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DOWNHOLE MONITORING INSTRUMENTATION AT CHINGLIAO SITE AND ITS MONITORING DATA ANALYSIS

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ABSTRACT

The in-situ liquefaction monitoring downhole array was installed at Chingliao, Hobee, Tainan, by the liquefaction research group funded by National Science Council in July, 2002. One surface triaxial accelerometer, three depths low frequency triaxial accelerometers, and four pore water pressure transducers were installed in this site. The pore water pressure and seismic response at ground surface and within the soil deposit induced by earthquake will be monitored in full time using personal computer. The monitoring system is now working and waits to be triggered whenever the ground motion is big enough to trigger the recording system. 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 and Hilbert-Huang transform method. The study shows that the analytic result is relevant to model order, the intensity of earthquake, the distance between receivers, and the relation among the frequency component of the earthquake, time and amplitude in Hilbert-Huang transform result. The resonant frequency of soil can be estimated for structural design preliminarily by linear-invariant system identification.

Keywords: soil dynamics, downhole array, instrumentation, system identification.

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.

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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 and Hilbert-Huang transform method. There were two larger earthquake to be recorded and analyzed in this paper.

THE CHINGLIAO SITE, TAIWAN

Site Description

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. One of the sand boils in the liquefaction at Chingliao is shown in Figure 2. 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.

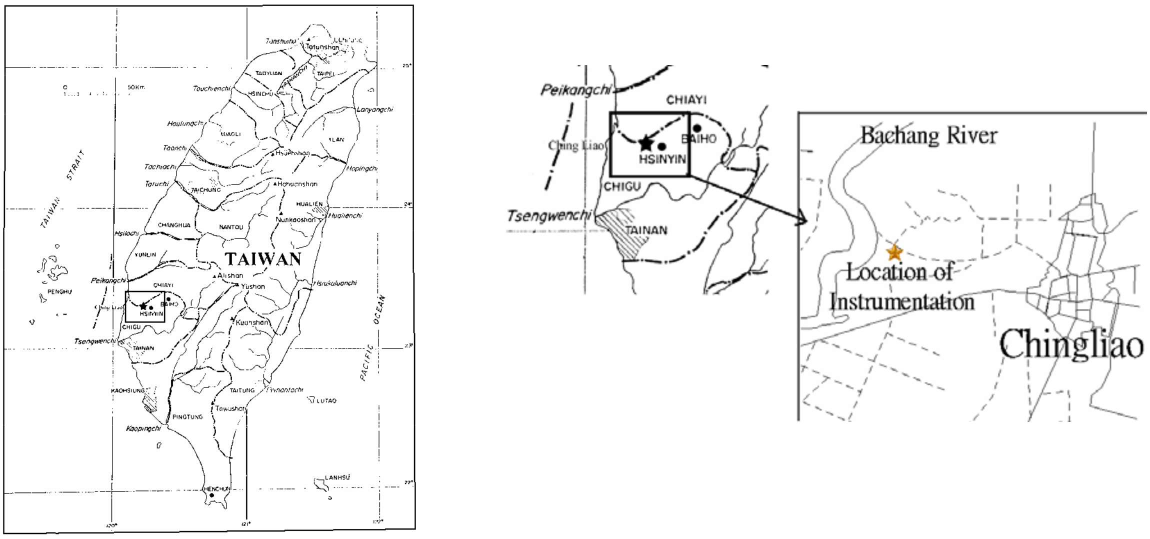

Figure 1. Location of Chingliao site

Instruments Installed at Site

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.

Figure 2. Sand boils in a rice field at Chingliao during the Chiayi earthquake

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”.

DATA ANALYSIS METHODS

Parametric System Identification

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. This model is one kind of parametric autoregressive moving average (ARMA) model. It is an analysis of discrete time series, and can be written as follows:

$$y_t = a_1 y_{t-1} + a_2 y_{t-2} + \ldots + b_0 x_t + b_1 x_{t-1} + \ldots \qquad (1)$$

Where y_j = the actual output data series; x_j = the input data series; t = the time step counter.

