EARTH SCIENCES SECTOR
GENERAL INFORMATION PRODUCT 23

Site period estimations in the Fraser River delta using microtremor measurements - experimental and analytical studies

Ventura, C E; Onur, T; Hao, K X -S

2004

Originally released as: Site period estimations in the Fraser River delta using microtremor measurements - experimental and analytical studies, Ventura, C E; Onur, T; Hao, K X -S; in, Proceedings of the 13th World Conference on Earthquake Engineering; 2004; 15 pages (GSC Cont.# 2003299)

13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1075

SITE PERIOD ESTIMATIONS IN THE FRASER RIVER DELTA USING MICROTREMOR MEASUREMENTS - EXPERIMENTAL AND ANALYTICAL STUDIES

Carlos E. VENTURA[1], Tuna ONUR[2], and Ken X.-S. HAO[3]

SUMMARY

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 deploying an advanced national earthquake monitoring system in urban centres at risk. A demonstration network as part of this program is partially completed in a 6-km by 8-km area straddling 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 1-km between each instrument (Figure 1).

[1] Prof. of Civil Engineering, Univ. of British Columbia, Vancouver, BC, Canada. ventura@civil.ubc.ca
[2] Postdoctoral Research Fellow, Geological Survey of Canada, Sidney, BC, Canada. Onur@NRCan.gc.ca
[3] Consultant, CCJ GeoServices Co., Richmond, BC, Canada.

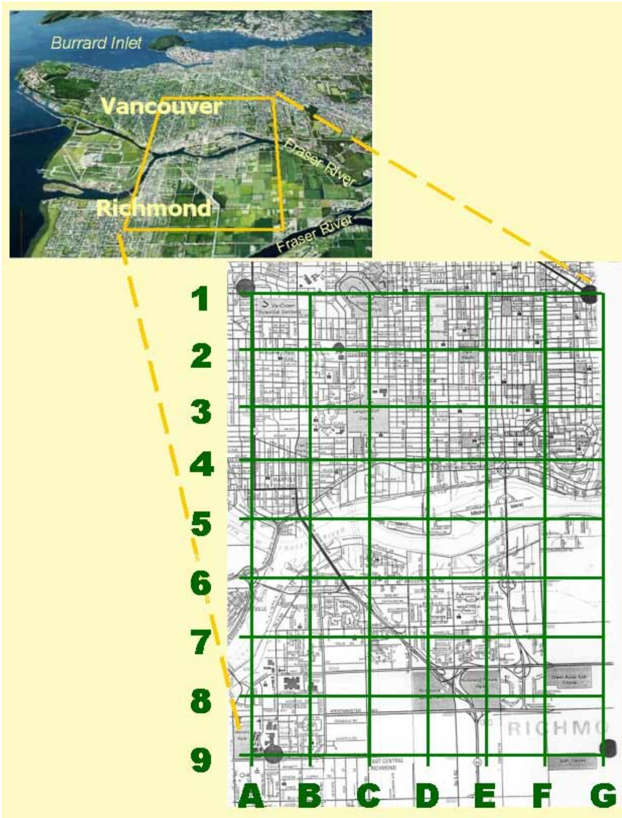

Figure 1. Overview of the study area

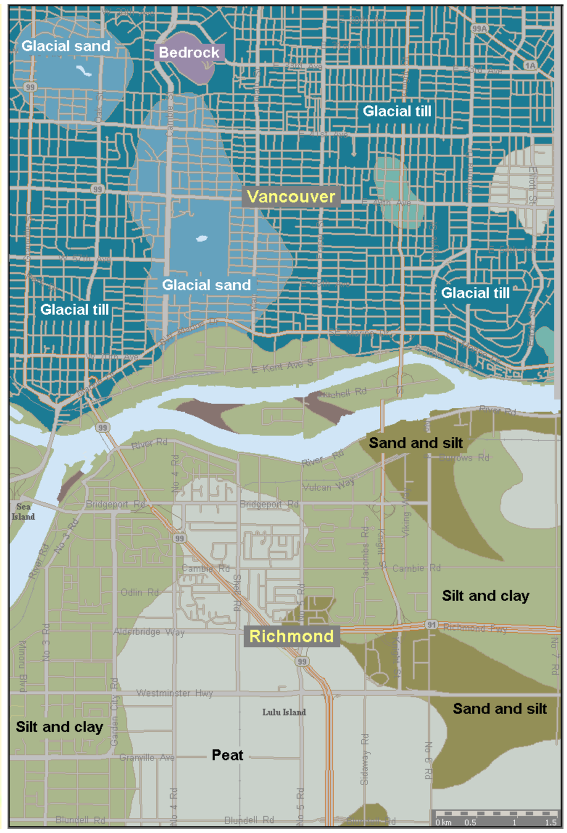

Figure 2. Surface geology of the study area

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

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 measurements provide a relatively inexpensive and simple tool to obtain one of the key parameters in site response, the site period.

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 addition, a preliminary site response modelling was carried out using the 1-D site response program SHAKE [2]. Each site was modelled as a 3-layer column, bedrock overlaid with Pleistocene sediments overlaid with Holocene sediments. Site periods obtained by SHAKE modelling are presented and compared with the site periods obtained from microtremor measurements.

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 northwest corner of study area and some relatively thin (less than 50 m) Holocene deposits of silt and clay along the Fraser River (Figure 2a).

The southern section of the study area lies 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 2b). These sediments overlie Pleistocene sediments, which in turn overlie the 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 two past 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 is ongoing discussion about the applicability of it in various site conditions and ground shaking levels, it has been widely used to estimate the dominant period of soil deposits [6, 7, 8].

Three approaches are commonly used to analyze data from MTM; power spectral densities obtained directly from the Fourier amplitudes, spectral ratios relative to a 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 recognised 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 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.

