COMPREHENSIVE EARTHQUAKE SITE AMPLIFICATION ASSESSMENT FOR GREATER VANCOUVER

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ABSTRACT
Soft thick sediments of the Fraser Delta in Vancouver are well known to amplify seismic waves at frequencies related to their characteristics. In this study, all available strong-motion recordings from 7 moderate earthquakes of magnitude (M) > 4.3 between 1976 and 2015 are utilized to provide a comprehensive assessment of observed site amplification in Greater Vancouver. Microtremor measurements conducted near these strong motion stations are used to calculate horizontal-to-vertical (H/V) spectral ratios. H/V ratios from earthquake recordings and microtremor measurements in the Fraser delta consistently demonstrate an amplification of about 6-8 at lower frequencies (0.3 Hz). Upper-to-lower and horizontal-to-vertical spectral ratios from borehole recordings from the 2015 earthquake are compared to theoretical amplification of the 1D soil model. The fundemental frequencies are well captured by the 1D model, however peak amplitudes are slightly overpredicted.

RÉSUMÉ
Les sédiments mous et épais du delta du Fraser au Vancouver, sont connus par leurs amplification des ondes sismiques à des fréquences liées à leurs caractéristiques. Dans cette étude, tous les enregistrements de mouvements forts disponibles provenant de 7 séismes de magnitude modérée (M) > 4,3 entre 1976 et 2015 sont utilisés pour fournir une évaluation complète de l'amplification du site observé dans Vancouver. Les mesures de 'microtremor' effectuées près de ces stations de mouvement fort sont utilisées pour calculer les rapports spectraux horizontal-vertical (H/V). Les rapports H/V des enregistrements de tremblements de terre et des mesures du 'microtremor' dans le delta du Fraser montrent systématiquement une amplification d'environ 6 à 8 pour des fréquences plus basses (0,3 Hz). Les rapports spectraux supérieurs à inférieurs et horizontaux à verticaux provenant des enregistrements de forage du séisme de 2015 sont comparés à l'amplification théorique du modèle de sol 1D. Les fréquences fondamentales sont bien captées par le modèle 1D, par contre, les amplitudes maximales sont légèrement surestimées.

1. INTRODUCTION

Amplification of seismic waves due to the local geology, specifically soft soils, has been confirmed in many previous earthquakes, 1985 Mexico earthquake and the 1994 Northridge earthquakes (Rayhani and El Naggar 2007). It is well known that amplification at a specific site can occur at certain frequencies related to the stiffness and depth of geologic structure beneath. Severe ground shaking resulting from amplified waves can induce significant damage to structures and trigger landslides and liquefaction of soils.

Greater Vancouver, the largest metropolitan area in British Columbia (BC), is located in one of the most seismically active regions in Canada (Rogers et al. 1998). The Fraser river delta, in southern Vancouver, has a substantial and increasing population and a number of vital economic facilities, including port facilities, the Vancouver International Airport, a ferry terminal and hydroelectric transmission cables (Cassidy and Rogers 1999). The Fraser River delta is mainly composed of alluvial sediments that modify the amplitude and frequency of seismic waves (Cassidy and Rogers 2004).

Amplification hazard in Vancouver is associated with the presence of deep soft soils in the Fraser River delta area. Cassidy and Rogers (2004) observed a peak amplification at frequencies 1.5 to 4 Hz in the Fraser delta from 4 previous earthquakes. Molnar et al. (2013) demonstrated that earthquake recordings at 3 thick delta sites exhibit a consistent low fundamental frequency (~0.3 Hz; 3 seconds) and relatively low amplification (≤ 3). The thickest Holocene delta sediments exhibit microtremor horizontal-to-vertical (H/V) spectral ratio peaks around 0.2 Hz (5 sec) (Onur et al. 2004). Agreement between low-level earthquake and microtremor H/V spectral ratios at Victoria sites was demonstrated by Molnar et al. (2006). Other studies have tried to assess the applicability of theoretical site response to represent observed amplification at the surface in Fraser River delta. Using two 300 m deep boreholes in Fraser delta as site models, Harris et al. (1998) predicted a significant 1D amplification at longer periods (3.5 to 5s) in contrast to the observed amplification. Further, Finn et al. (2003) compared theoretical site response analysis in Fraser delta to the 1996 earthquake recordings. They concluded that 1D analysis predicted the recorded response only at deep sites, while neither 1D nor 2D predicted that of shallow sites. Understanding and assessing the amplification hazard in Vancouver is a first step to effectively reduce its effects on communities.

