

Evaluating Site Response in the Greater Vancouver Area Using Moderate Earthquakes

Cassidy, John F., Rogers, Garry C.

ABSTRACT

Three-component, digital recordings of two recent moderate earthquakes (the 1996 M=5.1 Duvall, Washington and the 1997 M=4.3 Georgia Strait) provide valuable new insight into the response to seismic shaking in the greater Vancouver area, particularly on the Fraser River delta. The 1997 data set is especially important as it contains the first three-component recordings made on bedrock in greater Vancouver. Using the method of spectral ratios, we estimate the site response for each of the strong motion instrument soil sites. On the Fraser River delta, amplification is observed over a relatively narrow frequency range of 1.5-4 Hz (0.25-0.67 s period), with peak amplification of 4-10 (relative to crystalline bedrock) for the thick soil delta centre sites, and about 7-11 for the delta edge sites. Relative to firm soil, the peak 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, and in many cases slight attenuation is observed.

INTRODUCTION

Greater Vancouver lies within one of the most seismically active areas of Canada (Rogers 1998). As recent earthquakes have demonstrated, seismic waves can be amplified by the local geological structure, particularly thick sedimentary basins (e.g., see Celebi et al. 1987; Pitarka and Irikura 1996). 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 and located on the delta, it is important to understand the potential for seismic amplification in this region.

Two recent moderate earthquakes (Figure 1): the May 1996 M=5.1 Duvall, Washington earthquake, ~180 km to the southeast of Vancouver; and the June 1997 M=4.3 Strait of Georgia earthquake, ~40 km to the west 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.

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 till 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 shear-wave velocity near 500 m/s but with considerable variability (Luternauer and Hunter 1996).

Tertiary bedrock is between 200 and 1000 m below most of the Fraser delta (Figure 2), with an average depth of about 500 m (Britton et al. 1995). 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 (Hunter et al. 1997). 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 (Hunter 1995), with average

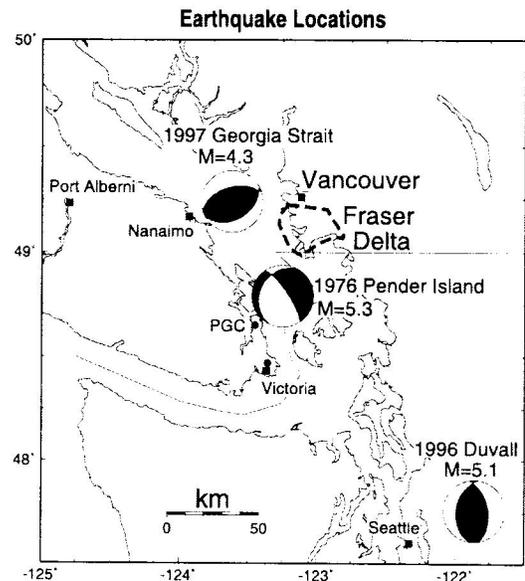


Figure 1. Location map showing the epicenters and focal mechanisms of the 1997 $M_w=4.3$ Georgia Strait earthquake, the 1996 $M_w=5.1$ Duvall earthquake, and the 1976 $M_w=5.3$ Pender Island earthquake. Also shown is the outline of the Fraser River delta (heavy dotted line), and the Vancouver Island bedrock site PGC.

values of about 200 m/s, but about 100 m/s near the surface in many places to the north (Figure 2b), from a thickness of about 300 m in the basin center to 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 (Clague et al. 1998).

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 moderate earthquakes: the 1976 Pender Island M=5.3 earthquake; the 1996 Duvall M=5.1 earthquake; and the 1997 Georgia Strait M=4.3 earthquake (Figure 1). Note that these data sets represent "weak" ground motion, with peak ground accelerations of 2.5-5.3% gravity (0.25-0.53 g), 0.5-1.5% g, and 0.2-2.4% g, respectively. Details of these data sets are given in Weichert and Milne (1980), Weichert et al. (1996), and Cassidy et al. (1998), respectively. Analysis of these data sets, summarized in this article, are presented in Cassidy et al. (1997), Rogers et al. (1998), and Cassidy and Rogers (1999). For a description of the strong motion network currently deployed in this area see Rogers et al. (1999).

