ESTIMATING SITE PERIODS IN VANCOUVER AND VICTORIA, BRITISH COLUMBIA USING MICROTREMOR MEASUREMENTS AND "SHAKE" ANALYSES

Tuna Onur, Geological Survey of Canada, Sidney, BC
Sheri Molnar, Geological Survey of Canada, Sidney, BC
John Cassidy, Geological Survey of Canada, Sidney, BC
Carlos E. Ventura, Department of Civil Engineering, University of British Columbia, Vancouver, BC
Ken X.-S. Hao, CCJ GeoServices Co., Richmond, BC

ABSTRACT
This paper presents site period investigations conducted in two cities in southwestern British Columbia (BC), Vancouver and Victoria. These cities are among the highest risk cities in Canada in terms of earthquake ground shaking hazard, and need reliable site response models to provide a basis for microzonation of relative hazard levels in urban areas. Microtremor measurements in the greater Vancouver area were carried out at nodes on a 1-km grid within a 6-km by 8-km region. This area includes a range of site conditions, and is selected for the pilot application of an urban seismic instrumentation project (Canadian Urban Seismology Program - CUSP) undertaken by the Geological Survey of Canada (GSC). In Victoria, the measurements were carried out at locations of BC Hydro and GSC strong-motion instruments, and on a variety of geological conditions throughout the city. Site periods were obtained from frequency-domain analyses of microtremor measurements. The same sites were analysed using SHAKE, a one-dimensional site response program that propagates vertically incident shear waves from bedrock outcrop or halfspace through a column of horizontally layered soil. All the sites have permanent strong motion instruments installed, which will allow comparative analyses when these instruments record earthquake shaking in the future.

RÉSUMÉ
Cet article présente une étude des périodes naturelles de sol pour deux villes du sud-ouest de la Colombie Britannique, Vancouver et Victoria. Ces villes sont parmi les villes ayant le plus gros risque au Canada en terme de risque de tremblement de terre. Elles ont donc besoin de modèles fiables de réponse de sol fournissant une base pour le micro-zonage des niveaux relatifs de risque en milieu urbains. Des mesures de micro-vibrations ambiantes dans le district du Vancouver Métropolitain ont été effectuées aux noeuds d'une grille 1-kilomètre dans une région de 6 kilomètres par 8 kilomètres. Ce secteur inclut une gamme d'états de sites et est choisi pour l'application pilote d'un projet d'instrumentation sismique urbain (Programme canadien de sismologie urbaine) entrepris par la Commission géologique du Canada (CGC). À Victoria, les mesures ont été effectuées aux sites d'instruments pour secousses fortes de BC Hydro et de la CGC, ainsi que pour une variété de conditions géologiques à travers la ville. Les périodes naturelles de sol ont été obtenues par analyses des mesures de vibrations ambiantes dans le domaine des fréquences. Les mêmes sites ont été analysés avec SHAKE, un programme de réponse de sol unidimensionnel qui propage verticalement les ondes de cisaillement incidentes depuis un affleurement rocheux ou un demi-espace à travers une colonne de sols stratifiés horizontalement. Tous les sites sont instrumentés avec des appareils pour secousses fortes qui permettront des analyses comparatives quand ces instruments enregistreront les secousses de tremblement de terre à l'avenir.

1. INTRODUCTION

Southwest British Columbia is one of the most seismically active regions in Canada. The two largest urban centres in the province of British Columbia, Vancouver and Victoria, are located in this region. Greater Vancouver spans a wide variety of geological settings. Much of the City of Vancouver lies on till (Pleistocene) while the City of Richmond lies on thick (up to 300 m) young (Holocene) delta sediments deposited by the Fraser River (Figure 1). Victoria, on the other hand, has extremely variable geology, where depth to bedrock can vary from 0 up to 30 m within a city block (Figure 2, adapted from Monahan et al., 2000).

