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VARIATION IN GROUND SHAKING ON THE FRASER RIVER DELTA (GREATER VANCOUVER, CANADA) FROM ANALYSIS OF MODERATE EARTHQUAKES

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SUMMARY

The thick, soft soils of the Fraser River delta, just south of Vancouver, Canada, are home to critical infrastructure such as one of North America's busiest port facilities, Canada's second busiest airport, and key transportation and power-transmission facilities for 2-3 million people. This area is one of the most seismically active regions in Canada.

We have utilised recordings of recent moderate (1996 M=5.1 at 180 km distance, 1997 M=4.3 at 40 km distance) and large (2001 M=6.8 at 230 km distance) earthquakes to examine site response in the greater Vancouver, region, with an emphasis on the Fraser River delta. These suites of accelerograms have relatively low amplitudes (0.015g for the 1996 records, 0.024g for the 1997 records, and 0.035g for the 2001 records). The 1997 data set is significant as it contains the first three-component recordings made on bedrock in greater Vancouver, and the 2001 data set is significant as it contains longer-period energy. We compute spectral ratios to estimate the site response for each of the soil sites.

We find frequency-dependent amplification of up to 12 times (relative to competent bedrock) near the edge of the delta. Here, the amplification occurs over a relatively narrow frequency range of 1.5-4 Hz (0.25-0.67 s period). Near the centre of the delta (where the soft soils are thickest) peak amplification of 4-10 times (relative to bedrock) is measured. Relative to firm soil, the amplification ranges from 2-5 for the thick soil delta centre sites, and 2-6 for the delta edge sites. At higher frequencies, little or no amplification or even slight attenuation is observed.

The Geological Survey of Canada is currently deploying a dense urban seismograph network (~1km spacing) which crosses the northern edge of the Fraser delta to address varying site response in more detail.

INTRODUCTION

Greater Vancouver lies within one of the most seismically active areas of Canada [1]. As recent earthquakes have demonstrated, seismic waves can be amplified by the local geological structure, particularly thick sedimentary basins (e.g., see [2] and [3]). The thick, soft sediments of the Fraser River delta have the potential to modify the amplitude and frequency of seismic waves. Given the substantial population, vital economic facilities, and critical links to Vancouver Island located on the delta, it is important to understand the potential for seismic amplification in this region.

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Recent moderate to large earthquakes (Figure 1): the May 1996 M=5.1 Duvall, Washington earthquake, ~180 km to the southeast of Vancouver; the June 1997 M=4.3 Strait of Georgia earthquake, ~40 km to the west of the city, and the 2001 M=6.8 Nisqually earthquake, ~230 km south of the city, triggered the strong motion seismograph network in the greater Vancouver area, providing the first three-component digital recordings of ground shaking in this region. This allows us to evaluate, for the first time, seismic site response in the greater Vancouver area.

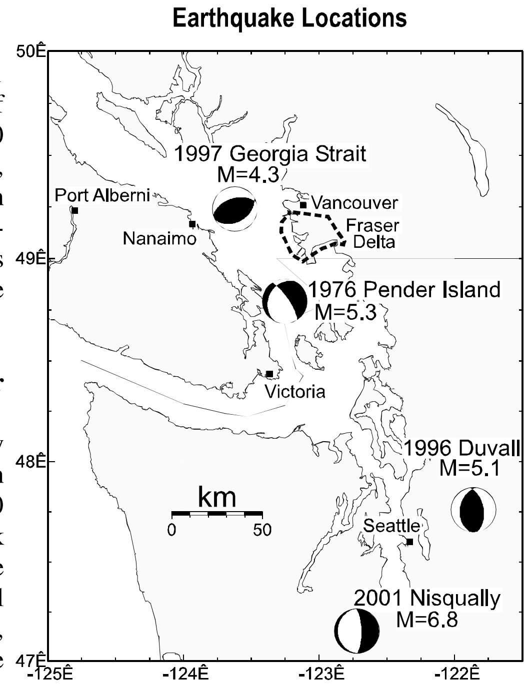

Figure 1. Location and focal mechanisms of earthquakes discussed in this article.

