Ambient Vibration Testing of Three Unreinforced Brick Masonry Buildings in Vancouver, Canada

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Abstract

This paper presents the results of a series of ambient vibration tests conducted on three low-rise unreinforced brick masonry buildings located in the Chinatown district of Vancouver, British Columbia, Canada. The tests were intended to collect preliminary information on the dynamic properties of the buildings. Measurements were taken on selected locations of each structure to determine their overall mode shapes, modal frequencies and modal damping. Selected areas of the buildings were also measured in more detail to determine local modes of vibration. In addition, microtremor measurements were conducted in the vicinity of the buildings to determine the period of the site and asses the potential effects of soil-structure interaction, which could have a significant effect on the seismic performance of the buildings during a severe earthquake.

Introduction

This project was initiated by the Vancouver Chinatown Revitalization Committee to collect preliminary information for several buildings in the Chinatown district of Vancouver, British Columbia. A series of ambient vibration tests were carried out on three buildings, as well as two sets of microtremor measurements to characterize the site dynamics. Researchers from the Earthquake Engineering Research Facility at the University of British Columbia applied their standard techniques and testing equipment to achieve these objectives. This paper describes the buildings tested, the tests and results, and the methodologies and equipment used.

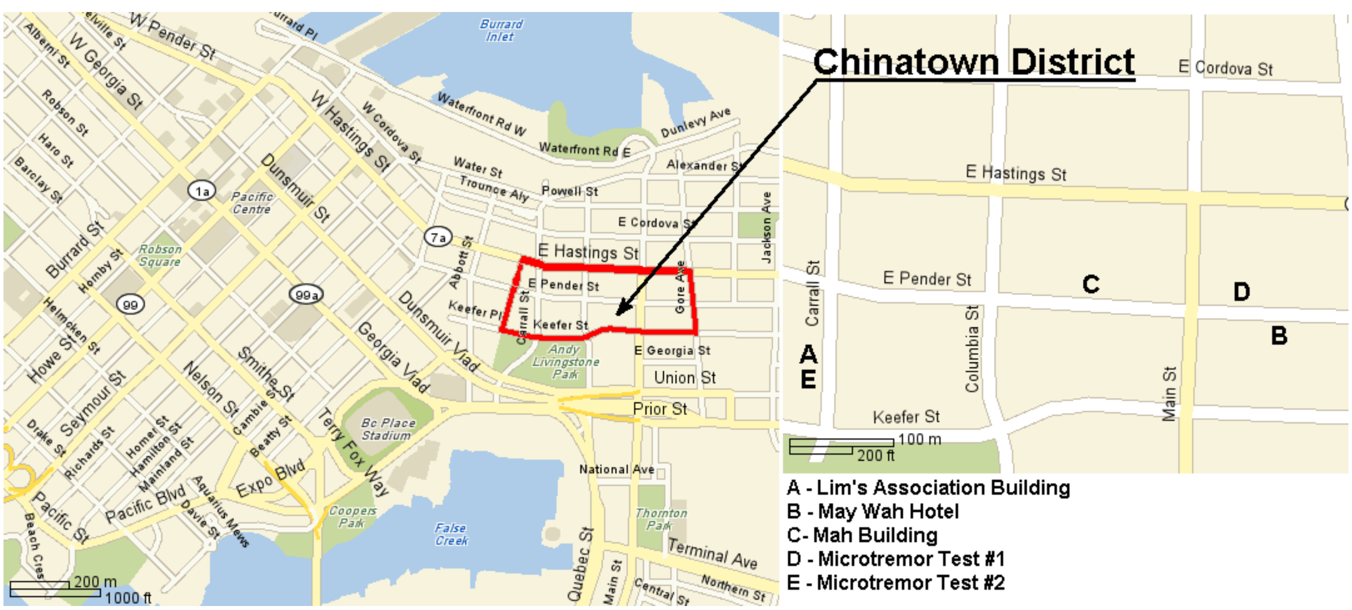

Figure 1: Downtown Vancouver map (left) and Inset (right) showing test locations

Figure 2: The Lim's Association Building

Figure 3: The May Wah Hotel

Figure 4: The Mah Building

Description of Buildings

The tests were performed on and around three buildings in the Chinatown district of Vancouver, BC. This area is on the east end of the downtown core area, as shown in Figure 1. The inset shown in the right of the figure shows the locations of the three buildings tested. They were the Lim's Association Building, shown as Point A, the May Wah Hotel, shown as Point B, and the Mah Building, shown as Point C. Two points were taken for the microtremor measurements, Points D and E. Each of the three buildings were built in the early 1900's, although the exact dates are not known.