Figure 1. Approximate representation of surface geology in the Greater Vancouver area (blue: glacial till, yellow: Holocene delta sediments, green: bedrock)

Figure 2. Surface geology in the Greater Victoria area (blue: glacial till, yellow: Holocene deposits, green: bedrock)

Predicting site response is an important step in estimating the effects of earthquakes on buildings and other structures. As the seismic waves travel from bedrock to the surface, the soil deposits that they pass through change certain characteristics of the waves, such as amplitude and frequency content. These changes can be studied either by modelling the soil layers through which the waves travel or by recording the waves at the surface of the soil deposits. There are challenges in either approach. Although recording the actual ground motion is the most accurate way to investigate ground response, it requires a permanent strong motion instrument installed and waiting to record for long periods of time. Small earthquakes may be recorded frequently and very low amplitude ambient vibrations of the ground can be recorded any time with sensitive instruments, however ground response to strong shaking (for peak accelerations higher than 0.2g) is non-linear and differs from linear ground response at lower levels of shaking. Depending on the site of interest, typical return periods of moderate to large earthquakes that can cause non-linear soil response can be in the order of several hundred years. In addition, one such earthquake may not be sufficient to characterise the site as seismic waves coming from different directions may cause different response, as may earthquakes with different magnitude-distance combinations and mechanisms (strike-slip, normal, thrust, etc.) Analytical modelling, on the other hand, allows multiple scenarios of earthquake ground shaking, i.e. several earthquake records with different characteristics can be applied to the model, but it requires a detailed knowledge of the stratigraphy and mechanical properties of the different layers of soil, such as unit weight, shear modulus (or shear wave velocity) and damping. Non-linear modelling requires even more complex parameters often harder to obtain, such as modulus reduction-strain and damping-strain relationships if an equivalent linear approximation of the non-linear response will be used, or for fully non-linear calculations, cyclic non-linear stress-strain models or advance constitutive models. To overcome the shortcomings and challenges of each approach, it is often better to use a combination of analytical modelling together with available recordings of weak and strong ground motions, which provides the most robust understanding of the site response. Recordings of weak motions from small or far away earthquakes and microtremor measurements can be used to test the linear response calculated by the analytical models and to calibrate the analytical models.

A key parameter that characterises the ground response and can be used for calibrating analytical models is the site period. This paper presents findings from an ongoing study on site periods in two largest urban centres in southwestern British Columbia, Vancouver and Victoria. Site periods are estimated using both microtremor measurements and analytical models. When the project is complete, the full dataset will be available as a CD-ROM collection of raw data from microtremor measurements (ASCII format), processed data, and analytical models at the sites where measurements were conducted when information on subsurface geology was available. This paper concentrates on those sites where permanent strong motion instruments are installed or are intended to be installed in the near future, so that the findings from microtremor measurements and analytical modelling can be compared, in the future, with real earthquake recordings.

2. SUBSURFACE GEOLOGY

2.1 Vancouver

The northern arm of the Fraser River roughly divides the Greater Vancouver metropolitan area into two distinct regions in terms of site response (Figure 1). To the north, the City of Vancouver lies on glacial till (Pleistocene), while to the south, the City of Richmond lies on Holocene delta sediments of varying thickness deposited by the Fraser River. Detailed surveys of the subsurface geology under the Fraser River delta were carried out by the Geological Survey of Canada using various geophysical and geotechnical methods (a compilation of some of these studies is given in Clague et al., 1998). In general, the Fraser River delta consists of Holocene deposits that lie on Pleistocene deposits, which in turn lie on bedrock. The transition boundaries from bedrock to Pleistocene, and Pleistocene to Holocene layers are where the highest impedance contrasts occur. Contour maps of the depth to Pleistocene and depth to bedrock in the delta based on the geophysical and geotechnical surveys are given in Figure 3 (Hunter, 2004) for the area where microtremor measurements described in this paper were conducted.

2.2 Victoria

In the Greater Victoria area, overconsolidated Pleistocene deposits (till) that have high shear wave velocities overlie bedrock. In much of the city, the till is overlain with “grey clay”, which in turn is overlain with “brown clay”. These two make up the “Victoria clay”, which is a unit of glaciomarine clayey silt with scattered pebbles that forms a blanket-like deposit. Grey clay, a lower, soft to firm clay, is in most places gradationally overlain by a desiccated and oxidized crust of stiff, brown clay. These two facies were deposited in the same depositional environment and are distinguished on the basis of post-depositional changes (Monahan et al., 2000). The thickness of deposits greatly varies across the city.

