International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics

1991 - Second International Conference on Recent Advances in Geotechnical Earthquake Engineering & Soil Dynamics

12 Mar 1991, 10:30 am - 12:00 pm

Development of Shear Modulus Reduction Curves Based on Lotung Downhole Ground Motion Data

C.-Y. Chang
Geomatrix Consultants, San Francisco, California

Y. K. Tang
Electric Power Research Institute, Palo Alto, California

C. M. Mok
Geomatrix Consultants, San Francisco, California

H. T. Tang
Electric Power Research Institute, Palo Alto, California

M. S. Power
Geomatrix Consultants, San Francisco, California

See next page for additional authors

Recommended Citation

Chang, C.-Y.; Tang, Y. K.; Mok, C. M.; Tang, H. T.; Power, M. S.; and Stepp, J. C., "Development of Shear Modulus Reduction Curves Based on Lotung Downhole Ground Motion Data" (1991). *International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. 16.
https://scholarsmine.mst.edu/icrageesd/02icrageesd/session01/16

Author

C.-Y. Chang, Y. K. Tang, C. M. Mok, H. T. Tang, M. S. Power, and J. C. Stepp

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 1.44

Development of Shear Modulus Reduction Curves Based on Lotung Downhole Ground Motion Data

C.-Y. Chang, Senior Engineer, Geomatrix Consultants, San Francisco, California

C.M. Mok, Senior Staff Engineer, Geomatrix Consultants, San Francisco, California

M.S. Power, Principal Engineer, Geomatrix Consultants, San Francisco, California

Y.K. Tang, Project Manager, Electric Power Research Institute, Palo Alto, California

H.T. Tang, Program Manager, Electric Power Research Institute, Palo Alto, California

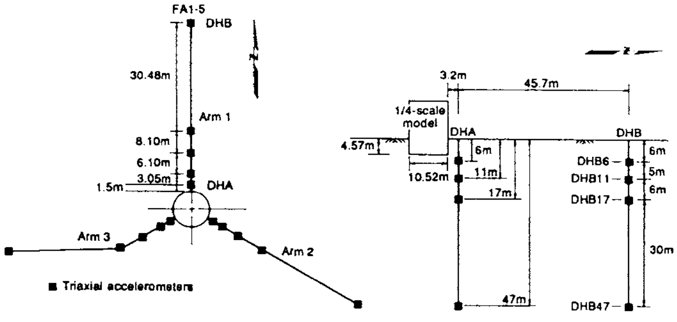
J.C. Stepp, Manager, Electric Power Research Institute, Palo Alto, California

SYNOPSIS: In this study, equivalent shear moduli (or shear-wave velocities) and their variations with shearing strain at the Lotung seismic experiment site were back-calculated from recorded downhole array ground motions. Ground motion data for various levels of shaking (peak ground surface accelerations ranging from 0.03g to 0.21g) recorded during seven earthquakes were used in the analyses. Results show that downhole array ground motion data can be used to infer in-situ dynamic soil properties over a wide strain range.

INTRODUCTION

Shear moduli of soils and their variations with shearing strain are commonly determined through laboratory dynamic tests. Because of effects of sampling disturbance and other factors such as specimen size, equipment compliance, loading conditions, and so on, there are large uncertainties in inferred in-situ dynamic soil properties based on laboratory tests (NSF/EPRI, 1989). Field geophysical data are generally used to define shear moduli at small shearing strains (less than about 10^{-4} percent). Attempts have also been made to determine in-situ dynamic soil properties at higher strains (i.e. shearing strains higher than about 10^{-3} percent) directly in the field (Shannon & Wilson, Inc. and Agbabian Associates, 1975). However, the field testing techniques have not been successful due to difficulties in generating and transmitting large dynamic energy to soil media to induce large uniform strains. Downhole ground motions recorded during strong earthquake shaking compensate for the inadequacies of both the laboratory and the field testing in furnishing experimental data for inferring in-situ dynamic soil properties at higher strains. The purpose of this study is to infer soil properties directly from earthquake response measurements and, by comparing the earthquake- and laboratory-based properties, to arrive at conclusions as to whether shear modulus reduction curves determined using laboratory tests provide a reasonable characterization of soil behavior at the Lotung seismic experiment site in Taiwan.

The Electric Power Research Institute (EPRI), in cooperation with the Taiwan Power Company (TPC), has constructed two model structures (1/4-scale and 1/12-scale models of a nuclear plant containment structure) at a site in Lotung, a seismically active region in northeast Taiwan, for soil-structure interaction (SSI) research (Tang, 1987). As part of an extensive instrumentation program, accelerometers were installed in two downhole arrays at the site to record earthquake ground motions at depth and at the ground surface. Figure 1 shows the locations of surface accelerometers and the two downhole arrays. The two downhole arrays, designated DHA and DHB, are located approximately 3 m and 49 m, respectively, from the edge of the 1/4-scale model. Three-component accelerometers oriented in EW, NS, and vertical directions are installed at depths of 6, 11, 17, and 47 m. Ground motions recorded at the free-field downhole array DHB have previously been analyzed to examine nonlinear soil response and to evaluate analytical techniques for ground response analyses of soil sites undergoing strong nonlinear response (Chang et al., 1989 and 1990). In this study, these data are analyzed to estimate variations of shear modulus with shearing strain of the site soil. The back-calculated shear modulus reduction curves are compared with laboratory test data. The results of this study provide part of the basis for the recommendation made at a recent EPRI/NSF workshop on dynamic soil property and site characterization (1989) to utilize downhole array earthquake ground motion data to infer and verify in-situ dynamic soil properties.



