Empirical Model of Vertical Ground Motions for Engineering Design

U. S. Geological Survey Grant N. 01HQGR0027

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Program Elements: I, II

Keywords: Strong ground motion, amplification, site effects, engineering seismology

Investigations Undertaken

The goal of this investigation is to study the nature of vertical ground motions, i.e., whether they are primarily composed of longitudinal (*P*) or shear (*S*) waves, as a function of frequency, and investigate the possible nonlinear response of soil to longitudinal deformation. These questions are addressed empirically by considering large amounts of borehole and surface strong-motion records from California and Japan. The vertical motions are typically simulated, for the purposes of engineering design, as vertically propagating *P*-waves, in the assumption that the properties of nonlinear compressional deformation of soil can be obtained though the extrapolation of those known for shear deformation. Strictly speaking, these underlying premises lack empirical validation. First, the dominance of *P*-waves in vertical motions has not been strictly substantiated. Second, nonlinearity in compressional deformation may be distinctly different from that in shear deformation and needs to be specifically characterized notwithstanding the assumptions regarding shear-wave nonlinearity. The project aims at clarifying these open questions.

Results

First, we used surface records of the five most significant recorded earthquakes in California to determine the relative contribution of *S*- and *P*-waves to vertical motions, at both rock and soil sites. The total of 279 soil and 109 rock records from the 1983 *M* 6.4 Coalinga, 1987 *M* 6.1 Whittier Narrows, 1989 *M* 7.0 Loma Prieta, 1992 *M* 7.3 Landers, and 1994 *M* 6.7 Northridge earthquakes were utilized. The records were processed, corrected, and compiled in uniform format by W. J. Silva (Pacific Engineering and

Analysis), a consultant to the project. Using vertical-component records, we identified the *SV*- and *P*-wave windows and calculated the ratio of their Fourier spectra in the frequency band from 0.5 to 12.5 Hz. Figure 1 summarizes the results of this study for rock (left) and soil (right) sites. The graphs show the mean ratio of *SV*- to *P*-wave spectra, ± one standard deviation, and the 95 % confidence interval of the mean. Our conclusion is that, contrary to the existing practice, the *SV*-wave dominates the vertical motions by a wide margin at lower frequencies, at both rock and soil. Its contribution is progressively reduced toward higher frequencies, so that around 10 Hz and above the *P*-wave contribution is nearly as strong. Based on the results of these analyses, one can conclude that modeling vertical motions as vertically propagating *P*-waves may be incorrect at low frequencies, and may be justified at frequencies approaching 10 Hz and above.

