DISTRIBUTION OF PEAK HORIZONTAL ACCELERATION AND PEAK HORIZONTAL PARTICLE VELOCITY WITH DEPTH MEASURED DURING EARTHQUAKES

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Abstract

Peak horizontal acceleration (PHA) and peak horizontal particle velocity (PHPV) have been obtained from acceleration time histories measured in several downhole strong motion arrays during earthquakes to evaluate the influence of soil stiffness on their distribution with depth at soil sites. The magnitudes of PHA and PHPV are integral to the seismic design of engineered underground systems such as pipelines, tunnels, and buried structures. Estimates of shaking at the ground surface, such as those derived from attenuation relationships, without including the effect of embedment, may be overly conservative for seismic design of buried structures. The degree of conservatism would tend to increase as the depth of embedment increases.

Strong motion data from numerous vertical arrays throughout the world are available for an empirical analysis approach. Three criteria were established to select data from sites considered to be the most useful for this study: 1) the downhole array must be in the free-field; 2) the shear wave velocity profile must be known over the range of sensor depths; and 3) the ground surface acceleration for one of the recorded earthquakes must be at least 100 cm/s/s. Using these criteria, data from four regions in Japan and one site in Taiwan, which include 21 downhole arrays in the free field, were evaluated. Most notable are data from sites at Lotung, Taiwan, and the Chiba Experiment Station, Japan, because several moderate to strong earthquakes have been recorded at both sites. Furthermore, the difference in relative stiffness between these two sites is significant, providing an important basis for comparison.

The results of this analysis show that the distribution of PHA and PHPV with depth is strongly dependent on the soil stiffness and the predominant wavelength as estimated from site period. The distribution of peak horizontal acceleration generally tends to decrease by about one-half within the upper 0.2 wavelengths of the ground surface. The PHPV tends to reduce more gradually with increasing depth and to be nearly independent of soil stiffness.

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Introduction

Peak horizontal acceleration (PHA) and peak horizontal particle velocity (PHPV) are key parameters used in the seismic design and analysis of buried pipes, lined tunnels, and other buried engineered structures (e.g., American Society of Civil Engineers, 1983). Estimates of PHA and PHPV should correspond to the depths at which the pipe, lined tunnel, or other buried structure exists. For soil profiles in which the stiffness (shear wave velocity, V_s) tends to increase with depth and excessive pore pressures are not generated during earthquake ground shaking, values of PHA and PHPV will generally decrease with increasing depth.

Numerical methods used to compute ground motions at specific depths (e.g., Toki and Cherry, 1973; and Schnabel et al., 1972), require that a design acceleration time history, or suite of time histories, must be selected and used in the analysis. A more practical means of evaluating depth-dependent ground motion parameters is to use empirical attenuation relationships (Abrahamson and Shedlock, 1997) to estimate peak horizontal acceleration and peak horizontal particle velocity at the ground surface, PHGA and PHGPV, respectively. Then, empirical reduction factors can be applied based on the depth of interest and the relative soil stiffness.

Using analog earthquake recordings from downhole arrays, Sykora et al. (1996) showed that the distribution of PHA tends to significantly decrease with increasing depth in the upper 10 meters. The gradient of reduction in PHA was found to be strongly dependent on the average shear velocity; the reduction in PHA was found to occur more rapidly with depth as the stiffness of the soil profile increased. The reduction of PHPV with depth is much less abrupt in the upper 10 meters and nearly independent of soil stiffness. Sykora et al. (1996) also showed that reductions of PHA can be much greater than 50 percent, a theoretical value corresponding to a relatively high frequency pulse traveling down an elastic beam. The pulse analogy does not include amplification effects that would tend to occur for greater wavelengths of motion.

The purpose of this paper is to further evaluate the influence of soil stiffness based upon additional strong motion data and to consider the effect of predominant wavelength in distributions of PHA and PHPV with depth. The empirical approach, as reported by Sykora et al. (1996), is summarized along with compilations of key information from each of the sites.

Empirical Approach

Downhole strong motion arrays have been installed at numerous sites throughout the world, including the U.S. Consequently, downhole recordings are becoming more readily available for analysis. Pitilakis et al. (1996) recently compiled descriptions of some of the more prominent arrays and the data collected to date at each. At the present time, however, most of the downhole arrays have yet to record large seismic events.

Two empirical approaches have been used to evaluate the distribution of ground motion with depth. The first approach, reported by Fukushima et al. (1995), involves deriving attenuation relationships that include earthquake magnitude and epicentral distance as primary independent variables. Depth is included as an independent variable, allowing for the estimation of the distribution of PHA and PHPV given an earthquake magnitude, epicentral distance, and

depth of interest. The data base used by Fukushima et al. (1995) includes 500 accelerometer records from three downhole arrays in Japan. Another method, reported by Sykora et al. (1996), involves a more direct evaluation of the influence of soil stiffness that considers predominant site response from a number of events of varying magnitude and distance. The method by Sykora et al. (1996) was continued for the present study.

