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Metro Vancouver Seismic Microzonation Mapping: Advancements and Guidelines

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ABSTRACT

Achievement of probabilistic seismic hazard mapping that incorporates local seismic site effects for western Metropolitan Vancouver resulted in many scientific advances and revived development of guidelines related to use and development of seismic microzonation mapping in British Columbia. Key advancements in seismic site characterization include data-driven updates to seismic parameter distributions, development of region-specific predictive relationships, application of large-scale seismic array testing to achieve shear-wave velocity (Vs) profiling at significant depth (< 2 km), and developing mitigative data analysis methodologies to overcome geological site complexities (e.g., lateral site variability, velocity reversals) and their impact to interpretation and inversion of surface wave dispersion data. Key advancements in the region's seismic microzonation specific to variability in low-level earthquake shaking is achieved by identifying 7 unique classes of empirical site amplification spectra from earthquake and microtremor recordings at ~45 and over 2,200 locations respectively, and mapping spatial variance of site peak frequency(ies). Evaluation of empirical nonlinear soil behaviour at seismic stations elsewhere in the world equivalent to Metro Vancouver site conditions in/validates our regional site de/amplification model developed from numerical 1D site response analyses. Advancement in communication and use of seismic microzonation mapping throughout Canada was undertaken with both technical and non-technical end-users, including an online survey questionnaire and in-person workshop. The Metro Vancouver seismic microzonation mapping project revived development of professional practice guidelines of seismic microzonation mapping in British Columbia, led by the Engineers and Geoscientists of British Columba (EGBC). The developed EGBC professional practice guidelines introduces seismic microzonation mapping including the concept of map levels based on quality and quantity of underlying data and accompanying level of (seismic) analyses and provides guidance on the use of seismic microzonation maps to multiple end-users (e.g., structural and geotechnical engineers, risk management, local government) as well as their development in particular to earthquake shaking, landslide, and liquefaction hazards.

Keywords: Seismic microzonation, Amplification hazard, Liquefaction hazard, Landslide hazard, Seismic hazard mapping.

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. The project is led by the Institute of Catastrophic Loss Reduction and University of Western Ontario 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. Previous papers in this special session documented 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], a "geotechnical layer" velocity model to 1 km depth developed from the compiled geodatabase and larger-scale ambient noise tomography (ANT) velocity models of southwest British Columbia to 60 km depth; and (3) detailed methodologies to achieving seismic hazard mapping of western Metro Vancouver including shaking (de/amplification) hazard inclusive of both 1D site and 3D basin effects [3], and seismic-induced landslide [4] and liquefaction [5] hazard potential.

This paper focuses on scientific advancements accomplished during the MVSMMP not documented in other papers of this special session as well as MVSMMP activities (2017-2019) to engage with stakeholders and understand end-user interaction with previous seismic microzonation mapping in Canada. This paper also documents engagement with the Engineers and Geoscientists of British Columbia (EGBC) (2021-2024) including technical peer review of the MVSMMP and development of professional practice guidelines for (future) development and use of seismic microzonation mapping in British Columbia.

ADVANCEMENTS IN SEISMIC SITE CHARACTERIZATION IN WESTERN METRO VANCOUVER

Key advancements in seismic site characterization by the MVSMMP included performing multi-method non-invasive *in situ* seismic testing [1] which enabled data-driven updates to seismic parameter distributions, development of region-specific predictive relationships, application of large-scale seismic array testing to achieve shear-wave velocity (Vs) profiling at significant depth (< 2 km), and developing mitigative data analysis methodologies to overcome geological site complexities (e.g., lateral site variability, velocity reversals) and their impact to interpretation and inversion of surface wave dispersion data.

Shear-wave velocity (Vs) depth (z) relationships of geologic units

Monahan and Levson [6] achieved the first large-scale compilation of geodata for southwestern British Columbia, also with the purpose to achieve seismic microzonation mapping of Greater Victoria and Chilliwack. The average shear-wave velocity (Vs) and one standard deviation variability was reported for the major geologic units in southwest BC; however, the relationship of the geologic unit's Vs with depth (z) could not be developed. Following accomplishment of over 500 velocity depth profiles by the Geological Survey of Canada in the 1990's, a powerlaw Vs-z relationship was developed for Fraser River delta sediments ([7]; shown as the Hunter99 model in Figure 1). From the MVSMMP's compiled geodatabase, Assaf derived a total of 8 Vs-z relationships of major geologic units in western Metro Vancouver (Figure 1). Vs-z relationships of post-glacial sediments (Fig. 1a) are similar but distinct, noting the Hunter powerlaw relationship for all Fraser River sediments (not dependent to material type) is an average of the two potentially distinct Vs-z relationships for silt & clay & mixed soil and sand. The lowest Vs within western Metro Vancouver occurs in peat and organic silt, as expected, which primarily occurs in peat bog environments in western areas of the cities of Richmond and Delta. Vs-z relationships of Pleistocene-age Capilano sediments (not glacially overridden) and glaciated sediments (Fig. 1b) could not be determined previously from compiled invasive in situ datasets; Vs cannot be derived from very high cone and standard penetration method measurements (e.g., "met refusal"). Since the MVSMMP used multi-method non-invasive seismic testing, the Vs-z relationships for these stiffer geologic units could be derived for the first time.