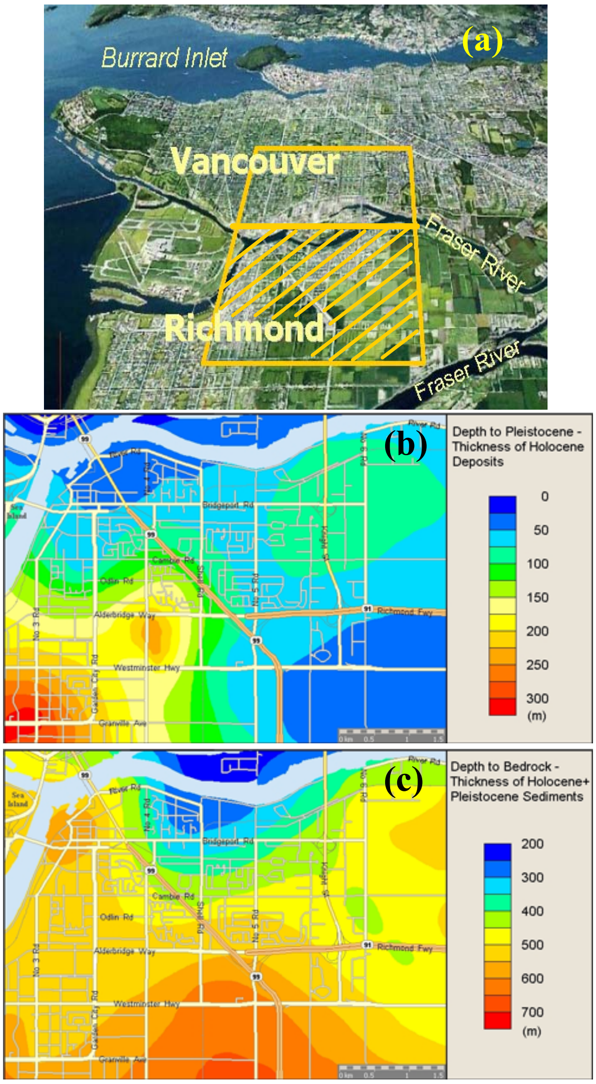

Figure 3. (a) Oblique air photograph of the study area. Depths of sediments in the hatched area are shown in (b) and (c). (b) Contour map of depth to Pleistocene (thickness of Holocene sediments). (c) Contour map of depth to bedrock (combined thickness of Holocene and Pleistocene sediments).

3. MICROTREMOR MEASUREMENTS

Two sets of microtremor measurements are described in this paper. Those in the Greater Vancouver area were carried out at CUSP strong motion instrument sites that are roughly 1-km apart on a grid in a 6 km by 8 km area (Figure 4). The microtremor measurements in the Greater Victoria area were carried out at 18 existing and planned strong motion instrument sites some of which are shown in Figure 5 (red squares) overlaid on surface geology.

Site periods were obtained using Nakamura's method (Nakamura, 1989), which is defined as the spectral ratio of horizontal components to vertical components recorded at the same site (H/V ratio). It is a relatively simple procedure that has been widely used and discussed in the literature (e.g. Field et al., 1990; Lermo and Chávez-Garcia, 1994; Lachet and Bard, 1994; Tsuboi et al., 2001; Rodriguez and Midorikawa, 2002).

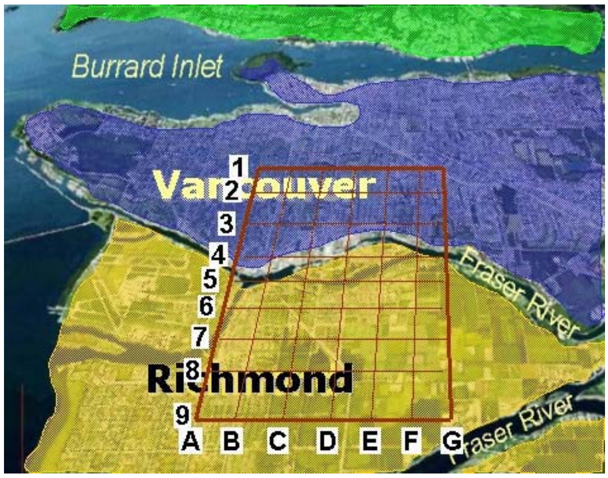

Figure 4. Microtremor measurement grid in the Greater Vancouver area.

