Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

The Metro Vancouver Seismic Microzonation Mapping Project: Overview and Multi-Method Approach to Regional Geodatabase Development

Sheri Molnar[1*], Alex Bilson Darko[2], Hadi Ghofrani[3], Sujan Adhikari[4], Mohammad Salsabili[5]

[1]Associate Professor, Department of Earth Sciences, University of Western Ontario, London, ON, Canada
[2]Project Manager, Metro Vancouver Seismic Microzonation Mapping Project, Inst. Catastrophic Loss Reduction, ON, Canada
[3]Research Scientist, Metro Vancouver Seismic Microzonation Mapping Project, U. Western Ontario, London, ON, Canada
[4]PhD Geophysics Candidate, Department of Earth Sciences, U. Western Ontario, London, ON, Canada
[5]Research Associate, Metro Vancouver Seismic Microzonation Mapping Project, Inst. Catastroph. Loss Reduction, ON, Canada
[*]smolnar8@uwo.ca (Corresponding Author)

ABSTRACT

Prediction of probabilistic earthquake ground motion inclusive of local site effects across Metro Vancouver is a multi-faceted challenge. The Institute of Catastrophic Loss Reduction and the University of Western Ontario are performing seismic microzonation hazard mapping of Metro Vancouver with support from the British Columbia (BC) Ministry of Emergency Management and Climate Readiness. The goal of this multi-year project (2017-2024) is to produce 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. These Metro-Vancouver-specific probabilistic seismic hazard maps are developed using the 6th national seismic hazard model (2020 National Building Code) at 2% and 10% probability of exceedance risk levels. A comprehensive geodatabase specific to seismic hazard prediction is compiled for the region. Pre-existing geodata, primarily invasive *in situ* geodata, are compiled from various public and private data sources. In addition, field campaigns of multi-method non-invasive seismic testing were accomplished to supplement the geodatabase, including: (1) single-station microtremor method testing at over 2,000 locations to obtain amplification frequency spectra and peak resonance frequencies, (2a) combined active- and passive-source surface wave array testing at over 120 locations to obtain Rayleigh wave dispersion curves (inverted jointly with peak frequencies to obtain the shear-wave velocity (Vs) depth profile resolved to major impedance contrast(s) in the upper hundreds of meters) and (2b) extended to significant depth (~2 km) from large-aperture surface wave array testing, (3) Vs refraction surveying for select sites with sloping ground, and (4) downhole compression-wave and Vs logging in 4 existing water wells. The developed geodatabase enables data-driven seismic site characterization across the Metro Vancouver region, including descriptive statistics of geodata, region-specific predictive relationships, 1D soil column to 3D regional-volume modelling, and generation of seismic-hazard-input susceptibility maps (e.g., Vs_{30}, $Z_{1.5}$, T_0, post-glacial sediment thickness, landslide or liquefaction susceptibility). This special session informs practicing earthquake engineering professionals of the project's methodologies prior to public release of Metro Vancouver seismic microzonation map deliverables in June 2024.

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

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 University of Western Ontario (S. Molnar, Principal Investigator) and the Institute of Catastrophic Loss Reduction and with support from the British Columbia (BC) Ministry of Emergency Management and Climate Readiness.

The MVSMMP is mapping seismic hazards for western communities of Metro Vancouver including 16 municipalities, 6 First Nation land reserves, and 1 electoral area: Village of Horseshoe Bay, District of West Vancouver (including Sunset Beach), District of North Vancouver, City of North Vancouver, Electoral Area A (University Endowment Lands and University of British Columbia), City of Vancouver, City of Burnaby, City of New Westminster, Village of Anmore, Village of Belcarra, City of Port Moody, City of Coquitlam, City of Port Coquitlam, City of Richmond, City of Delta, City of Surrey, City of White Rock, Tsawwassen First Nation (a Treaty First Nation member of the Greater Vancouver Regional District), Musqueam First Nation (Musqueam 2, 4, and Sea Island 3 land reserves), Squamish First Nation (Capilano 5, Mission 1, Seymour Creek 2, Kitsilano 6 land reserves), Semiahmoo First Nation (Semiahmoo land reserve), Tsleil-Waututh First Nation (Burrard Inlet 3 land reserve), and Kwikwetlem First Nation (Coquitlam 1 and 2 land reserves). The mapping is achieved at scales of 1:50,000 to 1:25,000; although access to the maps as digital GIS layers or shapefiles allows users to zoom in further, the seismic hazard prediction is not achieved at a higher scale than 1:25,000.

This special session informs practicing earthquake engineering professionals of the project's methodologies prior to public release of Metro Vancouver seismic microzonation map deliverables in 2024.

