THE APPLICATION OF AFMM AIDED SYSTEM IDENTIFICATION ON GROUND VIBRATION MONITORING DATA ANALYSIS

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ABSTRACT :

The parametric system identification method has been used to construct soil layer models and compute average model parameters of the ground vibration monitoring data at ChingLiao. However, from the laboratory tests, the results show that the dynamic properties of soil are not always constant. An important goal of this study is to verify the soil properties changing with time. Before analyzing the data set, it is segmented into time-variant and time-invariant parts by adaptive forgetting through multiple models method (AFMM). Soil properties are estimated by both time-variant and time-invariant parametric modeling methods showing changes of system parameters. The results of this study show that the AFMM can reduce the error of estimation for time-variant model and has advantages of sorting data set in analysis. The modal frequencies decrease during main shaking area after a certain threshold strain and they are relevant to earthquake intensity. Damping ratios might be underestimated without segmentation while modal frequencies might be overestimated. The results show that there is a limit for linear time-variant models to identify earthquakes above seismic intensity 6. If non-linear time-variant models can be used to simulate the strong ground motion, the result would be more accurate.

KEYWORDS: **EARTHQUAKE, SOIL PROPERTIES, SYSTEM IDENTIFICATION, AFMM.**

1. INTRODUCTION

Seismic Hazards induced by soil liquefaction during earthquakes are common, with many incidents during the 921 Chi-Chi earthquakes in 1999. Many structures and transportation facilities were damaged due to soil liquefaction during this earthquake. After that, there are many studies on soil liquefaction behavior and soil liquefaction potential evaluation in Taiwan. However, the soil behavior observed in laboratory tests has to be verified with in-situ test results or monitoring data. Although there were many liquefaction cases during the 921 Chi-Chi earthquakes in Taiwan, none of in-situ liquefaction monitoring vibration and pore water pressure history data was retrieved due to the lack of downhole monitoring instrumentation at that time. Besides, the in-situ seismic responses and liquefaction criteria for the soils during earthquakes are still not known very well. Most of in-situ liquefaction studies were post-liquefaction analysis, and the process from in-situ pre-liquefaction to liquefaction is an important area of study. The installation of in-situ soil liquefaction monitoring systems is necessary and urgent at this time.

Seismic downhole array data provide a unique source of information on actual soil behavior and local site amplification [Chang et al., 1996, Elgamal et al., 2001, Ysujihara et al., 1990, Wang et al., 2001]. Currently, downhole arrays are being increasing deployed on a worldwide scale. Compared with the existing array, this downhole instrumentation is on a small scale, and is specially for monitoring soil liquefaction in the soil deposit. A total of six holes were drilled in this geotechnical downhole array. Besides the surface triaxial accelerometer, three holes were for three depths of low frequency triaxial accelerometer. Two holes, each with two depths, were installed with pore water pressure transducers for monitoring excess pore water pressure. One hole was installed with a Sondex settlement system to measure the ground settlement after soil liquefaction. All the sensors were installed in August 2003. The purpose of this paper is to present the installation of downhole liquefaction instrumentation in the soil deposit for studying the soil behavior during earthquake. The data measured from monitoring system of the downhole array is used to calculate the soil dynamic parameters with the parametric system identification. An important goal of this study is to verify the soil properties changing with time. Before analyzing the data set, it is segmented into time-variant and time-invariant parts by adaptive forgetting through multiple models method (AFMM). Soil properties are estimated by both time-variant and time-invariant parametric modeling methods showing changes of system parameters. There are two larger earthquakes to be recorded and analyzed in this paper.

2. INSTALLATION OF INSTRUMENTATION

The site located at Chingliao, Hobee, Tainan, Taiwan was selected for the downhole soil liquefaction instrumentation. The map of the site is shown in Figure 1. As shown in this figure, Chingliao is located in southwestern Taiwan. The soil in the rice field in the site was in liquefied many places during the Chiayi earthquake that happened on October 22, 1999. The Chiayi earthquake happened just one month after the 921 Chi-Chi Earthquake occurred. The site is located beside Bachang River. The ground water table is generally located at a shallow depth. The soil deposits have an alluvium profile, and the region is part of Chia-Nan Plain, the coastal plain of western Taiwan. Alluvial deposits of clay, silt, sand, and gravel cover the coastal plains in Taiwan. The alluvium is the flood plain of many leading streams, such as Bachang River at the site. The alluvial soils are generally loose, and are very susceptible to soil liquefaction.