Figure 5. Location of the microtremor measurements in the Greater Victoria area.

3.1 Field Procedures – Vancouver Dataset

The hardware used for the microtremor measurements in the Greater Vancouver area 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, and before data was recorded, measured signals were converted to accelerations with an amplitude range of ±3000 μm/s^2, and resolution of 0.005 μm/s^2. The sampling rate was 100 samples per second. 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 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.

3.2 Field Procedures – Victoria Dataset

Microtremor recordings in the greater Victoria area were conducted with an Orion seismic recorder and a three-component, broadband CMG-40T sensor with a functional bandwidth of 0.033 Hz (30 sec) to 50 Hz (0.020 sec). The measurements were recorded at a 200 Hz sampling rate.

Microtremor measurements were conducted between 30 June to 18 November 2003. The weather ranged between dry, sunny, and warm to wet, cloudy, cold and windy. Recording times varied from 15 minutes to 21 continuous hours. The 21-hour recording was conducted on a thicker soil station (GTP) that recorded overnight. A day-to-night variation in amplitudes was observed as expected. However, little difference was observed in the spectral ratios over the 21 hours. All segments were fairly stable and clearly showed the peak fundamental frequency between 2-4 Hz for this particular site. Further details on data collection for this data set are given in Molnar and Cassidy (2004).

3.3 Data Processing

The acceleration and velocity time series from the two datasets were processed as follows: (1) trend and offset removed, (2) band pass filtered (0.1-25 Hz), and (3) differentiated to obtain accelerations (Victoria dataset). For each site, four to twenty 2-minute data windows were chosen depending on the length of the records. Relatively quiet periods of the record were preferred and large amplitude impulses were avoided. The 2-minute data windows were cosine tapered, and Fourier transformed to obtain the respective acceleration amplitude spectra. The horizontal spectra were first smoothed with a 15-point running mean filter (0.75 Hz), and then divided by that of the similarly smoothed vertical component creating a microtremor spectral (H/V) ratio.

3.4 Site Periods from Microtremor Measurements

The H/V ratio plots for Vancouver and Victoria sites are given in Figures 6 and 7, respectively. In Figure 6, C1 is a bedrock site and has a fairly flat response until frequencies higher than 10 Hz. A9 on the other hand is on the thickest Holocene sediments in the study area and its H/V plot peaks around 0.2 Hz (5 sec). In general, grids 1 to 4 lie on Pleistocene till and H/V ratios peak between 0.65 Hz to 2 Hz, (site periods of 0.5 sec to 1.5 sec). Grid 5 lies on varying site conditions and hence shows variation in H/V ratios. Grids 6 to 9 lie on Fraser River delta. Natural periods of these sites are, in general, longer than 0.5 sec. At the southwest corner of the study area (A8-B9), where the Holocene sediments are thickest, broad peaks in periods longer than 2.5 seconds are apparent, which suggests that response at this frequency band (roughly between 0.15 Hz and 0.4 Hz) might be significant if an earthquake with substantial energy at these frequencies occur, e.g. very large earthquakes that create long-period surface waves that attenuate slower than body waves. One such possible earthquake that would affect Vancouver and Victoria is a megathrust earthquake at the Cascadia subduction zone.

The change in response from till (north) to delta sediments (south) can be followed in Grid B. Sites B1 through B5 are on till with increasing depth. Correspondingly, the peaks progressively shift to lower frequencies (B1 ~ 1.5 Hz to B5 ~ 0.5 Hz), and the site periods shift progressively to longer periods (B1 ~ 0.7 sec to B5 ~ 2 sec). Sites B6 through B9 are on Holocene deposits of progressively increasing thickness overlying the till. At B6, where roughly 30 m Holocene sediments overlie the till, an even lower frequency peak is starting to become apparent and remains strong for the rest of the sites south to B9 (200-300 m thick Holocene sediments).

Three east-west lines can be examined to follow the change in till thickness to the north (Grid 3), and the change in thicknesses of both till and Holocene sediments to the south (Grids 6 and 9). The stratigraphy as obtained from the contour maps in Figure 3 is presented in Figure 8.

