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ABSTRACT

It has been recognized that the nature of the surface deposits can significantly alter the incident ground motion characteristics. Particularly, in large earthquakes, the soil deposits behave as a non-linear material. The characteristics of soil response during earthquake excitations are analyzed at Chiba vertical array site in Japan. Both frequency domain and time domain analyses are performed for investigation of non-linear soil response and identification of dynamic soil properties. In the frequency domain analysis, the frequency-dependent transfer function of soil is calculated as a ratio of the spectrum at uphole to the spectrum at downhole. Shear modulus and damping ratio are evaluated from peaks in the transfer function amplitude. In the time domain analysis, acceleration data from the site are processed directly for evaluation of site shear stress-strain hysteresis curve. The shear modulus and damping ratio are evaluated from shear stress-strain hysteresis curve using equivalent shear modulus and damping ratio approach. The results of both methods reveal the non-linear soil behavior for recorded strong ground motion at the site with surface PGA of more than 300 gal. The variation of identified soil shear modulus and damping ratio with shear strain amplitude is also examined at the site for both methods. These results indicated that both methods and laboratory results are in general agreement.

INTRODUCTION

The distribution of earthquake damage clearly reveals that the characteristics of earthquake ground motion depend strongly on the site effects. An earthquake motion can be amplified at certain frequencies depending on the physical properties of the soil. Also, soil materials show remarkable non-linearity in their stress-strain relationship. Therefore, it is important that the non-linear property of soil be taken into account in the analysis of site response during strong earthquakes. Consequently, investigation of the actual characteristics of soil response to seismic loading is an important aspect of earthquake engineering.

Non-linear soil behavior, occurring as the excitation level increases, is confirmed by numerous experimental results performed on soil samples as a typical hysteretic form (Hardin and Drnevich 1972, Ishihara 1976). However, it has been under assumption that the in-situ materials behave similar to soil samples. Idriss and Seed showed that surface deposits reveal non-linear behavior as increased damping and decreased shear wave velocity. However, there have only been a few studies of non-linear soil response from strong motion records (Zegal et al. 1995; Ghayamghamian and Kawakami 1996; Chang et al. 1996). Therefore, the actual non-linear behavior of soil in large earthquakes, which plays an important role in hazard mitigation, remains largely based on the response inferred from laboratory and model tests.

Recently, rapid increase in the number of permanent strong motion arrays, especially vertical arrays, and improvement in data quality were made at an international level. The vertical array data in non-linearity is favorable since the problem of source and path spectral contributions, which are a main obstacle to identifying non-linear site effects using the spectral ratio of one site to that of reference site, can be strongly overcome. This is due to the fact that the distance between uphole and downhole instruments is negligible for the source radiation and the wave propagation path effects, which often overshadow the non-linearity. Hence, the interest in studying the aspects of soil response to strong motions is increased. Besides, the need for determining the actual dynamic properties of in-situ soil has been emphasized because of significant influence on the evaluation of ground response. Shear modulus measured in the laboratory has often been compared with that measured in-situ for low shear strain. However, it still seems unclear whether the laboratory data could duplicate in-situ soil behavior up to the large shear strain prevailing during large earthquakes. Here, time domain and frequency domain identification procedures were employed to directly investigation on the non-linear soil response. These responses were than used to evaluate the shear moduli with shear strain amplitude. The earthquake data in Chiba vertical array in Japan are analyzed in this study.

EARTHQUAKE DATA AND SITE CONDITIONS

The Chiba dense array system is located about 30 km east of Tokyo and becomes operational in April, 1982. The instruments used are piezo-electric-type acceleration transducers with practically flat sensitivity between 0.1 and 30 Hz. Sets of three accelerometers in the three principal directions have been installed at GL -1, -5, -10, -20 and -40m in bore hole C0. Detailed descriptions of soil parameters for the sites at which the geotechnical and geophysical field explorations have been carried out are given in Table 1.