There are sixteen sensors installed in this location to fit the sixteen channels of the Analog-to-Digital converter card. The sensors include a ground surface three-directional accelerometer, three subsurface three-directional accelerometers and four pore water pressure transducers placed at four different depths to serve as a real-time liquefaction monitoring system. To measure the ground settlement induced by soil liquefaction, a Sondex settlement system was installed in this site. The specifications of these sensors are described below.

The triaxial accelerometers used are manufactured by Tokyo Sokushin Co. The model number of VSE-355T is for the surface accelerometer while the model number of VSE-355 is for the subsurface accelerometer. The frequency response of these accelerometers is from 0.018 to 100Hz. The range of measurement is ±2000gal, with sensitivity of 5mV/gal. The surface triaxial accelerometer has a waterproof capacity of 3kgf/cm^2 while the subsurface triaxial accelerometer has a waterproof capacity of 30kgf/cm^2. The downhole triaxial accelerometers were installed at depths of 8.2m, 10.5m and 31m, respectively.
The Data acquisition system in this project includes a personal computer with a one hour uninterruptible power system (UPS) and NI-6034E sixteen channels A-to-D converter. The NI-6034E A/D converter is manufactured by National Instruments. It is a 16-bit, 16 channels multifunction DAQ with continuous high-speed data logging at up to 200kS/sec. The sampling frequency is set to 512Hz in the soil liquefaction monitoring system. The time history data is saved with the name of the completed time as “mmddhhnn.tim”.

3. DATA ANALYSIS METHODS

This study uses system identification (SI) to analyze the retrieved data from monitoring station. The main purpose of system identification is to model the solving system by providing mechanical data or parameters. This technology is developed from the field of electronics or mechanics. The simple model is constructed of weighted polynomials, where the weights represent the relative input and output parameters. System parameter modeling involves inversion of input and output data for a statistical, parametric model of a predetermined form. The data measured from monitoring system of the downhole array is used to calculate the soil dynamic parameters with the parametric system identification. The goal of this study is to verify the soil properties changing with time. Before analyzing the data set, it is segmented into time-variant and time-invariant parts by adaptive forgetting through multiple models method (AFMM). Soil properties are estimated by both time-variant and time-invariant parametric modeling methods showing changes of system parameters. In this study the soil properties in the time-variant segment are estimated by RARX (Recursively the parameters of an ARX) model while the soil properties in the time-invariant segment are estimated by ARX (Auto-Regressive with eXogenous variables) model.