The three buildings feature similar structural systems, with unreinforced masonry load bearing walls at the sides of the buildings, with wood diaphragm floors connecting them.

Lim's Association Building

The Lim's Association Building is 3 stories high with a mezzanine level, and contains commercial space, a dance studio and meeting space for the Association. The building is approximately 40m long by 10m wide. The building has no adjacent structures on any side. A photo is shown in Figure 2.

May Wah Hotel

The May Wah Hotel is 4 stories high, and contains commercial space on the main floor and a hotel residency on the upper floors. It is a U-shaped building, with 2 wings separated at the south end. The two wings are connected at the top by what appears to be a series of timber beams. The building is approximately 40m long by 25m wide, with each wing being approximately 10m wide. The wings are inset slightly so they are not in contact with the adjacent buildings. A photo is shown in Figure 3.

Mah Building

The Mah Building is a 5 storey structure with commercial space on the main floor, a hotel on floors 1 to 3 and a 4^{th} floor meeting space for the Mah Society of North America. A photo is shown in Figure 4. As seen in the photo, this building has a more complex set of boundary conditions due its relation to the adjacent buildings.

Ambient Vibration Tests

The purpose of conducting ambient vibration testing in general is to obtain the dynamic characteristics of a structure, its natural frequencies, corresponding mode shapes and damping estimates. Unlike forced vibration testing, the forces applied to the structure in ambient vibration testing are not controlled. The structure is assumed to be excited by wind, traffic and human activity. The measurements, typically accelerations, are taken for a long duration to ensure that all the modes of interest are sufficiently excited.

The system used at the UBC Earthquake Engineering Research Facility (EERF) includes a 16-channel data acquisition system (Shown in Figure 5), and a series of force-balance type accelerometers and cables for the vibration measurements. Digitized acceleration signals are recorded with a notebook computer, and then analyzed on a separate PC at a later time. The system features a hardware lowpass filter of 50Hz. Since most structures of interest are very large and the measurement system is limited, a typical test features a set of reference sensors, which do not move throughout the test, and roving sensors, which take measurements over the entire structure in a series of setups. The reference sensors are then used in the analysis to correlate the data sets together, since the actual input is unknown and parameters such as the amplitude may vary from setup to setup.

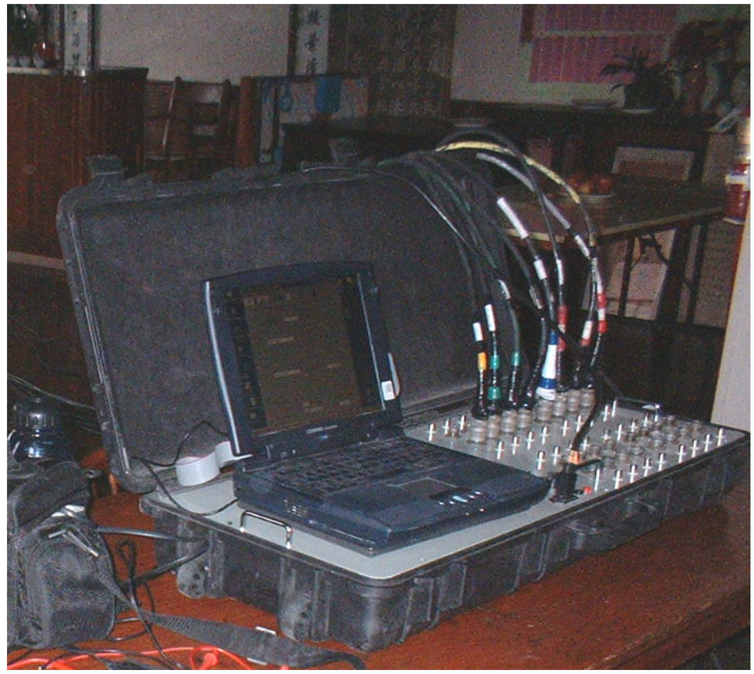

Figure 5: UBC EERF Data Acquisition System

The analysis is performed using the Frequency Domain Decomposition method, implemented with the ARTeMIS extractor software[1]. The analysis produces plots of singular value decomposition lines, which are similar to typical frequency spectra. Modes of the structure can then be selected from those plots using the classical peak picking method. Two of the primary advantages of the FDD method are its ability to separate the true signal from the noise, which can be very significant for low level accelerations such as in ambient testing, and the ability to distinguish closely spaced modes, which is where the classical method fails. A more recent version of the Extractor software features an Enhanced FDD method, which allows the user a better estimate of the frequencies and an estimate of the modal damping.

