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COMPARISON OF GEOPHYSICAL SHEAR-WAVE VELOCITY METHODS

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ABSTRACT

Seismic hazard site assessment within the Canadian building code is primarily based on the average shear-wave velocity of the upper 30 m combined with an appropriate multiplicative amplification hazard factor. The least expensive and time-consuming geophysical field method to provide a reliable shear-wave velocity profile is therefore of great interest to our engineering community. In greater Victoria, shear-wave velocity profiles are available from 21 seismic cone penetration tests (SCPT), four tests using the spectral analysis of surface waves (SASW) technique, and two tests using the continuous surface wave system (CSWS) technique. As all three methods involve an active source that generates shear-waves or surface waves, they generally offer a restricted investigation depth (a few tens of metres). A non-active source surface wave method that uses recordings of microtremor (ambient vibrations/cultural noise) has become popular worldwide due to its ease, economy, deep penetration depth (hundreds of metres), and most surprisingly, correlation with earthquake ground motions. This paper compares the peak frequency observed from (1) microtremors, (2) earthquake recordings (when available), and estimated from (3) 1-D SHAKE modelling, and (4) shear-wave velocity measurements at SCPT, SASW, and CSWS locations in greater Victoria. At SCPT sites, the calculated peak frequency is in close agreement with the microtremor peak frequency, as they sample to the same depth. By comparison, bedrock depth was not reached at SASW and CSWS test sites, and as a result the microtremor peak frequency is generally lower than that calculated from the SASW and CSWS shear-wave velocity values. Overall, the combination of the single-instrument microtremor method with an invasive (SCPT) method or another non-invasive (SASW and CSWS), but active source method, best demonstrated how the ground will respond, within the linear range, to a low-level earthquake.

Introduction

During an earthquake, the subsurface soil column acts like a filter with strain-dependent properties that can increase the duration and amplitude of shaking in a narrow frequency band related to the soil thickness, physical properties (P- and S-wave velocities, density), and the shape the surface and subsurface boundaries. The spectral content (amplitude, period, and phase) and duration of earthquake recordings can therefore be significantly affected by local site conditions, especially at unconsolidated soil and sediment sites with a near-surface impedance contrast with underlying bedrock. The resonant period of the ground is therefore of great importance for earthquake engineering.

The most reliable technique to provide an estimate of site effects is to record several tens of good quality

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earthquake recordings and perform site to reference (bedrock) or horizontal-to-vertical (h/v) spectral ratios to obtain the frequency of the peak earthquake amplification. In greater Victoria, there are two seismic cone penetration test (SCPT) sites with a strong-motion instrument that have recorded two to three weak motion (peak ground acceleration ≤ 0.8 %g) earthquakes.

The most influential parameter in determining strong ground motion is the subsurface shear-wave velocity (V_S) structure. The 2005 Canadian National Building Code is based on averaging the shear-wave velocity of the top 30 m (or equivalent) in order to designate a National Earthquake Hazard Reduction Program (NEHRP) amplification site class with an appropriate multiplicative amplification hazard factor. This is similar to current practice in the United States, and now Europe (Eurocode 8). Boore (2006) lists the various methods to provide a reliable S-wave velocity profile of a site that can be divided into invasive and non-invasive methods with subgroupings as shown in Table 1. Invasive methods require placing a seismometer beneath the Earth's surface, with the source at surface or downhole, whereas all equipment remains at surface for the non-invasive methods.

Table 1. Various methods to determine subsurface shear-wave velocity (from Boore, 2006).

Invasive Methods	**Non-invasive Methods**
a. Surface Source	a. Single station (h/v)
- Receiver in borehole	b. Multiple stations
- Receiver in cone penetrometer (SCPT)	- Active sources (linear spread of receivers)
b. Downhole Source	> SASW
- Suspension PS logger	> CSWS / MASW (Multiple Array)
- Crosshole	- Passive sources (2D array of receivers)
	> Frequency-wavenumber (FK)
	> Spatial autocorrelation (SPAC)
	> ReMi (receivers in line)
	- Combined active and passive source