Generally speaking, ARMA model will efficiently simulate the plate moving time history induced by an earthquake. The method has also been used in the analysis of vertical array earthquake data with a horizontal layered system. ARMAX (Auto-Regressive Moving Average eXogenous input) which used in this study is extension of this model. For this model, the moving average of the white noise is considered. It can be written as

$$\begin{aligned} y_t &= a_1 y_{t-1} + a_2 y_{t-2} + \ldots + b_0 x_t + b_1 x_{t-1} + \ldots + c_1 e_{t-1} + c_2 e_{t-2} + \ldots \\ &= \sum_{i=1}^{na} a_i y_{t-i} + \sum_{j=0}^{nb} b_j x_{t-j} + \sum_{k=1}^{nc} c_k e_{t-k} \end{aligned} \tag{2}$$

Where *e* is white noise, and *na*, *nb* and *nc* are the AR , MA and white noise orders respectively.

Hilbert-Huang Transform

Another method used in this study is Hilbert-Huang Transform(HHT). It is decomposed the arbitrary time series signal into many Intrinsic Mode Functions (IMF) by the method of Empirical Mode Decomposition (EMD) method. In order to find the instantaneous frequency and amplitude, the IMF is taken as the basis to proceed the Hilbert transform. And, then the signal can represent the instantaneous variation and characteristics. The analytic flow chart is shown in Figure 3.

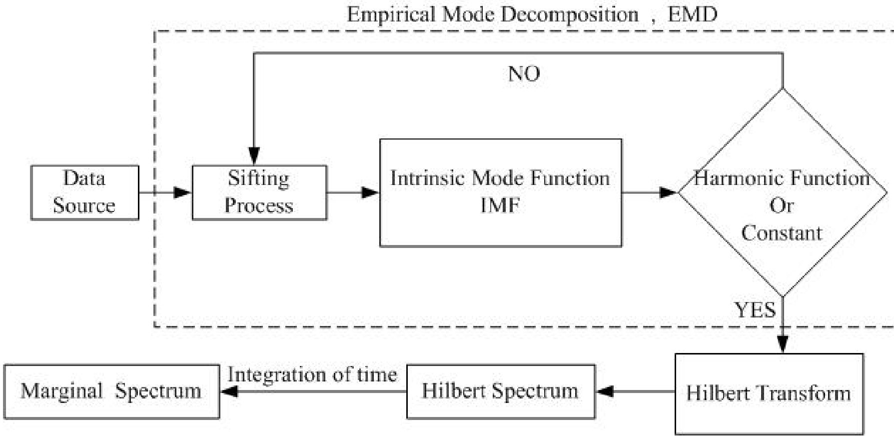

Figure 3. Flow chart of Hilbert-Huang Transform

The IMF must satisfy two conditions. The number of extrema and the number of zero crossings must either equal or differ at most by one in the whole data set. And the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero at any point.

At any time, it is possible to contain more than one vibration mode. The EMD method can decompose the data into many IMF components. The EMD is according to the experience to identify the intrinsic vibration modes by their characteristic time scales, and then it decomposes the data systematically. This process calls the sifting process.

Let $X(t)$ be a time series signal. And, it can be decomposed into n-IMF and a remainder *r*, which can be a mean trend or constant by repeating the sifting process. The equation can be expressed as

$$X(t) = \sum_{i=1}^{n} c_i + r_n \tag{3}$$

The process stops as long as the *r* becomes a harmonic function, and can not be decomposed any more IMF component.

HHT offers a method to define $Y(t)$ that is the convolution of $X(t)$ and $1/t$. It is obviously that the meaning of HHT is to lay emphasis on the partial characteristics of $X(t)$. $Y(t)$ is expressed as

$$Y(t) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{X(\tau)}{t-\tau} d\tau \tag{4}$$

Where $Y(t)$ is Hilbert Transform of $X(t)$, $X(t)$ is the time series, and PV is Cauchy principal value. By forming $X(t)$ and $Y(t)$ into the complex conjugate pair, one can obtain an analytic signal $Z(t)$ as

$$Z(t) = X(t) + iY(t) = a(t)e^{i\theta(t)} \tag{5}$$

Where $a(t) = \left[X^2(t) + Y^2(t)\right]^{\frac{1}{2}}$, and $\theta(t) = \tan^{-1}\frac{Y(t)}{X(t)}$.

Instantaneous frequency is defined as

$$\omega(t) = \frac{d\theta(t)}{dt} \tag{6}$$

After performing Hilbert-Huang Transform on every IMF component, the data can be expressed as

$$X(t) = \sum_{j=1}^{n} a_j(t) e^{i\int \omega_j(t)dt} \tag{7}$$

The equation (7) represents the instantaneous frequency and amplitude as a function of time in a three-dimensional plot. The amplitude-frequency-time plot is the Hilbert Amplitude Spectrum $H(\omega, t)$, simply called the Hilbert Spectrum.

