Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Metro Vancouver Seismic Hazard Mapping Inclusive of 1D and 3D Basin Effects

J. Assaf[1], H Ghofrani[2], M. H. El Naggar[3], S. Molnar[2*]

[1] University of Western Ontario/WSP, Vancouver, BC
[2] University of Western Ontario, Dept. Earth Sciences
[3] University of Western Ontario, Dept. Civil and Environmental Engineering
[*]smolnar8@uwo.ca (Corresponding Author)

ABSTRACT

The Metro Vancouver seismic microzonation mapping project is achieving the first region-specific earthquake shaking hazard mapping in all of Canada, developed from one-dimensional (1D) and three-dimensional (3D) numerical earthquake simulation predictions and the region's probabilistic seismic hazard. To achieve 1D site response analyses (SRA), region-specific reference site conditions are determined and input time histories compatible with probabilistic seismic hazard of the 2020 National Building Code (NBC) at the 2% and 10% probability of exceedance in 50 years hazard levels are developed. Linear and nonlinear 1D SRAs are performed at 51 sites to capture the regional subsurface variability. Differences between the 1D SRA amplifications and empirical amplification of one ground motion model (GMM) of the 2020 NBC probabilistic seismic hazard model confirm the need to achieve 1D SRA for region-specific amplification. Trends between SRA amplification and important seismic site characteristics (Vs_{30}, T_0) are assessed to develop a region-specific predictive 1D site amplification model for regional-scale mapping. Physics-based 3D ground motion simulations are conducted using parallelized finite-difference wave propagation for large magnitude crustal and intraslab earthquake rupture scenario models; Cascadia mega-thrust interface scenarios were simulated by the University of Washington's M9 project. The suite of 3D simulated motions is used to quantify basin amplification by partitioning the total residual, as the difference between the 3D simulated motion and the GMM or non-basin prediction. Long-period ground motions (> 1 s) are increased by inclusion of 3D basin amplification estimates in the deepest locations in southwestern Metro Vancouver (Richmond and Delta). The planned Metro Vancouver earthquake shaking hazard map deliverables includes a suite of ~10 maps at ~5 select spectral periods (PGA, 0.2 s, 1.0 s, 2.0 s, 5.0 s) and at 2 hazard levels (2% and 10% probability of exceedance in 50 years).

Keywords: Vancouver, Site effects, Site response, Amplification, Basin Amplification.

INTRODUCTION

The Metropolitan (Metro) Vancouver seismic microzonation mapping project (MVSMMP) is a multi-year (2017-2024) research project to generate a suite of region-specific seismic hazard maps that capture local earthquake site effects, specifically earthquake shaking inclusive of 1D site and 3D sedimentary basin effects and seismic-induced liquefaction and landslide hazard potential (https://metrovanmicromap.ca, Molnar et al. [1]). The project is led by the University of Western Ontario with the Institute of Catastrophic Loss Reduction and with support from the British Columbia (BC) Ministry of Emergency Management and Climate Readiness. The MVSMMP study area is western Metro Vancouver, including 16 municipalities, 4 First Nation communities, and 1 electoral area. This paper provides detailed methodology to achieve seismic hazard mapping of western Metro Vancouver including shaking (de/amplification) hazard of both 1D site and 3D basin effects. Other papers in this special session document development of: (1) a comprehensive geodatabase for western Metro Vancouver involving over 120 days of multi-method non-invasive *in situ* seismic testing [1]; (2) three-dimensional (3D) velocity models [2], seismic-induced landslide mapping [3], liquefaction hazard potential mapping [4], advancements in microzonation and guidelines [5].

This paper focuses on achieving the region-specific mapping of shaking hazard using 1D site and 3D basin simulations to update the 6th generation national seismic hazard model's (2020 National Building Code of Canada) probabilistic ground motions for the region. Details and preliminary results of the 1D site and 3D basin simulations are presented in this paper.

1D SITE RESPONSE ANALYSES

Site effects represent the effect of near surface geology on the propagation of seismic waves arriving at a site. Ground motion models (GMMs) predict earthquake ground motions based on three major variables: source parameters (e.g., magnitude, stress drop), source-to-site (path) distance, and site parameters (e.g., the time-averaged shear wave velocity (Vs) of the upper 30 meters (Vs_{30}), depth (Z) to a Vs of 1.0 or 2.5 km/s ($Z_{1.0}$ or $Z_{2.5}$), and peak site frequency (f_{peak})). The applicability of the inherent site effect model in each regional GMM is often assumed valid when the two regions share similar seismotectonic and geological settings. However, site effects are best captured through region-specific models developed using representative information from that region. Due to the limited quantity of observed earthquake recordings in Metro Vancouver, 1D site response analysis (SRA) is conducted to develop a region-specific site effects (de/amplification) model for Metro Vancouver.

The compiled comprehensive Vs depth (z) profile (Vs(z)) database of the MVSMMP [1] with over 800 locations) is examined to select sites for SRA. Figure 1 shows the locations of 51 sites that are identified to have sufficient *in situ* measurements (e.g., Vs(z), borehole lithology, depth to glacial till (z_{gl})) to perform 1D SRA. These 51 sites are spatially distributed to provide a representative sample of the subsurface site conditions across Metro Vancouver. The input time histories and SRA modeling details at the 51 sites are provided in the following sections.

