IDENTIFICATION OF NONLINEAR SITE RESPONSE FROM TIME VARIATIONS OF THE PREDOMINANT FREQUENCY

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ABSTRACT :

The predominant frequency decrease and de-amplification of spectra on strong motion at a soil site are recognized as occurring nonlinear site effects. In this study, the strong motion and weak motion events recorded by the LSST borehole array in Taiwan and the Port Island borehole array in Japan are analyzed by spectral ratio method with the Short Time Fourier Transform (STFT) and Wavelet analysis. The spectral ratios of surface to borehole sites are calculated to analyze the predominant frequency variations with time. On the weak motion events, the predominant frequency keeps at around one frequency and does not varies with time from beginning to end of the motions. It demonstrated that the soil response is linear on the weak motion events. Based on the analysis of the strong motion records, it shows the predominant frequency varies from the frequency that is the same as the weak motion event's result at the window before the strong shaking part, then the predominant frequency decrease during the strong shaking parts, after the strong shaking portion it move back to around the same as that of the weak motion part. So, according to this behavior we can identify the soil response is linear or nonlinear during the time history of the strong motion events through the variation of predominant frequency with time.

KEYWORDS: Nonlinear site effect, Predominant frequency, Spectral ratio method, Wavelet analysis

1. INTRODUCTION

In recent years, several large earthquakes were recorded by vertical arrays. Using the spectral ratio method on the borehole data already provide direct evidence of the significance of nonlinear site effects in different parts of the world. Wen *et al.* (1995) demonstrated nonlinear soil response on strong motion records of the LSST array in Taiwan, and Aguirre and Irikura (1997) also demonstrated the presence of the nonlinearity during the 1995 Hyogo-ken Nanbu earthquake in Port Island, Japan.

Spectral ratio of a two-station pair involves analyzing the near-surface amplification and predominant frequency, calculated from data records of surface and borehole instruments. The amplification function is controlled by the wave velocity and damping in the soil layer between the two stations. The predominant frequency becoming difference between weak and strong motions is an indication of nonlinearity (EPRI 1993; Beresnev and Wen, 1996).

In this study, the spectral ratio method with the Short Time Fourier Transform (STFT) and Wavelet analysis for an event is introduced to identify the variation of predominant frequency with time and then to determine the soil response is linear or nonlinear based on the variation of dominant frequency.

2. DATA AND METHOD

In this study, data used by Wen *et al.* (1995) and Aguirre and Irikura (1997) to demonstrate nonlinear soil response by two-station (surface and borehole) spectral ratio analysis were utilized. Then we calculated from the same earthquake data with the time-frequency analysis method, and the results between strong and weak motion events were compared to evaluate linear/nonlinear site response during that earthquake.

The locations of LSST array (Wen et al., 1986) on the surface is shown in Figure 1a, and there is a 1/4 scale model structure in the center. The two borehole arrays, designated as DHA and DHB, were located on the northern arm approximately 3.2 and 46.7 meters from the 1/4 model with accelerometers at depth of 6, 11, 17, and 47 meters, respectively, as shown in Figure 1b. Table 1 gives the LSST array data, including 11 weak motion events with peak ground acceleration (PGA) less than 60 *gals* and 3 strong motion events with PGA greater than 150 *gals*.

(a) (b)