The 1997 Georgia Strait earthquake provides the largest data set to date in the Vancouver area, and the first that includes three-component bedrock recordings. This 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

The Holocene sediments pinch-out rapidly to only a few metres on the north shore of this area, the reader is referred to a collection of papers published in a Geological Survey of Canada Bulletin (Clague et al. 1998).

seismograph network in the greater Vancouver area have been triggered by three nearby moderate earthquakes: the 1976 Pender Island M=5.3 earthquake; the 1996 Duvall M=5.1 earthquake; and the 1997 Georgia Strait M=4.3 earthquake (Figure 1). Note that these data sets represent "weak" ground motion, with peak ground accelerations of 2.5-5.3% gravity (0.25-0.53 g), 0.5-1.5% g, and 0.2-2.4% g, respectively. Details of these data sets are given in Weichert and Milne (1980), Weichert et al. (1996), and Cassidy et al. (1998), respectively. Analysis of these data sets, summarized in this article, are presented in Cassidy et al. (1997), Rogers et al. (1998), and Cassidy and Rogers (1999). For a description of the strong motion network currently deployed in this area see Rogers et al. (1999).

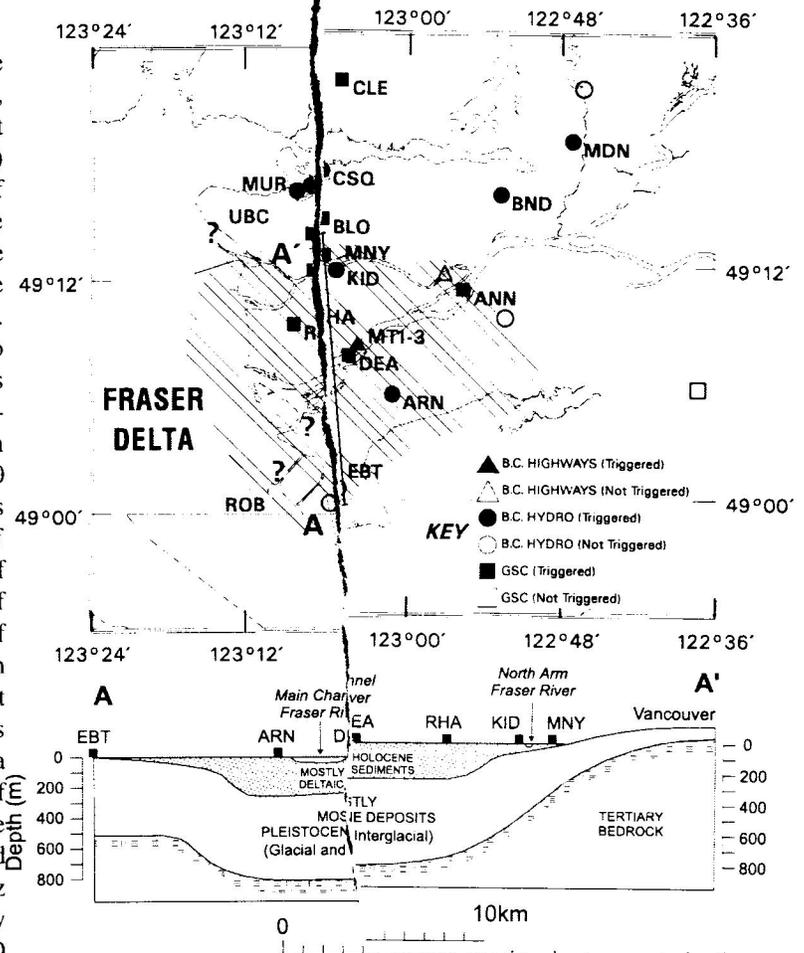


Figure 2. top) Location of the strong motion instruments in the greater Vancouver area. The shaded area represents the extent of the soft, mainly alluvium Holocene sediments shown in the cross-section (along line A-A') in Figure 2 (bottom). Solid symbols indicate sites that triggered, open symbols sites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

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 Cassidy et al. (1997) and Cassidy and Rogers (1999). 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 both the 1996 and 1997 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 bottom) 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). 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 (Cassidy et al. 1997) to a localized low-velocity layer of silt and sand beneath this site (Monahan et al. 1995). 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).

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. Cassidy and Rogers (1999) 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. Hartzell et al. (1996) 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 (Borcherdt 1970; Hartzell et al. 1996) - in which the spectrum of the site being considered is divided by that from a nearby reference site (generally competent bedrock). This