Shear-Wave Velocity Methods

Shear-wave velocity profiles in greater Victoria were acquired from 21 SCPTs with maximum depths ranging from 4 to 41 metres, and from four Spectral Analysis of Surface Wave (SASW) tests and two Continuous Surface Wave System (CSWS) tests at sites where the subsurface was too dense for cone penetration. A SCPT (Robertson *et al.*, 1992) is performed by pushing an instrumented cone-tipped rod into the ground at a constant rate using a modified drilling rig. Tip resistance, sleeve friction, and dynamic pore pressure are recorded digitally every 5 cm to determine stratigraphy. In Victoria, the rod is pushed to refusal indicating that either bedrock or dense soil has been encountered. Shear-waves arrivals are recorded every metre of penetration by a geophone located within the rod, 20 cm behind the tip, using a sledge hammer to strike a horizontal steel beam beneath the drill rig as the source. Interval velocities for each metre are calculated using the difference between the arrival times for successive measurements. In comparison, SASW testing (Stokoe *et al.*, 1994) is a non-intrusive geophysical technique that uses the variation in the velocity of surface (Rayleigh) waves with frequency to model the V_S profile of a site. Rayleigh waves are generated by hammer impacts on a metal plate, and are recorded by a pair of geophones with varying seperation between themselves, and from the plate. The CSWS method (Matthews *et al.*, 1996), a more current version of the SASW method, instead using a computer controlled vibrating source and multiple receivers spread equidistantly in a line. The CSWS is regarded as more accurate and effective than the SASW method. The depth penetration of surface wave methods depends on the velocity of the material being tested: SASW and CSWS testing can penetrate to depths of 10-15 m in soft soils, and up to 30 m in stiff soils.

The invasive SCPT method requires relatively soft soils for penetration, creates some disturbance of the ground surface, and only two tests (30 m depth) can be acquired per day. However, the test is sensitive to minor changes (friction, strain, resistance), and samples a very small volume making it very site specific. In comparison, the active source non-invasive surface wave methods (SASW/CSWS) can be used at stiffer sites that are impenetrable to the cone test, but still have limited sampling depth. These methods use an averaging technique, and minor variations like thin seams are lost, but the bulk properties are well represented.

Microtremors (ambient vibrations) are short period vibrations that result from coastal effects, atmospheric loading, wind interaction with structures and vegetation, and cultural sources such as traffic, trains, construction, and factories. To record microtremors, most researchers use only one or a few seismometers that can measure very weak ground motions. Less equipment and time are required in the field than conventional well-logging, seismic reflection/refraction studies, or artificial source surface wave techniques. As sensors are temporarily placed on the Earth surface, there is no environmental impact. Most importantly, due to the wide range of noise sources, microtremors occur over a wide frequency range (0.02 to 50 Hz), which makes it possible to explore to depths of more than 100 m (Horike, 1985).

Microtremors are recorded with a three-component seismometer that includes two orthogonal horizontal components, and one vertical component. A microtremor time series recording represents the convolution of (1) source effects, (2) propagation effects of the source to receiver, (3) the effect of the recording instrument, and (4) the response of the site. These four effects are multiplied in the frequency domain, and given certain assumptions, the division of horizontal Fourier amplitude spectrum by the vertical spectrum can remove the first three effects, thereby isolating the site response. This single-instrument microtremor method (Nakamura, 1989) provides the peak period and amplitude of the linear site response to background vibrations. Molnar and Cassidy (2006) demonstrated that the microtremor peak frequency and amplitude can used for engineering design as they are similar to results obtained at earthquake recording sites in greater Victoria. The cumulative microtremor campaigns performed across southwestern British Columbia are summarized in Molnar *et al.* (2007).

Geologic Setting of Greater Victoria

Victoria has highly variable geology, including bedrock, glacial till, glaciomarine clays and Holocene organic soils (Monahan and Levson, 2000). At least three glaciations (Nasmith and Buck, 1998) created overconsolidated Pleistocene material (till) and an irregularly scoured bedrock surface. As relative sea level rose after the last glaciation, a grey glaciomarine clayey silt (termed grey Victoria clay) was deposited in low-lying areas. Relative sea level subsequently fell due to isostatic uplift, and sections of this grey clay were exposed, oxidized, and desiccated to a hard, brown crust (termed brown Victoria clay). Where the grey clay was not exposed, it is sometimes overlain by up to 6 m of Holocene organic silt and peat (Monahan and Levson, 2000). The typical geologic profile of greater Victoria therefore has a strong near-surface impedance contrast between the Victoria clay atop overconsolidated glacial material or competent bedrock. Combined with moderate seismicity, Victoria provides a classic setting for site response studies.

Based on the 21 SCPT and 4 SASW field tests, a shear-wave velocity model has been revised for the principal Quaternary geologic units across greater Victoria (Monahan and Levson, 2001). Bedrock in greater Victoria consists of igneous and metamorphic rocks (Nasmith and Buck, 1998), and is estimated to have high shear-wave velocities (1000 – 2500 m/s; Hunter *et al.*, 1999). The average shear-wave velocity and uncertainty ($\pm 1\sigma$) of other geologic units, based on n measurements, is as follows: till and overconsolidated sediments earlier than the last glaciation, 475 ± 78 m/s (n=25); Colwood sand and gravel, 330 ± 55 m/s (n=17); Colwood delta slope, 192 ± 40 (n=10); brown Victoria clay, 213 ± 50 m/s (n=49); grey Victoria clay at less than 20 m depth, 132 ± 28 m/s (n=97); and Holocene organic soils, 76 ± 28 m/s (n=9).