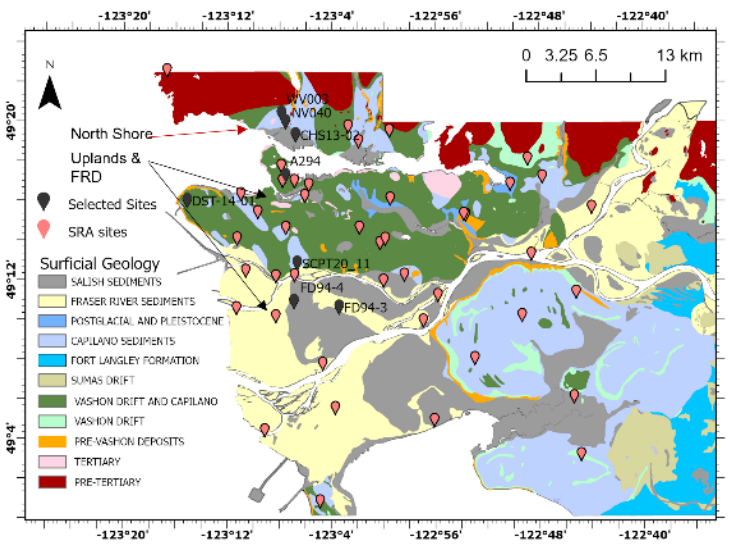

Figure 1. Locations of 51 sites (black and pink ballons) selected for 1D SRA in Metro Vancouver overlaid on the compiled Quaternary geology map.

Input Time Histories

Input time histories are typically applied at a selected reference site condition (i.e., half-space) in the 1D SRA. The reference site conditions at the base of the 51 sites are variable; Tertiary sedimentary rocks of the Georgia Basin underlies the Uplands and Fraser River delta areas, and Pre-Tertiary plutonic rock underlies the North Shore area. The Vs(z) of Tertiary and Pre-Tertiary rocks from the MVSMMP database [1] are examined and compared to the inherent Vs(z) of western North America crustal source GMMs [6]. Based on this comparison, the reference site condition (base of 1D SRA model, depth at which input motions are applied) for the Uplands and Fraser River Delta (FRD) is selected as V_{S30} = 760 m/s, and a Vs_{30} = 1500 m/s is selected for the North Shore area. The 6th Generation Seismic Hazard Model of Canada (CanadaSHM6; [7]) is used to develop the target spectrum at the selected reference conditions for each of the three earthquake sources (North American crustal, Juan de Fuca intraslab, and Cascadia interface) for input time histories development at two probabilities of exceedance (POE) (2 and 10 % in 50 years). Two locations in the FRD and Uplands (reference Vs_{30} = 760 m/s), and one site in the North Shore (reference Vs_{30} = 1500 m/s) are selected for scaling the time histories. For each earthquake source type and POE, 11 time histories are selected from available earthquake catalogs and linearly scaled to the source-specific target spectrum (between PGA and 6.5 seconds) such that their geometrical mean does not fall below 90 % of the target spectrum. A total of 66 time histories are scaled for each of the three sites for the two POEs. Time histories at SRA sites are obtained by linearly scaling time histories developed at one of these 3 sites. Following this procedure, 66 input time histories are derived for each SRA site representing the 3 earthquake source type scenarios and the 2 selected POEs.

1D Site Models

Material properties (soil types, unit weights, Vs, plasticity index) are obtained from the Metro Vancouver project's geodatabase [1, 8] and available geotechnical reports. Dynamic modulus reduction and damping (MRD) curves are determined from a literature review of geotechnical reports in the Metro Vancouver project's geodatabase (e.g., [9]). The Seed and Idriss upper and lower MRD curves [10] are used for sands and sand and gravels and Vucetic and Dobry MRD curves [11] are used for silts and silts, clays, and glacial sediments. The MRD curves for glacial sediments are assigned a higher PI with depth to consider the effects of increasing effective stress with depth. Site characteristics of 8 SRA sites are listed in Table 1.

Both linear and nonlinear 1D SRAs are performed for each site using DEEPSOIL (version 7; [12]). The modified Konder-Zolasko (MKZ) model is fit to the reference MRD curves using the non-Masing fitting tool. The small-strain damping (Dmin) obtained from the fitted MKZ model is also adopted for linear analysis.

Table 1. Site characteristics of 8 SRA sites.

Location	Site	Vs_{30} (m/s)	T_0 (s)$^+$	z_{gl} (m)	z_{brk} (m)
FRD	FD94-4	140	5.20	235	526
FRD	FD94-3	206	3.77	19	464
FRD	SCPT20-11	195	2.06	22	200
Uplands	A294	427	0.21	1	16
Uplands	DST14-01	422	1.53	3	200
North Shore	CHS13-02	231	1.73	92	122
North Shore	NV040	489	0.36	3.4	49
North Shore	WV003	507	0.18	1	16

$^+$ T_0(s) calculated as $4\sum h_i/Vs_i$ where h_i and Vs_i are the thickness and Vs of layer i. z_{gl} = depth to glacial sediments. z_{brk} = depth to bedrock.

