



MEASURED VARIATION OF PEAK ACCELERATION AND PEAK PARTICLE VELOCITY WITH DEPTH AT SOIL SITES

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ABSTRACT

Two-component recordings of horizontal acceleration measured in downhole arrays from soil sites during earthquakes have been processed to evaluate the variations of peak acceleration and peak particle velocity with depth. Data from the LSST site at Lotung in Taiwan and the Chiba Experiment Station in Japan were used because several earthquakes, including events producing significant peak ground accelerations have been recorded at each of these sites. The LSST site has recorded 17 earthquakes as large as $M = 7.8$ between 1985 and 1986 at distances as close as 4 km, of which 11 were used for this study. The peak acceleration and peak particle velocity measured at the ground surface were as high as 258 cm/s/s and 31.3 cm/sec, respectively. At the Chiba Experiment Station, which has a stiffer profile, 24 earthquakes as large as $M = 7$ have been recorded between 1982 and 1989 at epicentral distances as close as 5 km, of which nine events were used in this analysis. The peak acceleration and peak particle velocity measured at a depth of 1 m at the Chiba site were as high as 400 cm/s/s and 16.7 cm/sec, respectively. The results indicate that the peak acceleration and peak particle velocity decreases rapidly with depth. The variation of peak acceleration with depth appears to be dependent on soil stiffness (and/or stiffness gradient) but is relatively independent of the amplitude of strong motion within the measured range of data. The variation of peak particle velocity is much less affected by stiffness.

KEYWORDS

Seismic shaking; strong motion recordings; seismic arrays; peak acceleration; peak particle velocity

INTRODUCTION

Peak horizontal acceleration and peak particle velocity are two ground motion parameters often used in the design and analysis of buried pipes, lined tunnels, and other underground structures (e.g., ASCE 1983). The values of these parameters used in such evaluations should correspond to the depth at which the pipe, lined tunnel, or other underground structure exists. Values of these parameters at the ground surface in the free-field can be estimated using, for example, empirical attenuation relationships (e.g., Abrahamson and Silva, 1995). However, such attenuation relationships presently do not allow for the estimation of these parameters at depths below the ground surface.

In general, it is expected that values of these parameters would be lower at depths. However, little specific guidance exists to estimate them, particularly at significant depths. Some preliminary evaluations using recorded data were reported in an NRC report (Chang *et al.* 1986). However, recorded data have not been widely reported in recent years. Elastic theory indicates that the amplitude of a simple waveform at a free end of a homogeneous system should be twice that of the amplitude of the incident motion. The influence of wave type, layering, non-linear soil response, wave dispersion, and non-vertical incident motion suggest, however, that a simple homogeneous and elastic system is not likely to be representative of actual conditions in the field.

The purpose of this paper is to present recorded variations of peak horizontal acceleration, a_{\max} , and peak horizontal particle velocity, V_{\max} , with depth during earthquakes at soil sites. The variations with depth of these parameters are expressed in terms of their values in the upper 1 m of the ground surface (referred to as "surface").

APPROACH

Recorded variations of a_{\max} and V_{\max} with depth from vertical arrays of strong motion instruments were used. A review of strong motion data available from downhole arrays suggested that a significant amount of data with peak ground accelerations greater than 100 cm/s/s exists for two sites: the LSST site at Lotung, Taiwan, and the Chiba Experiment Station in Japan. At the LSST and Chiba sites, one or more downhole arrays exist and several small to large earthquakes have been recorded. Therefore, the approach was to evaluate data from these arrays to establish trends and then use a single event recording from one other downhole array at a soil site where recorded a_{\max} exceeded 100 cm/s/s for comparative purposes.

Because it is desirable to use recorded values of the ground motion parameters that are not contaminated by soil-structure interaction effects, ground motions recorded in arrays that could likely have been influenced by wave scattering or inertial effects from a nearby structure were not included. For example, because the arrays at LSST are associated with a scale model of a nuclear reactor facility, many of the recordings, particularly at locations close to the scale model, are presumed to be influenced by the presence of the structure. Those records were not used in this study. For similar reasons, recorded data at the Waseda array in Japan (Chang *et al.* 1986) were not considered for this study.