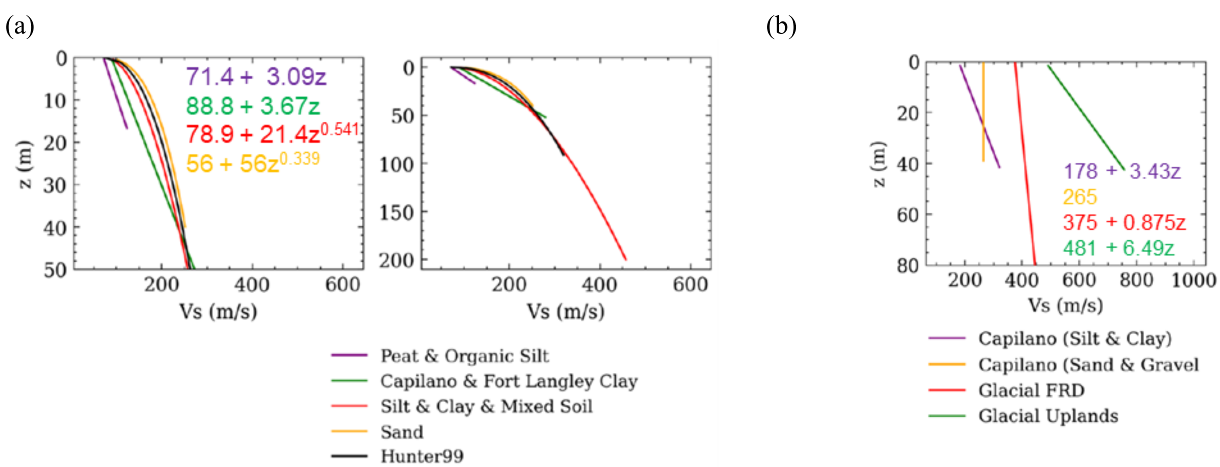

Figure 1. Average Vs(z) relationships for (a) post-glacial and (b) Pleistocene and older glacial and non-glacial (Capilano) sediment groupings (from [8]).

Region-specific predictive relationships

Predictive relationships that correlate between various geodata are derived from the MVSMMP geodatabase, including cone penetration testing (CPT) to Vs correlation relationships for Fraser River delta sediments [9] and standard penetration testing (SPT) to Vs correlation relationships for all, sandy, and clayey soil types [10]. Other relationships were derived to convert site peak frequencies from microtremor horizontal to vertical spectral ratio (HVSR) amplification spectra to sediment thicknesses: Assaf [11] developed a relationship between thickness of Fraser River delta sediments and the second MHVSR peak (f_{1HV}) applicable between 0 to 56 m depth, and Salsabili developed relationships between the fundamental site frequency (f_{0HV}) and depth to seismic bedrock (Vs ≥ 1000 m/s), and f_{1HV} and depth to glacial sediments (Vs ≥ 300 m/s).

Deep Vs(z) profiling

Assaf et al. [11] published the first deep Vs profiles from joint inversion of the MHVSR fundamental peak frequency (f_{0HV}) and combined passive- and active-source dispersion data for 16 sites in the Fraser River delta. During the 5th field campaign in 2022, the MVSMMP targeted 6 locations (Figure 2) for deep Vs profiling (≤ 2 km) to constrain Vs at depth within glacial sediments and transitioning into underlying Tertiary Georgia sedimentary basin rock and/or Coast Mountain plutonic igneous rock. Two nested large-aperture (0.5 to 2 km radius) circular arrays of six seismometers and a 13th central seismometer recorded ambient vibrations for 2 to 8 hours at the 6 large array sites (Fig. 2a). Low frequency (0.2 to 2 Hz) fundamental mode Rayleigh wave phase velocity dispersion estimates were derived and merged with higher-frequency dispersion estimates from smaller-aperture (0.5 to 30 m) seismic array testing of previous year's field campaigns (Fig. 2b). Inversion of these full frequency bandwidth dispersion curves (0.2 to 100 Hz) provide resolved Vs(z) model(s) (Fig. 2b) to ~1 km (Ladner) to ~4 km (Burnaby).