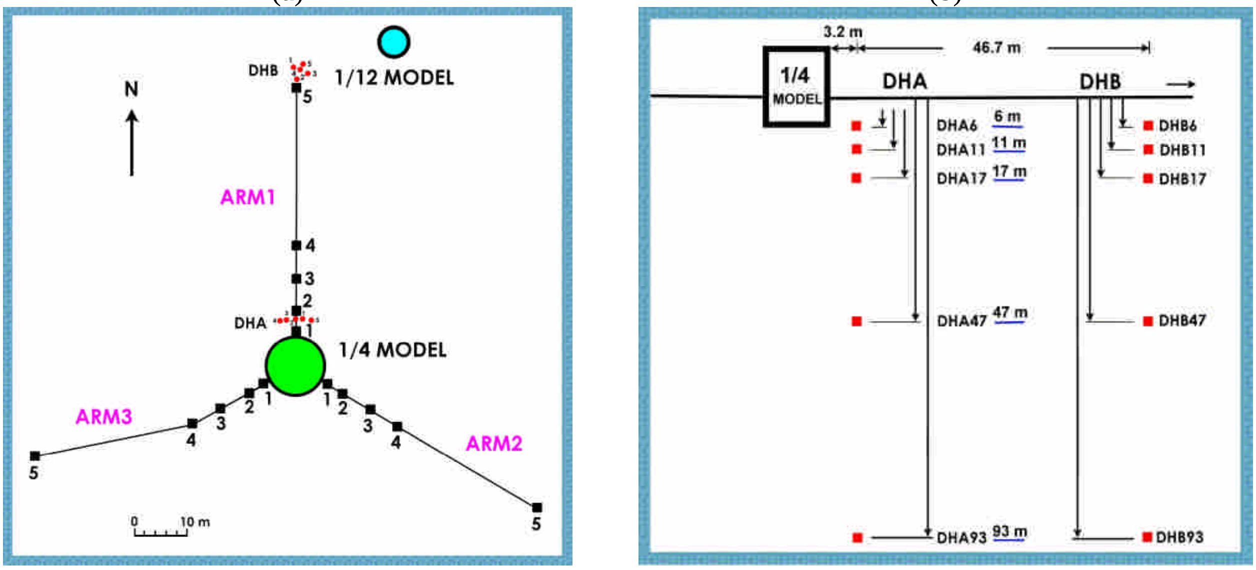

Figure 1 (a) The surface stations of the LSST array, and (b) The configuration of borehole stations of the vertical array in Taiwan (derived from Institute of Earth Sciences, Academia Sinica, Taiwan).

Table 1 Selected LSST events (Wen *et al.*, 1995).

Event	Date	Depth (km)	M_L	Δ (km)	PGA* (gal)
Weak motion					
6	08/04/86	11	5.4	31	35.4
8	20/05/86	22	6.2	69	35.0
14	30/07/86	02	4.9	05	57.5
20	10/12/86	98	5.8	42	23.8
21	06/01/87	28	6.2	77	31.8
22	04/02/87	70	5.8	16	43.4
Strong motion					
7	20/05/86	16	6.5	66	223.6
12	30/07/86	2	6.2	5	186.7
16	14/11/86	7	7.0	78	167.2

Note: PGA* is peak ground acceleration recorded at the free surface.

Figure 2 shows the location and borehole profile of the Port Island array in Japan. The 1995 Hyogo-Ken Nanbu earthquake was recorded by this array and liquefaction occurred in this man-made island. Table 2 shows 5 small events recorded by the Port Island array in Japan with PGA less than 15 *gals* before the 1995 Hyogo-Ken Nanbu earthquake, and an aftershock with PGA less than *50 gals*.