Grid 3 is representative of the till layers in Grids 1 through 4 with decreasing thickness towards east. The effect of the change in till thickness is observed in the H/V ratio peaks as they progressively shift towards higher frequencies from A3 to G3 although the change in frequencies is quite small.

Unlike the till depths to the north of the Fraser River, the thicknesses of both till and Holocene to the south are greatly variable. Grid 6 has fairly uniform Holocene thickness throughout but variable Peistocene till thickness. As the till thickness increases from A6 to B6, the H/V peak shifts to lower frequencies as expected. At In C6 and D6, where the Pleistocene depth decreases considerably, the peaks at low frequencies disappear. E6 and F6 exhibit peaks at gradually lower frequencies as expected from the thicker till at these sites.

Grid 9 traverses the thickest part of the delta. The thickest Holocene sediments occur at A9 while the thickest till occurs at D9. This grid displays large amounts of energy at very low frequencies that are difficult to resolve from the response recorded by the 1-sec instrument used for Vancouver measurements.

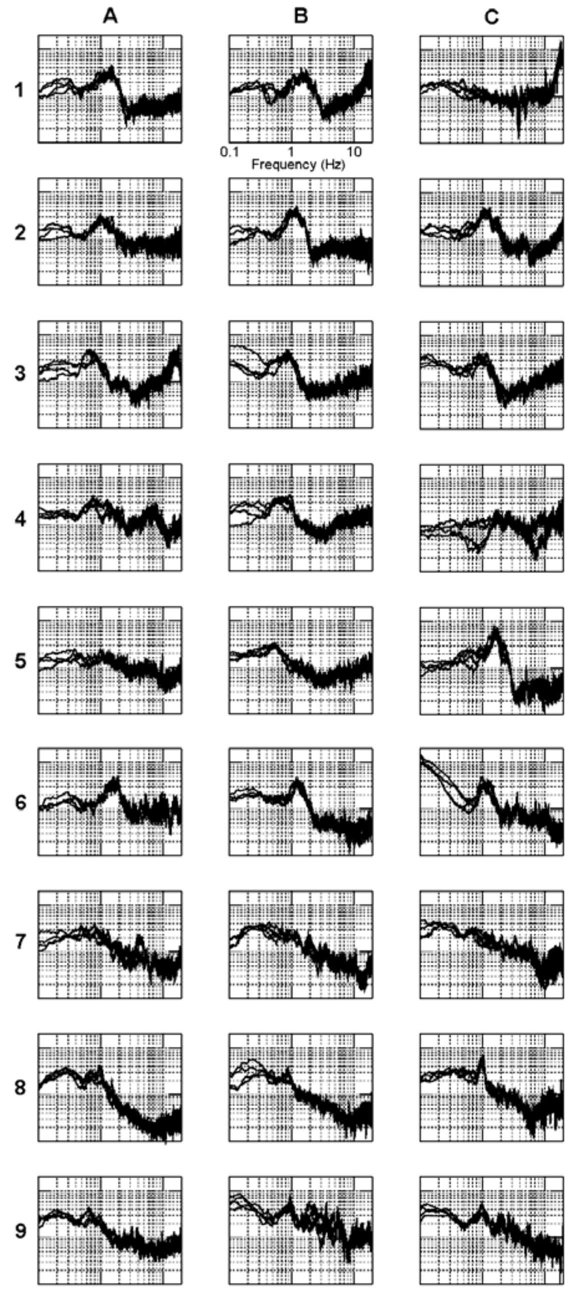

Figure 6. Log-log plots of H/V ratios calculated from microtremor measurements (Vancouver – grids A to C). Horizontal axis is given on the Grid B1 plot. Vertical axis is the amplitude of H/V ratios (0.1 to 20).