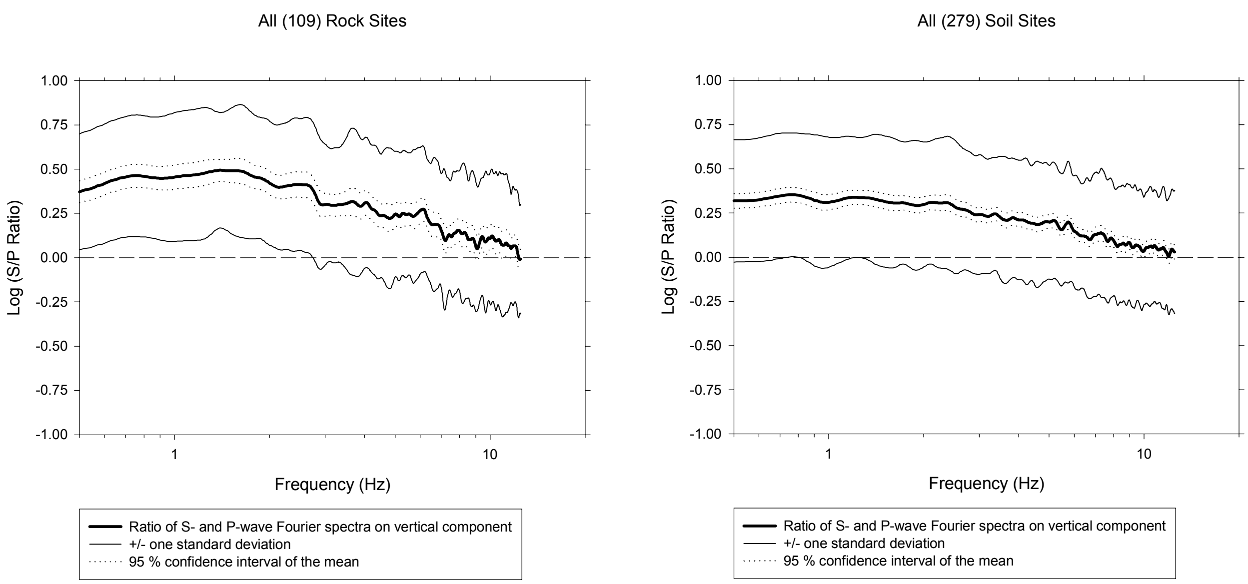


Figure 1. Average ratios of spectra of *SV*- and *P*-wave windows on vertical component of ground motions. Left: rock sites; right: soil sites.

Figure 1 shows that the mean *S*/*P* spectral ratios are very close to each other at rock and soil sites. A statistical *t*-test indicates that they are only significantly different, with 95 % confidence, between ~ 0.7 and 3 Hz, where the rock ratio slightly exceeds the soil ratio.

We also grouped the ratios into the distance (< 15 km and > 15 km) and peak-acceleration (< 0.1 *g* and > 0.4 *g*) bins, separately for rock and soil sites, to try to account for the distance and nonlinearity effects, respectively. We could not find any significant differences between the distance groups or between the acceleration groups, neither for rock nor for soil. The only difference was the difference between rock and soil similar to that mentioned above, regardless of whether the distance or acceleration bins were compared. This showed that the site category (rock vs. soil) is the only significant factor controlling the average ratios. The plausible explanation could be that the effect occurs in soil layers due to a combination of higher attenuation and higher nonlinearity in *S*-

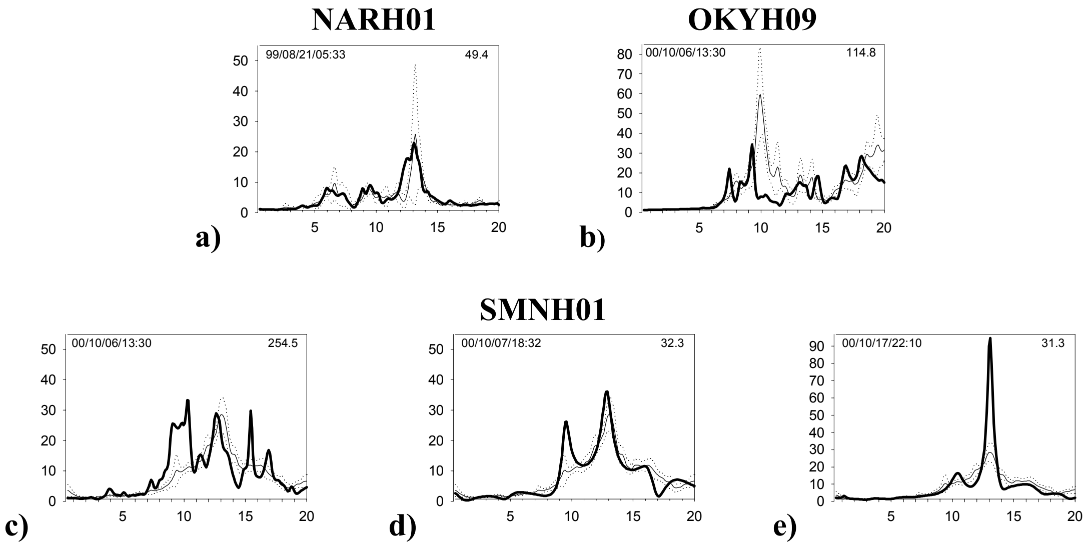
waves, which reduce their contribution relative to *P*-waves. However, we could not discriminate between these two factors.