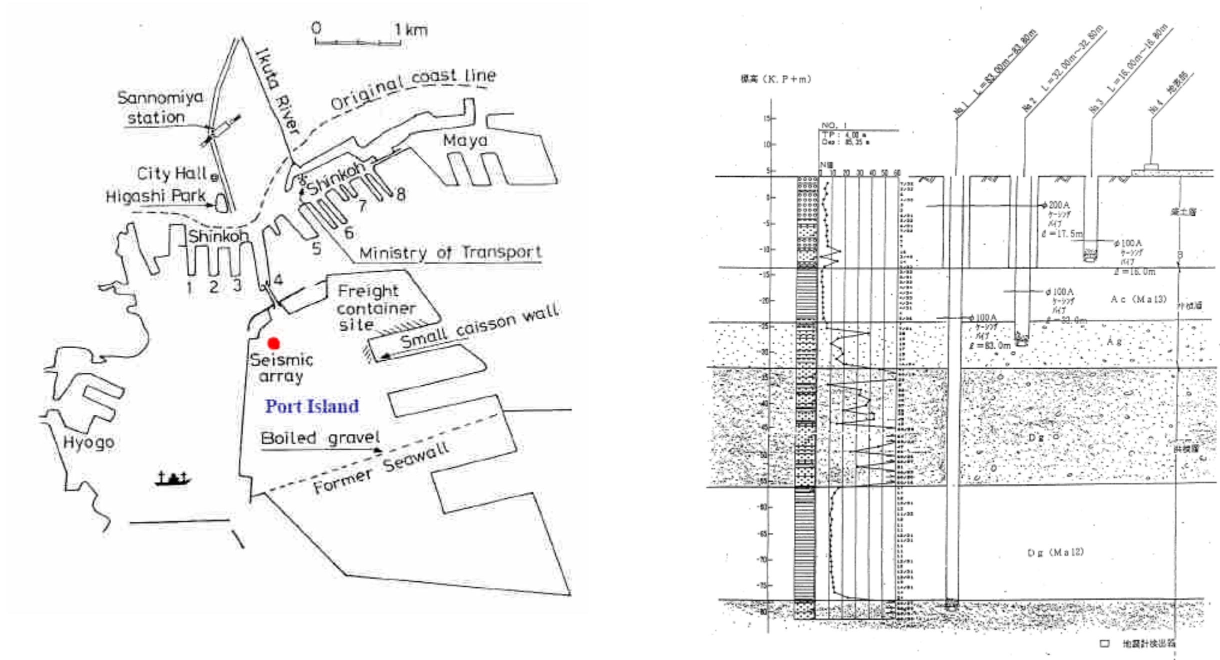

Figure 2 Location and borehole profile of the Port Island array in Japan (Aguirre and Irikura, 1997).

Table 2 Selected events recorded by the downhole array in Port Island, Japan.

Date	Time	Depth (km)	M_L	Δ (km)	PGA* (gal)
28/06/94	13:08:53.02	16.0	4.6	65.4	5.66
28/07/94	10:01:52.04	11.5	4.1	40.3	7.92
24/10/94	11:51:10.72	15.1	4.3	45.6	11.56
09/11/94	20:26:56.41	10.4	4.1	32.6	5.58
10/11/94	00:38:17.72	11.1	3.9	32.1	6.98
17/01/95	05:46:46.74	16.0	6.9	17.7	555.00
17/01/95	08:58:16.14	18.8	4.7	15.1	43.75

Note: PGA* is peak ground acceleration recorded at the free surface.

In this study, all the strong and weak motion records are analyzed to study the time variations of the dominant frequency by the following two different methods.

2.1. Short Time Fourier Transform Method

We propose the short time Fourier transform method to analyze the soil response, and there are some steps in this analysis:

a. Set the time series by window length (5.12 seconds) and moving length (1.28 seconds) of the events, and to improve the resolution of the frequency domain, we extend each window to 10.24 sec by add zero.
b. Add cosine taper to every time window and do the Fourier transform to frequency domain.
c. Average spectrum calculated from the root-mean-square of the two horizontal components.
d. Calculate the spectral ratios between surface and borehole stations.
e. Then, the spectral ratios of each window normalized by the maximum ratio respectively, and ignore that under 0.5 Hz.
f. Each regulative ratio was then smoothed 5 times using the 3-point average method with weightings of 1/4, 1/2, and 1/4.

Finally, we will get the variation of predominant frequency with time and identify the soil response is linear or nonlinear for week and strong motion events.

2.2. Wavelet Analysis Method

The Wavelet analysis method has roughly similar procedure as above mentioned method, and some main steps are：

a. Establish the wavelet basic function which is an association of the Gaussian function and the Fourier basic function.
b. Set the time and frequency on 2048X128 grids, and do the Wavelet transform to the frequency domain.
c. Calculate the root-mean-square of the two horizontal components to decrease the difference of the wave incident angle.
d. Calculate the spectral ratios between surface and borehole stations.
e. Normalize the spectral ratios of each window by the maximum ratio, respectively, and ignore the frequency band that is lower than 0.5 Hz.

Finally, we can analysis the variation of predominant frequency with time like that of the STFT method.

