Site Period Estimations Using Microtremor Measurements- Experimental and Analytical Studies in British Columbia

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ABSTRACT

This paper presents site period investigations at nodes on a 1-km grid within a 6-km by 8-km area in Vancouver and Richmond, BC. The area includes a range of site conditions, and is selected as the pilot application area for an urban seismic instrumentation project (Canadian Urban Seismology Program - CUSP) undertaken by the Geological Survey of Canada (GSC). The pilot project area is situated in one of the most seismically active regions in Canada and part of it lies on thick deltaic sediments that are known to have amplified ground motions during past earthquakes. Reliable site response models for the area are needed to quantify the amplification potential. Microtremor measurements provide a relatively inexpensive and simple tool to obtain one of the key parameters in site response studies, the site period. A series of microtremor measurements in the pilot CUSP area yielded site periods ranging from 0.05 seconds at bedrock outcrop to 4.2 seconds at some sites on the Fraser River delta in Richmond. Site periods were also estimated using a 1-D site-modeling program, SHAKE, for sites on the Fraser River delta. Each site was represented by a simplified 3-layer model with Holocene deposits, Pleistocene deposits and bedrock. The highest site period obtained from SHAKE modeling was 4.4 seconds about 3 km east of Richmond City Hall, for which the microtremor measurements indicated a site period of 4.2 seconds.

INTRODUCTION

The Geological Survey of Canada (GSC) has recently initiated the Canadian Urban Seismology Program (CUSP) aiming to help mitigate the impacts of earthquakes in Canada by developing and advanced national earthquake monitoring system in urban centers at risk. A demonstration network as part of this program is the partially completed 6km by 8 km area spanning across the Fraser River with the City of Vancouver to the North and the City of Richmond to the South. The final network is to consist of about 60 strong-motion recording instruments installed in a grid, with a distance of roughly 1km between each one (Figure 1).

This region, which forms the study area for this paper, is located in the most seismically active region in Canada, and is also highly populated with rapid ongoing urban development. The surface geology here ranges from bedrock outcrop to thick Fraser River delta sediments (figure 2, adopted from [1]). The southern section to of the study area , the Fraser River delta, has a high likelihood of amplification of earthquake shaking as well as liquefaction of cohesionless soils, which are saturated due to high ground water table of the delta. The study area is also of interest because of CUSP strong motion network, through which strong motion data will eventually be recorded.

Reliable site response models for the area are needed to estimate the amplification potential and the probabilistic and deterministic distributions of the peak and spectral amplitudes of ground shaking at the surface. Microtremor

[1] Currently employed by Risk Management Solutions, Inc, California

measurements provide a relatively inexpensive and simple tool to obtain one of the key parameters in site response, the site period. Microtremor testing was conducted at the CUSP locations in the summer of 2002. In the City of Vancouver, site periods of 0.5 seconds to 1 second were detected. In the City of Richmond, site periods were much longer periods; in the area of 4 seconds for most locations. However, inconsistencies were seen and it was concluded that the testing duration was not long enough to detect the longer period motions. In the summer of 2004, further testing was conducted for the City of Richmond using a longer duration.

This paper gives an overview of the site conditions in the CUSP demonstration network area and presents natural periods obtained from microtremor measurements conducted at the proposed instrument locations in the summers of 2002 and 2004. In addition, a preliminary site response modeling was carried out using the 1-D site response program SHAKE [2]. Each site was modeled as a 3-layer column, bedrock overlaid with Pleistocene sediments overlaid with Holocene sediments. Site periods obtained by SHAKE modeling are presented and compared with the site periods obtained from microtremor measurements.

