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EARTHQUAKE SITE RESPONSE STUDIES USING MICROTREMOR MEASUREMENTS IN SOUTHWESTERN BRITISH COLUMBIA

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ABSTRACT

In the linear range, the fundamental period and lower-bound estimate of site amplification can be easily determined from a single three-component seismic instrument recording of microtremor (ambient noise), by the horizontal-to-vertical (h/v) spectral ratio method. Across southwestern British Columbia, this technique has been utilized for (1) validation with available earthquake records, (2) seismic hazard assessment projects, (3) soil-structure interaction studies, and (4) comparison with shear-wave velocity measurement techniques. Comparison of microtremor and earthquake response at sites across SW British Columbia, show similar peak periods, and in Victoria, remarkably similar amplitudes. This validates the use of noise recordings for estimation of the fundamental period of a site to linear earthquake motion across SW British Columbia, as well as the estimated level of amplification in greater Victoria. Seismic hazard assessments at 18 greater Victoria schools, across the Fraser River delta, and along a 10-km stretch of the Sea-to-Sky highway that links Vancouver to Whistler (sites of the 2010 Winter Olympic Games) included the use of microtremor measurements for rapid and economical mapping of relative subsurface physical property variations. To investigate possible soil-structure interaction at five sites that host an earthquake recording instrument, noise measurements were conducted both inside, and outside of the structure. The resulting fundamental period compared with available indoor, weak-motion earthquake recordings are similar, suggesting little soil-structure interaction. Furthermore, examination of microtremor recordings made along a transect from the foundation of a 14-storey building to over 150 m away showed no deviation in site response. Comparison of microtremor response with shear-wave velocity measurement techniques are presented in 9CCEE Paper 1173.

Introduction

This paper highlights the varied application of the single-instrument microtremor method across southwestern British Columbia, Canada. This area exhibits a high level of seismic hazard due to its close proximity to the deep earthquakes under the Strait of Georgia / Puget Sound. The moderate seismicity combined with the majority of the provincial population, building stock, and infrastructure creates great concern for earthquake engineering.

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Microtremors are short period vibrations that result from coastal effects, atmospheric loading, wind interaction with structures and vegetation, and cultural sources. The single-instrument microtremor method initially proposed by Nogoshi and Igarashi (1971), and popularized by Nakamura (1989), produces an estimate of site geological conditions by providing the peak period of amplification from the horizontal-to-vertical (h/v) spectral ratio (amplification occurs where the ratio amplitude is greater than one). We regard site response as the presented h/v ratio for a site, shown as a function of frequency (Hz) and generated from Fourier amplitude spectra. In Canada, the single-instrument microtremor method has been used most extensively by studies across SW British Columbia (Molnar et al. 2007; Molnar et al. 2006a; Molnar et al. 2006b; Molnar and Cassidy 2006; Onur et al. 2004; Ventura et al. 2004), along with a study of the seismic microzonation for Montreal, Quebec (Chouinard et al. 2004), and at seismic instrument sites across Ontario (Read and Eaton 2005; Sneider et al. 2005).

In this paper, we present the ground's response from microtremors at strong-motion instrument sites compared with all possible earthquakes recorded (Table 1) at these sites to validate whether or not microtremors can be used as a proxy for linear earthquake response. We demonstrate the varied microtremor collections for seismic hazard mapping across the province; at greater Victoria schools, across the Fraser River delta, and along the Sea-to-Sky highway that links Vancouver to Whistler (sites of the 2010 Winter Olympic Games). Finally, we investigate how the linear ground response may be altered by engineered structures at surface (soil-structure interaction). We compared microtremor site response from inside and outside the structure that hosts a strong-motion earthquake instrument, along with earthquake recordings that were recorded by the indoor instrument. We also examine soil-structure interaction by presenting microtremor site response along a transect from the foundation of a 14-storey building to over 150 m away.

Table 1. List of earthquakes recorded at strong-motion instrument sites referred to in this paper.