Comparisons of ground motion parameters were made by plotting each component of a_{\max} at a particular depth versus the corresponding component of a_{\max} from the instrument at the ground surface in the same borehole. Acceleration time histories were baseline corrected and then integrated to obtain a_{\max} and V_{\max} . A collection of these "instrument pairs" of points were made and plotted by using recordings from a number of earthquakes. Linear regression lines through the origin were used to represent the "first-order" comparison of these data. The data were analyzed separately, by component, and collectively (both components) for each instrument pair.

DESCRIPTION OF ARRAYS AND EVENTS

LSST Site

The LSST site at Lotung, Taiwan, has number of triaxial accelerometers placed at various distances from a 1/4-scale, nuclear containment structure with a circular footprint (Tang 1987). The subsurface profile at the LSST array generally consists of recent alluvial sands overlying older alluvial sands and silts then Pleistocene-age clay deposits (Wen and Yeh, 1984). The total thickness of alluvium is about 48 m and the thickness of the Pleistocene-age deposits is about 140 m. Downhole instruments exist at two locations: adjacent to the scale 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 were: 0, 6, 11, 17, and 47 m. The approximate average profile of measured shear wave velocities to a depth of 60 m (Anderson and Tang 1987) is shown on Figure 1.

The LSST array recorded 17 earthquakes between 1985 and 1986, of which eleven were considered for this study as listed in Table 1. The magnitudes range from 3.7 to 7.8 with the strongest ground shaking producing a_{max} and V_{max} at the ground surface of 258 cm/s/s and 31.3 cm/sec, respectively.