Table 1. Soil parameters of Chiba vertical array

Layer No.	Depth (m)	Soil type	V_P (m/s)	V_S (m/s)	Density (g/cm^3)
1	1-5	loam	320	140	1.38
2	5-10	sandy clay	550	320	1.5

Earthquake records obtained from the vertical array system installed at Chiba site were used to analyze soil response to strong ground motions. The analyzed earthquakes are selected from Strong Motion Array Recorded Database in Japan published by the Association for Earthquake Disaster Prevention (AIJ, 1993). The earthquake data with maximum acceleration more than 300gal surface PGA (Peak Ground Acceleration) were recorded. This large earthquake together with small one at site are selected to provide the possibility for the investigation of linear and non-linear site responses. Table 2 shows the basic information on these earthquakes. In identification of soil response, the NS component of ground motion recordings between level -1 and -10 is used.

Table 2. Selected events in Chiba array for the analysis

Event No.	Date yy.mm.dd	Depth (km)	M (JMA)	Δ (km)	PGA (gal)
1	1987.12.17	58	6.7	45	301.1
2	1987.06.30	56	4.9	62	33.5

FREQUENCY DOMAIN IDENTIFICATION OF THE SYSTEM

The surface layer overlying a rigid basement exhibits the predominant resonance frequency (f), at $f=v_1/4h$, where v_1 is the shear wave velocity of the surface layer and h is its thickness. The amplification at resonance is expressed as $2/\alpha$, in which α is the impedance ratio defined as $\rho_1 v_1/\rho_2 v_2$ and ρ is density. Thus, the resonance frequency and amplification factor of the layer is proportional to the wave velocity and will be decreased as the strain increases. Because of this proportional relationship, the non-linear soil response can be investigated in the form of reduction in resonance frequency and amplification factor of the soil system with increases in the level of motion. Consequently, if an earthquake is divided to several time windows (i.e. different levels of shaking), the reduction in resonance frequency of soil transfer function should be seen as the level of shaking increases in those time windows.

The transfer function of soil can be obtained by spectral ratio of uphole to downhole for different time windows of the record. In spectral ratio analysis cross-spectrum is introduced. The cross-spectrum can reveal the true characteristics of the site, especially predominant frequency, due to effective removal of output noise (piersol, 1987). Here, the non-linear soil response analysis is mainly addressed using the predominant resonance frequency (for simplicity, hereafter referred to as resonance frequency). Accordingly, accelerograms recorded at uphole and downhole were divided into a number of 5.12s time windows (with 1024 data points) representing different levels of shaking. The time window divisions were used between the S-wave arrival and the end of the record (Fig. 1).

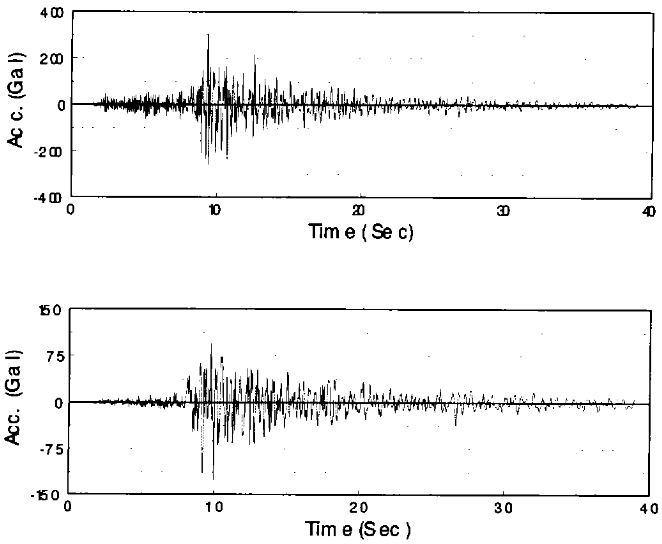

Fig. 1 Uphole and downhole accelerogram in the NS direction of event1.

The spectral ratio is calculated using the following procedure for each time window: (1) The cross- spectrum is calculated; (2) the spectra are smoothed using rectangular average filter having a band width of approximately 0.45 Hz; (3) the ratio of two smoothed spectra is calculated; (4) the square root is taken from spectral ratio. Three times consecutive smoothing were applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape.

In Fig. 2, the calculated transfer functions by spectral ratio analysis using cross-spectrum are shown. The transfer functions at each frame belong to the different 5.12s time windows. The decreases in resonance frequency can be seen in the time windows going from the end to the beginning of the record (corresponding to increasing in the level of shaking) for event 1 with 301 gal PGA . However, the resonance frequency seems unvarying for the event 2 with 60.9 gal PGA. The reduction in the resonance frequency with increasing level of shaking manifests the non-linear response of soil in Chiba site for event 1.