Year	Date	Magnitude	Depth	Distance and orientation from Victoria
1996	May 2	M_W 5.1	4 km	132 km, 123 degrees
1997	Jun 24	M_L 4.6	3 km	94 km, 348 degrees
1999	Dec 11	M_W 4.8	51 km	13 km, 26 degrees
2001	Feb 28	M_W 6.8	52 km	148 km, 161 degrees
2002	Sep 20	M_W 4.3	28 km	15 km, 68 degrees
2004	Jul 15	M_W 5.8	12 km	309 km, 295 degrees
2004	Jul 19	M_W 6.4	12 km	310 km, 292 degrees
2006	Jan 15	M_L 3.6	-	22 km, 322 degrees
2006	Jul 4	M_W 4.0	44 km	17 km, 143 degrees

Comparison of Earthquake and Microtremor Spectral Ratios

Worldwide, microtremor studies have shown that the peak amplitude of the microtremor h/v ratio tends to underestimate the peak amplitude of earthquake spectral ratios with respect to a reference (bedrock) site (Bard 1999 lists 14 studies with this conclusion). The h/v spectral ratio determined from microtremors has shown a clear peak that is well correlated with the fundamental resonance frequency at "soft" soil sites (Bard 2004; Horike et al. 2001; Lachet et al. 1996; Field and Jacob 1995; Lachet and Bard 1994; Lermo and Chavez-Garcia 1994). Numerical analysis suggests that microtremor site response can only be generated when the impedance contrast is greater than 3.5 (Malischewsky and Scherbaum, 2004), thus the good correlation at "soft" soil sites. Only a few studies claim rough agreement between the peak amplitude of the microtremor h/v ratio and earthquake site-to-reference spectral ratios (Molnar and Cassidy 2006; Mucciarelli et al. 2003; Horike et al. 2001; Lermo and Chavez-Garcia 1994). In general, the site response shown by the earthquake site-to-reference spectral ratio method is regarded as the best approximation for engineering use, whereas h/v spectral ratios from earthquakes and/or microtremors are regarded as providing the fundamental peak and lower bound estimate of amplification for a soil site.

