13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2121

SITE RESPONSE STUDIES IN VICTORIA, B.C., ANALYSIS OF M_W 6.8 NISQUALLY EARTHQUAKE RECORDINGS AND SHAKE MODELLING

Sheri MOLNAR[1], John F. CASSIDY[2], Stan E. DOSSO[3]

SUMMARY

The largest earthquake generated by the Cascadia subduction zone in over 50 years occurred on 28 February 2001. The M_w 6.8 Nisqually earthquake was located 150 km SE of Victoria, the capital city of British Columbia. The shaking of the earthquake caused peak horizontal ground accelerations (PGA) varying from 1.0 to 3.5 %g, and variation in Modified Mercalli Intensity (MMI) from not felt (I) to slight damage (VI) in greater Victoria. Amplification of seismic waves due to the local geology is investigated as the cause of varying PGA and MMI across greater Victoria. Site-specific comparisons of earthquake intensity and geology indicate significant differences in observed felt effects between high and low shear-wave velocity substrates (bedrock and Pleistocene till versus soft clay and peat). Overall, a trend of increasing intensity with decreasing shear-wave velocity was found for geologic units in greater Victoria. Standard spectral ratios (bedrock reference) and horizontal-to-vertical spectral ratios computed for each site are similar in period and amplitude. Thin soil sites (< 3 m) exhibit a relatively flat site response at periods > 0.1 s (< 10 Hz) like bedrock, whereas thicker soil sites (5-11 m) show peak amplification up to six times that of bedrock at 0.2-0.5 s (2-5 Hz). SHAKE modelling was conducted to compare with the observed Fourier amplitude spectra. The comparison showed that the peak amplification at each site could be attributed to the local geology amplifying the ground motion. A flat site response at periods > 0.1 s occurs for < 2.5 m of soil, and peak amplification between 0.2-0.5 s was modelled by 10 m of soft clay, thicker amounts of Pleistocene till, or a combination of both.

INTRODUCTION

The M_W 6.8 Nisqually earthquake occurred near Olympia, Washington causing nearly $2 billion dollars of damage in Washington State, and was felt over 350,000 km^2 [1]. Damage was relatively modest for an earthquake of this size in an urban area because it occurred at 52 km depth within the subducting Juan de Fuca (JdF) plate.

[1] Seismology Assistant, Geological Survey of Canada, Pacific Geoscience Centre, Sidney, BC, Canada. Email: sherimolnar@hotmail.com
[2] Earthquake Seismologist, Geological Survey of Canada, Pacific Geoscience Centre, Sidney, BC, Canada, Email: jcassidy@nrcan.gc.ca
[3] Associate Professor, School of Earth and Ocean Sciences, University of Victoria, Victoria, BC, Canada.

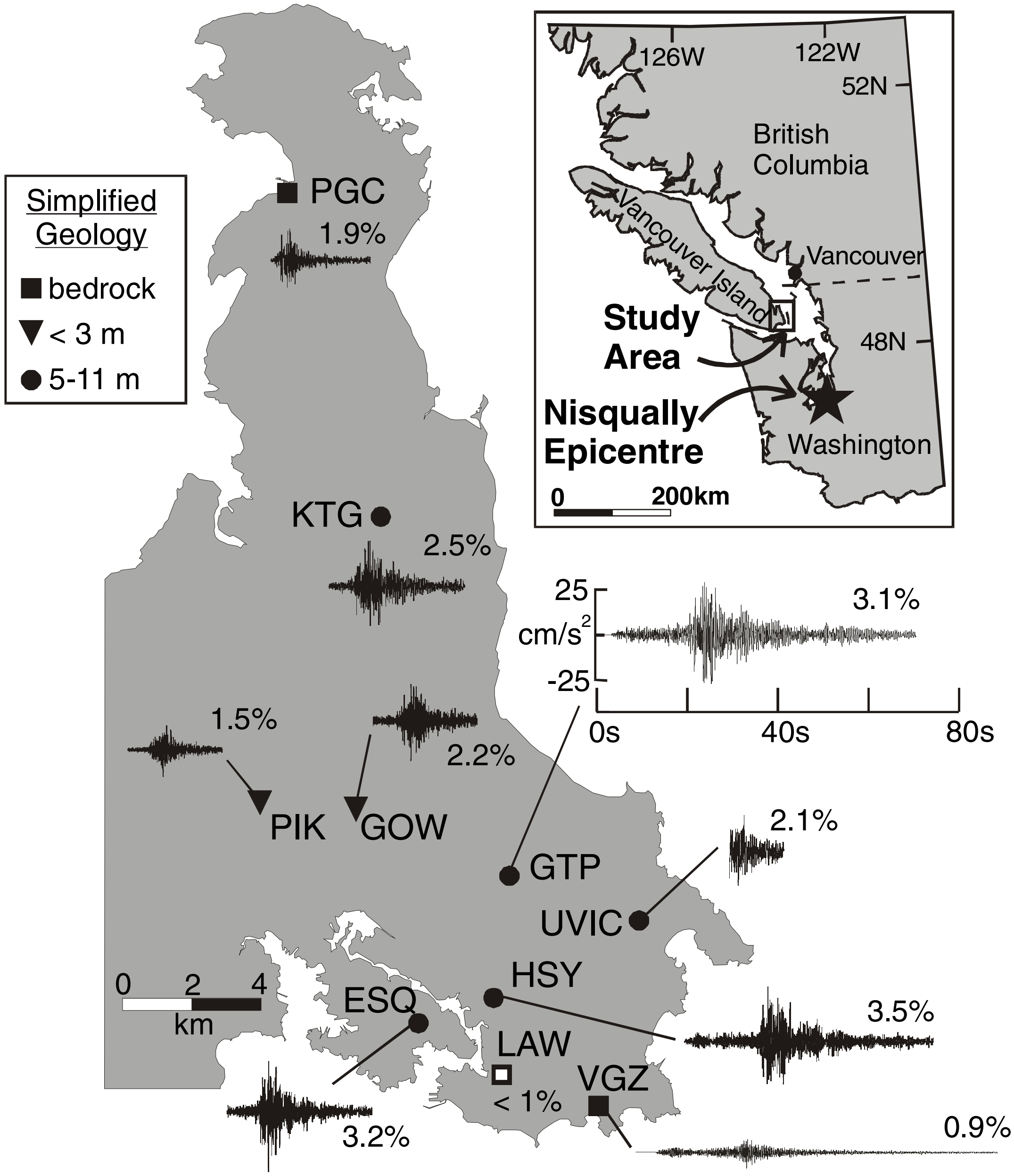

Figure 1. Greater Victoria area shown with strong-motion instrument locations, simplified geology, and peak horizontal ground acceleration (< 3.5 %g) recorded from the M_W 6.8 Nisqually earthquake. LAW instrument on bedrock did not trigger. VGZ acceleration trace from a vertical short period seismometer (see text).

In Victoria, British Columbia, 150 km NW of the epicenter (Figure 1, inset), most of the 350,000 residents felt the Nisqually earthquake. Reports of minor damage across the city included broken windows, pipes, water mains, and sewer pipes, as well as minor chimney damage. Over 750 felt reports were collected for this earthquake in the greater Victoria area, representing the largest such data set in Canada to date. These reports indicated a significant variation in the level of ground shaking across greater Victoria, with Modified Mercalli Intensities (MMI), Wood and Neumann [2], ranging from not felt (I) to minor damage (VI). The earthquake triggered strong-motion instruments at 32 sites in southwestern British Columbia [3], including eight sites in Victoria, providing the largest strong-motion data set for this region to date.

Peak horizontal ground accelerations ranged from 0.3-3.5 %g (2.9-34.2 cm/s^2) at epicentral distances of 150-300 km. The data recorded at Victoria (Figure 1) is "weak" strong-motion with linear site response and minimal source and path effect differences between sites.