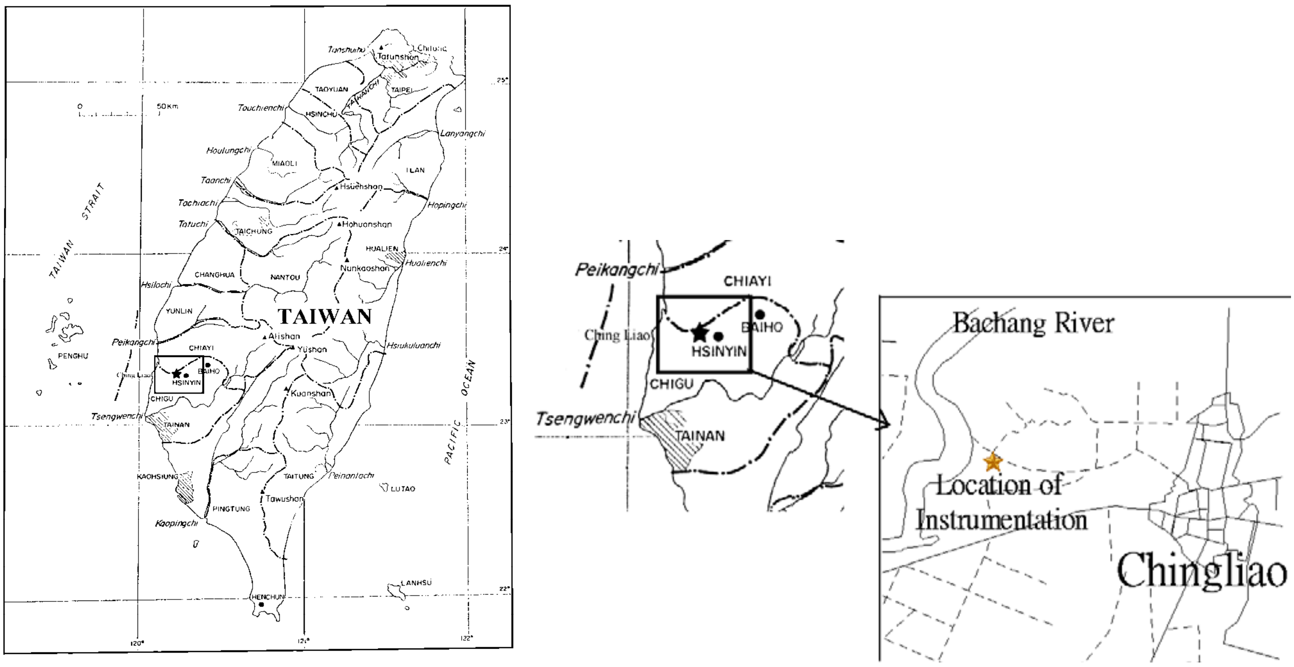


Figure 1 Location of Chingliao site

A simple model for characterizing a system is a polynomial mapping between system input and output. One such model, referred to as an autoregressive-moving average model with exogenous noise, characterizes the system as a weighted polynomial of past outputs (AR) and past and present inputs (MA) (e.g. Kanasewich 1981) with noise added as a direct term. Because every model is a combination of inputs, the moving average portion of inputs is certain and is not related to the naming of model. The following model is generally called an ARX model.

$$y_i = a_1 y_{i-1} + a_2 y_{i-2} + \cdots + a_{na} y_{i-na} + b_1 x_{i-1} + \cdots + b_{nb} x_{i-nb} + e_i = \sum_{j=1}^{na} a_j y_{t-j} + \sum_{j=1}^{nb} b_j x_{t-j} + e_i \qquad (3.1)$$

Where y is the actual output data sequence, x is the input sequence, a's and b's are the AR and MA parameters, respectively, e is the noise term, and the subscript is the time step counter. The output is seen as a combination of the input history acted upon by the "*b*" coefficients and the past outputs acted upon by the "*a*" coefficients. The input series, involving the "*b*" coefficients, is a noncausal moving average (MA) feed-through process (convolutional). The series involving weighted past output values ("*a*" coefficients) is a causal autoregressive (AR) process. The input and output time histories both contain all motions at their respective locations including reflections (downgoing and upgoing waveforms). The reflections (from stratigraphy) are a site property and are inherently accounted for by the inverse model. In fact, it has been shown by several authors (Goupillaud 1961; Claerbout 1968; Robinson and Treital, 1978) that seismic transmission through a layered system (e.g. stratigraphic column) is an autoregressive process.

Before analyzing the data set, it is segmented into time-variant and time-invariant parts by adaptive forgetting through multiple models method (AFMM). For a the time-discrete system, it can be presented as the following state space model:

$$\left.\begin{aligned} \theta_0(t+1) &= \theta_0(t) + w(t) \\ y(t) &= \varphi^T(t)\theta_0(t) + e(t) \end{aligned}\right\} \tag{3.2}$$

Where $e(t)$ and $w(t)$ are noise term. The system is time-variant as the covariance of $w(t)$ is not zero and the average is zero (Gaussian's distribution). The system is time-invariant as the covariance of $w(t)$ is zero and the average is zero. The typical result using AFMM to segment the data is shown in Figure 2. As shown in Figure 1, Zone I (time from the earthquake beginning recorded to the ground beginning to shaking) is time-invariant segment. The soil properties in the time-invariant segment are estimated by ARX model. Zone II (time from the ground beginning to shaking to the ground stop shaking) is time-variant segment. The soil properties in this segment are estimated by RARX model. Zone III (time from the ground stop shaking to the data stop recording) is time-invariant segment. The soil properties in this segment are estimated by RARX model. Therefore, each earthquake data record is divided to three parts to be analyzed. The variation of frequency and damping ratio for each zone are studied. The typical result for the segmented data is shown in Figure 3(a). The typical result for the un-segmented data is shown in Figure 3(b).