Comparison of Site Period for Particular Shear-Wave Velocity Methods

SCPT sites

Comparison of shear-wave velocity measurements is currently possible for 12 of the 21 SCPT sites in greater Victoria. The average shear-wave velocity (V_{Sav}) for 12 SCPT sites was calculated by $V_{Sav} = \sum(h)/\sum(t)$, where h is the interval thickness, and t is the interval shear-wave travel time for each V_S

measurement (i.e. h/V_S). The fundamental period (T) of a site (Finn, 1994) is calculated by: $T = 4*\sum(h)/V_{Sav}$. Since V_S is a low strain property of soil, this equation provides a reasonable estimate of the site period that would occur during a low-level earthquake. The site period was then converted to frequency ($f = 1/T$). The V_{Sav} and the calculated site frequency (and period) for the 12 SCPT sites are summarized in Table 2. These values are compared with the observed microtremor h/v ratio peak frequency, and earthquake h/v ratio peak frequency (when available). SHAKE is a 1-D modelling program (Schnabel *et al.*, 1972; Idriss and Sun, 1992), based on a continuous solution to the wave equation, adapted for transient motions using the fast Fourier transform. For each SCPT site, a 1-D soil column model (stratigraphy and thicknesses) was created for SHAKE input using the corresponding SCPT data. Shear-wave velocity values were assigned based on the greater Victoria shear-wave velocity model (Monahan and Levson, 2001). Therefore, the calculated site frequency and SHAKE site frequency for each SCPT site are generally similar.

Table 2: Comparison of calculated SCPT site frequency with site frequency determined by other methods.

SCPT Site	Depth to refusal (m)	V_S average (m/s)	Calculated site frequency / (period)	Microtremor peak frequency / (period)	SHAKE modelled peak frequency / (period)	Earthquake peak frequency / (period)	Comments
SCPT 4	9.70	139	3.57 Hz (0.28 s)	0.8, 2.5 Hz (0.40, 1.25 s)	3.33 Hz (0.30 s)		May overlie thick older Pleistocene material, 5 m grey clay
SCPT 5	13.60	126	2.32 Hz (0.43 s)	1.99 Hz (0.50 s)	2.38 Hz (0.42 s)		12 grey clay
SCPT 6	29.80	125	1.05 Hz (0.95 s)	2.03 Hz (0.49 s)	0.98 Hz (1.02 s)		24 m grey clay, sensitive to location error
SCPT 7	4.05	(130)+	N/A	1.42 Hz (0.70 s)	8.33 Hz (0.12 s)		Refusal in rock fill
SCPT 8*	40.75	157	0.96 Hz (1.04 s)	1.29 Hz (0.78 s)	0.85 Hz (1.17 s)		26+ m grey clay
SCPT 9	17.50	108	1.54 Hz (0.65 s)	1.90 Hz (0.53 s)	1.71 Hz (0.58 s)	1.75 Hz (0.57 s)	12 m grey clay
SCPT 10	16.35	122	1.86 Hz (0.54 s)	2.05 Hz (0.49 s)	2.04 Hz (0.49 s)		14 m grey clay
SCPT 11	25.10	142	1.42 Hz (0.70 s)	1.40 Hz (0.71 s)	1.17 Hz (0.85 s)	1.48 Hz (0.68 s)	18 m grey clay
SCPT 12	13.45	155	2.89 Hz (0.35 s)	1.50 Hz (0.67 s)	2.70 Hz (0.37 s)		Microtremor recordings within 100 m, 4 m grey clay
SCPT 13	6.45	258	9.99 Hz (0.10 s)	15.13 Hz (0.07 s)	8.33 Hz (0.12 s)		6 m brown clay
SCPT 14	12.55	179	3.56 Hz (0.28 s)	2.34 Hz (0.43 s)	4.10 Hz (0.24 s)		Colwood delta front, sensitive to location errors
SCPT 15*	9.15	291	7.96 Hz (0.13 s)	4.52 Hz (0.22 s)	8.33 Hz (0.12 s)		Colwood sand and gravel

+Artificial fill site, V_{Sav} = 130m/s (Monahan and Levson, 1997).
*Did not reach refusal, V_{Sav} and site period are minimum values.