FIELD TEST PROCEDURE

Stability of Microtremor Measurements

A common concern is whether MTM can be used to obtain a representative characteristic of ground motions due to variation of the sources with time. The stability of microtremor measurements to the variations of the sources with time was validated at a strong-motion station (MNY) site on the northern basin edge of Fraser River delta, 100 m north of the grid point C5 (Figure 1). The procedure included a series of 96 observations over a 10-day period. The analysis of the stability and variability of site frequencies and amplitudes, and investigation of the influence factors such as weather, ocean waves and local activity showed that the two site frequencies observed at MNY were fairly stable although the amplitudes fluctuated. The two frequencies were 0.2Hz, a relatively low frequency whose amplitudes were affected by the variation of sea waves, and 2.4Hz, whose amplitudes were controlled by the level of disturbance nearby, peaking during week days and decreasing at the weekends. Neither the frequencies nor the amplitudes were affected by weather conditions, such as air-temperature and rain.

Data Acquisition

The hardware used in the MTM consisted of velocity transducers, an amplifier, an analog-to-digital converter and a computer for data acquisition. The velocity sensors had a natural period of 1 second, amplitude range of ±3000 μm/s2, and resolution of 0.005 μm/s2. Three sensors were deployed for every measurement, two in two orthogonal horizontal directions and one in vertical direction. 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.

Microtremor measurements were carried out in May and June 2002. The weather was generally calm with no strong winds or rain. Measurement locations were as 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 the measurements had to be conducted on grass instead of concrete or asphalt pavement, a metal plate was set up underneath the sensors. Multiple measurements were carried out at locations where there was heavy traffic.

FIELD TEST RESULTS

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 (T_n) from which corresponding natural frequencies (f_n) 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. Sample plots of H/V ratios are presented in Figure 3. The three windows on red background display 300-second long time-histories for three components, two horizontal and one vertical. The three windows underneath the time-histories display the Fourier spectra, two horizontal components in blue and red, vertical component in yellow. The two windows to the right of the time-histories present the H/V ratios obtained using each horizontal component.

Table 1. Microtremor Measurement Results

Grid	Lat (N)	Long (W)	f_n (Hz)	T_n (sec)	H/V ratio	Confidence
A1	49.23833	123.1287	1.46	0.68	3.99	Very high
B1	49.23920	123.1246	1.65	0.61	2.60	Very high
C1	49.24181	123.1117	19.8	0.05	7.88	High
D1	49.24161	123.1008	1.90	0.53	1.80	High
E1	49.24079	123.0857	1.59	0.63	3.26	Very high
F1	49.24125	123.0674	2.20	0.45	2.70	High
G1	49.24059	123.0566	3.00	0.33	1.70	High
A2	49.23228	123.1403	1.10	0.91	2.62	High
B2	49.23338	123.1234	1.22	0.82	4.11	Very high
C2	49.23165	123.1130	1.10	0.91	3.63	Very high
D2	49.23154	123.0933	1.10	0.91	2.30	High
E2	49.23068	123.0876	1.46	0.68	2.62	High
F2	49.23084	123.0701	1.59	0.63	4.00	High
G2	49.22842	123.0558	0.80	1.25	2.20	High
A3	49.22165	123.1411	0.85	1.17	3.91	Very high
B3	49.22090	123.1241	0.85	1.17	4.08	High
C3	49.22408	123.1129	0.98	1.02	2.91	Very high
D3	N/A	N/A	N/A	N/A	N/A	N/A
E3	N/A	N/A	N/A	N/A	N/A	N/A
F3	49.22175	123.0694	1.30	0.77	2.20	High
G3	49.22163	123.0561	0.70	1.43	2.30	Very high
A4	49.21505	123.1417	0.73	1.37	3.67	Very high
B4	49.21609	123.1275	0.73	1.37	3.45	Very high
C4	49.21595	123.1129	1.80	0.56	1.90	Medium
D4	49.21444	123.0967	0.85	1.17	2.79	Very high
E4	49.21558	123.0870	0.85	1.17	2.56	Very high
F4	49.21349	123.0740	1.50	0.67	2.40	Very high
G4	49.21408	123.0590	0.61	1.64	3.96	Very high
A5	49.20460	123.1371	1.10	0.91	1.90	Medium
B5	49.20552	123.1262	0.61	1.64	2.70	Very high
C5	49.20729	123.1109	1.71	0.59	6.63	Very high
D5	49.20647	123.0985	1.60	0.63	5.30	Very high
E5	49.20506	123.0860	1.34	0.75	6.93	Very high
F5	49.20621	123.0695	3.05	0.33	4.46	Very high
G5	49.20578	123.0564	0.98	1.02	5.34	Very high

Table 1. (continued)

Grid	Lat (N)	Long (W)	f_n (Hz)	T_n (sec)	H/V ratio	Confidence
A6	49.19756	123.1357	1.50	0.67	4.20	Very high
B6	49.19584	123.1287	1.40	0.71	3.00	Very high
C6	49.19598	123.1112	0.98	1.02	3.88	High
D6	49.19541	123.1006	0.61	1.64	5.43	Very high
E6	49.19495	123.0855	1.10	0.91	3.87	Very high
F6	49.19626	123.0715	0.61	1.64	2.93	Very high
G6	49.19782	123.0581	1.20	0.83	3.05	Very high
A7	49.18375	123.1382	0.60	1.67	2.40	High
B7	49.18501	123.1262	0.24	4.17	3.62	Very high
C7	49.18272	123.1150	0.24	4.17	3.64	High
D7	49.18379	123.1000	0.61	1.64	3.79	Very high
E7	49.18379	123.0896	0.98	1.02	3.38	High
F7	49.18699	123.0716	0.61	1.64	2.27	Very high
G7	49.18535	123.0586	0.61	1.64	3.73	Very high
A8	49.17265	123.1394	0.24	4.17	3.41	High
B8	49.17574	123.1265	0.24	4.17	5.25	N/A
C8	49.17527	123.1124	0.98	1.02	4.85	Very high
D8	49.17083	123.0929	0.24	4.17	4.02	High
E8	N/A	N/A	N/A	N/A	N/A	N/A
F8	49.17525	123.0731	1.10	0.91	2.11	High
G8	49.17681	123.0675	0.85	1.17	2.49	High
A9	49.16407	123.1386	0.24	4.17	3.92	High
B9	49.16234	123.1233	0.98	1.02	4.66	High
C9	49.16487	123.1195	0.98	1.02	4.21	High
D9	49.16232	123.0991	0.24	4.17	4.77	Very high
E9	49.16513	123.0811	2.20	0.45	3.80	Very high
F9	49.16611	123.0698	0.73	1.37	2.89	High
G9	49.16935	123.0576	1.10	0.91	2.19	High