Description of Data Used in Analysis

Three criteria were established to select data to be used in this study:

1) the downhole array must be in a free-field setting, generally away from the influence of structural response;
2) the profile of measured shear wave velocity over the range of instrument depths must be reported; and
3) the PHGA for one earthquake must be at least 100 cm/s/s (~0.1g).

These criteria were selected in order to establish an initial set of data that could serve as the basis for current and future evaluations.

Using these criteria, data were selected from 21 downhole arrays positioned in four regional areas of Japan (Kobe/Osaka, Chiba, Sendai, and Narimasu) and the Lotung area of Taiwan. Data from numerous earthquakes have been retrieved from arrays at Chiba, Lotung, and Sendai. Data from single earthquake events were available from the three downhole arrays in Kobe/Osaka and one downhole array at Narimasu.

Brief descriptions of site conditions and array configurations for these sites are described below. The V_s profiles reported for each site are shown on Figure 1 and a summary of average V_s and site period, if V_s is known throughout the entire soil profile, is listed in Table 1. A depth of 40 m was selected as a baseline for comparison of average V_s because data are available to a maximum depth of 42 m at the Chiba array, the shallowest V_s profile reported of the selected sites. The magnitudes and epicentral distances of earthquakes that generated the recorded motions used in this study are compared on Figure 2. Magnitudes reported for Japanese earthquakes, unless otherwise noted, were assumed to be reported in accordance with the Japanese JMA scale and were converted to moment magnitudes for purposes of comparisons made on Figure 2.

Array at LSST Site

The LSST site at Lotung, Taiwan, has several triaxial accelerometers placed at various distances from a 1/4-scale model of a nuclear containment structure with a circular footprint. Downhole arrays exist at two locations: adjacent to the model (1.5 m from structure) and in the free field, at a horizontal distance of over 45 m from the structure. Only the data from the free field downhole array were used for this study. The depths of the accelerometers at this location are: 0, 6, 11, and 47 m.

The subsurface profile at the LSST site generally consists of recent alluvial sands overlying older alluvial sands and silts and Pleistocene-age clay deposits (Wen and Yeh, 1984). The total thickness of alluvium is about 48 m and the thickness of the underlying Pleistocene-age deposits is about 140 m. The depth to a significant impedance contrast (e.g., bedrock) is not known. The profile of V_s interpreted from updated measurements by Chang et al. (1996) in the upper 60 m is shown on Figure 1. The average V_s for the upper 40 m, as listed in Table 1, is about 215 m/s. The LSST array recorded 17 earthquakes between 1985 and 1986, of which eleven were considered for this study (as reported in Sykora et al., 1996). As shown on Figure 2, the magnitudes of earthquakes range from 3.7 to 7.8 and the epicentral distances range from 4 to 81 km. The PHGA recorded at the downhole array was 258 cm/s/s and the PHGPV was 31.3 cm/sec.

Nakano Array at Sendai

The Building Research Institute of Japan operates a network of eleven strong motion instrument stations, all including downhole arrays, in Sendai and Shiogama in the Miyagi Prefecture (Kitagwa et al., 1988; Okawa et al., 1992; and Pitilakis et al. 1996). Data from one downhole array, located at the Nakano primary school (NAKA), was included in this study because peak ground accelerations exceeded 100 cm/s/s for one of the earthquakes. The strong motion instruments are located at depths of 1, 30, and 61.1 meters.

As reported by Kitagawa et al. (1988), the site consists of 61.1 m of sand, clay, and gravel overlying tuff bedrock. The V_s profile is shown on Figure 1. A significant impedance contrast exists at the bedrock contact. As listed in Table 1, the average V_s in the upper 40 m is 230 m/s and the site period is estimated to be about 0.81 sec. This array has recorded over 22 earthquakes with magnitudes as large as M=7.1 (Okawa et al., 1992). The distribution of earthquake magnitude and distance for these events is shown on Figure 2 which indicates that nearly all of the earthquakes recorded at NAKA have been located at epicentral distances of 70 km or greater.