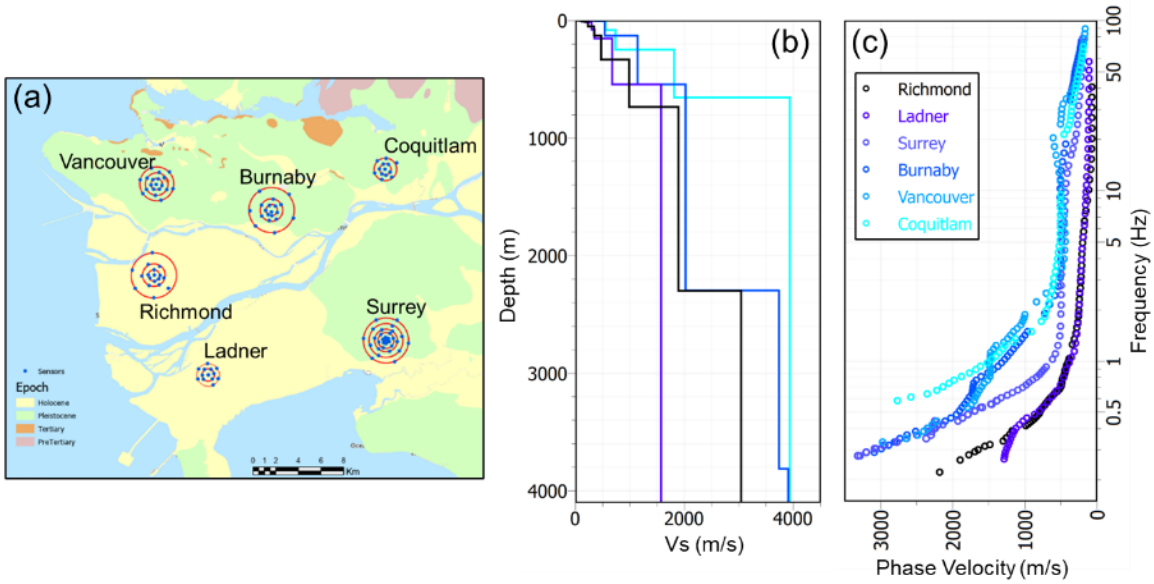

Figure 2. (a) Six large array sites in Metro Vancouver for which (b) the optimal Vs depth profile is determined from inversion of (c) fundamental-mode Rayleigh wave phase velocity dispersion curve.

Mitigative strategies to interpreting multi-mode surface wave dispersion data

Although the MVSMMP's use of multi-method non-invasive seismic testing enabled measurement of Vs in moderate velocity glacial sediments and high velocity rocks compared to penetrative invasive methods (see previous sections), it led to challenging data analysis and interpretation primarily in the uplands areas outside of the Fraser River delta. Velocity reversals (low velocity zones) may occur at surface or at depth. Typical scenarios of such velocity reversals in western Metro Vancouver include a surficial stiff desiccated layer often over a saturated and/or organic low velocity sediment, or alternating (inter)glacial sediments at depth, respectively. The former manifests as an apparent surface wave dispersion mode that increases in velocity at the highest frequencies while the latter manifests as an undulation within the mid-frequency range of the dispersion curve, e.g., velocity reversal (low velocity zone) at 3-4 Hz with higher velocity layer above (6-10 Hz) in Figure 3. Mode partitioning of the recorded surface wave energy is identified but separate mode identification is not possible; larger aperture seismic arrays with dense geophone spacing is required to identify discrete modes and is often not feasible. If the problem cannot be solved by improved data collection, then mitigative data analysis solutions are required. The appropriate solution would have been to discard the higher surface wave velocities that are not a measure of the fundamental surface wave mode (termed a cut dispersion curve; Fig. 3) as they violate the assumption of the inversion's forward model, resulting in inversion models that do not include a velocity reversal. This would be a conservative solution or result in a model without the higher velocity layer. The other end-member solution could be to input the mixed mode dispersion curve to the inversion (wrongly assigning mixed mode data as the fundamental mode), resulting in inversion models that overestimate the higher velocity layer (termed a full curve; Fig. 3). Our mitigative data analysis strategy [12] was to try inverting a partial dispersion curve that included likely fundamental mode estimates of the velocity reversal (i.e., "shoulders" of the higher velocity mixed mode) to generate velocity models that (partially) captured the velocity reversal. We find that the inverted partial dispersion curve provides a representative average seismic site characterization in terms of the time-averaged Vs of the upper 30 meters (Vs_{30}) between that of the conservative cut-curve and non-conservative full curve inversion models (Fig. 3) which is suitable for our seismic microzonation (Vs_{30}) mapping purposes; see [12] for further details.

