STRUCTURAL RESPONSE ANALYSIS OF A REINFORCED CONCRETE BUILDING WITH THE EXCITATION OF MICROTREMORS AND PASSING SUBWAY TRAINS

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ABSTRACT :

A period of more than 2 days measurements of the ambient seismic noise were conducted inside a reinforced concrete (RC) building in central Beijing. The temporal seismic array consists of 16 3-component short-period seismometers, with 2 on each floor, from the basements to the 7th floor in this 7-story RC building. Two types of analysis were conducted to the measured data to extract the structural response of the building: 1) the horizontal to vertical (H/V) spectral ratio method to the continuous ambient noise; and 2) the seismic interferometry analysis with a deconvolution procedure to the seismic sources generated by the passing subway trains. Both analyses indicate the fundamental resonance frequency of this RC building is about 2.2 Hz in EW and 2.9 Hz in NS, with an unknown mode at the frequency of 5 Hz. The H/V analysis indicates that the major noise source comes to the building from EW direction, consisting with the urban traffic layout in central Beijing area. The seismic interferometry analysis of the structural response to the passing subway trains gives an estimate of the damping ratio of this RC building is about 0.17, a very efficient level of damping to resonant vibrations. We conclude that structural analysis using the ambient seismic noise (microtremors) as excitation input may provide an economical and flexible way to supplement the traditional strong ground motion analysis using only accelerograms in building vulnerability assessment to seismic hazard. This project is supported by Ministry of Science and Technology of China with Project No. 2006DFA21650 and the Institute of Earthquake Science (Project No. 0207690229).

KEYWORDS: ambient seismic noise, H/V spectral ratio, resonance frequencies

1. INTRODUCTION

The city of Beijing is located in an active tectonic region. Historically, there were at least 11 great earthquakes with the maximum intensity of VI or greater occurred within a 100-km radius centered at the center of Beijing City in the last 500 years (State Seismological Bureau, 1995). The Sanhe-Pinggu (M~8) earthquake, the largest historic event occurred 65 km east of Beijing, severely damaged the city on September 2, 1679. In the surrounding area, the 1976 Tangshan (M7.8) earthquake occurred ~ 200 km in the east also made moderate damage in Beijing area.

The thickness of the Quaternary/Tertiary sediments varied from 0 m in the Northwest to more than 1000 m in the Southeast (Ding et al, 2004). The varying sediments may strongly affect earthquake ground motions by amplification and focusing/defocusing. This is the so called local site effect with important implications for seismic hazard. To study this local site effect, Chen *et al.* (2008) recorded ambient seismic noise (microtremors) over 600 sites inside Beijing's 5th beltway. With the use of the horizontal to vertical (H/V) spectral ratio method they have generated a map of the fundamental frequencies of the sediment (Figure 1).

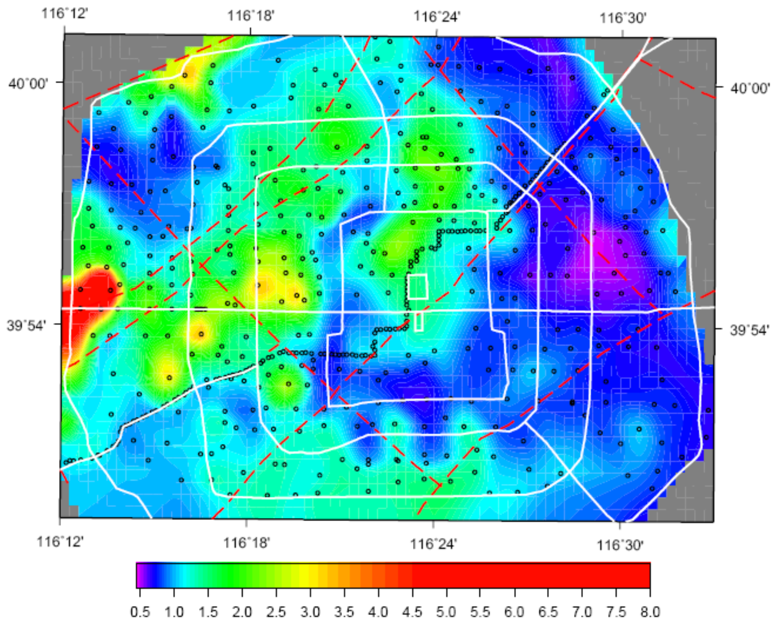

Figure 1 Map of the fundamental frequencies of Beijing sediment. The fundamental frequency of the RC building site is about 2-3 Hz (From Chen *et al.* 2008)