PROJECT METHODOLOGY

To achieve seismic microzonation mapping, a comprehensive geodatabase specific to seismic hazard (shaking, and liquefaction and landslide potential) prediction, i.e., local seismic site conditions, is compiled for the region [1, 2]. The philosophy of approach towards compiling a comprehensive regional geodatabase was to capitalize on existing geodata via data sharing agreements with data owners, primarily higher-cost geodata from invasive *in situ* testing or geotechnical laboratory testing of soil samples, and prioritizing MVSMMP data collection funding towards lower-cost non-invasive *in situ* seismic testing to supplement the geodatabase and achieve greater geodata density and adequate spatial coverage across the region. A total of five summer field campaigns of multi-method non-invasive seismic testing (Figure 1), as well as downhole velocity logging in 4 water wells, was funded by the MVSMMP. As geodata was compiled, preliminary seismic hazard susceptibility mapping and seismic hazard predictions could be accomplished and updated as the geodatabase evolved over the project years (Figure 1). In parallel, 3D block models of the region's seismic impedance layering and Vs were generated for the upper 1 km [3] from which 1D soil column or 2D planar cross-sections can be extracted for seismic hazard prediction. The developed geodatabase enabled data-driven seismic site characterization across the Metro Vancouver region, including descriptive statistics of geodata [2, 4, 5], region-specific predictive relationships [5, 6, 7], 1D soil column to 3D regional-volume modelling [3, 5], and generation of seismic-hazard-input susceptibility maps (e.g., Vs_{30}, $Z_{1.5}$, T_0, post-glacial sediment thickness, landslide or liquefaction susceptibility). Methodologies to achieve seismic hazard mapping inclusive of 1D and 3D site effects [8], and liquefaction [9] and landslide [10] hazard potential, are discussed in each respective conference paper of this special session. Additional achievements in local seismic site characterization and seismic hazard prediction of the MVSMMP are discussed in the last conference paper of this special session [11].

Stakeholder engagement hosted by the project (2017-2019), and professional peer review of the MVSMMP research and development of Seismic Microzonation Mapping Guidelines for British Columbia led by the Engineers and Geoscientists of British Columbia (EGBC) is described in Molnar et al. [11].

<table>
<tr><th>04/2017</th><th>2018</th><th>2019</th><th>2020</th><th>2021</th><th>2022</th><th>2023-03/2024</th><th>06/2024</th></tr>
<tr><td rowspan="4">Project launch and initial data collection</td><td colspan="4">Outreach to local governments and stakeholders for data collection</td><td>Finalize methodologies</td><td rowspan="3">Finalize and submit deliverables (map products)</td><td rowspan="4">Final project reporting</td></tr>
<tr><td>Field campaign (July)
713 MHVSRs & 44 Array sites</td><td>Field campaign (July)
696 MHVSRs & 42 Array sites</td><td>Field campaign (July-Aug)
352 MHVSRs & 20 Array sites</td><td>Field campaign (Aug.)
225 MHVSRs & 20 Array sites</td><td>Field campaign (Aug.-Nov.)
6 large arrays & ANT survey</td></tr>
<tr><td colspan="5">-------- Ongoing data and seismic hazard analyses --------</td></tr>
<tr><td colspan="3"></td><td colspan="3">EGBC Peer Review & Microzonation Guidelines</td></tr>
</table>

Figure 1. Timeline of the MVSMMP activities.

Validation with Earthquake Recordings

The MVSMMP also compiled all relevant recordings of earthquake shaking in Metro Vancouver from 12 earthquakes (spanning 1976 to 2018, magnitudes (M) of 3.6 to 6.8, maximum PGA of 5.5 %g) to systematically calculate and document earthquake site amplification (horizontal to vertical spectral ratio, HVSR) [12]. It was previously demonstrated that microtremor HVSR amplification spectra are consistent with earthquake HVSRs in Metro Vancouver [1]; the single-station microtremor method is a proxy for low-level earthquake site amplification throughout most of Canada. The MVSMMP compared (validated) more recent empirical microtremor and earthquake HVSR amplification spectra datasets with 1D site response modelling at 6 Fraser River delta sites [13] and at 3 instrumented borehole arrays on the Fraser River delta edge [14], respectively. Similarly, Molnar et al. [15] previously validated their 3D regional community velocity model of southwest British Columbia by comparison with earthquake recordings of the 2001 M 6.8 Nisqually, Washington, inslab earthquake; the MVSMMP compared (validated) the same 3D regional velocity model using earthquake recordings of the 2015 M 4.7 Victoria, BC, inslab earthquake [16]. A back-calculation paleo-liquefaction analysis in a probabilistic framework is performed for 4 Fraser River delta sites to constrain the moment magnitude and maximum ground acceleration of Cascadia interface earthquakes to have induced liquefaction given the site's measured resistance capacity and the 6th National Seismic Hazard Model (6NSHM) seismic demand [17]. Although gravity-driven mass wasting deposits are present in western Metro Vancouver, none have been determined to be a result of seismic triggering (i.e., there is no seismic-induced landslide inventory) to validate landslide hazard predictions. Empirical nonlinear site response from strong earthquake shaking at seismic stations elsewhere in the world that are deemed equivalent to Metro Vancouver (geologic setting, Vs depth profile, site period) are under investigation [18] to compare with the MVSMMP's 1D site response analyses at 51 sites [5].