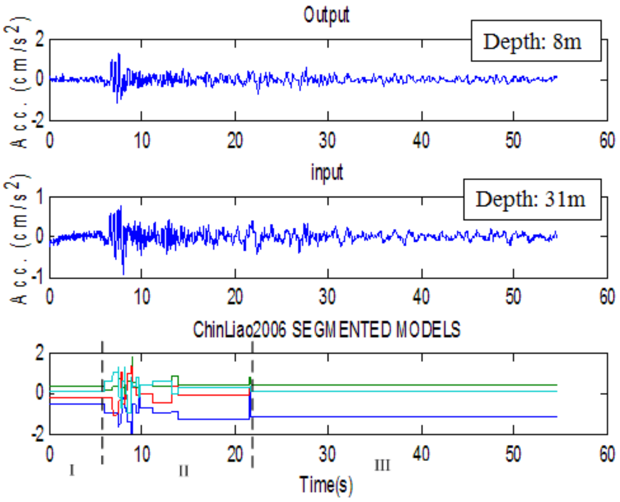
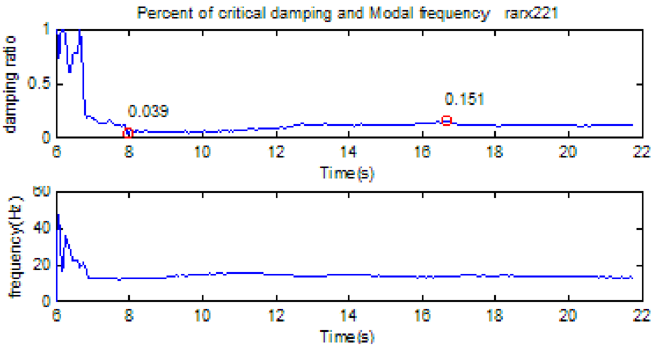
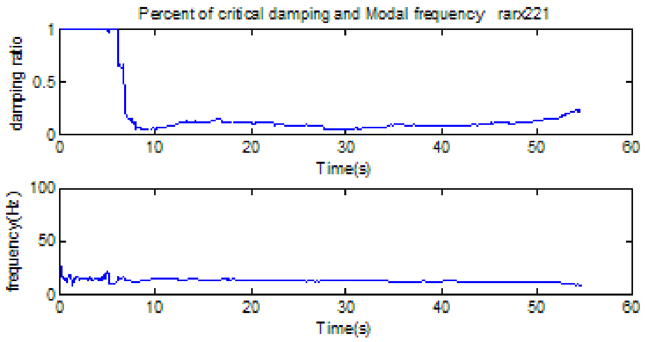


Figure 2 Typical result for data segmented using AFMM



(a) Result in time-variant zone (segmented)



(b) Result in time-variant zone (un-segmented)

Figure 3 Typical analysis results

4. RESULTS AND DISCUSSIONS

The data analyzed in this paper are from two earthquake events. The first event was scaled at a Richter Magnitude of 4.6 and occurred on April 12, 2005. The epicenter was located about 4.5km of the east of the Doneshan Station, Tainan, while the hypocenter was located at the depth of 5.2 km. The second event was scaled at a Richter Magnitude of 5.1 and occurred on June 4, 2006. The epicenter was located about 16.8km of the northeast of the Taidone Station, while the hypocenter was located at the depth of 21.8 km.

The difference between measured data and simulated data are compared to obtain the identification result. The goodness of fit is defined as:

$$fit = \left[1 - \frac{\sqrt{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}}{\sqrt{\sum_{i=1}^{N} (y_i - \mu)^2}} \right] \times 100\% \tag{4.1}$$

$$\mu = \frac{\sum_{i=1}^{N} y_i}{N} \tag{4.2}$$

Where y_i = the actual output data series; $\hat{y}_i$ = the simulation output data series.
The data of different soil layers from the two earthquakes were analyzed by 2 orders (*na* = *nb* = *nc* = 2), 4 orders and 6 orders to obtain the identification results. They are shown in the figure 4 to figure 7. As show in the figures, the fit increases as the order increases. Besides, the greater the earthquake is, the better identification result can be obtained.