(A) Surface Instrument Arrays

(B) Downhole Instrument Arrays (After Tang, 1987)

Figure 1. Location of Surface and Downhole Instrumentation, Lotung Experiment Site

LOCAL GEOLOGY AND SITE CONDITIONS

Geologic materials at the Lotung site generally consist of recent alluvium and Pleistocene sediments overlying Miocene sedimentary rock. The alluvium is approximately 40 to 50 m thick, and the underlying Pleistocene sediments are approximately 350 m thick. Detailed descriptions of the local geology and seismic velocity profiles are provided in Anderson and Tang (1989).

Soil profiles at the site show an upper layer about 30 to 35 m thick consisting predominantly of silty sand and sandy silt with some gravel. The soil beneath this layer consists predominantly of clayey silt and silty clay to a depth of about 400 m. The water table is within 0.5 m of the ground surface.

Geophysical investigations were conducted to determine the site shear-wave and compressional-wave velocities (Anderson and Tang, 1989). The investigation employed cross-hole and up-hole methods.

The shear wave velocity profile from the cross-hole tests is shown in Figure 2. One observes that the shear-wave velocity increases gradually from approximately 100 m/s at the ground surface to approximately 200 to 220 m/s at a depth of about 18 m. Below this depth, the shear wave velocity increases gradually to approximately 250 m/s to 280 m/s at a depth of 60 m. Between depths of 30 m to 33 m, the shear-wave velocity is higher (300 to 330 m/s). Below the 60 m depth, shear-wave velocities are about 320 m/s at depths of 60 m to 80 m, and 480 m/s at depths of 80 m to 150 m.

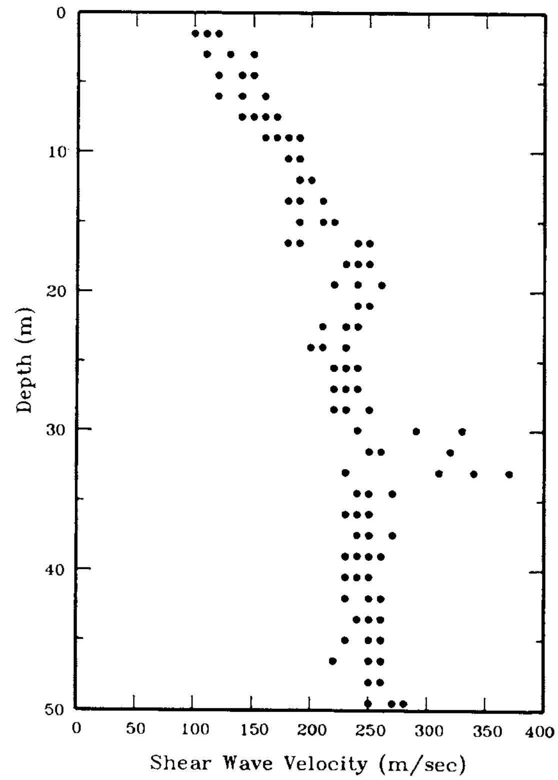


Figure 2. Low-Strain Shear Wave Velocity Profile from Geophysical Measurements

LOTUNG DOWNHOLE ARRAY GROUND MOTIONS

A number of earthquakes have been recorded at the Lotung site since the installation of the downhole instruments in October 1985. Peak accelerations recorded at the ground surface to date range from 0.03g to 0.26g. Table 1 summarizes ground motion data of seven earthquakes analyzed in this study. Downhole accelerograms from two small magnitude earthquakes (M_L 5.4 and 5.0), designated as LSST06 and LSST11, respectively, and a moderate earthquake (M_L 6.5), designated as LSST07, are shown in Figures 3, 4, and 5, respectively. Peak ground surface accelerations are 0.16g and 0.21g for the EW and NS component for event LSST07, 0.07g and 0.10g for event LSST11, and 0.04g and 0.03g for event LSST06.

ANALYSIS PROCEDURE

For vertical propagation of shear waves through a layered soil deposit, the resonant frequency of the transfer function for any depth (i.e. ratios of Fourier spectra of horizontal motion at the ground surface and at depth) is a function of shear modulus or shear-wave velocity of the soil deposit (Thomson,1950; Schnabel et al., 1972). For a fixed depth, changes in resonant frequencies reflect changes in shear modulus of the soil deposit. Based on these considerations, we can back-calculate an equivalent shear modulus or shear-wave velocity of a layer from the resonant frequency of the Fourier spectral ratio computed from the recorded downhole ground motions using equivalent linear approximations of a nonlinear system. Using ground motion data recorded from a number of earthquakes that represent various levels of shaking, the corresponding equivalent shear moduli can then be computed. Shearing strains induced in the soil associated with the estimated shear modulus values can be computed based on wave propagation theory, thus providing a basis for estimating shear modulus reduction curves.

Table 1. Summary of Earthquake Ground Motion Data Analyzed

Earthquake	Date	Magnitude	Epicentral Distance (km)	Focal Depth (km)	AZIM (deg)	Peak Ground Surface Acc*,g EW		
						EW	NS	Vert.
LSST No. 6	4/8/86	5.4	31.4	10.9	174	0.04	0.03	0.01
LSST No. 7	5/20/86	6.5	66.2	15.8	195	0.16	0.21	0.04
LSST No. 9	7/11/86	4.5	5.0	1.1	146	0.07	0.05	0.01
LSST No. 10	7/16/86	4.5	6.1	0.9	162	0.03	0.04	0.02
LSST No. 11	7/17/86	5.0	6.0	2.0	90	0.07	0.10	0.04
LSST No. 12	7/30/86	6.2	5.2	1.6	131	0.16	0.19	0.20
LSST No. 16	11/14/86	7.0	77.9	6.9	174	0.13	0.17	0.10

* Peak ground surface acceleration at Station FA1-5

The analysis procedure used in this study assumes that the strong portion of ground shaking is propagating vertically in the form of shear waves (SH-waves). We believe that this simplification is acceptable based on studies by Wolf and Obernhuber (1982) and Jones and Roesset (1970) which indicate that the resonant frequency of the transfer function is insensitive to the incidence angle of body waves less than 30 degrees from the vertical. Considering the low wave velocity of the near-surface soil deposits at the Lotung site, the assumption of vertically propagating shear waves seems reasonable for the earthquakes analyzed in this study. (Ishii et al.,1989, showed that the incidence angle of S-waves is approximately 6 degrees for event LSST07. The incidence angle of event LSST12, a shallow focus earthquake, was not computed by Ishii et al. However, based on the epicentral distance and the focal depth of the earthquake, the incidence angle is estimated to be about 11 degrees.) We believe that the effect of non-vertical incidence is small. While a portion of the energy in the seismogram propagates as compressional waves (P-waves) and converted phases, the largest amplitudes are in the SH-wave arrivals. We therefore consider the vertically propagating SH-wave model to be acceptable for the purpose of this study.

