NON-LINEAR SITE RESPONSE IN GROUND MOTIONS

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Non-linear response of the soil is investigated by comparing the spectral ratios (uphole/ downhole) using weak and strong motions. The frequency dependent transfer function of soil is calculated as a ratio of the spectra at uphole to the spectra at downhole, considering the horizontal component of shear wave. In spectral ratio analysis, auto and cross- spectra are employed. The reduction in the predominant frequency of transfer function with increases in excitation level reflects the non-linear response of soil. Furthermore, the in-situ strain dependent soil behavior is examined through the shear modulus - shear strain relationship. Additionally, a good consistency between the tendency of reduction in shear modulus ratio with shear strain increases, and reduction of predominant frequency with ground motion increases, confirms the significance of non-linearity in site effects study.

Key words : *Strong motions, transfer function, non-linear soil response, dynamic soil properties*

1. INTRODUCTION

It has been recognized that the nature of the surficial deposits can significantly alter the incident ground motion characteristics. Particularly, in large earthquakes, the soil deposits behave as a non-linear material.

An earthquake motion can be amplified at certain frequencies depending on the physical properties of the soil. 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.

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. Here in, the identification procedure developed by authors will be applied to the Chiba array data for investigation on the non-linear soil response (Ghayamghamian and Kawakami, 1996). These responses were than used to evaluate the shear moduli with shear strain amplitude.

2. EARTHQUAKE DATA AND SITE CONDITIONS

The Chiba vertical array site is considered in this study. Detailed descriptions of soil parameters for the site at which the geotechnical and geophysical field exploration have been carried out are given in Table 1. The three components of acceleration are installed at different depths. The NS component of acceleration in depths of 1 and 10m are selected for spectral ratios presented here. The data was recorded digitally at the rates of 500 samples per second. The analyzed earthquakes are selected from Strong Motion Array Recorded Data Base in Japan published by Association for Earthquake Disaster Prevention[3].

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

The small and biggest possible earthquake data has been selected for the site. Parameters of the events

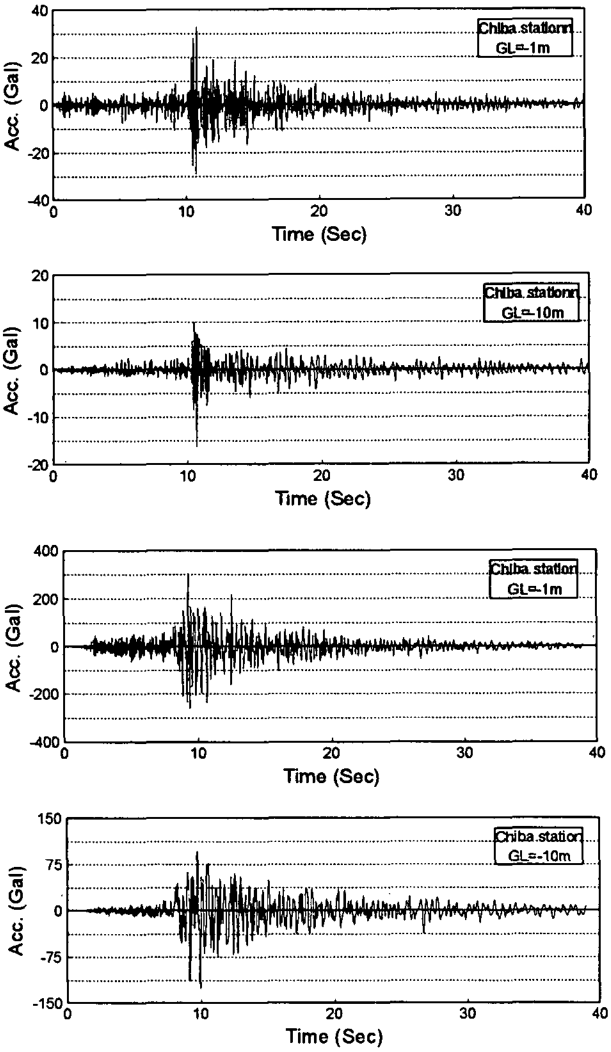

Fig.1 Uphole and downhole accelerograms in the NS direction for event 2 and 3 respectively.