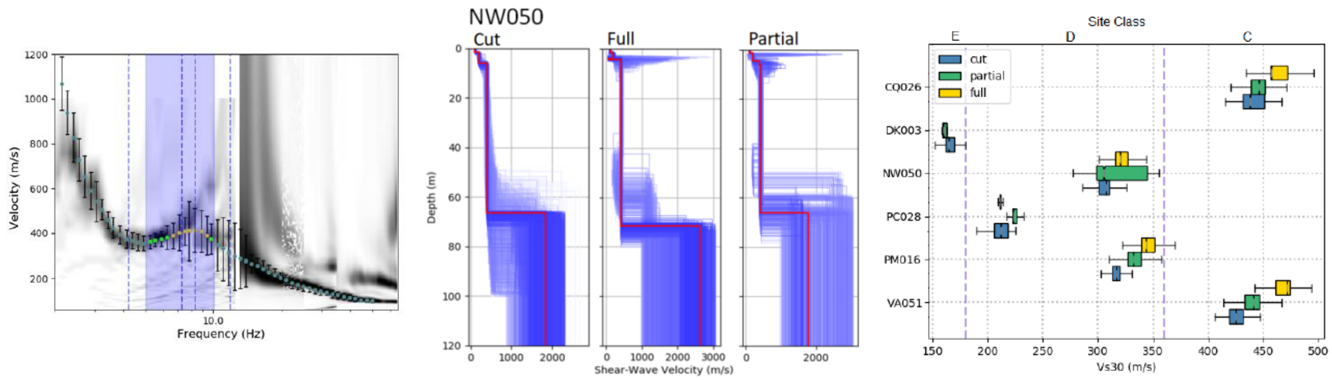

Figure 3. (left) Fundamental mode Rayleigh phase velocity dispersion curve for NW050 site showing full (all circles), partial (blue and green circles) and cut (blue circles only) dispersion data. (middle) Corresponding Vs profiles of the minimum misfit (red) and 5000 lowest Bayesian Information Criterion (BIC) models (blue shading) that fit the cut, full and partial dispersion data for site NW050. (right) Vs30 ranges from 5000 lowest BIC models for six Metro Vancouver array sites from joint inversion of f_{0HV} and the full, partial, or cut dispersion curve. (images compiled from [12])

Mitigative strategies to lateral site variability

Non-invasive *in situ* seismic methods involves sampling wave propagation with surface installed seismometers over a lateral area or volume of subsurface material compared to discrete depth sampling by some invasive *in situ* methods when the seismic source and receiver are close together. The aperture of seismic arrays must be varied to measure elastic material properties in the near surface (high frequencies) to at depth (low frequencies); the thick Fraser River delta and (inter)glacial sediments in western Metro Vancouver requires sampling to depths that are significant (hundreds of meters to 1 km). It is therefore natural that lateral site variability (dipping or variable depth resonators) will occur beneath aperture-varying seismic arrays, particularly where surface elevation changes rapidly over short distances (e.g., the North Shore). Since multi-method non-invasive *in situ* seismic testing is accomplished by the MVSMMP, we obtain a MHVSR amplification frequency spectrum at each installed seismometer location (~25 locations) of the varying aperture seismic arrays (Figure 4). If the MHVSR spectra are consistent with each other over the site area, then we have data-driven assurance that the seismic site conditions are consistent beneath the tested site volume. If the MHVSR spectra are not consistent, we can obtain an understanding where thinner (higher f0HV) and thicker (lower f_{0HV}) soils are present across the tested site. Figure 4 shows how varying f_{0HV} and MHVSR morphology amongst the 30 MHVSR locations for a West Vancouver site (WV0) indicates a northwest-southeast trend of thinner to thicker soils (i.e., the resonator is shallowing to the northwest). We use this knowledge to sub-divide the dispersion data analysis of the seismic array recordings into two northwest and southeast quadrants and thereby derive two fundamental-mode dispersion curves capturing lateral variability across the site. The MVSMMP's multi-method non-invasive seismic testing approach also included performing linear (2D) Vp and Vs refraction surveys parallel to the identified trend in f_{0HV}; in this way, the dipping depth of the resonator is imaged in a cross-sectional manner by a second independent seismic method. Figure 4 (bottom right) shows how the resulting seismic site characterization (Vs_{30}) is consistently higher in the southern than the northern quadrant from surface wave and Vp refraction testing for a different West Vancouver (WV064) site. The resulting seismic site characterization is higher resolution than intended for seismic microzonation mapping (two Vs_{30} values instead of one), but is honoured in the MVSMMP geodatabase (each Vs_{30} value is included with each quadrant's spatial coordinates). The variable seismic site conditions are captured over the relatively short distance.