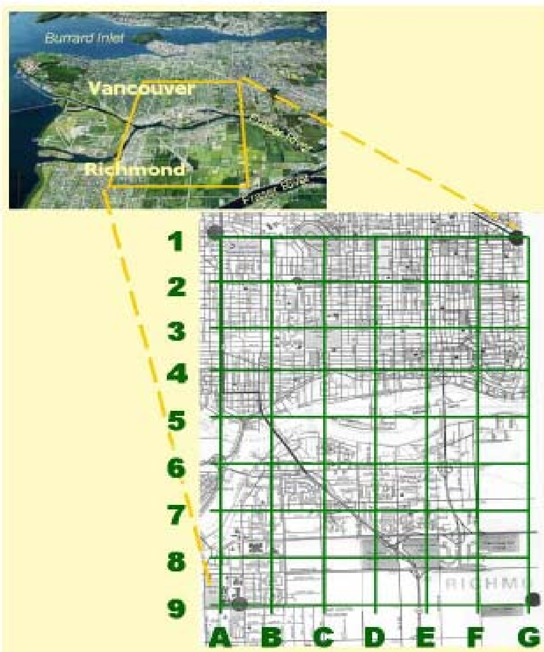

Figure 1. Overview of the study area

Figure 2. Surface geology of the study area

GEOLOGICAL SETTING

To the North of the Fraser River, surface geology mainly consists of glacial sediments such as till, with bedrock outcropping at the Queen Elizabeth park near the northwest corner of the study area and some relatively thin (less that 50m) Holocene deposits of silt and clay along the Fraser River (Figure 2).

The southern section of the study area lied on the Fraser River delta, which is a thick (up to roughly 300 m) accumulation of deltaic sediments such as sands and silts deposited entirely within the Holocene (Figure xx). These sediments overlie Pleistocene sediments, which in turn overlie Tertiary bedrock. Amplification potential varies greatly over the delta as the thickness of the Holocene sediments is extremely variable and the bedrock surface beneath the delta is highly irregular [3, 4]. The largest ground accelerations during the past tow earthquakes were recorded near the edge of the delta rather than on the thickest sediments [5].

SITE PERIOD ESTIMATIONS USING MICROTREMOR MEASUREMENTS

The use of microtremor measurements (MTM) in estimation of site response has been investigated since it was first proposed in the 1950s. Although there are ongoing discussion about the applicability of it in the various site conditions and ground shaking levels, it have been widely used to estimate the dominant periods of soil deposits [6,7,8].

Three approaches are commonly used to analyze data from MTM; power spectral densities obtained directly form the Fourier amplitudes, spectral ratios relative to reference site, and Nakamura's technique [9], which is defined as the spectral ratio of horizontal components to vertical components recorded at the same site (H/V ratio). Despite the recognized shortcomings of Nakamura's technique [10], it has gained popularity quite rapidly in recent years as it provides reliable estimates of dominant periods of ground motion.

Nakamura's technique describes the microtremors as Raleigh waves propagating in a single layer over a half-space, and assumes that the microtremor motion is due to local sources such as traffic, 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 vertical components at the surface (H/V ratio) gives an estimate of the period at which it peaks, corresponding to the site period.

UBC is currently looking into using Frequency Domain Decomposition as an approach to analyze Microtremor data. This method is put into practice by using the ARTeMIS Extractor software package [17]. 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. The soil areas are modeled as rigid plates with the sensor data placed at their center.

EQUIPMENT AND FIELD PEST PROCEDURE

Equipment

The equipment used for the Microtremor measurements in Richmond consisted of six sensors; two horizontal and one vertical, an amplifier, an analog-to-digital (A/D) converter and a laptop computer used for data acquisition. A generator was used to power the system. Data was acquired by running a worksheet created in DASYLab 7.0. The sensors are velocity transducers with a natural period of 1 second and an amplitude range of ±3000 μm/s2, with a resolution of 0.005 μm/s2. The amplifier unit improved the quality of the signals by extending the natural period to 5 seconds, filtering undesired frequencies and amplifying the signals. An 8-channel, 12-bit analog-to-digital (A/D) converter digitized the recorded data. The data acquisition computer was used to monitor the data collection, store the digitized data and to carry out preliminary data analysis on site. The tests in 2002 used the program DASam in order to collect and store the data. In 2004, a worksheet created in DASYLab [18] was run on a laptop computer to acquire the data. Preliminary on-site analysis was conducted using a second laptop computer