Test Details

The purpose of the tests was to obtain the natural frequencies, corresponding modes of vibration and damping estimates of each structure. In addition for both the Lim's Association and Mah Buildings a more detailed study of one floor was conducted to examine the behaviour of the diaphragms. Data was sampled at 200Hz for the Lim's and Mah Buildings, and at 500Hz for the May Wah Hotel. Each setup for all tests was recorded for a duration of 15 minutes.

For the Lim's Association Building, the reference sensors were placed on the 3rd floor, as well as the data acquisition system. For each floor, the sensor layout was identical except for a few additional transverse sensors on the 3rd floor. The sensor layout included four sensors per floor: three to measure transverse motion and one to measure the longitudinal motion.

For the May Wah Hotel, the reference sensors were placed on the 4th floor, and the data acquisition system was placed on the 3rd floor on a landing in the stairwell. For each floor, the sensor layout was identical. Eight sensors were used per floor: three sensors measuring transverse motion along each wing; and two orthogonal horizontal sensors at the north end of the building between the two wings. Testing on the roof was not possible due to hazards created by nesting seagulls. The sensors instead were clamped to fixtures close to the ceiling on the 4th floor.

For the Mah Building, the reference sensors were placed on the lower roof, and the data acquisition system was placed on the 2nd floor in a vacant room. For each floor, the sensor layout was identical. Four sensors were used per floor: three sensors measuring transverse motion and one measuring longitudinal motion at the north end of the building. The second floor was measured in more detail with three additional transverse sensors to measure the diaphragm behaviour, and the upper roof was similar to the Lim's Association Building and had one less transverse sensor.

Ambient Vibration Test Results

The tables of results shown present the mode number, the frequency obtained from the EFDD method, the computed standard deviation of the frequency, the damping ratio estimated obtained from the EFDD method and the standard deviation of the damping. The first mode of vibration is shown for each of the three buildings.

The results from the Lim's Association building are presented in Tables 1 and 2. Five modes were identified from the analysis of the complete set of data representing the entire building. The first mode, which is in the north/south (transverse) direction, is shown in Figure 6. From the analysis of the data from the 3rd floor only, only the first four modes are identified, which correlate to the first four of the complete test. Two additional higher modes are evident from the results, which have been labelled as mode 6 and 7, although this is not certain. There are no reported standard deviation values from the 3rd floor only test since there was only one data set used in the analysis.

The results from the May Wah Hotel are presented in Table 3. Seven modes were identified from the analysis of the data. The first mode, which is in the east/west (transverse) direction, is shown in Figure 7. The mode shape is presented as a set of two dimensional planes representing the centrelines of the various sections of the building.

The results from the Mah building are presented in Table 4. Eight potential modes were identified from the analysis of the data. The first mode, which is in the east/west (transverse) direction, is shown in Figure 8. The mode shape represents a line of sensors down the centre of the building, and is shown only in two dimensions.

For the Mah Building, the results of the detailed test of the 2nd floor were almost identical to that of Table 4 and are not presented here.

Table 1: Dynamic Characteristics from Lim's Association Building

Mode	Freq. [Hz]	Freq Std Dev [Hz]	Damping Ratio [%]	Damp Std Dev [%]
1	1.396	0.011	4.137	0.164
2	2.704	0.006	2.482	0.300
3	3.631	0.027	3.614	0.588
4	4.110	0.028	3.944	1.244
5	5.331	0.015	2.291	0.856

Table 2: Dynamic Characteristics from Lim's Association Building: 3rd Floor Only

Mode	Freq. [Hz]	Freq Std Dev [Hz]	Damping Ratio [%]	Damp. Std Dev [%]
1	1.409	N/A	3.995	N/A
2	2.712	N/A	2.332	N/A
3	3.662	N/A	2.635	N/A
4	4.146	N/A	2.559	N/A
6*	5.872	N/A	1.795	N/A
7*	6.244	N/A	1.574	N/A