1D Site Amplification Model

For the linear and nonlinear SRAs, the horizontal surface spectral acceleration is divided by the input motion's spectral acceleration to calculate the site amplification spectrum. The obtained amplification is compared to the Seyhan and Stewart [13] amplification model adopted in western North America crustal source GMMs of the 2020 NBCC [14], hereafter referred to as the BSSA14 amplification model. The BSSA14 linear site amplification is calculated given the Vs_{30} at each site (Table 1). The SRA amplification for North Shore sites with a higher reference site condition (Vs_{30} = 1500 m/s) are corrected to amplification with the same V_{S30} = 760 m/s reference as the FRD and Uplands and the BSSA14 amplification model by multiplying them by the mean 2020 NBCC generic amplification (ratio of 2020 NBC motions at Vs_{30} of 1500 m/s to 760 m/s). The mean linear amplification for each earthquake source (from 22 input time histories) at each SRA site is compared to the BSSA14 linear amplification in Figure 2. The mean linear amplification values from different earthquake source types are generally similar at each of the 8 sites presented here (similarity of red, green and blue lines in Figure 2). For sites with deep bedrock (FD94-4, FD94-3, SCPT20-11), the BSSA14 linear amplification is higher than the SRA amplification specifically at longer periods. For shallow sites (e.g., WV003), the SRA linear amplification exceeds the BSSA14 model's amplification at specific (resonance) periods.

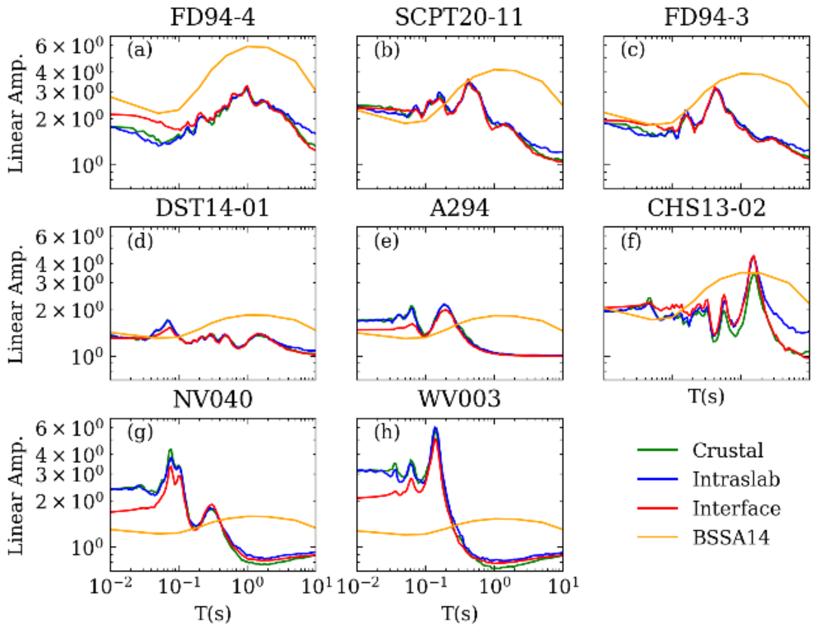

Figure 2. Mean linear amplification from 1D SRA for each earthquake source type at 8 sites in comparison to the BSSA14 GMM linear amplification model.

Figure 3 plots the linear and nonlinear SRA amplification at 8 spectral periods for the deep FRD site FD94-4 with respect to the input PGA at rock (PGA_r) for both POE input ground motion levels; 10 % POE input motions have lower PGA_r than 2 % POE, and linear SRA amplification from Figure 2 are plotted at a PGA_r of 0.001 g. The BSSA14 model's amplification calculated given the FD94-4 site's Vs_{30} of 140 m/s is also plotted in Figure 3 for comparison. More prominent de-amplification occurs as PGA_r increases due to nonlinear soil behaviour. The strongest observed de-amplification occurs for intraslab source input motions due to their higher PGA_r. The nonlinearity due to Cascadia interface source input motions can be stronger than that of North American crustal source motions with similar PGA_r for some periods due to their higher induced shear strains. Compared to the BSSA14 amplification model, SRA results demonstrate stronger nonlinearity manifested as a steep slope of decreasing amplification with increasing PGA_r.

