Region specific Vs_{30} across Metro Vancouver and impact to seismic design ground motions

Sujan Raj Adhikari, Sheri Molnar, Hadi Ghofrani
Department of Earth Sciences, Western University, ON, Canada

Jinfei Wang
Department of Geography and Environment, Western University, ON, Canada

ABSTRACT
Preliminary distributions and statistical measures of the average Vs of the upper 30 meters (Vs_{30}) are determined for 9 municipalities in Metro Vancouver through the Metro Vancouver seismic microzonation mapping project. The most common in situ Vs_{30} value (mode) within each municipality ranges from 180 to 2330 m/s revealing significant regional variation in site conditions. We compile two robust Vs30 datasets for site conditions dominated by Fraser River delta and uplands glaciated till and determine their Vs30 quartile ranges to be 180-250 m/s and 360-580 m/s respectively. Binning of Vs_{30} values by national building code (NBC) site class reinforces regional expectations, e.g., Burnaby and Vancouver are most commonly class C, but also identifies municipalities with high site class variability (North Vancouver, Coquitlam) and that class B is the least common regionally. We first validate implementation of the 6^{th} Canada seismic hazard model of the 2020 NBC in OpenQuake then predict 2020 NBC ground motions using each municipality's in situ Vs_{30} mode (represents X_V site classification) in comparison to if Vs_{30} is not measured (X_S site classification) and previous 2015 NBC motions for the respective site class. We observe that performing in situ Vs_{30} measurements are most likely to result in lower 2020 NBC X_V motions compared to X_S motions in Delta, Port Coquitlam, Burnaby and Vancouver.

RÉSUMÉ
Les distributions préliminaires et les mesures statistiques des Vs moyens des 30 mètres supérieurs (Vs_{30}) sont déterminées pour 9 municipalités de la région métropolitaine de Vancouver grâce au projet de cartographie de microzonation sismique de la région métropolitaine de Vancouver. La valeur Vs30 in situ la plus courante (mode) au sein de chaque municipalité varie de 180 à 2330 m/s, révélant une variation régionale significative des conditions du site. Nous compilons deux ensembles de données Vs_{30} robustes pour les conditions du site dominées par le delta du fleuve Fraser et le till glaciaire des hautes terres et déterminons leurs plages de quartile Vs30 à 180-250 m/s et 360-580 m/s respectivement. Le regroupement des valeurs Vs30 par classe de site du code national du bâtiment (NBC) renforce les attentes régionales, par exemple, Burnaby et Vancouver sont le plus souvent de classe C, mais identifie également les municipalités avec une variabilité élevée de classe de site (North Vancouver, Coquitlam) et cette classe B est la moins commune au niveau régional. Nous validons d'abord la mise en œuvre du 6e modèle canadien d'aléa sismique du NBC 2020 dans OpenQuake, puis prédisons les mouvements du sol NBC 2020 en utilisant le mode Vs_{30} in situ de chaque municipalité (représente la classification XV du site) par rapport à si Vs¬30 n'est pas mesuré (classification XS du site) et les motions NBC précédentes de 2015 pour la classe de site respective. nous observons que la réalisation de mesures Vs_{30} in situ est plus susceptible d'entraîner des mouvements NBC XV 2020 inférieurs par rapport aux mouvements XS à Delta, Port Coquitlam, Burnaby et Vancouver.

1 INTRODUCTION

The region of southwestern British Columbia (SWBC) is one of the most seismically active regions in Canada, located at the northern end of the Cascadia subduction zone. During the last 130 years, there have been ten moderate to large magnitude earthquakes within 250 km of Vancouver (Rogers 1998). The most recent large magnitude (M > 7) earthquake was the 1946 M7.3 shallow crustal event (15 km depth) under Vancouver Island. Crustal earthquakes result from compressional forces within the North American plate overriding the Juan De Fuca plate. Inslab events are common in the Strait of Georgia and Puget Sound, Washington. The 2001 M6.8 Nisqually earthquake was an inslab event (52 km depth) in southern Puget Sound, northeast of Olympia, Washington, and widely felt in Victoria and Vancouver (Dewey et al. 2002). The largest magnitude earthquakes occur at the interface of the Cascadia subduction zone, producing a M9 in 1700 AD (Atwater et al. 2005). If a similar M9 Cascadia earthquake occurs near Vancouver, the Insurance Bureau of Canada (AIR Worldwide 2013) estimates $ 62 billion CAD in direct losses and $ 1.7 billion CAD in indirect losses.

Seismic hazard analysis forecasts the impact of earthquakes in terms of ground shaking at a specific location or over a region. For a given deterministic earthquake, a regional ground motion prediction equation is used to predict ground motions. Probabilistic seismic hazard analysis (PSHA) quantifies the hazard from all earthquakes in a given area, considering their distance from the site of interest, based on earthquake magnitude and frequency of occurrence (Cornell 1968, McGuire 2004). PSHA is the standard of practice for developing seismic hazard models worldwide. PSHA mainly follows a four-step methodology: identifying source zones, determining their magnitude recurrence, using attenuation relations to calculate ground motions and integration to determine their annual frequency of exceedance (Atkinson and Goda 2011).