This paper provides a comprehensive site response analysis from the largest earthquake data sets recorded in Vancouver, with 2011 and 2014 earthquake results presented for the first time. The acceleration spectral amplitudes at different stations for earthquakes between

1976 and 2015 were computed and compared. For the three most recent earthquakes (2011, 2014 and 2015), the observed H/V ratios at 2 strong motion stations were calculated and compared to microtremor measurements conducted nearby. Amplification at lower frequencies (< 1 Hz), expected by Cassidy & Rogers (2004) & Harris et al. (1998) but not observed from previous earthquakes, is clearly demonstrated for the first time from the weak motions of the 2011 and 2014 earthquakes. Both H/V ratios from these earthquakes and microtremor measurements show an amplification of up to 8 at 0.3 Hz at thick Fraser River delta sites. The first observed site amplification at 3 borehole arrays near the Port Mann bridge during the 2015 earthquake (Jackson et al. 2017) is analyzed further here. Using cross correlation analysis between recordings at different depths, the shear wave velocity (V_S) between each instrumented depth ("layers") were calculated and used to build a theoretical 1D elastic parameter soil model for these boreholes. Comparison between the 1D theoretical and observed site amplification gives insights about applicability of the former to predict earthquake site response at these borehole sites. Results show that fundemental frequencies generally agree, but amplification from 1D model overpredicts the observed amplitudes.

2. GEOLOGY OF VANCOUVER

The Fraser delta is made up of soft Holocene sediments mainly silts and sands up to 300 m thickness that have been deposited since the last glaciation 11,000 years ago (Clague 1998). These Holocene deposits overlay Pleistocene sediments mostly composed of ice compacted till and glaciomarine silts and sands (Rogers et al. 1998). Both layers pinch out to the north from known thicknesses of 300 m and 500 m to only several meters below the city of Vancouver. The Tertiary bedrock consists of Miocene sandstone and shales with a depth range of 200 m to 1000 m, on average 500 m depth (Britton et al. 1995). The shear wave velocity measurements in the Holocene Fraser delta area have an average V_S of 200 - 300 m/s that depends on depth. The average velocity of Pleistocene glacial sediments is ~ 500 m/s and the Tertiary bedrock velocity is more than 1500 m/s (Hunter et al. 2016).

3. DATA SETS AND PROCESSING

The characteristics of the earthquakes used in this study are presented in Table1.

From 1976-2001, trigger-based strong-motion accelerometers recorded 4 moderate earthquakes in Vancouver (Table 1). These earthquakes were recorded at 4 trigger-based strong-motion stations. Figure 1 shows MNY and KID stations are located near the edge of the delta with KID southern to the northern arm of Fraser river, RHA is located in the middle of the delta underlain by thick soft soils, and BLO station is located on Pleistocene firm sediments to the north of the delta. The records represent relatively weak ground motions with peak amplitudes less than 5.3 % gravity (g). Time series data processing and analysis followed that presented in Cassidy and Rogers (2004) and Molnar et al. (2004).

Table 1. Characteristics of the available recorded earthquakes in Vancouver between 1976 and 2015.

Earthquakes	Year	Depth (km)	Moment Magnitude (Mw)	Distance* (km)
Offshore Vancouver	2015	60	4.7	~ 71
Vancouver Island	2014	10	6.6	~ 300
Vancouver Island	2011	22	6.3	~ 300
Nisqually, WA	2001	52	6.8	~220
Georgia Strait	1997	3	4.3	~ 40
Duvall, WA	1996	4	5.1	~ 180
Pender Island	1976	62	5.3	~ 50

*Epicentral distance to Vancouver.

The horizontal components were rotated to the radial (SV) and transverse (SH) components, based on the earthquake-station azimuth. A fast Fourier transform is used to convert the time-series to amplitude spectra which were smoothed using an 11-point running mean filter. Spectra are truncated at 0.5 Hz and 10 Hz at the low and high frequency ends as there is little energy from most earthquakes outside that frequency range.

For the 1976 Pender Island earthquake, only recordings at RHA and ROB are available. For the 1997 Georgia Strait earthquake, the BND recording at BND is used as a proxy for BLO considering both stations are located on glacial till.

In 2002, the Geological Survey of Canada installed 3-component Internet Accelerometers (IA) which record continuously. The IAs recorded the 2011, 2014 and 2015 earthquakes. The 2011 moment magnitude (M) 6.3 and 2014 M 6.6 earthquakes occurred west of Vancouver Island, about 300 km away from Vancouver. Even though their recorded peak accelerations were very weak (~0.2 %g), these earthquakes contained significant long period energy in contrast to previous earthquakes. The 2015 M 4.7 earthquake, 71 km southwest of Vancouver, had a 4 %g recorded peak amplitude (Jackson et al. 2017). Four IAs, nearby the four older trigger-based strong motion stations (Figure 1b), were chosen to compare their spectral amplitudes from these more recent earthquakes to those of the previous earthquakes.