The H/V spectral ratio technique has been widely used in assessing the response of the ground to microtremors and the inference of site amplifications to seismic strong ground motion. Cara *et al.* (2003) studied seismic noise variations by the H/V spectral ratio, and got the fundamental frequency of the Clofiorito plain. Parolai *et al.* (2002) calculated a new relationship between Vs, thickness of the sediments, and the resonance frequency by the H/V spectral ratio. In recent years, many researchers have successfully extended the usage of the H/V spectral ratio to study the response of a civil structure (e.g., the reinforced concrete (RC) building) to ambient seismic noise. This method has proven to be useful for tall and complicated buildings. Gallipoli *et al.* (2004) have studied the soil-structure interaction and the effects of damage based on H/V spectral ratio analysis of microtremors. Facke *et al.* (2006) also assessed the resonance frequencies of the Cathedral of Cologne (Germany) by H/V spectral ratio of ambient seismic noise.

The reinforced concrete (RC) buildings are the typical civil structure in Beijing. If the resonance frequencies of the RC buildings are coincident with the fundamental resonance frequency of the sediments, which is provided by the studies such as shown in Figure 1, the chance of structural damage may dramatically increase due to the resonance vibration when an earthquake strong ground motion excites the building. This paper describes the experimental setup and preliminary findings of the structural response of a RC building in central Beijing with the H/V analysis of microtremors and seismic interferometry procedure of the signals generated by the passing subway trains.

2. THE SEISMOMETER ARRAY

The building under investigation is a typical RC structure built in early 1980s. It has 8 floors (1 basement and 7 floors above the ground), The size of this rectangular building is 80 m in length, 25.3 m in height, and 15 m in width as sketched in Figure 2. The major axis of the building is in the EW direction, parallel to and on the north side of a major street with heavy traffic and Beijing's subway Line 1. Ambient seismic noise was observed in the RC building during a weekend, from the evening of a Friday to the morning of the next Monday, with a period of about 60 hours when the structure was least disturbed by human activities inside the building. The instruments used to record the micortremors were Guralp CMG-40T-1 short-period seismometers, which has an amplification plateau in the frequency band above 1 Hz, and the REFTEK data acquisition system. The sampling rate was 200 samples per second. Measurements were carried out from the basement to top floor, with instruments on both the east and west ends of the building (Figure 2).

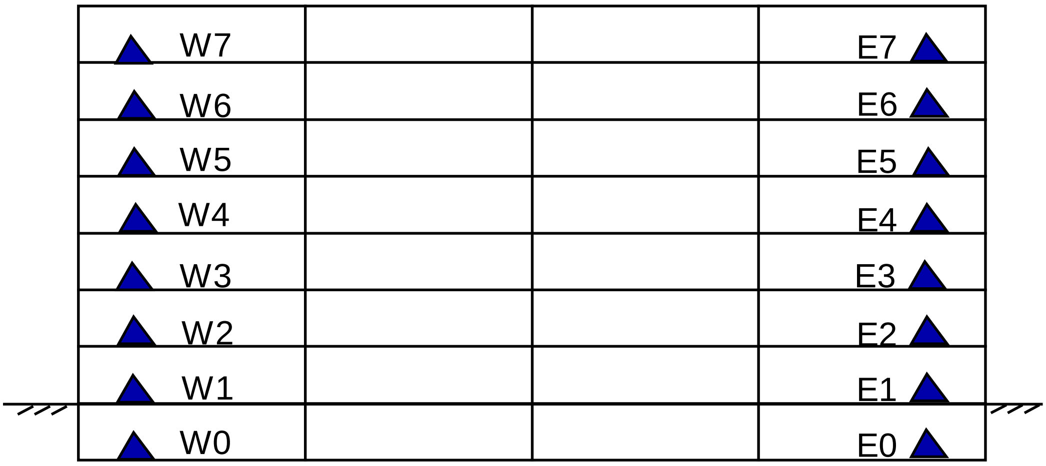

Figure 2 Structural section (EW) of the reinforced concrete building and the 16 Station locations: the H/V spectral ratio measurements were made at 16 different locations inside the building (basement, and the first to the seventh floor at both ends of the building)