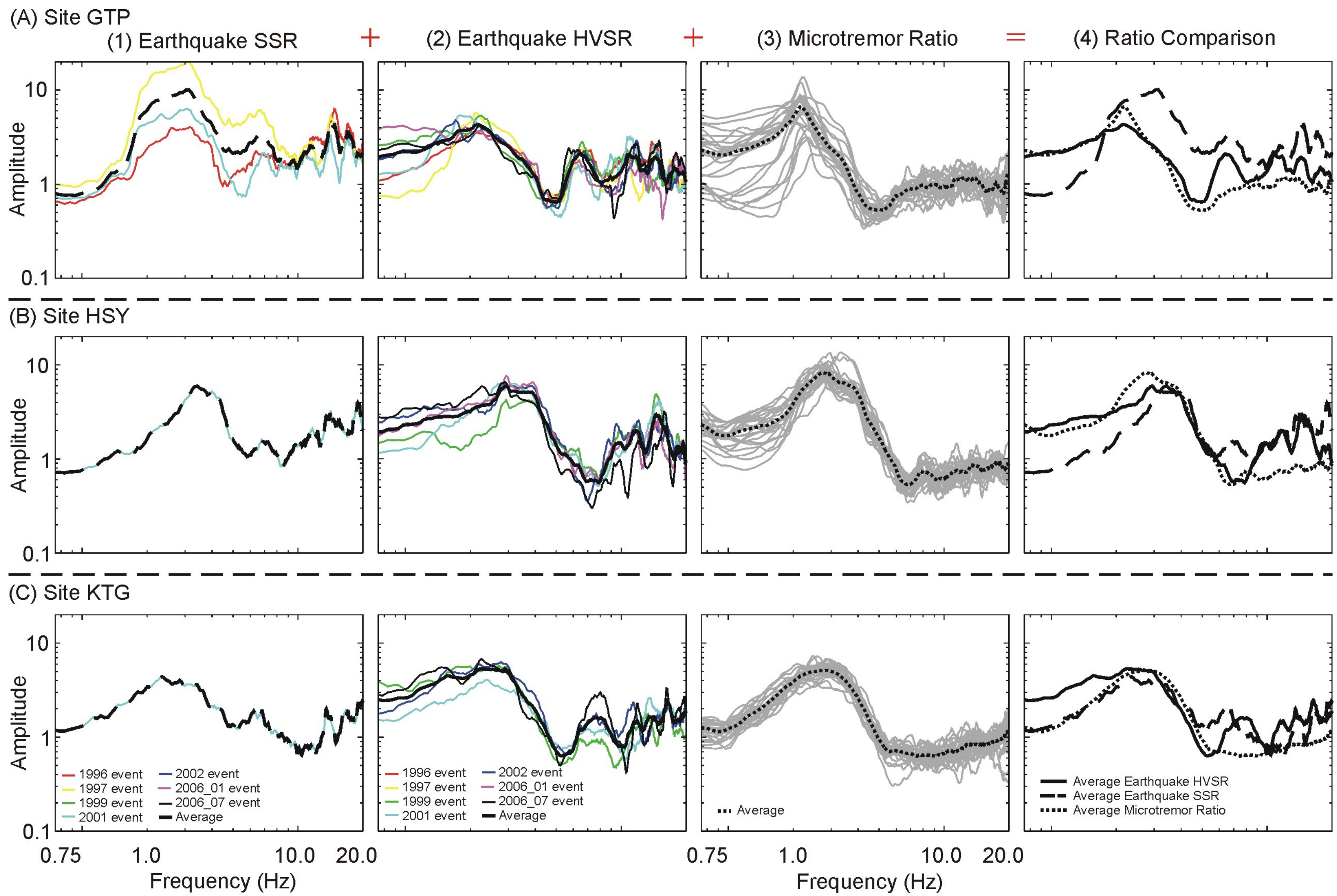

Figure 1. Comparison of (1) the average earthquake site-to-reference spectral ratios (SSR) with (2) the average earthquake h/v spectral ratios (HVSR) of up to seven earthquakes, and (3) the average microtremor h/v spectral ratio at three strong-motion instrument sites in greater Victoria. Log-log plots.

Fig. 1 demonstrates the remarkable similarity between the earthquake site-to-reference and h/v ratio response, with the microtremor h/v ratio response at three strong-motion earthquake recording sites in greater Victoria. Traditionally we have used strong-motion instrument earthquake recordings, rather than recordings from weak-motion sensors, as these instruments are designed to record the largest ground motions, and are generally present at sites of geologic interest (i.e. not bedrock). There are six BC Hydro substations in greater Victoria with a permanent strong-motion instrument. Since 1996, up to seven weak-motion (peak ground acceleration ≤ 5.5 %g) earthquakes, ranging in magnitude from M_L 3.6 to M_W 6.8, have been recorded at these sites (for earthquake details see Table 1). All six BC Hydro instrument sites show similar response regardless of excitation source (weak-motion earthquakes or microtremors) and spectral ratio method (Molnar and Cassidy, 2006). This suggests that microtremor recordings are valid for estimation of linear earthquake response at sites in greater Victoria.

Another source of strong-motion earthquake recordings comes from the Geological Survey of Canada. In 2002, they began to operate strong-motion instruments that continuously record and communicate in near real-time over the Internet (Rosenberger et al. 2007, Molnar et al. 2006b, Molnar et al. 2006c). These new instrumentation features have provided ~ 500 earthquake acceleration recordings across SW British Columbia (Cassidy et al. 2007) from only four earthquakes ranging in magnitude from M_W 4.0 to M_W 6.4. However, the recordings are all relatively low-level, varying in peak ground accelerations between 0.6 and 3.9 %g. Fig. 2 shows good similarity of the fundamental period of the h/v spectral ratio response from these earthquake recordings with the microtremor response at four strong-motion instrument sites across SW British Columbia (Molnar et al. 2006d).

