OBSERVED SPECTRAL CHARACTERISTICS OF VERTICAL GROUND MOTION RECORDED DURING WORLDWIDE EARTHQUAKES FROM 1957 TO 1995

Yousef BOZORGNIA[1], Kenneth W CAMPBELL[2] And Mansour NIAZI[3]

SUMMARY

A comprehensive near-source strong motion database was compiled. The database includes over 2,800 free-field uncorrected peak ground acceleration (PGA) values from 48 worldwide earthquakes and more than 1,300 free-field response spectra from 33 worldwide earthquakes. The database includes the data recorded within 60 km of the causative fault from earthquakes ranging from 4.7 to 7.7 in magnitude. Attenuation models of PGA and response spectra for both the vertical and horizontal components were developed as functions of magnitude, source-to-site distance, type of faulting, and local soil conditions. The study clearly demonstrates the strong dependence of vertical-to-horizontal (V/H) spectral ratio on oscillator period, source-to-site distance, and local soil conditions. V/H shows a weaker and more limited dependence on magnitude and type of faulting. The largest short-period V/H ratios are observed to occur on Holocene Soil at short periods and short distances where they can reach values in excess of 1.5 at 0.1-sec period. The largest long-period V/H ratios are observed to occur on Hard Rock where they can reach values as high as 0.7. We conclude that the standard engineering practice of assigning V/H a value of two-thirds is unconservative at short periods, especially for unconsolidated soil, but conservative at long periods, and should be modified.

INTRODUCTION

Characteristics of vertical ground motion have been studied by [Campbell 1982; Niazi and Bozorgnia 1989, 1991, 1992; Bozorgnia and Niazi 1993; Bozorgnia et al. 1995, 1996], among others. The main objective of this study is to generalize previous investigations and identify the characteristics of vertical response spectra and their differences with those of the horizontal component in terms of some fundamental properties of the earthquakes and stations that recorded them. These properties include earthquake magnitude, source-to-site distance, type of faulting, and local soil conditions. This objective was accomplished by compiling and analyzing a comprehensive database of near-source ground motions of numerous worldwide earthquakes.

STRONG-MOTION DATABASE

This study utilized a comprehensive worldwide database of near-source accelerograms that were recorded between 1957 and 1995. The database is an expanded and updated version of the one that was used by two of the authors to develop a near-source attenuation relationship for peak horizontal acceleration [Campbell and Bozorgnia, 1994; Campbell, 1997]. It was expanded to include response spectral ordinates and significant earthquakes that have occurred since 1992, including the 1994 Northridge and 1995 Kobe earthquakes. The database of Uncorrected PGA includes 2,823 PGA values from 48 worldwide earthquakes ranging from 4.7 to 7.7 in magnitude. The spectral database consists of 1,308 response spectra from 33 worldwide earthquakes. All of the earthquakes occurred in a shallow crustal tectonic environment and all of the recordings are considered to be free field.

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[1] *Exponent Failure Analysis Associates,149 Commonwealth Drive, Menlo Park, CA 94025, USA , e-mail: yousef@exponent.com*
[2] *EQE International, Evergreen, CO, USA*
[3] *Berkeley Geophysical Consultants, Berkeley, CA, USA*

The magnitude measure used to characterize the size of an earthquake is moment magnitude (M_W). The distance measure is defined as the shortest distance from the area of seismogenic rupture on the causative fault to the recording site, hereafter referred to as distance to seismogenic rupture (R_S) and it was restricted to 60 km or less.

The types of faulting were classified into three categories defined as Strike Slip, Reverse, and Thrust. Since there is only one normal-faulting event in the database, this earthquake was placed in the Strike Slip category. There are 20 Strike Slip, 7 Reverse, and 6 Thrust events in the Corrected database. Local soil conditions were classified into four categories defined as Holocene Soil (recent alluvium), Pleistocene Soil (older alluvium), Soft Rock, and Hard Rock.

REGRESSION ANALYSIS

We developed a consistent set of attenuation relationships for the horizontal and vertical components of PGA and spectral acceleration (SA) and use these to estimate V/H.