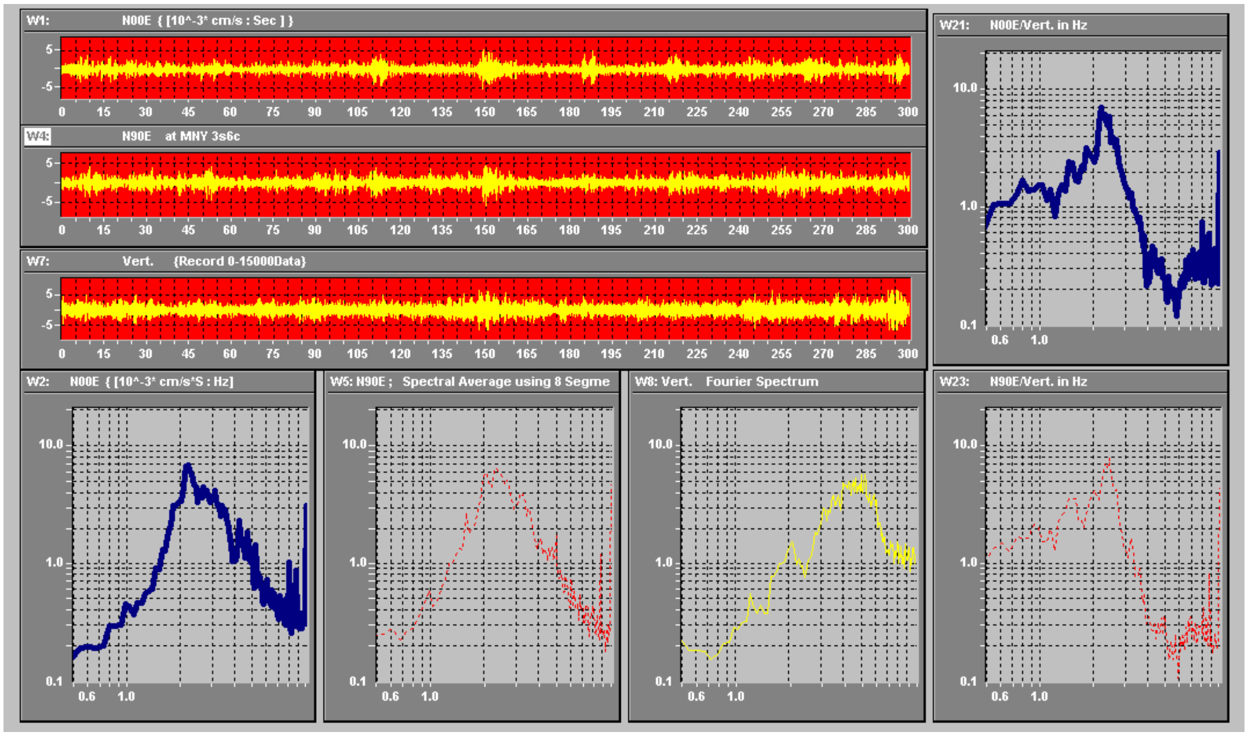

Figure 3. Sample H/V ratio plots

The natural periods obtained from MTM are overlaid on the surface geology maps in Figure 4. Although the general trend of short-period bedrock and long-period modern sediments can be observed in these maps, localized features such as the uncharacteristically short site periods of 0.45 seconds in the southeast corner (E9) and 0.67 (A6) and 0.71 (B6) seconds in the northwest corner of the Richmond study area do not seem to fit well with the surface geology distribution.

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 5, the distribution of the thickness of Holocene deposits in the Richmond study area [12] is presented overlaid by site periods obtained from MTM. The three anomalies mentioned previously can be explained by the shallow Holocene deposits in those areas. However, there are features that the Holocene thickness by itself is not enough to explain such as the long site period of 4.17 seconds in the south central study area (D9).

In Figure 6, 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 the long period site mentioned in the previous paragraph, the thickness of the Pleistocene, hence the depth-to-bedrock is the largest in the study area (just over 700 m).