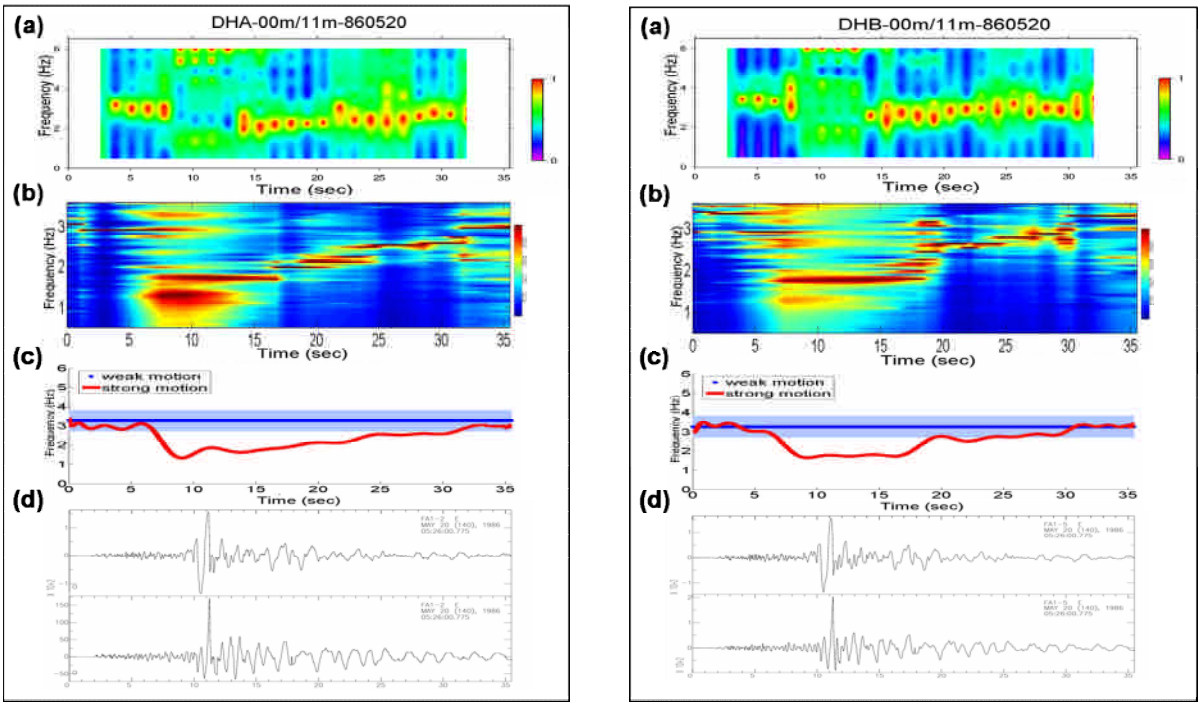

Figure 3 The results for the strong motion event of 20 May 1986 recorded by the DHA (left) and DHB (right) of LSST borehole array in Taiwan. Time-frequency spectral ratios of surface to 11-m depths borehole station calculated by the STFT method (a) and Wavelet analysis (b). Predominant frequency of the weak motion is shown in straight blue line and strong motion in curve red line (c). (d) Waveform recorded at the surface station. The upper and lower parts are EW and NS components, respectively.

3. RESULTS

3.1. LSST Array in Taiwan

The results for the earthquakes of May 20, July 30, and November 14, 1986 are shown in Figures 3 to 5. Each figure include: (a) the result from STFT method, (b) the result of Wavelet analysis, (c) predominant frequency of the weak motion (blue line) and strong motion (red line), and (d) the time history of surface station. The results shown in Figure 3 indicate that there are some modes on strong shear wave part, and the predominant frequency of the first mode is 1-2 Hz during this time period. It shows soil response during this time period is nonlinear.