Glaser (1996) has suggested that the method of using the transfer function to obtain the soil parameters. The modal frequencies ω_j and damping ratio ξ_j (Ghanem et al., 1991) can be obtain from the pole of transfer function, which represented the system. They are defined as

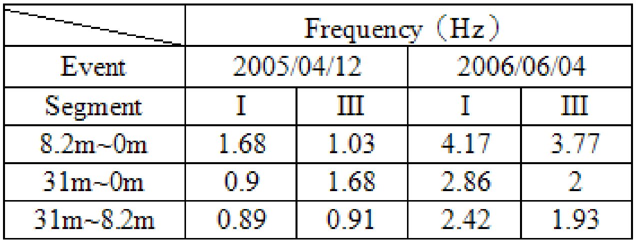
$$\omega_j = \frac{\sqrt{\lambda_j^2 + \delta_j^2}}{\Delta t} \tag{4.3}$$

$$\xi_j = \frac{\delta_j}{\sqrt{\lambda_j^2 + \delta_j^2}} \tag{4.4}$$

Where $\lambda_j = Arg(z_j)$, $\delta_j = -(0.5)\ln\left|z_j\right|^2$, z_j is the pole for the mode j, and Δt is the sample interval. The modal frequencies and damping ratios which determined from the pole are shown in Table 1 and Table 2 respectively. Comparing with the fundamental resonant frequency, we can know that the resonant frequency will be greater while the layer is closer to the surface. For the deeper layer, the resonant frequency will be lower and changing slightly. The east-west direction and the north-south direction have the same trend. The difference of resonant frequency between the E-W direction and the N-S direction is about 0.3Hz while the layer is closer to the surface, and it is almost the same as that of the deeper layer. Beside. The resonant frequencies of the event-2006-06-04 are higher than those of the event-2005-04-12. The resonant frequencies in zone III are a little bit lower than those in zone I. It may be cause by the main shock (amplitude) in zone II. Results also show that the resonant frequency is related to the earthquake intensity. The resonant frequency is lower as the earthquake intensity is higher. The damping ratios of this site are calculated and are shown in Table 2. From the Table 2, it can be known that the damping ratio is greater for deeper soil layer.

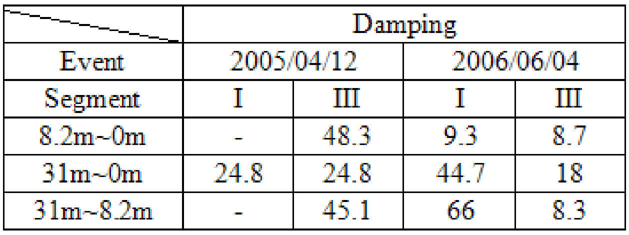
The system identification results for the two events (event-2005/04/12 and event-2006/06/04) for various soil layers are shown in Figure 4 to Figure 7. Each figure presents the result of each segmented zone, the goodness of fit, the frequencies and damping ratios calculated, and relative displacement. The parameters calculated belong to high mode value. It is not used in the practical purpose. As shown in the figures, the damping ratios are related to relative displacement. The damping is become to higher if the relative displacement goes up. The maximum strain is decreased with depth and thickness of soil layer.

Table 1 Fundamental resonant frequency.



	Frequency（Hz）			
Event	2005/04/12		2006/06/04	
Segment	I	III	I	III
8.2m~0m	1.68	1.03	4.17	3.77
31m~0m	0.9	1.68	2.86	2
31m~8.2m	0.89	0.91	2.42	1.93

Table 2 Damping ratio.



	Damping			
Event	2005/04/12		2006/06/04	
Segment	I	III	I	III
8.2m~0m	-	48.3	9.3	8.7
31m~0m	24.8	24.8	44.7	18
31m~8.2m	-	45.1	66	8.3

5. CONCLUSIONS

From this study, the following conclusions can be drawn:

1. The system is assumed to be a linear time-invariant in the parametric system identification. The identification result is not good for the farer distance between two receivers, which corresponds to the thickness of soil layer. This implies that to obtain a good result, the soil layer between two receivers should not be too far away, and the soil properties should be homogenous. Besides, it will get better result when the earthquake is stronger, that is because the monitoring system received higher signal-to-noise ratio data.
2. As results shown, frequency response is related to the earthquake intensity. The resonant frequency is lower for the stronger earthquake intensity.
3. Damping is calculated using RARX model in time-variant segment in the 2005/04/12 event. The results show that the damping is ranged from 50% to 70% for large relative movement. However, the damping is dropped to the range from 5% to 10% for low relative movement. The frequencies obtained from time-variant segment belong to the high mode. It is not the first and second mode in practical usage.
4. The damping changing with time is insignificant for the low intensity (seismic intensity 2) case in the 2006/06/04 event.