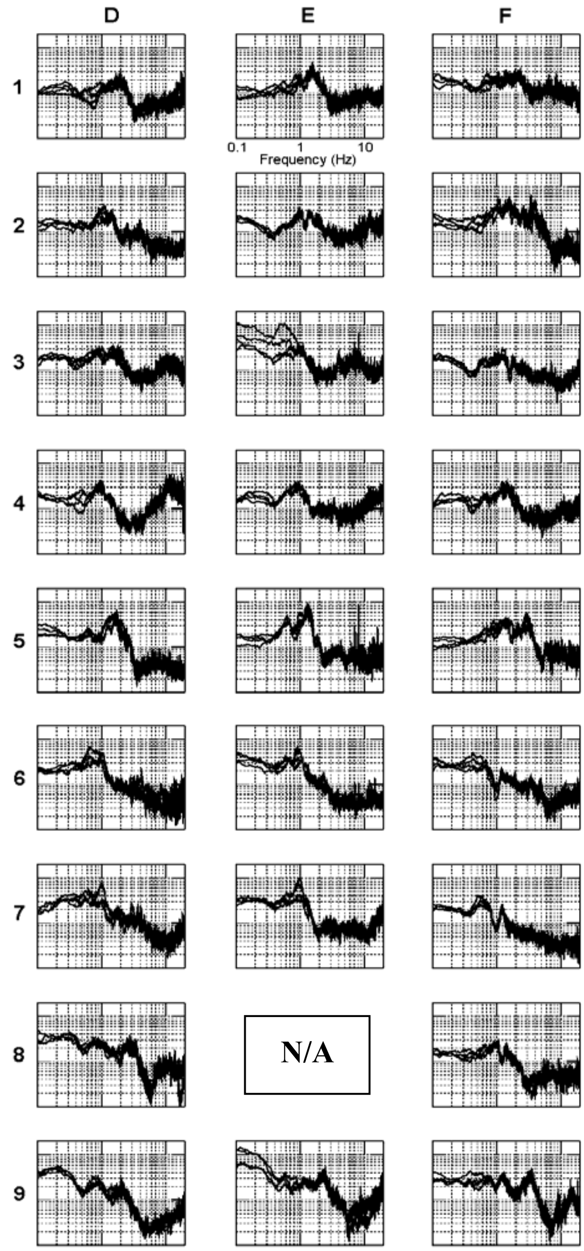

Figure 6 (continued). Log-log plots of H/V ratios calculated from microtremor measurements (Vancouver – grids D to F). Horizontal axis is given on the Grid E1 plot. Vertical axis is the amplitude of H/V ratios (0.1 to 20).

The knowledge of subsurface geology underneath the Victoria sites is of variable amount and quality. The sites shown in Figure 5 overlaid on surface geology are three TILL sites (TILL2, TILLA and TILL6), GTP, ESQ, HSY, VGZ, and five FAIR sites (FAIR2, FAIRD, FAIR7, FAIRA, FAIRB). The three TILL sites are on Pleistocene till, GTP lies on 5 to 6 m clay underlain with an estimated 30 m till. ESQ site is on 4 to 5 m of clay underlain with bedrock. HSY lies on 11 m clay over bedrock. VGZ is on bedrock. Out of the five FAIR sites, FAIR2 is on till, FAIRD is on bedrock outcrop while FAIRA, FAIRB are on peat over clays of varying thickness and FAIR7 is on clay over thin till (exact thickness not known). Of the remainder of the sites, PGC lies on bedrock (quartz diorite), PIK is on less than 3 m thick silt over bedrock, GOW is on less than 3 m clay over bedrock, and KTG is on 10 m clay over 16 to 17 m till, and COLW is at a location in the middle of Colwood delta, which is thought to be the thickest part of the delta (thickness of deposits not known). H/V plots of bedrock sites are fairly flat until higher frequencies (5 to 10 Hz). Till sites show peaks at 2 to 4 Hz range. Sites on clays and delta sediments exhibit peaks at relatively lower frequencies.