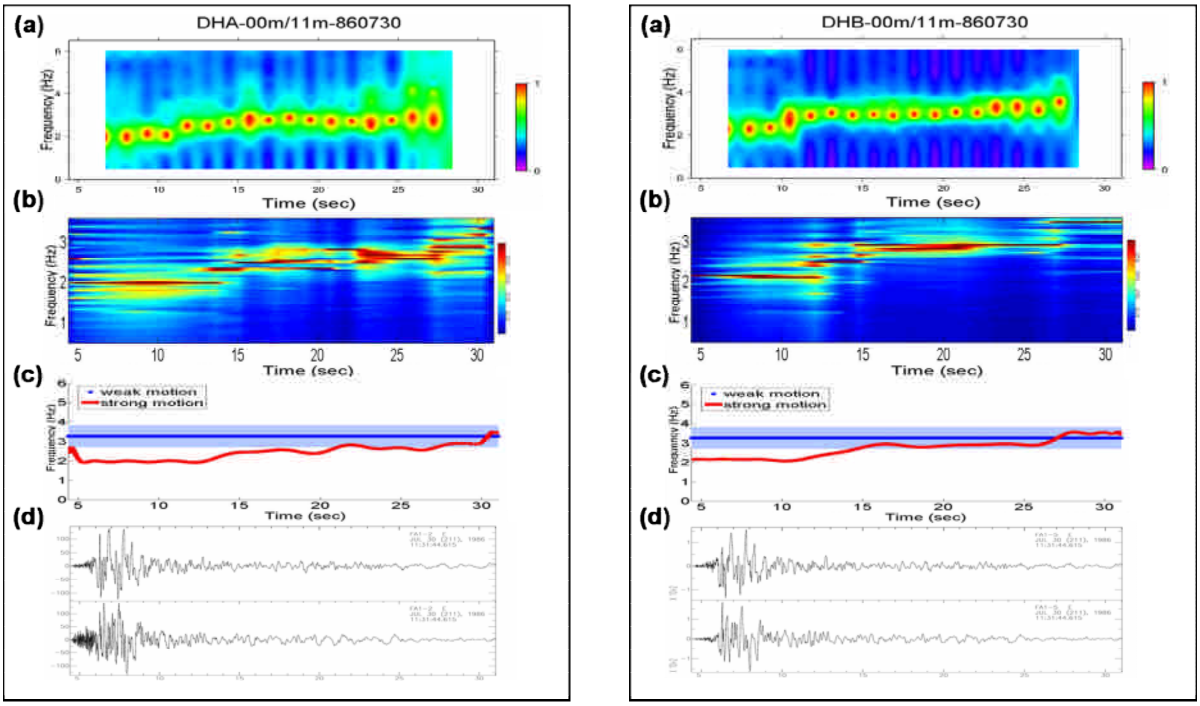

Figure 4 The results for the strong motion event of 30 July 1986 recorded by the DHA (left) and DHB (right) of LSST borehole array in Taiwan. Time-frequency spectral ratios of surface to 11-m depths borehole station calculated by the STFT method (a) and Wavelet analysis (b). Predominant frequency of the weak motion is shown in straight blue line and strong motion in curve red line (c). (d) Waveform recorded at the surface station. The upper and lower parts are EW and NS components, respectively.