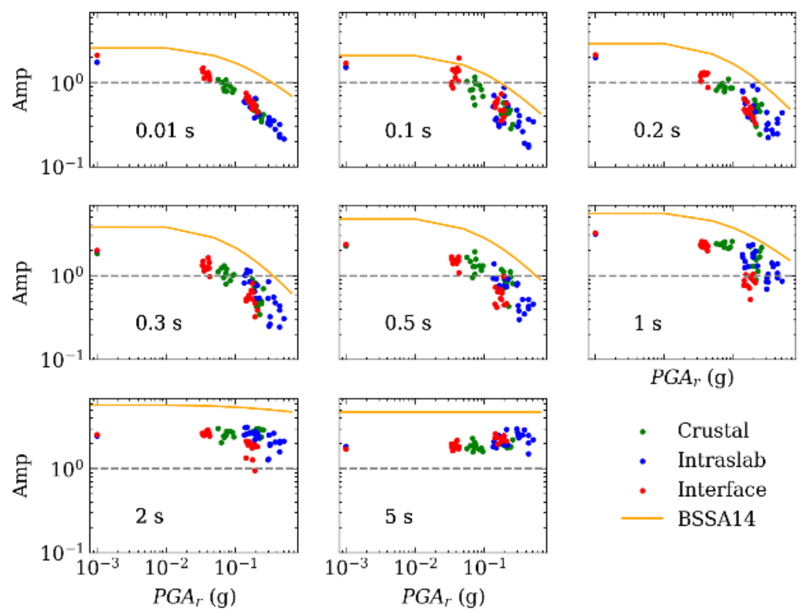

Figure 3. SRA linear and nonlinear amplification with PGA_r in comparison to BSSA14 amplification at FRD site FD94-4 (z_{gl} = 235 m).

Our SRA amplification results from the 8 sites indicates that the BSSA14 ergodic amplification model predicts weaker nonlinearity than predicted from SRA at sites with thick, soft post-glacial sediments in Metro Vancouver and underestimates the SRA amplification at shallow sites with a strong impedance contrast. Shallow site conditions in the North Shore are similar to Central Eastern North America (CENA) site conditions where a strong impedance contrast between soil and (Paleozoic to Precambrian) bedrock exists near surface. For such site conditions, it is expected that Vs_{30}-based amplification may not capture the resonance amplification [15] and T_0 may be a more powerful predictive amplification proxy.

Trends in SRA amplification with Vs_{30} and T_0 are therefore of interest to develop a region-specific amplification model for seismic microzonation mapping purposes. Figure 4 shows the linear and nonlinear SRA amplification with PGA_r from all three earthquake sources at all 8 sites according to 3 major categories of Vs_{30} representing soft (140-295 m/s) to stiff (422-507 m/s) site conditions. Figure 4 shows nonlinearity (deamplification) increases with PGA_r for lower Vs_{30} sites, and less significantly for higher Vs_{30} sites. Similar trends are observed with T_0 (not shown here). It is expected that a combination of both Vs_{30} and T_0 can better capture site-specific (SRA) amplification regionally in Metro Vancouver than just V_{S30} alone. A region-specific amplification model based on Vs_{30}, T_0, and PGA_r is under development from 1D SRAs at all 51 sites to achieve shaking hazard microzonation mapping.

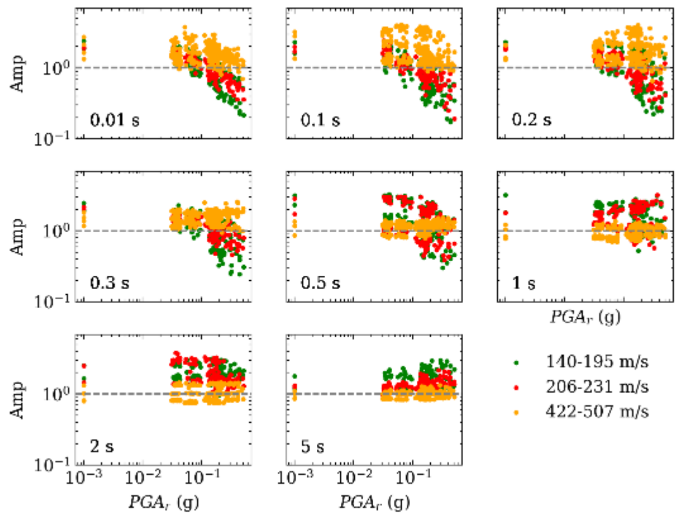

Figure 4. SRA linear and nonlinear amplification with PGA_r at 8 spectral periods for all 8 sites considering different Vs_{30} categories (colours).

3D BASIN EFFECTS

1D SRA can underestimate ground motions at longer periods due to additional basin amplification not accounted for in 1D modeling. It is well known that the Late-Cretaceous Georgia sedimentary rock basin beneath Metro Vancouver can produce additional long-period amplification due to the interaction between the 3D basin structure and the incident seismic waves [16, 17, 18]. This interaction can lead to surface wave generation at the edges of the basin which cannot be captured by 1D SRA. Combination of the shallow 1D SRA amplification results with surface ground motions predicted using 3D wave propagation simulations will provide a more complete understanding of regional site amplification in Metro Vancouver.

The 3D base elastic model used to accomplish 3D finite-difference wave propagation simulations is an updated version of the Stephenson et al. [19] Pacific Northwest 3D velocity model. The physical model is represented by six geologic units (continental basin sediments, crust, and mantle; and oceanic sediments, crust, and mantle) characterized by compressional velocity (Vp), Vs, and density. A non-basin 3D model [16] was also generated by setting the minimum V_P to 5.5 km/s, effectively replacing basin sediments with inferred basement. The non-basin velocity model is based on the typical 1D velocity profile for rock sites in southwest British Columbia.

While this work uses the mentioned existing 3D Vs model, Ghofrani et al. [2] presents the planned improvement of the existing 3D Vs model in southwest BC model through integrating two separate sources of information: (1) Ambient Noise Tomography survey achieved by MVSMM to refine the deeper model layers (up to 60 km), and (2) a geotechnical layer from MVSMM regional geodatabase to generate higher-resolution layers at shallow depths (< 1 km depth). The improved 3D Vs model is expected to better reflect the 3D settings in southwest BC.

