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Identification of site response using 3-D array records

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ABSTRACT: The purpose of this paper is to study the dynamic characteristics of soil deposits during earthquake excitation. Generally, soil deposits are known to exhibit significant nonlinear behavior under strong earthquake excitation. Observation of soil response between ground surface and downhole data provides informations on soil nonlinearity between strong shaking and weak motion. Based on the evolutionary power spectral analysis, simplified wave type separation can be done. A systematic identification method is proposed to identified the hysteresis behavior of soil deposit. Bilinear hysteretic restoring force with small yield displacement of soil deposit was observed.

1 INTRODUCTION

It is generally agreed that a particular surface accelerogram reflects to some degree the characteristics of the near-surface soil layers at the recording site. This effect of soil conditions on the intensity and frequency content of earthquake ground motions has been extensively studied in recent years (Rõesset 1970; Gazetas 1979; Aki 1988). Because of the lack of noticable local geology and site effects in earthquake records obtained at soil sites, the site response during earthquake remains a great interesting to engineers. Since the installation of SMART-1 array (with extension station on outcropping bedrock: E02) and LSST array (include downhole array: DHA), many earthquake events have been recorded by these two arrays. These data provides a lot of informations to study the effects of dynamic soil behavior on response during earthquakes.

Generally, the analytical model for assessing local site effects has been developed by using 2-dimensional model, and the transfer functions between the free surface and the half-space outcrop for incident P, SV or SH waves from half-space at an incident angle have been derived by many investigators. Since the transfer function between bedrock and soft soil is significantly influenced by the location and path of wave propagation, it is believed that real data should be used to estimate local site effects. To extract the dynamic properties of soil from strong motion records therefore it requires the consideration of soil nonlinearity. Such a problem belongs to the nonlinear system identification. System identification of soils can provide a tool for the estimate of in-situ dynamic characteristics of soil. The procedures available for nonlinear identification is executed in time domain analysis. In the time domain, one is concerned with parameter estimates based on recursive techniques, maximum likelihood and related techniques. The objective of this study is to evaluate the dynamic soil properties during earthquakes by using system identification techniques and the discussion on local soil amplification.

2 EARTHQUAKE OBSERVATION

Taiwan is a part of the Ryuku-Taiwan-Philippine arc system and can be viewed as a tectonic transition zone between two subduction zones with very different geometries. The complicated tectonics leads to high rate of seismicity in Taiwan region. In the Northeast corner of Taiwan, high concentrations of both shallow and intermediate depth earthquakes have been recorded. Because of this fact, the SMART-1 array has been arranged in this area near the city of Lotung in the Lanyang Plain (Hoshiya 1984). In order to study the soil-structure interaction of containment of power plant during earthquake, the Electric Power Research Institute (EPRI) and Taiwan Power Company have jointly constructed a three-dimensional array called LSST array which is located between stations O07 and O08 of SMART-1 array. This dense array also consists of eight downhole accelerometers at depths down to 47 meters and fifteen surface accelerograms. Up to now, many good earthquake data had been recorded by this LSST array which provide data to study the soil-structure interaction as well as the dynamic characteristics of soil. Some events of the recorded earthquakes have been used to study the response of soil deposit during earthquakes.

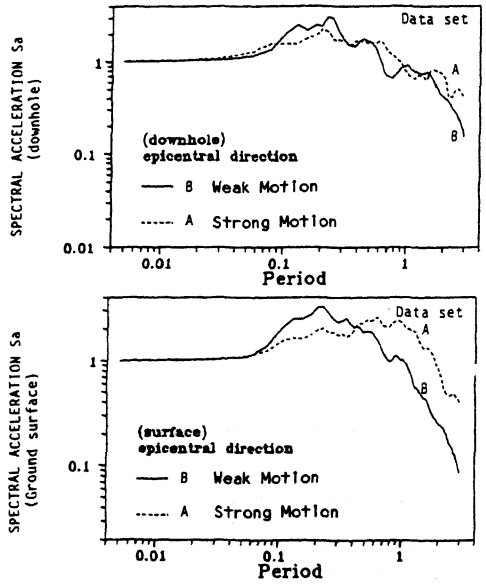

Fig.1 Mean acceleration response spectra of downhole and ground surface seismic data.