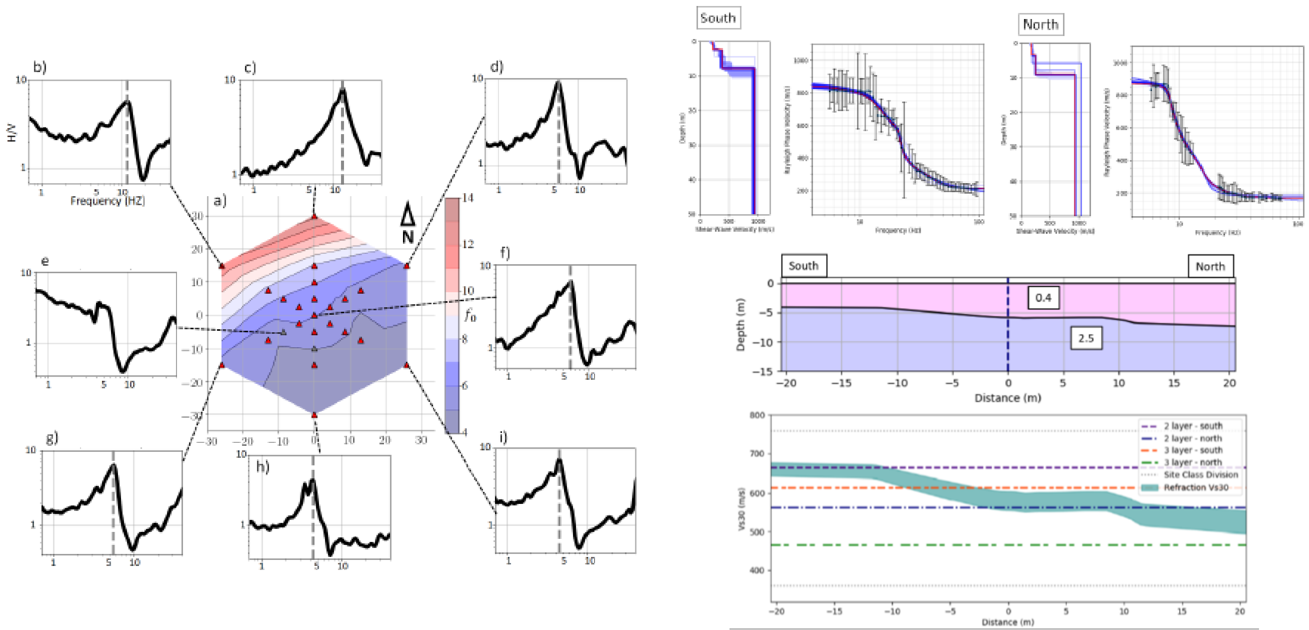

Figure 4. (left) Map of contoured f_{0HV} (shading) at each seismometer location (triangles) at the WV0 array site. Time-averaged MHVSR spectrum at selected locations are shown as solid black lines; f_{0HV} is marked by a vertical dashed line. (right) Inverted Vs models and dispersion curve for northern and southern quadrants of WV064 array site (top), Vp (in km/s) refraction model (middle), and comparison of Vs_{30} determined from joint inversion of f_{0HV} and dispersion data (2 and 3 layer models) with refraction-derived model from south (-20 m) to north (20 m) at the WV064 array site.