Table 1. Soil Stiffness Summary for Array Sites

Array Site	Soil Thickness (m)	Average Shear Wave Velocity, V_s (m/s) Upper 40 m	Over Soil Height	Estimated Site Period* (sec)
Multiple-Event Sites				
LSST	> 60	215	-	-
NAKA	61.1	230	300	0.81
Chiba	> 42	340	-	-
Single-Event Sites				
KPS	83.5	200	290	1.14
TPS	> 100	290	-	-
TRC	> 97	290	-	-
Narimasu	42	345	350	0.48

* Estimated based on the average shear wave velocity over the soil height.
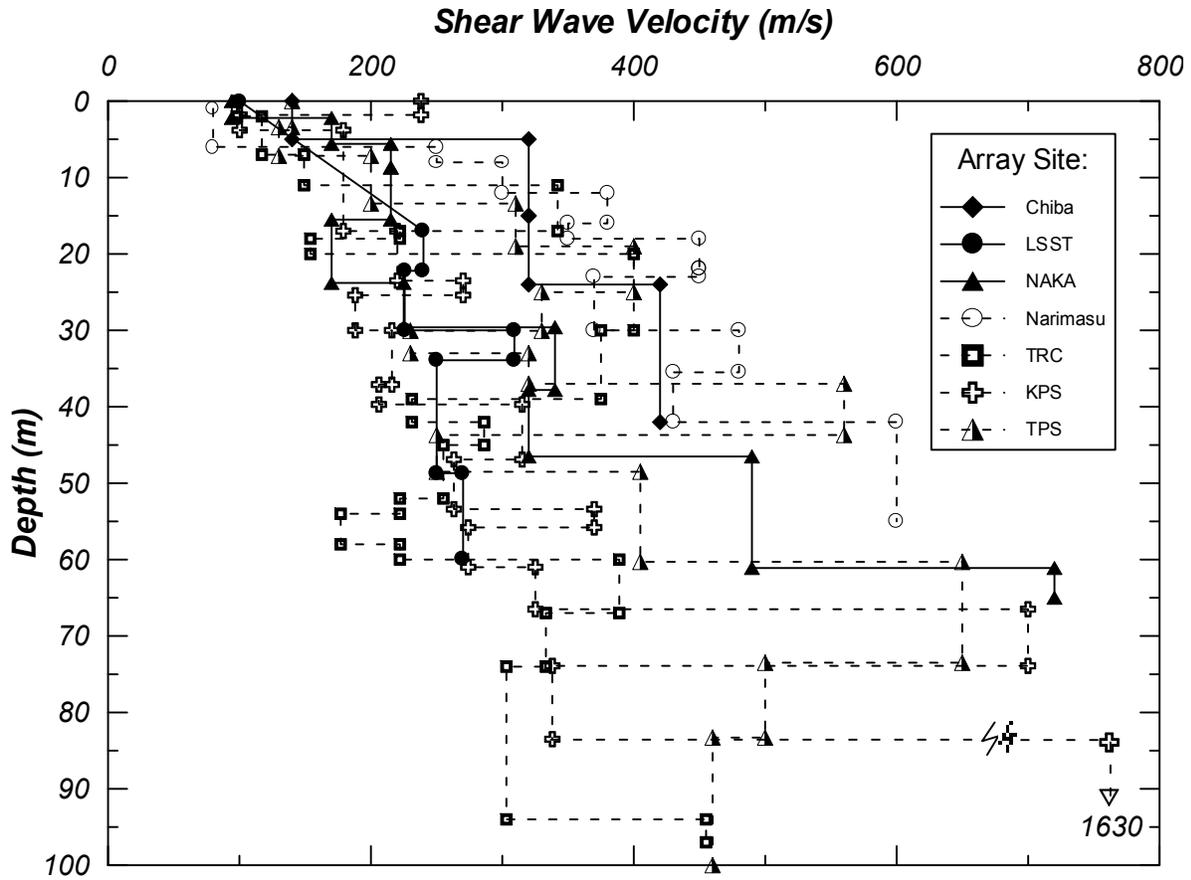
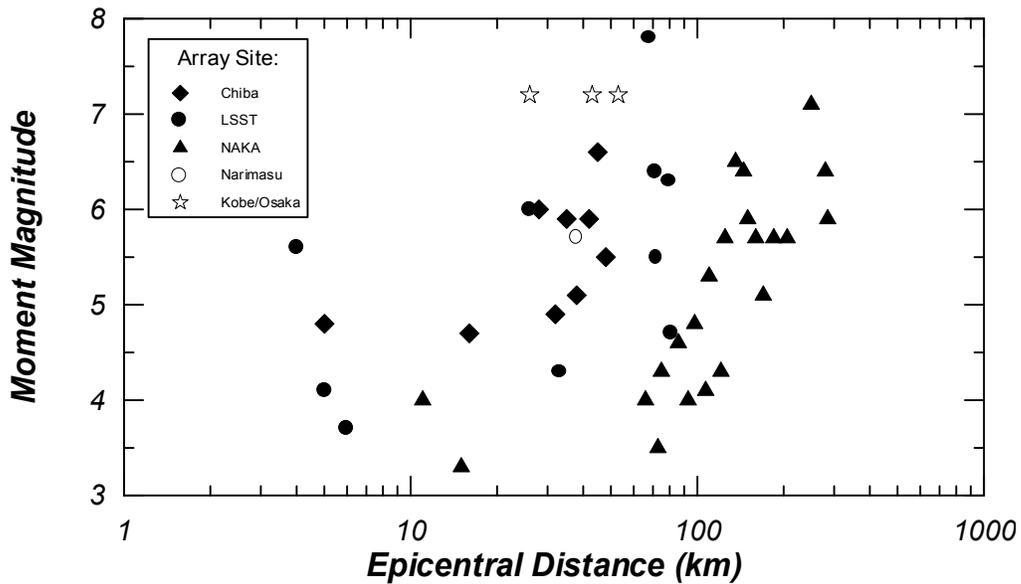Figure 1. Measured distribution of shear wave velocity with depth at downhole arrays