After considerable exploratory analyses, the following equation was finally selected to represent the attenuation of PGA and SA for both horizontal and vertical components:

$$\begin{aligned}\ln Y = {} & c_1 + c_2 M_W + c_3 (8.5 - M_W)^2 + c_4 \ln(\{R_S^2 + [(c_5 S_{HS} + c_6 \{S_{PS} + S_{SR}\} + c_7 S_{HR}) \\ & \exp(c_8 M_W + c_9 \{8.5 - M_W\}^2)]^2\}^{1/2}) + c_{10} F_{SS} + c_{11} F_{RV} + c_{12} F_{TH} \\ & + c_{13} S_{HS} + c_{14} S_{PS} + c_{15} S_{SR} + c_{16} S_{HR} \qquad (1)\end{aligned}$$

where Y is either the vertical component (Y_V) or the geometric average of the two horizontal components (Y_H) of PGA or SA in g (g = 981 cm/sec^2); M_W is moment magnitude, R_S is the distance to seismogenic rupture in km; $S_{HS} = 1$ for Holocene Soil, $S_{PS} = 1$ for Pleistocene Soil, $S_{SR} = 1$ for Soft Rock, $S_{HR} = 1$ for Hard Rock, and $S_{HS} = S_{PS} = S_{SR} = S_{HR} = 0$ otherwise; $F_{SS} = 1$ for Strike Slip faulting, $F_{RV} = 1$ for Reverse faulting, $F_{TH} = 1$ for Thrust faulting, and $F_{SS} = F_{RV} = F_{TH} = 0$ otherwise; and c_1 through c_{16} are regression coefficients.

We found that there was a considerable degree of period-to-period variability in the regression coefficients that caused the predicted spectra to be very jagged near the limits of the magnitude and distance ranges. In order to reduce this jaggedness to an acceptable degree, we carried out a partial smoothing of the regression coefficients for the horizontal and vertical components of SA.

Figures 1 and 2 show how the predicted horizontal and vertical response spectra scale with magnitude, distance, local soil conditions, and type of faulting. The horizontal spectra clearly show a trend towards increasing predominate period with increasing magnitude. This trend is largely missing in the vertical spectra. The dependence of predominant period on distance for both the vertical and horizontal spectra is negligible, except possibly at 60 km. It should also be noted that the predominate periods of the horizontal spectra (0.2 to 0.5 sec) are longer than those of the vertical spectra (around 0.1 sec).

The horizontal spectra show relatively little difference between the different soil categories at short periods for the distance shown (R_S = 10 km). However, the horizontal Hard Rock spectrum is much smaller than that of the other soil categories at longer periods. The vertical spectra, on the other hand, are all quite similar for the different soil categories, except for the larger amplitude for Holocene Soil at short periods. Both the horizontal and vertical spectra show the same tendency towards higher amplitudes for Reverse and Thrust faulting at short and moderate periods. At periods greater than about 1.0 sec, however, these differences become negligible. This trend of decreasing difference in SA with increasing period for different types of faulting is consistent with the expected effects of dynamic stress drop and the expectation that Reverse and Thrust faulting is generally associated with higher stress drops.

V/H SPECTRAL RATIO

The horizontal and vertical regression results can be used to derive an attenuation relationship for V/H. Investigation of the plots of the normalized residuals of ln V/H versus magnitude and distance demonstrated the validity of the procedure. Figure 3 demonstrates the effect of soil conditions on V/H as a function of magnitude and distance. Also shown on Figure 3 is the effect of fault type. Only at very short and very long periods is V/H different for the three faulting categories. At short periods, Strike Slip faulting has higher V/H but differences between Reverse and Thrust faulting are barely distinguishable. The differences at long periods might not be significant, since there are fewer recordings at these periods. Soil effects are most pronounced for Holocene Soil (at short periods) and Hard Rock (at long periods). The difference in Holocene Soil diminishes with decreasing magnitude and increasing distance, however, the difference in Hard Rock remains relatively constant at all magnitudes and distances. At small magnitudes and large distances, the only effect of local soil conditions that remains is higher V/H on Hard Rock a periods exceeding about 0.2 sec.

The dependence of V/H on distance for each of the soil categories is demonstrated in Figure 4. The effect of distance is most pronounced for Holocene Soil, but the other soil categories show significant scaling at longer periods where V/H increases with distance. Once a distance of 60 km is reached, most of the dependence of V/H on distance at short periods has ended but differences at longer periods remain significant.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be drawn regarding the prediction of the vertical response spectrum and the V/H spectral ratio:

An analysis of residuals determined that the estimation of the V/H spectral ratio from attenuation relationships developed independently from the horizontal and vertical components of PGA and SA are unbiased, so that these attenuation relationships can be used to estimate V/H.