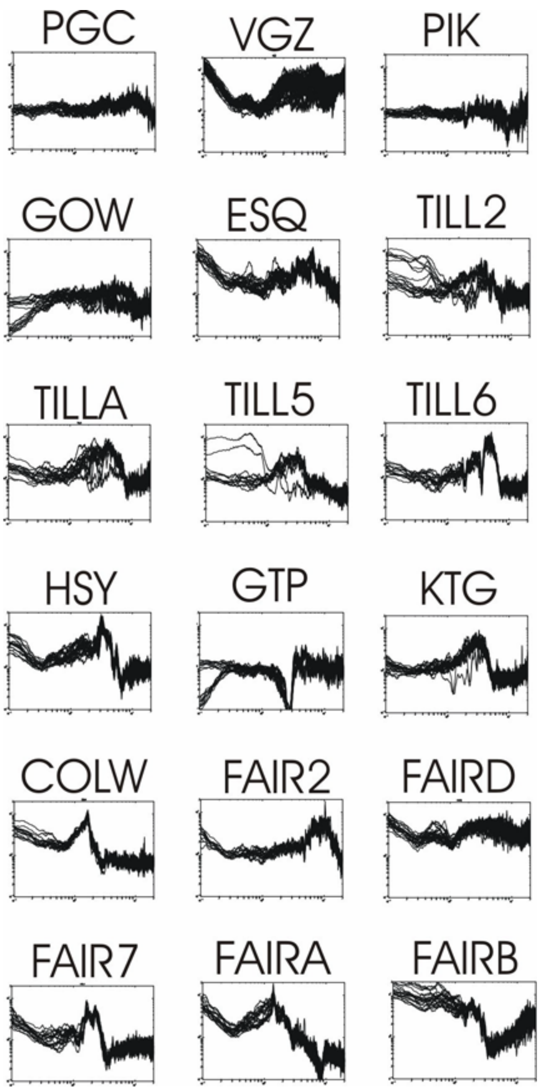

Figure 7. H/V ratios calculated from microtremor measurements (Victoria sites). Axes the same as Figure 6.

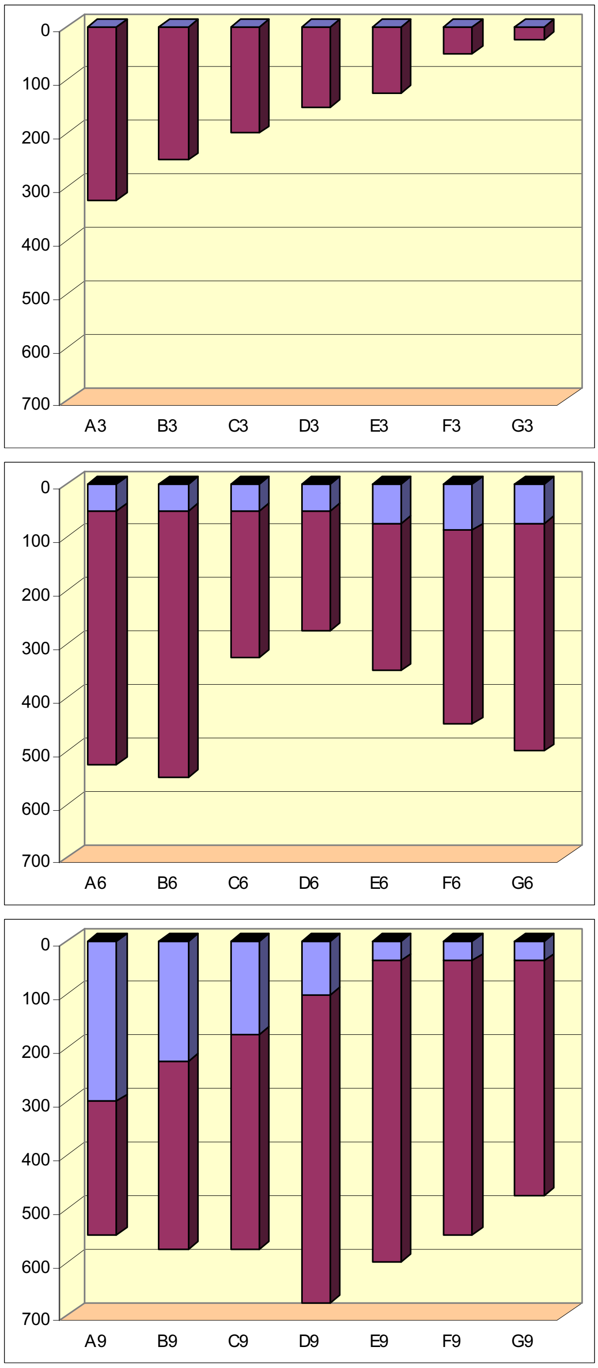

Figure 8. Soil profiles for Grids 3, 6 and 9 in Vancouver. Blue represents Holocene and purple represents Pleistocene sediments. The inverted y-axis displays depth (m) from the surface.