Local site conditions alter earthquake shaking. Softer soils tend to amplify ground motions, which had been well recognized after the devastating earthquake effects of the 1985 M8.1 Michoacan, Mexico and 1989 M6.9 Loma Prieta, California earthquakes. Ground motion amplification results from reduced seismic impedance from deeper rock into overlying soils as well as due to resonance within the soil column. At sites with a high impedance contrast, the fundamental resonance site frequency, f_0 (inverse of site period), depends on the soil's average shear wave velocity (Vs) and its thickness. In southwest mainland British Columbia, Quaternary sediments vary from stiff glacial tills to soft deltaic sediments of several hundreds meters thickness overlying glaciated bedrock (Armstrong 1984). Across Metro Vancouver, this variety in local site conditions leads to variable earthquake ground shaking (e.g., Armstrong 1984, Cassidy et al. 1997, Jackson 2017, Molnar et al. 2020). Site effects are simplified to a site term within ground motion prediction equations based primarily on the time averaged Vs of the upper 30 meters (Vs_{30}). Down-/ cross-hole, seismic cone penetration (SCPT), seismic reflection or refraction surveys are a few examples of in situ Vs profiling methods to determine Vs_{30}. An understanding of Vs_{30} is important to accurately predict earthquake ground motion. As part of the Metro Vancouver seismic microzonation mapping project (Molnar et al. 2020), Vs profiling measurements are compiled from available public and private sources as well as performed at over 100 locations (Adhikari et al. 2021).

Natural Resources Canada (NRCan) has generated national seismic hazard maps for Canada since 1965. The most recent 6th generation national seismic hazard model (CanadaSHM6;Kolaj et al. 2020a) and its predicted ground motions (2% probability of exceedance in 50 years) are the basis for seismic design in the 2020 national building code (NBC). NBC first adopted the use of Vs_{30} for earthquake site classification in 2005. In the 2020 NBC, Vs_{30} is used directly (not site class) to predict ground motions. The CanadaSHM6 is implemented within the OpenQuake (OQ) engine, a seismic hazard and risk modelling software developed by the Global Earthquake Model (GEM) Foundation (Pagani et al. 2014, 2020).

This paper implements use of in situ Vs_{30} (2020 NBC X_V site classification) to determine CanadaSHM6 ground shaking hazard for multiple cites of Metro Vancouver. When in situ Vs_{30} is unknown, 2020 NBC X_S site classification based N_{60} or S_u is used to determine ground motions. We evaluate 2020 NBC ground motions for X_V and X_S site classifications for select municipalities in Metro Vancouver as well as with the previous 2015 NBC (CanadaSHM5) motions for the respective site class.

2 SIXTH GENERATION SEISMIC HAZARD MODEL

Shallow crustal earthquakes of the continental North American plate, deeper inslab earthquakes of the subducting oceanic Juan de Fuca plate, and subduction interface earthquakes of the Cascadia subduction zone are the major earthquake sources of southwestern British Columbia. Figure 1 shows the CanadaSHM6 seismic source zones of SWBC. Inslab seismicity within the subducting Juan de Fuca plate is captured by four areal zones with earthquake depths increasing eastward: Juan De Fuca plate bending onshore (JDFN), Georgia Strait Puget Sound East (GTPE), Georgia Strait Puget Sound Central (GTPC), and Georgia Strait Puget Sound West (GTPW). Modelling of inslab sources is improved in CanadaSHM6 by using three distinct areal source zones with increasing depth of seismicity eastward: GTPW at 50 km, GTPC at 55 km, and GTPE at 60 km depth ((Kolaj et al. 2020b).

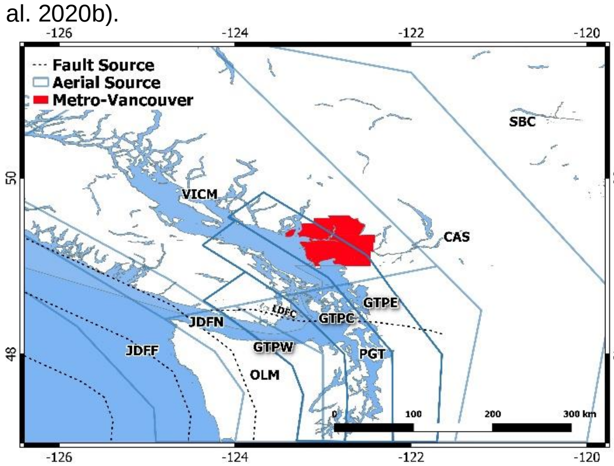

Figure 1. Seismic source zones of CanadaSHM6 in SWBC.

Shallow seismicity in the overlying North American plate is captured by 7 areal source zones: Cascades mountains (CAS), Vancouver Island Coast Mountains (VICM), Juan De Fuca plate bending onshore (JDFF), Puget Sound (PGT), Olympic Mountains (OLM), Southern British Columbia (SBC). The seismicity is assumed to be uniform in each zone. CanadaSHM6 also includes fault seismicity of the Leech River and Devil Mountains faults (LDFC; (Halchuk et al. 2019)) and the Cascadia subduction zone with a updated number of mega-thrust ruptures. CanadaSHM6 also includes updated ground motion models by adding revised aleatory uncertainty (sigma) and site amplification models (Kolaj et al. 2019). Most notable to this paper, in CanadaSHM6, Vs_{30} is used directly in the GMMs over a continuous range between 140 m/s and 1100 m/s (Kolaj et al. 2020a) rather than a selected average Vs_{30} representative of each NBC site class used in the three previous NBC versions of 2005, 2010, and 2015 in western Canada.