Victoria is located at the northern portion of the CSZ where active subduction of the oceanic JdF plate beneath the continental North America (NA) plate has produced 36 moderately felt earthquakes (MMI ≥ IV) within the past 139 years, eight of which have caused minor damage [4]. Damaging JdF plate earthquakes include the 1949 M_W 7.1 Puget Sound earthquake, the 1965 M_W 6.5 Seattle earthquake, and the 2001 M_W 6.8 Nisqually earthquake. Two large NA plate earthquakes have occurred on Vancouver Island this century: a M_S 6.9 event in 1918, and a M_S 7.3 event in 1946. Victoria is the city in Canada with the highest seismic hazard because it is closest to the CSZ. The determination of site response and the comparison of intensity information with local geology in Victoria is therefore of great interest and will provide an important baseline for future seismic hazard studies.

GEOLOGIC SETTING

The geology of greater Victoria includes a wide variation of substrata, including bedrock, Pleistocene till, glaciomarine clays and Holocene organic soils [5]. Glaciers eroded the bedrock surface to a very irregular topography. The depth to bedrock can vary from 0-30 m in the space of a city block [6]. The geological unit of particular concern with respect to earthquake amplification is a soft, grey, glaciomarine clay, locally termed the "grey Victoria clay". Weathering processes oxidized and desiccated the soft, grey clay, producing a brown, hard crust termed the "brown Victoria clay". Brown Victoria clay is at the surface in much of the Victoria area atop the grey Victoria clay.

Monahan and Levson [5] developed a detailed Quaternary geological map of the greater Victoria area from over 5000 geotechnical borehole logs, several hundred water well logs, and nearly 3000 engineering drawings for municipal sewer and water lines. A shear-wave velocity model for the principle Quaternary geological units in greater Victoria was developed from 15 seismic cone penetration tests and spectral analysis of four surface wave tests [7]. A relative amplification hazard map of greater Victoria was created by Monahan et al. [8] that rated amplification hazard of the geologic units based on the U.S. National Earthquake Hazard Reduction Program (NEHRP) site classes for susceptibility to amplification. The average shear-wave velocity and resulting range (± 1σ) of these geologic units, based on n number of measurements by Monahan and Levson [7], is as follows: Pleistocene till, 499 m/s (420-577 m/s, n = 17); brown Victoria clay, 213 m/s (164-262 m/s, n = 28); and grey Victoria clay at less than 15 m depth, 132 m/s (104-160 m/s, n = 69). The corresponding NEHRP site classes for these particular units are C, D, and E, respectively [9].

This paper compares the amplification hazard map based on NEHRP site class to intensities as reported from the weak ground shaking of the Nisqually earthquake. Table 1 lists the amplification hazard ratings based on NEHRP site class for geologic units of interest in greater Victoria.

Table 1. Amplification hazard ratings of geologic units in greater Victoria.

Unit	Geologic Description	NEHRP Site Class	Amplification Hazard Rating*	NEHRP Amplification Factor+
R1	Bedrock; nearly continuous outcrop	A-B	vl	0.8 – 1
R1/2	Areas of thin soil cover and nearly continuous outcrop undifferentiated	A-C	vl-l	0.8 – 1.2
R2	Thin soil cover over bedrock with scattered outcrops	A-C	vl-l	0.8 – 1.2

T	Thick (> 10 m) older Pleistocene deposits	C	l	1.2
C3	< 5 m of Victoria clay over thick (> 10 m) older Pleistocene deposits	C	l	1.2
C4a	> 5 m of Victoria clay and < 3 m of grey Victoria clay over thick (>10 m) older Pleistocene deposits	C-D	l-m	1.2 – 1.6
C1	Areas where units R2 and C2 cannot be differentiated with data available; also includes areas with > 5 m of Victoria clay, but < 3 m of grey Victoria clay	C-E	l-h	1.2 – 2.5
C4	> 5 m of Victoria clay and < 3 m of grey Victoria clay over thick (>10 m) older Pleistocene deposits	C-E	l-h	1.2 – 2.5
G1	Sand and gravel of the Colwood delta and outwash plain	D	m	1.6
C2	> 3 m of grey Victoria clay, under brown Victoria clay and over thin (< 10 m) older Pleistocene deposits	D-E	m-h	1.6 – 2.5
O1	Holocene peat over grey Victoria clay	E-F	h-vh	≥ 2.5

*vl = very low, l = low, m = moderate, h = high, vh = very high. +relative to 0.1g acceleration on bedrock (NEHRP site class B) at short period motions (0.1-0.5 s).

MACROSEISMIC DATA

Felt reports were collected in two ways: by voluntary submission of the online web form maintained by the Geological Survey of Canada's Pacific Geoscience Center (PGC) and by door-to-door canvassing. The felt report form can be found at http://www.pgc.nrcan.gc.ca/seismo/intens.htm. The selection of areas for door-to-door canvassing was based on previous seismic hazard investigations [10, 11] and concentrated on small areas having large variations in local geology [5]. The felt report database was completed by July 2001, five months after the earthquake, totaling over 750 felt reports. An examination of response over the five month collection period suggests that the felt report database is not biased by the date of the report received [4].

The algorithm used to assign intensities from the collected felt report data is based on a study by Dengler and Dewey [12] of the 1994 M_W 6.7 Northridge, California earthquake. The procedure involves assigning numerical values to each answer in a felt questionnaire for a specified area or "community". The numerical values for each question are then averaged, and a weighted sum over all questions is computed. This weighted sum of averages is then converted to an intensity value, termed a Community Decimal Intensity (CDI). Based on the reading of over half the felt reports and a comparison of CDI and United States Geological Survey MMI, a particular range of CDI was assigned to each MMI level [4].

In this study, the "community" that provides the CDI is represented by the six-digit Canadian postal code. This provides a high-resolution locator, as the postal code corresponds to the length and half the width of a city block (i.e. one side of a city block). Each postal code is georeferenced to a five-digit latitude and longitude point in the middle of its respective postal code area, creating a postal code intensity map.

Intensity Comparison with Geology

To compare the intensities of the Nisqually earthquake to geology, the postal code intensity map was overlain on the greater Victoria amplification hazard map of Monahan et al. [8]. In this way, intensity is compared with the average shear-wave velocity of each geologic unit (i.e. NEHRP site class).

Regional comparison using postal code

The average community decimal intensity (ACDI) of a particular geologic unit was determined by averaging the intensity of all areas with the same geology. For example, all the postal code CDI points of bedrock (R1) areas were averaged to determine the ACDI of that particular geologic unit. The result is 11 geologic units with ACDI values plotted as a function of amplification hazard rating in Figure 2.

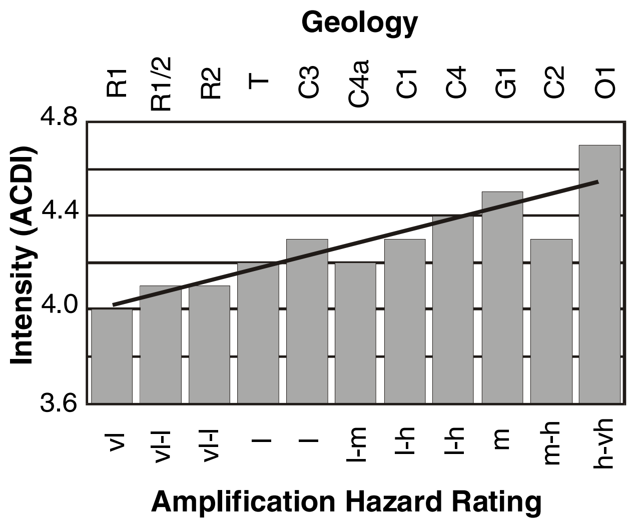

Figure 2. Graph of average community decimal intensity (ACDI) versus amplification hazard rating of geologic units in greater Victoria using the six-digit Canadian postal code as the intensity locator. Geology as described in Table 1. Trend line is least squares fit to data points.