Data Acquisition

The original set of microtremor measurements were carried out in May and June 2002. The weather was generally calm with no strong winds or rain. Measurement locations were close as possible to the proposed CUSP instrument locations; however care was taken to avoid direct heavy traffic pulses, manholes, foundations or other underground structures. When measurements had to be conducted on grass instead of concrete or asphalt, a metal plate was set up underneath the sensors. Multiple measurements were carried out at locations where there was heavy traffic. Data was recorded for 5 minutes.

The second set of Microtremor measurements were carried out in August 2004. The weather ranged from cold and raining to sunny and calm. The Microtremor measurements were taken at grid squares A to E, in the East-West direction and 6 to 9 in the North-South direction, excluding grid square E8 because there was no suitable place for testing. They were conducted as close as possible to locations to the original test sites in Richmond. Testing at location B6 had to be done across the street from the original site because of heavy construction. As in previous tests, care was taken to avoid direct heavy traffic pulses, manholes, foundations or other underground structures. When measurements had to be conducted on grass or dirt instead of asphalt pavement or concrete, a metal plate was set underneath the sensors. A compass was used to determine bearing and the two horizontal sensors were placed orthogonally to measure in the East-West and North-South directions. (See Appendix B for the sensor arrangement photographs). The amplifier filter was set to a period of 5 seconds in order to capture low frequency vibrations. The data was recorded for 30 minutes at a sampling rate of 100 samples per second. A "tap test" was conducted at the end of each test to ensure proper set up. It was found that in tests performed at grid squares B6, B8, B9, C6, C9 and D9 channels 2 and 3 were reversed.

RESULTS OF MICROTREMOR TESTS

2002 Microtremor Tests

The software, DASam [11] was used for data acquisition and preliminary analysis, such as producing plots of time-histories, Fourier spectra, and spectral ratios. An engineering spreadsheet, DADisp was the platform for the calculation of Fourier spectra, identification of dominant periods and spectral amplitudes, and for the calculation of H/V ratios.

Nakamura's method was used to obtain natural periods (Tn) from which corresponding natural frequencies (fn) were obtained, and amplitudes of the H/V ratios. The results are given in Table 1. A confidence level for each measurement is also indicated. "Very high" corresponds to 90%, "High" to 70% and "Medium" to 50%, respectively. The results in Table 1 show that the site periods in the region vary from about 0.3 sec to about 4.2 sec, and that the H/V amplification ratios vary from about 2 to about 8. Refer to [16] for full details.

The thickness of the sediments is a key factor that affects the site period. Within the Fraser River delta the thickness of the sediments varies significantly. In Figure 3, the distribution of the thickness of Holocene deposits in the Richmond study area [12] is presented overlaid by site periods obtained from the 2002 MTM. The inconsistencies in the site periods, which were the reason for repeating the tests in 2004, can be seen in the Southwest corner of the plot. Sites B9, C8 and C9 show relatively low periods for the thickness of the Holocene in that area.

In Figure 4, the site periods are presented on a depth-to-bedrock map, which gives the combined thickness of Holocene and Pleistocene sediments. Although the Holocene deposits are relatively shallow (approximately 100 m) at site D9 the thickness of the Pleistocene, and hence the depth-to-bedrock, is the largest in the study area (just over 700 m).