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:

$$fit = \left[1 - \frac{\sqrt{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}}{\sqrt{\sum_{i=1}^{N} (y_i - \mu)^2}} \right] \times 100\% \tag{8}$$

$$\mu = \frac{\sum_{i=1}^{N} y_i}{N} \qquad 9)$$

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

$$\omega_j = \frac{\sqrt{\lambda_j^2 + \delta_j^2}}{\Delta t} \tag{10}$$

$$\xi_j = \frac{\delta_j}{\sqrt{\lambda_j^2 + \delta_j^2}} \tag{11}$$

Where $\lambda_j = Arg(z_j)$, $\delta_j = \text{-}(0.5)\ln\left|z_j\right|^2$, 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 show 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 lower than those of the event-2005-04-12 about 0.1~0.2Hz.

From the Table 2, it can be known that the damping ratio of this site is about 8%~15%. It also shows that damping ratio is greater for deeper soil layer.

Figure 8 is the Hilbert spectrum and the mean frequency for the depth of 31 meters of the event-2006-06-04. The figure shows that it contain more energy for high frequency component and distributing over the earthquake vibrated violently, but its frequency bandwith is wide. The low frequency component is more concentrated, and it carries not only more energy for vibrating violently but also through the process of the earthquake acted.

Comparing with Table 1 obtained from the parametric system identification and the mean frequency obtained from the HHT method, it shows that the identification result for layer closer to surface is the high frequency component. For deeper layer, the frequency shows the phenomenon that distributing form high frequency to low frequency. The result of system identification shows the fundamental resonant frequency of deeper soil layer is about 1.8~2.0Hz, which is located between components IMF-3 and IMF-4 of the HHT.

Table 1　Fundamental resonant frequencies

	Frequency（Hz）			
Event	2005/04/12		2006/06/04	
Direction	EW	NS	EW	NS
8.2m~0m	4.6	4.3	4.3	4.2
10.5m~0m	3.9	3.7	-	-
10.5m~8.2m	3.8	3.7	-	-
31m~0m	2.0	2.1	1.9	1.9
31m~8.2m	2.0	2.0	1.8	1.9
31m~10.5m	2.0	2.0	-	-

Table 2　Damping ratio

	Damping ratio			
Event	2005/04/12		2006/06/04	
Direction	EW	NS	EW	NS
8.2m~0m	10.03	13.11	10.64	12.39
10.5m~0m	15.40	11.65	-	-
10.5m~8.2m	13.14	8.09	-	-
31m~0m	9.06	9.90	12.03	11.01
31m~8.2m	10.89	10.71	14.24	12.83
31m~10.5m	13.89	12.61	-	-

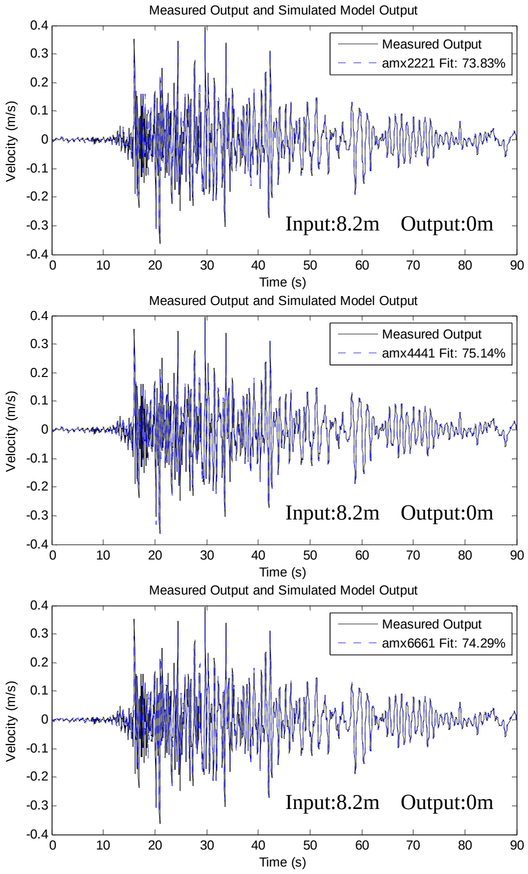

Figure 4. 005/04/12 N-S direction (8.2m-0m)