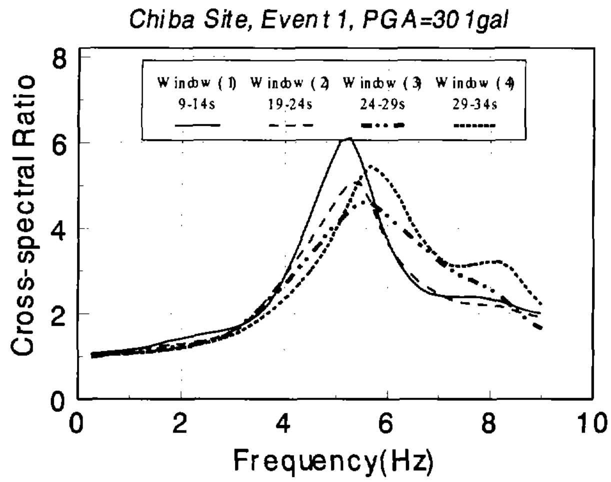

Fig. 2 The transfer function for different time windows of event 1.

In Fig. 3, the transfer functions obtained for the largest and smallest levels of shaking from the time windows analyzed for events at the site are shown. A 0.75 Hz shift of the resonance frequency is clearly seen in this figure. However, there is no clear trend of deamplification effect in the spectral ratio of time windows for event 1 time windows. Nevertheless, the spectral ratios derived from the smallest and largest time windows (Fig. 3) expose the clear deamplification in the Chiba site.

Based on the above results, it is possible to investigate the actual soil behavior up to relatively large shear strains. For this purpose, the resonance frequencies obtained from transfer function of time windows for all events, at each site, are divided by the largest resonance frequency obtained among them. From the resonance frequency ratio, f/f_0, the shear modulus ratio can be given as $f/f_0 = v/v_0 = (G/G_0)^{1/2}$, where v/v_0 and G/G_0 are velocity and shear modulus ratios respectively.

To show strain dependent non-linear soil properties, the strain

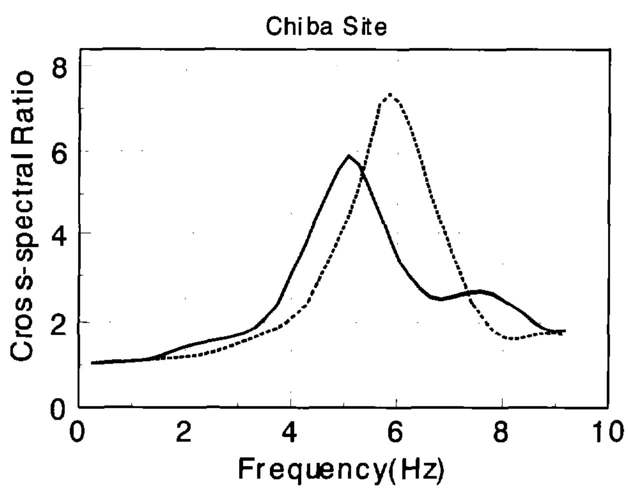

Fig. 3 The transfer function derived from largest and smallest levels of shaking at the time windows.

time history need to be calculated. The strain is calculated by two times integration from accelerographs at uphole and downhole divided by distance between accelerograms. In view of instrument and digitization inaccuracies, displacement time histories include base line drifts in the form of spurious very low frequency components. These drifts in displacement estimates were eliminated using bandpass rectangular Finite Impulse response (FIR) filter. This filtering procedure introduces no phase shifts. For evaluation of strain, the calculated strain time histories are divided into the windows corresponding to the time windows that are used in the spectral ratio analysis. The shear modulus ratios are related to the maximum value of strain in strain windows. The calculated shear strain-shear modulus relationships are shown in Fig. 4. There is a fairly well defined trend in which the shear modulus ratio decreases with the increasing shear strain. In addition, comparison of the experimental and laboratory results in Fig. 4 demonstrates concrete agreement between actual and experimental ones.