The IA acceleration time series of the 2011, 2014, and 2015 earthquakes were filtered below 0.1 and above 20 Hz, and baseline corrected and rotated to the transverse and radial components. The 2015 earthquake had significant high frequency content, similar to earthquakes between 1976 and 2001; Instrument noise contaminates the recordings for frequencies less than about 0.5 Hz. Duration of the acceleration time history for 2011 and 2014 earthquakes were much longer than the 2015 earthquake due to their large magnitude and far distance. Time windows for the 2011 and 2014 earthquakes were taken as 180 seconds to make sure the full energy of the S wave is captured. The spectral amplitudes of the 2015 earthquake for time windows of 40 seconds and 180 seconds time were very similar, a time window of 180 seconds was used for comparison with the 2011 and 2014 earthquakes.

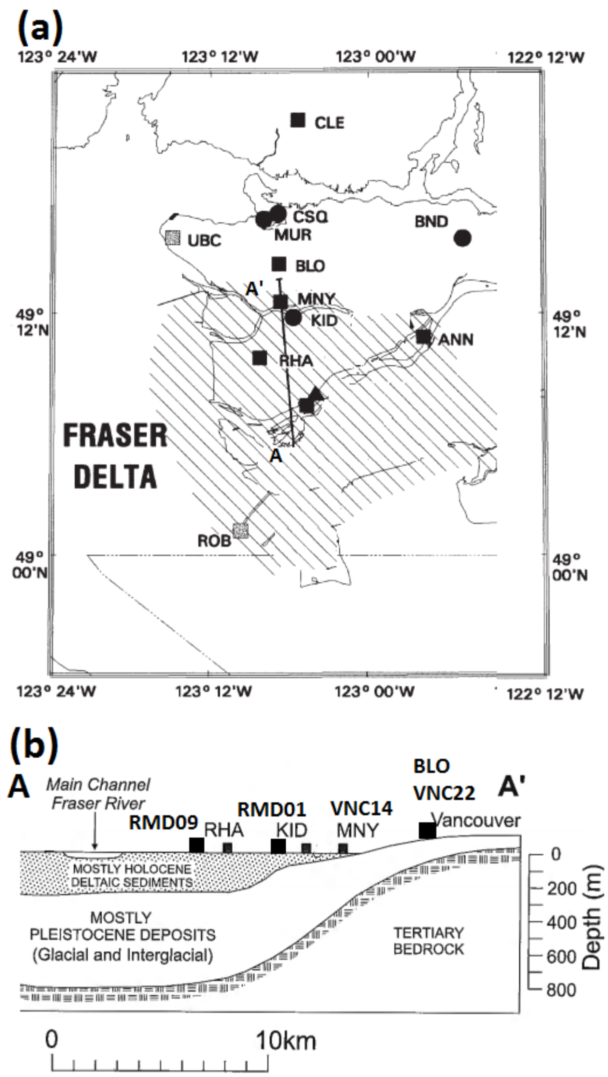


Figure 1(a). Location of strong-motion stationsin Greater Vancouver before 2002. The hatched area represents the extent of the soft Holocene delta sediments shown in cross-section (along line A-A') in Figure 1b. (b). Simplified cross-section of the Fraser River delta. Locations of strong motion stations shown by squares. Locations of Internet Accelerometer stations (RMD09, RMD01, VNC14, and VNC22) are labelled.

3.1 Horizontal to vertical spectral ratios

The 2011, 2014 and 2015 transverse-to-vertical (SH/V) ratios are compared to microtremor measurements conducted previously nearby 2 IA stations: RMD09 (center of the delta) and VNC14 (edge of the delta) shown in Figure 1b.

Microtremors were recorded for 30 minutes with a broadband seismometer (Onur et al. 2004). 5-minute time windows were extracted and filtered with a band pass filter from 0.1 – 25 Hz. The computed spectral amplitudes were smoothed with a 15-point running mean filter and averaged for the 6 time windows. The average horizontal spectrum was divided by the vertical spectrum. Only the peak frequency and amplitude are reported here.

Frequencies higher than 2 Hz were not retrievable for the 2011 and 2014 earthquake recordings as the high frequency attenuated with distance. Lower frequencies (< 0.5 Hz) were not as well retrieved for the 2015 earthquake. There are spectral limitations of the earthquake H/V ratios in comparison the the microtremor H/V ratios.

3.2 Borehole array recordings

The 2015 earthquake produced the first borehole earthquake recordings in British Columbia. Three boreholes installed at terminus ends of the Port Mann Bridge are instrumented with acclerometers at three depths in each borehole (vertical arrays). Boreholes 1 and 2 (900 m apart) are located beneath the north bridge approach and Borehole 2 is located beneath the south bridge approach. Three tri-axial accelerometers are installed in each borehole between surface and 57 m maximum depth. Table 2 summarizes the depths and geologic formations at each borehole.