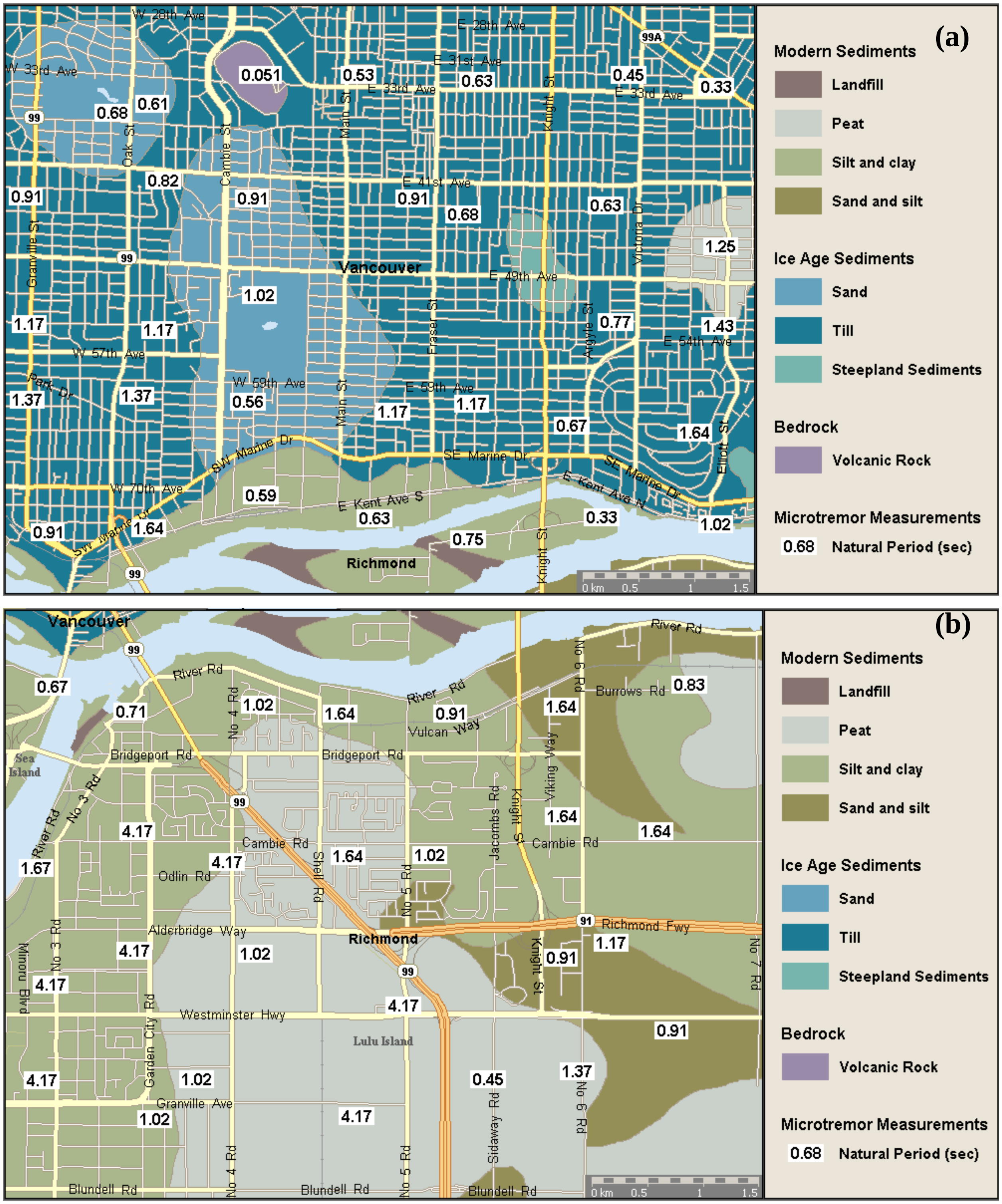

Figure 4. Site periods obtained from microtremor measurements overlaid on surface geology on: (a) Vancouver side (b) Richmond side of the Fraser River

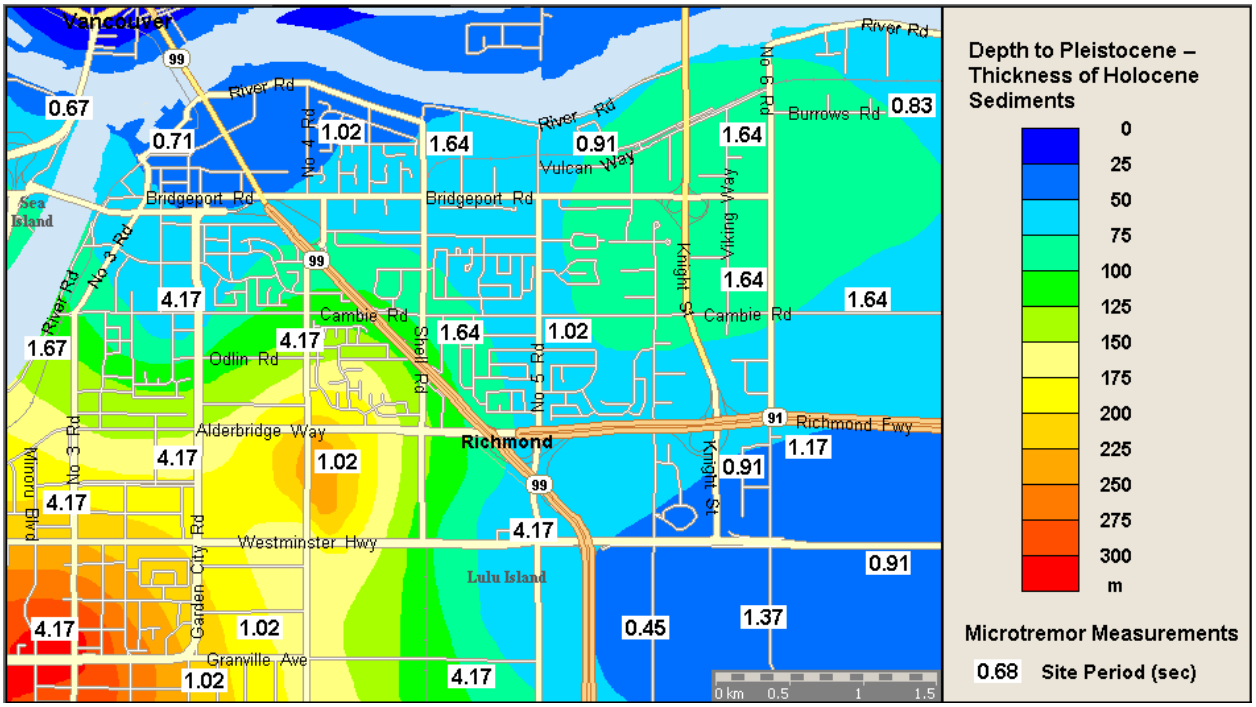

Figure 5. Thickness of Holocene sediments in the Fraser River delta (Richmond) overlaid with site periods obtained from microtremor measurements