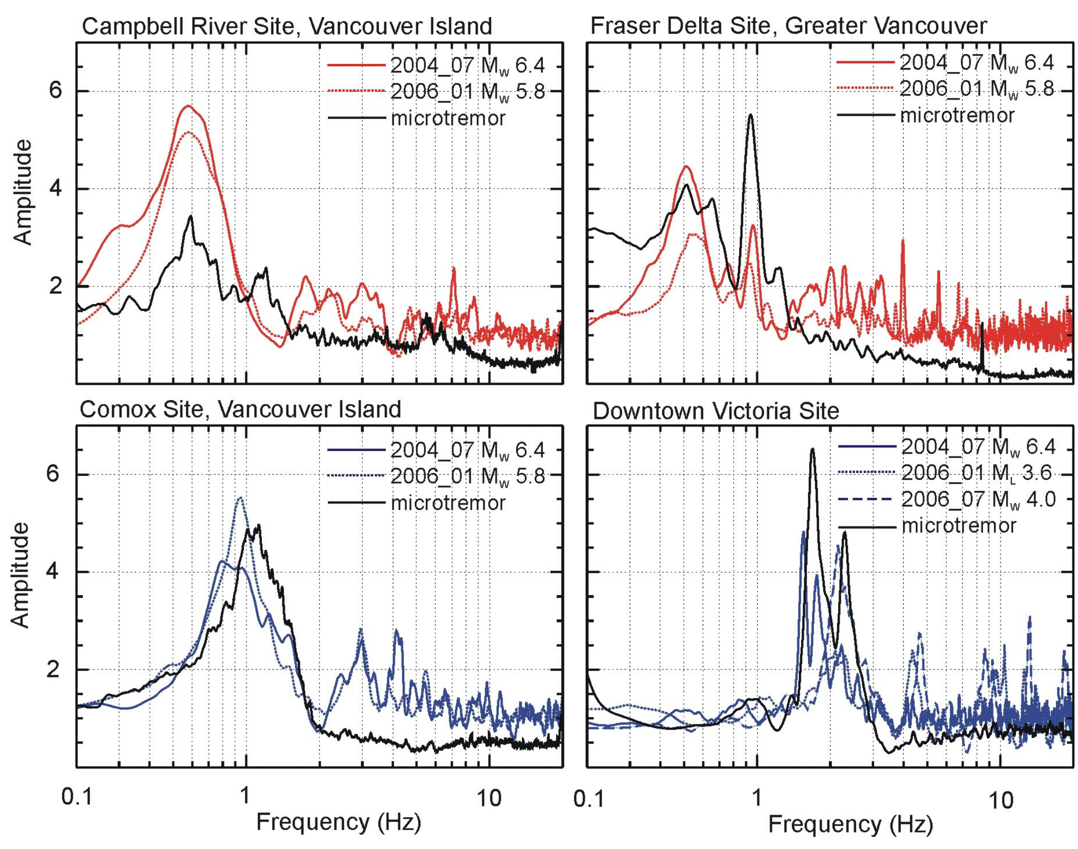

Figure 2. Comparison of the h/v spectral ratio from up to four weak-motion earthquakes and microtremors at four sites across SW British Columbia. Log-linear plots.

Overall, for SW British Columbia we observe excellent agreement in the fundamental period of a site between earthquake and microtremor spectral ratio responses, and good agreement in the level of amplification, especially at sites in greater Victoria. We also consistently observe that the microtremor response at higher modes is always lower than that of the earthquake response. In these examples, the microtremor underestimates earthquake response amplitude at frequencies greater than 2 to 3 Hz. Figures 1 and 2 demonstrate the validity of the single-instrument microtremor method as a proxy for earthquake site response across SW British Columbia.

Hazard Mapping Projects

Three microtremor campaigns have been conducted in SW British Columbia to provide a quick, first estimate of linear site response for seismic microzonation purposes. One campaign involved 193 microtremor recordings at 18 greater Victoria schools as part of a seismic hazard assessment project. Fig. 3 provides as an example of how the microtremor site response is able to demonstrate a change in geological conditions surrounding a school building. The peak amplification shifts to lower frequencies as the ground conditions soften and /or the amplifying layer thickens. The project was able to identify areas of concern for amplification seismic hazard for future borehole testing, and/or identify zones of the school for potential amplification hazard.