4. 1-D “SHAKE” MODELLING

The sites that lie on at least one layer of soil deposit over bedrock and for which subsurface geology information is available were modelled using a 1-D site response program, “SHAKE”, which propagates vertically incident shear waves from bedrock through a column of horizontally layered soil (Schnabel et al., 1972).

Earlier SHAKE modelling and analysis of one of the sites (Vancouver – A9) had suggested a predominant site period of 4.5 sec (Harris et al., 1998). In addition, the CUSP sites in Vancouver were previously studied by the authors with SHAKE analyses on simplified three-layer (Holocene-Pleistocene-Bedrock) models of the Fraser River Delta (Ventura et al., 2004). The site period obtained for the site A9 from three-layer modelling was 4.1 sec. In this study, multi-layer modelling of the CUSP sites was carried out with information from boreholes nearby and past geotechnical and geophysical surveys of the delta.

The thickness and shear wave velocity used for each soil layer were obtained from boreholes and seismic reflection surveys (Hunter, 2004; Monahan and Levson, 2001). 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 (Monahan, 2003), which were estimated from cone penetration tests and bulk density measurements (Dallimore et al., 1995; Dallimore et al., 1996). 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 (Monahan and Levson, 2001). Both Holocene and Pleistocene layers were divided into sublayers with shear wave velocities increasing by depth. 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).

In Victoria, six of the 18 strong-motion instrument sites, where microtremor measurements were conducted, had detailed subsurface geology information available. These sites were modelled with SHAKE. Details on SHAKE modelling of earthquake recordings at the Victoria sites are presented in Molnar et al. (2004).

Site periods obtained from preliminary SHAKE analyses are presented in Table 1. Results from simplified three-layer modelling conducted earlier (Ventura et al., 2004) are also presented for comparison. In general, more detailed multi-layer model provided longer site periods. Specific site periods were not selected from the microtremor measurements as in some cases the peaks at low frequencies could not be identified accurately as discussed in the conclusions.

Table 1. Site periods from analytical modelling

Sites	Site periods (sec)	
Vancouver	Three-layer model	Multi-layer model
A6	3.0	3.1
B6	3.1	3.3
C6	2.0	2.2
D6	1.6	2.9
F6	2.7	3.2
A7	3.3	3.8
B7	3.3	4.1
C7	3.0	4.3
D7	2.7	3.4
E7	2.9	3.0
F7	2.8	3.6
A8	3.6	5.4
B8	3.5	5.4
C8	3.8	5.3
D8	3.9	4.6
A9	4.1	4.7

5. CONCLUSIONS

Site period investigations in Vancouver and Victoria were presented. These studies are currently ongoing with the aim of improving the analytical models and comparing findings to strong motion recordings at these sites.

Microtremor measurements were conducted to obtain site periods through H/V ratio technique. The two sets of measurements described in this paper, Vancouver and Victoria measurements differ in the instruments used and the length of records obtained. Three main findings from processing and analysing these datasets are:

1) Use of a broadband recording instrument for long-period sites is recommended. The 1-sec transducers, even with the help of an amplifier that allows undistorted response up to 3-5 sec, do not adequately capture long-period response.

2) Taking longer recordings than the typical 5-minute is recommended for long-period sites to ensure that the fundamental site period is excited. Existence of a strong long-period source is also important, such as ocean waves during a storm.

3) Taking long recordings is desirable also to allow processing with long windows. The 2-minute windows used in this paper provided reasonable resolution for most sites.

Analytical modelling provides means to analyse site response due to different types of earthquakes and several levels of ground shaking. However, detailed subsurface information is required, which may often not be available. A benchmark parameter to test and calibrate analytical models is the site period, which can be obtained easily and cost-effectively from microtremor measurements. This paper presented preliminary modelling of some sites where microtremor measurements were conducted and subsurface geology was relatively better known. Future research will attempt to calibrate these initial models using the microtremor measurements and test them against existing strong motion records obtained at some of these sites and future strong motion recordings.

6. ACKNOWLEDGEMENTS

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