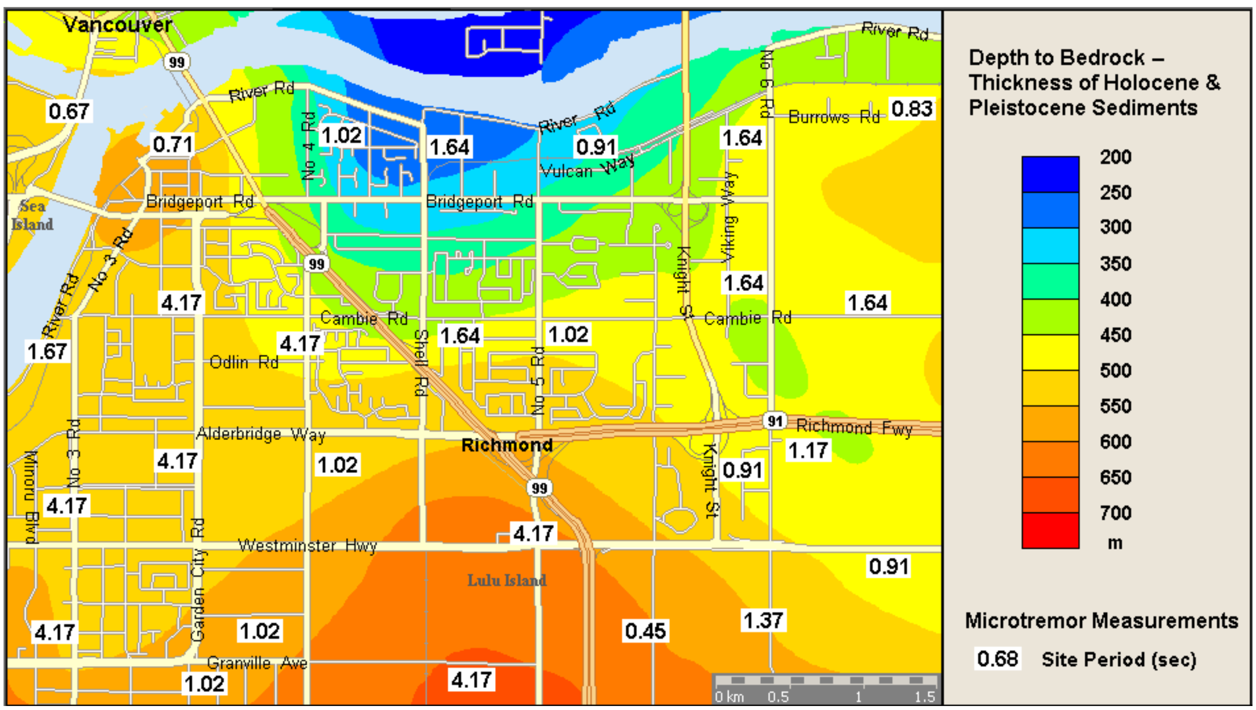

Figure 6. Combined thickness of Holocene and Pleistocene sediments in the Fraser River delta (Richmond) overlaid with site periods obtained from microtremor measurements

SITE MODELLING RESULTS

In this section the results of a simple preliminary modelling are presented and compared with the measured values. The same CUSP sites in the Richmond area were modelled 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 are summarized in Table 2, which were obtained from boreholes and seismic reflection surveys [12]. The average unit weights used for modelling are 19.5 kN/m^3 for Holocene deposits, 23.3 kN/m^3 for Pleistocene and 25.0 kN/m^3 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 site periods obtained from the SHAKE modelling are presented in Table 2 and compared with the MTM periods in Figure 7. It can be seen in this figure that the SHAKE periods are generally larger than the MTM periods, but at some sites there is a good match between the two. To further understand the reasons for these differences, the SHAKE periods are also overlaid on depth-to-Pleistocene map (thickness of Holocene deposits) and depth-to-bedrock map (thickness of Holocene and Pleistocene sediments) in the Richmond study area (Figures 8 and 9, respectively). 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 modelling 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.

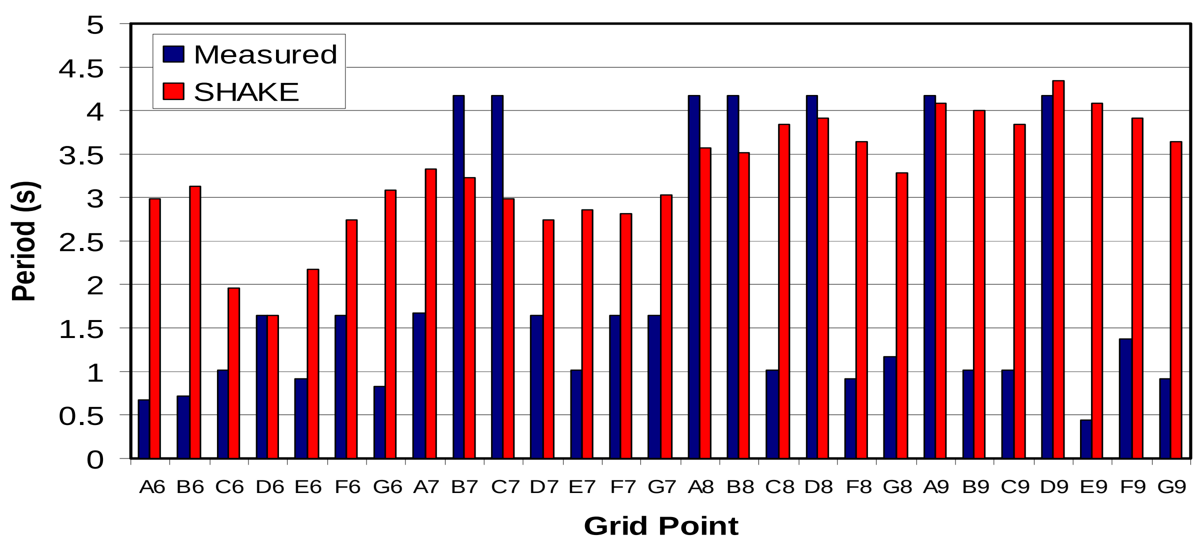

Figure 7. Comparison of site periods for the Richmond area.