Fig. 1 shows the peak frequency comparison of the four methods at SCPT site 9, including weak motion earthquake recordings. The peak frequency determined from the four different methods is similar. This site is located in southern Victoria and samples soft Holocene organic soils overlying 12 m of the grey clay facies. The site geology is representative of the "softest" geology that can be found in Victoria. The earthquake and microtremor h/v ratios show a single peak, suggesting that the soil column is vibrating as a single layer. The SHAKE modelled spectrum has multiple peaks (modes) due to the inherent layering of the model. SCPT 11 also shows good agreement between the four methods.

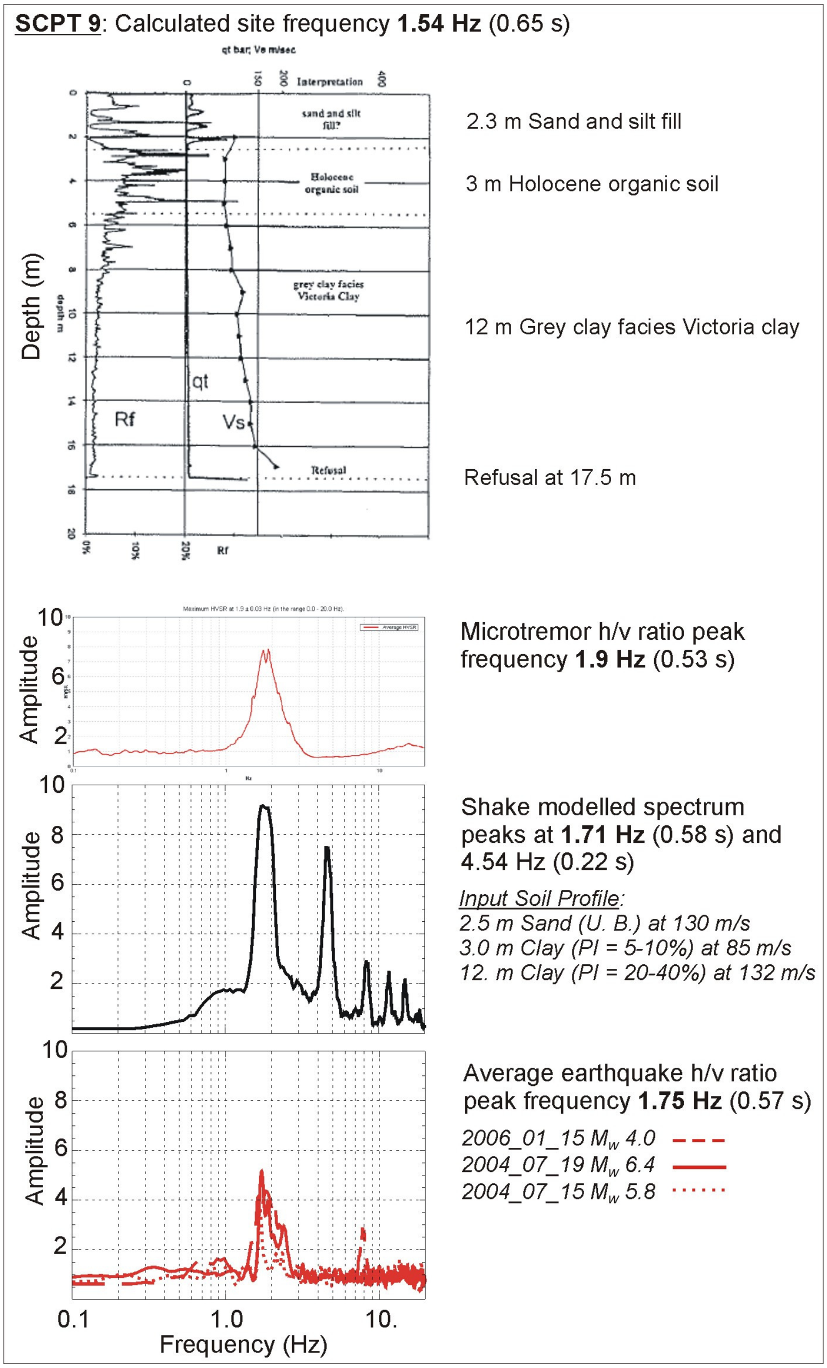

Figure 1. Comparison of peak frequency at SCPT 9 located in downtown Victoria from SCPT measurements, microtremor, SHAKE modelling, and weak earthquake motion. SCPT parameters: V_S = shear-wave velocity, qt = tip resistance, and Rf = friction ratio.