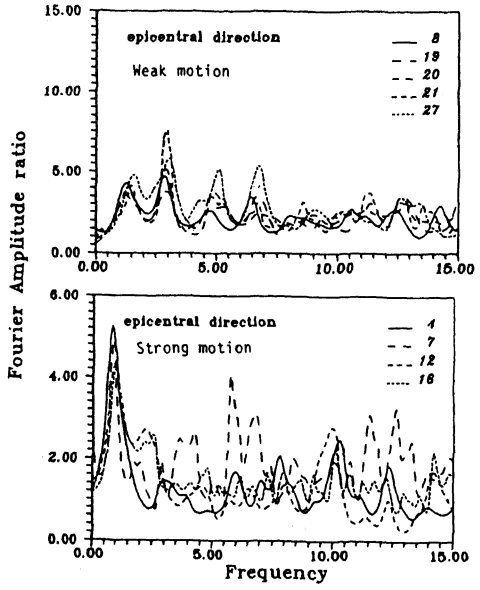

Fig.2 Fourier amplitude ratio between ground surface and downhole for weak motion and strong motion.

2.1 Variation on acceleration spectra

Figure 1 shows the averaged acceleration spectra for two sets of earthquake data of surface ground and downhole, respectively. The set A is picked from strong motion data and set B from weak motion ones. Apparently, the acceleration spectra curves of ground surface are quite different for Data set A from Data set B. Long period waves are observed from surface motion observation in Data set A. The downhole data do not show such phenomenon in long period range. This phenomenum can also be explained as the effect of strong soil amplification as well as the nonlinearity in soil deposit during strong ground shaking.

2.2 Variation of soil amplification

Figure 2 shows the Fourier amplitude ratio between seismic motion of ground surface and downhole, i.e., soil amplification function. The fundamental frequency of soil deposit for different strong motion excitation is not quite similar because of the source effect, path effect and nonlinearity of soil deposit. However, the amplification functions of different events calculated from weak motion are quite similar.

3 EVOLUTIONARY SPECTRA OF SEISMOGRAM

To gain insight into the effect of the depth of relative soft subsurface on the strong ground motion, evolutionary power spectrum analysis (Kameda 1980) can be adopted to separate surface waves and body waves and recognize the amplification of seismic waves between surface and downhole motions during strong motion. Therefore, the evolutionary power spectra generated by multifilter technique in the direction to the epicenter are examined in the following calculation.

Figure 3 shows a typical example of evolutionary power spectra of strong motion records at LSST array site (station FA1-2) based on the 1986 earthquake (event 16). The filter damping β_o has been fixed at $\beta_o = 0.05$ for the calculations of evolutionary spectra of downhole data and surface data. This example shows that the location of focus plays an important role in identifyng the waves. For event 16 (depth $= 6.9\,km$, $\Delta = 77.9\,km$), the depth of fault is quite shallow and surface waves which propagate in multi-layered media and have dispersion characteristics can be roughly separated from body waves. The separation frequency can also be determined at $0.6\,Hz$.

To gain insight about the role of local soil amplification between the soil surface and downhole ($-47\,m$ depth), the peak amplitude of evolutionary power spectra was observed. The amplification is greater for body waves than for surface waves in this example. To make a better understanding on the site response during earthquake excitation, time domain analysis of soil behavior by system identification is executed.