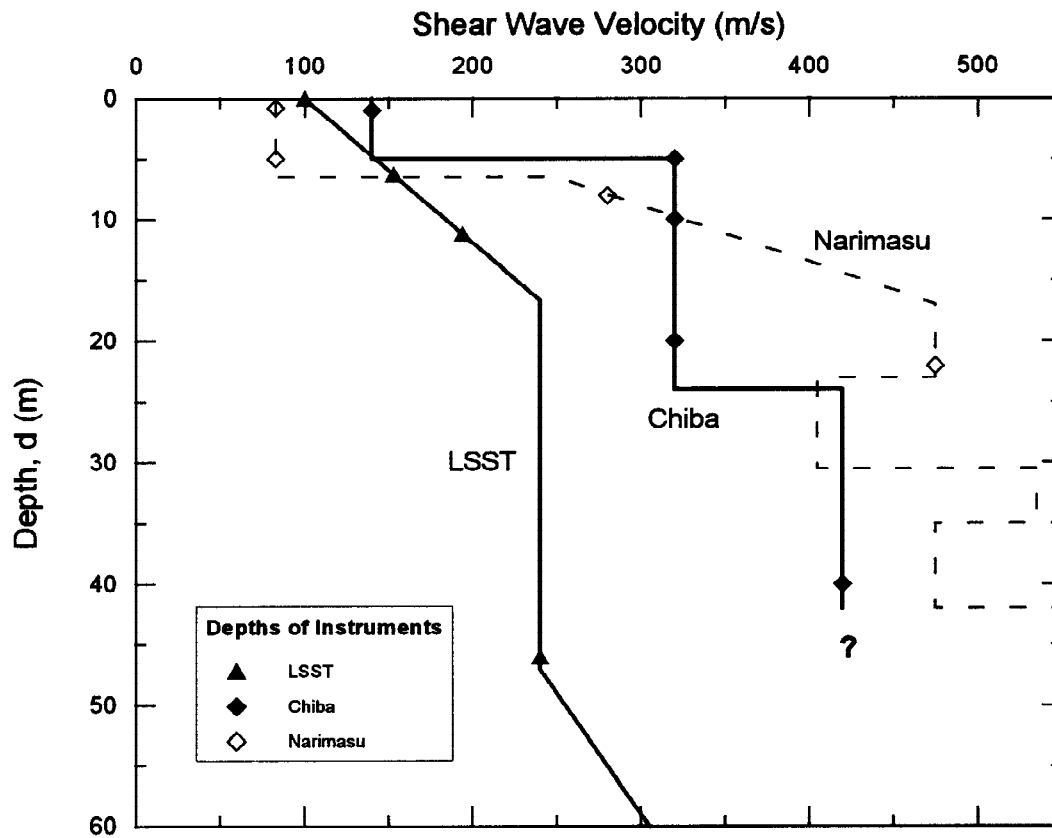


Figure 1. Profiles of shear wave velocities for array sites considered

Chiba Experiment Station

The Chiba Experiment Station is located about 30 km east of Tokyo, Japan, and consists of strong motion instruments at 15 plan locations over about a 85,000-square-meter area. The instruments are scattered at depths of 1, 5, 10, 20, and 40 m. The subsurface profile generally consists of about 7 m of loam and sandy clay overlying diluvium sand (Katayama *et al.* 1990). The depth to bedrock is unknown. The approximate average profile of measured shear wave velocities to a depth of 40 m is shown on Figure 1. Based upon the stratigraphy and profile of measured shear wave velocities, the Chiba site is stiffer than the LSST site.

The Chiba array has recorded 24 earthquakes as large as $M \leq 6.7$ between 1982 and 1989 at epicentral distances as close as 5 km. A subset of nine events was used in this analysis as listed in Table 1. The strongest ground shaking produced a_{max} and V_{max} at a depth of 1 m of 400 cm/s/s and 16.5 cm/sec, respectively.

Narimasu Array

Downhole and companion surface recordings of single earthquake events at the Narimasu site in Japan were also used for comparative purposes. The Narimasu array (as reported by Chang *et al.* 1986) has five bi-axial horizontal instruments at depths of 0.8, 5, 8, 22, and 55 m and is located at a soil site. The

Narimasu array recorded a magnitude $M=5.7$ event on August 4, 1974, at an epicentral distance of 38 km. The recorded peak acceleration in the upper instrument was 104 cm/s/s. Peak particle velocities were not reported. The profiles of shear wave velocity are shown on Figure 1. As shown on Figure 1, the Narimasu array is softer than Chiba at depths less than 10 m but stiffer at greater depths.

Table 1. Earthquake events recorded at LSST and Chiba arrays

| Site | Date | Magnitude | Focal Depth (km) | Epicentral Distance (km) | Peak Horizontal Component at/near Ground Surface* | |
|--------------------|---------------|-----------|------------------|--------------------------|---|-----------------|
| | | | | | Acceleration (cm/s/s) | Velocity (cm/s) |
| <u>LSST Array</u> | | | | | | |
| | Nov. 7, 1985 | 4.7 | 79 | 81 | 26 | 1.3 |
| | Jan. 16, 1986 | 6.0 | 10 | 26 | 258 | 31.3 |
| | Apr. 8, 1986 | 4.3 | 11 | 33 | 35 | 2.1 |
| | May 20, 1986 | 6.4 | 16 | 71 | 204 | 31.3 |
| | May 20, 1986 | 5.5 | 22 | 72 | 34 | 2.5 |
| | Jul. 16, 1986 | 3.7 | 1 | 6 | 39 | 1.0 |
| | Jul. 30, 1986 | 5.6 | 2 | 4 | 187 | 19.3 |
| | Jul. 30, 1986 | NA | NA | 5 | 49 | 1.9 |
| | Jul. 30, 1986 | 4.1 | 2 | 5 | 49 | 1.9 |
| | Nov. 14, 1986 | 7.8 | 7 | 68 | 168 | 24.6 |
| | Nov. 14, 1986 | 6.3 | NA | 80 | 37 | 7.3 |
| <u>Chiba Array</u> | | | | | | |
| | Feb. 27, 1983 | 6.0 | 72 | 35 | 66 | 4.0 |
| | Dec. 17, 1984 | 4.9 | 78 | 5 | 30 | 1.0 |
| | June 8, 1985 | 4.8 | 64 | 16 | 33 | 1.5 |
| | Oct. 4, 1985 | 6.1 | 78 | 28 | 113 | 5.3 |
| | Nov. 6, 1985 | 5.0 | 63 | 32 | 88 | 3.9 |
| | Dec. 17, 1987 | 6.7 | 58 | 45 | 400 | 16.5 |
| | Jan. 16, 1988 | 5.2 | 48 | 38 | 117 | 4.3 |
| | Mar. 18, 1988 | 6.0 | 96 | 42 | 86 | 3.6 |
| | Feb. 19, 1989 | 5.6 | 55 | 48 | 71 | 2.2 |