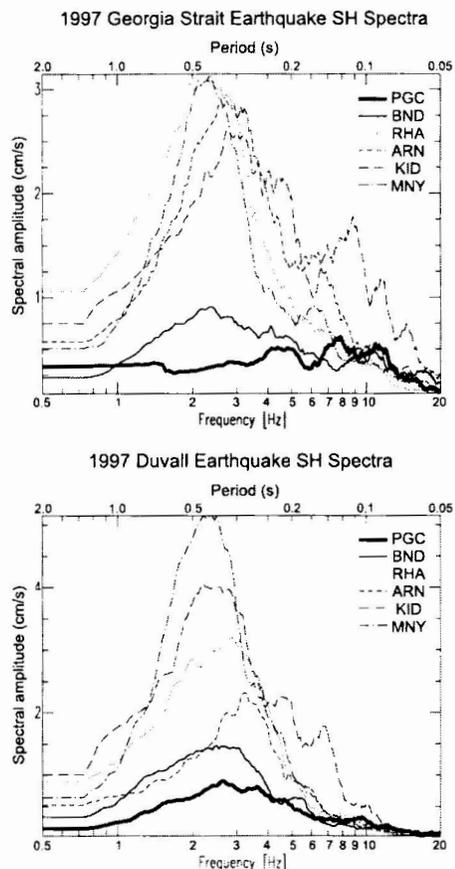


Figure 3. Smoothed (see text) SH spectra of select recordings of the 1997 Georgia Strait earthquake (top) and the 1996 Duvall earthquake (bottom). The thick solid line is the PGC bedrock recording; the thin solid line is the BND firm soil recording; other lines represent Fraser delta soil sites.

suppresses earthquake source and path effects and isolates the site response. Details of the processing technique can be found in Cassidy and Rogers (1999). 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 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).

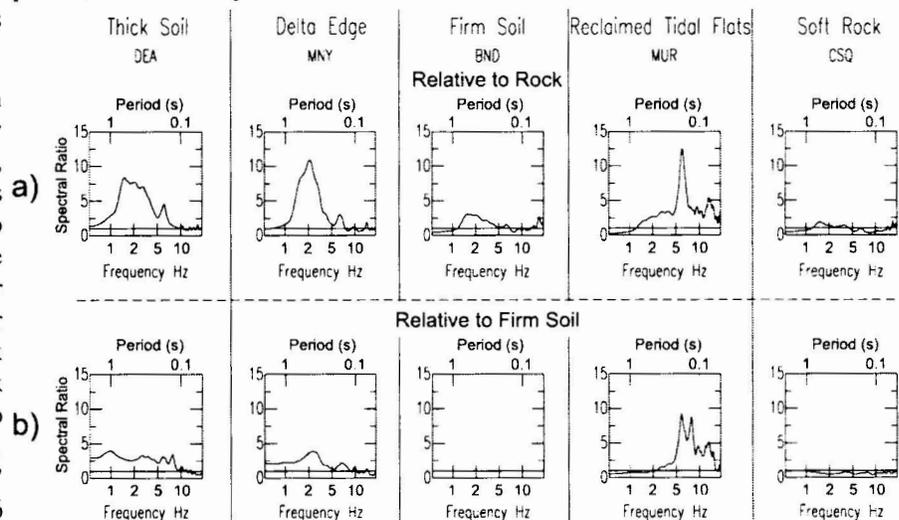


Figure 4. a) SH-wave spectral ratio for the 1997 Georgia Strait earthquake (relative to the PGC bedrock recording) for selected greater Vancouver sites. The horizontal line in each plot represents a ratio of one. b) As in Figure 4a, but spectral ratios are relative to the firm soil site BND. With the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

1996 Duvall and 1976 Pender Island Earthquakes

The spectral ratios for the Duvall earthquake (see Cassidy and Rogers, 1999) 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 (Cassidy and Rogers, 1999).

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 Rogers et al. (1998).

SEISMIC HAZARD IMPLICATIONS AND CONCLUSIONS

The spectral ratios obtained from moderate, 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., Su et al. 1998; Hartzell 1998).

Both the Georgia Strait earthquake data set and the Duvall earthquake data set 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 (> 2 s) on the thick soils near the centre of the delta (e.g., Harris et al. 1998). 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.

Both 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 laid 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. Hartzell et al. 1996).

Acknowledgements

We gratefully acknowledge Ken Beverley, Richard Baldwin, John Carter, and Taimi Mulder for their assistance in the collection and processing of the strong motion data, and Richard Franklin and Robert Kung for helping to prepare figures. Many thanks to Dieter Weichert for reviewing this manuscript. We thank B.C. Hydro for allowing us to include their data in this analysis. Figure 1 was generated using Generic Mapping Tools (Wessell and Smith, 1995). Geological Survey of Canada Contribution No. 1998237.

References

- Borcherdt, R.D. 1970. Effects of local geology on ground motion near San Francisco Bay, *Bulletin of the Seismological Society of America*, **60**: 29-61.
- Britton, J.R., Harris, J.B., Hunter, J.A., and Luternauer, J.L. 1995. The bedrock surface beneath the Fraser River delta in British Columbia based on seismic measurements. *in*, Current Research 1995-E; Geological Survey of Canada, p. 83-89.
- Cassidy, J.F., Rogers, G.C., and Weichert, D.H. 1997. Soil response on the Fraser Delta to the $M_w=5.1$ Duvall, Washington, earthquake. *Bulletin of the Seismological Society of America*, **87**: 1354-1361.
- Cassidy, J.F., Rogers, G.C., Weichert, D.H., and Little, T.E. 1998. Digital strong ground motion recordings of the June