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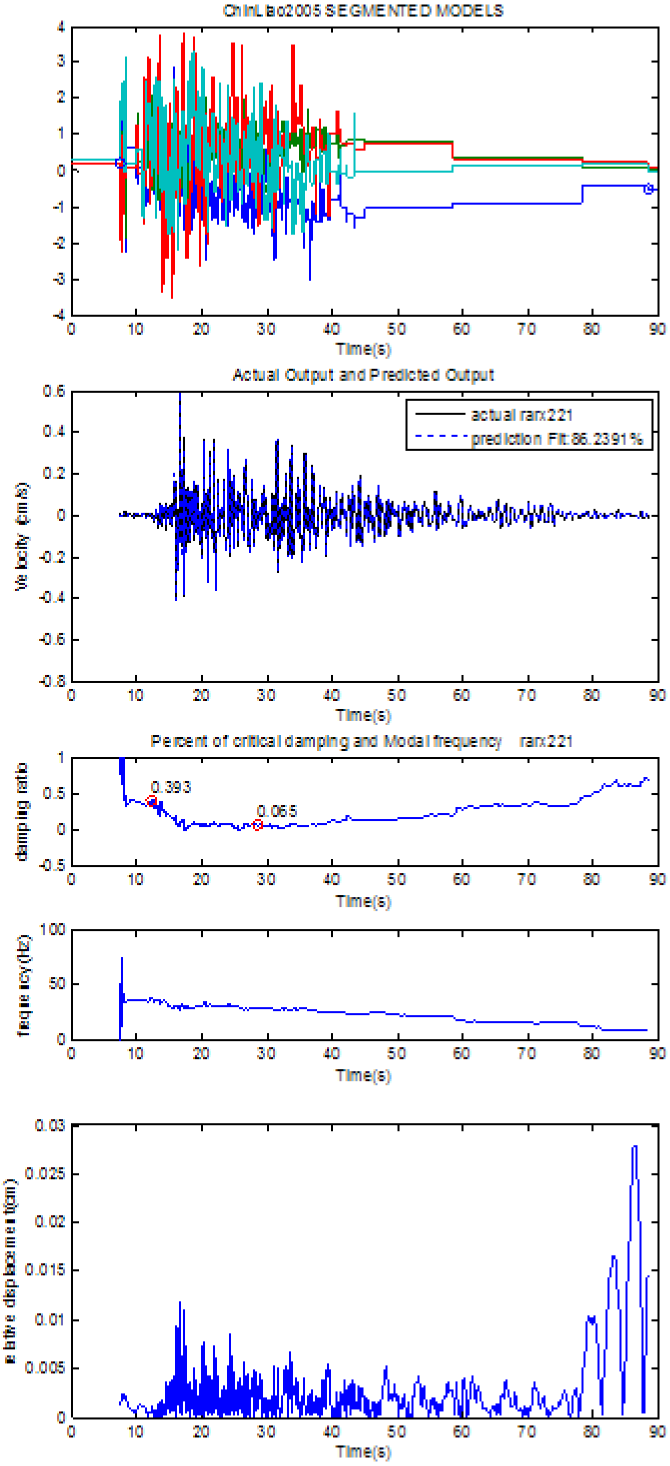

Figure 4 2005/04/12 EW direction (8.2m-0m)