3. THE H/V SPECTRAL RATIO METHOD APPLIED TO MICROTREMORS

As an example, the top row of Figure 3 shows the fast Fourier transform (FFT) of the three components of micortremors recorded on the third floor. The FFT of the 3-component velocigrams shows that the horizontal components have vibration peaks around 3 and 12 Hz. In addition, the EW component has a small peak at 5 Hz. Meanwhile, the vertical component shows a single peak about 12 Hz. The FFT results imply that this RC building vibrates in all directions at 12 Hz, but vibrates horizontally primarily at around 3 Hz. In contrast to the simple FFT analysis, the bottom row of Figure

3 shows the ratio of EW/V, NS/V, and H/V. Clearly, the results of EW/V, NS/V, and H/V, show that the strongest resonance of this RC building occurs at the frequency of about 2.2 Hz, a feature much more characteristic than the simple FFT results as shown in the top row.

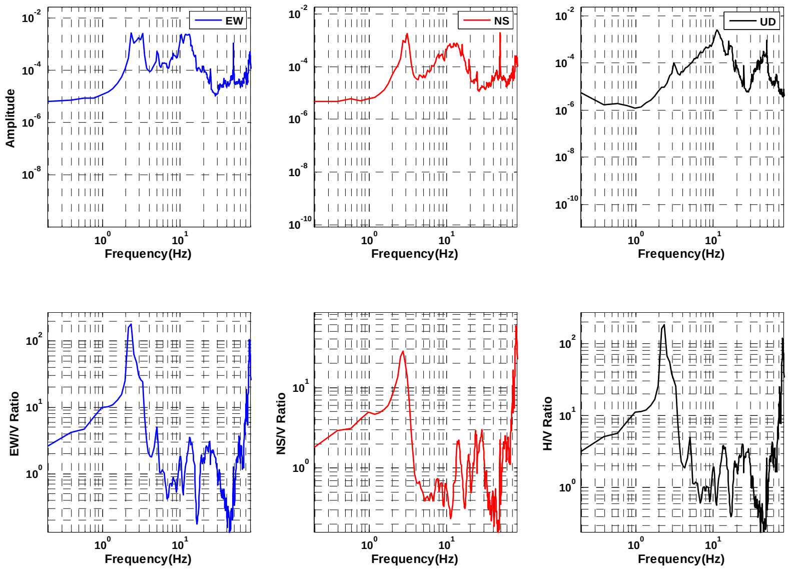

Figure 3 The spectra of the three components of the recorded particle velocity on the third floor (top row) and the spectral ratios of EW/V, NS/V, and H/V (bottom row)