The 3D elastic equations of wave motion are solved using the finite difference (FD) scheme of Olsen [20] with fourth-order accuracy in space and second-order accuracy in time with a maximum resolvable frequency of 0.5 Hz (2 s) [16, 17]. The minimum Vs in the Georgia basin model is set to 625 m/s; hence, the surface of the 3D basin model represents over-consolidated Pleistocene glacial sediments or stiff soil sites.

Basin Amplification from Crustal and Intraslab Earthquake Scenarios

A total of eight potential large blind-thrust shallow North America (NA) plate earthquakes in the Georgia basin region are simulated within 100 km of Greater Vancouver; locations and rupture characteristics of scenario earthquakes were based on recurrent shallow seismicity and a chosen kinematic rupture model of the 1994 Mw 6.7 Northridge, California, blind-thrust earthquake, respectively [16]. A total of 10 deep subducting Juan de Fuca (JdF) plate earthquakes were simulated within 100 km of Greater Vancouver [17]. Simulations were calibrated using seismometer and strong-motion instrument recordings from the 2001 Mw 6.8 Nisqually earthquake. Scenario earthquakes include deep (> 40 km) subducting JdF plate earthquakes, simulated in locations congruent with known seismicity.

Two methods are used to calculate the basin (long period) amplification from the crustal and intraslab scenario's 3D simulated motions. Method 1 partitions the residuals from the 3D simulated motions and the motions predicted by the BSSA14 GMM for the same site conditions (V_{S30}) into an event term and systematic site misfits (referred to as site terms). The site term is the systematic misfit resulting from the difference between amplification at a particular site and the global Vs_{30}-based site-response model. No specific trend could be observed using different GMMs; in other words, the same amount of basin amplification based on the BSSA14 model seems to be applicable for other western North America crustal source GMMs (e.g., other GMMs of NGA-west2). Method 2 uses the residuals from the 3D simulations and an additional simulation using the non-basin 3D model (i.e.,1D crustal model) for reference site conditions without basin effects. The 1D crustal model does not include the geometry of the sedimentary basin. After performing event-specific fits, the differences between within-event residuals from 3D and 1D simulations result principally from the 3D basin model's "site" response. Using simulated motions from all scenario events, the mean site amplification for each site, relative to the reference condition from the 1D simulations, can then be computed using mixed-effects regression analysis.

The basin amplification from all crustal scenarios (intraslab scenarios analysis is still in progress) using Methods 1 and 2 are plotted in Figure 5a and b, respectively, according to each of the 475 considered site's $Z_{2.2}$ (depth to a Vs 2.2 km/s) in comparison to empirical basin amplification from Campbell and Bzorogina [25], assuming $Z_{2.5}$ equivalent to $Z_{2.2}$. Basin amplification of Method 2, while broadly similar to those from Method 1, are lower on average than basin amplification of Method 1. Residuals patterns are significantly scenario-dependent, which is more evident in Method 2; there is a large dispersion around the mean at larger basin depths ($Z_{2.2}$ > 3000 m). Both methods help understand the epistemic uncertainty associated with predicting 3D basin amplification. Based on these results, basin amplification factors will be considered in seismic microzonation mapping of Metro Vancouver at deep basin sites ($Z_{2.2}$ > ~2.5-3.0 km) in Delta and Richmond. For shallower basin sites, basin amplification factors are near unity and Vs_{30} and/or a combination of Vs_{30} and T_0 would be sufficient to capture the (shallow) site effects.

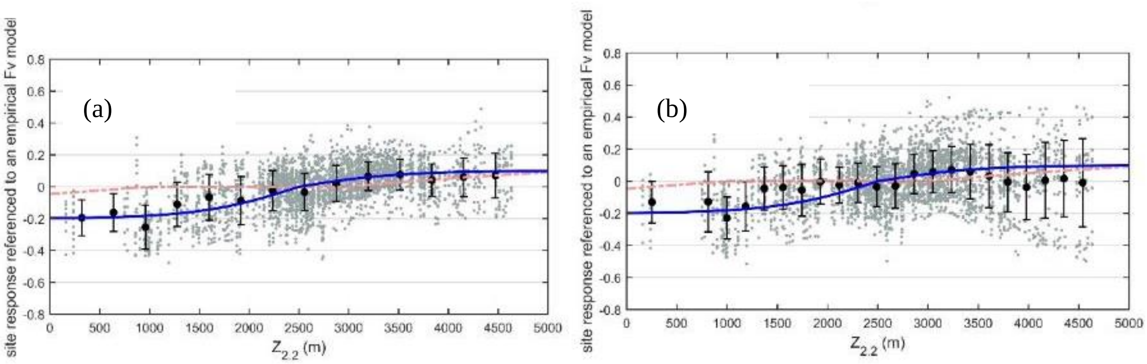

Figure 5. *Basin amplification (best fit line) referenced to 760 m/s (blue) in comparison to Campbell and Bozorgnia basin model [25] model (pink) based on (a) Method 1 and (b) Method 2. Grey circles show residuals from all scenarios at each site. The mean and +/-1 standard deviation of residuals within $Z_{2.2}$ bins are shown by filled black circles and vertical bars, respectively.*