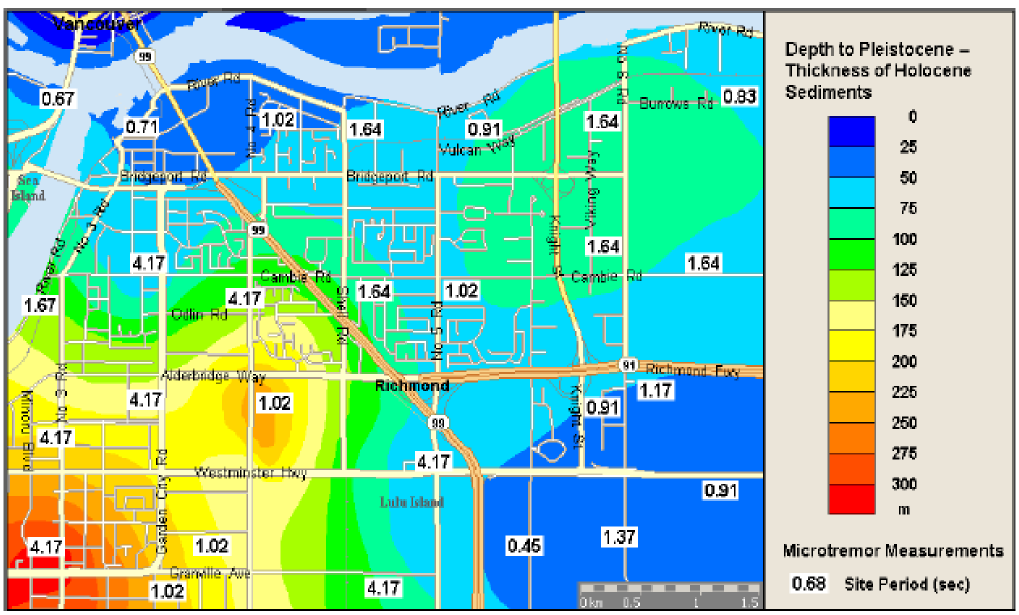

Figure 3: Thickness of Holocene sediments in the Fraser River delta (Richmond) overlaid with site periods obtained from microtremor measurements

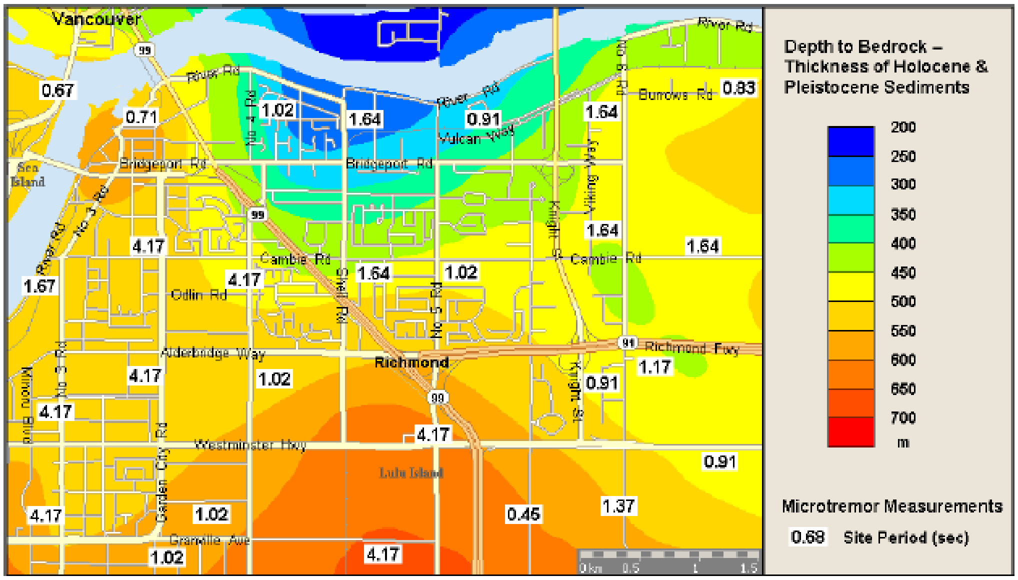

Figure 4. Combined thickness of Holocene and Pleistocene sediments in the Fraser River delta (Richmond) overlaid with site periods obtained from microtremor measurements

2004 Microtremor Tests

Nakamura's technique was carried out using a MathCAD 11 [19] worksheet created by Dr. Carlos Ventura. Frequencies less than 0.05Hz and greater than 20Hz were not of interest and were therefore filtered out. Thirty averages with 60% overlap were taken according the Welch's Method. The H/V spectral ratios shown are the result of taking the RMS of the east and North spectral ratios. The first significant peak of the H/V spectral ratios was taken to the dominant frequency of the site. Other significant frequencies were table 2 and a sample of the normalized H/V spectral curve for site C6 is shown in figure 5.