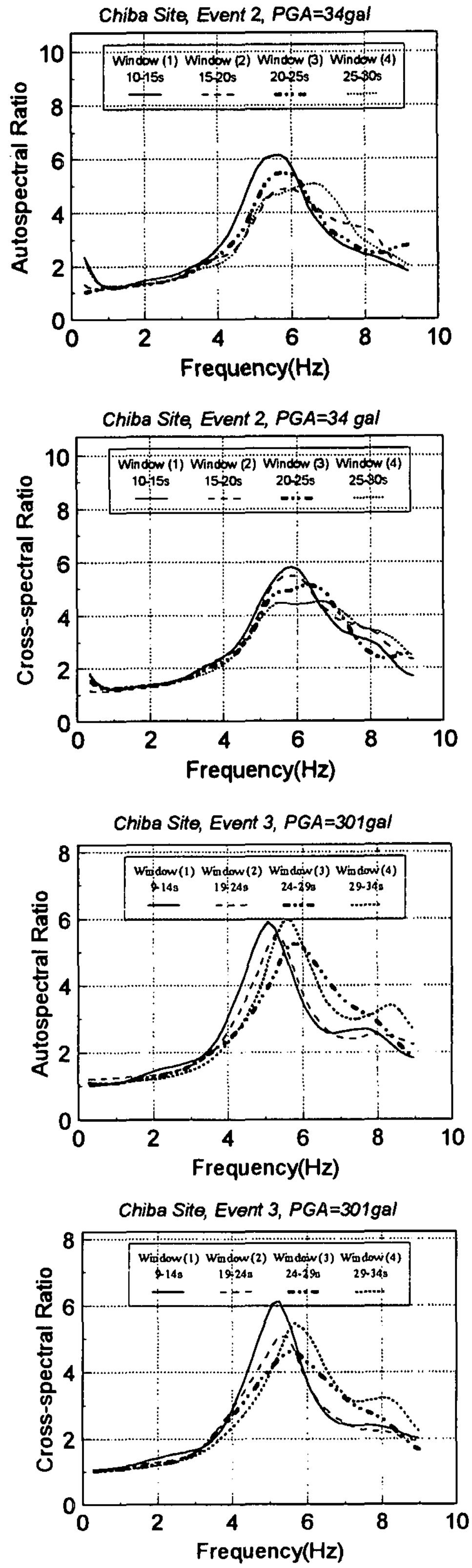

Fig 2. The transfer function calculated by using auto- and cross-spectra for different time windows of events 2and 3.

selected for the analysis are listed in Table 2. The surface PGA of selected strong motion is 301 gal. Figure 1 shows some examples of recorded event at uphole and downhole in Chiba site.

Table 2. Selected events in Chiba array for the analysis

Event No.*	Date yy.mm.dd	Depth (km)	M	Δ (km)	PGA (gal)
1	1989.03.06	55	6.1	55	28.9
2	1987.06.30	56	4.9	62	33.5
3	1987.12.17	58	6.7	45	301.1

* Event number does not correspond to the original classification and is given number
Δ: Epicentral distance

3. NON-LINEAR IDENTIFICATION OF SOIL SYSTEM

The surface layer overlying a rigid basement exhibits the predominant resonance frequency, f, at $f=v/4h$, where v is the shear wave velocity of the surface layer, and h is its thickness. Thus, the resonance frequency of the layer is proportional to the wave velocity and will be shifted downward 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 of the soil with increases in the level of motion. Consequently, if an earthquake record is

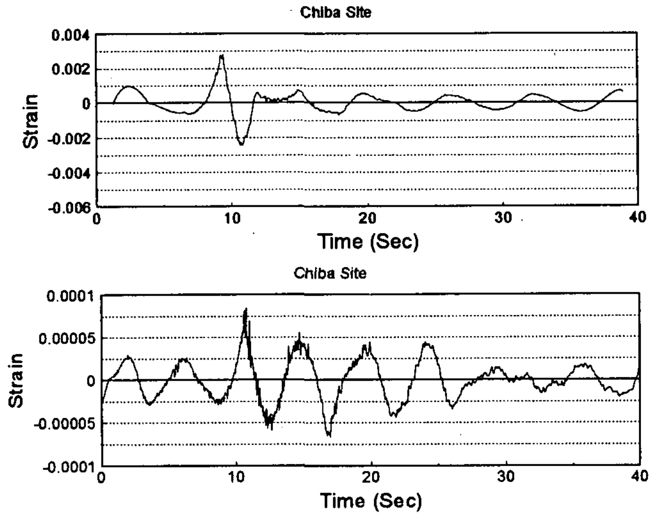

Fig.3 Strain time histories derived from uphole and downhole accelerograms for events 2 and 3 respectively.