Using cross correlation analysis of pairs of signals at different depths within a borehole (Elgamal et al. 1995), the interval Vs between each instrumented depth is obtained. A 1D Vs profile for each of the 3 boreholes was derived (Jackson et al. 2017; Table 2). Based on the relatively deep depth of this event (60 km), shear waves are assumed to travel vertically and therefore the time delay in shear wave propagation can be assumed as a good estimation of Vs. The 1D Vs profiles in Table 2 were used to compute the linear 1D theoretical amplification function (Haskell 1960). Peak amplitudes of the 2015 earthquake (< 4.7 %g) indicate nonlinear behaviour of the soil is unlikely (Rayhani et al. 2008).

The ratio of the transverse horizontal component at the top accelerometer to the transverse horizontal component at the bottom accelerometer (situated in till) (Jackson et al. 2017), is compared here to the linear theoretical amplification function derived from the 1D Vs profile.

4. RESULTS

4.1 Spectral amplitudes

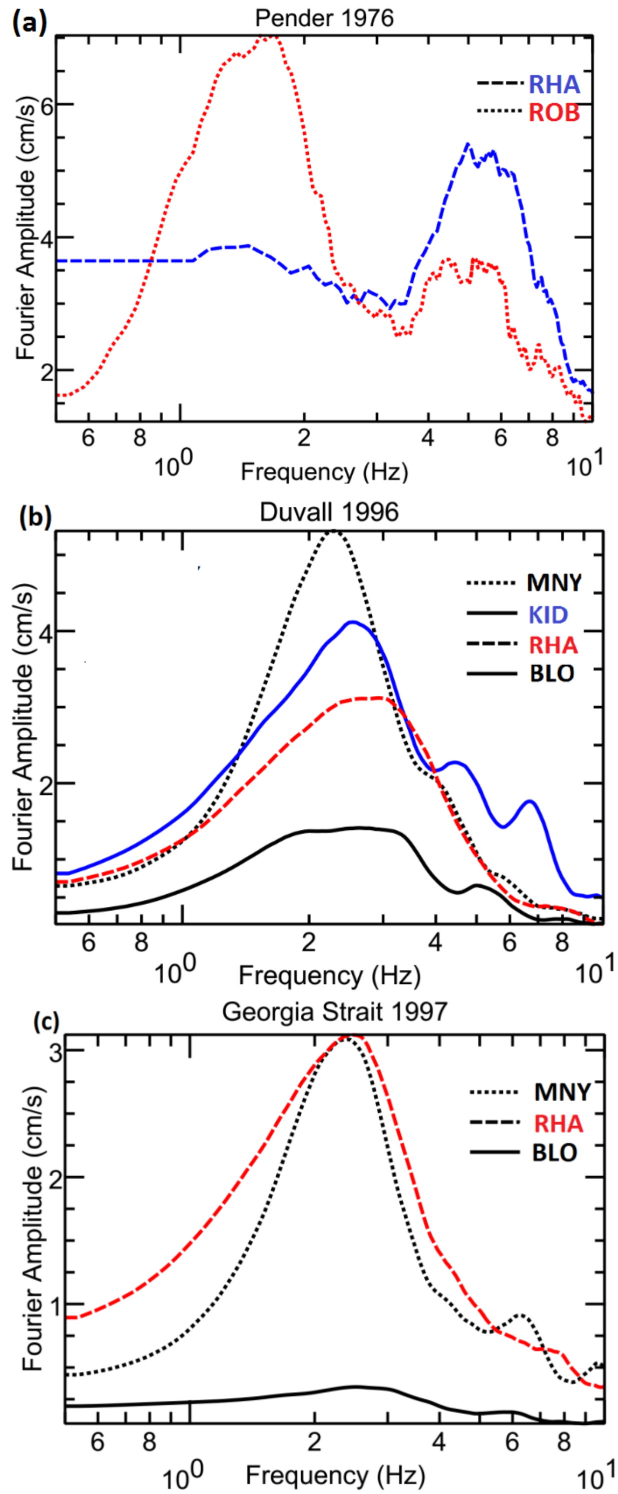
Figure 2 shows the transverse amplitude spectrum of each earthquake recording at four locations. The IA stations chosen for comparison are located nearby the old strong motion stations that were replaced, so four locations are represented here.