Figs. 2 and 3 show the peak frequency comparison of three different methods at SCPT sites 14 and 15, respectively. SCPT 14 is located on the Colwood delta front, and SCPT 15 is located on the Colwood sand and gravel delta itself. In both cases, the microtremor h/v peak period is longer than that based on the geology (calculated site frequency based on the SCPT measurements, and the SHAKE modelled spectrum). In both cases, the microtremor peak period is longer than calculated or modelled. This suggests that on the Colwood delta front at SCPT 14, which met refusal, there is dense glacial Pleistocene material present to produce the longer period. Atop of the Colwood delta at SCPT 15 the rod friction reached levels high enough to stop cone penetration. Using the $T = 4*\sum(h)/V_{Sav}$ relationship, 18.4 m of the the Colwood sand and gravel is expected at SCPT 15, as the microtremor peak period is 0.22 s, and the average shear-wave velocity is 335 m/s (Monahan and Levson, 2001).

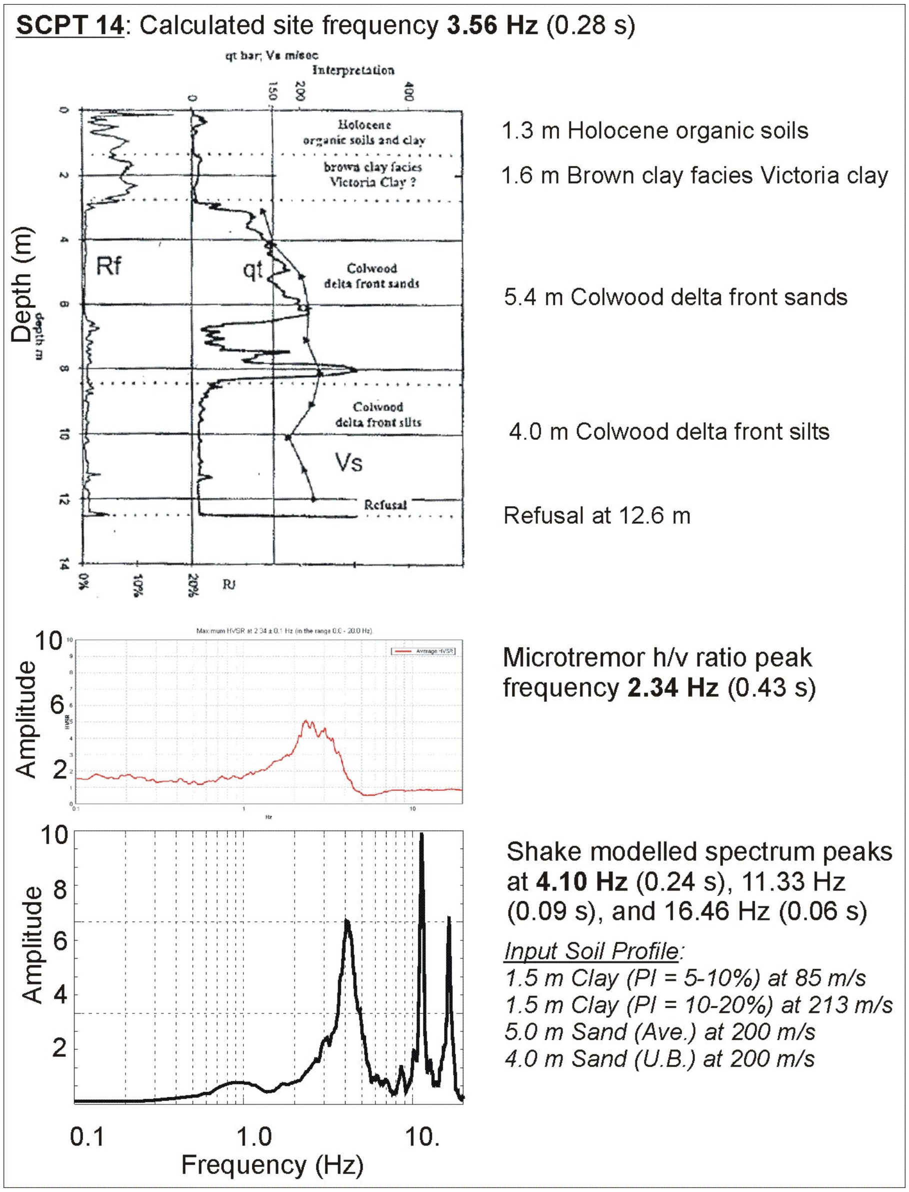

Figure 2. Comparison of peak frequency at SCPT 14 located on the Colwood sand and gravel delta front from SCPT measurements, microtremor, and SHAKE modelling. SCPT parameters: V_S = shear-wave velocity, qt = tip resistance, and Rf = friction ratio.