Table1: Site Frequencies and calculated Site period.

	Site Frequency (Hz)		Site Period (s)	
Grid Point	First Significant Peak	Other Significant Peak	First Significant Peak	Other Significant Peak
A6	0.273		3.66	
A7	0.238		4.20	
A8	0.252	1.020	3.97	0.98
A9	0.217	1.250	4.61	0.80
B6	0.217	1.015	4.61	0.99
B7	0.259		3.86	
B8	0.238	0.938	4.20	1.07
B9	0.252	1.020	3.97	0.98
C6	0.287	0.952	3.48	1.05
C7	0.203	0.931	4.93	1.07
C8	0.208	0.960	4.81	1.04
C9	0.245	1.022	4.08	0.98
D6	0.217	1.030	4.61	0.97
D7	0.175	1.020	5.71	0.98
D8	0.196	1.010	5.10	0.99
D9	0.248		4.03	
E6	0.212	0.938	4.72	1.07
E7	0.210		4.76	
E8				
E9	0.270		3.70	

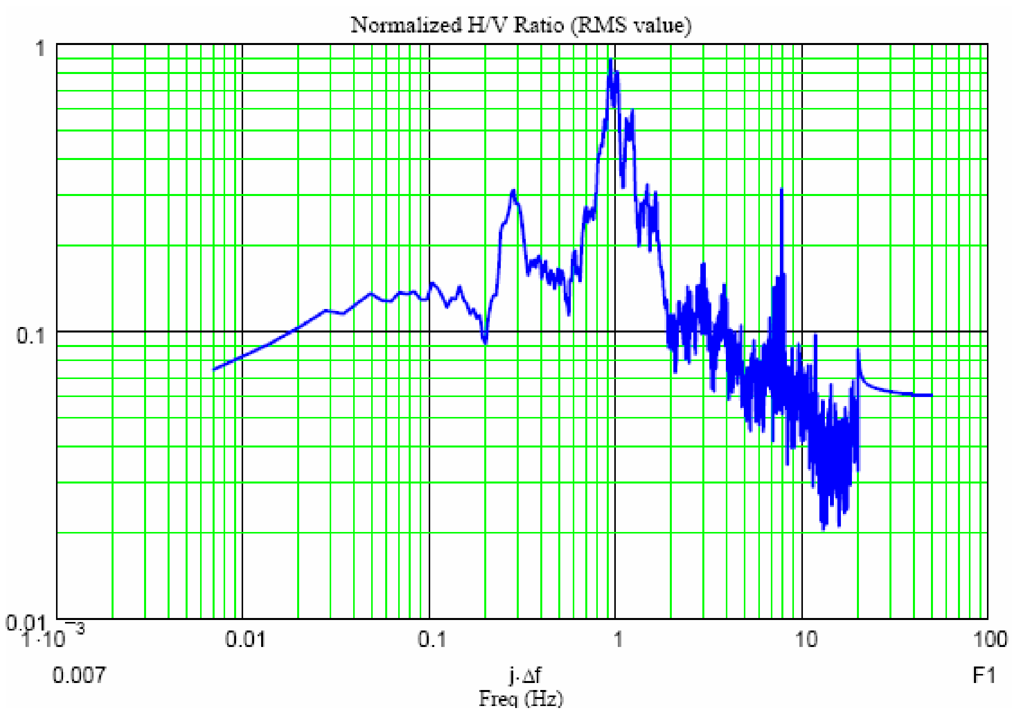

Figure 5: Sample H/V plot from MathCAD Analysis

Periods of around 4 seconds were seen consistently throughout the sites, with the exception of C7, C8, D7 and D8 which were closer to five seconds. In many sites, a second significant peak near was also identified. These were all in the range of 1 sec. This explains the values achieved from the 2002 tests. Since the durations were only 5 minutes, the longer period motions were not detected. A plot comparing the results from both the 2002 and 2004 tests can be seen below. (Figure 6)