The V/H spectral ratio is a strong function of oscillator period, source-to-site distance, and local soil conditions, and a weaker function of magnitude and type of faulting. The largest short-period V/H ratios are observed to occur on Holocene Soil at short periods and short distances where they can reach values in excess of 1.5 at 0.1-sec period. The largest long-period V/H ratios are observed to occur on Hard Rock where they can reach values as high as 0.7. Generally V/H is 0.5 or less at the longer periods (0.3 to 2.0 sec).

We conclude that the standard engineering practice of assigning the V/H ratio a value of two-thirds is unconservative at short periods, especially for unconsolidated soil and in the near-source region, but conservative at long periods, and should be modified.

ACKNOWLEDGEMENTS

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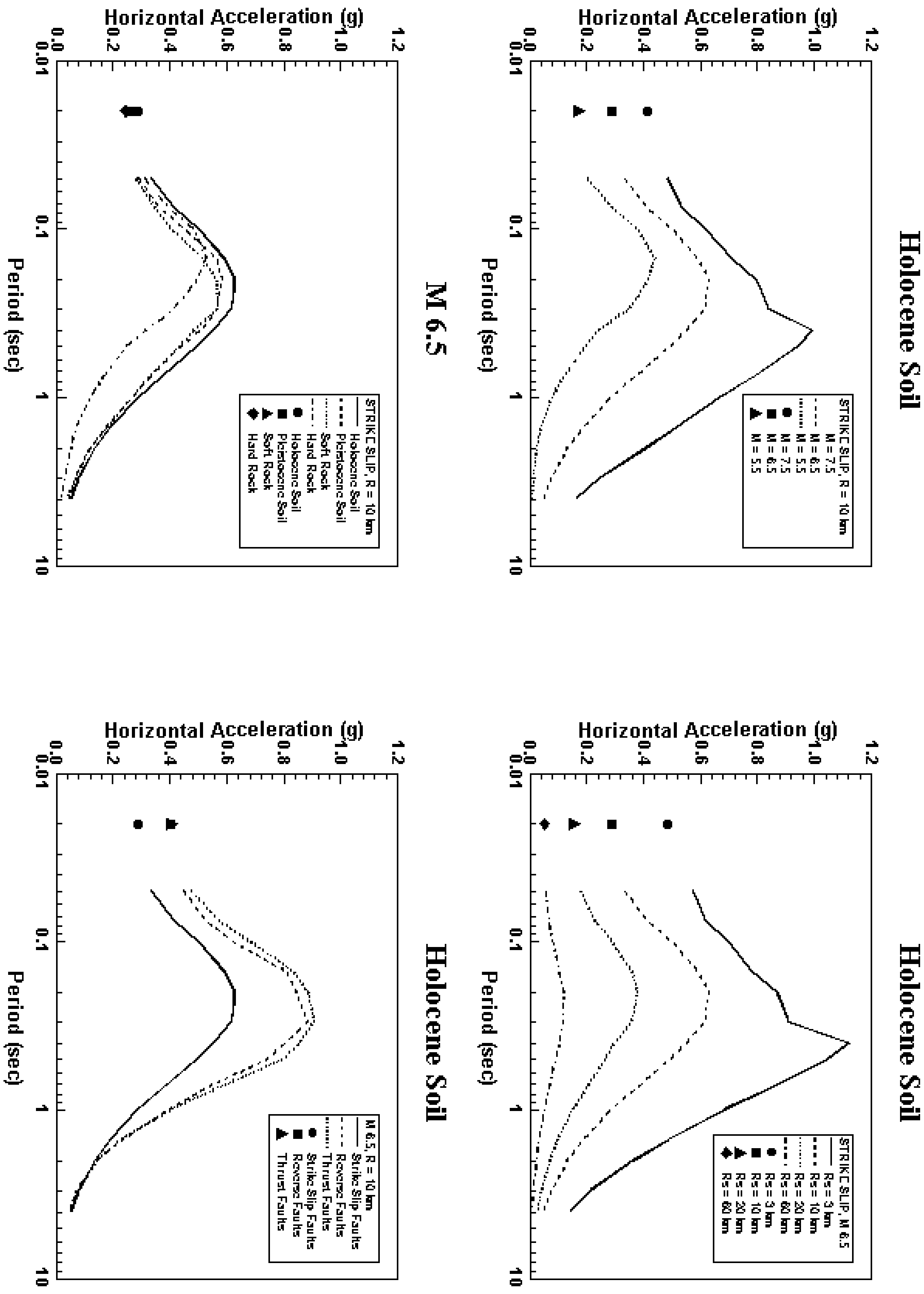