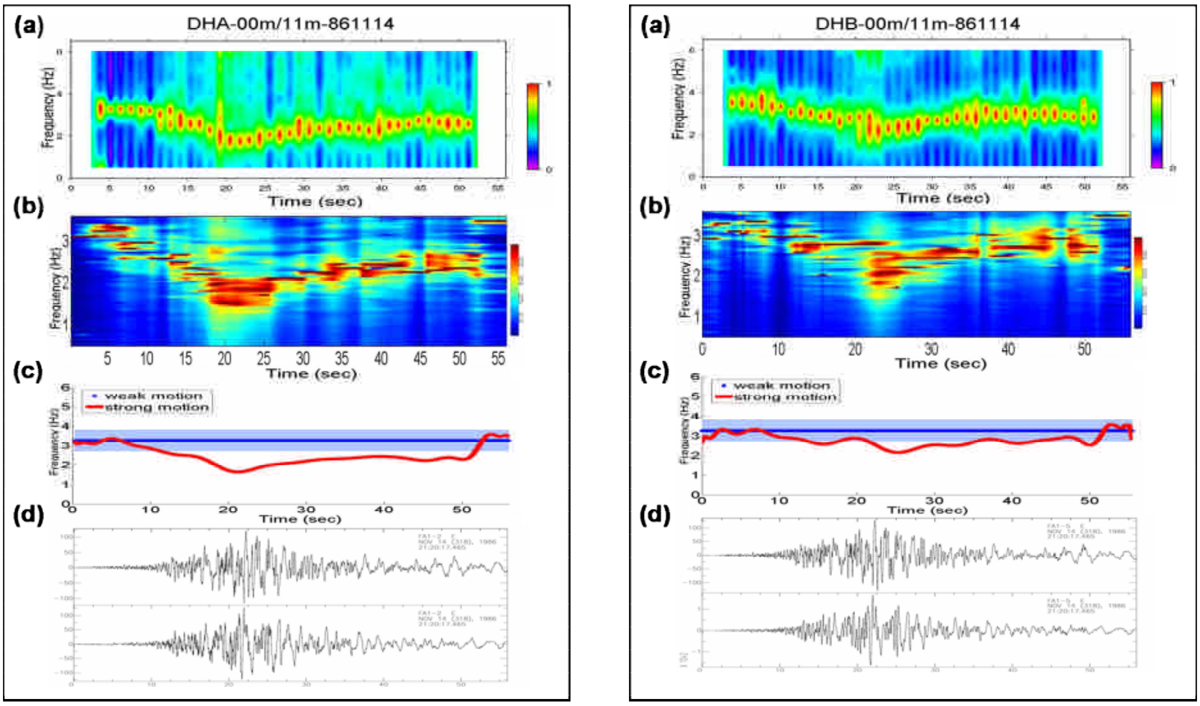

Figure 5 The results for the strong motion event of 14 November 1986 recorded by the DHA (left) and

DHB (right) of LSST borehole array in Taiwan. Time-frequency spectral ratios of surface to 11-m depths borehole station calculated by the STFT method (a) and Wavelet analysis (b). Predominant frequency of the weak motion is shown in straight blue line and strong motion in curve red line (c). (d) Waveform recorded at the surface station. The upper and lower parts are EW and NS components, respectively.

In this study, the predominant frequency at the window before the strong motion part is about 3 Hz which is the same as that of the weak motion response and it shows linear soil response at these time periods. During the strong shaking parts, the predominant frequency of the shear wave is decrease to 2 Hz and shows nonlinear soil response occurred at this time window. After the strong motion part, the predominant frequency returns to 2.5-3 Hz immediately and it means soil response back to linear at that time period.

3.2. Port Island Array in Japan

The results reflected in Figure 6 indicate the case of 1995 Hyogo-ken Nanbu earthquake recorded in Port Island. The predominant frequency after the strong shear wave is decreasing to less than 2 Hz and can not return to about 4 Hz. That is the predominant frequency of the weak motion response. This is due to the mainshock caused the soil liquefied. And 3 hours after the mainshock, the predominant frequency returns to about 3 Hz which is less than 3.5-4 Hz, and this shows the soil characteristic can't return to the original situation due to the liquefaction effect.