Ground motions from different earthquake sources (North American crustal, Juan de Fuca intraslab, and Cascadia interface) may give rise to differences in basin response due to their differences in depth and crustal structure. Frankel et al. [21] found that variations in earthquake location cause large variations in low-frequency spectral accelerations in simulations of the Seattle basin response to large interface Cascadia subduction earthquakes. For a given earthquake source category, there will be differences due to differences in the angle of incidence with which the seismic waves enter the basin. The preliminary results of our study of basin amplification based on intraslab scenario earthquakes ground motions suggest that they are not drastically different from crustal events at a resolved frequency of 0.5 Hz

Basin Amplification from Cascadia Mega-Thrust Earthquake Scenarios

3D simulated motions from the USGS-UW **M**9 project [21] are used to assess basin amplification in Metro Vancouver from Cascadia mega-thrust interface earthquake scenarios [22]. The simulated ground motions were derived from 3D finite-difference simulations for periods exceeding 1 s that explicitly considered basin effects, and synthesis with stochastically modelled motions for periods less than 1 s. These synthetic broadband ground motions were developed using the Pacific Northwest CVM developed by the USGS [23]; a spatial uniform-grid resolution of 500 m, which explicitly considers deep sedimentary basins in the region (e.g., Seattle basin, Georgia sedimentary basin). The velocity model was utilized in the 3D finite difference simulations; thus, the simulated ground motions account for basin amplification effects at periods greater than 1 s. We group the stations into basin, basin-edge, and outside basin (i.e., reference) sites based on their locations with respect to $Z_{2.5}$ (depth to Vs of 2.5 km/s).

We calculate the averaged basin amplification factors (BAFs) from the broad-band synthetics of the M9 project's 30 Cascadia interface earthquake scenarios for sites in the basin with $Z_{2.5}$ of 3.0 km and larger, relative to non-basin reference sites located approximately at the $Z_{2.5}$ = 1.0 km isocontour (Figure 6). The log averaged BAFs at periods of 1–10 s ranges from about 1.5 to 2.2, with a broad peak of ~2.0 between 1.5 and 2.0 s. The amplification is scenario dependent and can range anywhere between ~1.2 and ~4.0 (i.e., ±1 standard deviation of the BAF values at 1.5 s). Rupture characteristics of each scenario are important and contribute to the variability of the simulated ground motions at a wide range of periods.

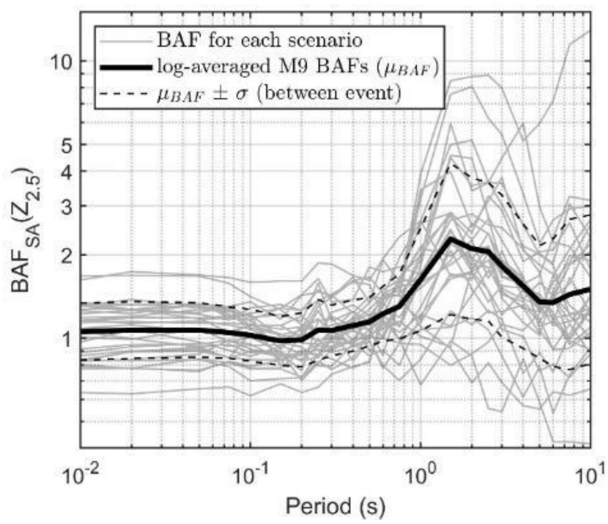

Figure 6. Basin amplification factor (BAF) determined from broadband synthetics of 30 Cascadia interface earthquake scenarios for sites in the Georgia basin (within mainland Vancouver) with $Z_{2.5} \geq 3.0$ km. Each thin gray line represents the amplification for a given scenario. The expected and ±1 standard deviation of the BAF from interface earthquakes are shown with the tick solid and thin dashed black lines, respectively.

COMBINING 1D SITE AND 3D BASIN AMPLIFICATION

The previous sections described the 1D SRA and 3D physics-based simulations considered for obtaining a region-specific amplification model inclusive of 1D site and 3D basin effects for Metro Vancouver. The long period (T > 1 s) basin amplification from 3D simulations will be added to the 1D SRA amplification model. It is expected that these basin amplification factors will be applicable to Metro Vancouver areas with $Z_{2.2}$ (~ $Z_{2.5}$) > 2.5 km corresponding to southwestern Metro Vancouver (cities of Richmond and Delta). The final developed region-specific amplification model including 1D site and 3D basin amplification will be integrated within the CanadaSHM6 GMMs to replace the empirical amplification models developed from other regions in the world (e.g., California and Japan). This requires replacing the mean site amplification and proper handling of the aleatory variability (standard deviation) inherent in GMMs and the epistemic uncertainties in the developed site amplification. Probabilistic seismic hazard analyses with our region-specific amplification model modifications to the CanadaSHM6 GMMs will be performed using OpenQuake [24]. These PSHA results will be combined with seismic microzonation susceptibility maps of Vs_{30}, T_0, PGA_r, and $Z_{2.5}$ or $Z_{2.2}$ developed by the MVSMMP to obtain a region-specific hazard-consistent surface shaking hazard maps for 2 and 10 % POE in 50 years risk levels at five selected periods.