* Measured at or near ground surface (depth of 0 m for LSST; depth of 1 m for Chiba)

NA = not available

RESULTS

Comparisons between the peak horizontal acceleration at or near the ground surface and the peak horizontal acceleration at some depth are shown on Figures 2 and 3 for recordings from the LSST and Chiba arrays, respectively. Each of the plots on Figures 2 and 3 present a separate comparison corresponding to a particular instrument depth. For example, Figure 2a shows a comparison between a_{\max} at the surface, $(a_{\max})_{\text{surface}}$, versus a_{\max} at a depth of 6 m, $(a_{\max})_{d=6m}$, at the LSST array. In this particular case, 20 data points were used, which represent two components of motion from the one vertical array used during 10 earthquake events (the instrument did not trigger for 1 of the 11 earthquake events listed in Table 2). Significantly more data exists for each plot in Figure 3 for the Chiba arrays because 15 vertical arrays were used whereas only one vertical array was used from the LSST site. Similar comparisons were made for peak particle velocity but are not shown.

As shown on Figures 2 and 3, a majority of the data used for comparisons have a small amplitude ($a_{\max} < 100$ cm/s/s). However, one event recorded by the Chiba array ($M = 6.7$ on December 17, 1987) and four

events recorded by the LSST array ($M = 6.0, 6.4, 5.6,$ and 7.8 on January 16, May 20, July 30, and November 14, 1986, respectively) produced stronger ground shaking ($a_{\max} > 200$ cm/s/s).