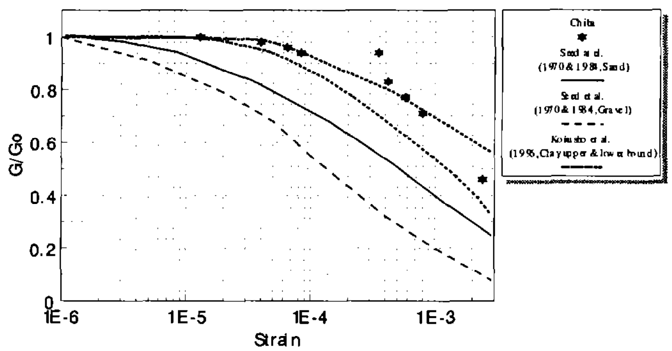

Fig. 4 Back calculated shear modulus-shear strain relationship from the analysis in frequency domain.

TIME DOMAIN IDENTIFICATION OF THE SYSTEM

A technique is employed to estimate the average shear stress and strain histories directly from the acceleration records (Zeghal et al. 1995; Elgamal et al. 1995). The hysteretic curve was obtained from the stress-strain relationship for different time windows of the record. The time windows are selected in the same manner as those used in earlier spectral ratio analysis, in order to make the results comparable with each other. Using the equivalent linear approach, the actual dynamic soil properties can be identified by quantifying the results of the stress-strain hysteresis curves.

The shear stress and strain time histories were directly evaluated from acceleration time histories recorded at the uphole and downhole accelerometers. The one-dimensional seismic lateral response of the site, expressed as $\partial\tau/\partial z = \rho\ddot{u}$, where z = depth coordinate, $\tau=\tau(z,t)$ is horizontal shear stress, $\ddot{u} = \ddot{u}(t,z)$ is absolute horizontal acceleration, t = time and ρ = mass density, was used to evaluate the stress time histories. By integrating the equation of motion and using the stress-free surface boundary condition, the shear stress at any depth z may be expressed as $\tau(z,t) = \int_0^z \rho \ddot{u} dz$. The simple second-order-accurate discrete form of this equation for midway between two accelerograms at uphole and downhole locations can be written as $\tau(t) = \rho H(3\ddot{u}_u + \ddot{u}_d)/4$, where $\ddot{u}_u$ and $\ddot{u}_d$ are accelerations at uphole and downhole locations, respectively, and H is the distance between them (Zeghal and Elgamal 1994). The mass densities used in the calculation of stress time history at the sites is assumed to be 1.38 g/cm^3 at the Chiba site.

As explained before, the shear strain was calculated by the relative displacement between uphole and downhole locations as $(u_d - u_u)/H$, where u_d and u_u are the displacements at downhole and uphole locations, respectively, and H is the distance between them. This equation provides an average strain between two recording points and is second-order-accurate for midway between these recording points (Zeghal and Elgamal 1994).

Accuracy of estimated shear stress and strain amplitudes is a function of the distance between the recording points and the recorded acceleration wavelengths ($\lambda = v_s/f$, where v_s is shear wave velocity and f is frequency). The above discrete formulas can only capture waves below a certain frequency, which is determined by the distance between the recordings. Theoretically, the highest frequency corresponds to a wavelength four times the distance between recording points. Based on this criterion, and in view of the fact that the records were collected near the top and bottom of the downholes, the high cut off frequency for shear stress and strain estimates is calculated. Hence, a meaningful result can be obtained by using filtering techniques to process the records.

Generally, digital filters can be divided into two categories: (1) recursive or infinite impulse response (IIR); and (2) non-recursive or finite impulse response (FIR). Normally, FIR filters are stable and possess phase linearity while the IIR filters must be designed for those attributes (Subia and Wang 1995).

In this analysis, the rectangular bandpass FIR filter was designed in the frequency domain. This filter provided a unit gain factor over the desired frequency band and introduced no phase shift in the filtering procedure. This filter was able to remove undesirable contributions of high-frequency stress components and low-frequency strain drifts from the available seismic records. Fig. 5 shows the frequency range of significant acceleration response and the limits of the filters. In this figure, the plots of the filtered and non-filtered acceleration Fourier amplitudes confirm the adequacy of the employed filter.