Comparison of intensity with geology does show an overall general increase of ACDI with a decrease in shear-wave velocity of geologic units in greater Victoria. The NEHRP amplification factors for a moderate (0.1g) shaking, short period (0.1-0.5 s) ground motion earthquake relative to bedrock (NEHRP site class B) [13], listed in Table 1, suggests that over a two-fold increase in ground motion could have resulted from the Nisqually earthquake. The range in ACDI determined for the geologic units from the Nisqually earthquake is only 0.6 units (i.e. intensity (MMI) range of III-VI). However, measured ground motions in the greater Victoria area from this earthquake show up to six times the amplification of bedrock at 2-5 Hz in areas of 5-11 m of Victoria clay (see Spectral Ratios section).

Site-specific comparison using House Address

The resolution of the amplification hazard map is higher than that of the six digit Canadian postal code, with geologic variations mapped within a city block. This mismatch in resolution sometimes results in felt report information plotted in the wrong geologic unit. House address, a site-specific locator, plots the intensity of each felt report in its correct geology. A small area of Victoria (Fairfield) is used for the case study of site-specific location. The area was heavily canvassed door-to-door based on the rapid change in geology within a small area, the locations of damage from the 1946 earthquake [10], and results of the 1996 Duvall earthquake felt report survey [11]. The site-specific intensity points in Fairfield were overlain on the amplification hazard map to calculate the ACDI of each geology. The result is nearly a full intensity (MMI) difference between each amplification hazard rating. Hence, residents in Fairfield situated on rock hardly felt the earthquake, on thick Pleistocene till watched hanging objects swing, on thick soft clay watched a few objects topple and trees sway, and on Holocene peat over soft clay saw pictures knocked out of place and furniture move.

Figure 3 shows an increase in ACDI with increasing amplification hazard for both regional and site-specific comparisons. The intensity on bedrock and overconsolidated glacial deposits (low category) is low compared to moderate values on varying thicknesses of Quaternary clay deposits (moderate category), and the highest intensity occurred in areas of Holocene peat over soft clay deposits (high category). Figure 3 shows that the use of house address to locate felt reports results in a more pronounced increase of ACDI with amplification hazard rating than using postal codes. This suggests that if all felt reports could be located by house address the positive correlation of ACDI with amplification hazard rating would likely become more pronounced.

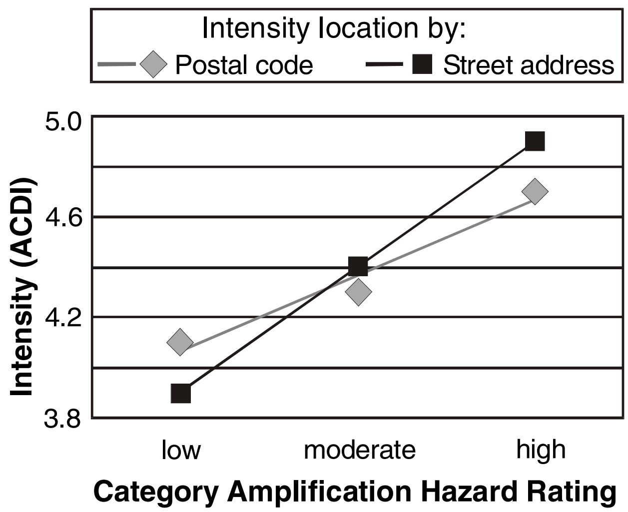

Figure 3. Graph of average community decimal intensity (ACDI) versus amplification hazard category locating intensity by postal codes and by house address. Low category includes geologic units R1, R1/2, R2, and T (described in Table 1), moderate category units are C1-4, and the high category unit is O1.

STRONG MOTION DATA

Ten strong-motion instruments were in operation across greater Victoria (Figure 1) at the time of the Nisqually earthquake. These sites sample a wide range of geological conditions from bedrock to thin soil (< 3 m) to thicker soil (5-11 m). The Geological Survey of Canada (GSC) maintains four of these sites; three in Victoria and one at the Pacific Geoscience Centre (PGC), 30 km north of the city. The six other instruments are maintained by British Columbia Hydro (BCH) at electrical substations. Of the three strong-motion instruments that are located on bedrock (PGC, VGZ, LAW; Figure 1), only PGC recorded ground motion from the Nisqually earthquake and can be used as a bedrock reference. A vertical-component, short-period seismometer was recording at the Gonzales Observatory (VGZ). To compare the vertical seismogram at VGZ with the vertical accelerograms at the other sites, the seismogram was high pass filtered at 0.1 Hz to remove noise, differentiated to obtain an acceleration time history, and interpolated from 100 to 200 Hz sampling rate. The Law Courts (LAW) instrument situated on bedrock did not trigger at a threshold of 1 %g. In all other cases, the trigger occurred on the S-wave.

Digital processing was conducted using the Strong Motion Analyst (SMA) program [14]. The processing involved: (1) baseline correction for each component; (2) band-pass filtering (0.167-25 Hz); (3) integration of acceleration to produce velocity and displacement; and (4) rotation of the horizontal components to form radial (SV) and transverse (SH) components. The recorded acceleration time histories ranged in length from 20-70 s (Figure 1). In all cases, the peak ground acceleration (PGA) occurred within the first 5 s of the S-wave train. The lowest PGAs occurred at the bedrock sites, VGZ and PGC. The vertical acceleration for VGZ is 0.6 %g and using the horizontal-to-vertical ratio of 1.5 for rock [15], the horizontal acceleration (shown in Figure 1) is estimated at 0.9 %g. This is consistent with the nearby LAW instrument on bedrock not triggering at 1 %g threshold. Felt reports gathered from the LAW location also suggest a low level of ground shaking [4].

Spectral Ratios

Ground motion amplitude spectra were computed for each site using a 15-s data window which began ~2 s before the S-wave arrival and contained most of the recorded seismic energy. The data window was detrended, cosine tapered and fast Fourier transformed to produce amplitude spectra. The spectra were smoothed using a 15-point running mean filter (0.75 Hz full width).

The ground motion amplitude spectrum (A) is considered to be the product of the earthquake source effect (E), propagation effects from the source to the recording site (P), the recording instrument effect (I), and the site response (S): $A(f) = E(f) \cdot P(f) \cdot I(f) \cdot S(f)$. The site response includes the effect of the uppermost several hundred meters of rock and soil and the surface topography at the recording site. The 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, and geometry at the site [16]. The greatest challenge in estimating the site response involves removing the source and path effects. In this study two methods are used: standard spectral ratios and horizontal-to-vertical spectral ratios.

Standard Spectral Ratios

The most common technique for estimating site response is the standard spectral ratio method [17, 18]. In this method, the amplitude spectrum of a soil site (A_s) is divided by that of a nearby bedrock site (A_b):

$$\frac{A_s(f)}{A_b(f)} = \frac{E_s(f)P_s(f)I_s(f)S_s(f)}{E_b(f)P_b(f)I_b(f)S_b(f)} \cong \frac{S_s(f)}{S_b(f)} \cong S_s(f).$$

The result is that the response characteristics of the soil column are preserved, whereas the effects of the source, travel path, and the recording instruments are removed as they are assumed to be the same as for the bedrock reference site. Finally, the bedrock site is assumed to be free from amplification (i.e. $S_b(f) = 1$), thereby isolating the amplitude spectrum of the soil column.