To develop shear modulus reduction curves for the near-surface soils at the Lotung site, the following procedure was followed:

(1) Fourier spectra of motions recorded at the ground surface and at depths of 6 m, 11 m, and 17 m were computed for each earthquake given in Table 1. Total durations of the accelerograms were used.

(2) Fourier spectra were smoothed using a one Hz moving triangular averaging operator.

(3) Ratios of the smoothed Fourier spectra between the ground surface and depths of 6 m, 11 m, and 17 m, (i.e. surface/6 m, surface/11 m, surface/17 m), were computed. Resonant frequencies of the Fourier spectral ratios were estimated.

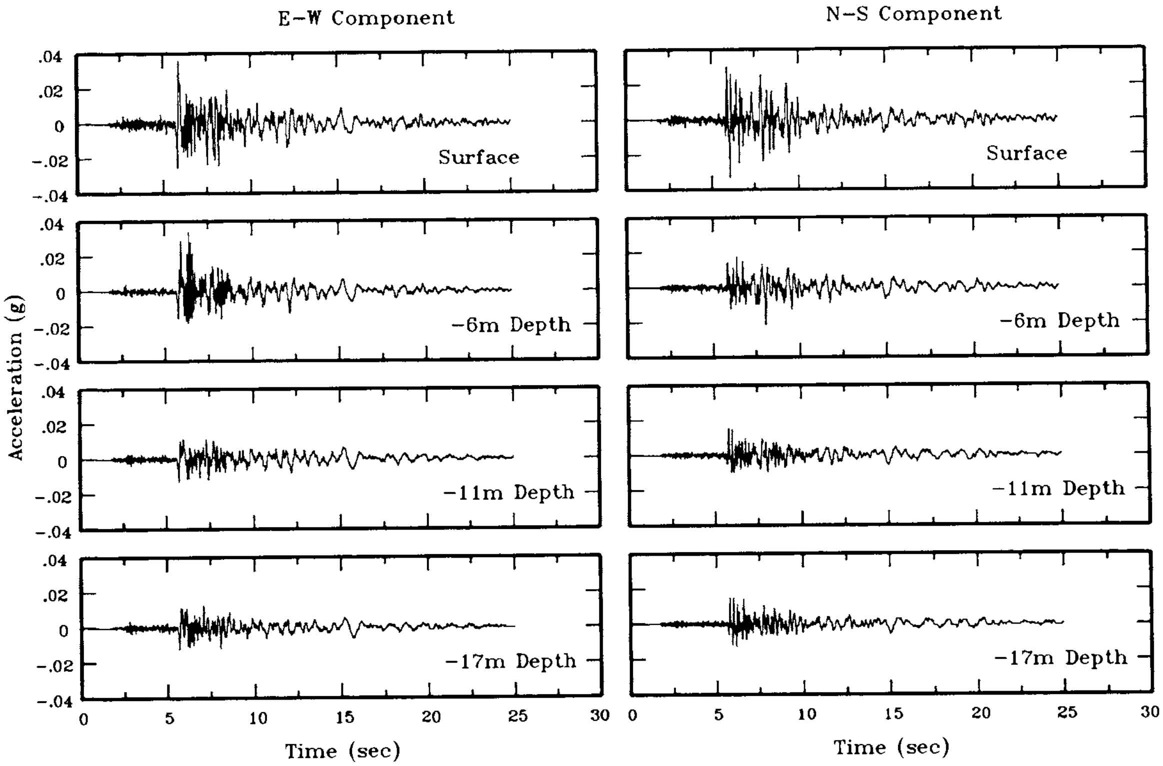


Figure 3. Accelerograms Recorded at Downhole DHB, Event LSST06

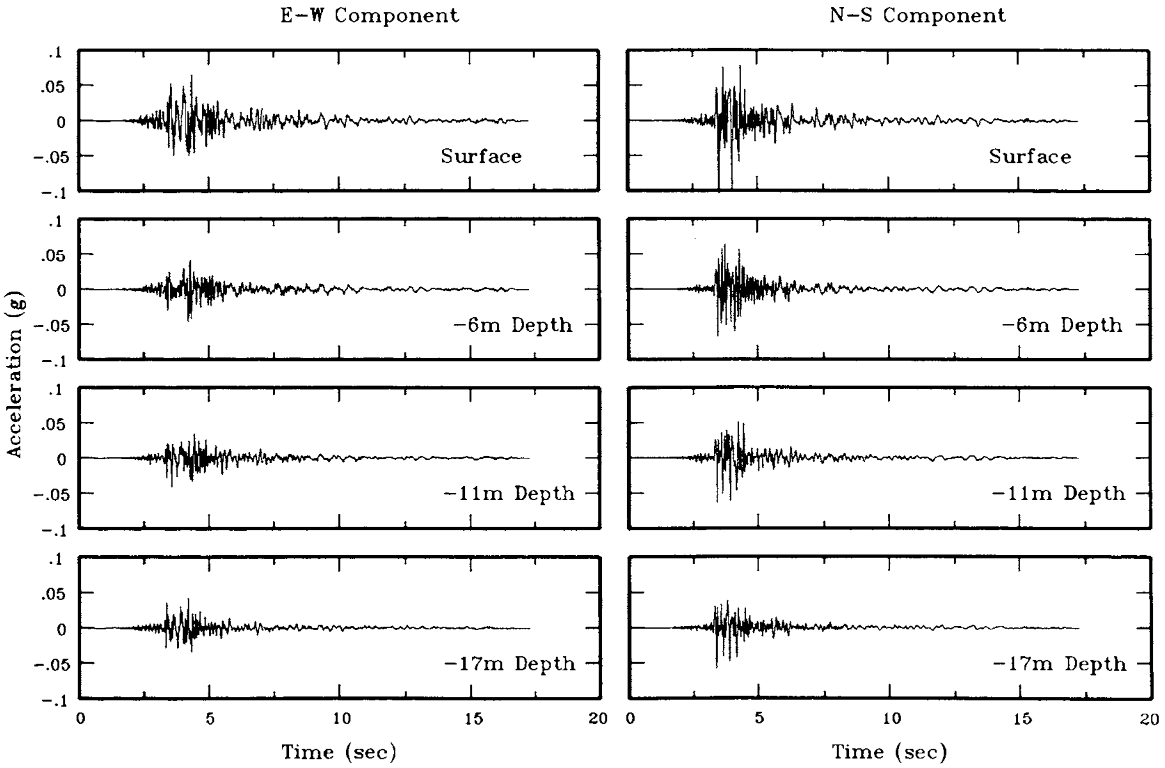


Figure 4. Accelerograms Recorded at Downhole DHB, Event LSST11

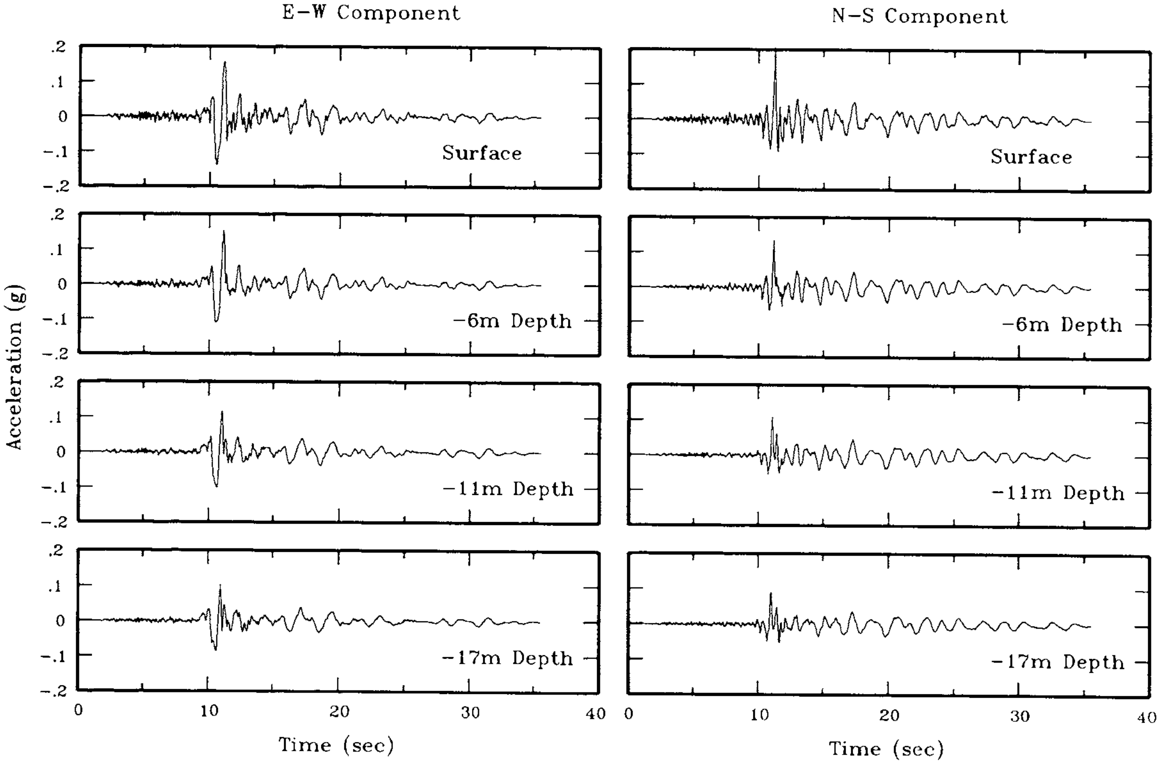


Figure 5 Accelerograms Recorded at Downhole DHB, Event LSST07

(4) Equivalent shear-wave velocities for each depth interval were back-calculated using the resonant frequencies of the Fourier spectral ratios in conjunction with the two-layer solution derived by Madera (Dobry et al., 1976). The top layer was defined between the ground surface and the 6m depth, and the subsequent layers were between the 6m-11m depths, and the 11m-17m depths. The two-layer solution developed by Madera is a closed-form solution to the equation of motion of body waves that travel vertically through a two-layer soil profile (e.g. layer A on top of layer B). The equation of motion of S-waves is