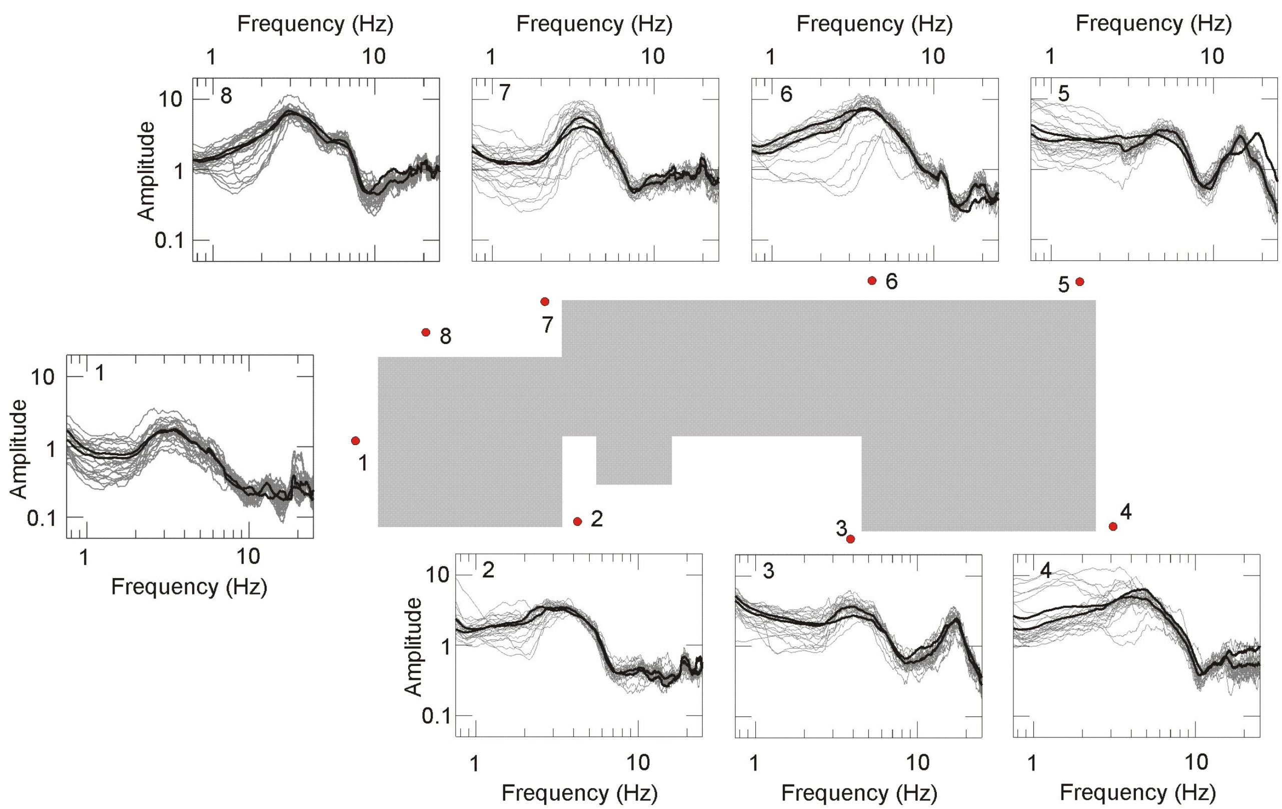

Figure 3. Microtremor site response at 8 sites surrounding a greater Victoria school building. The peak amplification shifts to lower frequency (longer period) with an increase of soft amplifying material and/or a decrease in average shear-wave velocity (i.e. the peak shifts towards the left). Log-log plots.

The Fraser River delta, south of Vancouver, has been mapped at 36 locations with microtremor measurements spaced at every kilometre in a 9x7 km grid (Onur et al. 2004; Ventura et al. 2004). The Fraser River delta has formed over the last 11,000 years, depositing sediment into the Strait of Georgia. Bedrock is about 200 to 1000 m below most of the delta, with an average depth of about 500 m (see Figure 6 in Ventura et al. 2004). The delta is composed of Holocene-age sediments (mainly alluvium) and

Pleistocene glacial and interglacial deposits. The unconsolidated fine-grained Holocene sediments are up to about 300 m thick and are mainly silts and sands. Fig. 4 spatially depicts variation of the microtremor site response for the 36 grid locations across the Fraser River delta. The earthquake recordings shown in Fig. 2 from the Fraser River delta site correspond to site G6 in Fig. 4.