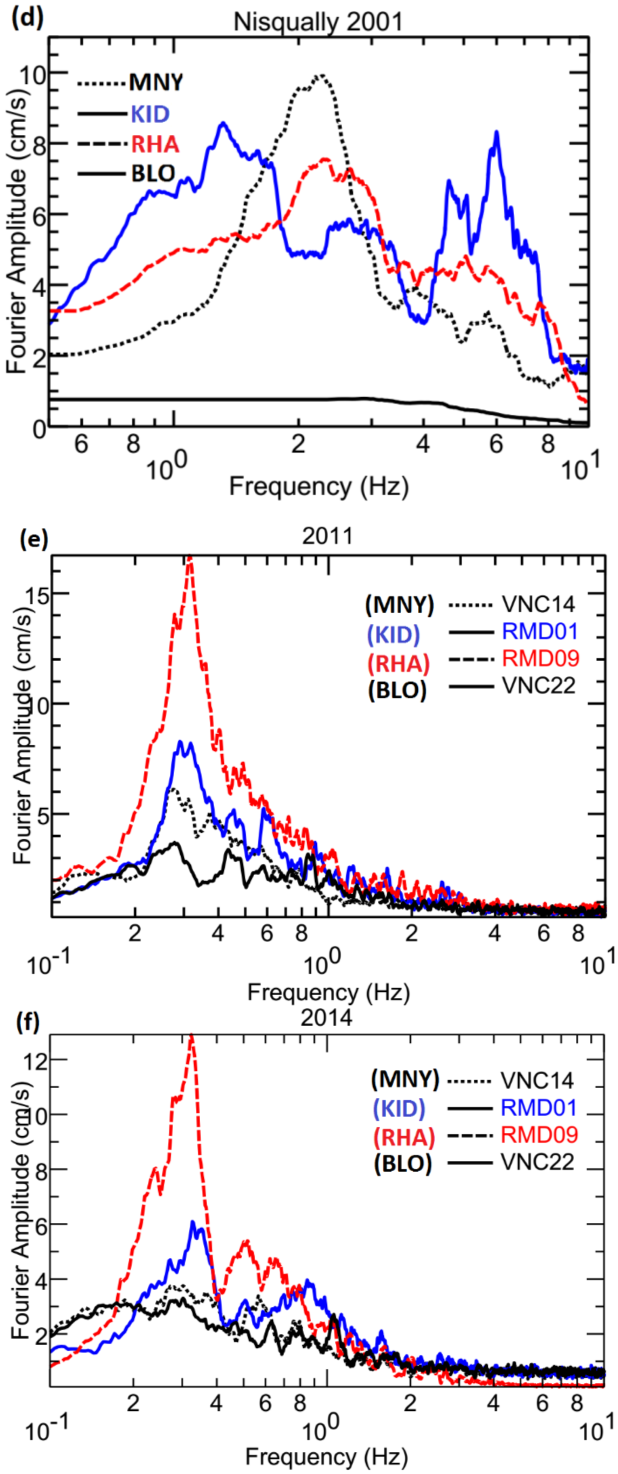
In general, stations located on stiffer till sediments (BLO, VNC22, BND) exhibit the lowest amplitudes. The spectral peak amplitudes for all earthquakes shown in Figure 2, except for the 2011 and 2014 earthquakes, occur between 2 and 6 Hz. At higher frequencies (~8 Hz), rapid attenuation of amplitudes occurs.

The 1996 Duvall sprecta (Fig. 2b) are amplified 2 to 4 times relative to the stiff BND site. In Figure 2c, a higher amplification up to 10 is observed at both the center (RHA) and edge of the delta (MNY) for the 1997 Georgia Strait earthquake. The 2001 Nisqually earthquake (Fig. 2d) shows slightly lower peak frequencies and amplification of up to 10 relative to the firm soil site BLO compared to the 1997 earthquake. The spectral amplitudes of the 2015 earthquake (Figure 2g) show an amplification of about 2 to 3 at the three soil stations compared to the firm soil site (VNC22). For these four earthquakes, the response at MNY (or VNC14) station located at the edge of the delta shows similar or higher spectral amplitudes compared to RHA (or RMD09) located at the thick center of the delta. This observation has been related to the large velocity contrast between Holocene and Pleistocene sediments at shallow depths near the edge of the delta where the two layers pinch out (Figure 1) and is well documented in literature (Cassidy and Rogers 1999; Rogers et al. 1998).

Recordings of the 2011 and 2014 earthquakes, ~300 km away from Vancouver, were very weak with peak ground acceleration of 0.2 %g. In contrast to the previously mentioned earthquakes, the peak spectral amplitudes of the 2011 and 2014 earthquakes were between 0.2 and 0.4 Hz and attenuation occurring rapidly after ~ 1-2 Hz (Figure 2e and 2f). These earthquakes had significant low frequency content due to their larger magnitude and the long travelled distances for which attenuation of higher frequencies occurred. As in, the waveforms are dominated by surface waves rather than body waves. The peak amplification at RMD09 is about 4 times that of the firm soil site (VNC22) in both earthquakes. This amplification at very low frequencies is consistent with the geology of deep soft sites at the center of the delta and has been expected by many authors such as Harris et al. (1998) and Cassidy and Rogers (2004), but never observed in the older moderate earthquakes. Moreover, the amplitudes at the center of the delta at RMD09 are much higher during these events than that at the edge of the delta at VNC14 and RMD01. The amplification at the edge of the delta is only about 2 relative to firm soil for both earthquakes. This is different from the observations made from lower magnitude and closer earthquakes (Fig. 2a-d, g) discussed in the previous paragraph.