ADVANCEMENTS IN REGIONAL MICROZONATION OF LOW-LEVEL EARTHQUAKE SHAKING

Empirical Earthquake Site Effects

Previous to the MVSMMP, Molnar and Cassidy [13] demonstrated that the MHVSR method provides amplification frequency spectra consistent with earthquake HVSR and site-to-rock (site) amplification at seismic recording stations in southwest British Columbia in terms of f_{0HV} and its amplification (A_{0HV}); seismometer recordings of microtremors (ambient vibrations) for up to an hour provides empirical site amplification information (f_{0HV} and A_{0HV}) consistent with low-level earthquake site amplification. Over four summer field campaigns, over 2,000 locations were tested across western Metro Vancouver to provide an average MHVSR spectrum that is compiled into an empirical site amplification database [14] with all available earthquake HVSRs at ~45 locations [15]. Approximately six unique types of site amplification spectra are identified (Figure 5, see [14] for details on how determined); all the geologic variability across western Metro Vancouver corresponds to only 6 different types of seismic site effect. In Figure 5, a flat low amplification spectrum (I) is indicative of rocky site conditions, low peak amplification (II, VI) is indicative of stiff glaciated sediments, high peak amplification (V) is indicative of low velocity sediments over a high velocity resonator, and moderate single (IV) to double (III) peak amplification is common on the Fraser River delta where Holocene deltaic sediments overlie glacial sediments over sedimentary rock (double peaks occur when resonance modes of the two upper layers are distinct; one peak occurs when the resonance modes of the two upper layers merge or coincide, see [14] for details and where these types of site amplification occur within Metro Vancouver). Figure 5 shows the spatial variation in the fundamental MHVSR peak (often coinciding with the site's fundamental frequency or inverse of site period) at over 2,000 locations across western Metro Vancouver. The largest scientific advancement (unknown prior to the MVSMMP) is identification of relatively low frequency f_{0HV} (long site periods) in southern Vancouver along the northern arm of the Fraser River and over most of Surrey and into White Rock. These uplands areas have moderate Vs glaciated sediments (300-800 m/s) that must be thick to very thick to correspond to f_{0HV} of ≤ 1 Hz and ≤ 0.5 Hz in southern Vancouver and Surrey, respectively.

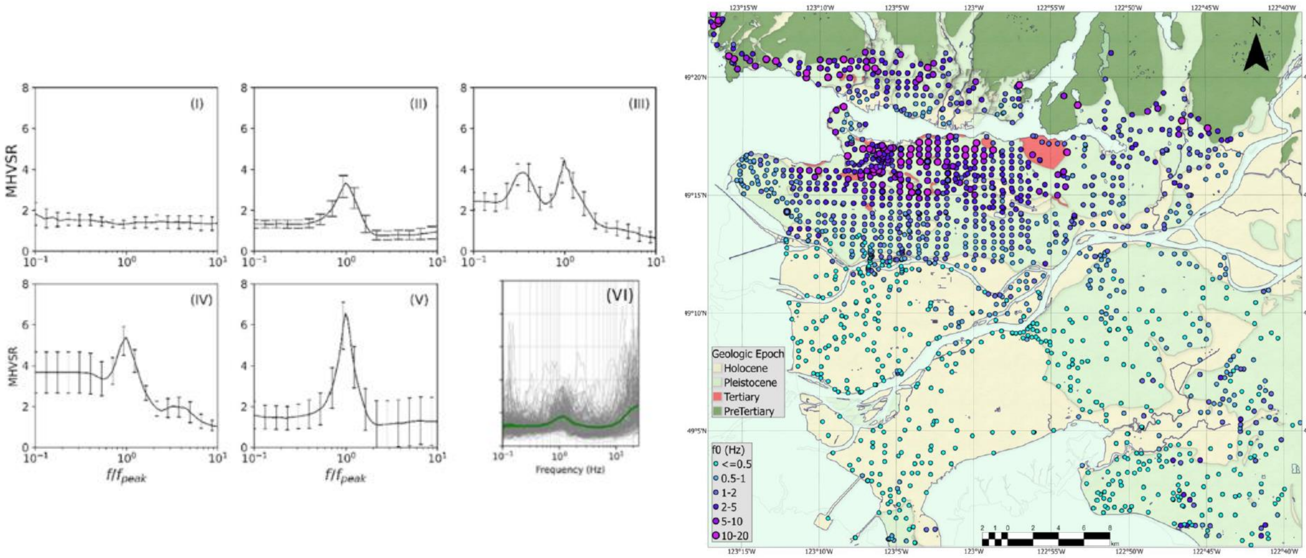

Figure 5. (left) Typical MHVSR amplification response (normalized by f_{0HV}) within western Metro Vancouver. (right) Over 2,000 MHVSR locations (circles) depicting f_{0HV} (colouring) overlaid on a simplified surficial geologic map.

