is approximately proportional to the reciprocal of the square root of the propagation velocity. As proposed by Joyner and others (Ref. 6) in analyzing strong-motion data from the 1979 Coyote Lake earthquake, we use shear velocity, measured over a depth of one quarter wave length of the period of concern, for predicting the site effect on ground motion. This method of predicting site effects does not account for resonance effects, involving reinforcing multiple reflections. Narrow band measures of ground motion such as Fourier spectra or undamped response

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spectra are certainly affected significantly at some sites by resonance. Broader band measures such as we propose to predict, however, will in general be less affected. Resonance effects appear in undamped response spectra as sharp peaks at the resonant frequency. Such peaks are substantially reduced in the 5 percent damped spectral values we propose to predict, as is demonstrated in studies by Boore and Joyner (Ref. 7).

ESTIMATING THE SITE EFFECTS

To estimate the site effects we start with the predictive equations of Joyner and Boore (Ref. 1, 2, 3), which have the form

$$\log y = c_o + c_1 (M-6) + c_2 (M-6)^2 + c_3 \log r + c_4 r + S \qquad (1)$$

$$5.0 \leq M \leq 7.7$$

$$r = (d^2 + h^2)^{1/2}$$

$$S = 0 \text{ at rock sites}$$

$$= c_5 \text{ at soil sites}$$

where y is the ground motion parameter to be predicted, M is moment magnitude (Ref. 8) and d is the closest distance from the site where ground motion is being predicted to the vertical projection on the earth's surface of the rupture surface for the earthquake. The parameters c_o through c_5 and h have been determined from strong-motion data by regression analysis. At the strong-motion sites where shear-wave velocity data are available we take the residuals of log y with respect to the values predicted by equation (1) for rock sites. We then do a linear regression between those residuals and the logarithm of the shear-wave velocity averaged over a depth of one-quarter wavelength of the period of interest. This in many cases requires us to extend the downhole shear-wave velocity profile to depths substantially greater than the deepest measurement, using whatever geologic data is available. To decouple the site-effects variation from the earthquake-to-earthquake variation, we do the regression using the following equation:

$$\log R_{ij} = p_i + c_6 V_j \qquad (2)$$

where R_{ij} is the residual for earthquake i at site j, V_j is the average shear velocity to the appropriate depth at site j, and p_i and c_6 are parameters determined by the regression. Figure 1 shows a log-log plot of the residuals against shear-wave velocity for peak horizontal ground velocity. The regression using equation (2) gives us the slope of the straight line relating the logarithm of ground motion residual to the logarithm of site shear velocity, but it does not give us a unique intercept. We obtain the intercept by requiring that the average site effect term calculated using the shear-wave velocity be the same as the average calculated for the same group of stations using the simple rock versus soil classification. The resulting site effect term can be cast in the form

$$S = c_6 \log \left(\frac{V}{V_o}\right) \qquad (3)$$

where V is the local shear-wave velocity and V_0 is a reference velocity. Values of c_6 and V_0 are given in Table 1 for the various ground-motion quantities to be predicted, except for peak acceleration and a few of the short period response values for which the correlation between the logarithm of ground motion residual and the logarithm of shear velocity is not statistically significant at the 90 percent level. The values of c_6 given in Table 1 are generally close to the 0.5 value derived by requiring conservation of energy along tubes of rays. It is not clear why the values are less than 0.5 for response spectra at periods less than 1.0 s or why there is no statistically significant correlation with shear wave velocity for peak acceleration or for response spectra at periods less than 0.3 s. There are at least two possible reasons for values greater than 0.5. If we take account of density differences and if density correlates positively with shear velocity, as one would expect, then the coefficient of the logarithm of the velocity ratio would exceed 0.5. Resonance effects could also contribute to a larger coefficient. One should also bear in mind that the argument involving energy conservation along ray tubes is essentially a body-wave argument, and may not adequately describe the amplification, particularly at long periods, if surface-wave propagation is significantly involved.

In an attempt to understand why peak horizontal acceleration and response spectra at periods less than 0.3 s did not show a statistically significant correlation with local shear wave velocity, we also tried a linear regression against two independent variables, local shear-wave velocity to a depth of one-quarter wavelength and depth to overlying rock. The idea was to see if two mutually cancelling effects were present. The analysis was performed using two alternative definitions of rock: (1) material characterized by shear-wave velocity in excess of 750 m/s; (2) material characterized by shear-wave velocity in excess of 1500 m/s. The first value corresponds generally to soft sedimentary rock and the second to hard crystalline rock. In the case of peak acceleration and short-period response, the results showed no statistically significant correlation with either shear-wave velocity or depth to rock, for the 750 m/s definition of rock. Peak acceleration was analyzed using the 1500 m/s definition of rock, and the results in that case also showed no correlation with either variable. For peak velocity and longer-period response spectra, the results showed significant correlation with both shear wave velocity and depth to rock for the 750 m/s definition of rock. For the 1500 m/s definition an analysis of peak velocity showed correlation only with shear-wave velocity. The correlation with depth to rock noted for the 750 m/s definition was in the sense of decreasing ground motion with increasing depth. The coefficient relating ground motion to depth was relatively small, and, although formal tests indicated statistical significance at better than the 90 percent level, we frankly doubt the validity of the correlation. For reasonable values of Q, anelastic attenuation is not large enough to account for the correlation. Moreover, if the strong-motion data from the 1971 San Fernando earthquake are analyzed separately, the results do not show significant correlation. All things considered, we do not believe it appropriate with the present data set to use depth to rock in predicting site effects. Figure 2 shows the residuals of peak horizontal velocity corrected for site effects with equation (3) plotted against depth to rock using the 750 m/s definition of rock. It seems clear that we are not losing much by not using depth to rock in our prediction scheme.