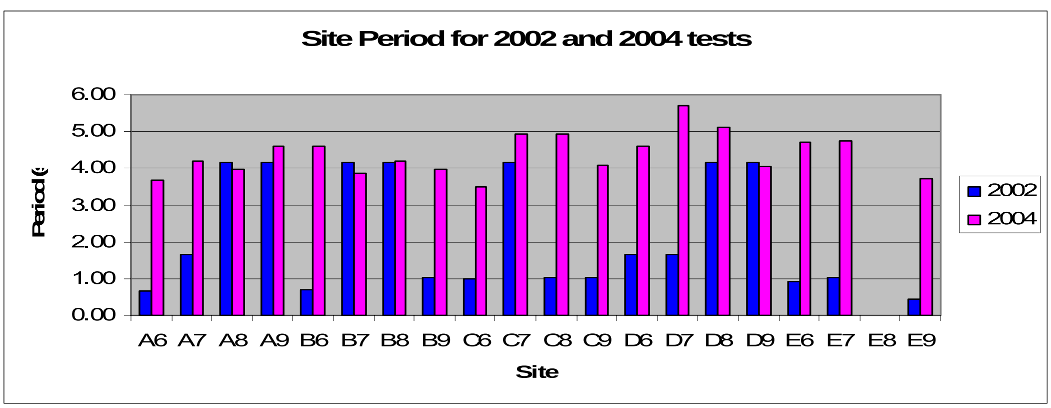

Figure 6: Comparison of Site Periods from 2002 and 2004 Tests

SITE MODELLING RESULTS

In this section the results of a simple preliminary modeling are presented and compared with the measured values. The same CUSP sites in the Richmond area were modeled using the 1-D site response program SHAKE [2]. The stratigraphy was simplified to three layers; Bedrock, Pleistocene deposits and Holocene deposits. The thickness and shear wave velocity used for each layer were obtained from boreholes and seismic reflection surveys [12]. The average unit weights used for modeling are 19.5 kN/m3 for Holocene deposits, 23.3 kN/m3 for Pleistocene and 25.0 kN/m3 for bedrock [13], which were estimated from cone penetration tests and bulk density measurements [14, 15]. The thickness of the Holocene sediments range from 35 m to 300 m in the study area and the average shear wave velocity of these sediments vary with depth. This variation was taken into account using shear wave velocity versus depth data compiled from surface refraction and seismic cone penetrometer surveys conducted in this area [4]. Low amplitude input ground motion (PGA: 0.11g) was used such that no inelastic response of the site was generated. Site periods were obtained from the peaks of amplification spectra (ratio of spectra at the top of the soil column to the spectra at the bottom).

the SHAKE periods are generally larger than the MTM periods, especially in the southwest corner of the study area, but at some sites there is a good match between the two. The site periods range from 1.64 seconds at the northern edge of the delta (D6) to 4.35 seconds at the southern boundary of the study area (D9). The distribution generally reflects the thickness of the sediments, both Holocene and Pleistocene. The deepest Holocene sediments are at the southwest corner of the study area (roughly 300 m), and the deepest Pleistocene sediments are at the southern boundary of the study area (roughly 525 m). Geotechnical properties of the sediments highly vary by depth, especially at this range of several hundred metres. The first order modeling presented here uses average shear wave velocities for Holocene sediments. The variation of the velocities by depth is roughly taken into account by changing the average velocity based on the thickness of the sediments. To see more detailed results please refer to [16].