Figure 2. Magnitude and epicentral distances of earthquakes generating ground motions at arrays used for this study

Arrays at Chiba Experiment Station

The Chiba Experiment Station is located about 30 km east of Tokyo, Japan, and consists of strong motion instruments spread over an area of about 85,000 square meters (Nagata et al., 1990; Pitilakis et al., 1996). Downhole arrays were installed at 15 locations. Typically, each downhole array had instruments at one or two depths, generally at 5, 10 20, and/or 40 m, in addition to the "surface" instrument at a depth of 1 m.

The subsurface profile generally consists of about 7 m of loam and sandy clay overlying diluvial sand (Katayama et al. 1990). The depth to bedrock was not reported. The V_s profile is shown on Figure 1. The average V_s to a depth of 42 m, the maximum depth to which measurements were made, is about 340 m/s. The Chiba arrays have recorded 24 earthquakes between 1982 and 1989. A subset of nine events was used in this analysis (as reported by Sykora et al., 1996). As shown on Figure 2, the magnitudes of earthquakes range from 4.8 to 6.7 and the epicentral distances range from 5 to 48 km. The PHGA recorded at the downhole arrays was 400 cm/s/s and the PHGPV was 16.5 cm/sec.

Arrays in Kobe/Osaka Region

The 1995 Hyogo-Ken Nanbu M=7.2 earthquake produced strong ground shaking in the Kobe-Osaka region that was recorded at a few downhole arrays. Data from three of these arrays—Kainan Port Sub-Station (KPS), Takasago Power Station (TPS), and the Technical Research Center (TRC)—were used in this study (Sugito et al., 1996; Sato et al., 1996). Data from downhole arrays at which liquefaction is known or suspected to have occurred, was purposely not used (e.g., Port Island array). Strong motion instruments at these downhole arrays generally exist at depths of 0, 25, and 100 meters, although exceptions exist.

The subsurface conditions for these three sites vary considerably. The profiles of V_s were generally measured to depths of about 100 m as shown on Figure 1. Average shear wave velocities are listed in Table 1. The average V_s in the upper 40 m for the three sites, as listed in Table 1, are: 200 m/s for KPS, 290 m/s for TPS, and 290 m/s for TRC. A large impedance contrast exists at the KPS site at a depth of 83.5 m and the estimated site period is about 1.14 sec. As shown on Figure 2, the epicentral distance for the M=7.2 earthquake ranged from 26 to 53 km. The values of PHGA for the three sites were: 127, 195, and 652 cm/s/s for KPS, TPS, and TRC, respectively. The values of PHGPV for the three sites were: 9.2, 42, and 50 cm/s, respectively.

Array at Narimasu

The Narimasu downhole array has five bi-axial horizontal instruments at depths of 0.8, 5, 8, 22, and 55 m. This site, which was the subject of one of the first studies on the variation of ground motions with depth (Chang et al., 1986), is located on alluvial deposits consisting of interbedded sands, gravelly sands, and silts. The profile of measured V_s is shown on Figure 1. A significant impedance contrast exists at a depth of 42 m. As listed in Table 1, the average V_s in the upper 40 m is 345 m/s; the estimated site period is 0.48 sec. As shown on Figure 2, the

Narimasu array recorded a magnitude M=5.7 event in August 1974 at an epicentral distance of 38 km. The recorded PHGA was 104 cm/s/s. PHGV values were not reported.

Data Analysis

The process of analyzing the distribution of PHA and PHPV at each site involved independently correlating PHA (or PHV) at each instrument depth with PHGA (or PHGPV) from the surface instrument. Consistency of instrument direction (component orientation) was maintained for these comparisons. The number of data, or "instrument pairs," for each correlation generally consisted of two horizontal components of motion for each earthquake recorded. In the case of the Chiba site, where fifteen downhole arrays exist, a number of data were available for each correlation. The collection of instrument pairs for each depth at each site were then evaluated statistically. The slope of the best-fit relationship defines the ratio of PHA to PHGA (or PHV to PHGPV) at that depth.