divided into 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 functions of soil can be obtained by the spectral ratio of uphole to downhole for different time windows of the record. In spectral ratio analysis auto and cross- spectra are introduced. The auto and cross- spectra can reveal the true characteristics of the site, especially predominant frequency, due to effective removal of input and output noise. 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 5.12s time windows representing different levels of shaking. The time window divisions were used between the S-wave arrival and, generally, the end of the record.

The spectral ratio is calculated using the following procedure for each time window: (1) The cross- and auto spectra are calculated; (2) the spectra are smoothed using a rectangular average filter having a band width of approximately 0.5 Hz; (3) the ratio of two smoothed spectra is calculated; (4) the square root is taken from the spectral ratio. Three times in succession smoothing was applied to the raw spectra. This number was chosen empirically considering its visual effect on the spectral shape. Fig. 2 shows an example of the transfer functions for events 2 and 3. In addition, to show strain dependent non-linear soil properties, the strain is calculated from the relative displacement between uphole and downhole readings divided by their distance. The base line correction is also applied in the calculation. Fig.3 shows the results of calculated strain time histories between uphole and downhole at the depths of 1 and 10m for events 2 and 3 of Chiba site.

In Fig. 2, the examples of transfer functions calculated by spectral ratio analysis using auto and cross- spectra are shown. The transfer functions at each frame belong to the different 5.12 s time windows. The decrease in resonance frequency can be seen in the time windows going from the end to the beginning of the record (corresponding to an increase in the level of shaking) for events 3 with 301.1 gal PGA . However, the resonance frequency seems unvarying for the event 2 with 40.5 gal PGA. The reduction in the resonance frequency with increasing level of shaking manifests the non-linear response of soil in Chiba site for events 3.

The comparison of resonance frequencies calculated by cross-spectrum and autospectrum shows that the results of these two techniques are quite consistent. Furthermore, the stability of results is examined by a variety of data samples. These facts confirm the accuracy in calculation of resonance frequency for each time window. The authenticity of using the end part of the strong motion record (coda of strong shear wave) as a weak motion is proved by comparison of transfer functions derived from the coda part of strong motion and weak motion (small earthquakes) as shown in Fig.4. As can be seen, the amplification functions are in agreement, especially for resonance frequency. This suggests that the amplification function calculated from the coda part of strong motion is a good approximation for weak motion amplification function.

In Fig.5, the transfer functions obtained for the largest and smallest levels of shaking from the time windows analyzed for all events at each site are shown. A shift of the resonance frequency is clearly seen in this figure. However, there is no remarkable change in the

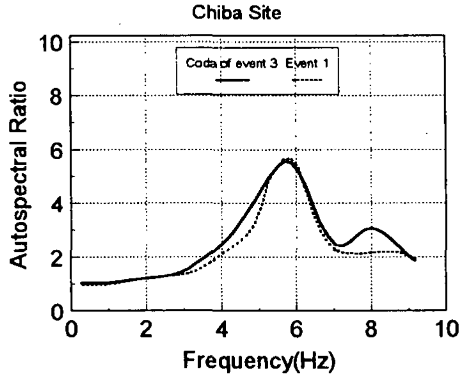

Fig.4 The transfer function from the coda part of strong motion and records of the small earthquake.

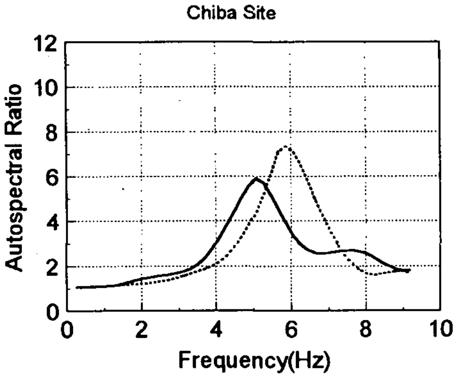

Fig.5 The transfer function of the largest (continouos line) and smallest (dotted line) shaking level time windows.

resonance frequency for event 2 which suggests a linear response. In spite of the evident shifting in the resonance frequency with the level of shaking, there is no clear trend of deamplification effect in the spectral ratios of different time windows for each earthquake (Fig.2). Nevertheless, the spectral ratios derived from the smallest and largest shaking levels time windows (Fig.5) expose the clear deamplification where the strong motions of 301.1 gal was analyzed.