Geological overview of greater Vancouver and the Fraser River delta

Most of greater Vancouver is underlain by Mesozoic and Tertiary volcanic and sedimentary rocks. There are some bedrock outcrops in the city of Vancouver. The shear wave velocity in the bedrock is 1500 m/s or greater [J. Hunter, personal communication]. This bedrock surface is overlain by Pleistocene glacial and interglacial deposits made up of ice-compacted tills and glacial, marine, and glaciofluvial deposits. These deposits mantle most of the greater Vancouver area, and are exposed at the surface in many areas. The Pleistocene sediments have an average shear-wave velocity near 500 m/s but with considerable variability [4].

Tertiary bedrock is between 200 and 1000 m below most of the Fraser delta (Figure 2), with an average depth of about 500 m [5]. The bedrock is overlain by Pleistocene sediments as thick as 500 m near the centre of the delta. The Pleistocene surface is irregular in shape, with some localized topographic highs [6]. This surface is overlain by fine-grained Holocene age sediments that comprise the modern delta. The shear-wave velocities in the Holocene sediments increase with depth [7], with average values of about 200 m/s, but about 100 m/s near the surface in many places. The Holocene sediments pinch-out rapidly to the north (Figure 2b), from a thickness of about 300 m in the basin center to only a few metres on the north shore of the Fraser River. For more details on geological and geophysical studies in this area, the reader is referred to a collection of papers published in a Geological Survey of Canada Bulletin [8].

THE DATA SETS

Since being deployed in the early 1970's, instruments in the strong motion seismograph network in the greater Vancouver area have been triggered by three nearby significant earthquakes: the 1976 Pender Island M=5.3 earthquake; the 1996 Duvall M=5.1 earthquake; the 1997 Georgia Strait M=4.3 earthquake; and the 2001 Nisqually M=6.8 earthquake (Figure 1). Note that these data sets all represent "weak" ground motion, with peak ground accelerations of 2.5-5.3% gravity (g), 0.5-1.5% g, 0.2-2.4% g, and 0.3-3.5%g, respectively. Details of these data sets are given in [9], [10], [11], and [12], respectively. Analysis of these data sets, summarized in this article, are presented in [13], [14], and [15]. For a description of the strong motion network currently deployed in this area see [16].

The 1997 Georgia Strait and the 2001 Nisqually earthquakes provide the largest data sets to date in the Vancouver area, and the first that includes three-component bedrock recordings. The Georgia Strait earthquake (Figure 1) triggered strong motion instruments at a total of 13 sites in the greater Vancouver area (Figure 2a), including sites on bedrock, thick Holocene soil ("thick" meaning at least 100 m of Holocene sediments), and firm Pleistocene soil (glacial till). The Fraser delta sites (Figure 2) include two delta edge sites - MNY (located on a few metres of Holocene sediments underlain by about 100-200 m of Pleistocene sediments) and KID (45 m of Holocene sediments underlain by at least 150 m of Pleistocene sediments); and thick soil sites RHA and ARN (situated on at least 300 m of soft Holocene soils underlain by about 500 m of Pleistocene sediments), DEA (about 150 m of soft Holocene soils underlain by about 450 m of Pleistocene sediments), and ANN (situated on 100 m of soft Holocene soils underlain by about 150 m of Pleistocene sediments). Firm soil sites located just to the north of the Fraser River delta that triggered were BND and MDN. Both of these sites are situated on several metres of dense till overlying bedrock. Rock-sites that triggered were PGC on southern Vancouver Island (quartz diorite), BLO (situated on an outcrop of Tertiary basaltic bedrock just 3 km north of MNY), CSQ located 30 m underground in downtown Vancouver (situated on sandstone), and CLE (granitic rock), at the Cleveland dam in North Vancouver (Figure 2). One site (MUR) is located on very soft soil at the end of False Creek in downtown Vancouver.

Seven of the sites that triggered during the Georgia Strait earthquake also recorded the 1996 Duvall Washington earthquake, and hence the response to the two earthquakes can be compared. The common sites are RHA and ARN (delta centre "thick soil"), MNY and KID (delta edge), BND and MDN (firm soil), and PGC (bedrock). The sites common to both the Georgia Strait earthquake and the 1976 Pender Island earthquake are RHA and ANN ("thick soil" sites), and MNY (delta edge).