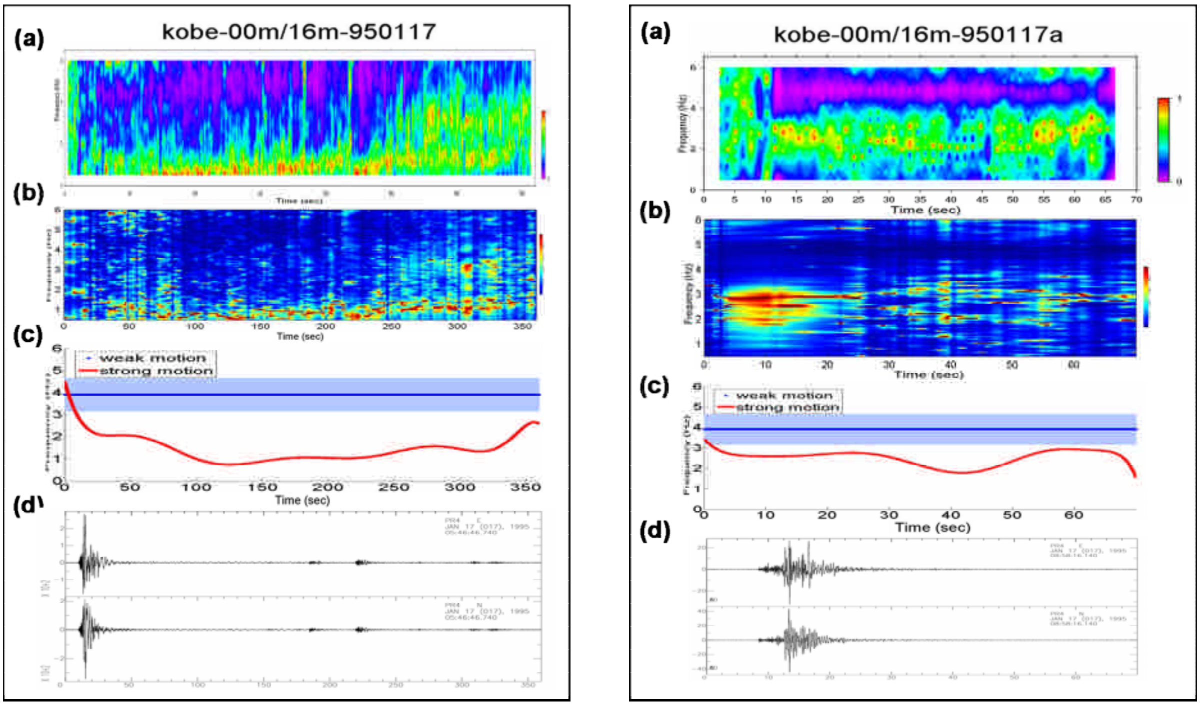

Figure 6 The results for the mainshock (left) and aftershock (right) of the 17 January 1995 Hyogo-ken Nanbu earthquake recorded by the Port Island borehole array in Japan. Time-frequency spectral ratios of surface to 16-m depths borehole station calculated by the STFT method (a) and Wavelet analysis (b). Predominant frequency of the weak motion is shown in straight blue line and strong motion in curve red line (c). (d) Waveform recorded at the surface station. The upper and lower parts are EW and NS components, respectively.

4. CONCLUSIONS AND DISCUSSIONS

In this paper, the spectral ratio with time-frequency analysis method was introduced to recognize nonlinear site response. The data from the LSST borehole arrays in Taiwan and the Port Island array in Japan, already shown to have nonlinear site response by previous spectral ratio analyses between surface and borehole stations (Wen *et al.*, 1995; Aguirre and Irikura, 1997) are used to show the applicability of these methods for nonlinear site response identification. These results are entirely consistent with those reported for the soil nonlinear response in previous studies.

For the LSST array in Taiwan, the predominant frequency varies with time from beginning to end of the week motion is about 3 Hz obviously and it demonstrates that the soil response is linear on the weak motion events. On the other situation, we can see the predominant frequency of the strong motion event is 3 Hz at the initial portion and it's the same with the weak motion result. So it shows linear soil response at this time period. Then the predominant frequency is decrease to 2 Hz during the strong motion portion, this indicate that the soil response is nonlinear in this time period. At the later portion after the strong motion part, the predominant frequency returns to about 2.5-3 Hz immediately and the soil response recovers to linear condition.

The result of the Port Island array in Japan, the predominant frequency varies with time from beginning to end of the weak motion is about 3.5-4 Hz. On the case of 1995 Kobe earthquake, the predominant frequency after the strong shear wave is decreasing to less than 2 Hz and never return back to the frequency of weak motion events before the Kobe earthquake because the Port Island is liquefied. And 3 hours after the mainshock, the predominant frequency returns to about 3 Hz which still is less than 3.5-4 Hz, and this shows the soil characteristic can't return to the original situation due to the liquefaction effect.

In this study, two methods were used to observe the variations of predominant frequency with time on the borehole arrays located in Taiwan and Japan. Based on the analysis of the strong motion records, it shows the predominant frequency varies from the frequency that is the same as the weak motion event's result at the time window before the strong shaking part, then the predominant frequency decrease during the strong shaking parts, after the strong shaking portion it move back to around the same as that of the weak motion part. So, according to this behavior we can identify the soil response is linear or nonlinear during the time history of the strong motion events through the variation of predominant frequency with time. Also, we anticipate that the same results will be generated by the Hilber-Hwang Transform method (Huang *et al.*, 1998) to improve the resolution in the time and frequency domains.

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