3 IMPLEMENTATION AND VALIDATION OF CANADASHM6 WITHIN OPENQUAKE ENGINE

OpenQuake hazard calculator uses the classical PSHA approach (Cornell 1968, McGuire 1976). The classical PSHA analysis allows calculating the probabilities of exceeding, at least once in a given time span, and at a given site, a set of ground motion parameter levels considering all possible earthquake ruptures defined in a seismic model. The mean annual rate of exceeding for a specific motion level x at a given site can be calculated using the following Equation 1:

$$\lambda(X \geq x) = \sum_{i=1}^{NS} Vi \iint P(X \geq x|m,R) f_i(m) f_i(R|m) dRdm \quad [1]$$

where NS = number of seismogenic sources; Vi = the annual rate of occurrence of earthquakes above the minimum magnitude for the i^{th} source; fi(m) = probability density distribution of magnitude within the i^{th} source, which is obtained using the Gutenberg-Richter relationship; fi(R|m) is the probability density distribution of epicentral distance R between various locations within source i^{th} and the site where hazard is estimated; and P(X ≥ x |m,R) = conditional probability that a given earthquake of magnitude *m* and source-to-site distance *R* will exceed ground motion level x.

The OQ engine supports PSHA input models accounting for epistemic uncertainties by means of a logic tree structure. Using the Ground Motion Field Calculator embedded in the OQ engine, multiple ground-motion field realizations can be computed, each realization sampling the aleatory uncertainties in the ground-motion model. We use the CanadaSHM6 input files that were used to produce values proposed for the 2020 National Building Code of Canada (Kolaj et al. 2020a). The PSHA input model includes the seismic source characterization capturing all seismicity within 500 km of the site of interest, with the respective epistemic uncertainties and GMM characterization that determines the ground motions. A logic tree approach is applied to weight alternative parameters characterizing seismic sources (e.g., b value, maximum magnitude). Likewise, a logic tree approach is used to weight the various GMMs per seismic source and all the possible realizations are created. The OQ earthquake rupture forecast tool creates a list of earthquake ruptures based on the source model by defining a grid in source zone to delineate the area sources and the magnitude- frequency distribution. Earthquake ruptures are then characterized by a probability of occurrence over a specified time period. Similarly, the OQ earthquake rupture forecast calculator determines the appropriate site-to-rupture distance which will be used in calculating the ground motion fields. The OQ classical hazard curve tool generates seismic hazard curves, hazard maps, and uniform hazard spectra by solving the PSHA integration process (i.e. Equation 1).

To validate our implementation of the CanadaSHM6 model in OQ, we perform a PSHA for Vancouver City Hall for a reference site condition of Vs_{30} = 450 m/s. Our calculated 2% probability of exceedance in 50 years UHS agrees well with NRCan's CanadaSHM6 UHS. The percentage difference at peak ground acceleration (PGA) between the two calculations is 0.2%, at spectral acceleration (Sa) of 0.2 seconds is 0.4%, and at Sa (2.0 s) the values are the same.

4 GEOLOGICAL SETTING

A simplified geological map in Figure 2 shows that Metro Vancouver consists of softer Holocene deposits and stiffer Pleistocene and older glacial tills and diamicton. Quaternary sediments have a maximum thickness of 800-1000 m in Lander compared to only several meters at the edge of the Fraser River delta (Hunter et al. 1998). The Fraser River delta, south of Vancouver, is a lowland region with deltaic silts and sands up to 300 meters thick (Rogers 1998). Proglacial Quadra sand deposits are found around Vancouver, West Vancouver, and North Vancouver. These proglacial deposits were covered by glacial till and gravelly ice-contact sediment of the Pleistocene epoch which laid the foundation for Vancouver, Burnaby, and Surrey (Armstrong 1990). These Quaternary sediments of three major glaciations covered the irregular, glacier-eroded bedrock. Early Cretaceous sedimentary rocks are exposed in sea cliffs and along steep slopes of the Fraser Lowland and older plutonic granitic rocks outcrop in the North Shore mountains.

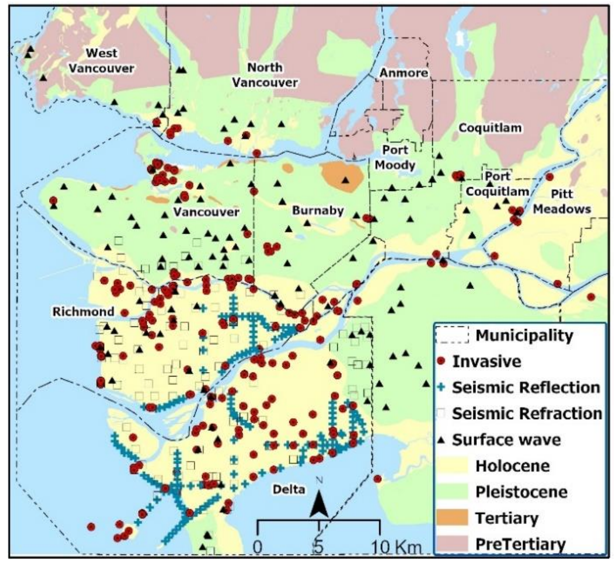

Figure 2. Simplified geological map of Metro Vancouver (modified from Roddick 1965, Armstrong and Hicock 1979, Blaid-Stevens 2008, Bednarski 2014). Locations of in situ Vs profiles are shown; symbols note in situ method type (see text in Section 5).