$$\rho \frac{\partial^2 x}{\partial t^2} = \frac{\partial}{\partial z}\left(G \frac{\partial x}{\partial z}\right) \qquad (1)$$

where ρ = mass density of soil
x = $x(z,t)$ = horizontal soil displacement
z = vertical coordinate
t = time
G = ρV_S^2 = shear modulus of soil
V_S = shear-wave velocity

The solution to Eq. (1) with boundary conditions of zero relative displacement at the bottom boundary of the layers A and B, and zero shear stress at the ground surface is

$$\tan\left(\frac{\pi}{2}\frac{f}{f_A}\right)\tan\left(\frac{\pi}{2}\frac{f}{f_B}\right) = \frac{\rho_B}{\rho_A}\frac{H_B}{H_A}\frac{f_B}{f_B} \qquad (2)$$

where f_A, f_B = fundamental frequencies of layers A and B,respectively
f = fundamental frequency of the total soil layer
ρ_A, ρ_B = mass densities of layers A and B, respectively
H_A, H_B = thicknesses of layers A and B, respectively
$H = H_A + H_B$ = total thickness of layers A and B

Knowing the fundamental resonant frequencies of layer A and the two-layer profile (f_A and f, respectively), the fundamental frequency (f_B) of layer B can be computed from Eq.(2). The shear-wave velocities of layers A and B are computed by $V_{SA} = 4H_Af_A$ and $V_{SB} = 4H_Bf_B$.