An example of a correlation and linear curve fitting is shown on Figure 3 for data from the Chiba site. As shown on Figure 3, values of PHA measured in downhole arrays at instrument depths of 10 m are compared with the corresponding PHGA at the same downhole array. At the Chiba site, where data at a depth of 10 m exist in 11 of the 15 downhole arrays, each earthquake would produce as many as 22 instrument pairs (2 components times 11 arrays) if all the instruments were operating properly. The 198 data shown on Figure 3 represent 22 instrument pairs from nine earthquakes. For data from arrays at which only one earthquake has been recorded (i.e., three Kobe-Osaka arrays and the Narimasu array), the ratios of acceleration were averaged between the two horizontal components of motion (i.e., average of two values).
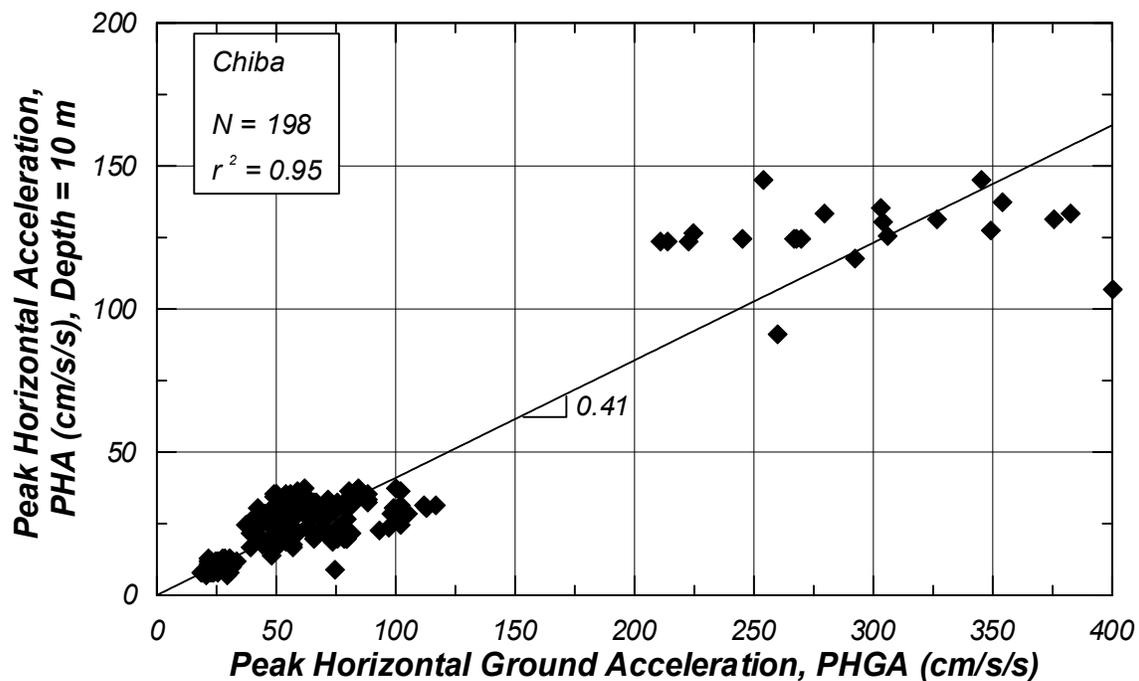

Figure 3. Example of data evaluation for multiple events used for LSST and Chiba arrays

As shown on Figure 3, the slope of the best-fit line through the origin is 0.41 which represents the ratio of PHA to PHGA at a depth of 10 m for the Chiba site. The coefficient of determination (r^2) for this correlation is 0.95 which is typical for the correlations performed on data from Chiba and Lotung. As described by Sykora et al. (1996), the collection of recorded data from LSST and Chiba appear to be independent of the amplitude of ground shaking within the range of recorded motions (PHGA $\leq$ 400 cm/s/s and PHGPV $\leq$ 31.3 cm/s) suggesting that linear curve fitting is appropriate. The data on Figure 3 for PHGA greater than 200 cm/s/s is indicative of variation in ground surface response for one earthquake and not of non-linear response.