5. REGION SPECIFIC V_{S30} ESTIMATES

The Metro Vancouver seismic microzonation mapping project is a multi-year project to map earthquake hazards including shaking (amplification), liquefaction and landslide hazards (Molnar et al. 2020). To achieve spatial coverage for regional seismic microzonation mapping, we compile multiple forms of geoinformation from agencies and online sources. Adhikari et al. (2021) documents development of the Metro Vancouver mapping project geodatabase. Figure 2 shows the locations of over 680 in situ Vs depth profiles of the geodatabase. Invasive Vs profiling methods include downhole, crosshole and seismic cone penetration testing (SCPT). Non-invasive Vs profiling methods include surface wave dispersion measurement techniques (SASW, MASW, AVA) which are inverted to provide Vs profiles. Other non-invasive seismic methods include seismic refraction and reflection methods. We use the 680 in situ Vs profiles shown in Figure 2 to calculate Vs_{30}, rounded up to the nearest 10 m/s. When Vs profiles are shallower than 30 m, Vs_{30} is calculated using the extrapolation method of Wang and Wang (2015). We group Vs_{30} values for each of 9 selected municipalities in western Metro Vancouver, the municipalities and number (n) of Vs_{30} values are: West Vancouver (WVC), 6; a combined city and District of North

Vancouver (NVC), 16; Vancouver (VAN) including UBC's endowment lands, 85; Burnaby (BNB), 19; Coquitlam (CQT), 12; Port Coquitlam (PCT), 12; Richmond (RMD), 243; New Westminster (NWM), 7; and Delta (DTA), 280.

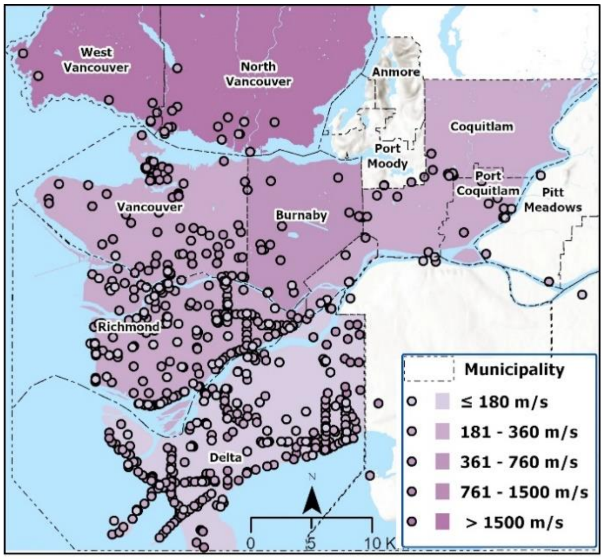

Figure 3. Region specific Vs_{30} map of western Metro Vancouver. Municipalities are shaded according to their modal Vs_{30} value.

The majority of Vs profiles occur in the softer Holocene Fraser River delta (RMD and DTA). Figure 3 shows the calculated Vs_{30} values compared to each municipality's Vs_{30} mode. For the three municipalities with exposed Coast Mountain rocks along the North Shore (WVC, NVC and CQT), a calculated average rock Vs_{30} of 2330 m/s is used to supplement their Vs_{30} datasets; our Metro Vancouver geodatabase includes ≤ 10 Vs profiles in Coast Plutonic Complex (CPC) rocks throughout the Lower Mainland.

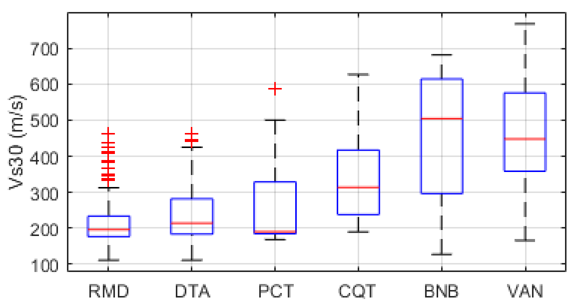

Figure 4. Box and whisker Vs_{30} plots (red line is median) of select Metro Vancouver municipalities.

The number of rock Vs_{30} values added is proportional to a crude approximation of the exposed rock in each municipality; we use 70% for WVC (n = 4), 50% for NVC (n = 8), and 20% for CQT (n = 2). We select to use modal Vs_{30} to communicate the most frequent Vs_{30} value within each municipality (Figure 3); the practicing geotechnical engineer will most frequently encounter the modal Vs_{30} value. The lowest modal Vs_{30} values are 180 m/s in Delta, 190 m/s in PCT and 200 m/s in Richmond. These municipalities are dominated by low lying softer Holocene sediments of the Fraser River delta. Figure 4 shows median and quartile ranges of Vs_{30} values for select municipalities. We determine an assumed modal Vs30 of 200 m/s for NWM; there is no statistical difference in the 7 NWM Vs30 values compared to the much larger Fraser River delta RMD and DTA datasets. Coquitlam, Vancouver and Burnaby have increasing modal Vs30 values of 250 m/s, 360 m/s, and 630 m/s, respectively. It is expected for Vs_{30} to increase in these municipalities with an increase in the dominant ground condition towards stiffer glaciated tills and/or exposed rock. The increasing Vs_{30} trend continues for NVC and WVC (2330 m/s) with greater area of exposed rock within each municipality. The modal Vs_{30} value is most robust for RMD and DTA with hundreds of in situ Vs measurements; Vs_{30} distributions and associated statistics are considered preliminary at this time for all other municipalities (ongoing work).