Table 3: May Wah Hotel Dynamic Characteristics

Mode	Freq. [Hz]	Freq Std Dev [Hz]	Damping Ratio [%]	Damp. Std Dev [%]
1	2.849	0.012	3.312	0.355
2	3.814	0.036	2.716	0.136
3	4.394	0.042	2.593	1.458
4	5.620	0.025	2.369	0.594
5	6.217	0.036	2.511	0.424
6	6.960*	0.116	1.217	0.274
7	7.204	0.033	1.565	0.759

Table 4: Mah Building Dynamic Characteristics

Mode	Freq. [Hz]	Freq Std Dev [Hz]	Damping Ratio [%]	Damp. Std Dev [%]
1	2.334	0.005	2.543	0.318
2	3.066	0.016	3.79	1.910
3	3.512	0.025	2.615	0.292
4	3.734	0.086	1.269	0.207
5	4.252	0.008	1.925	0.360
6	4.810	0.043	2.037	0.959
7	5.004	0.023	2.323	0.153
8	5.488	0.019	1.479	0.881

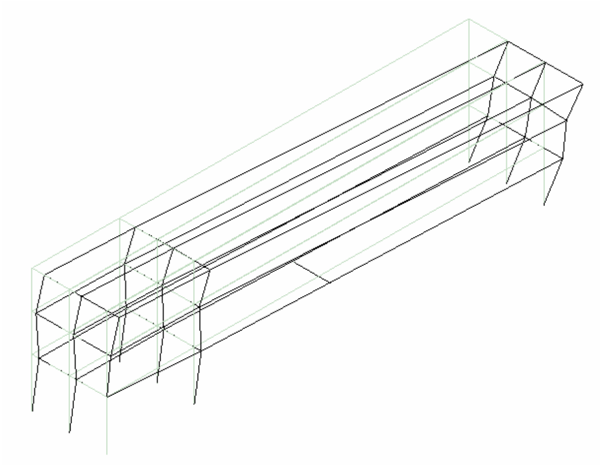

Figure 6: Lim’s Association Mode 1 – 1.396 Hz

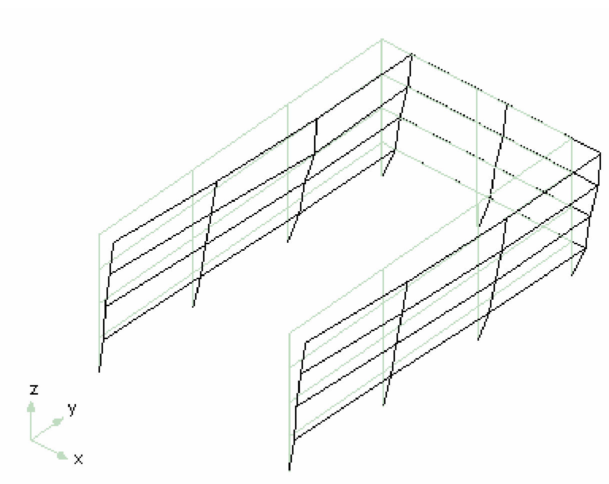

Figure 8: May Wah Hotel Mode 1 - 2.849 Hz

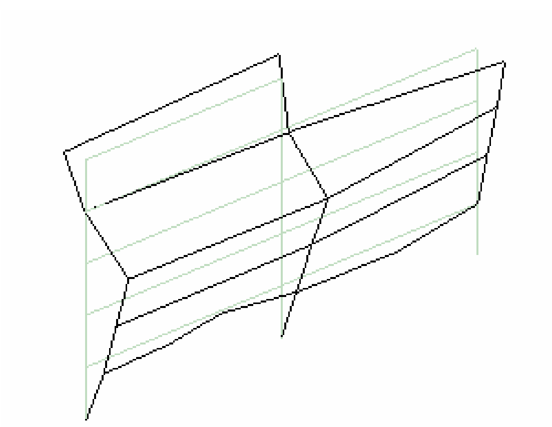

Figure 9: Mah Building Mode 1 – 2.334 Hz

Discussion of Ambient Vibration Results

For the Lim’s Association building the modes are typically defined by a transverse displacement, with larger displacements at the east side of the structure. This is due to the layout of the structure, since the west end of the building features an addition which was built at a later time, and makes that end apparently stiffer. There are no buildings adjacent and all of the modes are independent of boundary conditions except for the ground.