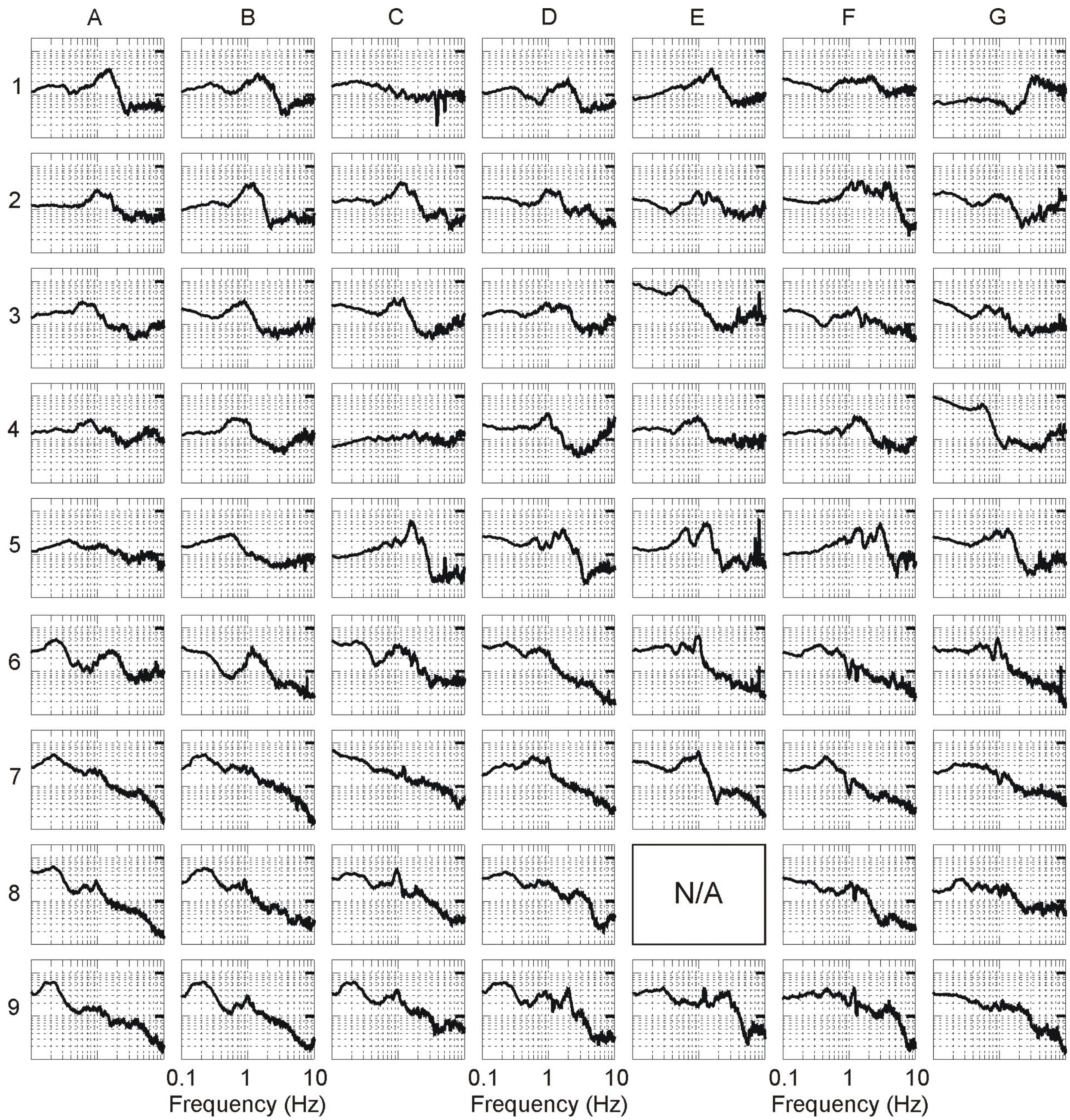

Figure 4. Variation in the average microtremor site response at 36 sites collected every kilometer in a 9x7 km grid across the Fraser River delta. Log-log plots with h/v ratio amplitude on the vertical axis from 0.1 to 20. See Figure 6 (Ventura et al. 2004) for depth to bedrock of southern sites.

The third campaign involved collecting 50 microtremor recordings in a corridor along a 10-km stretch of the Sea-to-Sky highway that links Vancouver to Whistler as part of a seismic hazard assessment for the area. Fig. 5 shows the locations of the 50 microtremor recordings and four selected microtremor responses. Sites beside the Squamish River sample Holocene floodplain deposits (S2 and B2) and consistently show peak amplification at relatively low frequencies around 0.3 Hz to 0.5 Hz (2 to 3.3 s). Site response of the stiffer gravel fan deposits (C9) show peak amplification at higher frequencies between 1 to 2 Hz (0.5 to 1 s). Sites in the rocky Garibaldi Heights (G7) were among the stiffest with relatively flat site response below 10 Hz (0.1 s). The results of this study were used in the determination of a seismic amplification hazard map that will be used in a multi-hazard assessment project of the area.