GROUND MOTION SPECTRA

Details of the data processing and computation of the ground motion spectra are given in [13], [15], and [12]. The horizontal components of ground motion were rotated, based on the earthquake-station azimuth to form the radial (SV) and transverse (SH) components and the spectra were smoothed using an 11-point running mean filter (0.5 Hz half-width). Spectra are truncated at 0.5 Hz at the low-frequency end (2 seconds period), as there is little energy from this earthquake at these frequencies. At the high-frequency end, we truncate the spectra at 20 Hz (0.05 s period) as they are dominated by locally generated cultural noise at higher frequencies. All records have been corrected for distance effects (1/R geometrical spreading). In Figure 3 we present the SH-spectra for sites in the greater Vancouver area (and PGC) that recorded the 1996, 1997, and 2001 earthquakes. Shown in Figure 3 (top) are the SH-spectra for the Georgia Strait earthquake for PGC (bedrock), BND (firm soil), KID and MNY (delta edge sites) and ARN and RHA (thick soil sites). These spectra are similar to those observed at the same stations for the 1996 Duvall earthquake (Fig. 3 middle) in that the bedrock spectra shows the lowest amplitude; the firm soil spectrum shows an amplitude about double that of bedrock (at frequencies less than about 4 Hz); and the soil sites show a peak amplification of up to about 10 relative to bedrock at 2-4 Hz (0.25-0.5 s period). The 2001 Nisqually data show the same pattern (Figure 3 bottom), with the bedrock trace (BLO) having the lowest amplitude, firm soil (BND) with an amplitude about double that of bedrock, EBT (a till site on the Fraser Delta) showing similar amplitudes to that of BND, and the soft soil Fraser Delta sites RHA and MNY with significant amplification at frequencies of 1.5-4 Hz. At frequencies above about 8-10 Hz, there is little or no difference between the soil and rock amplitudes - with the exception of the site KID where the spectra for both earthquakes show several pronounced peaks between 4-10 Hz that are attributed [13] to a localized low-velocity layer of silt and sand beneath this site [17]. However there are also some differences in the spectra; notably in the amplitudes of the thick soil sites ARN and RHA. For the Duvall earthquake, the peak SH-amplitude at those sites was about one-half that of the delta edge sites MNY and KID (Figure 3); for the Georgia Strait earthquake, the peak spectral amplitudes at the thick soil sites are comparable to those of the delta edge sites (Figure 3).

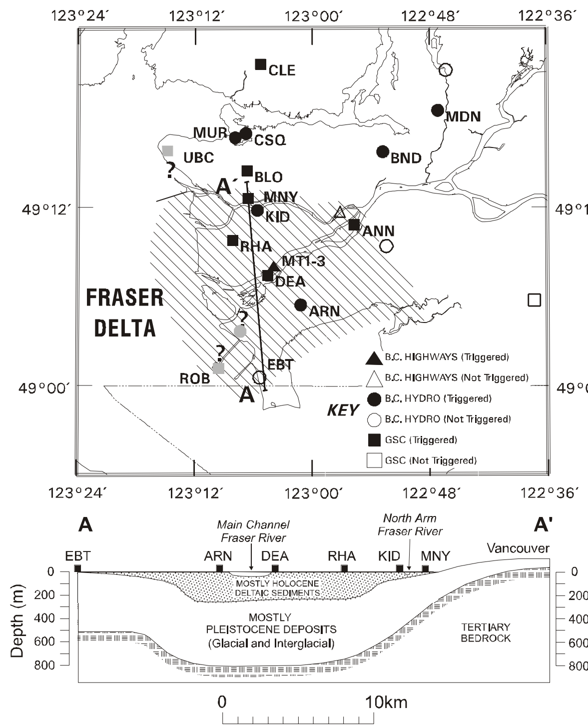

Figure 2. top) Location of the strong motion instruments in the greater Vancouver area. The hatched area represents the extent of the soft, mainly alluvium Holocene sediments shown in cross-section (along line A-A') in Figure 2 (bottom). Solid symbols indicate sites that triggered, open symbols sites that did not trigger. Question marks indicate instruments that were not operational at the time of the earthquake. **bottom)** Simplified (see text) cross-section of the Fraser River delta showing Tertiary bedrock, Holocene and Pleistocene sediments. Locations of the closest strong motion instruments are shown.