A more detailed study of the 3rd floor of the Lim’s Association building was performed in an attempt to identify the diaphragm behaviour. Although it was not readily apparent at the lowest frequencies, the measurements did illustrate in more detail the transverse bending behaviour of the building. The mode shapes describe a flexibility of the diaphragm along the length of the building in the transverse direction, which suggests that it should not be assumed to act as a rigid floor.

The modes shown in Table 2 are extracted from the same data as those in Table 1, but the frequencies reported vary slightly. This is due to the fact that only one of the three data sets was used in the analysis, and the numbers are different due to less data being used.

For the May Wah Hotel, the modes are defined more by the shape of the building, which is a U-shape. As as a result, there are two separate wings, and in the case of the first mode both wings move in the same direction. For the second mode they move opposite, etc. Although this building is in the middle of the block, with buildings adjacent on both sides, the main part of the building is not in contact with the adjacent structures, since the building steps inwards above the first floor.

For the Mah building, the definition of the mode shapes is not as clear as with the other two buildings, mainly due to the more complicated boundary conditions. There are buildings in contact on both sides, and in addition, the Mah building is taller than the adjacent buildings, two stories higher. This creates more complicated mode shapes, although the structure appears to vibrate in its first mode as a simple beam with a pin connection part way along its length, with a cantilevered free end. In the first mode, the lower part of the building moves with the adjacent buildings, while the top part moves in the opposite direction. The higher modes are more difficult to describe.

Microtremor Measurements

The purpose of conducting microtremor measurements is to obtain an estimation of site response for a particular location. Three approaches are commonly used to analyze microtremor data; power spectral densities obtained directly from the Fourier amplitudes, spectral ratios relative to a reference site, and Nakamura's technique[2], which is defined as the spectral ratio of horizontal components to vertical components recorded at the same site (H/V ratio). It is common to perform tests over a period of time to observe the stability of the measured site response, in order to provide a reliable prediction of the period of potential earthquake motion at that site.

Nakamura's technique describes the microtremors as Rayleigh waves propagating in a single layer over a half-space, and assumes that the microtremor motion is due to local sources such as traffic and human and construction activity nearby. It further assumes that the vertical component of ground motion is not amplified by the soil layer. Hence, the spectral ratio of the horizontal to the vertical components at the surface (H/V ratio) gives an estimate of the period at which it peaks, corresponding to the site period.

The equipment used for the UBC EERF microtremor testing system consists of six velocity transducers; two horizontal and one vertical, an amplifier, an analog-to-digital (A/D) converter and a laptop computer used for data acquisition. For the selection of the test location, care is taken to avoid heavy traffic, manholes, foundations and other underground structures. The sensors are placed so that the two horizontal sensors are orthogonal, preferably facing North and East. The analysis is carried out using Nakamura's method, plotting the H/V spectral ratios that are the result of taking the RMS of the east and North spectral ratios. The most significant peak of the H/V spectral ratio is taken to be the dominant frequency of the site.

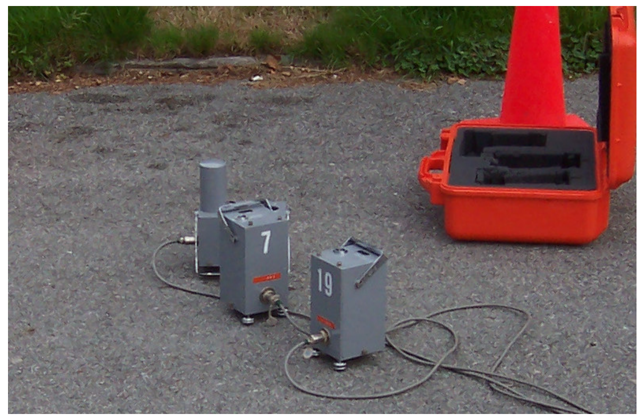

Figure 9: Microtremor sensors

Test Results

For the two locations described earlier in this paper, both vertical and horizontal measurements were recorded, with a sampling rate of 200Hz at Location 1 and 100 Hz at Location 2, and a duration of 10 minutes for each. From the analysis of the normalized H/V ratio plots (shown in Figure 10 and 11), the pertinent information obtained is presented in Table 5.