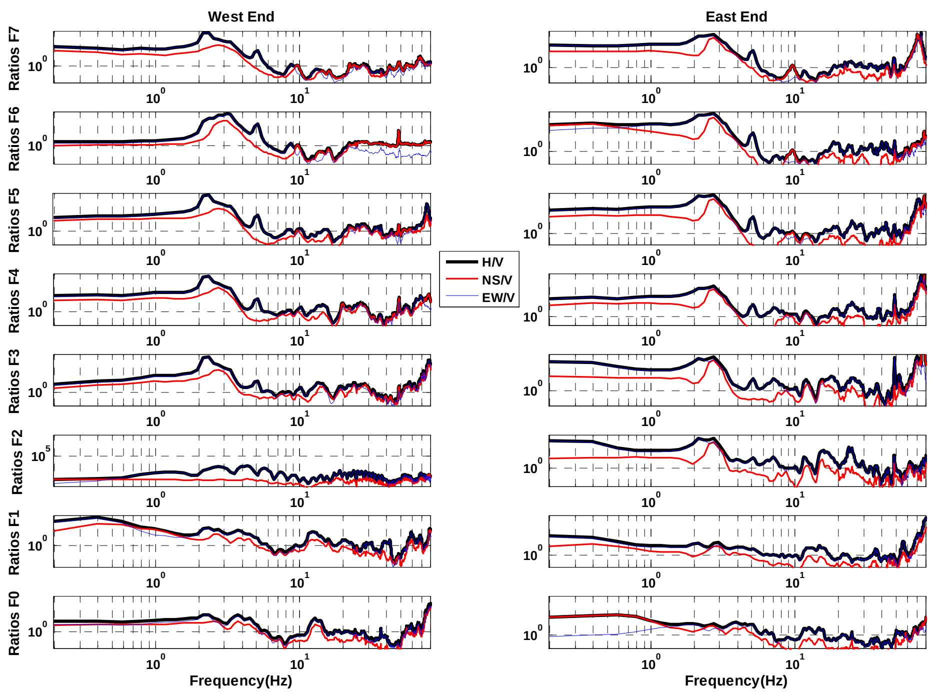

Figure 4 The spectral ratios of H/V, NS/V, and EW/V on each floor of the west end (left panel) and the east end (right panel). Clearly, the ratio of H/V is primarily dominated by the ratio of EW/V

Figure 4 presents the H/V results of records on all floors. Apparently, The EW/V spectral ratios have three clear peaks: 2.2 Hz, 5 Hz and 9-12 Hz. The NS/V spectral ratios have two clear peaks: around

2.9 Hz and 9-12 Hz. Since EW/V ratios are generally larger than the NS/V ratios, the H/Vs are apparently dominated by the ratios of EW/V. The resonance amplification at 2.2 Hz is larger at the west end than the east end, especially in the higher floors. This might be caused by the fact that the west end is a free end, whereas the east end is attached to another building. Preliminarily, we interpret the 2.2 and 2.9 Hz peaks as the primary resonance frequency of this building in EW and NS, respectively. The 9-12 Hz peak maybe the response frequency of the RC building to traffic noise, as shown by previous study (Beijing Jiaotong University, 2007), which reported the traffic noise (from buses, cars, trucks, and subway vibrations) has a dominant frequency of about 10 Hz at a few tens meters from the main road. This is consistent with our H/V results obtained from this RC building. Nevertheless, the cause of the 5 Hz peak in the EW direction is currently unknown.

4. STRUCTURAL RESPONSE FROM THE H/V SPECTRAL RATIOS

The empirical height-resonance period relationship for RC buildings was summarized by Hong and Hwang (2000) in the form of Eqn. 4.1.

$$T = C \times H^{\alpha} \tag{4.1}$$

With the parameters C=0.0294, and α =0.804. For the height of the observed building approximately 25.3 m, we can get the resonance frequency of this RC structure is about 2.5 Hz. This is consistent with the H/V spectral ratio result of 2.2-2.9 Hz.

Since the main noise source of the building is the surface traffic and the subway along the EW main street, the EW/V spectral ratio is much higher than the NS/V spectral ratio. Figure 5 shows the relationship of the resonance amplification as the function of the azimuth at the west end of the third floor. It is clear that the peak amplification occurred at about 2.2 Hz. The main noise energy comes from east (0 degree) and west (180 degree). The secondary peak amplification occurred at about 5.0 Hz is also concentrated in the EW direction.