Empirical Nonlinear Site Response

Empirical nonlinear site response from recorded strong motions does not exist for southwest British Columbia; the strongest recorded earthquake ground motions are relatively weak (maximum of 5.5 %g in Metro Vancouver). Paleo-liquefaction features of sand dykes and sand blows have been documented by John Clague [e.g., 16] at 12 locations in the Fraser River delta and Serpentine-Nikomekl valley. Back calculation analyses [16, 17] suggest either a M ≥ 8.5 mega-thrust Cascadia earthquake or a moderate-to-large magnitude and closer shallow crustal earthquake are capable to trigger nonlinear site response and ultimately liquefaction features in western Metro Vancouver. How nonlinear site response will manifest (degree of deamplification and/or shift of site period to longer periods) in western Metro Vancouver is therefore largely unknown. The MVSMMP examined this problem in two ways: (1) performing numerical 1D equivalent linear and nonlinear site response analyses for 51 representative locations [8], and (2) examination of earthquake time-series and HVSR amplification of weak-to-strong earthquake recordings elsewhere in the world that are deemed equivalent to seismic site conditions (e.g., geologic setting, Vs depth profile, site period) in western Metro Vancouver [18]. Figure 6 shows earthquake HVSR amplification spectra of weak (grey lines) to strong (red line) earthquake motions recorded at thick lakebed seismic stations (TH35, AE02, CE23) and a basin edge site (DR16) in Mexico City that have equivalent f_{0HV} to Fraser River delta sites. Deamplification at f_{0HV} is apparent for the strong shaking event compared to weaker events at the deeper AE02 and CE23 sites but is not observed consistently at all four stations. A minor shift in f_{0HV} to lower frequency (longer period) potentially occurs at sites AE02 and DR16. These results are generally consistent with equivalent sites in the Kanto basin of Japan (not shown), noting deamplification also occurs at higher frequencies for the Japan sites. Thus far, these empirical nonlinear site response observations for sites equivalent to western Metro Vancouver are consistent with our 1D numerical modelling that shows stronger deamplification than present in the inherent site amplification models of the regional (ergodic) ground motion models of the 6th national seismic hazard model, i.e., the 2020 NBC design ground motions. We are investigating if our numerical 1D site response analyses are consistent with the observed negligible shift in empirical site period to longer periods (minimal soil softening behaviour).

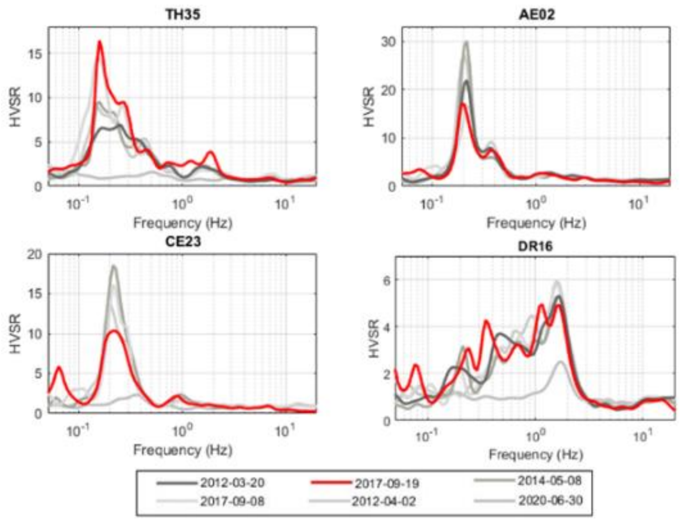

Figure 6. Earthquake HVSR spectra of weak (grey) to strong (red) earthquake recordings at 4 Mexico City seismic stations.

STANDARDIZATION OF SEISMIC MICROZONATION MAPPING IN BRITISH COLUMBIA

Stakeholder Engagement

The MVSMMP hosted annual project updates with invited regional stakeholders from 2017 to 2019. The 2017 engagement was the inaugural project announcement and call for geodata sharing. An annual project update presentation was provided to invited stakeholders again in 2018, in combination with a project progress update to EERI-BC and invited lectures to the Vancouver Geotechnical Society and Vancouver Island Geotechnical Group members. In 2019, the annual project update was combined with a half-day workshop involving stakeholder feedback and their comprehension of different example seismic microzonation map products (e.g., non-earthquake-specific liquefaction susceptibility compared to seismic-triggered liquefaction hazard potential) and whether their comprehension varied with presentation styles (e.g., colouring, data shown as points versus zones) [19]. Similarly, the 2019 workshop was expanded into an online survey questionnaire and referenced existing seismic microzonation maps elsewhere in Canada for broader feedback [19, 20]. Feedback from both the workshop and survey responses indicate that communicating hazard to intermediate users (e.g., emergency managers, land use planners) using technical metrics is ineffective without supplementary information. Additionally, participants expressed importance of visual simplicity, access to background data, and interactive capabilities (e.g., GIS feature layers). Overall, feedback highlighted that a lack of standardization in seismic microzonation map products in Canada leads to misinterpretation, particularly when comparing maps between different regions [19, 20].

EGBC Peer Review

In 2021, the MVSMMP transitioned from invited stakeholder engagements to professional peer review by a committee assembled and led by the Engineers and Geoscientists of British Columbia (EGBC). The peer review committee consists of structural and geotechnical engineers and a consulting urban planner. Peer review is accomplished in parallel with the MVSMMP's biannual reporting cycle.