The results from correlations on horizontal acceleration are presented versus (instrument) depth in Figure 4. Data from multiple-event sites (LSST, NAKA, and Chiba) are shown on Figure 4 with solid symbols (consistent with symbols used in Figures 1 and 2) and are connected with solid curves. Data from single-event sites (KPS, TPS, TRC, and Narimasu) are generally shown with open symbols (consistent with symbols used in Figures 1 and 2) and a dashed curve. This convention was chosen to represent the opinion that the data from multiple-event sites is considered to be more useful in terms of evaluating the distribution of PHA with depth.
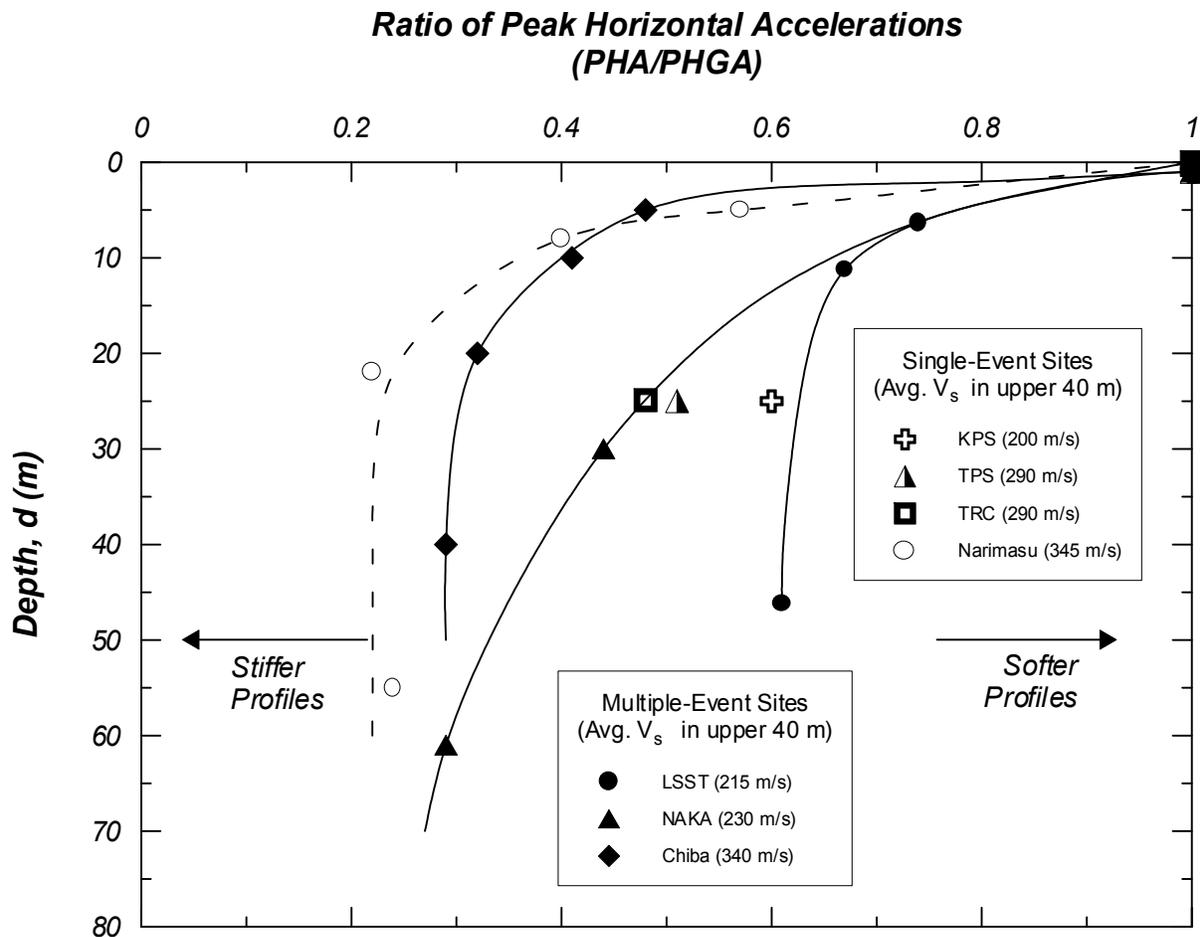

Figure 4. Ratio of peak horizontal ground acceleration versus depth

The data presented in Figure 4 indicate that the PHA is reduced significantly in the upper 5 to 10 m. At three sites, the reduction of PHA appears to be nearly complete within depths of about 30 m. The values of PHA at depths greater than 30 m are in the range of 20 to 60 percent of the PHGA. The large reduction in PHA that tend to occur near the ground surface suggests that some adjustment may be recommended when comparing results from different sites to account for embedment of the surface instrument. The surface instruments at LSST, KPS, TPS, and TRC are on the ground surface whereas the surface instruments at NAKA, Chiba, and Narimasu are at a depth of 0.8 to 1 m. The general effect of accounting for embedment of the surface instruments is to shift the data points and curves shown on Figure 4 to the left.

For purposes of evaluating the effect of soil stiffness, the average V_s in the upper 40 m, as listed in Table 1, is shown in the legend of Figure 4. Based on the data plotted in Figure 4, the distribution of PHA with depth is strongly dependent on the soil stiffness.   This finding is inconsistent with the conclusions of Toki and Cherry (1973). For a given depth, the reduction of PHA increases as the stiffness of the soil profile increases. The reduction in PHA for the sites considered varies by a factor of about 3 corresponding to a range of average V_s of 215 to 345 m/s.