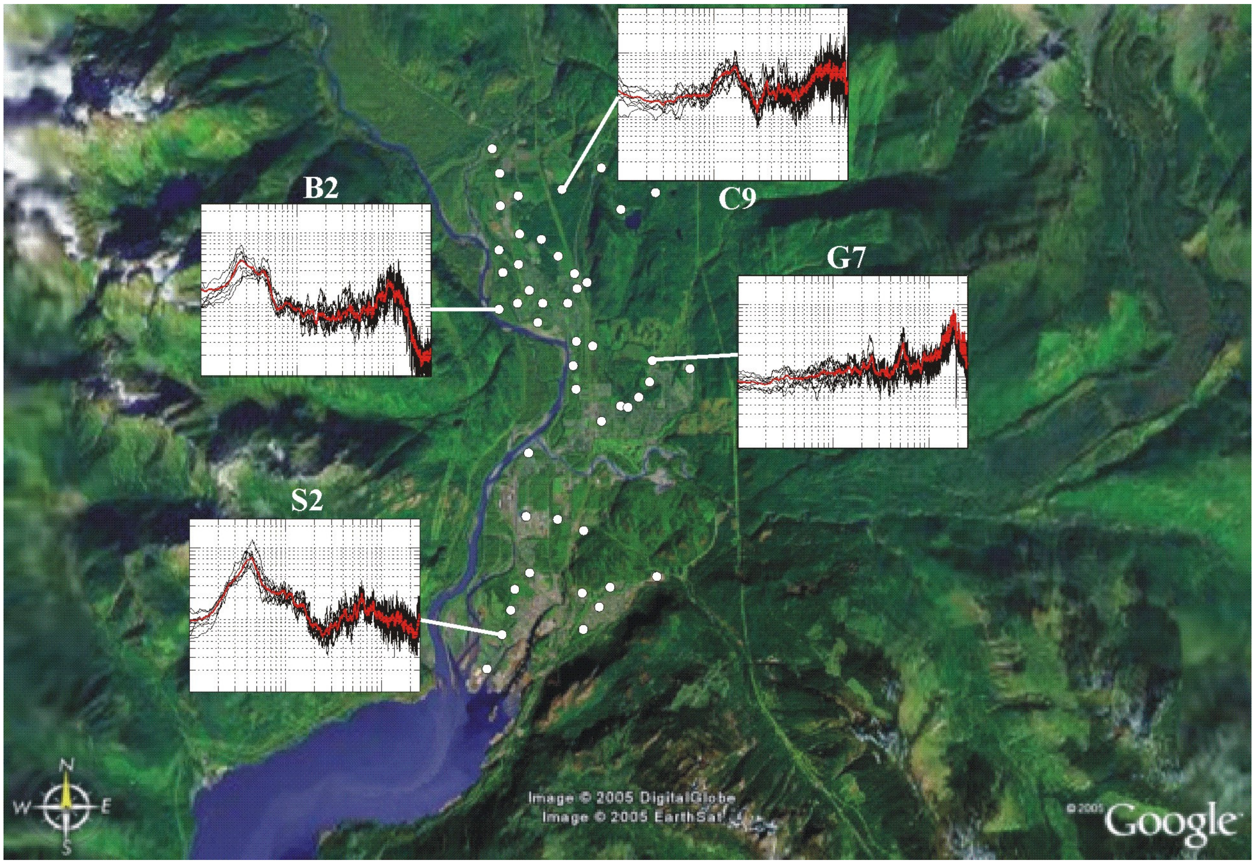

Figure 5. Google Earth aerial image of the 50 microtremor recording sites along a 10-km stretch of the Sea-to-Sky Highway that links Vancouver with Whistler. Log-log plots with frequency on the horizontal axis from 0.1 to 20 Hz (0.05 to 10 s) and h/v ratio amplitude on the vertical axis from 0.1 to 20.

Soil-Structure Interaction

Strong-motion instrument sites in the greater Vancouver region were chosen to compare the microtremor site response inside and outside (within 50 m) the structure(s) that house the instrument. Three sites recorded low-level earthquake response from the 2004 M_W 6.4 offshore Vancouver Island earthquake, 300 km distant. Fig. 6(a) shows similar microtremor site response from inside and outside the three strong-motion instrument locations that are consistent with their respective low-level earthquake site response. This demonstrates minor structural influence in the observed linear site response. Fig. 6(b) shows consistent microtremor h/v spectral ratios for recordings that are between 60-160 m away from a 14-story building of natural period 1.4 s (0.71 Hz). Recordings on the footprint of the building are relatively flat at > 1.5 Hz (0.67 s), related to construction excavation and/or densification, which is not present at the other sites investigated (60-160 m).