Figure 1—Dependence of horizontal SA on moment magnitude, source-to-site distance, local site conditions, and type of faulting.

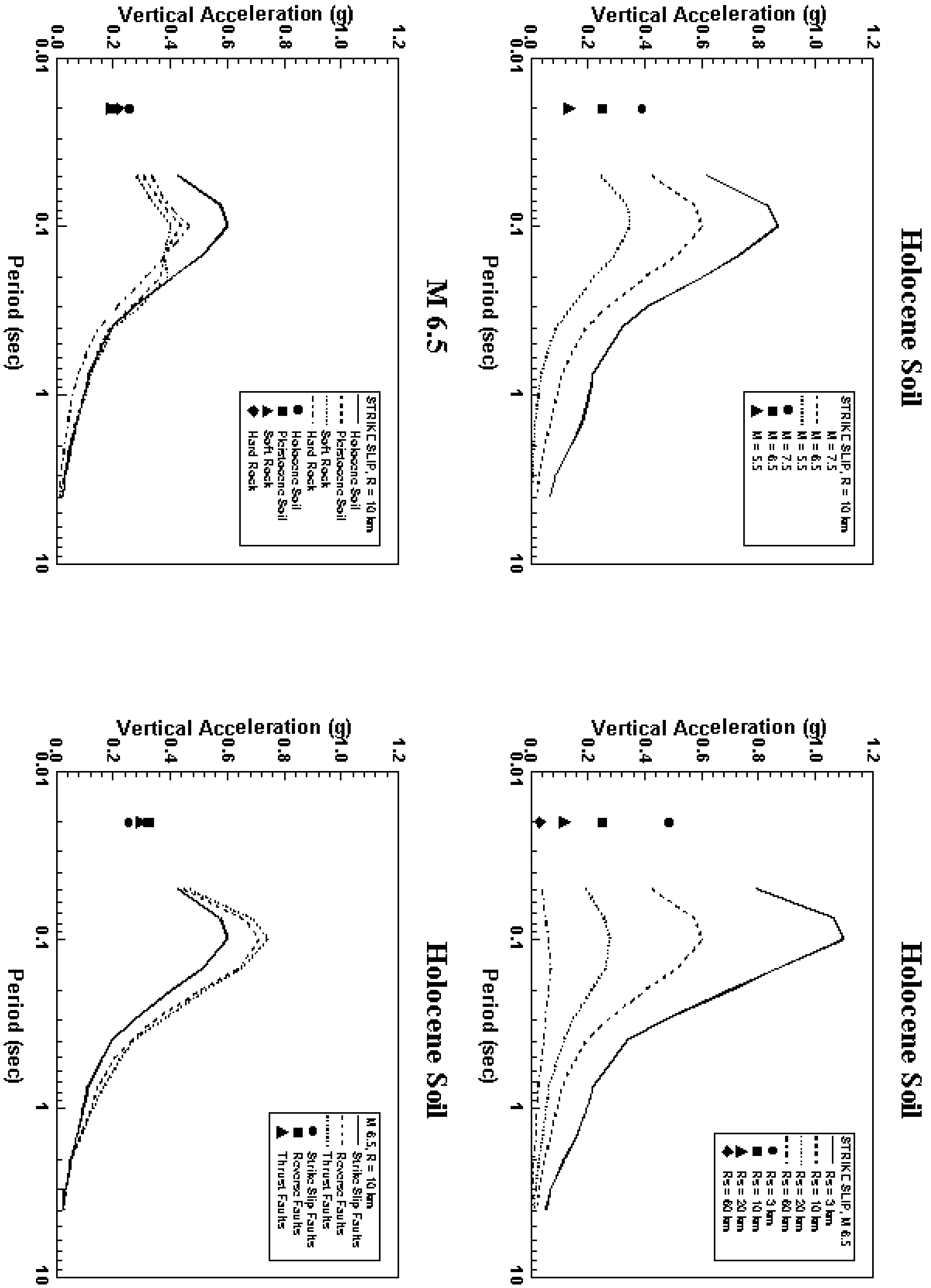

Figure 2—Dependence of vertical SA on moment magnitude, source-to-site distance, local site conditions, and type of faulting.