These differences may be attributed to wave-type and propagation path (e.g., the interaction of energy from a certain direction with the local geology or topography), as the direction of approach for these two earthquakes is significantly different: the Duvall earthquake was located 180 km to the SE of Vancouver, and the Georgia Strait earthquake was located 40 km to the west of the city. [15] compared the SV and SH spectra for all sites for both earthquakes and found the largest differences between SV- and SH- amplitudes were for the recordings of the Georgia Strait earthquake on the thick soil sites (e.g. at ARN the SH- amplitude was approximately double that of SV). This suggests that the differences in the spectra between the two earthquakes at the thick soil sites on the centre of the delta are likely caused by the direction of approach of the waves or by path effects due to the different epicentral distances. [18] noted the distance range of 30-40 km from the Northridge earthquake produced higher amplitudes, and higher variability in the Los Angeles basin which they attributed to propagation path effects.

SITE RESPONSE

We estimate the site response using the method of spectral ratios [19] and [18] - in which the spectrum of the site being considered is divided by that from a nearby reference site (generally competent bedrock). This suppresses earthquake source and path effects and isolates the site response. Details of the processing technique can be found in [15]. After examining all of the bedrock spectra for the Georgia Strait earthquake, they concluded that the PGC recording is a valid bedrock reference spectrum (PGC is the only bedrock site common to both the Georgia Strait and the Duvall earthquakes). In addition, spectral ratios were computed for all Fraser delta sites using the firm soil reference spectrum for the site BND, about 10 km to the north of the delta. The latter is more appropriate for building code considerations, as firm soil is used as the "reference" in the National Building Code of Canada (NBCC).

1997 Georgia Strait Earthquake

In Figure 4a we present the SH spectral ratios for selected greater Vancouver strong motion instrument sites relative to bedrock (PGC). The sites are DEA (thick soil), MNY (delta edge), BND (firm soil), MUR at the edge of reclaimed tidal flats at the end of False Creek, and the "soft-rock" downtown Vancouver site CSQ. Relative to bedrock, the ground motions at the thick soil sites are amplified by factors of 7-10 over the frequency range 1.5-4.0 Hz (0.25-0.67 s period). However, at frequencies greater than 8-10 Hz (periods less than 0.1-0.125 s) there is no amplification, and, in some cases, modest attenuation. The delta edge sites show a similar pattern, but with amplification of 8-11 times that of bedrock. The firm soil sites show amplification of 2-4 over the frequency range 2-10 Hz (periods of 0.1-0.5 s). The recordings