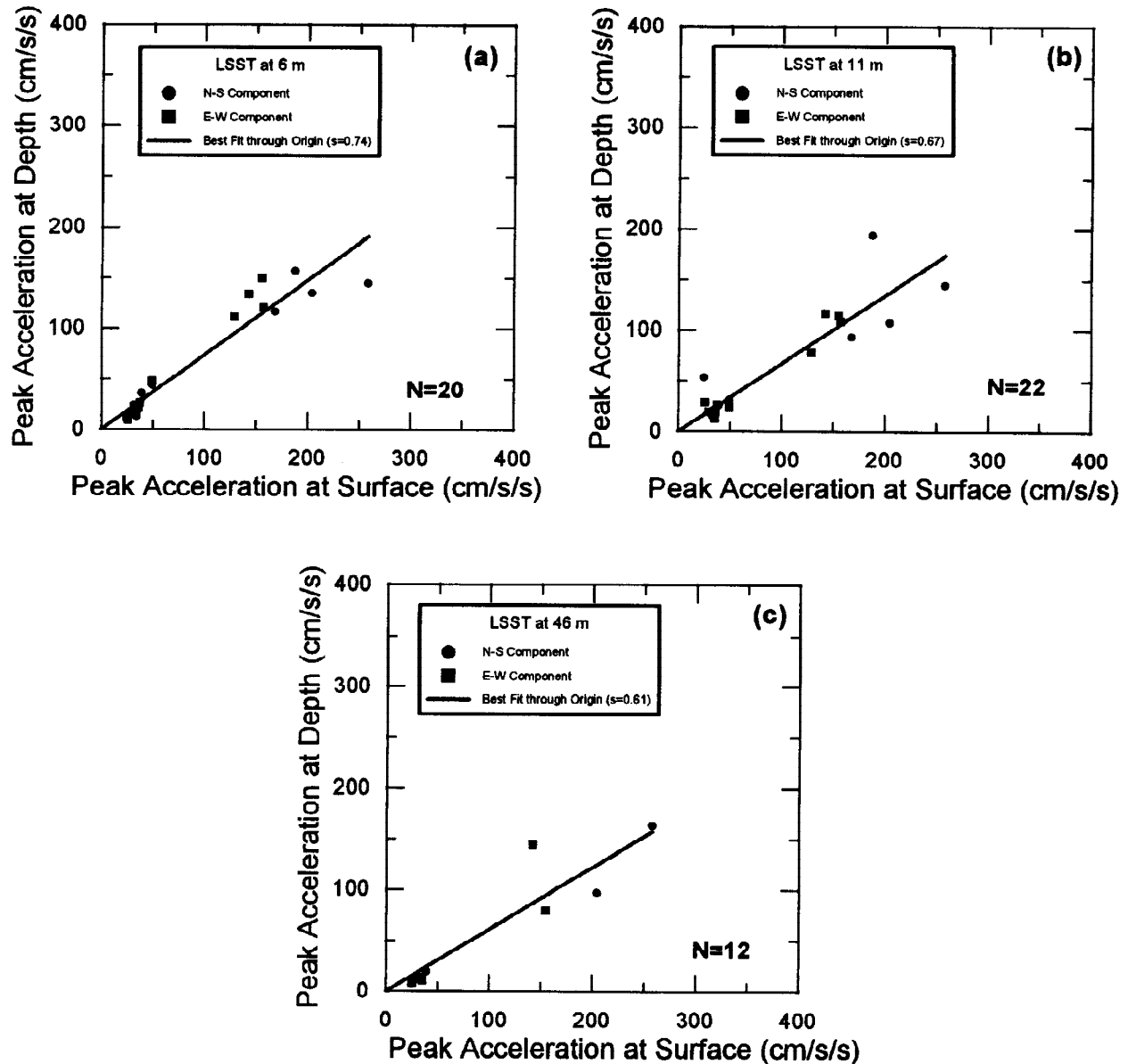


Figure 2. Comparison of peak horizontal accelerations measured at LSST site

The linear regression lines through the origin are shown on Figures 2 and 3 for each combined data set; the corresponding slope of the linear regression line, s , is listed in the legend. The coefficients of determination (r^2) for the a_{\max} and V_{\max} comparisons ranged from 0.92 to 0.98. The distributions of data among the linear regression lines shown on Figures 2 and 3 suggest that the $(a_{\max})_{\text{surface}}$ versus $(a_{\max})_d$ relations appear generally linear and do not appear to depend on values of $(a_{\max})_{\text{surface}}$ for the range of $(a_{\max})_{\text{surface}}$ measured ($26 \leq (a_{\max})_{\text{surface}} \leq 400$).

The data shown on Figures 2 and 3 are identified by horizontal component. The instruments were aligned in the North-South (N-S) and East-West (E-W) directions at both sites. As it turned out, linear regression lines representing each component of a_{\max} and V_{\max} were consistently different for each component at each site, despite a wide variation in direction azimuths from the earthquake events. The reduction in ground motion parameters with depth was greater for the N-S component than the E-W component response. This consistency may reflect three-dimensional stiffness and site response effects.