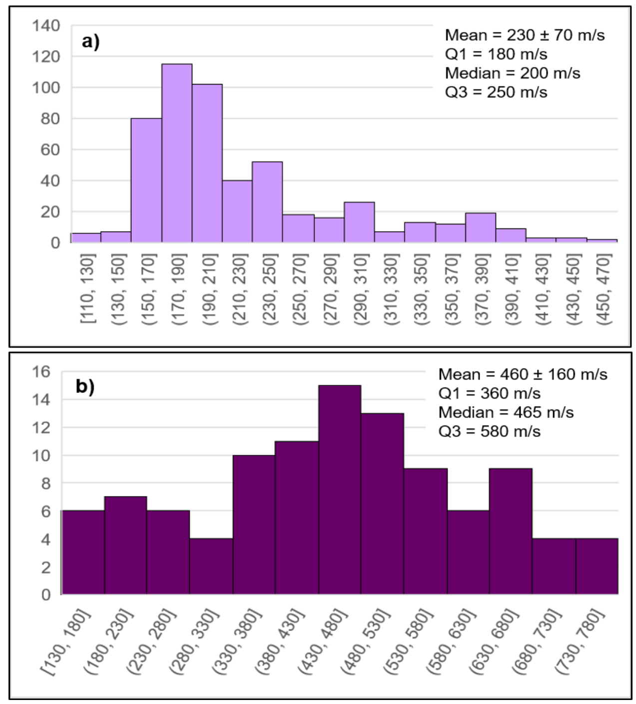

Figure 5. Vs_{30} histogram for (a) DTA, NWM, and RMD (n = 530) and (b) BNB and VAN (n = 104). Q1 and Q3 are first and third quartile, respectively.

We further group Vs_{30} values from the 9 municipalities into two robust subsets (Figure 5): DLT, NWM and RMD (n = 530) and BNB and VAN (n = 104). DLT, NWM and RMD all include softer Holocene sediments of the Fraser River delta; the majority of Vs_{30} values (75% or Q3) are less then 250 m/s. In contrast, BNB and VAN are uplands areas dominated by glaciated till deposits resulting in higher Vs_{30} values. The variability in Vs_{30} is higher (one standard deviation of 160 m/s compared to 70 m/s) primarily because Vs_{30} values have increased. The geology within each municipality is relatively similar for each of the two subsets and there is no overlap in the majority of Vs_{30} values (Q1 to Q3) for the two subsets. It is common to consider Vs_{30} values in terms of the associating earthquake site class used in NBC seismic design codes since 2005. Figure 6 shows distribution of each municipality's Vs_{30} values binned by NBC site class and its associated Vs_{30}

range, normalized according to the Vs_{30} population. WVC and NVC have Vs_{30} distributions that span NBC site class A to C and A to D, respectively. Both BNB and VAN are dominated by NBC site class C as expected; BNB has a more bimodal NBC site class distribution (dominantly C then E) compared to VAN. The modal NBC site class of these municipalities is site class C; NVC is the exception with a modal NBC site class D (40%). CQT is similar to NVC with a wide NBC site class distribution from A to D, with greater proportion corresponding to class D (50%). PCT, RMD and DTA are dominated by lower NBC classes D (> 50%) and E (15-35%). PCT has a balanced distribution around class D with equal distribution into higher class C and lower class E, whereas DTA and RMD are skewed towards lower class E. Interestingly, NBC site class B is rare throughout Metro Vancouver.

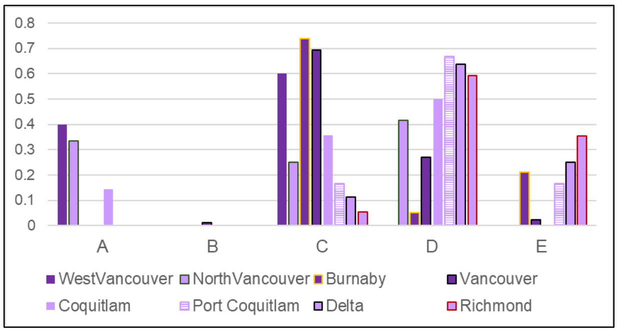

Figure 6. Normalized Vs_{30} distributions by NBC site class for 8 Metro Vancouver municipalities. Municipalities with a modal NBC site class of C and D are shaded purple and light purple, respectively.

The use of earthquake site class in NBC 2005 to 2015 resulted in step function 'jumps' in Canadian seismic design ground motions; a select average Vs_{30} value within each class was used to determine the design ground motions. Figures 3 to 6 serve as evidence to the practicing geotechnical engineer that a default NBC site class C assumption for "Vancouver like" glaciated till sites and a default class D assumption for Fraser River delta sites is correct for ~60-70% of sites. However, there are two important points for consideration as NBC 2020 progresses to direct use of Vs_{30}: (1) these Vs_{30} values are skewed towards the lower half of each class (Vs_{30} is dominantly lower than the mid-point of the class' Vs_{30} range) and (2) NBC site class (and Vs_{30}) is skewed towards lower NBC site classes, i.e., if not C or D then D or E respectively. We therefore investigate impact to Canadian design ground motions based on region specific Vs_{30} estimates in Metro Vancouver in the next section.

6. IMPACT OF Vs_{30} TO CANADASHM6 GROUND MOTIONS

With a validated CanadaSHM6 implemented within OQ, we proceed to calculate 2020 NBC ground motions for 7 select municipalities considering their respective modal Vs_{30} value. We do not determine 2020 NBC ground motions for WVC and NVC in this paper as the CanadaSHM6 model of (Kolaj et al. 2020a) is not valid for use above Vs_{30} 1100 m/s in western Canada. Table 1 summarizes CanadaSHM6 motions for the 7 selected municipalities at a 2% probability of exceedance in 50 years. Figure 7 shows seismic hazard curves in term of PGA (g) for 4 selected municipalities based on their respective modal Vs_{30}. Ground motions are highest for municipalities with the softest ground condition (lowest Vs_{30}) regardless of hazard level.