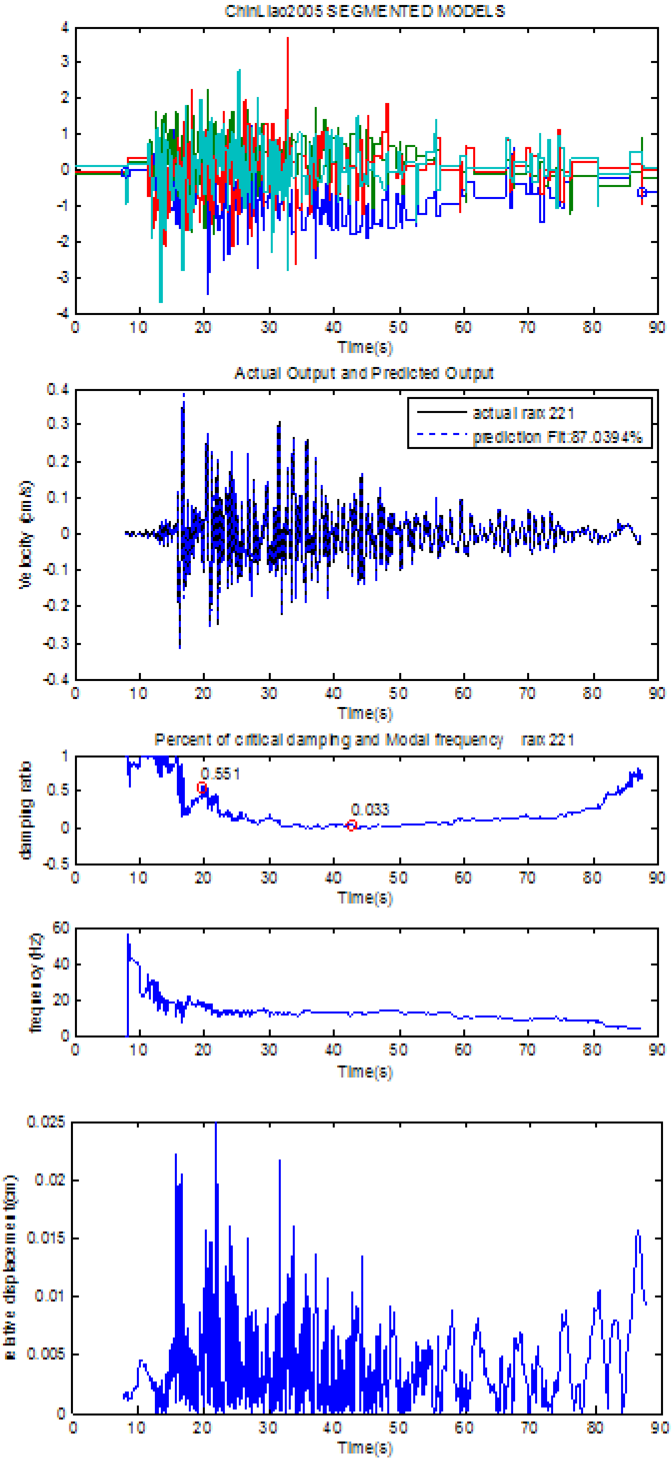

Figure 5 2005/04/12 EW direction (31m-8m)