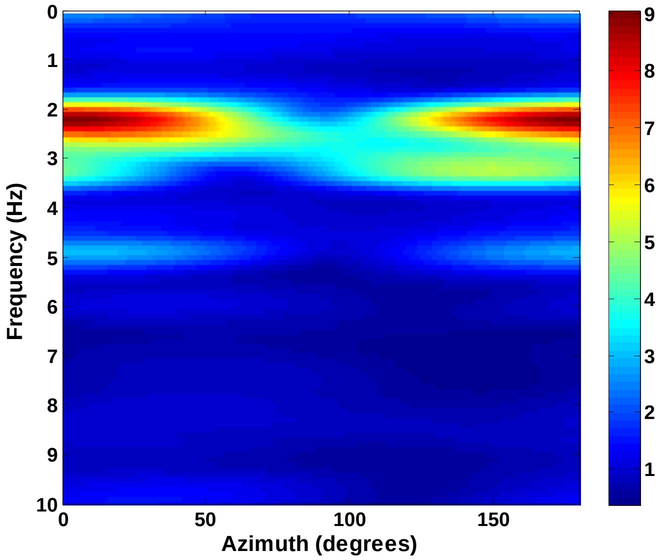

Figure 5 The relationship of the resonance amplification and the azimuth of the record at the west end of the third floor. It is clear that the peak amplification occurred at about 2.2 Hz

5. RESPONSES OF THE STRUCTURE TO PASSING SUBWAY TRAINS

Besides using the passive ambient noises to characterize this RC building, we have also analyzed the response of the building to the signals from the passing subway trains. The subway line is almost directly beneath the building. All of the instruments at each floor clearly recorded these signals (Figure 6a). We have extracted the building response from the subway signals by using a seismic interferometry method (Snieder and Safak, 2006). Instead of using correlation, we employed the deconvolution process to separate the building response from the excitation and the ground coupling by deconvolving the motion recorded at different levels in the building with the record in the basement. Thus the deconvolved waves can provide information on the motion of the fundamental mode of the building (Snieder and Safak, 2006). It is clear that low-frequency vibrations are gradually increasing with the building floors as shown in Figure 6b. These vibrations consist of the resonance of the building. The resonance frequency can be found from the spectra of each floor in Figure 6c. Three segments with pronounced peaks can be found at 2.4 Hz, 5.0 Hz and around 10 Hz, respectively. The results extracted from the subway train analysis are consistent with those of microtremor H/V spectral ratio analysis.