The data shown in Figure 4 suggest that the distribution of PHA with depth may be a function of the predominant wavelength of ground shaking during an earthquake. The site period was estimated for three sites (KPS, NAKA, and Narimasu) where the V_s profile was known over the complete soil thickness (refer to Table 1). For these three sites, the data presented in Figure 4 were replotted with depth normalized to the predominant wavelength (average V_s over the soil thickness times site period) as shown on Figure 5. The data plotted on Figure 5, as compared to data from the same sites plotted on Figure 4, show a narrowing in the range of response. A majority of the reduction in PHA appears to occur within about 0.2 wavelengths. The data shown on Figure 5 still show a dependence on soil stiffness, with the PHA decreasing with increasing average stiffness at a given depth.

The reduction in PHPV with depth is shown on Figure 6. The data shown on Figure 6 were evaluated in a manner similar to that used for PHA. Data were not available from the Narimasu site for this comparison, however. The distribution of PHPV appears to be considerably more narrow for a given depth than the distribution for PHA shown on Figure 4. The reduction in PHPV appears to be less pronounced in the upper 10 to 20 m as compared with the reduction in PHA. Also, the data for PHPV appear to show much less evidence for a dependence on V_s. The range of distribution again narrows when depth is normalized to the predominant wave length although few data are available.

Summary and Conclusions

Data from 21 downhole arrays from four regions of Japan and one site Taiwan at which strong ground shaking has been recorded during earthquakes have been used to empirically evaluate the distribution of PHA and PHGV with depth at soil sites. PHA was found to reduce significantly within the upper 10 m and to be about one-half of the surface value within the upper 20 m. In terms of predominant wavelength, a majority of the reduction in PHA appears to occur within about 0.2 wavelengths of the ground surface. The rate of reduction and magnitude of overall

reduction were found to be strongly dependent on the average V_s. PHPV was also found to decrease significantly with depth, but at a much lower rate than PHA. The distribution of PHPV with depth appears to be much less dependent on the average V_s than PHA. The total reduction in PHPV at greater depths, however, appears to be comparable to the total reduction in PHA.

These findings suggest that the depth of embedment should be considered when selecting ground motion parameters for seismic design of buried pipes, lined tunnels, and other buried engineered structures. Otherwise, depending on the depth of embedment, the PHA and PHPV could each be overestimated by as much as a factor of 5. The results of empirical correlations shown on Figures 4, 5, and 6 provide a basis for estimating PHA and PHPV for seismic design.
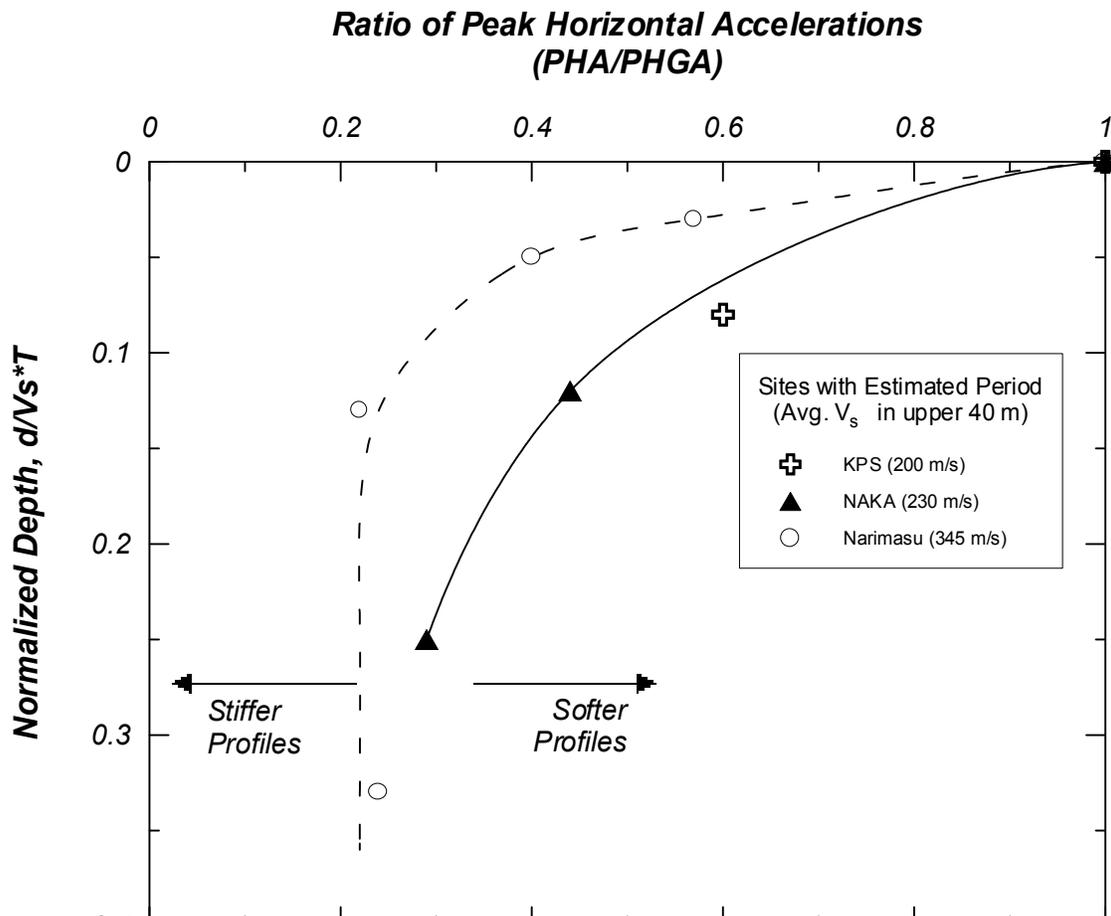
Ratio of Peak Horizontal Accelerations (PHA/PHGA)