Table 1: 2020 NBC (CanadaSHM6) ground motions

City	Latitude	Longitude	Mode Vs_{30}	PGA (g)	SA (0.2)	SA (2.0)
Delta	49.089	-123.052	180	0.56	1.21	0.54
Richmond	49.184	-123.112	200	0.53	1.17	0.49
New Westminster	49.221	-122.899	*200*	0.52	1.17	0.41
Port Coquitlam	49.248	-122.785	190	0.46	1.02	0.44
Coquitlam	49.297	-122.755	250	0.44	0.98	0.34
Vancouver	49.248	-123.090	360	0.48	1.09	0.31
Burnaby	49.247	-122.993	630	0.39	0.89	0.20

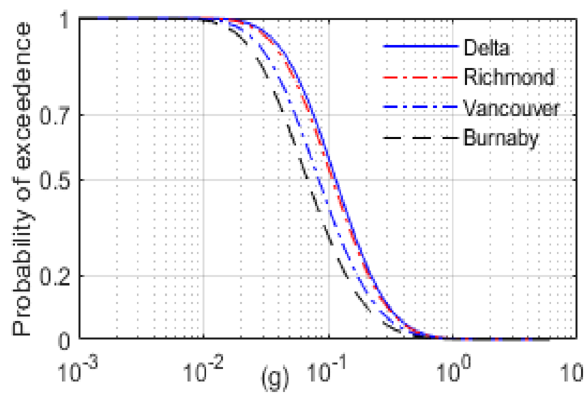

Figure 7. Hazard curve PGA (g) for DTA, RMD, VAN, BNB cities

For select municipalities, Figures 8 and 9 compares 2020 NBC CanadaSHM6 UHS spectra (left panels) depending on X_V or X_S site classifications as well as with 2015 NBC CanadaSHM5 UHS spectra for the respective site class. According to the proposed 2020 NBC, X_V is used when in situ Vs_{30} measurements are available for the site of interest, e.g., Vs_{30} = 200 m/s is X_{200}; modal Vs_{30} is used for each of our municipalities of interest, i.e., the most common in situ Vs_{30} value in each municipality. When in situ Vs measurements are not available to determine Vs_{30}, X_S site classification is determined from in situ N_{60} or S_u measurements averaged over the upper 30 meters, where $_S$ is class A to F, e.g., 15 kPa < S_u ≤ 50 kPa is X_D. In the adopted 2015 NBC, sites are designated into six classifications (A to F) based on in situ Vs_{30}, N_{60} or S_u, e.g., Vs_{30} of 200 m/s corresponds to site class D (180 m/s < Vs_{30} ≤ 360 m/s). Figures 8 and 9 also compares 2020 NBC Sa(2.0) ground motions according to Vs_{30} (right panels) for site classes X_V and X_S with 2015 NBC Sa(2.0) motions for the respective Vs_{30}-based site class. It is readily observed how 2015 NBC and 2020 NBC X_S motions are step-wise functions whereas the 2020 NBC X_V motions are continuous functions depending on Vs_{30}. Since X_S motions correspond to the highest motions within each site class' Vs_{30} bounds (Kolaj et al. 2020a) use of in situ Vs_{30} measurement (X_V) will often be the most impactful at the upper Vs_{30} limit of each site class.