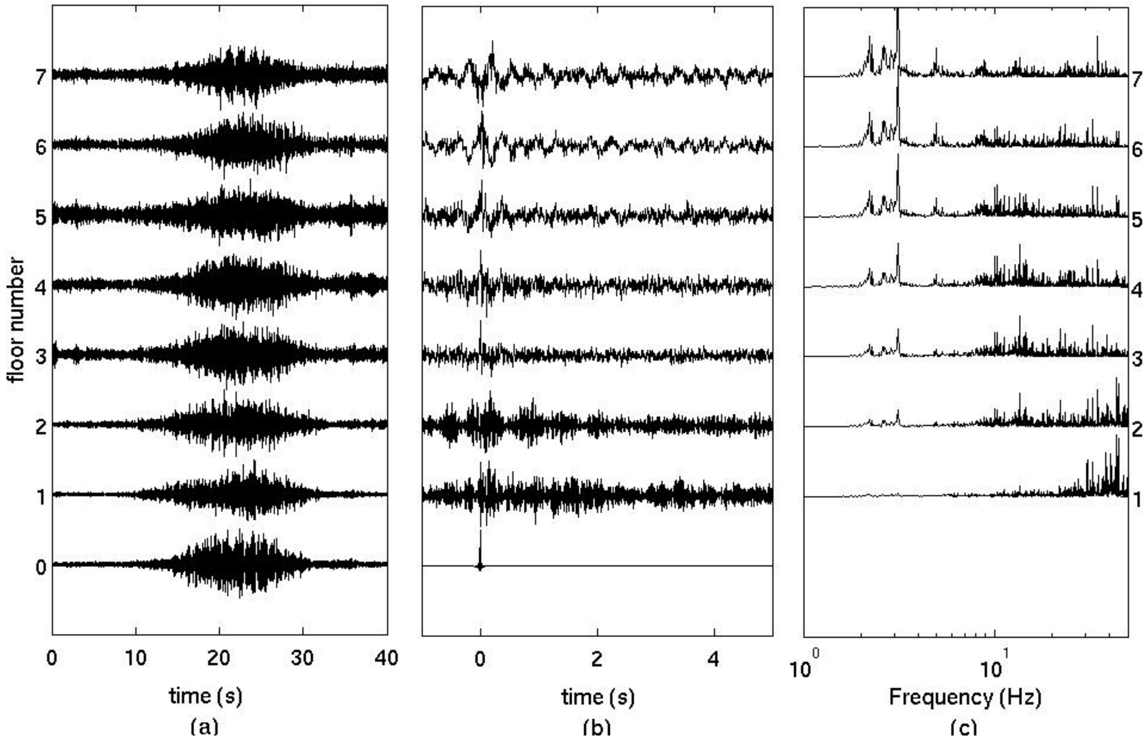

Figure 6 Left panel: The NS-component accelerograms (derived from the original velocigrams) of one passing of the subway train from the basement to the 7th floor at the west end of the Building. Central panel: Waveforms at all floors after deconvolution with the waves recorded in the basement. Low-frequency vibrations in higher floors can be observed. Right panel: The spectra of the deconvolved waves in the range of 1-50 Hz. The time domain signals in the left and central panels are normalized by the maximum in each channel

The attenuation can be further quantified by the resonance decays with time in the deconvolved waves. We bandpass filtered the deconvolved waves with cutoff frequencies of 1 and 5 Hz since the fundamental mode is about 2-3 Hz. The natural logarithm of the envelope of the bandpass-filtered waveforms is shown in Figure 7. According to Snieder and Safak (2006), the slope of the decay of the envelopes has a relationship with the quality factor Q as the following function: slope $= -\omega / 2Q$. For the slope of the best fit lines is -2.29, the Q of this building is about 3, and the damping ratio γ of this RC building to the resonance is 0.17

according to Eqn. 5.1.

$$\gamma = 1/2Q \tag{5.1}$$

Apparently, the design of the building to resist resonant vibrations is quite efficient with this high damping ratio.

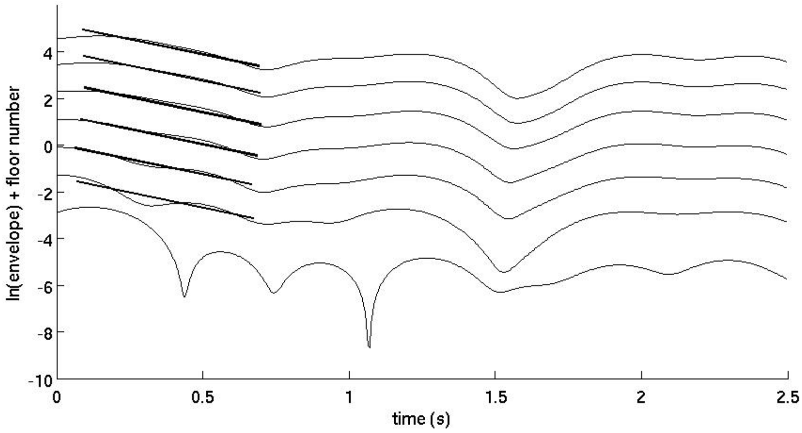

Figure 7 The natural logarithm of the envelope of the deconvolved waves in Fig.6b. The thick lines are the best fit lines to each curve

6. CONCLUSIONS

We have applied the H/V spectral ratio analysis of microtremors to study the resonance frequency of a reinforced concrete building in Beijing. We found that the resonance frequency of this building is around 2.2-2.9 Hz. Seismic interferometry analysis using the signals generated by the passing subway trains supported the findings obtained from the microtremor H/V analysis, with the consistent resonance frequency peaks appeared at the same frequency ranges. In conclusion, we found the average resonance frequency of the building is about 2.4 Hz, with an unknown mode at the frequency of 5 Hz, and the city traffic is the main noise source to generate a peak frequency around 10 Hz. The fundamental frequency of the sediment at the site where this RC building located is also about 2-3 Hz. It is reasonable to assume that this RC building may have the potential to be resonant with incoming strong motion excitations. Fortunately, this RC structure was designed with a very efficient damping ratio of 0.17 and large amplitude resonance should be effectively absorbed. As an alternate or supplement to traditional acceleration observation, analyses using the more sensitive short-period seismometers to record microtremors and signals generated by other active noise sources (e.g., the subway trains) as the excitation input to a structure may provide an economical and flexible way to assess building vulnerability in an urban area for seismic hazard reduction studies.

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