The 2011 and 2014 earthquakes provide the first set of recordings in Vancouver demonstrating peak spectral amplitudes at lower frequencies (<1 Hz). This can help quantify and constrain amplification at lower frequencies in case of a large magnitude earthquake (Ghofrani et al. 2017).





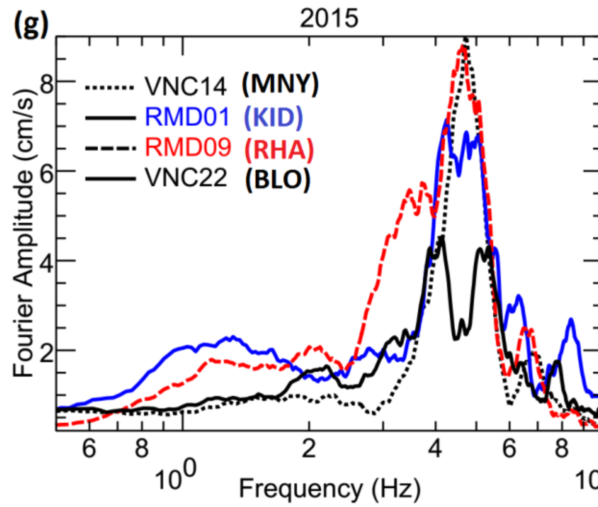


Figure 2. Smoothed transverse spectral amplitudes at 4 locations that recorded earthquakes between 1976 and 2015 in Vancouver.

4.2 Earthquake H/V ratios compared with microtremor peak frequencies

Figure 3 shows transverse H/V ratios from the most recent earthquakes 2011, 2014, and 2015 at 2 IA stations located at the center and edge of the delta in comparison to the peak frequencies of H/V ratios from microtremor measurements conducted nearby these stations. The H/V of the 2011 and 2014 earthquakes show a first peak at 0.3 Hz with amplitude of 6 and 8, respectively, for RMD09 station. A smaller peak ~3 is also observed around 1 Hz for both earthquakes. Both Harris et al. (1998; Fig. 5 and 6) and Molnar et al. (2013; Fig. 6) reported first spectral peak 0.2-0.4 Hz and a higher peak around 1 Hz at deep Fraser delta sites. The 2015 H/V predicts a similar peak at 1 Hz but shows a peak of 5 at a frequency range of 3 to 5 Hz. The two microtremor H/V peaks at this station fit well with both the peak amplitudes and peak frequencies of the 2011 and 2014 earthquakes.

For the VNC14 station, the H/V of the 2011 and 2014 earthquakes show small peaks ~ 2.5 at lower frequencies, while the 2015 earthquake shows a high peak (~ 5) at 4 to 6 Hz. The microtremor H/V peak is ~ 3 at ~ 0.9 Hz.

In general, the same pattern of a high frequency H/V peak from the 2015 earthquake is observed at 2 sites of differing geology. The frequency content of the earthquake source, where the 2011 and 2014 events are lower frequency and the 2015 is a higher frequency event, excites different modes of the underlying geology.

Both microtremor peaks at RMD09, at the center of the delta, are consistent in amplitude and frequency with the peaks from the H/V of the weak motions of 2011 and 2014, a similar conclusion was reached by Molnar and Cassidy (2006) when comparing microtremor to weak ground motions in Victoria. However, comparison at more sites with various local geologies will be conducted to judge the validity of the H/V of microtremor measurements as a proxy of site amplification in Vancouver.