Figure 6 shows the hysteresis curves obtained from the shear stress versus shear strain plots for the large earthquakes at the Chiba site. It shows the changes in shear modulus and material damping ratio in the time windows going from the arrival of the S-wave to the end of the record (*i.e.* a decrease in the level of shaking) for event 1 with 301 gal PGA. In Fig. 7 the loading cycle within a time window for event 1 was selected in such a way that they revealed how these cycles change with different levels of shaking. The changes of the shear modulus and damping ratio in the selected loading cycles can be seen in these figures. This reduction of shear modulus and increase in damping ratio associated with the level of shaking reveals the non-linear response of the soil. However, there is no such phenomenon in

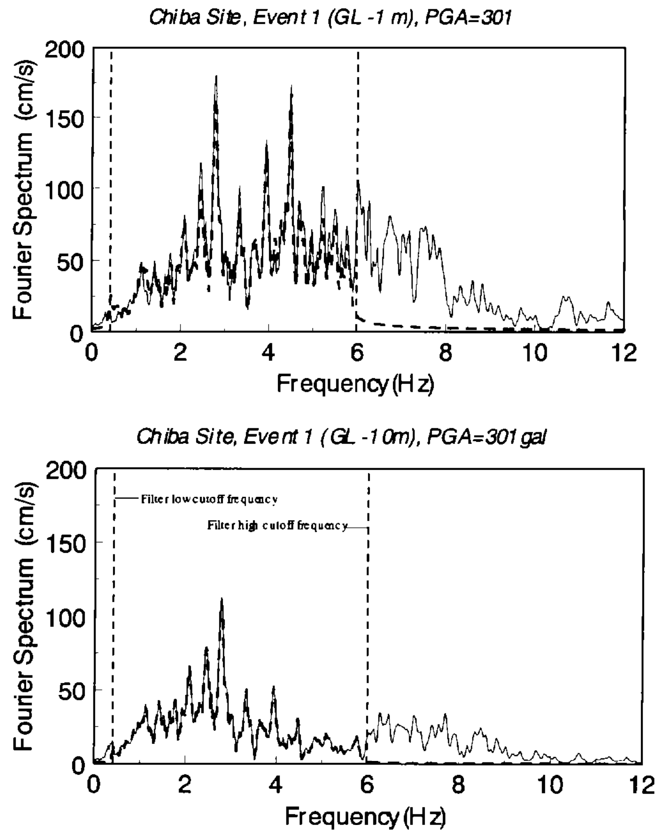

Fig.5 Non-filtered and filtered Fourier Spectrum with employed filter cutoff frequencies.

the hysteresis curves in the time windows for event 2, which have PGA of 33.5 gal. The explanation for this observation is that small levels of PGA do not result in non-linear behavior in these events (Ghayamghamian and Kawakami, 2000).

The shear modulus and material damping ratio of the soil at the site were determined by the shear stress-strain hysteresis curves using equivalent shear modulus and damping ratio approach. The basic concept of this approach is well-documented (Ishihara 1976). The variations of the soil shear modulus and damping ratio with strain amplitude were investigated by the following procedure, which was carried out for each time window: (1) the number of cycles were counted; (2) the equivalent shear modulus and damping ratio were evaluated for each cycle; (3) the average values of equivalent shear modulus and damping ratio for all cycles within the time window were calculated and considered as a representative of the actual shear moduli and damping ratios for that time window; and (4) the average shear modulus and damping ratio were related to the maximum value of the filtered strain in the same time window. The computed shear modulus was normalized by the low-amplitude shear modulus G_0, and was used to define the modulus ratios. In the calculation of shear modulus ratio G/G_0, the initial shear modulus G_0, was estimated from the predominant resonance frequency of the site transfer function based on the soil profile model at each site (Ghayamghamian 1997).

The calculated shear modulus-shear strain and damping ratio-shear strain relationships, which are obtained by the above procedure, are shown in Fig. 8. A clear trend of shear modulus degradation and damping ratio increase with increasing shear strain can be observed in these figures. Unfortunately, there are no laboratory results available for the site under consideration.