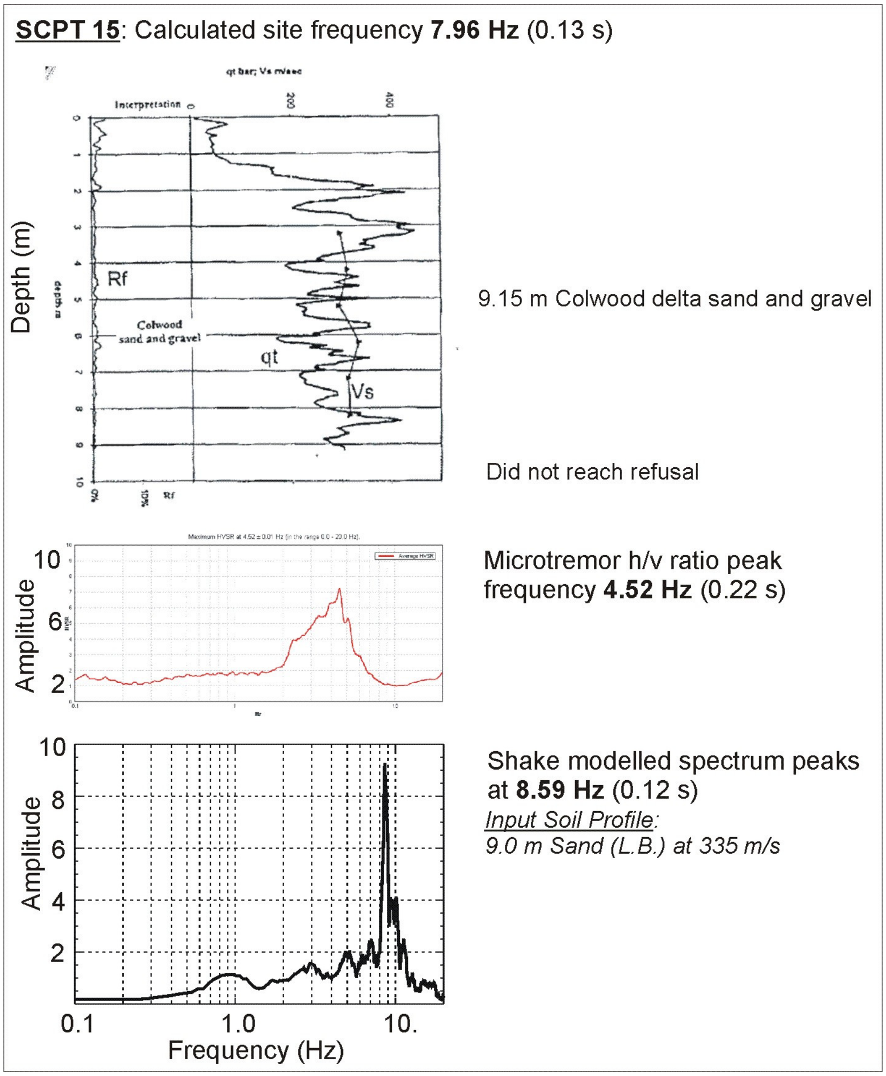

Figure 3. Comparison of peak frequency at SCPT 15 located on the Colwood sand and gravel delta from SCPT measurements, microtremor, and SHAKE modelling. SCPT parameters; V_S = shear-wave velocity, qt = tip resistance, and Rf = friction ratio.

SASW sites

Table 3 lists the calculated site frequency from the SASW measurements together with the microtremor peak frequency. At the four SASW sites, the maximum depth of investigation ranged from 9 to 17 m, and in all cases did not reach bedrock. The calculated peak period is therefore a minimum, and is generally lower than the microtremor peak period. The microtremor method has sampled deeper to produce a longer peak period.

Table 3. Comparison of SASW site frequency (and period) with microtremor peak frequency.