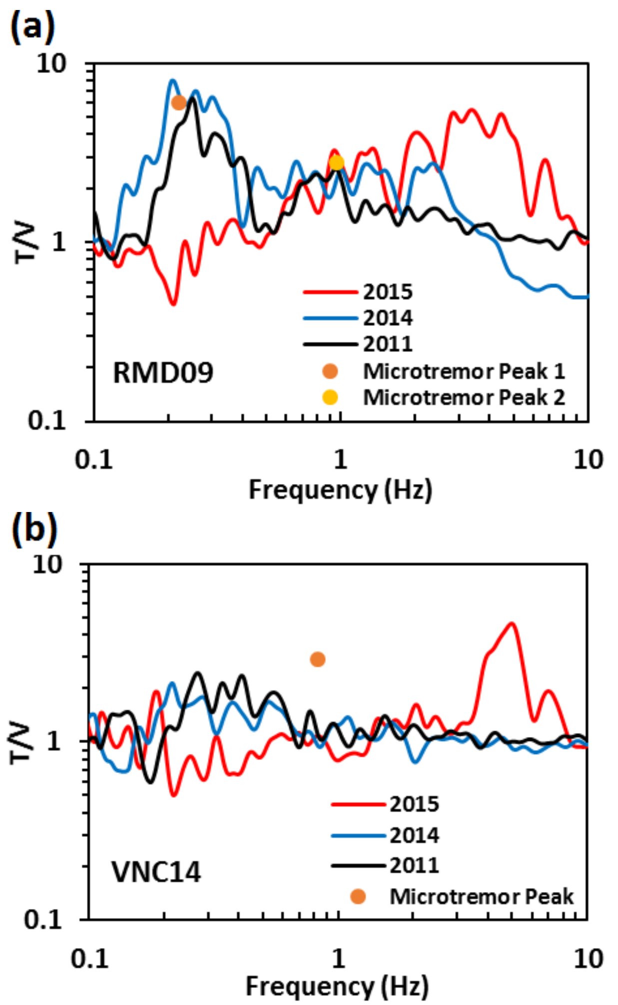


Figure 3. H/V of the 2011, 2014, and 2015 earthquakes along with H/V peaks from microtremor measurements at (a) RMD09 and (b) VNC14 stations.

4.3 Comparison of observed and theoretical amplification for the three borehole arrays

Cross correlation analysis was done between two upper and lower sensor pairs to determine the time shift in the recorded waveforms. The two time shifts in north-south and east-west directions were very similar and the average value was considered. The distance between the two sensors was divided by the resulting time shift to determine V_S of the depth interval. The results of the cross correlation analysis are presented in the Table 2. The average unit weight of Holocene deposits is 19.5 kN/m3 (Onur et al. 2004). The damping ratio for soils was taken as 4 % and the input motion was applied at a rigid half space boundary condition as recommended by Kwok et al. (2007) for within motion. DEEPSOIL software was used for computing the 1D response at the surface and the corresponidng amplification function (Hashash et al. 2016).

Figure 4 shows the results of observed and computed theoretical amplification at each borehole. The peaks of H/V of the top sensor for all boreholes (H1/V1 shown in blue) are higher amplification and shifted to lower frequencies compared to the ratio of the top horizontal to the bottom horizontal component (H1/H3 shown in green). The difference between the two ratios is the largest in Borehole 1 where the first peak of H1/V1 is about 14 at 0.8 Hz and the first peak of H1/H3 is about 7.5 at 1.4 Hz. The fact that the H/V accounts for amplifications coming from lower depths, unlike H1/H3 which only considers depths between sensors 1 and 3 (upper ~ 60 m maximum), could explain the larger amplitudes and shift to lower frequencies (Rayhani and El Naggar 2008). A higher frequency peak at 3.5 Hz is observed in both the H1/V1 and H1/H3 ratios.

The 1D theoretical amplification shown in red in Figure 4 predicts a higher peak amplification for all the boreholes compared to the two empirical earthquake ratios. The theoretical peak frequencies coincide with the H1/H3 peak frequencies in Borehole 1 and 2 and to a lesser extent in Borehole 3. This validates the V_S values of the layers between the sensors values derived from cross correlation analysis.

Table 2. Details of borehole arrays description with the peak ground acceleration recorded during the 2015 earthquake and the shear wave velocities obtained from cross correlation analysis.

Borehole	Sensor	Depth (m)	Shear[1] wave velocity (m/s)	Soil type and thickness
	1	-4		3 m landfill
			153	6 m dense sand
				5 m firm clayey-sand
1	2	9		25 m dense sand
			266	2 m v. dense sand
				3 m till
	3	41		Till
	1	2		2 m brown sand
				2 m grey silt/peat
			243	23 m grey sand
				1 m gravel & cobbles
2				5 m grey clay
	2	36		5 m clay with gravel
			243	5 m grey silt & sand
	3	46		Till
	1	16		13.5 m grey sand
			245	3.5 m grey clayey silt
	2	33		2.5 m grey silt
				2.5 m silt, gravel
3				1.5 m coarse sand
			167	3.5 m silt & clay
				11 m grey clay
				3 m sand with gravel
	3	57		Till

[1] obtained from cross-correlation analysis

The 1D site model for each borehole captures the fundamental and higher modes peak frequencies at the three boreholes. The higher predicted peak amplification is possibly due to the rigid boundary condition assumed. An elastic half space would probably be a better representative of the till underneath the bottom accelerometer leading to lower amplification peaks.