The ratios were computed by dividing the site spectra by the reference bedrock spectra at PGC (for both the SV and SH components). The method is applicable to this study because the distances between sites in Victoria (< 25 km) are small compared to the distance to the Nisqually epicenter (150 km), and the sites all have a similar azimuth (340º-344º) with respect to the epicenter, such that source and travel path effects between sites is small. The horizontal components at PGC have low (< 4) peak amplitudes at 0.2 s (5 Hz) and 0.3 s (3 Hz) for the SV and SH direction, respectively. This suggests that there is a site response of the bedrock at PGC that will cause slightly lower amplitude of the SSR at these periods.

Figure 4a,b shows the spectral ratios for seven soil sites with respect to PGC (solid line) for the SV and SH components, respectively. The thin soil sites, GOW and PIK, show a flat site response at periods > 0.1 s (< 10 Hz) like bedrock, with some amplification at shorter periods (< 0.1 s, > 10 Hz). In contrast, the thicker soil sites (GTP, KTG, HSY, and UVIC) have peak amplification up to six times that of bedrock at periods of 0.2-0.5 s (2-5 Hz). ESQ has four times the amplification of bedrock at a shorter period of 0.13 s (8 Hz).

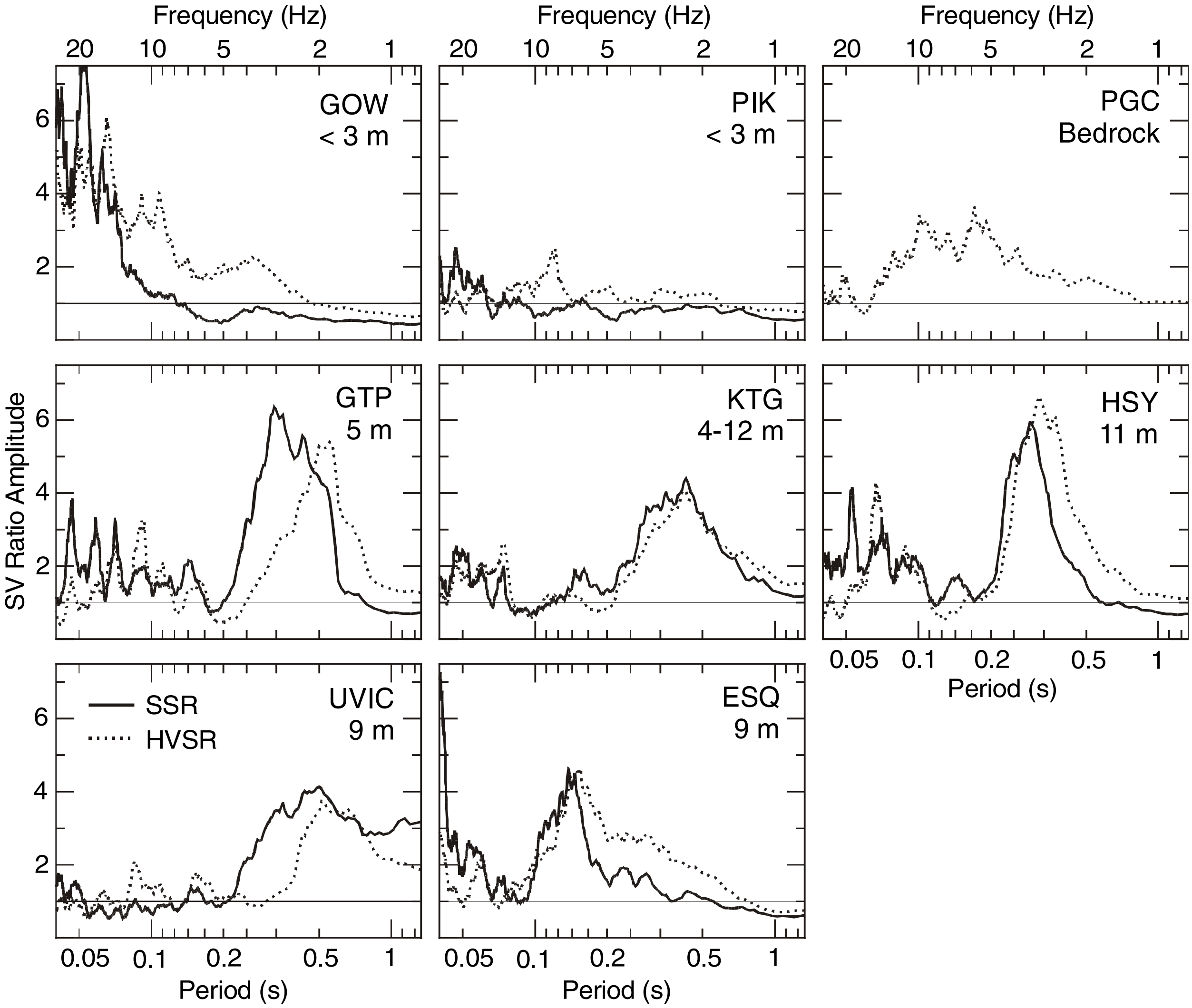

Figure 4a. SV standard spectral ratio (PGC bedrock reference) and H/V spectral ratio for each site.

Horizontal-to-Vertical Spectral Ratios

The horizontal-to-vertical spectral ratio method requires only a single-station earthquake recording and uses the vertical component as reference. Lermo and Chavez-Garcia [19] first applied the H/V ratio technique using spectra produced by earthquake S-waves. The standard spectral ratio method is generally the preferred spectral ratio method if a bedrock recording is available because the H/V ratio method has not provided consistent results [20, 21, 22]. It is generally agreed that the H/V ratio method recovers the fundamental amplification period, but that the amplitude is usually lower than that from the standard spectral ratio method [23, 24, 25].

The H/V ratios were computed in a manner similar to that for the standard spectral ratios with the SV and SH spectra for a particular site divided by the vertical spectrum for that site. Figure 4a,b shows the H/V ratios (dotted line) at each site for the SV and SH components, respectively. Overall, there is good agreement between H/V ratios computed using SV and SH waves (the north-south and east-west components show similar H/V ratios, not shown). The largest difference is at GTP, where the SV ratio shows a peak of ~5 at 0.5 s (2 Hz) compared to a peak of ~3 at ~0.7 s (~1.5 Hz) for the SH ratio. The H/V ratio for PGC suggests a site response of ~1.0-3.5 at periods of 0.07-0.7 s (1.5-15 Hz) at this bedrock site. Thin soil sites generally show a flat site response with amplification at short periods (< 0.1 s, GOW; 0.13

s, PIK), whereas thicker soil sites (GTP, KTG, HSY, and UVIC) show amplification of ~3-7 at periods of 0.25-0.70 s (1.5-4.0 Hz).