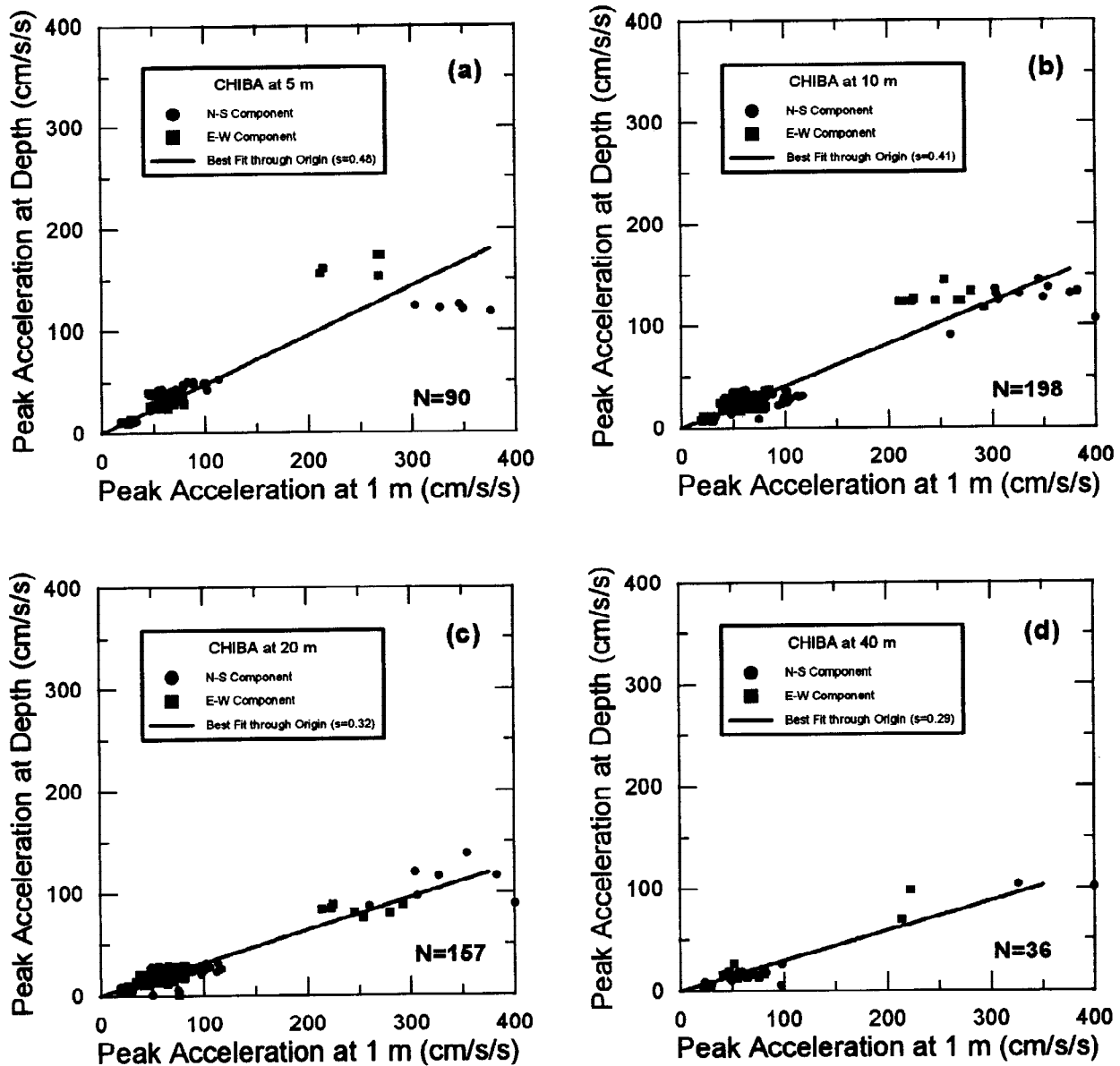


Figure 3. Comparison of peak horizontal accelerations measured at Chiba array

The linear regression lines presented in Figures 2 and 3 are compared in Figure 4 to evaluate the variation of a_{\max} (Figure 4a) and V_{\max} (Figure 4b) with depth. In Figure 4, the slope of linear regression lines (representing both components) are plotted as solid symbols versus the depth of the lower instrument used in the comparison. General trends of the data points from the LSST and Chiba sites are represented with shaded regions as shown on Figure 4. Also shown on Figure 4a are data from a single event recorded at Narimasu as described earlier.