CONCLUSIONS

This paper presents the EGBC peer-reviewed methodology [5] to achieve shaking hazard mapping inclusive of 1D site and 3D basin effects for western Metro Vancouver. Numerical 1D and 3D physics-based modelling are utilized to determine 1D site and 3D basin amplification in Metro Vancouver and to develop a region-specific site amplification model to update the inherent site amplification models of the CanadaSHM6 GMMs. The current amplification factors in CanadaSHM6 GMMs neglect basin amplification and are developed from different regions and thus don't capture local site effects in Metro Vancouver. The region-specific amplification model is expected to better represent ground motions specific to Metro Vancouver.

51 sites that represent the variability in the subsurface conditions in Metro Vancouver are selected for 1D SRA to develop a region-specific site effects (de/amplification) model. The 1D SRA results for the 8 sites presented here indicate that an ergodic GMM (BSSA14) site amplification model for western North America crustal source earthquakes predicts higher linear amplification compared to SRA linear amplification at deeper sites in Metro Vancouver, and underestimates linear SRA amplification at shallow sites, specifically in North Vancouver where a strong impedance exists between glacial sediments and Pre-Tertiary rock. In terms of nonlinearity, deep soft sites in Metro Vancouver exhibit stronger nonlinearity and SRA de-amplification at short periods compared to the GMM's nonlinear model. Trends between SRA amplification and Vs_{30}, T_0, and PGA_r were assessed. A region-specific site effects (de/amplification) model will be developed using shaking hazard susceptibility maps of Vs_{30} and T_0 due to the wide range of Metro Vancouver subsurface conditions (very shallow to very deep).

As 1D SRA can underestimate amplification at longer periods, 3D physics-based wave propagation simulations are conducted within a regional velocity model [2] for crustal, intraslab and interface earthquake scenarios to estimate basin amplification. The suite of 3D simulated motions for crustal and earthquake scenarios is used to quantify basin amplification by partitioning the total residual, as the difference between the 3D simulated motion and the GMM or non-basin 3D simulations prediction, at periods > 2 s. Basin amplification factors at periods of 1–10 s for Cascadia interface earthquake scenarios ranges from about 1.5 to 2.2, with a broad peak of ~2.0 between 1.5 and 2.0 s. To include 3D basin amplification, the 1D SRA amplification will be modified to reflect the additional basin amplification at long periods (> 1 s) from different earthquake sources. Thus, the final region-specific amplification model will be based on Vs_{30}, T_0, PGA_r and basin term (e.g., $Z_{2.5}$) parameters. The developed region-specific amplification model will replace the inherent site amplification model of each CanadaSHM6 GMM in the probabilistic seismic hazard analysis to regionally predict site-specific earthquake ground motions in Metro Vancouver. The MVSMMP will produce ~10 shaking hazard maps for western Metro Vancouver at ~5 spectral periods and for the selected 2 and 10% probability of exceedance in 50 years risk levels.

ACKNOWLEDGMENTS

We are grateful to Erin Wirth, Nasser Marafi, and Art Frankel for sharing the M9 project's interface earthquake simulated ground motions. Project funding was provided by the Institute of Catastrophic Loss Reduction with support from the BC Ministry of Emergency Management and Climate Readiness.

REFERENCES

[1] S. Molnar, A. Bilson Darko, H. Ghofrani, S. Adhikari, M. Salsabili (2023). The Metro Vancouver seismic microzonation mapping project: Overview and multi-method approach to regional geodatabase development, CCEE-PCEE, June 25-30 2023, Vancouver, BC, Canada, Paper 258, 8 p.

[2] H. Ghofrani, S. Adhikari, A. Ojo, M. Salsabili, A. Sirohey, S. Molnar (2023). Physics-based seismic hazard simulations and 3D velocity structure models for southwest British Columbia, Joint Canadian and Pacific Conference on Earthquake Engineering (CCEE-PCEE), June 25-30 2023, Vancouver, BC, Canada, Paper 257, 12 p.

[3] A. Fallah Yeznabad, S. Molnar, H. El Naggar (2023). Seismic hazard mapping for Greater Vancouver: Probabilistic Approach and enhanced gridding method, CCEE-PCEE, June 25-30 2023, Vancouver, BC, Paper 289, 12 p.

[4] A. Javanbakht, J. Assaf, M. Salsabili, A. Sadrekarimi, H. Ghofrani, S. Molnar (2023). Metro Vancouver liquefaction hazard mapping, CCEE-PCEE, June 25-30 2023, Vancouver, BC, Paper 275, 10 p.

[5] S. Molnar, A. DenToom, J. Assaf, A. Sirohey, C. Boucher, N. Gomez Jaramillo, M. Fyfe, A. Bilson Darko (2023). Metro Vancouver seismic microzonation mapping: Advancements and guidelines, CCEE-PCEE, June 25-30 2023, Paper 288, 9 p.

[6] Al Atik, L., and N. A. Abrahamson (2021). A methodology for the development of 1D reference VS profiles compatible with ground-motion prediction equations: Application to NGAWest2 GMPEs, Bull. Seismol. Soc. Am., doi: 10.1785/0120200312

[7] Kolaj, M., Allen, T., Mayfield, R., Adams, J., & Halchuk, S. (2019). Ground-motion models for the 6th Generation Seismic Hazard Model of Canada. In 12th Canadian Conference on Earthquake Engineering.