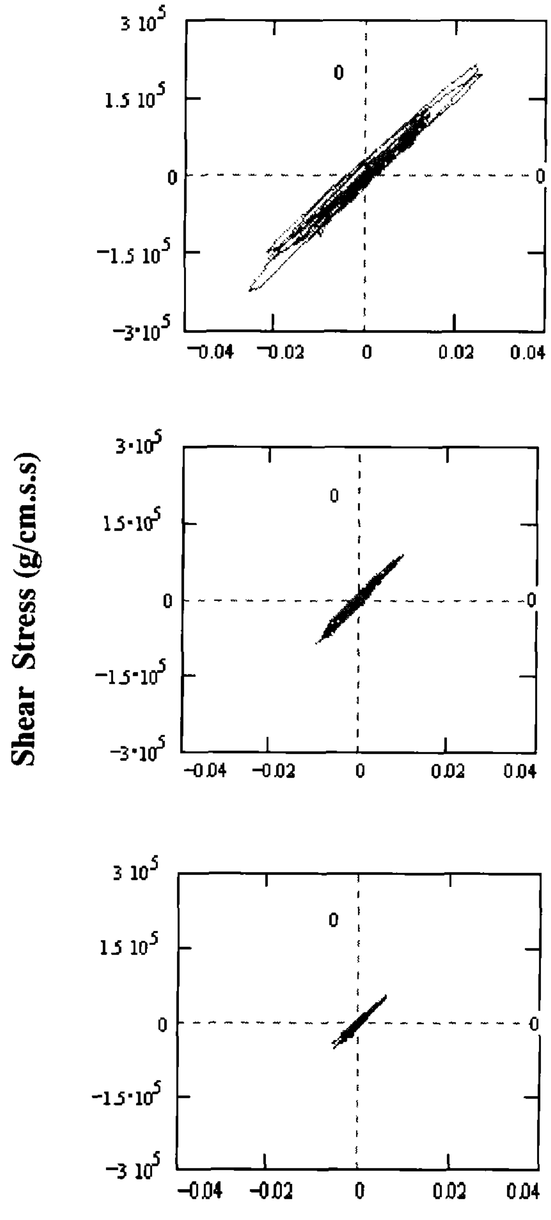

Fig. 6 Shear stress versus shear strain starting from upper window for 9-14 s , 14-19 s and 19-24 s time windows of event 1.

Therefore, the result of the site was compared with the typical laboratory results in Fig. 8 (Seed and Idriss 1970, Seed et al. 1984, Kokusho 1996). The evaluated soil shear moduli and damping ratios at the Chiba site are limited by the clay and sand curves. These results are consistent with their soil profile shown in Table 1. As a result, the evaluated shear modulus and damping ratio are in general agreement with the laboratory tests.

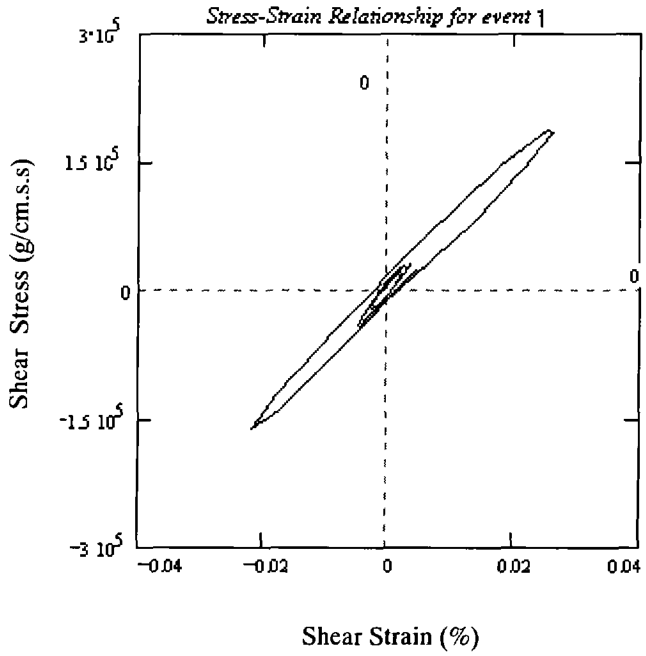

Fig. 7 Shear stress versus shear strain for selected loading cycles in different time windows.

CONCLUSION AND DISCUSSION

Downhole ground motions recorded at Chiba vertical array site in Japan were used in this paper to investigate non-linear site response and in-situ dynamic soil properties. The site response on weak and strong ground motions were compared using frequency-dependent transfer function of the soil and stress-strain hysteresis curves. For each event at the site, the entire data records, from the S-wave arrival to the end of the record were examined by using 5.12 s time windows. The frequency-dependent transfer functions and stress-strain hysteresis curves were derived for each of the time windows. The response of the soil changed for different time windows (*i.e.* different levels of shaking), and determined non-linear behavior of the site.