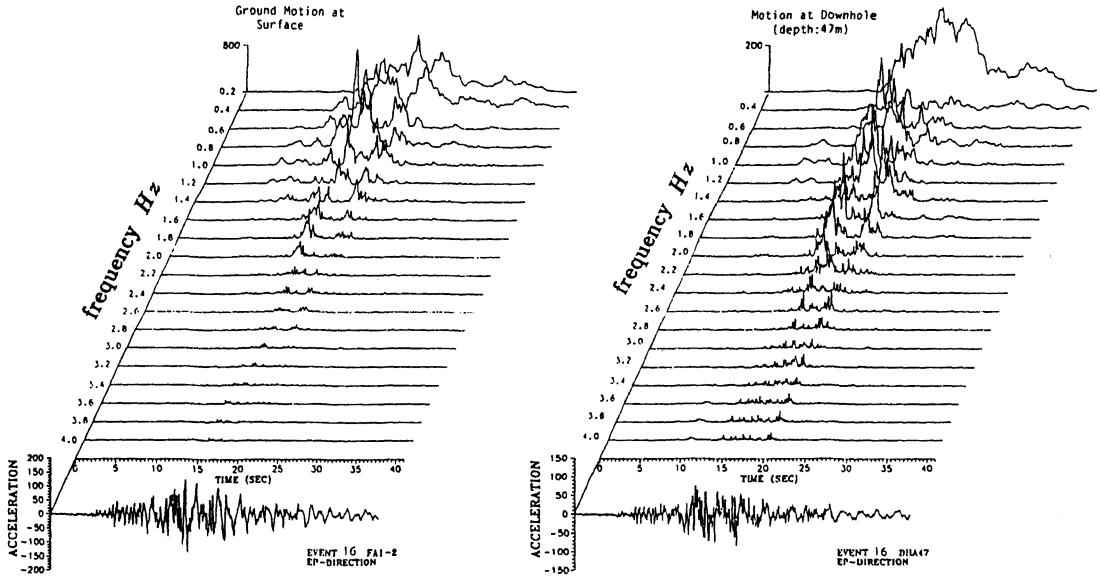

Fig.3 Evolutionary spectrum of Downhole data (DHA) and surface motion data (FA1-2) for Event-16 (November 14, 1986 earthquake) along epicentral direction.

4 TIME DOMAIN IDENTIFICATION ON SITE RESPONSE

To study the nonlinear dynamic characteristics of a soil deposit during earthquake excitation, time domain identification techniques are utilized to analyze the downhole and surface earthquake data. This section presents the approach for evaluating the seismic influences on soil deposit using the sequential regression analysis and the extended Kalman filtering technique. For simplicity, a multilayer soil system subjected to a seismic excitation, and the equation of motion for i-th mode can be written as

$$\ddot{y}_i + q(y_i, \dot{y}_i) = p_i \, \ddot{y}_{N+1} \tag{1}$$

where $\ddot{y}_{N+1}$ is the acceleration at the $(N+1)$-th layer, and $\ddot{y}_i$ is the relative acceleration of i-th mode between the $(N+1)$-th layer and the free surface, $q(y_i, \dot{y}_i)$is the nonlinear or linear soil resistance, and p_i is the participation factor of i-th mode.

4.1 Sequential regression algorithm

This method can take the advantage of the parameter identification methods utilized in the time domain. We apply this method for analyzing the seismic response of soil deposit. Generally, the equation of motion for the system can be written in terms of the state variables and rearranged to solve for the stiffness and damping parameters from time response measurements. For such a system of N degrees of freedom (N layers), equations of motion of the system can be written in the partitioned form (Caravani 1977)

$$[C \quad , \quad K] \begin{pmatrix} \dot{\mathbf{X}}(t) \\ \mathbf{X}(t) \end{pmatrix} = f(t) - M\,\ddot{\mathbf{X}}(t) \tag{2}$$

Define a parameter vector $\hat{p}$

$$\hat{p} \equiv \langle C_1 \cdots C_N \quad , \quad K_1 \cdots K_N \rangle^T \tag{3}$$

This equation (2) can be rearranged and put in the form as

$$H\,\hat{p} = q \tag{4}$$

where H is a $N \times 2N$ matrix and

$$q = f(t) - M\,\ddot{x}(t)$$

If the rank of H equals the dimensions of $\hat{p}$ (or $2N$), a least-squares solution can be found in the form

$$\hat{p} = \left[H^T \quad H\right]^{-1} H^T\, q \tag{5}$$

The least-squares solution can be computed at one time-point and update at the next time-point by means of the recursive formulation. This technique is applied to analyze the seismic data recorded on free-field and at downhole array. Equivalent linear system is assumed for each 4 seconds time interval. The equation of motion of soil deposite for fundamental mode is shown as

$$\ddot{x} = \left[-\dot{x}\,,\ -x\,,\ -\ddot{x}_g\right] \begin{Bmatrix} a_1 \\ a_2 \\ a_3 \end{Bmatrix} = H\,\hat{a} \tag{6}$$

where $\ddot{x}_g$ is the acceleration at downhole where the input is considered.