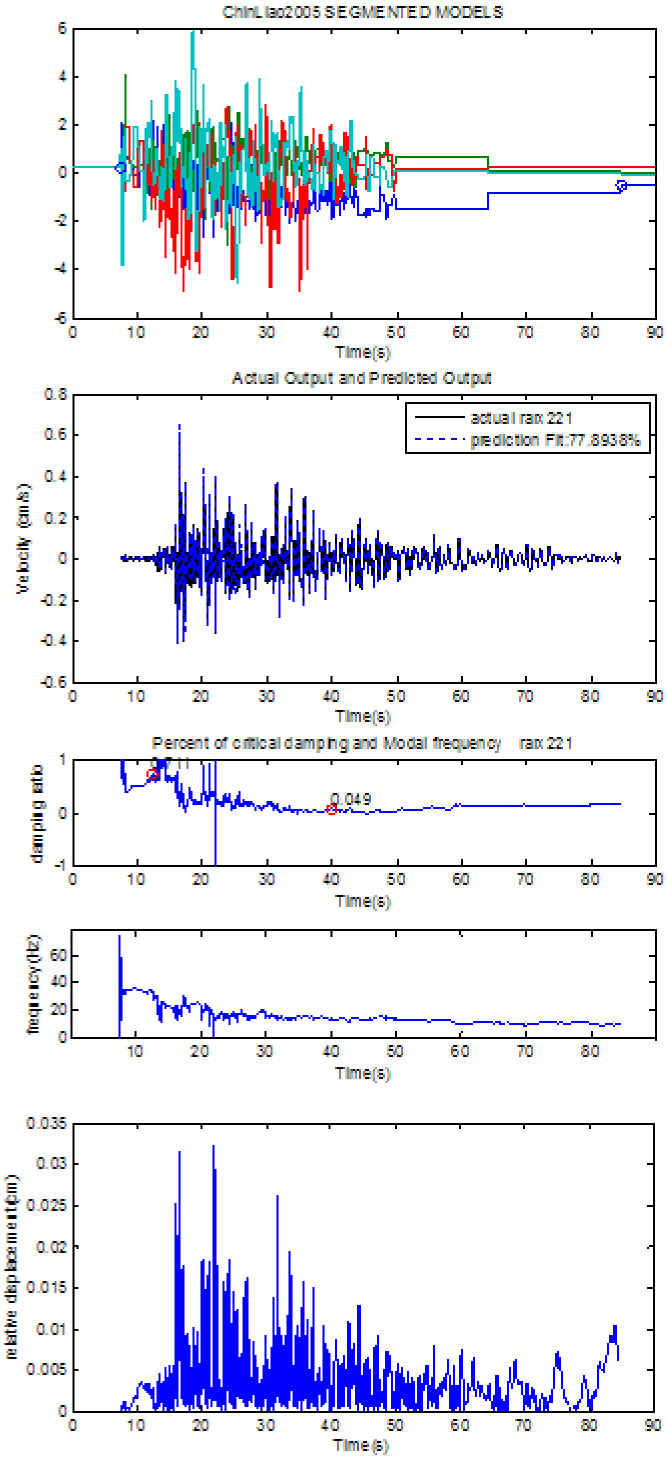

Figure 6 2005/04/12 EW direction (31m-0m)

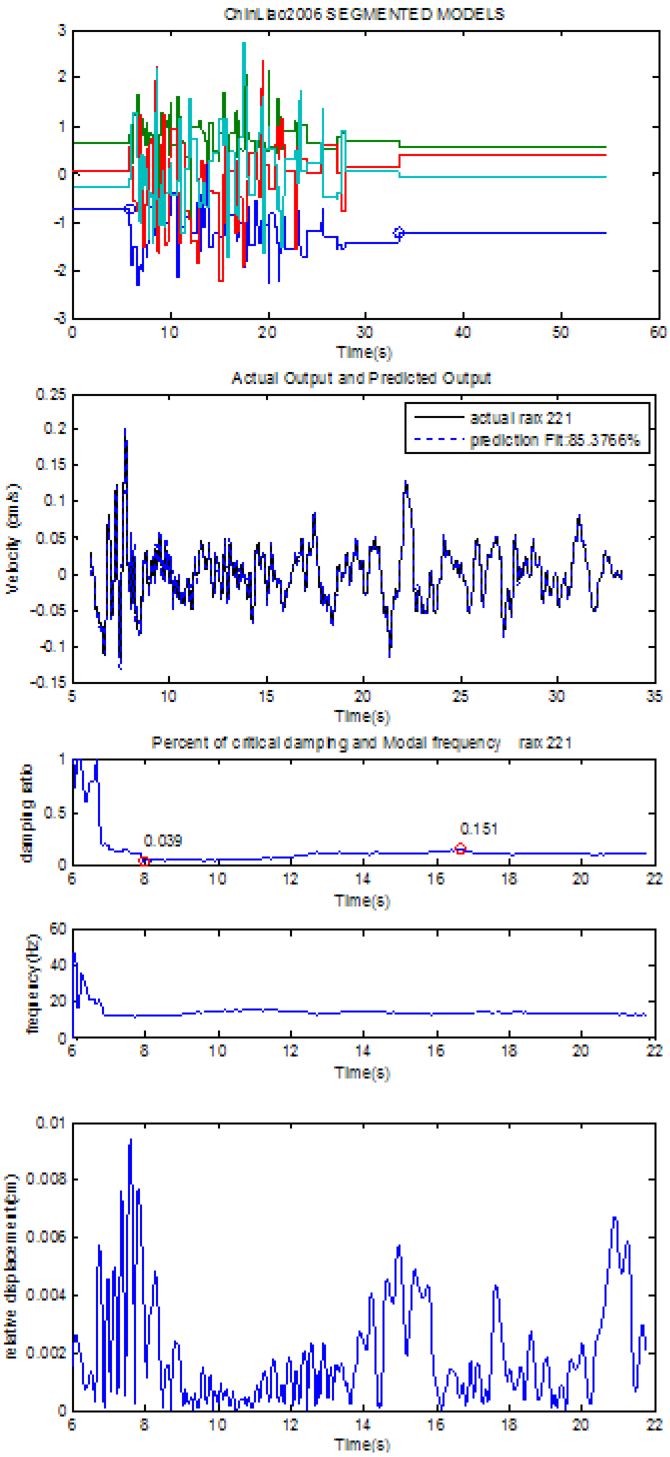

Figure 7 2006/06/04 EW direction (31m-0m)