(5) Shearing strains in each soil layer for each earthquake were computed from ground response analyses using the computer code SHAKE (Schnabel et al., 1972). In these analyses, shear-wave velocities or shear moduli computed in step 4 were assigned to each soil layer. Values of soil damping were selected by iterative procedures using the damping curves (i.e. variations of damping ratio with shearing strain) from the laboratory test data) and effective shearing strains computed in the ground response analyses (i.e. deconvolution analyses). Input motions to the ground response analyses were the recorded ground surface motions.

(6) Using data computed in steps 4 and 5 for each earthquake listed in Table 1, variations of normalized shear modulus (i.e. shear modulus reduction factor) with effective shearing strain were developed for each soil layer. Values of normalized shear moduli were computed by dividing equivalent shear moduli computed in step 4 by low-strain shear moduli obtained from average shear-wave velocities from the cross-hole geophysical measurements shown in Figure 2. Values of effective shearing strain were defined as the peak shearing strains multiplied by 0.65 as commonly used in SHAKE.

ANALYSIS RESULTS

Fourier spectral ratios computed for depth intervals 0m-6m, 0m-11m, and 0m-17m are shown in Figures 6, 7, and 8 for events LSST06, LSST11, and LSST07, respectively. The spectral ratios of 0m-6m for the three events are compared in Figure 9 which shows that the resonant frequencies decrease from about 4.5 - 4.8 Hz to about 3.0 - 3.5 Hz as the peak ground surface acceleration increases from 0.03g and 0.04g of event LSST06 to 0.16g and 0.21g of event LSST07. Equivalent shear-wave velocity profiles computed from the fundamental resonant frequencies are shown in Figures 10, 11, and 12 for events LSST06, LSST11, and LSST07, respectively. Also shown in Figures 10 through 12 are the shear-wave velocities determined from geophysical methods. It can be seen that the shear-wave velocities computed from low levels of shaking during event LSST06 are only slightly lower than the shear-wave velocities from geophysical methods (Figure 10). This confirms the adequacy of the geophysical measurements for low strain conditions. As expected, equivalent shear-wave velocity decreases as levels of shaking increase. Equivalent shear wave velocities computed for event LSST07 are substantially lower than the shear-wave velocities from geophysical methods (Figure 12), indicating considerable shear modulus reduction (i.e. strong soil nolinearity) at this site during moderate earthquake shaking.

Variations of normalized shear modulus with effective shearing strain (both the data and fitted modulus reduction curves) for soil layers 0m-6m, 6m-11m, and 11m-17m are shown in Figure 13. The fitted curves (the curves for layers 0m-6m and 6m-11m are similar and are combined) are compared with data from laboratory cyclic triaxial and resonant column tests (Anderson and Tang, 1989) in Figure 14. It can be seen that the back-calculated shear modulus reduction curves are in good agreement with data from the cyclic triaxial tests for strains in the range of $3x10^{-2}$ percent to $2x10^{-1}$ percent. The curves are in reasonably good agreement with data from the resonant column tests for strains lower than about $2x10^{-3}$ percent, and are approximately 10 to 20 percent lower than the test data for strains in the range of $5x10^{-3}$ to $2x10^{-2}$ percent.

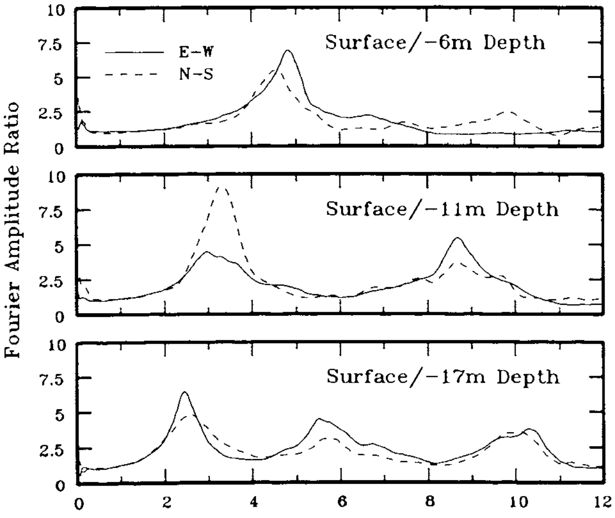


Figure 6. Fourier Amplitude Ratio from Recorded Motions at Downhole DHB, Event LSST06

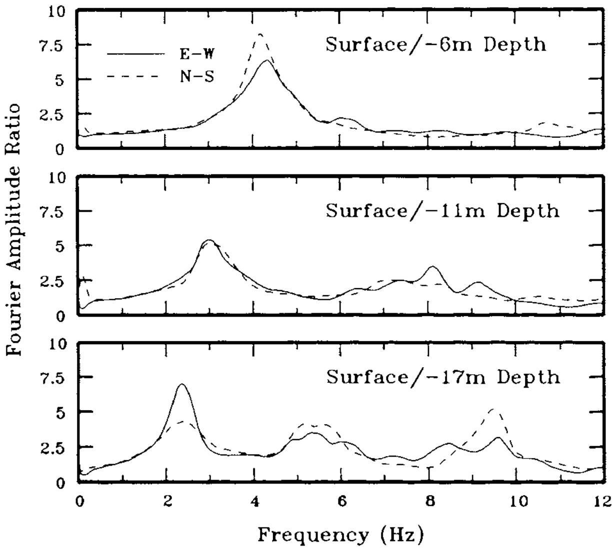


Figure 7. Fourier Amplitude Ratio from Recorded Motions at Downhole DHB, Event LSST11