Figure 5. Ratio of peak horizontal ground acceleration versus depth normalized to wavelength

Acknowledgments

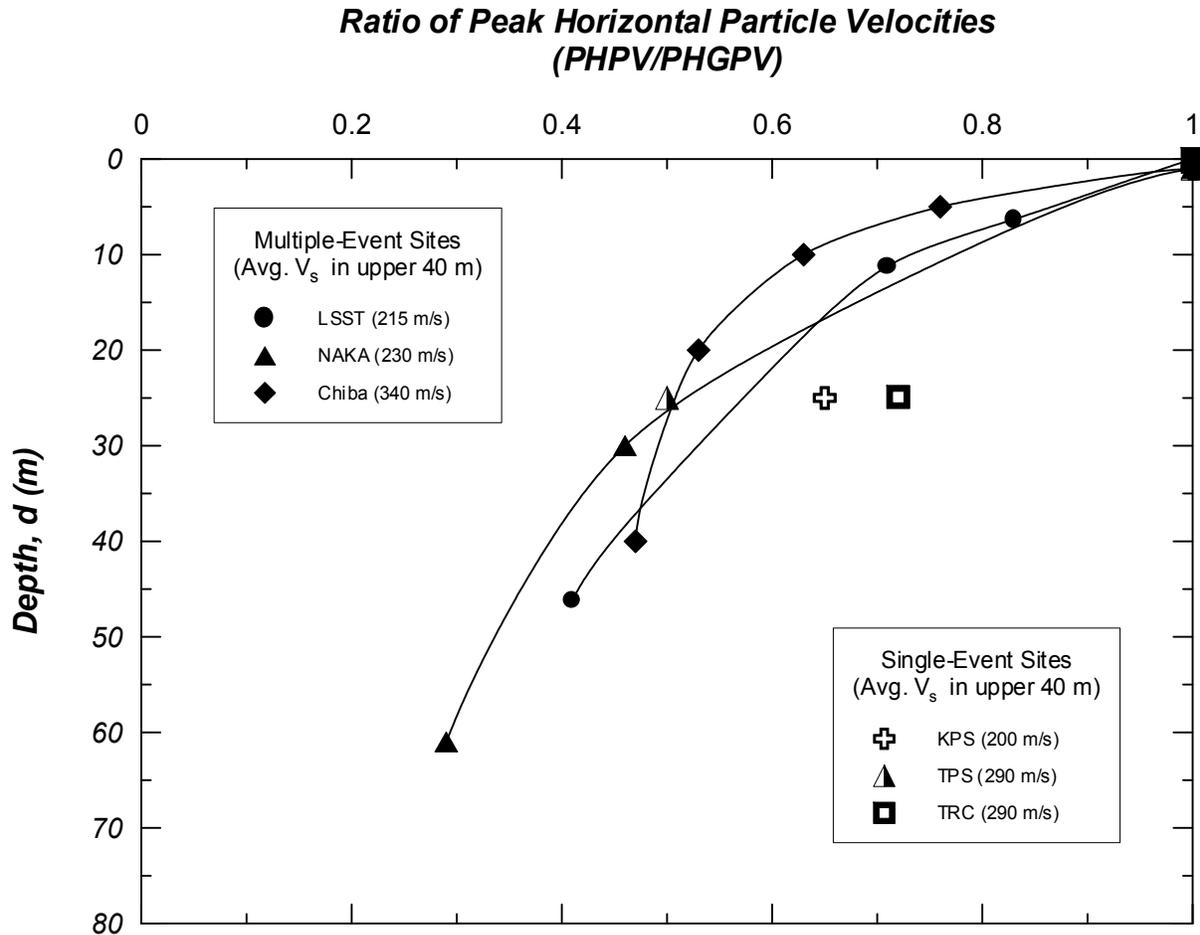## Ratio of Peak Horizontal Particle Velocities (PHPV/PHGPV)

Figure 6. Ratio of peak horizontal particle velocity versus depth

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