Dynamic soil properties play a significant role in accurate estimation of the non-linear seismic response of surface soil deposits. Therefore, it is an important task to determine these effects from actual earthquake records. In this paper, the variation of soil shear modulus and damping ratio with shear strain amplitude was also examined. For each window, representative shear modulus and damping ratio were estimated using peaks of transfer function and an equivalent shear modulus and damping ratio approach in frequency and time domains respectively. The shear moduli inferred from event that produced strong ground motions at the site was substantially lower than those from event that produced weak ground motion. In addition, the material dampings inferred from strong motion were higher than those produced by weak ground motion. The results were summarized in the form of shear modulus-shear strain and damping ratio-shear strain relationships. These results were also compared with published soil properties obtained from in-situ and laboratory test procedures. A comparison of the evaluated shear modulus and damping ratio with laboratory values generally demonstrated good agreement.

The results obtained from stress-strain hysteresis curves in the time domain with the results from spectral ratio (uphole/downhole) analyses in the frequency domain were compared. These results indicated that both methods and laboratory results are in general agreement. Some differences arose from the different values of initial shear modulus estimates in the frequency and time domain analyses. More unbiased results were obtained by making a correlation between the calculated shear moduli from spectral ratio analysis and stress-strain hysteresis curves (Fig. 9). The similarity between the results of time and frequency domains analysis demonstrates the accuracy of the results. However, the shear moduli inferred from hystersis stress-strain relations in the time domain have higher values than those of spectral ratio analysis. This may be related to the large distance between accelerometers in the time domain analysis or noise effect in the spectral analysis in the frequency domain. All of this field evidence verifies the significance of non-linearity soil behavior during strong motions.

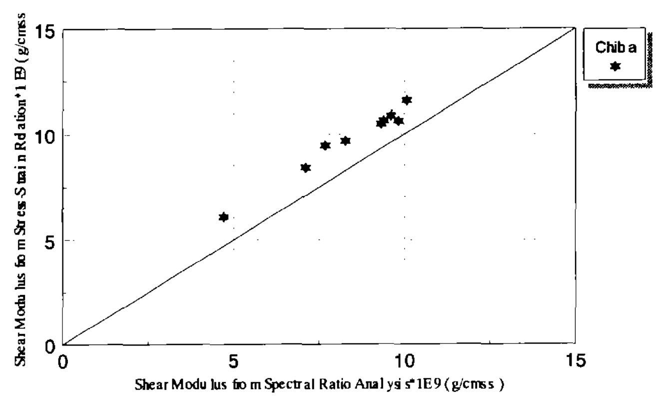

Fig. 9 Correlation between shear moduli estimated in time and frequency domain analysis.

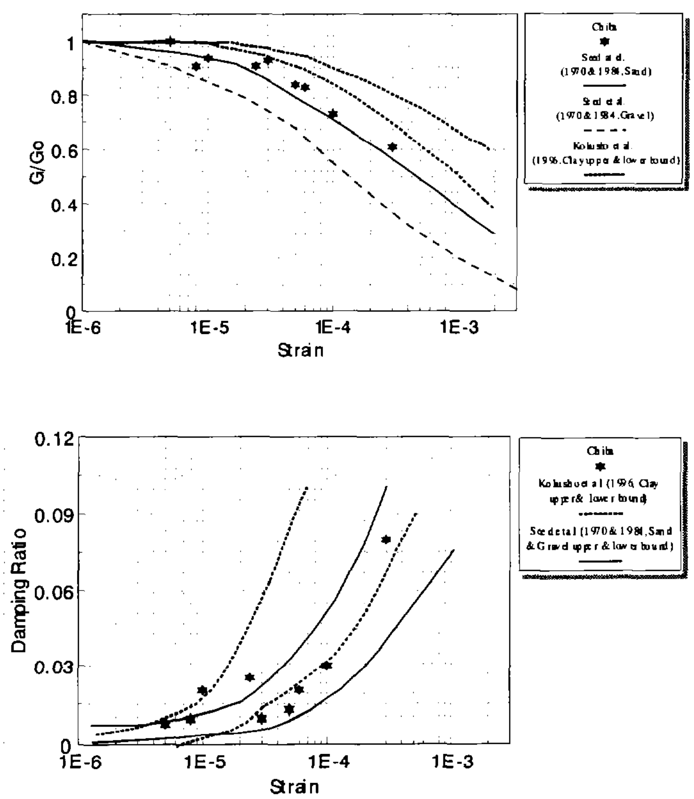

Fig.8 Back calculated shear modulus-shear strain and damping ratio-shear strain relationship from the analysis in time domain.