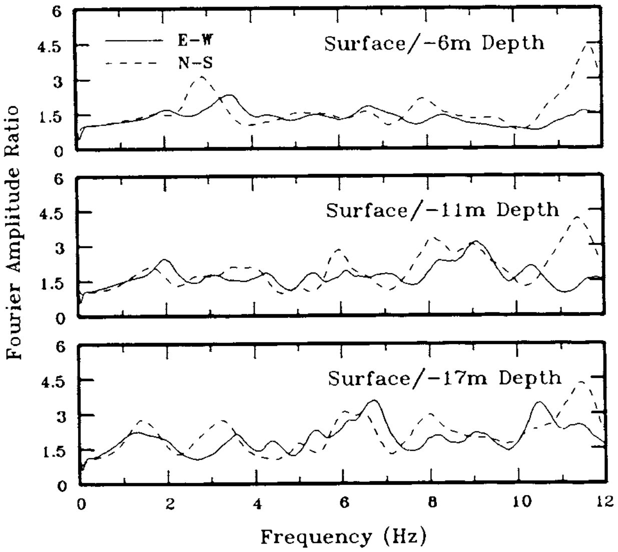


Figure 8. Fourier Amplitude Ratio from Recorded Motions at Downhole DHB, Event LSSt07

SUMMARY AND CONCLUSIONS

The study has demonstarted that downhole ground motion data, if obtained from closely spaced instruments, can be effectively utilized to back-calculate in-situ dynamic soil moduli and their variations with levels of ground shaking. The back-calculated properties can be used to assess the adequacy and uncertainties associated with various testing techniques, both field and laboratory, in characterizing in-situ dynamic soil properties.

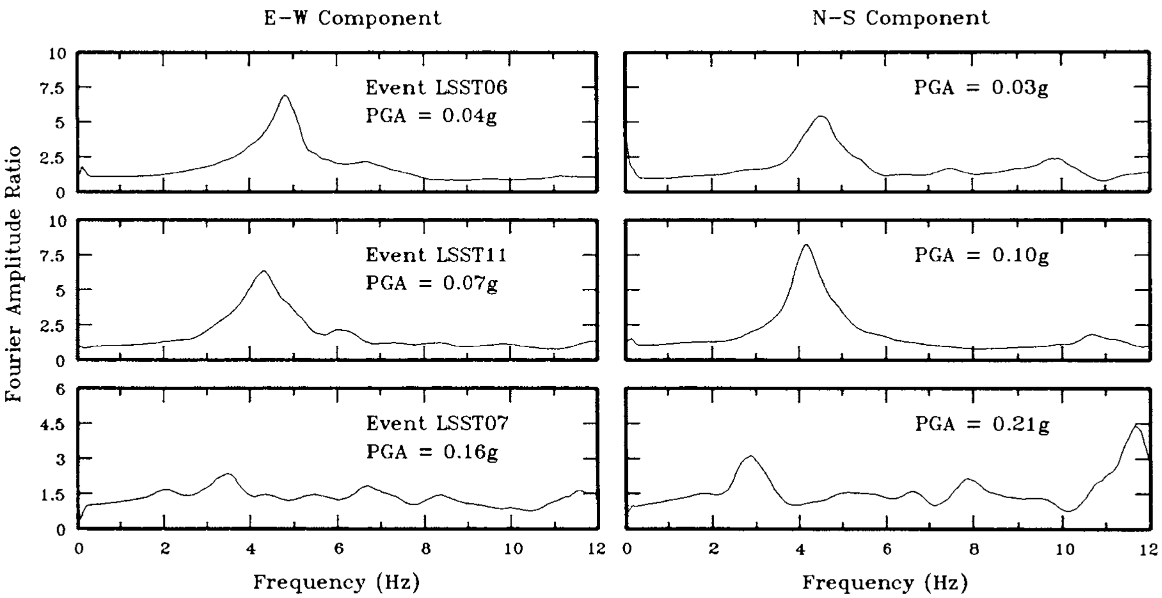


Figure 9. Fourier Amplitude Ratio from Downhole Ground Motions (Surface to −6m Depth)

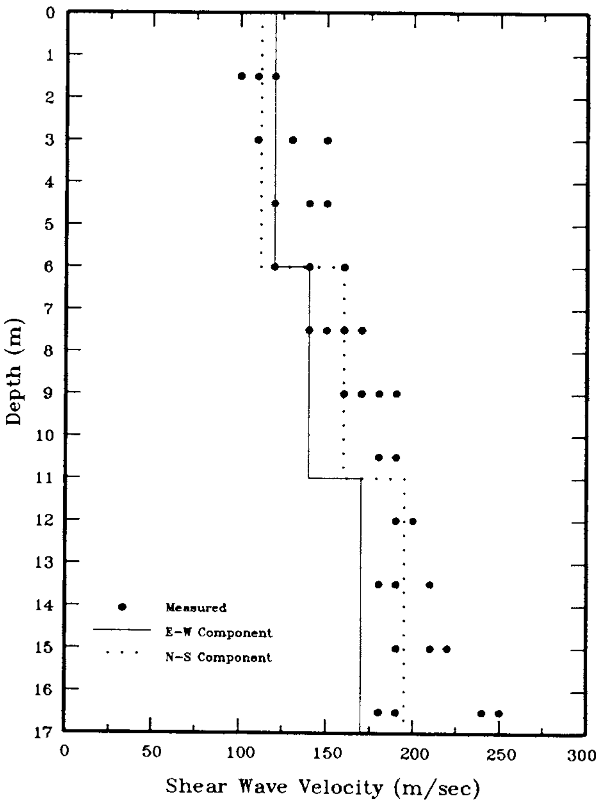


Figure 10. Comparison of Computed Equivalent Shear Wave Velocity Profile with Geophysical Measurements, Event LSST06