4. IDENTIFICATION OF DYNAMIC SOIL PROPERTIES

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 functions of different 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 $f/f_0 = v/v_0 = \sqrt{G/G_0}$ where v/v_0 and G/G_0 are velocity and shear modulus ratios respectively. For evaluation of strain, the calculated strain time histories are divided into the windows corresponding to the time windows which are used in the spectral ratio analysis. The shear modulus ratio is related to the maximum value of strain in the same time window. Fig.6 shows the calculated shear strain-shear modulus relationship. There is a fairly well defined trend in which the shear modulus ratio decreases with the increasing shear strain. In addition, results of the shear strain - shear modulus relationships for all events are combined in Fig.7. Comparison of the actual and laboratory results in Fig.7 demonstrates good agreement between actual and experimental ones especially in shear modulus reduction behavior.

5. DISCUSSION AND CONCLUSIONS

In this study, the amplitude-dependent site amplification effects are investigated using the data of Chiba vertical array in Japan. Furthermore, an attempt is made to examine the actual in-situ dynamic soil behavior in these sites. For these reasons, the soil response on weak and strong ground motions are compared using uphole/downhole spectral ratio. For the most part, the whole length of data after S-wave arrival is investigated in this analysis by using 5.12 s time windows.

The resonance frequencies obtained from spectral ratios at different time windows display a clear change with level of ground motion shaking. Furthermore, the direct comparison of transfer functions derived from the coda part of strong motions and independent small earthquakes showed that the coda amplification can be regarded as an amplification of weak motion. The above facts suggest that both weak and strong motion amplification functions can be assessed by only one strong record. Additionally, the presented method also demonstrates the ability to trace a nonlinear trend by using only one strong earthquake.

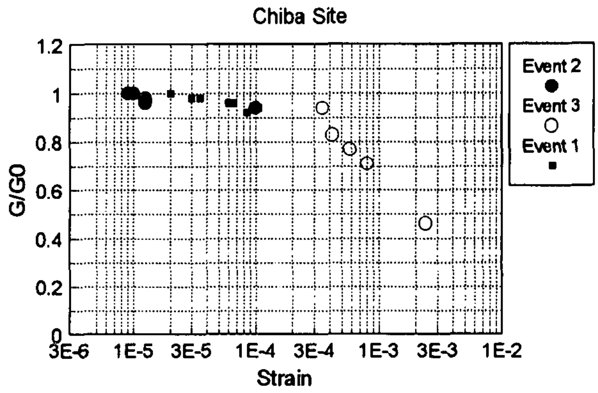

Fig.6 In situ shear strain - shear modulus relationships from the analysis of all events at the site.

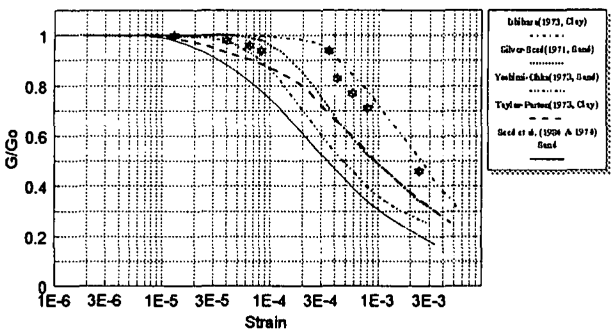

Fig.7 Comparison of actual in situ shear strain-shear modulus relationships and experimental results.

The other conclusion of this study is an attempt to answer whether the in-situ dynamic soil behavior can be duplicated by laboratory analysis up to large shear strains. The comparison of shear modulus - shear strain relationship obtained from all events (Figs. 6 and 7) with laboratory results confirm the assumption that in-situ materials behave similarly.

Finally, the consistency between the results of frequency shifting derived from transfer functions (Fig.2) and calculated shear strain-shear modulus relationships (Fig.6) verified the significance of non-linearity study during strong motions.

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