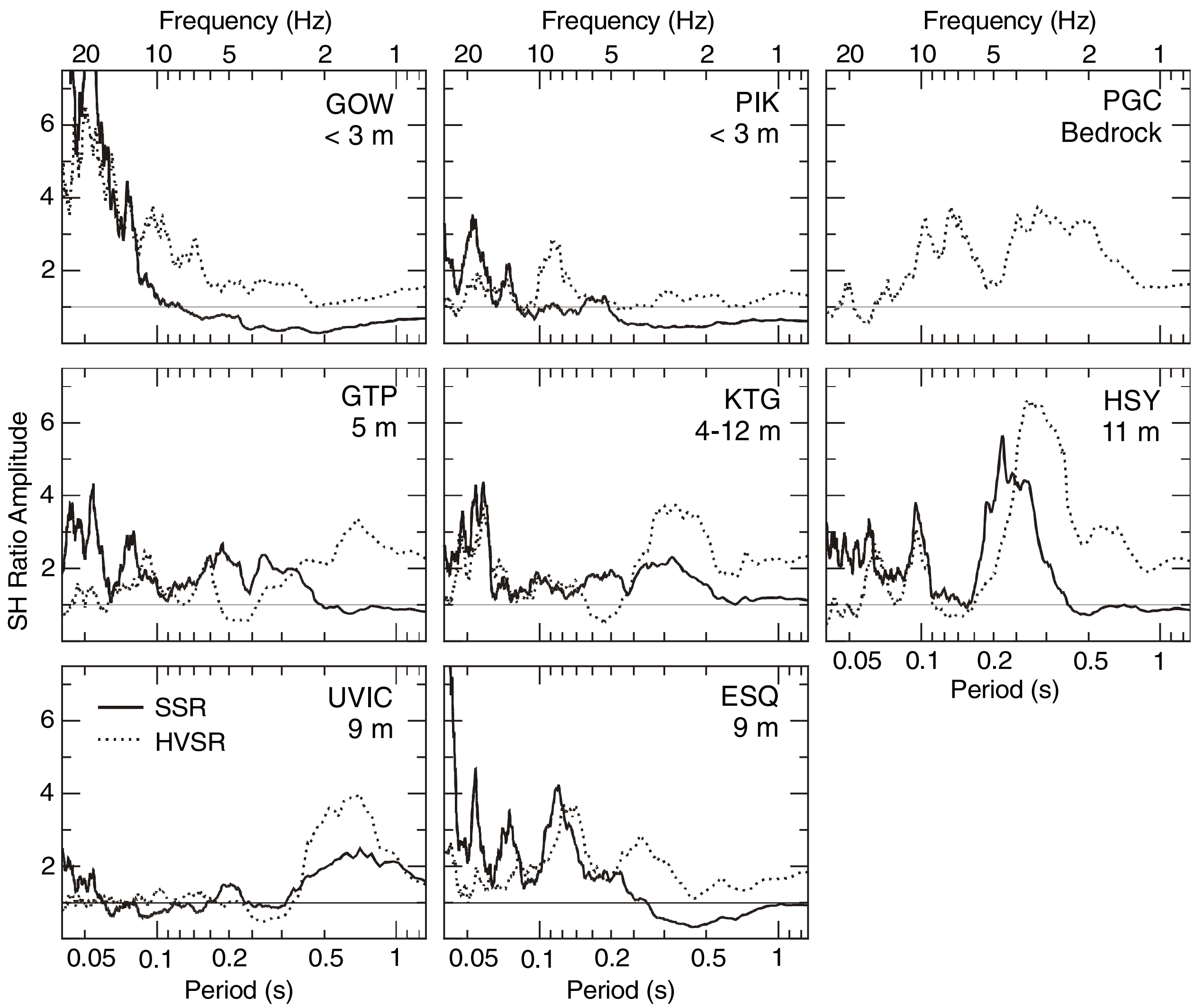

Figure 4b. SH standard spectral ratio (PGC bedrock reference) and H/V spectral ratio for each site.

Figure 4 also allows direct comparison of the standard spectral ratio with the H/V spectral ratio at each site. Both methods exhibit a very similar site response at each soil site, and in many cases the amplitudes match remarkably well. Both methods show peak amplification at < 0.13 s (> 8 Hz) for the thin soil sites, GOW and PIK, and at 0.2-0.5 s (2-5 Hz) for the thicker soil sites, GTP, KTG, HSY, and UVIC. The SH amplitude spectra (Figure 4b) for both ratio methods shows more variability than the SV component. The agreement of the H/V spectral ratio with the standard spectral ratio for the SV component (Figure 4a), suggests that the H/V method can provide reliable amplitudes, which had been previously noted only by Lermo and Chavez-Garcia [19].

SITE RESPONSE MODELLING

The SHAKE modelling program [26, 27] was used to constrain the soil properties required to reproduce the major features of the amplitude spectra at each site. SHAKE is based on a continuous solution to the wave equation [28], adapted for transient motions using the fast Fourier transform. To carry out the SHAKE modelling, a 1-D geologic model of the soil column was created for each site based on geologic data from boreholes and test pits provided by BCH.

The generated ground acceleration at the top of the soil profile was used to create the SHAKE amplitude spectrum to compare with the observed amplitude spectra at each site. Effort was focused on matching the overall shape of the amplitude spectra and the relative differences between sites. The iterative forward modelling involved varying three key parameters: layer thickness, shear-wave velocity, and unit weight. Of the three parameters, only layer thickness was not tightly constrained at each site and could provide significant changes to the model spectra. Consequently, the best-fit models were developed by adjusting layer thickness. The shear-waves incident at the base of this model consisted of the first 15 s of each PGC horizontal component (SV and SH), cosine tapered, and converted to units of g. Only select sites are chosen to present the lessons learned from SHAKE modelling. See Molnar et al. [29] for complete discussion of the modelling results at each site. Note that this program does not account for topography, subsurface focussing, basin-edge or 3-D effects, which could also contribute to the site response.

Thin soil site

The geology of PIK comes from four test pits that show 0.34 - 3 m of soft, organic silt atop bedrock. The spectra based on the initial model (Figure 5) show a large peak at 7 Hz. This peak, attributed to the 3 m of silt in the initial model, is not seen in the observed Nisqually earthquake spectra. The soil profile was thinned to < 1 m, shown in Figure 5 (stratigraphic column) as the model spectra. The model spectra varies little from the input bedrock (PGC) spectra showing only slightly higher amplitude at > 15 Hz, which is a better fit with the observed Nisqually earthquake spectra. Overall, the spectra of PIK are very similar to the input bedrock spectra, even slightly attenuated at periods > 0.1 s (< 10 Hz) suggesting that there is little soil present at this site and no significant site response.

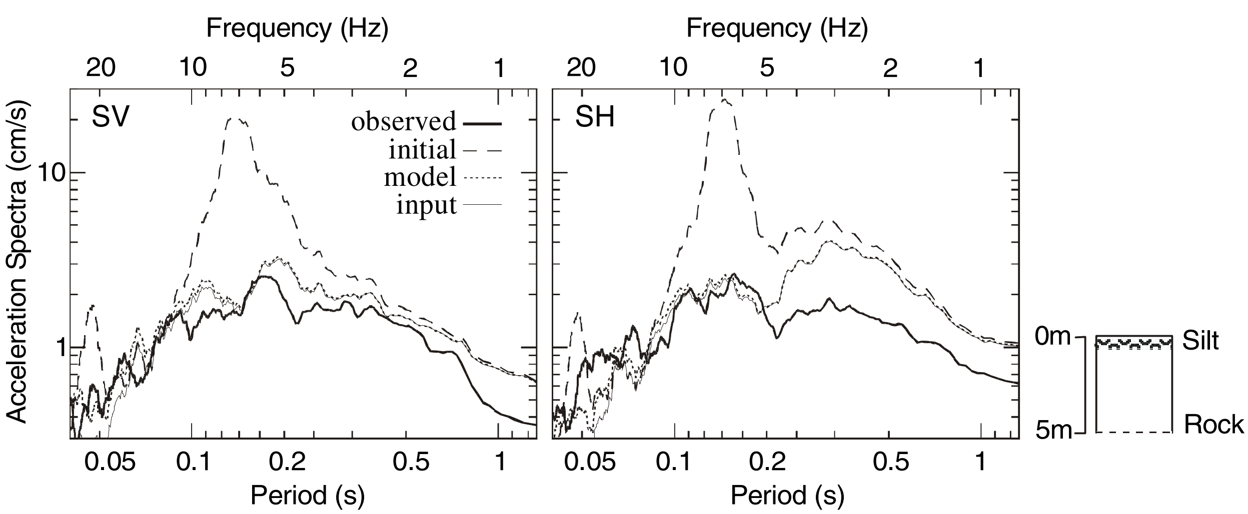

Figure 5. PIK modelling results and final geologic soil profile. Spectra shown are the observed Nisqually earthquake spectra (thick solid line), the initial model spectra (dashed line), the best-fit model (dotted line) and the input bedrock (PGC) spectra (thin solid line).