Table 5: Microtremor Results

Test Location	1st Significant Peak	2nd Significant Peak	Most Significant Peak	Site Period
Test #1 – Point D	0.5 Hz	1.8 Hz	7.2 Hz	0.139 sec
Test #2 – Point E	1.3 Hz	7.3 Hz	7.3 Hz	0.137 sec

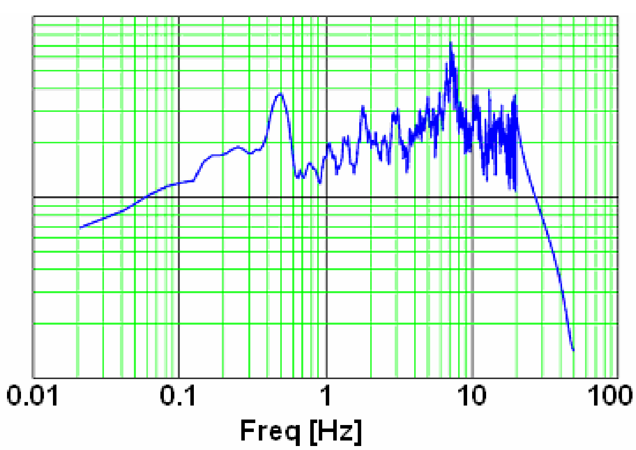

Figure 10: Normalized H/V Ratio, Test #1

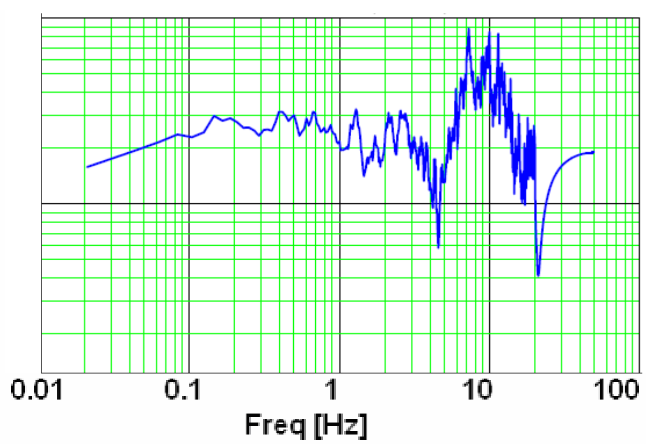

Figure 11: Normalized H/V Ratio, Test #2

Discussion of Microtremor Tests

It was evident from the results of the microtremor tests that the site frequency for the Chinatown district is in the range of 7 Hz. This value is close to the range of the higher modes of vibration for the buildings measured, as shown in the ambient vibration test results. This raises the possibility of soil-structure interaction and should be addressed for retrofit design considerations. The dynamic response of the buildings during a severe earthquake can be significantly affected by soil-structure interaction effects. This can also be of extra significance for older unreinforced buildings such as those in this study.

Conclusions

The intention of the tests described in this paper was to provide some preliminary information about the dynamic behaviour and the dynamic site conditions for three buildings in the Chinatown district of Vancouver, BC. The Lim's Association Building, the May Wah Hotel and the Mah Building were each tested by researchers at the UBC EERF. In addition, two microtremor tests were performed at locations near these buildings.

The ambient vibration tests of the three buildings were successful at obtaining the fundamental modes and several higher modes for each. The first two buildings had the best quality results, and the mode shapes were the most well defined. This is likely due to the boundary conditions, since those buildings were independent from the adjacent buildings, and the Mah Building was not. This resulted in poorer definition of the mode shapes for the Mah Building, which was not only in contact with the adjacent buildings but was taller than them as well. The fundamental frequency for each building was 1.4, 2.8 and 2.3 Hz for each of the Lim's Association, May Wah Hotel and Mah Building respectively. Modes extracted for each were in the range of 1.5 to 7.0 Hz. More detailed testing of one floor of the Lim's Association and Mah building was also performed. While the results from those tests illustrated the flexibility of the buildings in the transverse direction, there was no clear indication of the deformation between the two exterior walls. It is still most likely that the floors do not behave as a rigid diaphragm.

The results of the Microtremor tests were successful at obtaining the site periods for the two locations, which were both similar and approximately 0.14 seconds. The frequency found (7 Hz) is in the range of the higher modes of the buildings and soil-structure interaction may be an issue, and should be considered for possible retrofit design.

Acknowledgements

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[2] Nakamura, Y. (1989) "A method for Dynamic Characteristics Estimation of Subsurface using Microtremor on the Ground Surface", QR of RTRI, Vol. 30, No. 1, pp. 25-31