[8] Adhikari, S.R., Molnar, S. (2021). Significance of geodatabase development for seismic microzonation in Metropolitan Vancouver. In: 17th World Conference on Earthquake Engineering, 27 Sept. – 2 Oct. 2021, Sendai, Japan, Paper 4521
[9] Anderson, D. L., Byrne, P. M., DeVall, R. H., Naesgaard, E., Wijewickreme, D., Adebar, P., ... & Yan, L. (2007). Geotechnical design guidelines for buildings on liquefiable sites in accordance with NBC 2005 for Greater Vancouver Region. Greater Vancouver Liquefaction Task Force Report, University of British Columbia
[10] Seed, H. B. and Idriss, I. M. (1970). "Soil moduli and damping factors for dynamic response analyses." Report No. EERC 70-10, Earthquake Engineering Research Center, University of California, Berkeley, California, 40p.
[11] Vucetic, M. and Dobry, R. (1991). Effect of soil plasticity on cyclic response. Journal of Geotechnical Engineering; 117(1): 89-107.
[12] Hashash, Y.M.A., Musgrove, M.I., Harmon, J.A., Ilhan, O., Xing, G., Numanoglu, O., Groholski, D.R., Phillips, C.A., and Park, D. (2020). "DEEPSOIL 7.0, User Manual". Urbana, IL, Board of Trustees of University of Illinois at Urbana-Champaign
[13] Seyhan, E. and Stewart, J.P. (2014). Semi-empirical nonlinear site amplification from NGA-West2 data and simulations. Earthquake Spectra 30: 1241–1256
[14] Boore, D.M., Stewart, J.P., Seyhan, E. and Atkinson, G.M. (2014). "NGA-West2 Equations for Predicting PGA, PGV, and 5% Damped PSA for Shallow Crustal Earthquakes," Earthquake Spectra, 30(3): 1057–1085
[15] Hassani, B., and G. M. Atkinson (2018). Site-effects model for central and eastern North America based on peak frequency and average shear-wave velocity, Bull. Seismol. Soc. Am. 107, 338-350
[16] Molnar, S., Cassidy J.F., Olsen, K.B., Dosso, S.E. and He, J. (2014). "Earthquake Ground Motion and 3D Georgia Basin Amplification in Southwest British Columbia: Shallow Blind-Thrust Scenario Earthquakes," Bulletin of the Seismological Society of America, 104(1): 321–33
[17] Molnar, S., Cassidy J.F., Olsen, K.B., Dosso, S.E. and He, J. (2014). "Earthquake Ground Motion and 3D Georgia Basin Amplification in Southwest British Columbia: Deep Juan de Fuca Plate Scenario Earthquakes," Bulletin of the Seismological Society of America, 104(1): 301–320
[18] Ghofrani, H., & Molnar, S. (2019). 3D Sedimentary Basin Effects in the Metro Vancouver Area and Its Seismic Hazard Implications: Updates and Validations of the Georgia Basin Velocity Model. In 12th Canadian Conference on Earthquake Engineering. Quebec City, Canada.
[19] Stephenson W J 2007 Velocity and density models incorporating the Cascadia subduction zone for 3D earthquake ground motion simulations, version 1.3 Open-File Report 2007-1348 U.S. Geological Survey, Earthquake Hazards Ground Motion Investigations
[20] Olsen, K. B. (1994). Simulation of three-dimensional wave propagation in the Salt Lake Basin, Ph.D. Thesis, University of Utah.
[21] Frankel, Arthur, et al. "Broadband Synthetic Seismograms for Magnitude 9 Earthquakes on the Cascadia Megathrust Based on 3D Simulations and Stochastic Synthetics, Part 1: Methodology and Overall Results, Methodology and Overall Results." Bulletin of the Seismological Society of America 108.5A (2018): 2347-2369.
[22] Preetish Kakoty, Carlos Molina Hutt, Hadi Ghofrani, Sheri Molnar; Spectral acceleration basin amplification factors for interface Cascadia Subduction Zone earthquakes in Canada's 2020 national seismic hazard model. *Earthquake Spectra* 2023;; 39 (2): 1166–1188. doi: https://doi.org/10.1177/87552930231168659
[23] Stephenson WJ, Reitmann NG and Angster SJ (2017) P- and S-wave velocity models incorporating the Cascadia subduction zone for 3D earthquake ground motion simulations—Update for OFR 2007-1348. Open-File report no. 2017-1152. Reston, VA: US Geological Survey, 40 pp
[24] Pagani,M,Monelli, D,Weatherill, G, Danciu, L,Crowley,H, Silva,V, Henshaw, P,Butler, R,Nastasi,M, Panzeri,L,Simionato,M, Vigano, D (2014):OpenQuake Engine:An open hazard (and risk) software for the Global Earthquake Model, Seism.Res.Lett.,85 (3), 692–702.
[25] Campbell, Kenneth W., and Yousef Bozorgnia. "NGA-West 2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear elastic response spectra." *Earthquake spectra* 30.3 (2014): 1087-1115.