SASW Site	Depth (m)	V_S average (m/s)	Calculated site frequency / (period)	Microtremor peak frequency / (period)
Airport	9.0	298	8.28 Hz (0.12 s)	5.60 Hz (0.18 s)
Royal Roads	11.0	349	7.94 Hz (0.13 s)	10.01 Hz (0.10 s)
UVic	17.0	353	5.19 Hz (0.19 s)	1.87 Hz (0.53 s)
Veyaness	9.0	413	11.47 Hz (0.09 s)	2.20 Hz (0.45 s)

Fig. 4 shows the peak frequency comparison of an SASW site (Veyaness) with the microtremor peak frequency. At this site, the SASW method sampled 9 m deep, and the resulting peak period (0.09 s) is much lower than the microtremor peak period (0.45 s). The depth to bedrock is assumed to be much deeper as this site is located atop of a drumlinoid ridge, an elongated glacial feature composed of dense glacial Pleistocene material (till). In order to produce the microtremor peak period (0.45 s) with SHAKE modelling, over 45 m of Pleistocene material (with an average shear-wave velocity of 500 m/s) is required. The SASW method was chosen for these sites because the subsurface was determined to become too dense for cone penetration (SCPT). Combined with the knowledge of the near surface shear-wave velocity SASW information, the addition of microtremor data allows an estimate of bedrock depth.

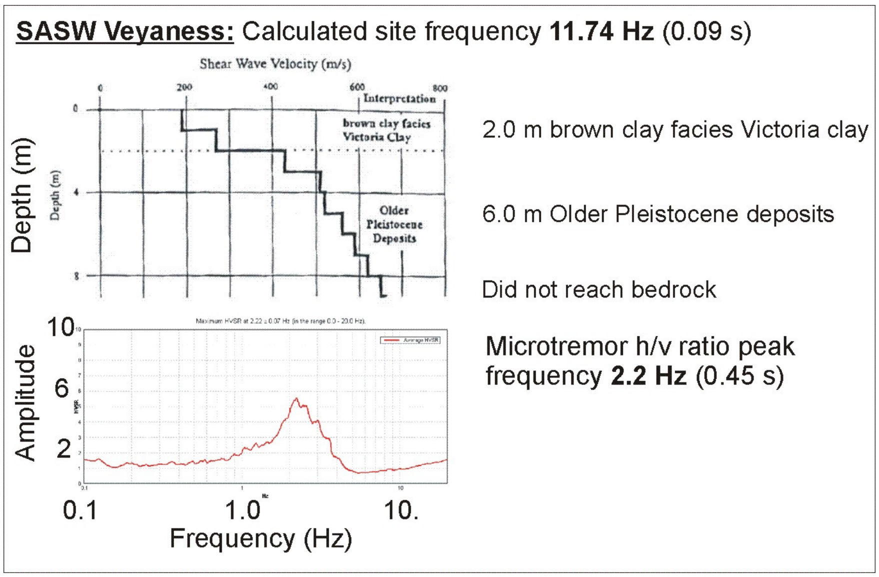

Figure 4. Comparison of peak frequency at SASW Veyaness located atop of a glacial drumlinoid ridge of dense glacial Pleistocene material (till) from SASW testing and microtremor recording.

CSWS Sites

Two CSWS tests conducted in 2006 produced shear-wave velocity profiles to 12.5 m and 21 m depth. The two tests are located within ~ 50 m at a greater Victoria school that is located atop a drumlinoid ridge of dense glacial Pleistocene material that would have been too dense for cone penetration.

Fig. 5 compares the CSWS shear-wave velocity profiles with the microtremor site frequency. The CSWS profiles have been interpreted to exhibit three stratigraphic units, but the microtremor response shows two peaks. At CSWS test site 1, the microtremor h/v ratio peaks at 1.68 Hz (0.59 s) and 5.96 Hz (0.17 s). At CSWS test site 2, the microtremor peaks occur at 1.71 Hz (0.58 s) with a much broader peak at 8.69 Hz (0.12 s). Comparing microtremor response at sites 3 to 6 (moving relatively southward away from the CSWS test locations), the second peak becomes more prevalently composed of two peaks. This suggests that the response of the three stratigraphic units becomes most pronounced the furthest away from the CSWS test locations. Specifically, the CSWS profiles show that the uppermost unit thins from CSWS site 2 towards CSWS site 1, while the thickness of the middle layer is relatively constant, suggesting that as the uppermost unit continues to thin with respect to the deeper layers, a higher frequency mode of vibration emerges.

Conclusions

What is the best method to determine how the ground will respond to an earthquake? We have presented microtremor and earthquake (when available) h/v spectral ratio response at sites in greater Victoria together with shear-wave velocity measurements. The methods examined included both invasive (SCPT), and non-invasive techniques, including both active (SASW, CSWS), and passive source (the single-instrument microtremor method). Sites with relatively soft soil are generally investigated with the SCPT method. In Victoria, the SCPT cone generally penetrated to bedrock, and therefore the entire soil column susceptible to earthquake ground motion was determined. The calculated peak period from the SCPT measured shear-wave velocities was therefore generally in close agreement with the microtremor peak period, as they sampled to the same depth. In comparison, at sites too dense for cone penetration, SASW and CSWS methods were employed, but were unable to reach bedrock depth, providing shear-wave velocities to depths between 9 m and 21.5 m. As a result, the microtremor peak period is generally longer than that calculated from the SASW and CSWS shear-wave velocity values. Overall, the best demonstration of how the ground will respond to an earthquake would be the combination of the single-instrument microtremor method with either an invasive (SCPT) method or another non-invasive (SASW and CSWS), but active source method.