Thicker soil sites

The geology at GTP is fairly uniform as constrained by 12 drill holes and nine test pits. The initial soil profile consists of 1.8 m of medium to stiff, sandy to clayey silt over 3.7 m of stiff to very stiff, silty clay.

These two soil layers occur atop very dense, bouldery till with an unknown thickness, as bedrock was not reached in any of the geological samples. The initial model spectra (Figure 6) showed a poor fit to the observed Nisqually earthquake GTP spectra. The initial spectra have a peak at 0.14 s (7 Hz) and do not contain the dominant peak at 0.25-0.5 s (2-4 Hz) present in the observed spectra. To produce the 0.2-0.5 s peak amplitude shown by the best-fit model spectra required 30.5 m of till beneath the two soil layers (stratigraphic column).

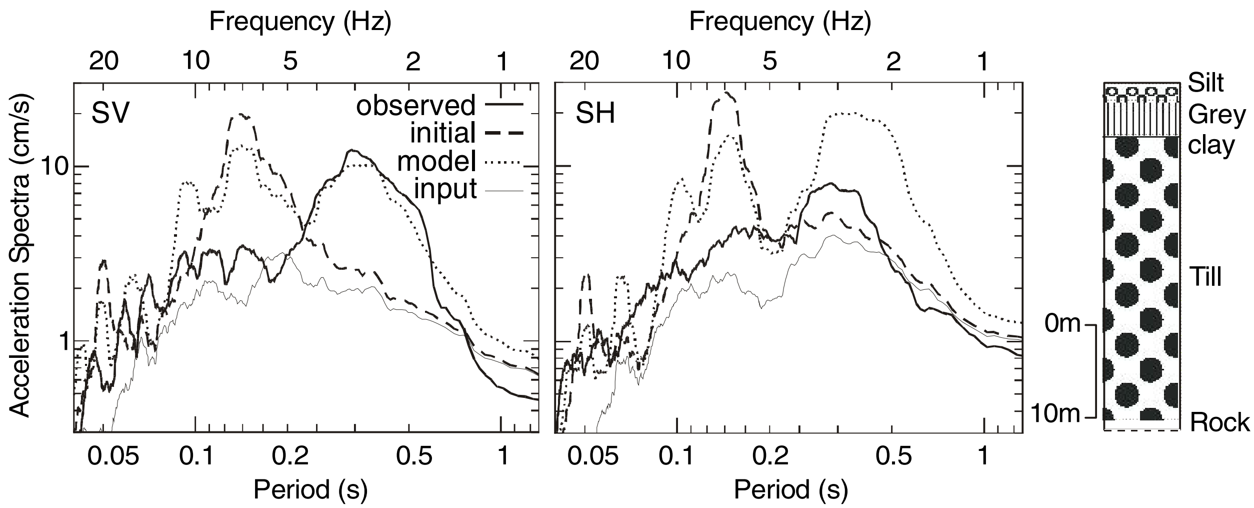

Figure 6. GTP modelling results and final geologic profile. Spectra shown as described in Figure 5.

The initial geologic profile for HSY based on 10 boreholes consists of 1.7 m of clay, 2.6 m of brown Victoria clay, 6.7 m of grey Victoria clay, and 0.4 m of sandy gravel atop bedrock. The initial model spectra (Figure 7) includes a dominant peak at 0.2-0.4 s (2.5-5 Hz), similar to the observed Nisqually earthquake HSY spectra, suggesting that the peak amplitude results from the 11 m of clay. The initial model was altered by the addition of 7.9 m of till to the base of the clay column (stratigraphic column). The resulting model spectra in Figure 7 shows a better match with the observed spectra than the initial model at all periods (i.e. matches higher-order peaks).

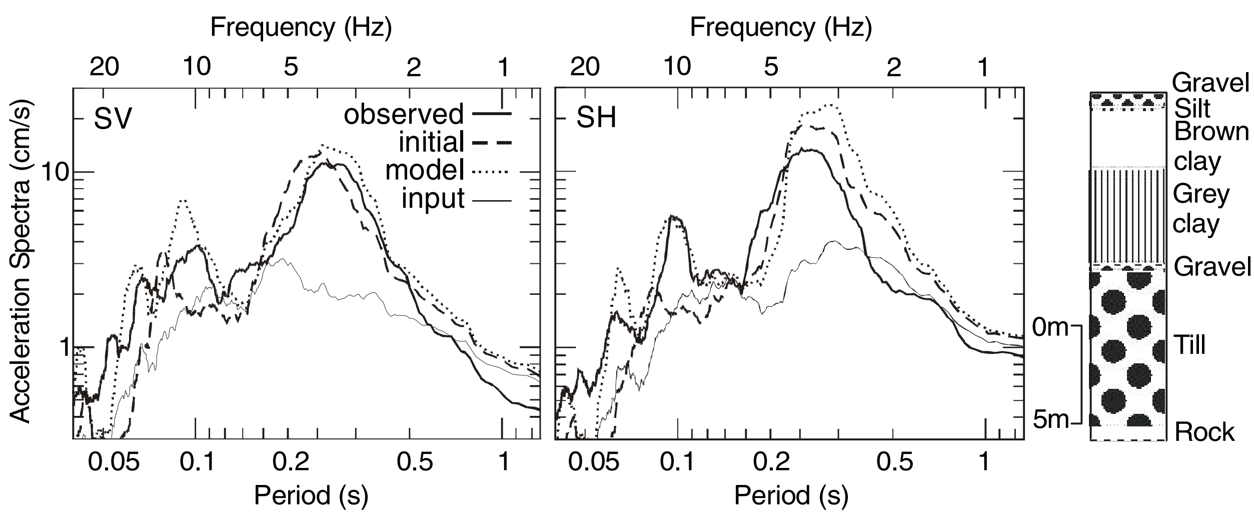

Figure 7. HSY modelling results and final geologic profile. Spectra shown as described in Figure 5.

The geology of KTG was available from five test pits within the substation and surrounding water well logs that indicate a layer of 4-12 m of clay above till, with bedrock at ~30 m depth. The initial KTG model spectra (Figure 8) used was the initial soil profile of GTP (Figure 6) and showed poor agreement with the observed Nisqually earthquake KTG spectra. The clay and till layers were thickened to 9.9 m and 16.7 m, respectively (stratigraphic column) to produce the best-fit modelled spectra, which matches the observed peak amplitude at 0.25-0.5 s (2-4 Hz) as well as higher-order peaks at 0.17, 0.1, and 0.07 s (6, 10, and 15 Hz).