The data shown on Figure 4 indicate that a_{\max} and V_{\max} decrease rapidly with depth, particularly within the upper 10 m. For a_{\max} , the data from the LSST site, which is the softest site of the three considered, show the least amount of reduction with depth. The single-event acceleration data from the Narimasu array, which has the stiffest profile at depth, shows the greatest amount of reduction in a_{\max} . The data from the Chiba site, which is slightly softer than the Narimasu site, shows significant reduction in a_{\max} , but not as much as the data from Narimasu. Because the Narimasu, Chiba, and LSST sites appear, respectively, to have decreasing order of shear wave velocity gradient near the ground surface (see Figure 1), some of the

trends in reduction of a_{\max} may also be related to these differences in gradients. For V_{\max} , the data from Chiba and LSST show a similar trend.

CONCLUSIONS

An empirical analysis of recorded strong motion data from the downhole array at the LSST and Chiba sites suggests that both a_{\max} and V_{\max} decrease rapidly with depth, particularly within the upper 10 m. The variation of peak acceleration with depth appear to be dependent on the stiffness (and/or stiffness gradient) as represented by the shear wave velocity profile with the reduction in a_{\max} with depth being greater for stiffer soil sites than for softer soil sites. The variations in ground motion with depth appear to be, in general, independent of the amplitude of ground shaking within the range of recorded motions ($a_{\max} \leq 400$ cm/s/s and $V_{\max} \leq 31.3$ cm/s). The variation of horizontal peak particle velocity indicates only a slight dependence on the stiffness of the profile.