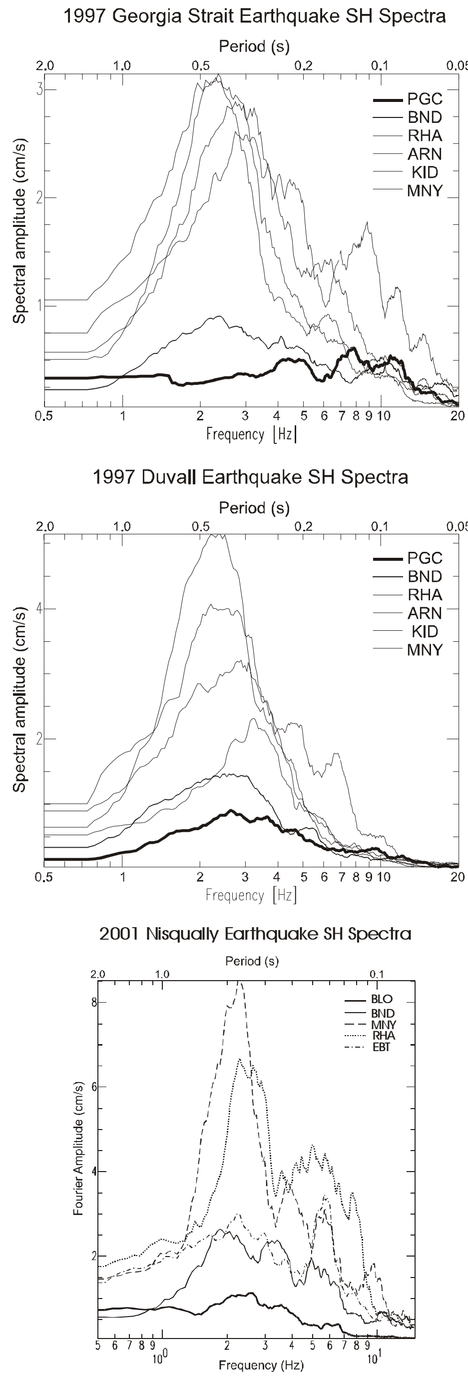

Figure 3. Smoothed (see text) SH spectra of select recordings of the 1997 Georgia Strait earthquake (top), the 1996 Duvall earthquake (middle), and the 2001 Nisqually (bottom). The thick solid line is a bedrock recording (PGC for the top and middle, BLO for the bottom plot); the thin solid line is the BND firm soil recording; other lines represent Fraser delta soil sites.

from MUR show the most pronounced amplification of all the sites - but in a very narrow frequency band of 5-7 Hz (0.14-0.2 s period). This is likely resonance associated with the reclaimed tidal flat sediments (several metres of soft sandy deposits over dense till) at this site.

Spectral ratios relative to the firm soil site BND (Figure 4b) show similar patterns to the bedrock ratios, but with reduced amplification factors as would be expected. In Figure 4b we see that in most instances the peak amplification exceeds the factor of 2 allowed for in the NBCC for soil sites (>15 m of soil). The "thick soil" delta centre sites show a peak amplification of 2-5 times relative to firm soil. At DEA the peak is near 1 Hz (1 s period), at the "delta edge" site MNY, amplification of 2-6 relative to firm soil is observed with a peak near 2 Hz (0.5 s period). The site MUR exhibits the most pronounced amplification - with a factor of nearly 10 relative to the firm soil site at frequencies centered near 5 Hz (0.2 s period) and 8 Hz (0.125 s period).

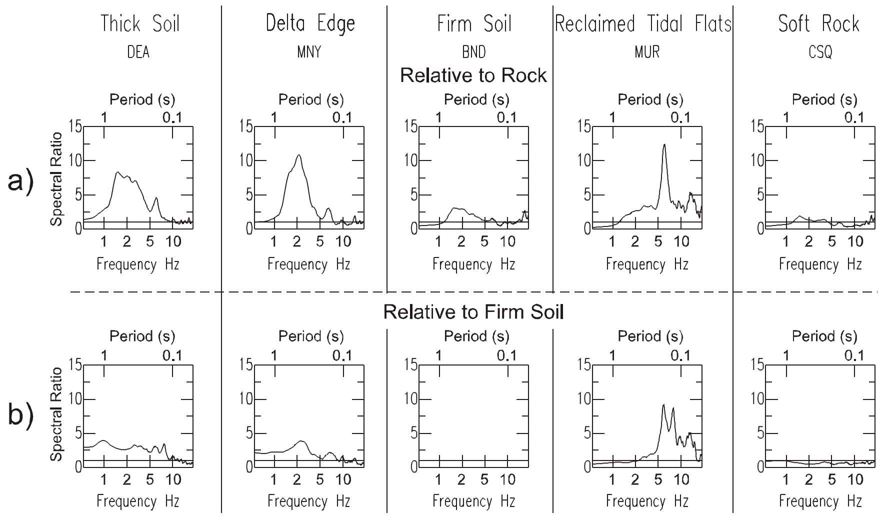

Figure 4. a) SH-wave spectral ratio for the 1997 Georgia Strait earthquake (relative to the PGC bedrock recording) for selected greater Vancouver sites. The horizontal line in each plot represents a ratio of one. **b)** As in Figure 4a, but spectral ratios are relative to the firm soil site BND. With the exception of the site MUR, amplification factors relative to firm soil are less than about six.