With the assumption of equivalent linear model for each 4 second interval, Fig. 4 shows the estimated equivalent linear parameters of soil deposit.

For the first four seconds, because the rato of signal to noise is small, so the estimated parameters are not reliable, therefore we estimate the parameters based on the data taken from latter time intervals.

But after 4 seconds the estimated parameters are much more reliable. It is found that the estimated parameters are not constant with respect to time and we may conclude that the response of soil behavior is not linear during those three earthquakes.

4.2 Extended Kalman filter technique

With the same idea of sequential regression, the extended Kalman filter is also used to identify this problem. Consider a discrete linear system described by

$$\begin{aligned} X(i+1) &= \Phi(i+1,i)\ X(i) \\ Y(i) &= H\ X(i) + \eta(i) \end{aligned} \tag{7}$$

where $X(i)$ is an m-dimensional state vector, $Y(i)$ is an n-dimensional observation vector, $\Phi(i+1,i)$ is the nonsingular state transition matrix of the system, and $\eta(i)$ is an n-dimensional noise vector which is assumed to be independent of $X(i)$ and a white Gaussian noise with zero mean and nonzero covariance matrix. To obtain state solutions and their fast convergency to the optimal ones, the weighted global iteration procedures are used (Kameda 1980). If one considered the vibration of soil deposit as a single-degree-of-freedom nonlinear system, its equation of motion can be represented as

$$\ddot{y} + f(y,\dot{y}) = -p_f\ \ddot{x}_g \tag{8}$$

in which $\ddot{y}$ is the relative acceleration between the input and output, and $\ddot{x}_g$ is the input acceleration. In order to reflect the elasto-plastic forces as a consequence of the deformation of the system in both loading and unloading processes, the restoring force $f(y,\dot{y})$ appearing in hysteretic loop is assumed to be a piecewise linear function of y and may be represetned mathematically by the set of equation as

$$f(y,\dot{y}) = \bar{c}\ \dot{x} + \tilde{h}(y) \tag{9}$$

where $\bar{c}$ is the linear viscous damping, $\tilde{h}(y)$ is a path-dependent function.

For the analysis in this paper, we adopt the bilinear hysteretic model to representing the path-dependent character. Three parameters adopted in this model are k_1 = initial elastic stiffness, y_d = yielding displacement and k_2 = stiffness after yielding. The unloading stiffness is the same as the initial elastic stiffness. The state vector for this system can be expressed as

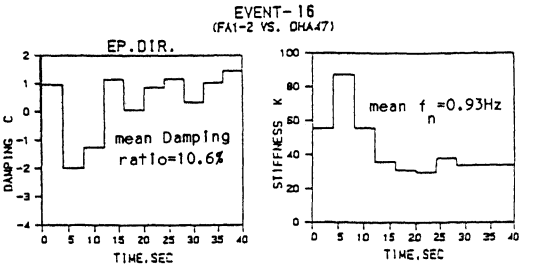

Fig.4 Estimated model parameters (damping and stiffness) of equivalent linear system by sequential regressional analysis.

$$\bar{x} = \begin{Bmatrix} x \\ \dot{x} \\ c \\ k_1 \\ k_2 \\ y_d \\ A \end{Bmatrix} \equiv \begin{Bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_7 \end{Bmatrix} \tag{10}$$

and

$$\dot{\bar{x}} = \begin{Bmatrix} x_2 \\ -x_2 x_3 - h - x_7 \ddot{x}_g \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{11}$$

The result of the analysis for event 16 shows that the linear model can not correctly represent the soil behavior during strong shaking. On the other hand, the bilinear model can represent the soil restoring force more accurately. Figure 5 shows the comparison in time domain response between predicted and the recorded motion. The errors among them are much smaller if the bilinear model is used to repressent the soil restoring force. It should be noted that the yield displacement of soil deposit at this site is small ($< 0.3\ cm$) and the consideration of nonlinear behavior of soil deposits subjected to strong motion is essential in this analysis.