The comparison of 2004 Microtremor measurement results to the 2002 MTM results and the SHAKE analysis results is shown below. The 2004 measurements are much closer to the analytical results than the 2002 tests. However in some cases, the measurements gave much longer periods in areas where the depth to bedrock is known to be shallower (gridline 6).

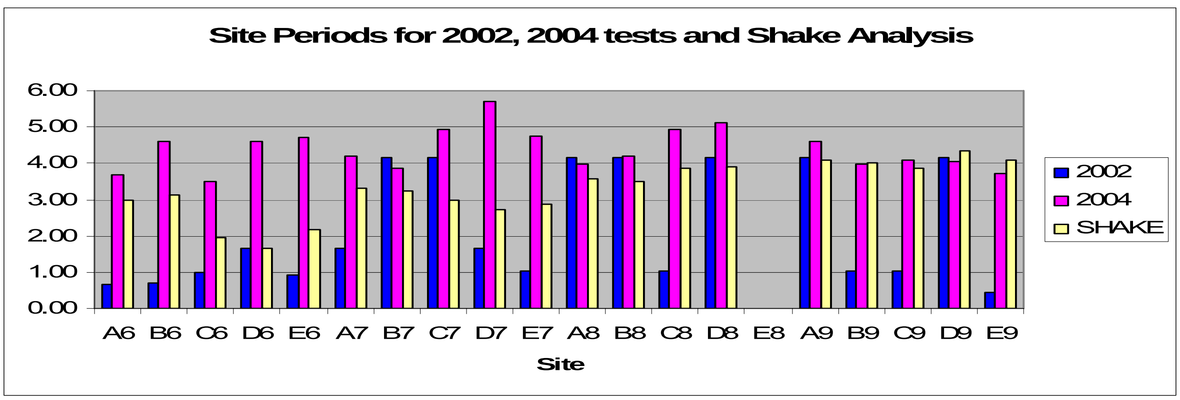

Figure 10: Comparison of Site Periods from 2002 and 2004 Tests and SHAKE Analysis

FREQUENCY DOMAIN DECOMPOSITION RESULTS

One of the limitations of Nakamura's H/V technique to determine site frequencies (or periods) is that the nature of associated ground motion is not determined, so there is no way to identify if the dominant motion associated with each of the peaks of the H/V spectrum is horizontal or vertical. If one treats the microtremor data as one case of output only modal data, it would then be possible to use the Frequency Domain Decomposition technique to determine dominant frequencies and their associated components of motion. The latter can be achieved by assuming that the location where the tri-axial measurement has been taken acts like a rigid plate moving along the horizontal and vertical directions. The preliminary results of the application of the Frequency domain Decomposition method for site A6 are shown below in figures 11 and 12. The four selected mode shapes have frequencies of 0.29Hz, 1.95 Hz, 3.76 Hz and 9.72 Hz.