- 1997, Strait of Georgia earthquake, Geological Survey of Canada Open File Report 3599, 39 pp.
- Cassidy, J.F., and Rogers, G.C. 1999. Seismic site response in the greater Vancouver, British Columbia area: Spectral ratios from moderate earthquakes, *Canadian Geotechnical Journal*, **35**, (in press).
- Celebi, M., Dietel, C., Prince, J., Onate, M., and Chavez, G. 1987. Site amplification in Mexico City (determined from 19 September 1985 strong-motion records and from recordings of weak motions), in *Ground Motion and Engineering Seismology*, A.S. Cakmak (Editor), Elsevier, Amsterdam, 141-152.
- Clague, J.J., Luternauer, J.C., and Mosher, D.C. (ed.) 1998. Recent Geological, Geophysical, Geotechnical, and Geochemical Research, Fraser River Delta, British Columbia, Geological Survey of Canada, Bulletin 525, 270 pp.
- Harris, J.B., Hunter, J.A., Luternauer, J.L., and Finn, W.D.L. 1998. Site amplification modelling of the Fraser delta, British Columbia, in *Recent Geological, Geophysical, Geotechnical, and Geochemical Research, Fraser River Delta, British Columbia*, (ed.) J.J. Clague, J.C. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, 211-216.
- Hartzell, S., 1998. Variability in nonlinear sediment response during the 1994 Northridge, California, earthquake. *Bulletin of the Seismological Society of America*, **88**: 1426-1437.
- Hartzell, S., Leeds, A., Frankel, A., and Michael, J. 1996. Site response for urban Los Angeles using aftershocks of the Northridge earthquake. *Bulletin of the Seismological Society of America*, **86**: S168-S192.
- Hunter, J.A. 1995. Shear wave velocities of Holocene sediments, Fraser River delta, British Columbia, in *Current Research 1995-A*, Geological Survey of Canada, 29-32.
- Hunter, J.A., Dallimore, S.R., and Christian, 1997. Borehole measurements of shear wave velocity discontinuities in Quaternary sediments, Fraser River delta, British Columbia, in *Current Research 1997-A*; Geological Survey of Canada, 159-165.
- Luternauer, J.L., and Hunter, J.A. 1996. Mapping Pleistocene deposits beneath the Fraser River delta: Preliminary geological and geophysical results, in *Current Research 1996-E*, Geological Survey of Canada, 41-48.
- Monahan, P.A., Luternauer, J.L., and Barrie, J.V. 1995. The geology of the CANLEX Phase II sites in Delta and Richmond British Columbia. In *Proceedings, 48th Canadian Geotechnical Conference, September 25-27 1995, Vancouver, B.C., Preprint Volume 1*. Canadian Geotechnical Society, pp. 59-68.
- Pitarka, A., and Irikura, K. 1996. Basin structure effects on long-period strong motions in the San Fernando Valley and the Los Angeles Basin from the 1994 Northridge earthquake and an aftershock, *Bulletin of the Seismological Society of America*, **86**: S126-S137.
- Rogers, G.C., Cassidy, J.F., Little, T., and Munro, P. 1999. Strong motion seismograph networks in Canada (this volume).
- Rogers, G.C., 1998. Earthquakes and earthquake hazard in the Vancouver area, in *Recent Geological, Geophysical, Geotechnical, and Geochemical Research, Fraser River Delta, British Columbia*, (ed.) J.J. Clague, J.C. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, 270 pp.
- Rogers, G.C., Cassidy, J.F., and Weichert, D.H., 1998. Variation in earthquake ground motion on the Fraser Delta from strong motion seismograph records, in *Recent Geological, Geophysical, Geotechnical, and Geochemical Research, Fraser River Delta, British Columbia*, (ed.) J.J. Clague, J.C. Luternauer, and D.C. Mosher; Geological Survey of Canada, Bulletin 525, 270 pp.
- Su, F., Anderson, J.G., and Zeng, Y. 1998. Study of weak and strong ground motion including nonlinearity from the Northridge, California, earthquake sequence. *Bulletin of the Seismological Society of America*, **88**: 1411-1425.
- Wessel, P., and Smith, W.H.F., 1995. New version of the Generic Mapping Tools released. *EOS Transactions of the American Geophysical Union*, **76**, 329 (abstract).
- Weichert, D.H., and Milne, W.G. 1980. Canadian strong motion records, Canada Department of Energy, Mines and Natural Resources, Earth Physics Branch Open File Report 80-1, 89 pp.
- Weichert, D.H., Cassidy, J.F., Rogers, G.C., Little, T., and Chandra, B. 1996. Canadian strong ground motions from the May 1996, Duvall, Washington earthquake, Geological Survey of Canada Open File Report 3390, 75 pp.