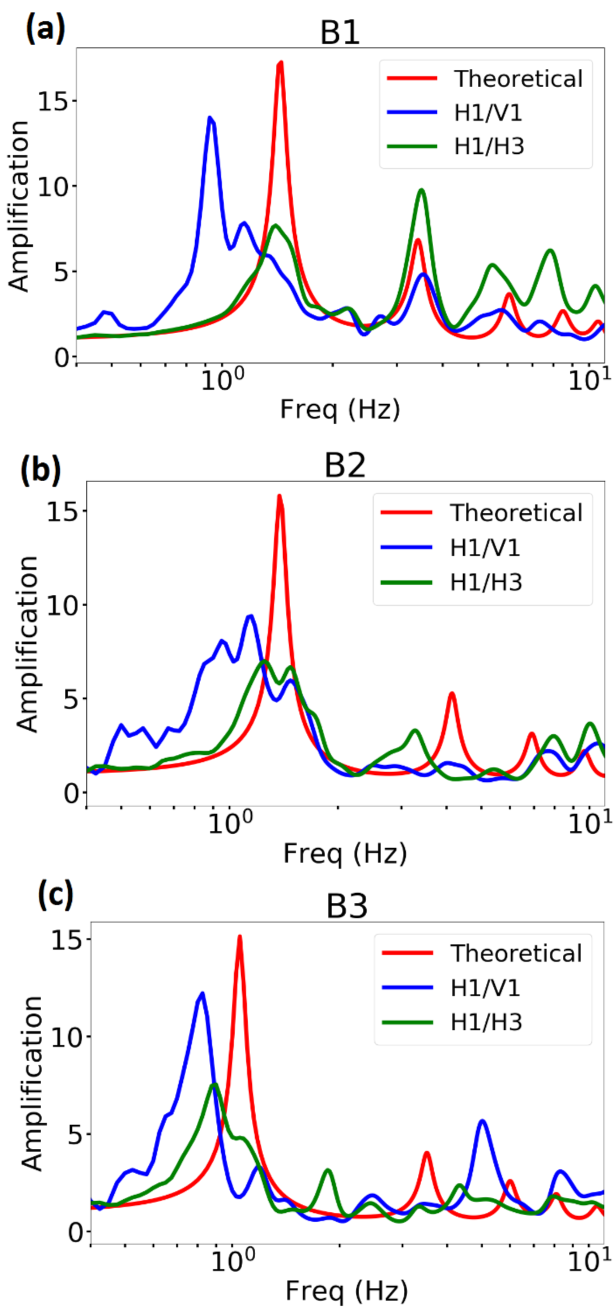


Figure 4. Amplification functions computed from H/V ratio at the uppermost sensor (H1/V1 in blue), horizontal component ratio of the top to the bottom sensor (H1/H3 in green), and theoretical 1D site amplification (in red) for (a) Borehole 1, (b) Borehole 2, and (c) Borehole 3.

These boreholes are of significant engineering importance to understand seismic site effects in Vancouver. Recordings from future earthquakes can significantly help understand the local site effects with depth near the Port Mann Bridge.

5. CONCLUSIONS

The spectral ratios of 7 moderate earthquakes between 1976 and 2015 recorded in Vancouver were revisited. The 2015 earthquake, similar to the set of earthquakes between 1976 and 2001, shows peak spectral accelerations at frequencies of 1.5 to 4 Hz. Previous studies of the older earthquakes demonstrated an amplification of 2 to 6 relative to firm till at frequencies of 1.5 to 4 Hz in the Fraser delta, whereas amplification at lower frequencies (<1 Hz) was poorly defined. The ground motions presented here for the 2011 and 2014 earthquakes provide the opportunity of quantifying and constraining the amplification at lower frequencies as they contained significant low frequency energy. At one station in the Fraser delta, spectral amplification of 4 relative to stiff till and an H/V peak of about 8 at a frequency of 0.2 to 0.3 Hz were determined for these two earthquakes.

The microtremor H/V method has gained large popularity in the past 10 years as a powerful tool for estimating site amplification due to its rapid measurement and low cost. However, its validity to fully model the site amplification at various site geometries and geologies is still debated. In this study, microtremor H/V ratios successfully predict H/V peaks from weak 2011 and 2014 ground motion earthquakes at a station on the Fraser River delta. Validating microtremor H/V ratios at various sites in Vancouver, can give reliability of this method to be used as a proxy of site amplification.

The first subsurface earthquake recordings in Vancouver were recorded in three borehole arrays during the 2015 earthquake. The H/V at the top sensor was compared to the horizontal-component spectral ratio of the top to the bottom sensor. The H/V ratio demonstrates higher peak amplification at slightly lower frequencies for the 3 boreholes possibly due to amplifications below the bottom sensor, situated at the top of stiff till. The 1D amplification model, built from V_S profiles via cross correlation analysis, predicts the peak frequencies but shows a slightly higher peak amplification due to the rigid boundary condition assumed for the input motion.

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