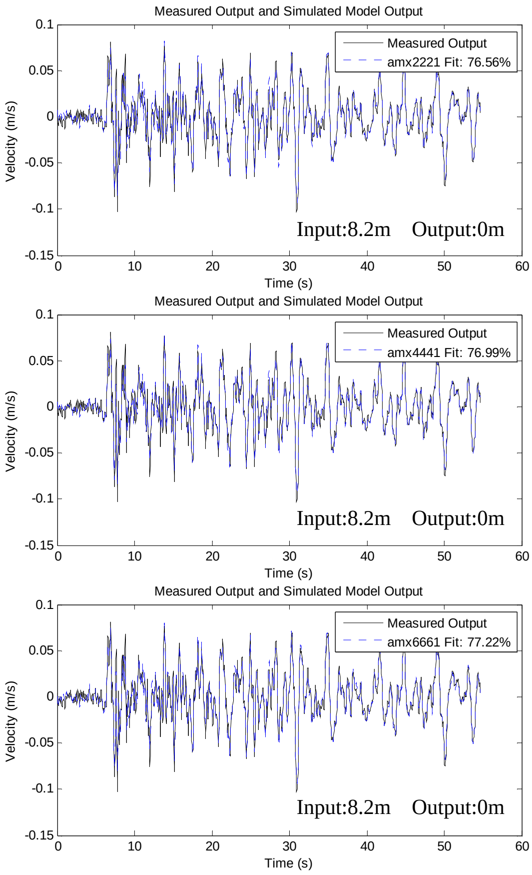

Figure 6 2006/06/04 N-S direction (8.2m-0m)

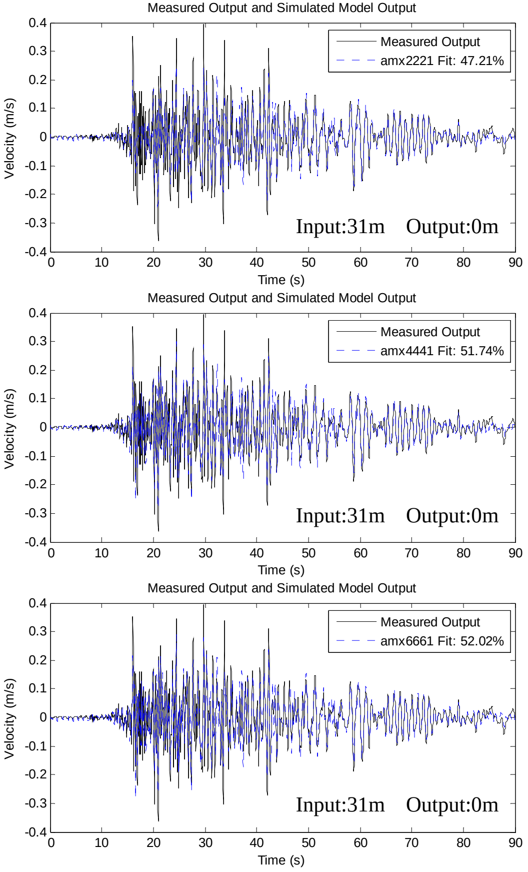

Figure 5. 2005/04/12 N-S direction (31m-0m)

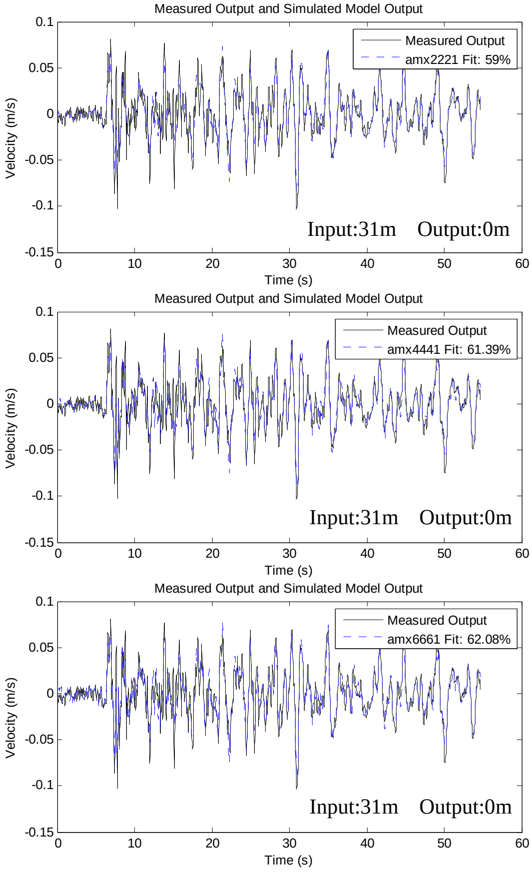

Figure 7 2006/06/04 N-S direction (31m-0m)