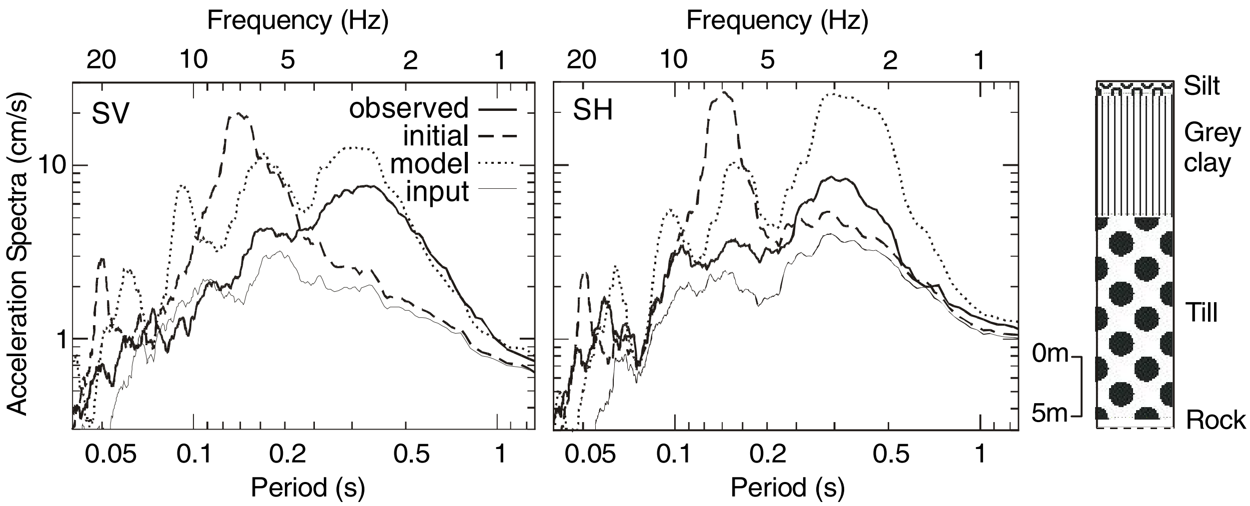

Figure 8. KTG modelling results and final geologic profile. Spectra shown as described in Figure 5.

The initial soil profile at ESQ developed from three boreholes consists of: 0.6 m gravel (fill), 2.4 m silt, 1.5 m clay, 5.2 m grey Victoria clay, and 0.6 m sand atop bedrock. The initial model spectra in Figure 9 shows a dominant peak at 0.25-0.5 s (2-4 Hz) that does not match the observed Nisqually earthquake ESQ spectra with 0.1-0.13 s (8-9 Hz) peak amplitude. The best-fit spectra are obtained by thinning the initial soil profile to 4.6 m (the minimum depth to bedrock found in boreholes at ESQ, stratigraphic column).

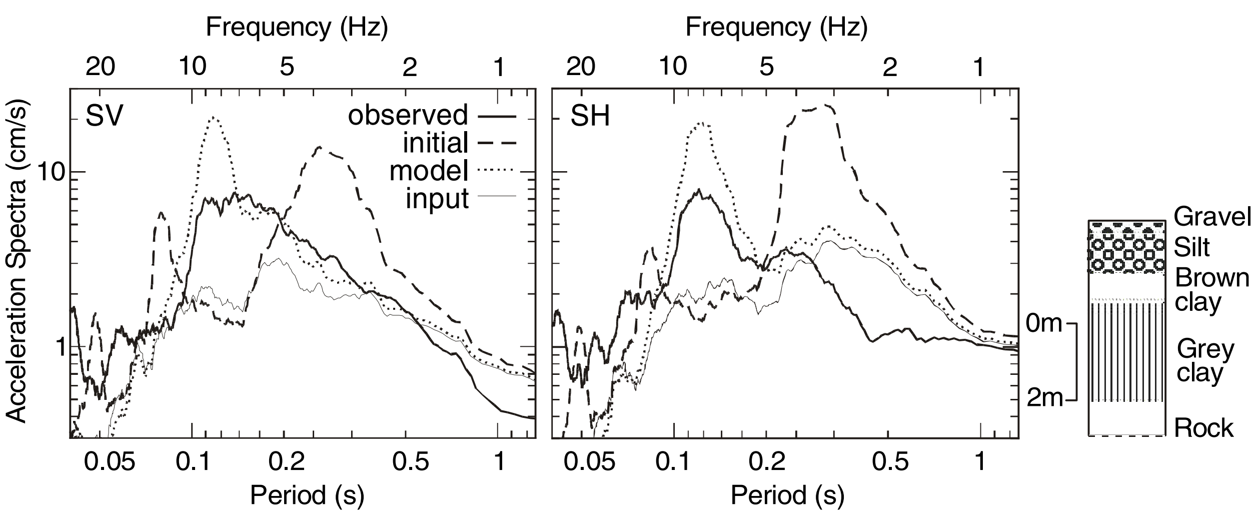

Figure 9. ESQ modelling results and final geologic profile. Spectra shown as described in Figure 5.

Summary of SHAKE modelling results

Numerical 1-D modelling of spectral amplitudes at the strong-motion sites indicated that the observed peak amplitudes from the Nisqually earthquake can be explained by site soil profiles consistent with geological observations. The observed Nisqually earthquake spectra at the thin soil sites, GOW (Figure 5) and PIK (not shown), demonstrated generally flat site response with peak amplitudes at relatively short periods of 0.07 s (15 Hz) and 0.17 s (6 Hz), respectively. The modelling of these sites showed that < 3 m of soft soil (NEHRP class E) produces higher spectral amplitudes at short periods. Geologic units with a thin layer of soil atop bedrock comprise 53% of greater Victoria [5].

The observed Nisqually earthquake spectra for the thicker soil sites were similar to each other with peak amplitudes at 0.2-0.5 s (2-5 Hz). Modelling for these sites showed that thick layers were needed to produce the observed peak amplitudes, but that the physical properties of the layer varied. If the layer was modelled as "grey Victoria clay" with shear-wave velocities around 132 m/s (NEHRP class E), the modelled peak amplitudes matched the observed amplitudes at ~ 10 m thick, shown at HSY (Figure 7). In Victoria, 12% of the city has thick deposits of "grey Victoria clay". If the layer was modelled as gravelly till with shear-wave velocities around 440 m/s (NEHRP class C), the peak amplitudes matched for > 30 m of Pleistocene till, shown by GTP (Figure 6). Thick Pleistocene till underlies 5.3% of the Victoria area. The modelling at KTG (Figure 8) required thick layers of both clay and till to match the observed spectra. The presence of Victoria clay above till is a common geologic occurrence in Victoria. Finally, if the Victoria clay is < 5 m thick the peak amplitude occurred at a shorter period of ~ 0.13 s (8 Hz), shown by ESQ (Figure 9). This geology is found in 8% of the city. Overall, the local geology of the eight strong-motion sites represents the dominant geologic units in the city of Victoria. Hence, the peak amplification recorded at these sites is sufficient to constrain the variation in ground motion that resulted from the Nisqually earthquake over the majority of the city.

CONCLUSIONS

A dataset of more than 750 felt reports of the Nisqually earthquake across greater Victoria, British Columbia, provided the first opportunity in Canada to conduct a detailed comparison between the variation in felt intensity (MMI I – VI) and local geology in an urban area. In a regional comparison (postal code locator with sub-city block resolution), average intensities were computed for each geology defined in a recently published amplification hazard map of Victoria. The results showed a positive correlation between intensity and amplification hazard rating. The lowest intensities were observed on bedrock and thin soil cover over bedrock, the highest intensities were observed on Holocene peat over soft clay. The maximum difference observed in intensity (ACDI) for the range of geologic units was 0.6 units. To examine this correlation in more detail, a small area with a uniform building style and a pronounced variation in geology was canvassed door-to-door. Felt intensity reports were located by house address with site-specific resolution. This detailed comparison showed a more pronounced correlation with local geology, and a full 1.0 unit difference in intensity (ACDI) between the geologic units. This study has demonstrated a good correlation between intensity and local geology across greater Victoria for the Nisqually earthquake. The correlation was most pronounced using the highest resolution (house address) for felt report location. These results are for a single earthquake at a relatively low-level of shaking (MMI I-VI). Nonetheless, combining this large intensity dataset with very detailed geologic mapping represents an important step in improving earthquake hazard estimates in urban areas of Canada using microzonation.

The Nisqually earthquake caused low levels of ground shaking (< 3.5 %g) and triggered eight of ten strong-motion instruments in greater Victoria. The standard spectral ratio technique showed that thin soil sites exhibit a flat site response at periods > 0.1 s (< 10 Hz) like bedrock, and have amplifications of two to twelve times that of bedrock at shorter periods (< 0.1 s, > 10 Hz). Thicker soil sites have peak amplification six times that of bedrock at 0.2-0.5 s (2-5 Hz). The H/V spectral ratio technique reveals similar site responses. The agreement between the two spectral ratio methods, in both fundamental peak period and amplitude, is notable.