Table 2. Site properties used in SHAKE modelling and resulting site periods

Grid	Layer Thickness (m)			Shear wave velocity (m/s)			Site Period (s)
	Holocene	Pleistocene	Bedrock	Holocene	Pleistocene	Bedrock	
A6	50	475	---	215	750	1700	**2.99**
B6	50	500	---	750	750	1650	**3.13**
C6	50	275	---	215	725	1625	**1.96**
D6	50	225	---	215	750	1600	**1.64**
E6	75	275	---	240	725	1650	**2.17**
F6	88	362	---	250	725	1700	**2.74**
G6	75	425	---	240	700	1750	**3.08**
A7	125	400	---	280	700	1700	**3.33**
B7	75	450	---	240	700	1650	**3.23**
C7	125	350	---	280	725	1650	**2.99**
D7	88	362	---	250	725	1625	**2.74**
E7	75	400	---	240	725	1600	**2.86**
F7	88	362	---	250	700	1700	**2.82**
G7	62	412	---	230	675	1725	**3.03**
A8	200	325	---	335	700	1700	**3.57**
B8	175	350	---	320	700	1675	**3.51**
C8	250	275	---	360	700	1700	**3.85**
D8	62	538	---	230	650	1700	**3.92**
F8	50	500	---	215	650	1675	**3.64**
G8	50	400	---	215	600	1750	**3.28**
A9	300	250	---	385	700	1750	**4.08**
B9	225	350	---	350	670	1770	**4.00**
C9	175	400	---	320	670	1750	**3.85**
D9	100	575	---	265	670	1800	**4.35**
E9	38	562	---	200	625	1750	**4.08**
F9	38	512	---	200	600	1725	**3.92**
G9	38	438	---	200	575	1700	**3.64**

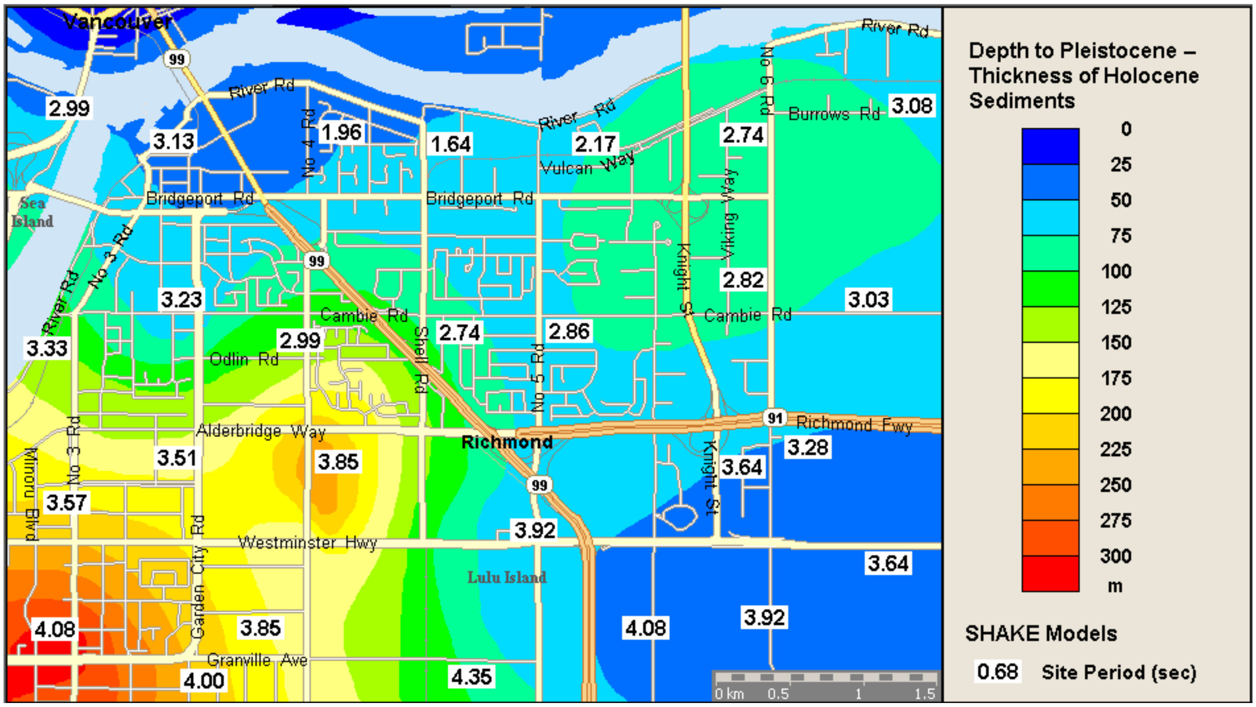

Figure 8. Thickness of Holocene sediments in the Fraser River delta (Richmond) overlaid with site periods obtained from SHAKE analyses