Both investigations of soil-structure interaction shown in Fig. 6 (a) and (b) show little influence in the soil "free-field" response. The presence of a structure at surface, even one as large as a 14-storey building, does not greatly affect the period(s) of amplification at linear levels of response. Similarly, a 13-storey reinforced concrete building in California (Pasadena Millikan library), shows little variation (less than 10%) in its fundamental period between ambient vibrations and four small earthquake recordings with maximum top accelerations < 20 cm/s^2 (Dunand et al. 2006).

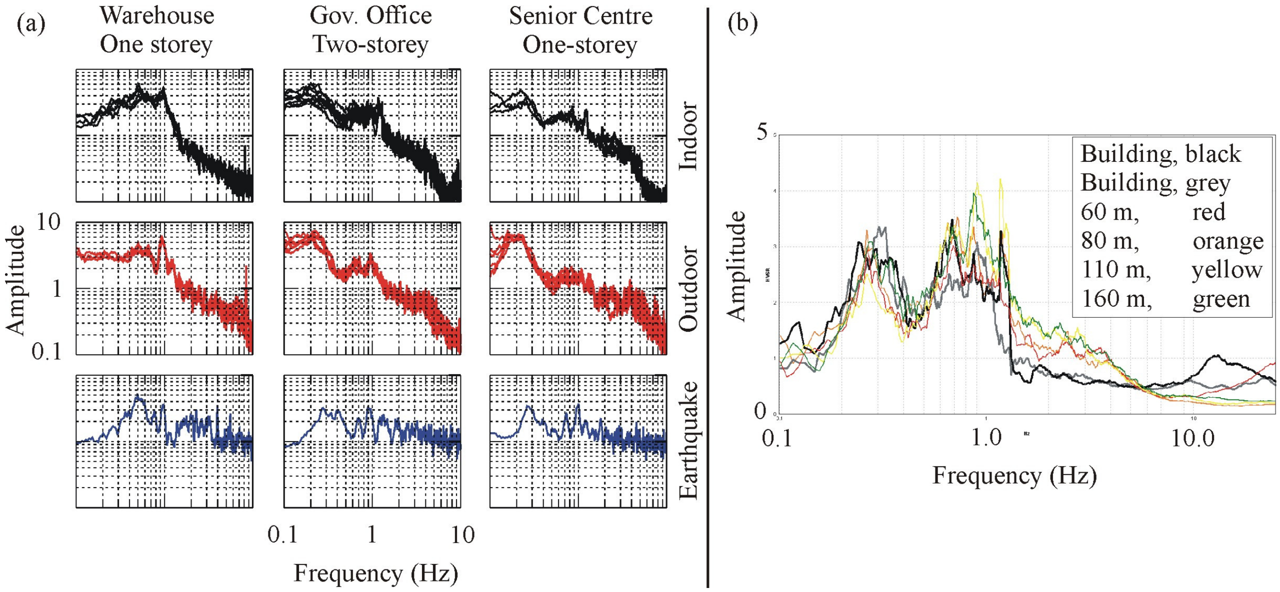

Figure 6. (a) Comparison of indoor and outdoor (within 50 m) microtremor and earthquake h/v spectral ratios at three strong-motion instrument locations in greater Vancouver demonstrate minor structural influence. Log-log plots. (b) Microtremor h/v spectral ratios 0 to 160 m distant of a 14-storey building are consistent. Log-linear plot.

Conclusions

The large volume of microtremor recordings in SW British Columbia have been collected and analyzed using the single-instrument horizontal-to-vertical spectral ratio method. Comparison of microtremor and earthquake spectral ratios at strong-motion instrument sites across SW British Columbia showed similar fundamental periods, and in greater Victoria remarkably similar amplitudes, validating the use of the method for linear earthquake site response. The microtremor method provided a quick and efficient first estimate of relative subsurface physical property variations as part of seismic hazard assessment projects for greater Victoria schools, the Fraser River delta, and a 10-km stretch of the Sea-to-Sky highway. Soil-structure interaction was investigated with two small case studies. First, microtremor site response from inside and outside the structure that hosts strong-motion instruments at three sites in greater Vancouver were consistent with each other and with low-level earthquake recordings, demonstrating minor structural influence on the linear site response. Secondly, examination of microtremor recordings gradually nearing a 14-storey building showed that the influence of the structure does not extend past its footprint. We have highlighted the different applications of the single-instrument microtremor method in southwestern British Columbia, Canada. A related paper by Molnar et al. (2007) presents a comparison of microtremor response with shear-wave velocity measurement techniques in greater Victoria.

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