An important lesson learned from modelling was that the amount of geologic knowledge at these sites was lacking as the initial geologic model spectrum generally did not closely match the observed spectrum. In all cases, changing the soil layer thickness created a best-fit with the observed spectrum because changes within the tightly constrained bounds of shear-wave velocity and unit weight information did not provide significant improvement to the initial model. Therefore, better constraints on the thickness of the shallow layers and knowledge of deeper structure would have been valuable. The fairly standard practice of 30 m boreholes with shear-wave velocity information at each instrument location would have been an asset and are greatly encouraged before instrument deployment.

The "weak" ground motion examined in this paper represents the largest ground motion data set in Victoria, British Columbia, to date. The combination of this data and the detailed amplification hazard map of greater Victoria provided the first opportunity to evaluate the variation in ground shaking across the city. The results of this study are from weak levels of ground motion only and do not apply to stronger levels of shaking due to soil non-linearity. The site response determined in this study can be applicable to other regions with large geological variations (soft soil atop of stiff glacial till and/or rock) and therefore is useful as a baseline for future detailed seismic hazard studies.

REFERENCES

1. Dewey JW, Hopper MG, Wald DJ, Quitoriano V, Adams ER. "Intensity distribution and isoseismal maps for the Nisqually, Washington, earthquake of 28 February 2001." Open File Report 02-346. United States Geological Survey, 2002.
2. Wood HO, Neumann F. "Modified Mercalli intensity scale of 1931." Bulletin of the Seismological Society of America 1931; 21: 277-283.
3. Cassidy JF, Molnar S, Rogers GC, Mulder T, Little TE. "Canadian strong ground motion recordings of the 28 February, 2001 M=6.8 Nisqually (Seattle-Olympia), Washington, earthquake." Open File Report 1737. Geological Survey of Canada, 2003.
4. Molnar S. "Investigating seismic hazard and site response in Victoria, BC: Analysis of felt reports and ground motion recordings from the 2001 Nisqually earthquake." M. Sc. Thesis. Victoria: University of Victoria, 2003.
5. Monahan PA, Levson VM. "Quaternary Geological Map of Greater Victoria." Geoscience Map 2000-2. Victoria: British Columbia Geological Survey, Ministry of Energy and Mines, 2000.
6. Nasmith HW, Buck GF. "The engineering geology of the Greater Victoria area." Karrow PR, White O, Editors. Urban Geology of Canadian Cities. St. John's Newfoundland: Geological Association of Canada, 1998: 21-38.
7. Monahan PA, Levson VM. "Earthquake hazard assessment in greater Victoria, British Columbia: Development of a shear-wave velocity model for the Quaternary deposits." Lefebure DV, McMillan WJ, McArthur JG, Editors. Geological Fieldwork 1996, Paper 1997-1. Victoria: British Columbia Geological Survey, Ministry of Employment and Investment: 467-479.
8. Monahan PA, Levson VM, Henderson P, Sy A. "Relative Amplification of Ground Motion Hazard Map of Greater Victoria." Geoscience Map 2000-3, Sheet 3B. Victoria: British Columbia Geological Survey, Ministry of Energy and Mines, 2000.
9. FEMA. "NEHRP recommended provisions for seismic regulations for new buildings." Washington, D. C.: Building seismic safety council; 1994.
10. Wuorinen V. "A preliminary seismic microzonation of Victoria, British Columbia." M.A. Thesis. Victoria: University of Victoria, 1974.
11. Levson VM, Monahan PA, Mate DJ. "Observed relationships between geology and liquefaction/amplification hazards." Proceedings of the 8th International Congress International Association for Engineering Geology and the Environment, Vancouver, Canada. II. Balkema, Rotterdam, Brookfield, 1998.

12. Dengler LA, Dewey, JW. “An intensity survey of households affected by the Northridge, California, earthquake of 17 January 1994.” Bulletin of the Seismological Society of America 1988; 88(2): 441-462.
13. Finn WDL. “Ground motion amplification factors for use in building codes.” Proceedings, International workshop on site response, Japan. Port and Harbour Research Institute, 1996: 105-117.
14. Kinemetrics. “KMI Strong motion analyst: User guide.” Pasadena: Kinemetrics; 2000.
15. Rogers GC. “Earthquakes and earthquake hazard in the Vancouver area.” Clague JJ, Luternauer JL, Mosher, DC, Editors. Geology and Natural Hazards of the Fraser River Delta, British Columbia. Geological Survey of Canada Bulletin 525, 1998: 17-25.
16. Hays WW. “Site amplification of earthquake ground motion.” Proceedings of the 3rd United States National Earthquake Engineering Conference, Charleston, USA. 1. Earthquake Engineering Research Institute, 1986.
17. Borcherdt RD. “Effects of local geology on ground motion near San Francisco Bay.” Bulletin of the Seismological Society of America 1970; 60(1): 29-61.
18. Borcherdt RD, Gibbs JF. “Effects of local geological conditions in the San Francisco Bay region on ground motions and the intensities of the 1906 earthquake.” Bulletin of the Seismological Society of America 1976; 66(2): 467-500.
19. Lermo J, Chavez-Garcia FJ. “Site effect evaluation using spectral ratios with only one station.” Bulletin of the Seismological Society of America 1993; 83(5): 1574-1594.
20. Lachet C, Bard P-Y. “Numerical and theoretical investigations on the possibilities and limitations of Nakamura’s technique.” Journal of the Physical Earth 1994; 42: 377-397.
21. Bonilla LF, Steidl JH, Lindley GT, Tumarkin AG, Archuleta RJ. “Site amplification in the San Fernando Valley, California: Variability of site-effect estimation using the S-wave, Coda, and H/V methods.” Bulletin of the Seismological Society of America 1997; 87(3): 710-730.
22. Triantafyllidis P, Hatzidimitriou PM, Theodulidis N, Suhadolc P, Papazachos C, Raptakis D, Lontzetidis K. “Site effects in the city of Thessaloniki (Greece) estimated from acceleration data and 1D local soil profiles.” Bulletin of the Seismological Society of America 1999; 89(2): 521-537.
23. Field EH, Jacob KH. “A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent.” Bulletin of the Seismological Society of America 1995; 85(4): 1127-1143.
24. Field EH. “Spectral amplification in a sediment-filled valley exhibiting clear basin-edge-induced waves.” Bulletin of the Seismological Society of America 1996; 86(4): 991-1005.
25. Lachet C, Hatzfeld D, Bard P-Y, Theodulidis CP, Savvaidis A. “Site effects and microzonation in the city of Thessaloniki (Greece): Comparison of different approaches.” Bulletin of the Seismological Society of America 1996; 86(6): 1692-1703.
26. Schnabel PB, Lysmer J, Seed HB. “SHAKE: A computer program for earthquake response analysis of horizontally layered sites.” Report No. UCB/EERC-72/12. University of California: Earthquake Engineering Research Center, 1972.
27. Idriss IM, Sun JI. “User’s Manual for SHAKE91: A computer program for conducting equivalent linear seismic response analyses of horizontally layered soil deposits.” University of California: Center for Geotechnical Modelling, Department of Civil and Environmental Engineering, 1992.
28. Lysmer J, Seed HB, Schnabel PB. “Influence of base-rock characteristics on ground response.” Bulletin of the Seismological Society of America 1971; 61(5): 1213-1232.
29. Molnar S, Cassidy JF, Dosso SE. “Site response in Victoria, British Columbia from spectral ratios and 1-D modelling.” Bulletin of the Seismological Society of America 2004; in press.