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Table 1. Parameters for predicting the site effect on peak horizontal acceleration, velocity, and pseudo-velocity response at 5 percent damping (Asterisks indicate that the correlation with shear-wave velocity is not statistically significant at the 90 percent level.)

	Period s	V_o m/s	c_6
Peak Acceleration		*	*
Peak Velocity		1190	-0.45
Pseudo-Velocity Response	0.1	*	*
	0.15	*	*
	0.2	*	*
	0.3	590	-0.28
	0.4	830	-0.33
	0.5	1020	-0.38
	0.75	1410	-0.46
	1.0	1580	-0.51
	1.5	1620	-0.59
	2.0	1620	-0.64
	3.0	1550	-0.72
	4.0	1450	-0.78

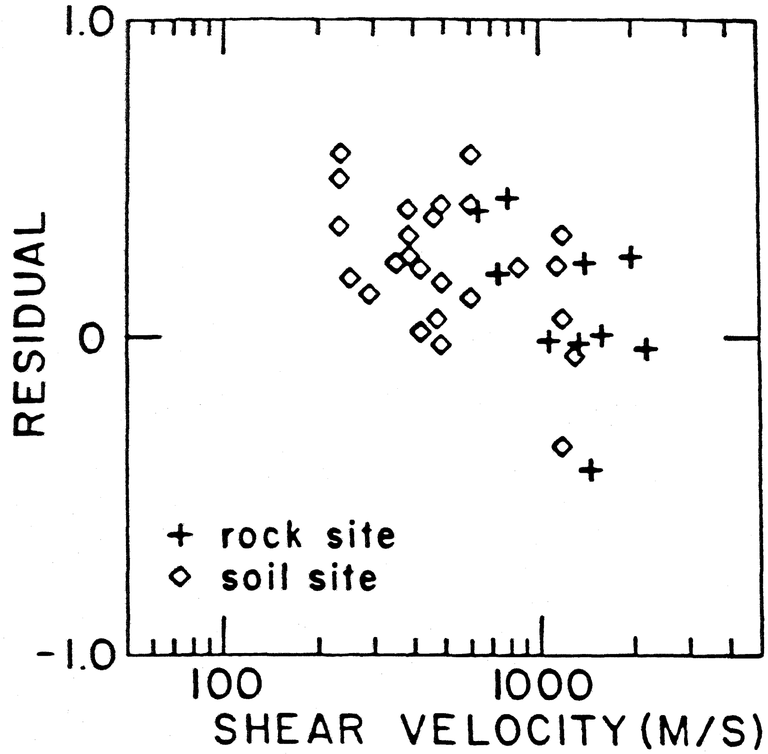

Figure 1. Residuals of the logarithm of peak horizontal velocity with respect to the values predicted by equation (1) for rock sites, plotted against the average shear-wave velocity to a depth of a one-quarter wavelength of a one-second wave.

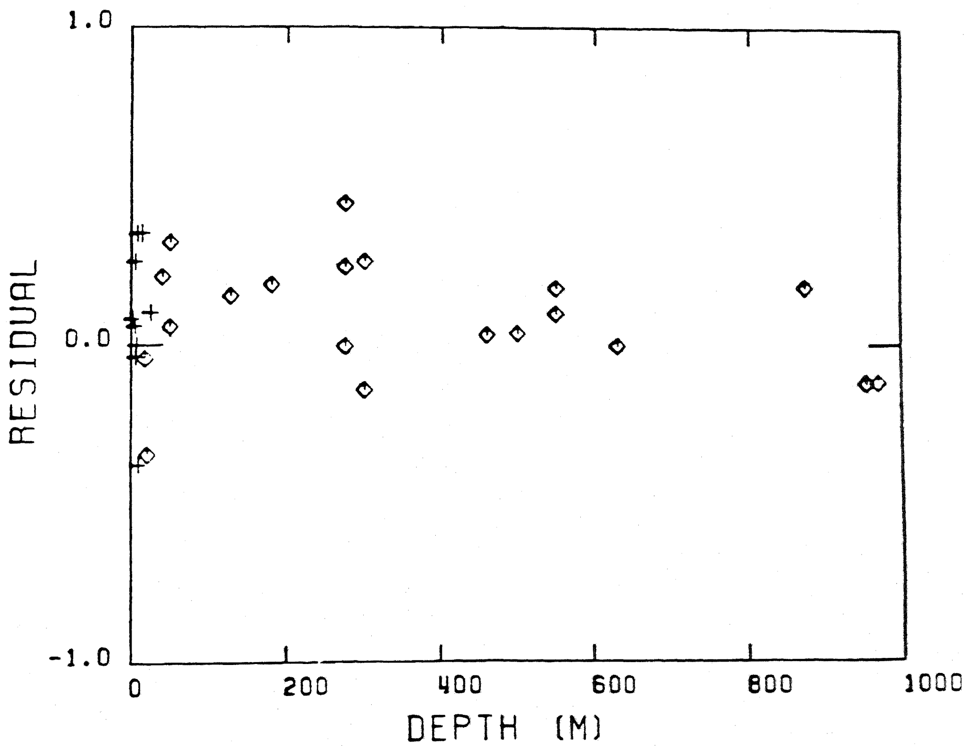

Figure 2. Residuals of the logarithm of peak horizontal velocity with respect to the values predicted by equation (1) for rock sites corrected for site effects using equation (3) and plotted against depth to rock. The definition of rock in this case is material with a shear wave velocity greater than 750 m/s.