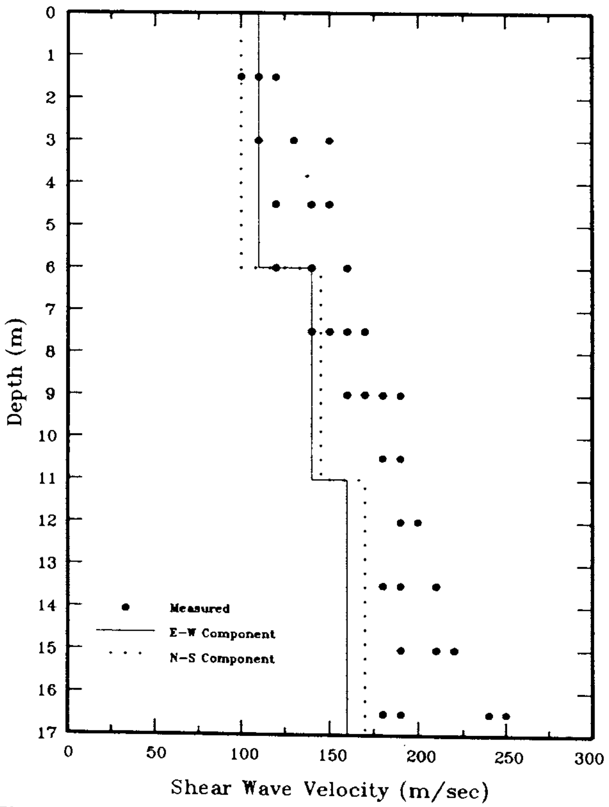


Figure 11. Comparison of Computed Equivalent Shear Wave Velocity Profile with Geophysical Measurements, Event LSST11

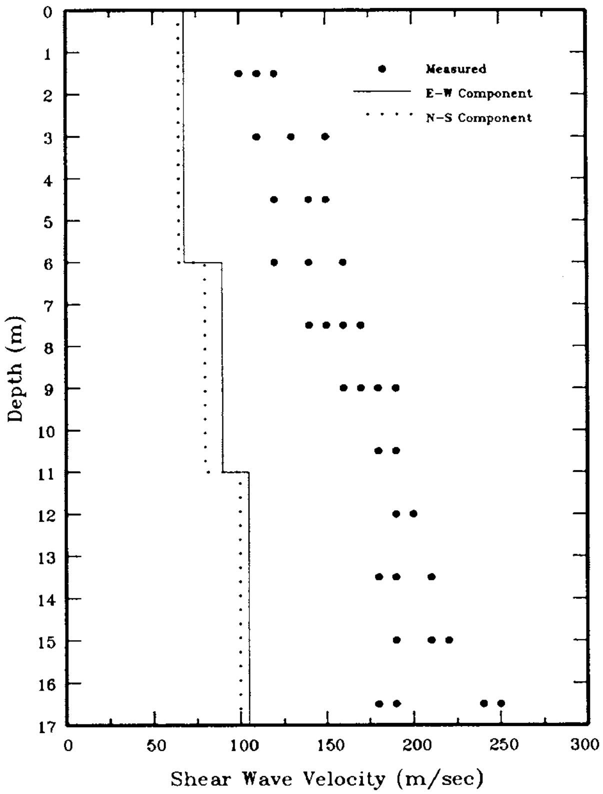


Figure 12. Comparison of Computed Equivalent Shear Wave Velocity Profile with Geophysical Measurements, Event LSST07

Based on this study using the Lotung array data, the following observations were made:

- The back-calculated shear-wave velocities for low levels of shaking (i.e. peak ground surface accelerations less than .03g) were only slightly lower than shear-wave velocities determined by geophysical methods, confirming the adequacy of the geophysical measurements for low-strain conditions.
- The back-calculated shear-wave velocities for moderate levels of shaking (i.e. peak ground surface accelerations in the range of 0.16g to 0.21g) were substantially lower than geophysical shear-wave velocities, indicating considerable shear modulus reduction (i.e. strong soil nonlinearity) at the Lotung soft soil site even during moderate earthquake shaking.
- The back-calculated shear modulus reduction curves were in reasonably good agreement with data from cyclic triaxial tests for strains in the range of $3x10^{-2}$ percent to $2x10^{-1}$ percent. They were in reasonably good agreement with data from resonant column tests for strains lower than about $2x10^{-3}$ percent, and were approximately 10 to 20 percent lower than the test data for strains in the range of $5x10^{-3}$ to $2x10^{-2}$ percent. The results indicate that the laboratory triaxial tests produced data that were reasonable for estimating shear modulus reduction curves at higher strains.

In conclusion, the results indicate that the analysis of downhole ground motion data, as recommended by the EPRI/NSF worksop on dynamic soil property and site characterization (1989), is useful for inferring in-situ dynamic soil properties. Additional array data need to be collected and analyzed from various site conditions, particularly soft cohesive and loose saturated granular site conditions.