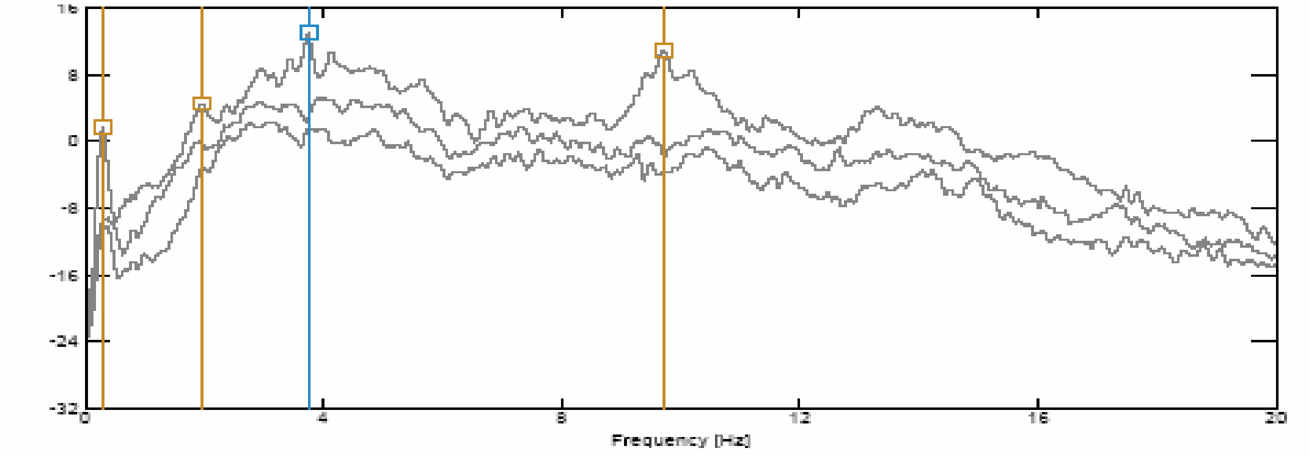

Figure 11: FDD Spectrum

Mode shape 1 (0.29Hz) is the fundamental frequency. These results match up well with the results achieved through Nakamura's technique, where the site frequency for A6 was found to be 0.273 Hz. Please note that modes 1 and two have horizontal motions and modes 3 and 4 are vertical.

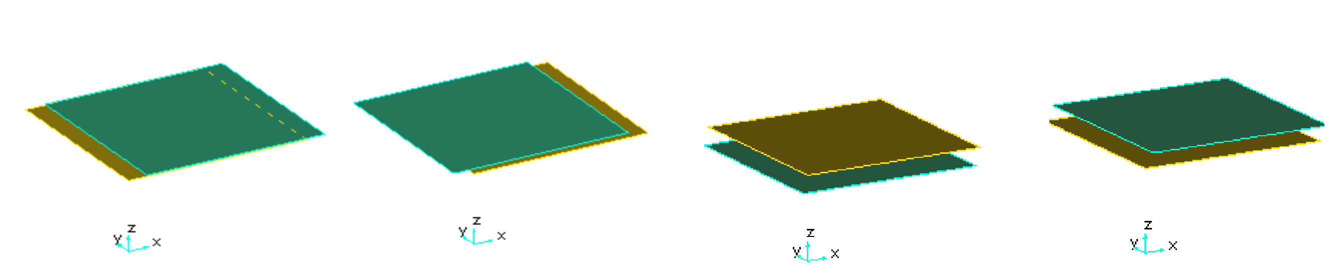

Figure 12: Mode Shapes

CONCLUSIONS

This paper presented a site period investigation at nodes on a 1-km grid within a 6-km by 8-km area in Vancouver, BC. The area investigated includes a range of site conditions, and has been selected as the pilot application area for an urban seismic instrumentation project (CUSP) undertaken by the Geological Survey of Canada. A series of microtremor measurements in the summer of 2002 at the pilot CUSP area yielded site periods ranging from 0.05 seconds at bedrock outcrop to 4.2 seconds at some sites on the Fraser River delta. Sites on the Fraser River Delta were retested in the summer of 2004 for a longer duration. Theses tests resulted in more accurate estimations of the site periods.

Site periods were also estimated using a preliminary 1-D site-modeling using program SHAKE for sites on the Fraser River delta. Each site was represented by a simplified 3-layer model with Holocene deposits, Pleistocene deposits and bedrock. The highest site period obtained from SHAKE modeling was 4.35 seconds roughly 3 km of Richmond City Hall, for which the microtremor measurements indicated a site period of 3.97 seconds. In general, there was a reasonable match between the two results, but in a few cases the periods computed by SHAKE were smaller than the MTM periods.

Preliminary results achieved using the Frequency Domain Decomposition method, implemented by the Artemis Extractor software, were close to those achieved by using Nakamura's technique. As far as the authors can tell, this is the first time that the F.D.D. technique has been used for this purpose, and the results are very promising. Further research will be conducted on the use of this method and complex models will be developed
.

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19 MathCAD Software, MathSoft Engineering and Education Inc., ©1986-2001www.mathsoft.com