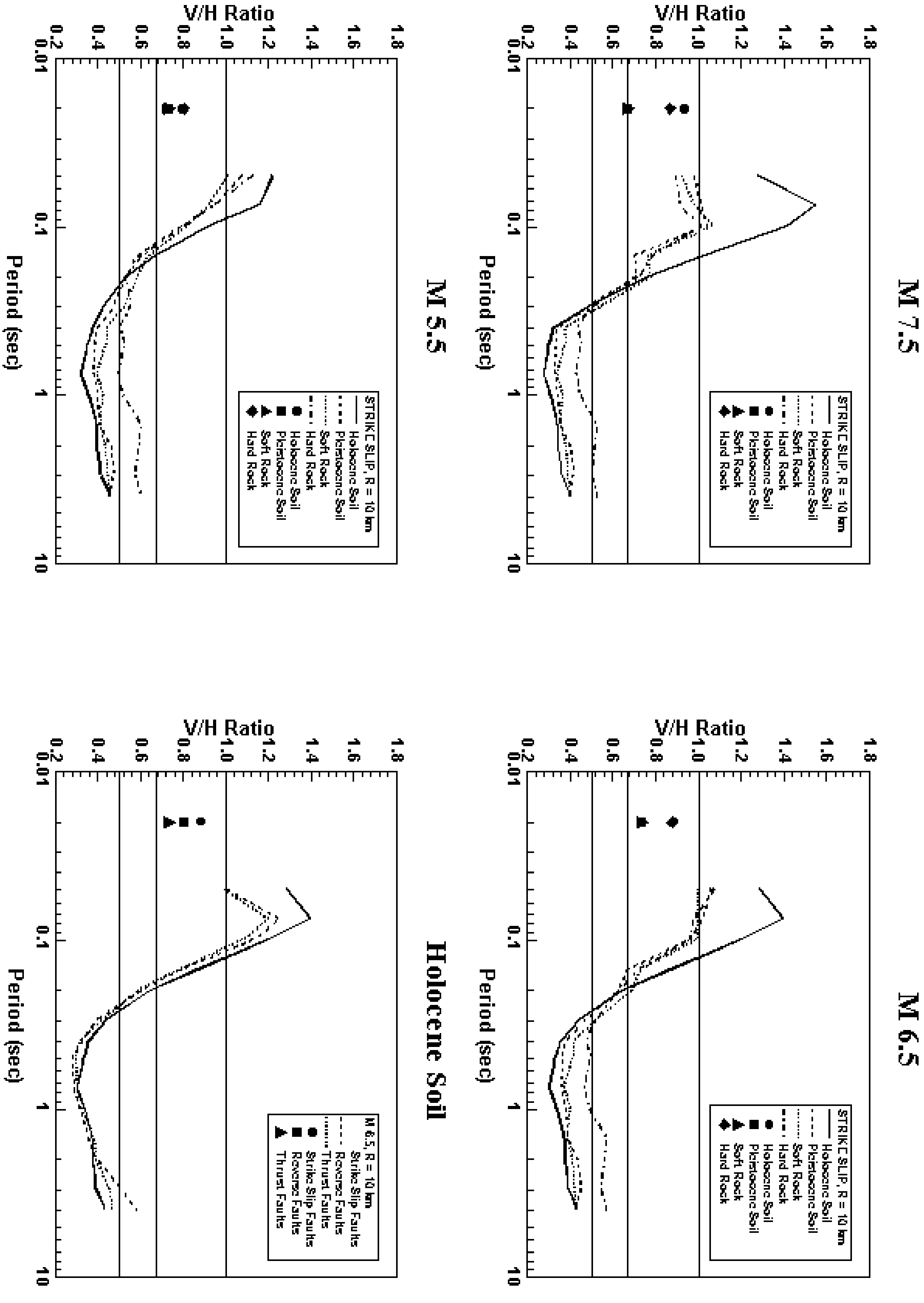

Figure 3—Behavior of V/H spectral ratio with moment magnitude, local soil conditions, and type of faulting.