Darragh *et al*. (1999) studied the variation in vertical-to-horizontal (*V*/*H*) spectral ratios with depth using the data from ten vertical strong-motion arrays in California, Japan, and Taiwan. On average, they found two distinct frequency ranges with the opposite depth dependence of *V*/*H* ratios. Below ~ 10 Hz, the ratios increased with depth, whereas above ~ 10 Hz the ratios decreased with depth. This finding can find explanation in the dominance of different wave types in the respective frequency bands, which we have found. The cross-over of 10 Hz, reported by Darragh *et al*. (1999), coincides with the frequency of transition between the *SV*-dominated vertical motions to the frequencies where *P*-waves are at least equally strong. Below 10 Hz, *SV*-waves dominate, and, because of ray bending, their contribution to vertical component is largest at depth. Above 10 Hz, *P*-waves are stronger but their contribution due to ray bending is just the opposite. The change in *V*/*H* ratios as a function of depth and our data on the dominance of different wave types in vertical motions are thus reconciled.

Second, we used data from the KiK-net network of borehole arrays in Japan to study the elastic nonlinearity effects in longitudinal waves. The KiK-net boreholes typically have instruments installed at the surface and the depth of ~ 100 m and have already recorded a number of seismic events in which acceleration in *P*-waves exceeded 0.1 *g*. Our database was compiled by W. J. Silva. The method of nonlinearity analysis is similar to that used by Beresnev and Wen (1995). The site amplification function is calculated by dividing the Fourier spectra of the surface and downhole vertical accelerograms in the *P*-wave window. The boreholes were selected where the recordings of both "weak" and "strong" events were available. The "weak" events are those whose peak acceleration in the entire trace is below 0.1 *g* on all components; the strong events are those whose peak acceleration in the *P*-wave window is above 0.1 *g* on at least one vertical component. These criteria were used to identify the records where nonlinearity in *P*-waves was most likely to occur.

Four boreholes were found (OKYH09, SMNH01, SMNH02, and TTRH02). Each of them penetrated a soft soil layer, underlain by rock, except SMNH02, which was in entirely in granite. In Figure 2, we plot the average amplification functions for the weak events (thin lines; dashed lines show the 95 % confidence interval of the mean) and the amplification functions for strong events (thick lines). The average weak-motion amplification curves are the same for a given borehole. In all cases, only one strong event was available. For each borehole, the events are arranged in the order of decreasing peak acceleration in the *P*-wave window, measured on the vertical component, shown in the upper right corner of each graph.

The nonlinearity in *S*-waves is well studied. Its common manifestations, as seen in amplification functions, are the shift in site resonance frequencies to lower values and the reduction in amplification, as amplitude of ground motion increases. These effects are caused by the reduction in shear-wave velocity and the increase in damping as strain increases. Similar patterns can be seen at boreholes OKYH09 (Fig. 2b), SMNH01 (Fig. 2c), and TTRH02 (Fig. 2h), i.e., for the strong events recorded by the boreholes penetrating the soft soil material. Considerable frequency shift of the main weak-motion amplification peak is seen on all of these graphs; the reduction in amplification is also seen in Figures 2b and 2h. The only strong event that does not show this pattern is that in



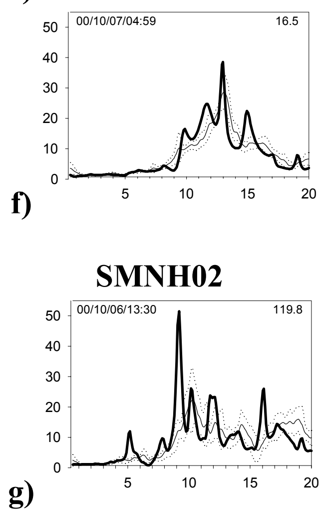


Figure 2. Site amplification functions at KiK-net boreholes. The boreholes are arranged in alphabetical order. The thin line shows the average weak-motion amplification function for a given borehole; dotted lines show the 95 % confidence interval of the mean. The thick line is the amplification function in a strong event. The origin time of the strong event and its peak acceleration in *P*-wave window on the vertical component (cm/sec^2) are provided in the upper left and right corners, respectively. For each borehole, the strong events are arranged in the order of decreasing acceleration.