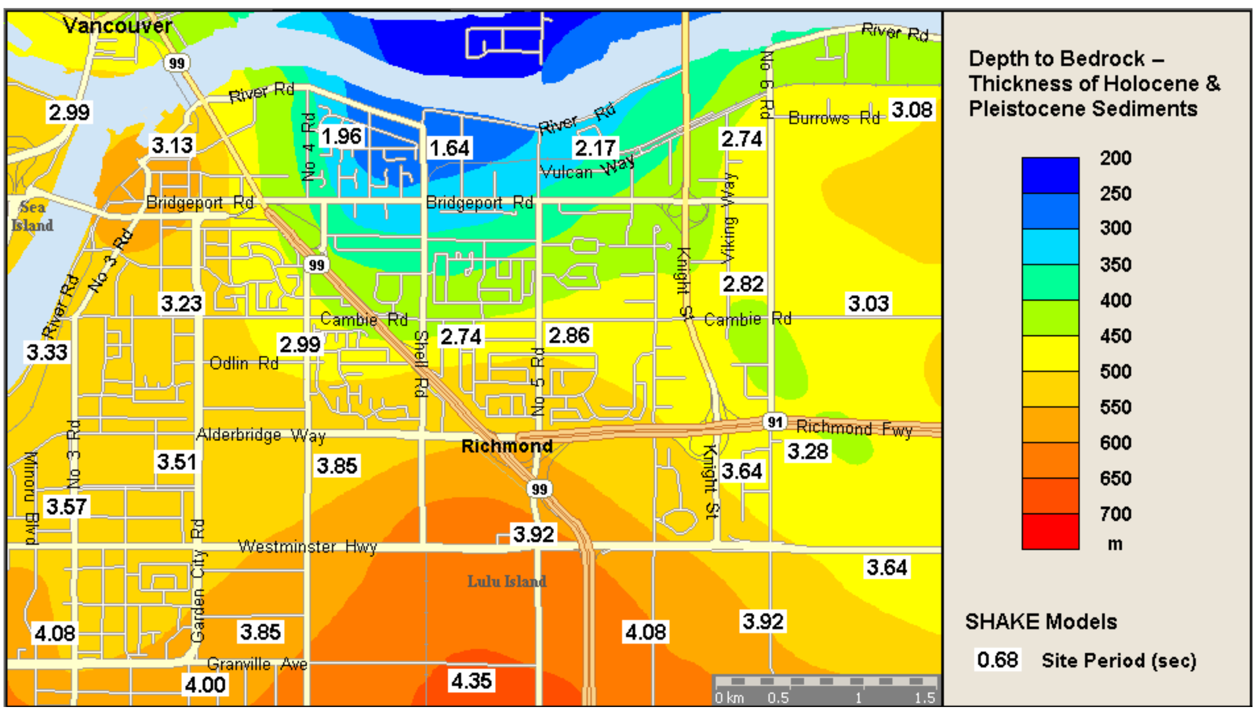

Figure 9. Combined thickness of Holocene and Pleistocene sediments in the Fraser River delta (Richmond) overlaid with site periods obtained from SHAKE analyses

SENSITIVITY OF SHAKE MODELLING TO SITE PARAMETERS

The effects of SHAKE modelling uncertainties on the site periods are presented in this section. The soil parameters that are investigated are thicknesses, unit weights and shear wave velocities of Holocene and Pleistocene deposits (Figure 10).

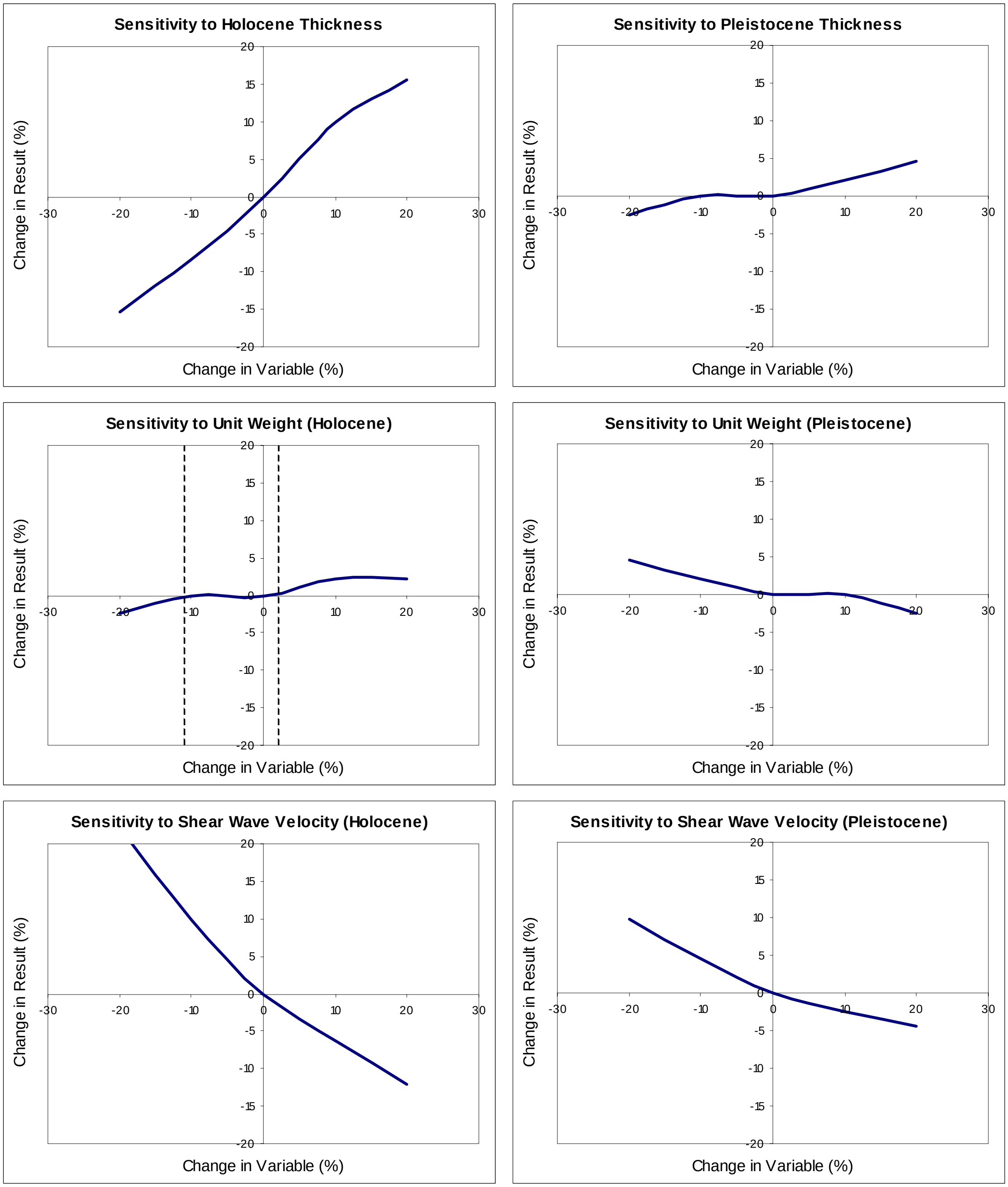

Figure 10. Sensitivity of site periods to soil properties

It is clear from Figure 10 that the results are most sensitive to the thickness and the shear wave velocity of the Holocene deposits. When the Holocene thickness is increased by 10% or the shear wave velocity of the Holocene sediments is decreased by 10%, the site period increases by 10%. In contrast, varying the unit weights does not seem to have much effect on the resulting site periods.