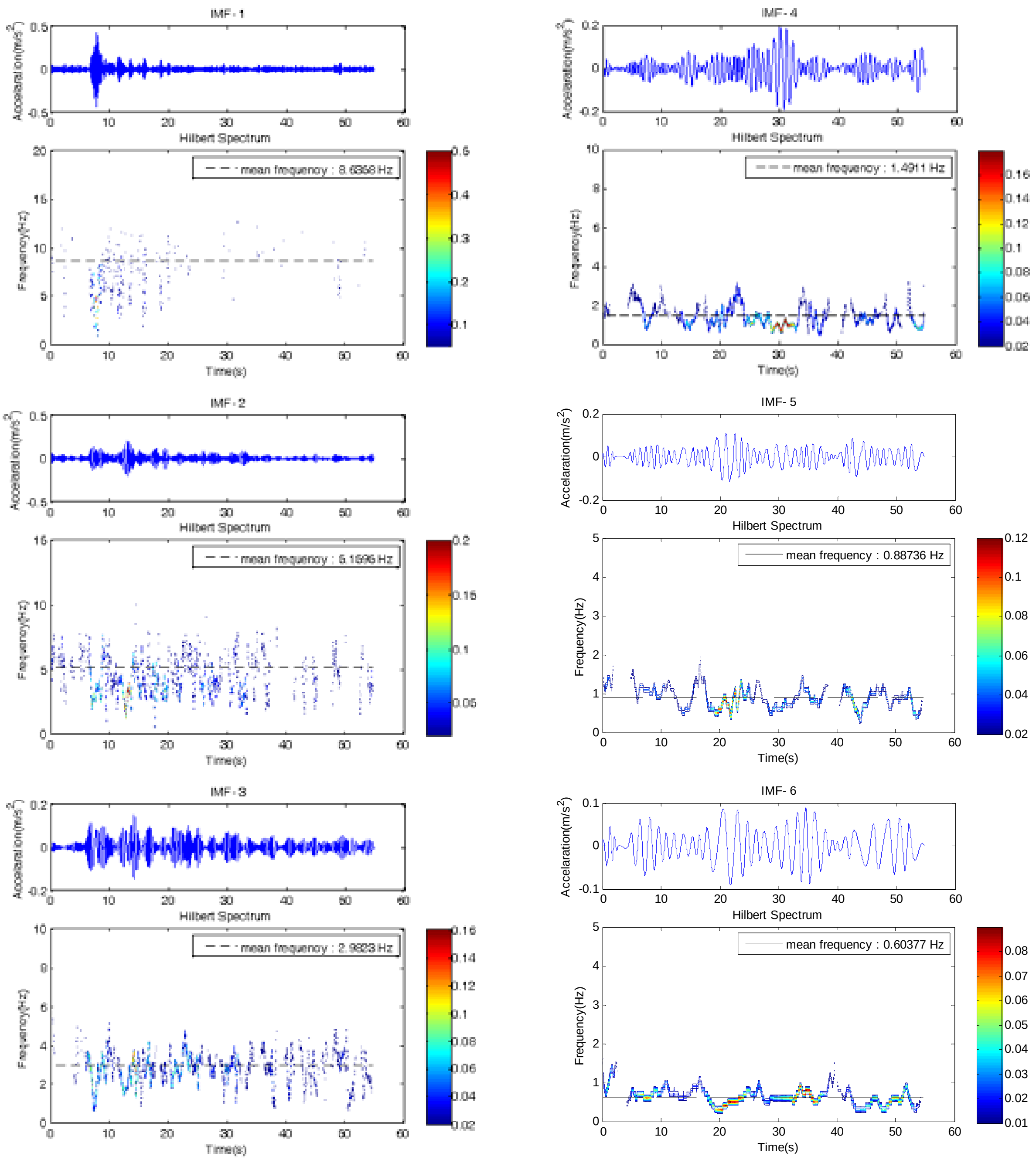

Figure 8. The Hilbert spectrum and the mean frequency for the depth @ 31m of the event-2006-06-04

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. Hilbert-Huang Transform is good for non-linear and non-stationary signal. It can catch the

instantaneous variation characteristics. Using this method, the relation among the instantaneous frequency, amplitude and time of the earthquake can be analyzed.

3. The frequencies obtained from both the parametric system identification and the HHT method are located between the frequency band of IMF-3 and IMF-4. Therefore, the resonant frequency of soil can be estimated by the linear-invariant system identification.

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