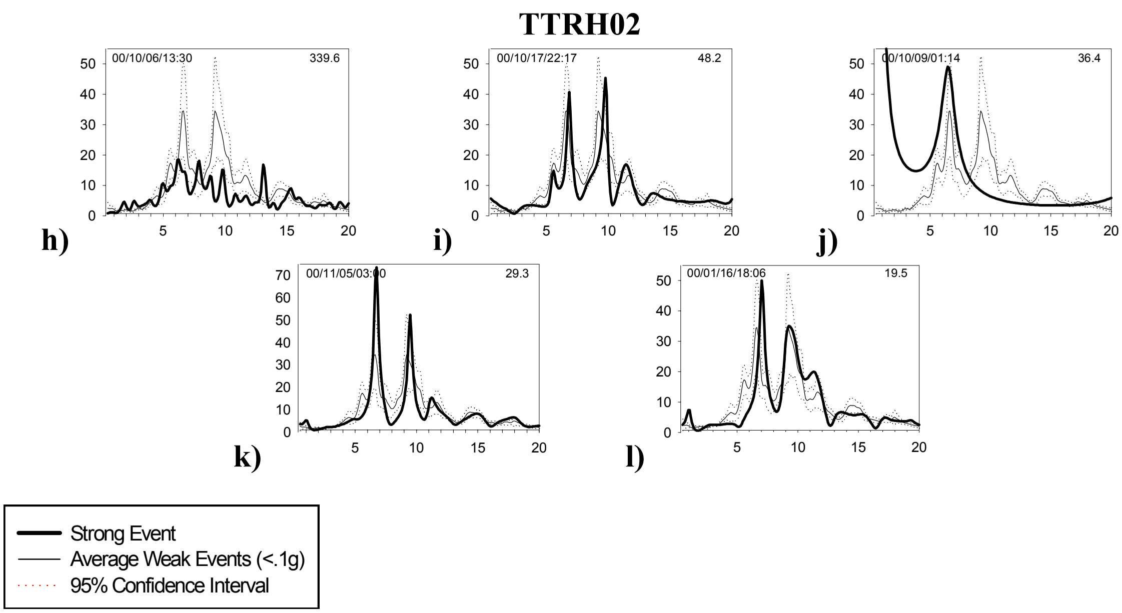


Figure 2g (borehole SMNH02); however, this is the only borehole that was drilled entirely in rock material.

For control purposes, we also plotted the amplifications for the boreholes SMNH01 and TTRH02 for the events that were neither “weak” nor “strong” (overall peak acceleration exceeding 0.1 *g* but *P*-wave peak acceleration still below 0.1 *g*) (Fig. 2, d-g and i-l). The downward shift in the resonance frequency disappears for all these events, supporting the conclusion that the shift observed in strong events is caused by *P*-wave nonlinearity.

Finally, Figure 2a provides another control example. The thick line corresponds to another “intermediate” event (neither “weak” nor “strong”) in a borehole NARH01, which is entirely in slate material. The amplification function for this event virtually coincides with the average weak-motion amplification. Overall, we conclude from the analyses in Figure 2 that nonlinear behavior of soil in compressional deformation is observable and can be manifested at *P*-wave accelerations exceeding 0.1 *g*. The nature of the effect is similar to that observed in *S*-waves.

Non-Technical Summary

This study addresses two outstanding issues in engineering simulation of vertical motions: which type of waves, shear or longitudinal, primarily forms the motions and what is the extent of nonlinear soil behavior in longitudinal waves. We found that vertical motions are dominated by shear waves at frequencies below 10 Hz; above this frequency, the contribution of longitudinal waves is equally strong. Second, by studying borehole data, we found observable nonlinear behavior in longitudinal waves in soil. The effects consist in the reduction in wave velocity and in wave amplification, similar to the nonlinearity known for shear waves.

Availability of Data

Database of surface and borehole accelerograms as text files in uniform format, used in this study, is available upon request. FORTRAN processing software used is also available. Contact: Igor Beresnev, 515-294-7529, beresnev@iastate.edu.

References

Beresnev, I. A. and K.-L Wen (1995). *P*-wave amplification by near-surface deposits at different excitation levels, *Bull. Seism. Soc. Am.* **85**, 1490-1494.

Darragh, B., W. Silva, and N. Gregor (1999). Bay Bridge downhole array analyses, Rept. submitted to Earth Mechanics, Inc., Fountain Valley, California.