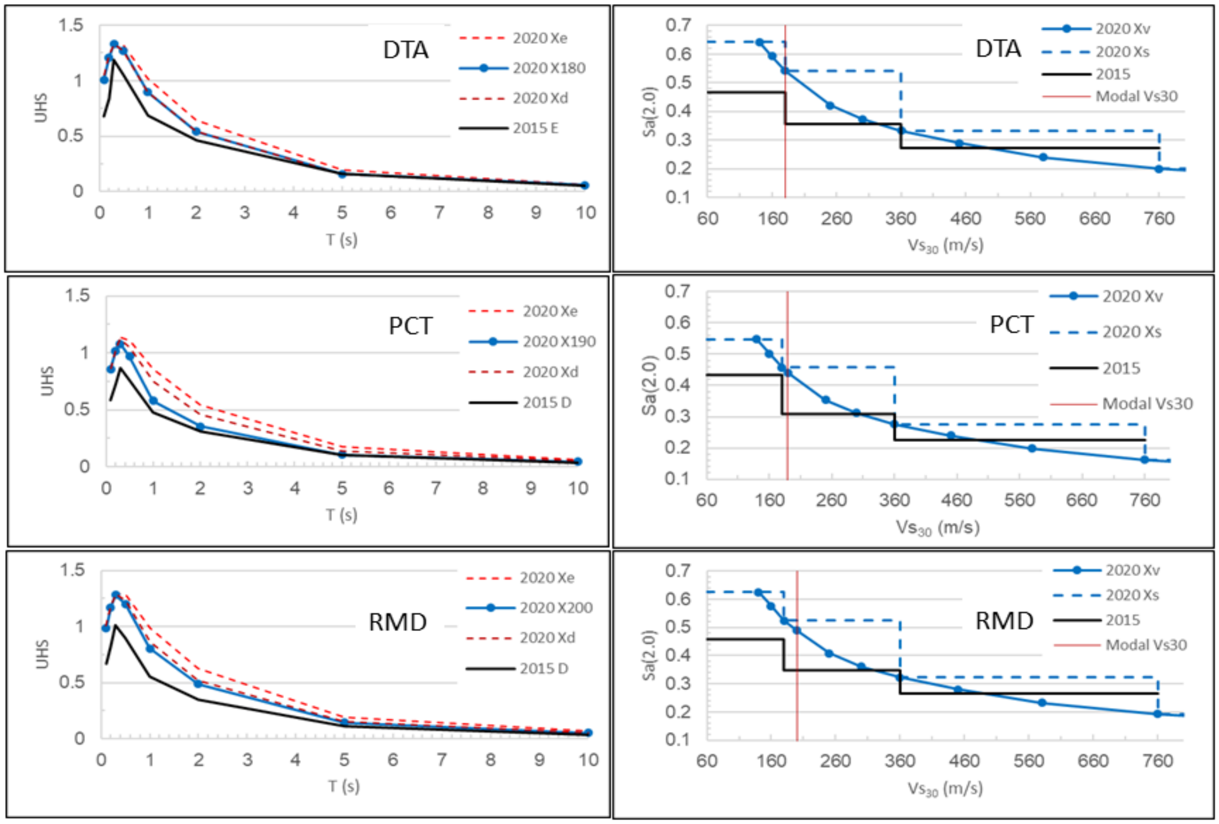

Figure 8. Comparison of 2020 NBC ground motions based on X_V or X_S site classifications for three select municipalities (X_V is based on modal in situ Vs_{30}) and 2015 NBC motions for the same respective site class.

Figure 8 focuses on 2020 NBC (X_V and X_S classifications) and 2015 NBC ground motions for the three municipalities with lower modal Vs_{30} values related to dominance of Fraser River delta site conditions. For DTA, X_{180} occurs at the boundary between X_D and X_E; X_{180} motions correspond to X_D motions. In other words, measuring an in situ Vs_{30} of 180 m/s, which we determine to be the most commonly measured Vs_{30} in DTA, results in 16% lower design ground motions than if Vs_{30} was not measured (X_E motions would apply based on N_{60} and s_u). PCT and RMD with increasing modal Vs_{30} also demonstrate lower design ground motions than if Vs_{30} was not measured although the design 'cost savings' is less; difference between X_D and X_V motions is smaller than the difference between X_E and X_D, i.e., X_{180}. The third quartile Vs_{30} value for DTA, PCT and RMD (75% of in situ Vs_{30} values are lower) is 245 m/s, 345 m/s and 288 m/s respectively (Figure 4). In situ Vs_{30} values in PCT are more likely to reach the upper range of class D than in DTA and RMD. Hence performing in situ Vs_{30} measurement at a site within PCT has the greatest potential to reduce 2020 NBC ground motions amongst the three municipalities. We have focused our discussion on Sa(2.0) motions and our comments are applicable at spectral periods > 0.3 s; at shorter periods, there is very little difference between X_V and X_S motions. In all cases, 2020 NBC motions are higher than the 2015 NBC ground motions of the respective site class; performing in situ Vs_{30} measurement in these municipalities cannot reduce design ground motions to the previous 2015 NBC design level.

Figure 9 focuses on 2020 NBC (X_V and X_S classifications) and 2015 NBC ground motions for three municipalities with higher modal Vs_{30} values related to thinner and/or stiffer site conditions. Modal Vs_{30} for CQT corresponds to a central class D designation, so having performed in situ Vs_{30} measurement (X_{250}) reduces design ground motions by as much as 23% between 0.3 and 2 seconds in comparison to when in situ Vs_{30} is not performed (X_D). Similar to DTA, VAN also has a modal Vs_{30} value at the boundary between X_D and X_C. The 'cost savings' in performing in situ Vs_{30} measurements to reduce design ground motions has the greatest impact at X_{360}; 39% reduction in Sa(1.0) motions between X_{360} and X_D classifications. The Vs_{30} quartile range for these three municipalities spans classes D and C with $Q_3 \leq 630$ m/s; hence the greatest reduction in 2020 NBC ground motions will occur when in situ Vs_{30} measurements are performed for the stiffest class D sites, i.e., there is less reduction in 2020 NBC ground motions when Vs_{30} is measured within class C. Notably once Vs_{30} is higher than approx. 500 m/s, performing in situ Vs_{30} measurements can reduce 2020 NBC ground motions below the current 2015 NBC design level. This situation should be more frequent in BNB compared to VAN; the median to Q3 range for BNB is 500-630 m/s compared to 450-580 m/s for VAN.