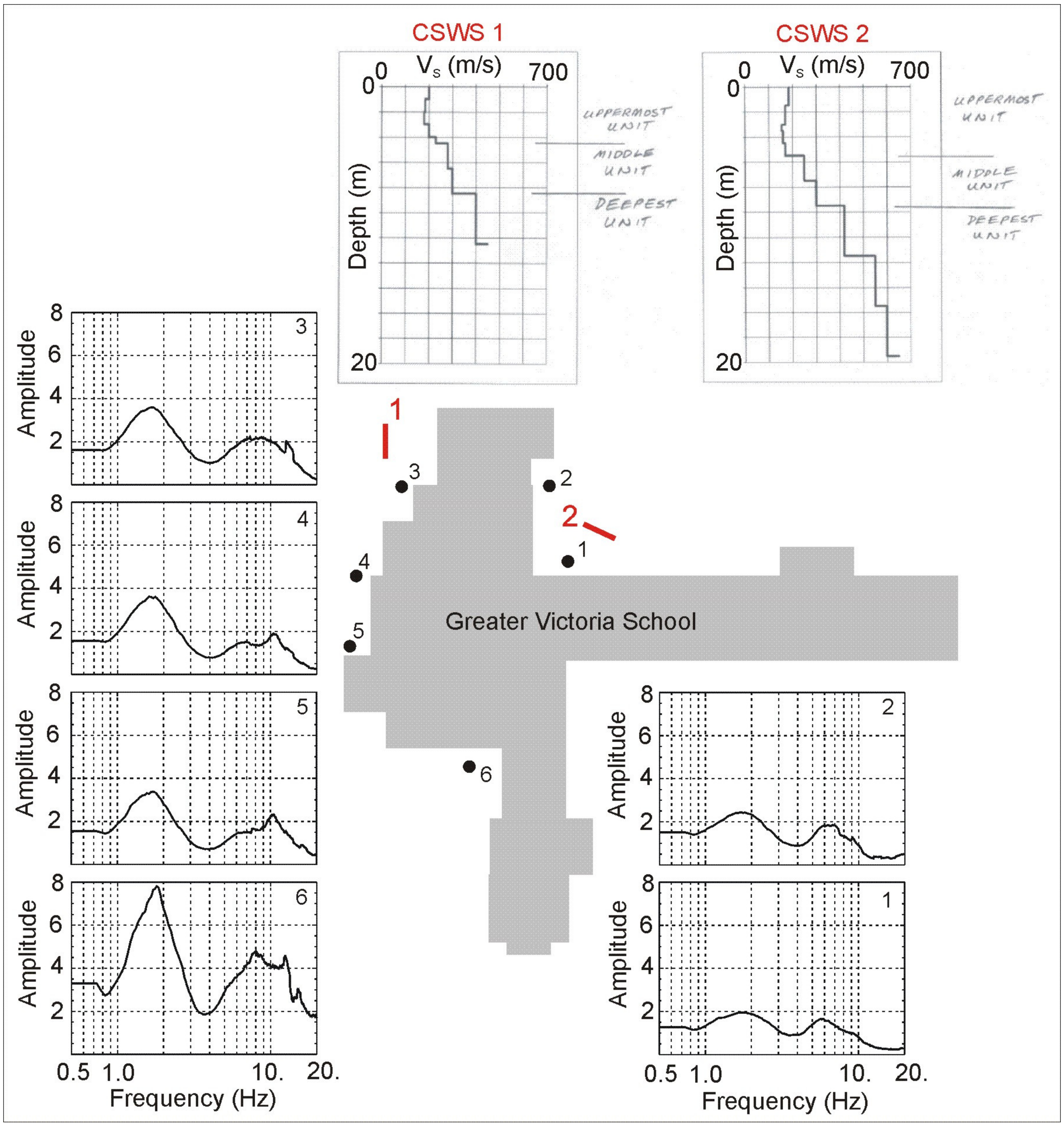

Figure 5. Comparison of peak frequency at CSWS test sites located atop of a glacial drumlinoid ridge of dense glacial Pleistocene material (till) from CSWS testing and microtremor measurements.

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