EGBC Professional Practice Guidelines

The Metro Vancouver seismic microzonation mapping project revived development of professional practice guidelines of seismic microzonation mapping in British Columbia, led by the Engineers and Geoscientists of British Columba (EGBC). These guidelines are intended to complement the Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP) and provide a common approach for carrying out seismic microzonation mapping projects in BC, as well as a common approach for using seismic microzonation maps in BC. The guidelines are not intended to be prescriptive or technical; instead, they are intended to outline the framework for good professional practice for both the development and use of microzonation maps.

The guidelines are written and organized in such a way to be useful to all readers of all backgrounds – from the general public to professionals and academics highly skilled in seismology and microzonation mapping, and everything in between including planners and local governments, structural engineers, and geotechnical engineers.

Like the MVSMMP, the guidelines cover three seismic hazards: landslide, shaking, and liquefaction. They start with an introduction directed to all readers to establish a common understanding of the three seismic hazards and the intent of seismic microzonation mapping, including defining common terminology for use throughout. Though not explicitly used in the

MVSMMP, the concept of map levels (1, 2, and 3) are introduced and used in the guidelines to differentiate between hazard susceptibility maps, which show local variation in the physical properties of the geological materials related to seismic hazard, and hazard potential maps, which take seismicity into account. Level 3 maps are hazard potential maps whereas Level 1 and 2 are hazard susceptibility maps. The levels are defined and further distinguished to require increasing amounts of data and more complex analysis as the levels increase. Other than the divide between a susceptibility map and a potential map, the levels exist on a sliding scale of detail and analysis to suit the project location, scope, and budget.

For end users, namely local governments, structural engineers, and geotechnical engineers, the guidelines focus on introducing microzonation maps in general and providing examples of appropriate use. Structural and geotechnical engineers are encouraged to use the maps to gauge the hazard susceptibility and/or potential to inform project scoping, feasibility and schematic designs, and as an indicator for where more site-specific information is required (for the detailed design). Similarly, local governments can use the maps to a high level to inform hazard planning and permitting policies, as well as asset management and emergency response and recovery, and as an indicator of where more site-specific information would be valuable.

For mapping professionals, the guidelines describe data requirements, sources of data, and mapping considerations that are applicable to all hazards as well as more detailed guidance on data requirements, analysis, and methodologies for individual hazards. The guidelines outline a consistent approach to hazard-specific microzonation mapping for each level of map; provide technical references and guidance, where appropriate; and reference several data sources and existing microzonation maps for the mapping professional's benefit.

Lastly, the guidelines outline general roles and responsibilities of the various professionals and stakeholders involved; describe minimum requirements for education, training, and experience to take on the development of microzonation maps; and highlight key considerations to meet Engineers and Geoscientists BC's quality management requirements.

CONCLUSIONS

This paper focused on scientific advancements accomplished during the MVSMMP not documented in other papers of this special session, including performing multi-method non-invasive *in situ* seismic testing which enabled data-driven updates to seismic parameter distributions, development of region-specific predictive relationships, application of large-scale seismic array testing to achieve shear-wave velocity (Vs) profiling at significant depth (> 2 km), and developing mitigative data analysis methodologies to overcome geological site complexities (e.g., lateral site variability, velocity reversals) and their impact to interpretation and inversion of surface wave dispersion data. Key advancements in the region's seismic microzonation specific to variability in low-level earthquake shaking is achieved by identifying 7 unique classes of empirical site amplification spectra from earthquake and microtremor recordings at ~45 and over 2,200 locations respectively, and mapping spatial variance of site peak frequency(ies). Evaluation of empirical nonlinear soil behaviour at seismic stations elsewhere in the world equivalent to Metro Vancouver site conditions (in)validates our regional site (de)amplification model developed from numerical 1D site response analyses.

Advancement in communication and use of seismic microzonation mapping throughout Canada was undertaken by the MVSMMP with both technical and non-technical end-users, including an online survey questionnaire and in-person workshop. Feedback highlighted that a lack of standardization in seismic microzonation map products in Canada leads to misinterpretation, particularly when comparing maps between different regions. This paper also documented engagement with the Engineers and Geoscientists of British Columbia (EGBC) including technical peer review of the MVSMMP and development of professional practice guidelines for (future) development and use of seismic microzonation mapping in British Columbia.

ACKNOWLEDGMENTS

This paper presents a selection of key scientific advancements of the Metro Vancouver seismic microzonation mapping project, found in journal article publications and (ongoing) theses of individual project (student) members, see references. The University of Western Ontario and Institute of Catastrophic Loss Reduction acknowledge collaboration with the Engineers and Geoscientists of British Columbia with support from the BC Ministry of Emergency Management and Climate Readiness.

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