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 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.

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 4.17 seconds. In general, the periods computed by SHAKE were larger than the MTM periods, but in a few cases there was a reasonable match between the two results.

To the south of the Fraser River, the site periods obtained from MTM vary from 0.67 seconds (A6) to 4.17 seconds (multiple sites including D9), whereas site periods obtained from SHAKE modeling vary from 1.64 seconds (D6) to 4.35 seconds (D9). The agreement is best at D6 (MTM: 1.64 sec, SHAKE: 1.64 sec), D8 (MTM: 4.17 sec, SHAKE: 3.92 sec), A9 (MTM: 4.17 sec, SHAKE: 4.08 sec), and D9 (MTM: 4.17 sec, SHAKE: 4.35 sec). While SHAKE values generally reflect the stratigraphy, MTM values may be affected by local variations in geology and may also be reflective of topographical (e.g. basin edge) effects and 3-D wave reflection/refraction effects due to the geometry and rapid change in thickness of the layers.

Among the parameters investigated, the analytical modelling is most sensitive to variations in the thickness and shear wave velocity of the Holocene deposits. Hence, better knowledge of the geographical and stratigraphical distribution of these parameters would improve the models. More refined models are currently in progress for the same sites, which will include several sublayers within each layer to better reflect the changes in soil properties by depth. This project is intended to proceed with a more detailed 1-D modelling followed by an examination of available data for more sophisticated modelling and analyses. In addition, a re-analysis of microtremor measurements is planned to obtain better resolutions at longer periods. Further microtremor measurements are also being considered for other urban areas of British Columbia, especially in other parts of the Vancouver region and Victoria on Vancouver Island.

ACKNOWLEDGEMENTS

Funding for the microtremor measurements was kindly provided by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by the Department of Civil Engineering at the University of British Columbia. The study greatly benefited from close co-operation with Jim Hunter (GSC), Pat Monahan (Monahan Petroleum Consulting), Garry Rogers (GSC) and John Cassidy (GSC), to whom the authors would like to extend their gratitude. The study relied very heavily on the geological structure of the Fraser Delta as delineated by continuing research at the Geological Survey of Canada.

REFERENCES

1. Turner RJW, Clague JJ, Groulx BJ, Journey JM. “GeoMap Vancouver – Geological map of the Vancouver metropolitan area.” Geological Survey of Canada Open File 3511, 1997.
2. Schnabel PB, Lysmer J, Seed HB. “SHAKE: A computer program for earthquake response analysis of horizontally layered sites.” Report No. UBC/EERC-72/12, Earthquake Engineering Research Center, University of California, Berkeley, CA, 1972.
3. Clague JJ, Luternauer JL, Monahan PA, Edwardson KA, Dallimore SR, Hunter JA. “Quaternary stratigraphy and evolution of the Fraser delta.” Clague JJ, Luternauer JL, Mosher DC, Editors. Geology and natural hazards of the Fraser River delta, British Columbia. GSC Bulletin 525, 1998: 57-90.
4. Hunter JA, Douma M, Burns RA, Good RL, Pullan SE, Harris JB, Luternauer JL, Best ME. “Testing and application of near-surface geophysical techniques for earthquake hazard studies, Fraser river delta, British Columbia.” Clague JJ, Luternauer JL, Mosher DC, Editors. Geology and natural hazards of the Fraser River delta, British Columbia. GSC Bulletin 525, 1998: 123-146.
5. Rogers GC, Cassidy JF, Weichert DH. “Variation in the earthquake ground motion on the Fraser delta from strong-motion seismograph records.” Clague JJ, Luternauer JL, Mosher DC, Editors. Geology and natural hazards of the Fraser River delta, British Columbia. GSC Bulletin 525, 1998: 195-210.
6. Kanai K, Tanaka T. “Measurement of the microtremor I.” Bulletin of the Earthquake Research Institute of Tokyo 1954; 32: 199-209.
7. Field EH, Hough SE, Jacob KH. “Using microtremors to assess potential earthquake site response: A case in Flushing Meadows, New York City.” Bulletin of the Seismological Society of America 1990; 80(6): 1456-1480.
8. Lermo J, Chávez-García FJ. “Are microtremors useful in site response evaluation?” Bulletin of the Seismological Society of America 1994; 84(5): 1350-1364.
9. Nakamura Y. “A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface.” Quick Report of Railway Technical Research Institute 1989; 30(1): 25-33 (in Japanese).
10. Lachet C, Bard P. “Numerical and theoretical investigations of the possibilities and limitations of Nakamura’s technique.” J. of Phys. Earth, 1994; 42: 377-397.
11. Seo K, Samano T, Yamanako H, Hao X-S, Takeuchi M, Kishino Y. “A simple procedure for predicting seismic motions with microtremor measurements.” Proceedings of the National Symposium on Effects of Surface Geology on Seismic Motion, Japan, 1989.
12. Hunter JA. “Contour maps of depth-to-Pleistocene and depth-to-bedrock in the Fraser River delta”, personal communication.
13. Monahan PA. “Average unit weights of Holocene sediments, Pleistocene sediments and bedrock in the Fraser River delta”, personal communication.
14. Dallimore SR, Edwardson KA, Hunter JA, Clague JJ, Luternauer JL. “Composite geotechnical logs for two deep boreholes in the Fraser River delta, British Columbia.” Geological Survey of Canada Open File 3018, 1995.
15. Dallimore SR, Edwardson KA, Hunter JA, Meldrum JL, Luternauer JL, Clague JJ. “Lithologic, geotechnical and geophysical logs for a deep borehole at Richmond City Hall, British Columbia.” Geological Survey of Canada Open File 3356, 1996.