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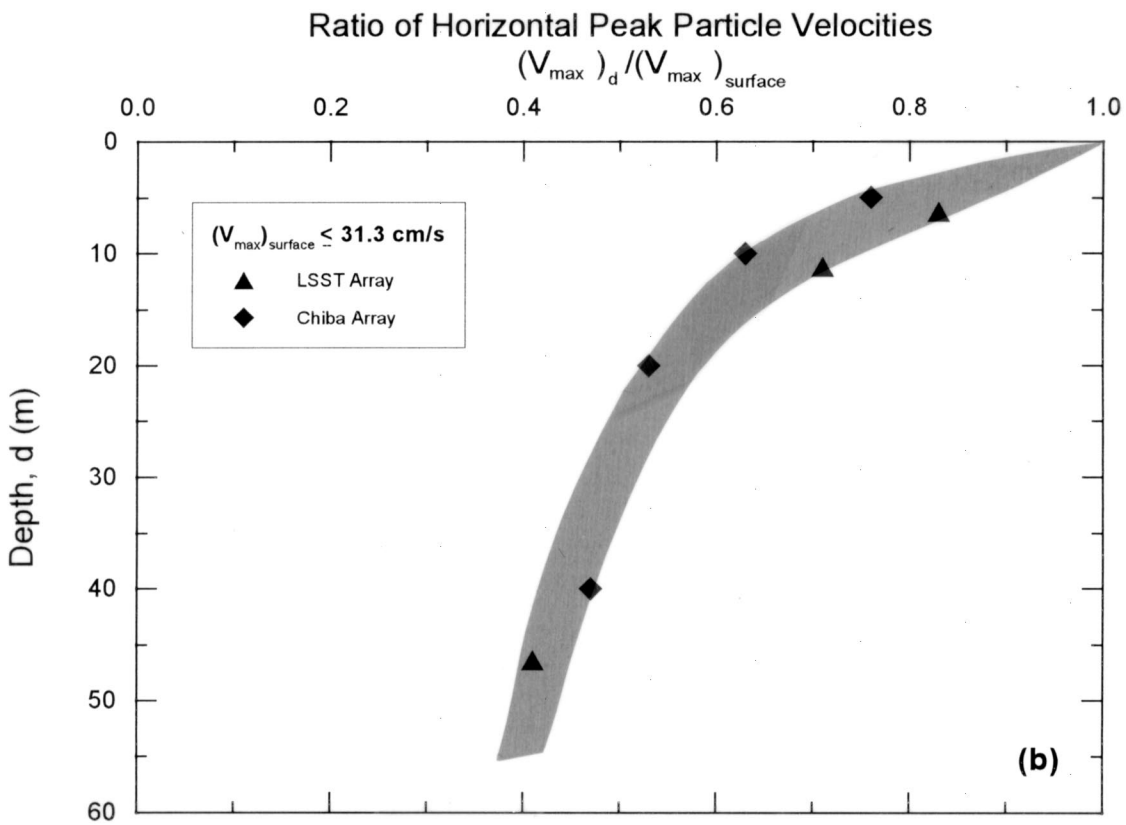
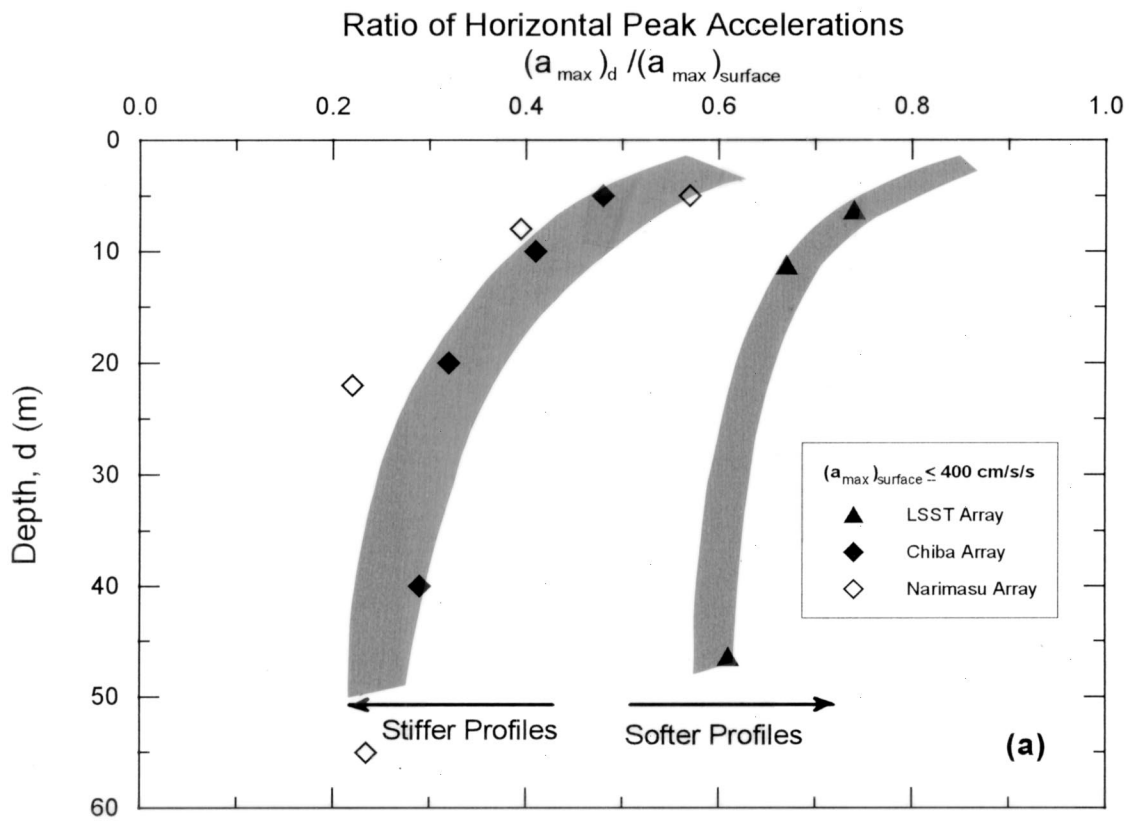


Figure 4. Variation of peak horizontal acceleration and peak particle velocity as measured at three vertical arrays