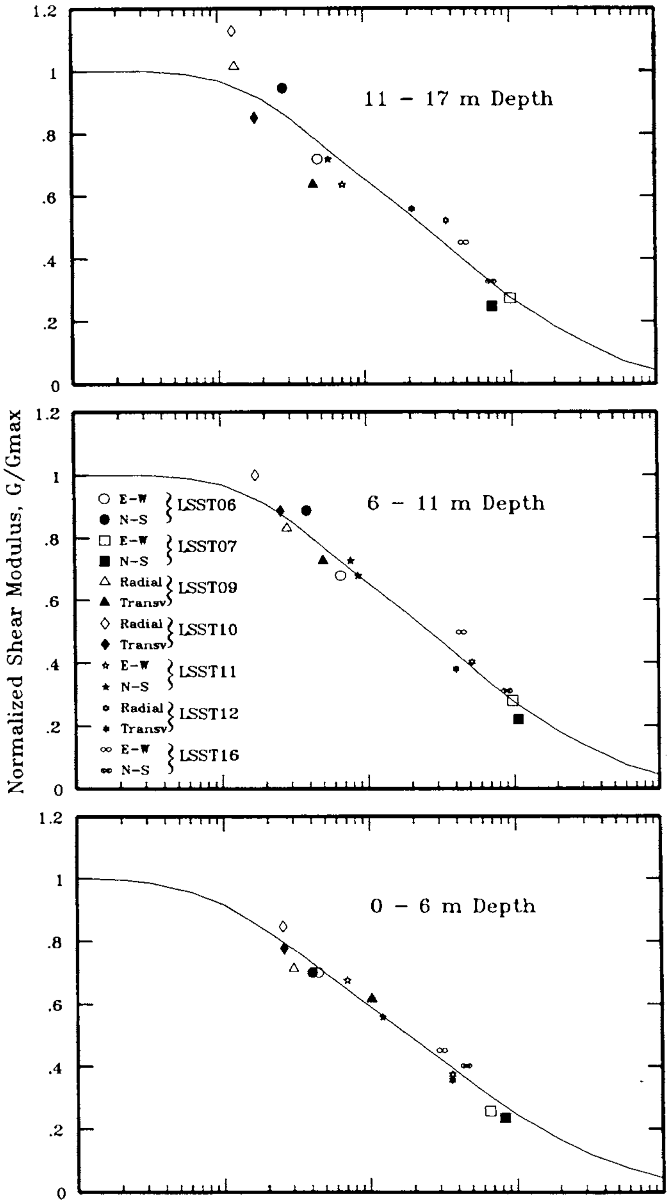


Figure 13. Variations of Normalized Shear Modulus with Effective Shear Strain Back-calculated from Downhole Ground Motions

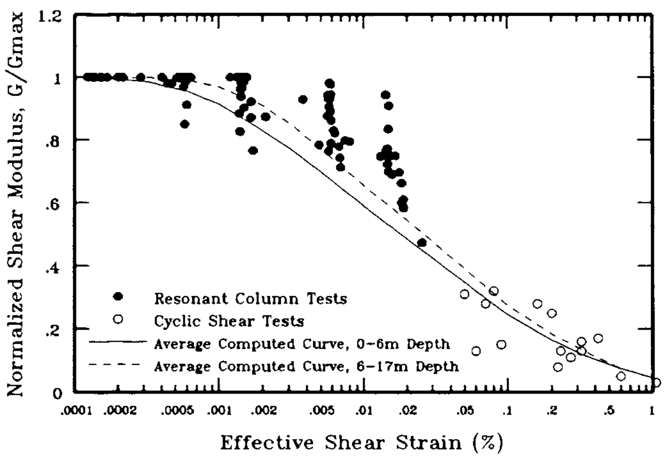


Figure 14. Comparison of Back-calculated Normalized Shear Modulus with Data from Laboratory Tests

REFERENCES

Anderson, D. G. and Tang, Y. K., "Summary of Soil Characterization Program for the Lotung Large-Scale Seismic Experiment", Procs., EPRI/NRC/TPC Workshop on Seismic Soil-Structure Interaction Analysis Techniques Using Data from Lotung, Taiwan, Vol. 1, EPRI NP-6154, March 1989.

Chang, C.-Y., Power, M. S., Tang, Y. K. and Mok, C. M., "Evidence of Nonlinear Soil Response during a Moderate Earthquake", Procs., 12th Int. Conf. on Soil Mechanics and Foundation Engineering, Vol. 3, Rio de Janeiro, Brazil, 1989.

Chang, C.-Y., Mok, C. M., Power, M. S., Tang, Y. K., Tang, H. T. and Stepp, J. C., "Equivalent Linear Versus Nonlinear Groung Response Analyses at Lotung Seismic Experiment Site", Procs., 4th U. S. National Conf. on Earthquake Engineering, Vol. 1, Palm Springs, California, May 1990.

Dobry, R. and others, "Simplified Procedures for Estimating the Fundamental Period of Soil Profile", Bulletin of Seismological Society of America, Vol. 66, No. 4, August 1976.

Electric Power Research Institute and National Science Foundation, "Workshop on Dynamic Soil Property and Site Characterization", Proceedings, EPRI/NSF Worksop, Palo Alto, California, November 9-10, 1989

Ishii, T. and others, "A Study on Seismic Wave Propagation in Lotung, Taiwan", Trans., 10th International Conference on Structural Mechanics in Reactor Technology, Vol. k1, pp. 7-12, 1989.

Jones, T. J. and Roesset, J. M., "Soil Amplification of SV and P Waves", Research Report R70-3, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1970.

Schnabel, P. B. and others, "SHAKE - A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites", Report No. UCB/EERC 72-12, University of California, Berkeley, 1972.

Shannon & Wilson, Inc. and Agbabian Associates (SW-AA), "In Situ Impulse Test, an Experimental and Analytical Evaluation of Data Interpretation Procedures", Report Prepared for U. S. Nuclear Regulatory Commission, NUREG - 0028., 1975.

Tang, H. T., "Large-Scale Soil-Structure Interaction", Electric Power Research Institute, Report EPRI NP-5513-SR, November 1987.

Thomson, W. T., "Tramsmission of Elastic Waves Through a Stratified Solid Medium", Journal of Applied Physics, Vol. 21, 1950.

Wolf, J. P. and Obernhuber, P. C., "Free-Field Response from Inclined SH-Waves and Love-Waves", Earthquake Engineering and Structural Dynamics, Vol. 10, pp. 823-845, 1982.