1996 Duvall , 1976 Pender Island, and 2001 Nisqually Earthquakes

The spectral ratios for the Duvall earthquake (see [15]) are similar to those for the Georgia Strait earthquake in that they all show a frequency-dependent response, with amplification in a narrow frequency band of about 1.5-4 Hz (0.25-0.67 s period), and slight attenuation at frequencies higher than about 8 Hz (periods less than 0.125 s). The primary difference between the spectral ratios for the Duvall and Georgia Strait earthquakes is the higher amplification level at the thick soil sites near the centre of the delta (peak amplifications of 4-6 for the Duvall earthquake compared to 7-10 for the Georgia Strait earthquake) that is attributed to path effects [15].

The 1976 Pender Island strong motion data are low-level, analogue recordings. There are no bedrock or nearby firm soil records in this data set, therefore spectral ratios cannot be computed to compare with those of the two recent earthquakes, nevertheless, a similar pattern of amplification at the lower frequencies, attenuation at the higher frequencies and evidence for resonance near the delta edge is observed. For a description and analysis of these data see [14].

Spectral ratios for the 2001 Nisqually earthquake [12] are similar to those shown here for the Georgia Strait earthquake.

SEISMIC HAZARD IMPLICATIONS AND CONCLUSIONS

The spectral ratios obtained from significant, nearby earthquakes provide new insight into the seismic hazard for this area. Relative to firm soil, the spectral amplifications range from 2 to 6 at the Fraser delta sites. We note that the current National Building Code of Canada only provides for an amplification factor of two in base shear at thick soil (>15 m) sites relative to firm soil (NBCC - 1995 Table 4.1.9.1.C). One must be cautious, however, in using amplification factors defined by weak motion for seismic hazard purposes, as non-linear effects tend to reduce amplitudes and shift frequencies once shaking exceeds about 25%g. Non-linear effects are still an area of active research (e.g., [20] and [21]).

All of the data sets clearly reveal the frequency-dependence of the response at the Fraser River delta sites. There is amplification at lower frequencies, typically peaking near 1.5-4 Hz (periods near 0.25-0.67 s). Slight attenuation is observed at frequencies higher than about 8 Hz (periods less than about 0.125 s). This frequency dependence is important because structures are damaged by earthquake energy near the natural resonant frequency of the building. The observed amplification at lower frequencies (longer periods) will affect mainly taller structures (up to about 20 stories at the low end of the spectra we present). Although the long period (>2 s) energy in these data sets are poorly defined, we would expect amplifications at longer periods on the thick soils near the centre of the delta (e.g., [22]). This could pose a hazard to larger structures (extremely tall buildings or large bridges). The attenuation that we observe at frequencies higher than about 8-10 Hz (periods less than 0.1-0.125 s) suggests that many small structures (1-2 storey) on the delta may be at no greater risk to damage from seismic shaking than similar structures built on rock.

Each of the earthquakes indicate that the greatest spectral amplification on the delta (factors of 8-11 relative to rock, or 2-6 relative to firm soil) is observed near the edge of the delta. Here, the most recent Holocene deposits are layed down on Pleistocene materials providing a large velocity contrast and both the Holocene and Pleistocene deposits thin to the point where soil resonances of seismic waves are in the range of the fundamental periods of common structures.

The most pronounced amplification observed is not on the Fraser River delta, but at the site MUR located on very soft soils at the end of False Creek in downtown Vancouver. Here, amplification (relative to firm soil) of about 10 times is observed over a very narrow frequency range of 6-8 Hz (0.125-0.17 s period).

Although there are many factors that we cannot address with these data sets (long-period response, basin edge effects, non-linear effects, near-field source and path effects, and topographic effects), we note that where thorough spectral site response studies have been done using moderate sized earthquakes as sources, there is a correlation between high site response spectral values and localized areas of damage (e.g. [23]). We note that with the deployment of a test dense urban network in the greater Vancouver area [24], more detailed studies of these possible effects will soon be possible.

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