5 CONCLUSIONS

Based on the seismic data on vertical array of LSST array, the identification has been made and the following conclusions are drawn:

(1) The comparison between the weak motion and strong motion on spectral amplitude and soil amplification shows that the significant difference between these two motions is quite obvious. For strong motion, the soil amplification function caused by different earthquakes are not similar. This can be considered as the significant influence of source mechanism and the path of propagation on the local soil amplification.

(2) The evolutionary power spectral analysis on surface and downhole accelerogram can separate body waves and surface waves. In the present

study, soil amplifications of this specific site caused from this event is mainly generated by body waves.

(3) Based on the results of system identification

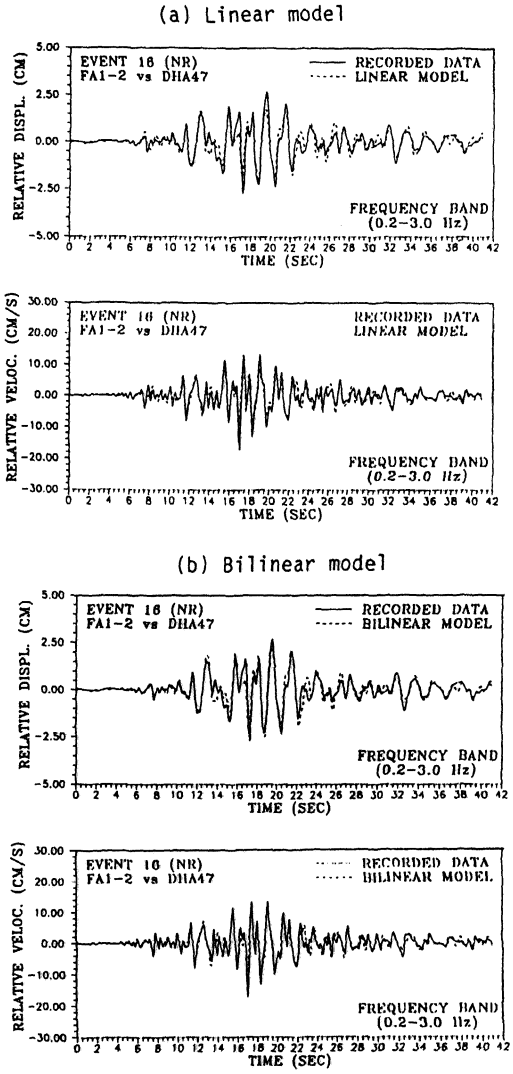

Fig.5 Comparison between the estimated and recorded ground motion data; (a) Using linear model; (b) Using bilinear model.

on soil response during strong earthquakes, it can be shown that the restoring force of soil deposit can be predicted with bilinear hysteretic model. From the analysis, it is found that the yield displacement of soil deposit at the specific site is small (less than 0.3 *cm*) and the consideration of nonlinear behavior of soil deposit is essential when it is subjectedto strong motion.

(4) The effect of source mechanism and source to site distance (path effect) have significant influence on the soil amplification. It may not be possible to use any simple theoretical model to estimate these effects on local site amplification.

Table 1: Results of identified model parameters for Event-16 (Nov 14, 1986 earthquake) downhole data.

Event 16 (0.0 Hz ~ 3.0 Hz)						
Model	Dir.*	C	K_1	K_2	Y_d	P_a
Linear	EP	1.3601 (12.12%)	31.531 (0.893Hz)	——	——	1.2785
	NR	1.8701 (15.61%)	35.882 (0.953Hz)	——	——	1.6188
Bilinear	EP	0.1051 (0.69%)	56.860 (1.20 Hz)	25.252 (0.799Hz)	0.315	1.3026
	NR	0.9333 (0.64%)	52.564 (1.154Hz)	29.852 (0.869Hz)	0.262	1.5530

* Dir. = Data transform to either epicentral or normal to epicentral direction.

ACKNOWLEDGEMENTS

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