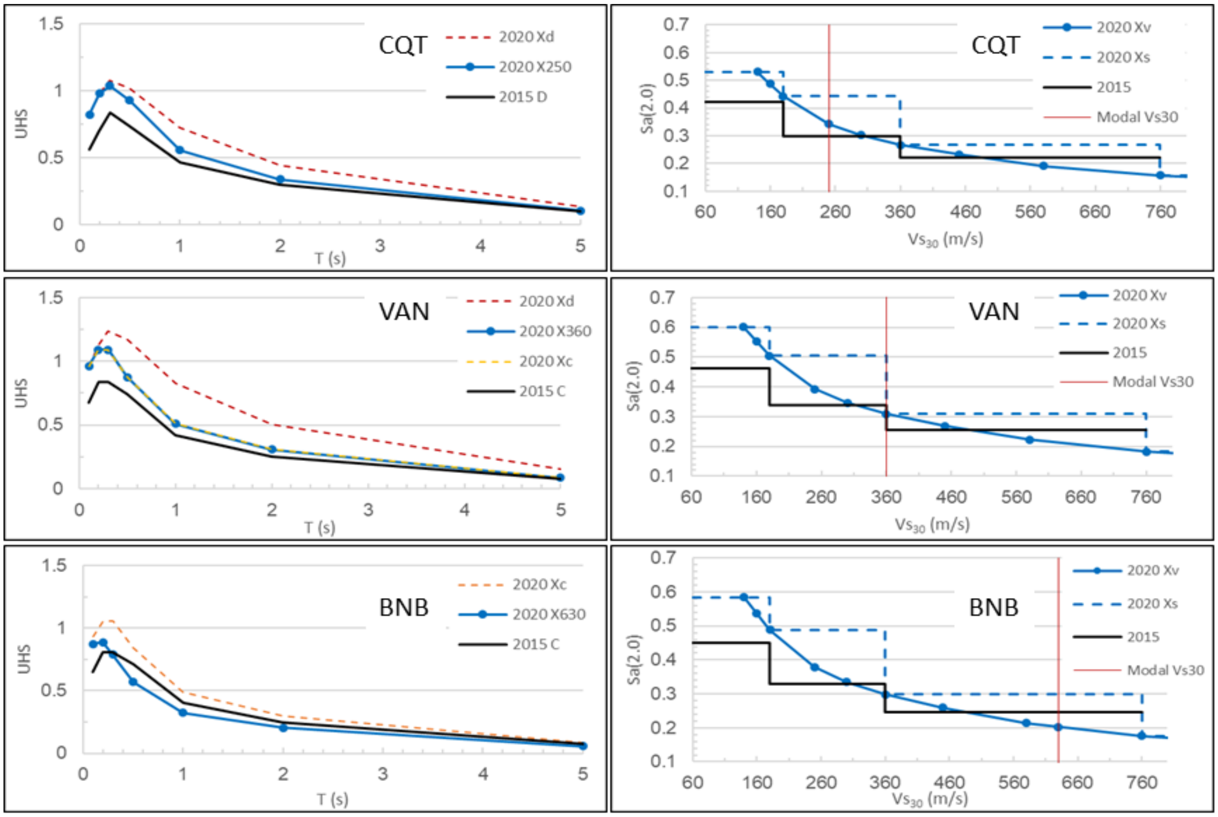

Figure 9. Same as Figure 8 for three other select municipalities.

7. CONCLUSION

The aim of this paper was to evaluate region specific in situ Vs_{30} measurements in western Metro Vancouver then the potential impact to 2020 NBC ground motions depending on Vs_{30} directly rather than NBC site class. Region specific Vs_{30} estimates were derived from 680 in situ Vs profiles from the Metro Vancouver seismic microzonation mapping project geodatabase. Preliminary Vs_{30} distributions and statistical measures were determined for 9 municipalities; modal Vs_{30} ranges from 180 to 2330 m/s across the region. We compiled two robust Vs_{30} datasets and determined the Vs_{30} quartile range to be 180-250 m/s for Fraser River delta and 360-580 m/s for uplands glaciated till site conditions respectively. When Vs_{30} is binned by NBC site class, we determine that: (1) site class B is rare, (2) WVC spans higher site classes A to C, (2) NVC and CQT have the widest span in site class (A to D) and therefore greatest variability in site conditions, (3) both BNB and VAN are dominantly class C as expected but BNB has a higher modal Vs_{30} than VAN and a more bimodal class C then E distribution, and (4) of the three lowest Vs_{30} mode municipalities, PCT has a balanced distribution around class D whereas DTA and RMD are skewed towards lower class E. We then implemented use of these region specific in situ Vs_{30} measurements to evaluate impact to 2020 NBC ground motions.

We first validated our implementation of the CanadaSHM6 within GEM OpenQuake to generate the 2020 NBC ground motions for Vancouver city hall. We then implemented use of in situ Vs_{30} (2020 NBC X_V site class) to determine CanadaSHM6 ground shaking hazard for multiple cites of Metro Vancouver in comparison to 2020 NBC motions when in situ Vs_{30} is not measured (X_S site class based on N_{60} or s_u) and 2015 NBC motions for the respective site class based on Vs_{30}. The most common in situ Vs_{30} value in DTA and VAN occurs at the upper limit of a NBC site class range and thereby having performed in situ Vs_{30} measurement results in the largest possible reduction in 2020 NBC (X_V) motions compared to 2020 NBC X_S motions when Vs_{30} is not measured. In addition, in situ Vs_{30} measurements of PCT and BNB most commonly occur within the upper Vs_{30} range of a particular site class. In situ Vs_{30} measurements in these two municipalities will result in significantly reduced 2020 NBC X_V motions compared to X_S motions and will notably be below the corresponding 2015 NBC design level.

A potential significant limitation in this paper is not considering NBC site class F ($Vs_{30} \leq 140$ m/s) and site designation exceptions (Table 4.1.8.4.-A in 2020 NBC). We are in the process of identifying liquefiable soil throughout the region (Javanbakht et al. 2021a, 2021b) which will impact site designation throughout DTA and RMD and smaller areas elsewhere. This paper highlights how in situ Vs_{30} measurements could lower 2020 NBC motions (X_V motions compared to X_S motions) when the 30 m profile is determined to not include liquefiable soils.

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