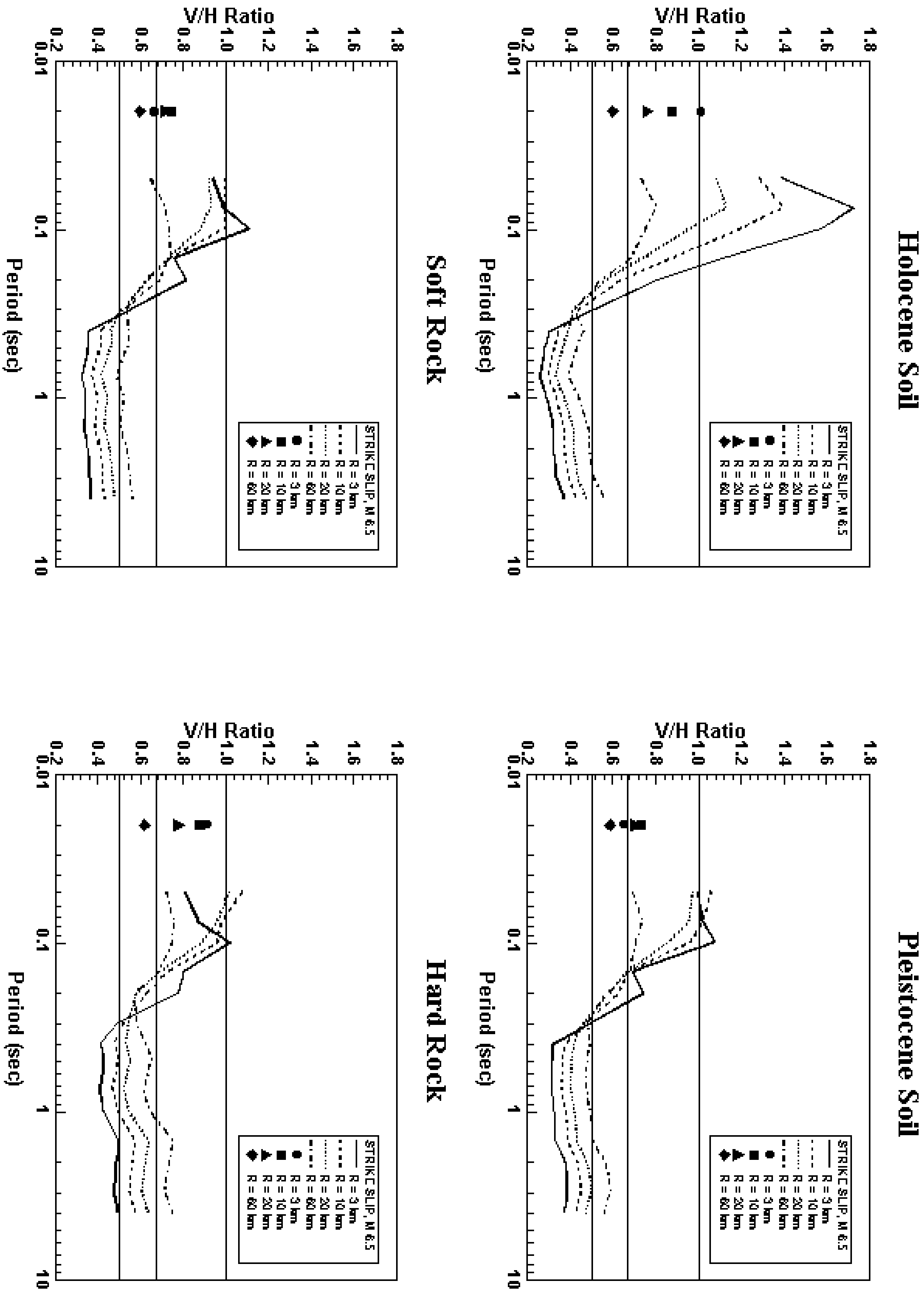

Figure 4—Behavior of V/H spectral ratio with local soil conditions and source-to-site distance