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REFERENCES

AIJ (Architectural Institute of Japan) [1993]. *Earthquake Motion and Ground Conditions*, Showa Kogyo Inc. Press, Tokyo, Japan.

Chang C. Y., Mok C. M. and Tang H. T. [1996]. "Inference of dynamic shear modulus from Lotung downhole data." J. Geotech. Eng., ASCE, 122(8), 657-665.

Database Advisory Committee and Working Sub-committee [1993]. "Strong motion array record database." Report No. 1, Association for Earthquake Disaster Prevention, Japan.

Elgamal A. W., Zegal M. and Parra E. [1995]. "Identification and modeling of earthquake ground response." Proc., 1st Int. Conf. on Earthquake Geotechnical Engineering, Special Keynote and Theme Lectures, Tokyo, Japan, 51-90.

Ghayamghamian M. R. and Kawakami H. [1996]. "On the characteristics of non-linear soil response and dynamic soil properties using vertical array data in Japan." Earthquake Eng. and Struc. Dyn., 25(8), 857-870.

Ghayamghamian M. R. [1997]. "Non-linear and linear response of the site with evaluation of actual dynamic soil properties using vertical array accelerograms and microtremors." Ph.D. Dissertation, Saitama University, Japan.

Ghayamghamian M. R. and H. Kawakami [2000]. "On-site non-linear hysteresis curve and dynamic soil properties", ASCE, *Geo. Div.,* 126(6), 543-555

Hardin B.O. and Drnevich V.P. [1972]. "Shear modulus and damping in soil: measurement and parameter effects." J. Soil Mech. Found. Div., ASCE, 98, 603-624.

Ishihara K. [1976]. Principle of Soil Dynamics, Kajima Inc. Press, Tokyo, Japan (in Japanese).

Katayama T., Yamazaki F., Nagata S., Lu L. and Turker T. [1990]. "Development of strong motion data base for the Chiba seismometer array." Rep. No. 90-1(14), University of Tokyo.

Kokusho T., Sato K. and Matsumoto M. [1996]. "Nonlinear dynamic soil properties back-calculated from strong seismic motions during Hyogoken-Nanbu Earthquake." Proc. of 10th WCEE, Mexico.

Oppenheim A. V., Willsky A. S. and Young I. T. [1983]. *Signals and systems,* Prentice-Hall.

Osaki Y. [1992]. Principal of earthquake spectral analysis, Kajima Inc. Press, Tokyo, Japan (in Japanese).

Seed H. B. and Idriss I. M. [1970] "Soil moduli and damping factors for dynamic response analyses." Rep. No. EERC 70-10, Earthquake Engineering Research Center, Univ. of California at Berkeley, CA.

Seed H. B., Wong R. T., Idriss I. M. and Tokimatsu T. [1984] "Moduli and damping factors for dynamic analysis of cohesionless soils." Rep. No. EERC 84-14, Earthquake Engineering Research Center, Univ. of California at Berkeley, CA.

Silver M. L. and Seed H. B. [1971]. "Deformation characteristics of sands under cyclic loading." J. of Soil Mech., 8, 1081-1098.

Subia S. R. and Wang M. L. [1995]. "Non-linear hysteresis curve derived by direct numerical investigation of acceleration data." Soil Dyn. and Earth. Eng., 14, 321-330.

Taylor P.W. and Parton I. M. [1973]. "Dynamic torsion testing of soils." Proc., 8th Int. Conf. on Soil Mech. and Found. Eng., International Society of Soil Mechanics and Foundation Engineering, 425-432.

Trifunac M. D. and Lee V. [1973]. "Routine computer processing of strong-motion accelerograms." Rep. No. EERL 73-03, Earthquake Engineering Research Laboratory, Pasadena, California.

Zeghal M., and Elgamal A. W. [1994]. "Analysis of site liquefaction using earthquake records." J. Geotech. Eng, ASCE, 120(6), 996-1017.

Zeghal M., Elgamal A. W., Tang H. T. and Stepp J. C. [1995]. "Lotung downhole array. II: evaluation of soil nonlinear properties." J. Geotech. Eng., ASCE, 121(4), 363-378.