REGIONAL GEODATABASE FOR SEISMIC HAZARD PREDICTION

The MVSMMP primarily compiled *in situ* (field-based) measures of local seismic site conditions within western Metro Vancouver. For seismic hazard (shaking) prediction, measures of spectral site amplification, Vs with depth, and site period are beneficial. The depth of investigation for shaking hazard prediction varies depending on scale: for 1D site response modelling, seismic site conditions to the depth of seismic bedrock (Vs > 760 m/s) are needed [5, 8]; for 3D wave propagation simulations, regional community velocity model(s) of elastic material properties (Vs, compression velocity, density) to a depth of ~60 km is needed [3, 8]. For liquefaction hazard prediction, measures of soil resistance with depth are beneficial, i.e., cone penetration test (CPT) and Vs depth profiles [9]. For landslide hazard prediction, measures of slope geometry, and friction angle and soil cohesion of geologic units, are beneficial [6, 10].

Compilation of Existing Geodata

Geodata for the MVSMMP were primarily compiled in two ways: (1) from previously acquired open and private geodata sources provided by 24 municipalities, agencies, and/or consulting firms, and (2) by performing field-based multi-method non-invasive seismic testing throughout the region. Open file resources (non-proprietary) from the federal, provincial, and municipal governments were compiled first (2017-2019), including topographical and geological maps, stratigraphic logs from the BC water well online database, and a compilation of over 500 velocity depth profiles from the Geological Survey of Canada [19]. From 2018-2022, proprietary geodata from 24 local geoconsultants, government organisations, stakeholder groups, and engineering firms were requested and collated in accordance with developed data-sharing agreements between both parties. The majority of the geodata were obtained by invasive *in situ* procedures (e.g., borehole stratigraphy, CPT, downhole seismic, and seismic cone penetration test (SCPT)) and geotechnical laboratory studies of discrete soil samples). More detailed description on the development of the geodatabase is documented in Adhikari et al. [2]. Currently, the number of geodata compiled from existing data sources (Figure 2a) consists of over 15,000 unique locations that includes 1389 CPT, 532 standard penetration testing (SPT), 797 Vs depth profiles, and more than 10,000 stratigraphic depth logs.

Multi-method Non-invasive Seismic Testing

Field campaigns of multi-method non-invasive seismic testing were accomplished to supplement the geodatabase (Figure 2b), including: (1) single-station microtremor horizontal to vertical spectral ratio (MHVSR) testing at over 2,000 locations to obtain amplification frequency spectra and peak resonance frequencies, (2a) combined active- and passive-source surface wave array testing at over 130 locations to obtain Rayleigh wave dispersion curves (inverted jointly with MHVSR peak frequencies to obtain the shear-wave velocity (Vs) depth profile resolved to major impedance contrast(s) in the upper hundreds of meters) and (2b) extended to significant depth (~2 km) from large-aperture surface wave array testing, (3) Vs refraction surveying for select sites with sloping ground, and (4) downhole compression-wave and Vs logging in 4 existing water wells.

MHVSR measurements were obtained at an average ~800 m grid resolution to capture the subsurface variability within the region (Figure 2b). At each site, single station measurements were typically performed for 20 minutes (uplands areas) to 60 minutes (lowland areas). Active-source multi-channel analysis of surface waves (MASW) and passive-source ambient vibration array (AVA) measurements were performed to obtain dispersion data over a wide frequency band to invert for Vs profiles. To achieve MASW testing, a linear array of 24 4.5 Hz vertical component geophones connected to a Geode seismograph was used with an 8 kg sledge hammer seismic source. Passive-source AVA measurements were performed using 6 Tromino® seismometers in a circular array geometry with a 7th central seismometer. The array aperture was typically varied four times with radii of 5, 10, 15 and 30 m at each site. These various active- and passive-seismic methods were implemented during five annual field campaigns (2018-2021).

The MVSMMP's multi-method non-invasive seismic testing approach was required to answer missing seismic site characterization information for the region (not previously known before the project): (1) Vs with depth for geologic units outside of the Fraser River delta [11], and (2) drift thickness and depth to rock (3D geomodels [3]) for the entire western Metro Vancouver region.

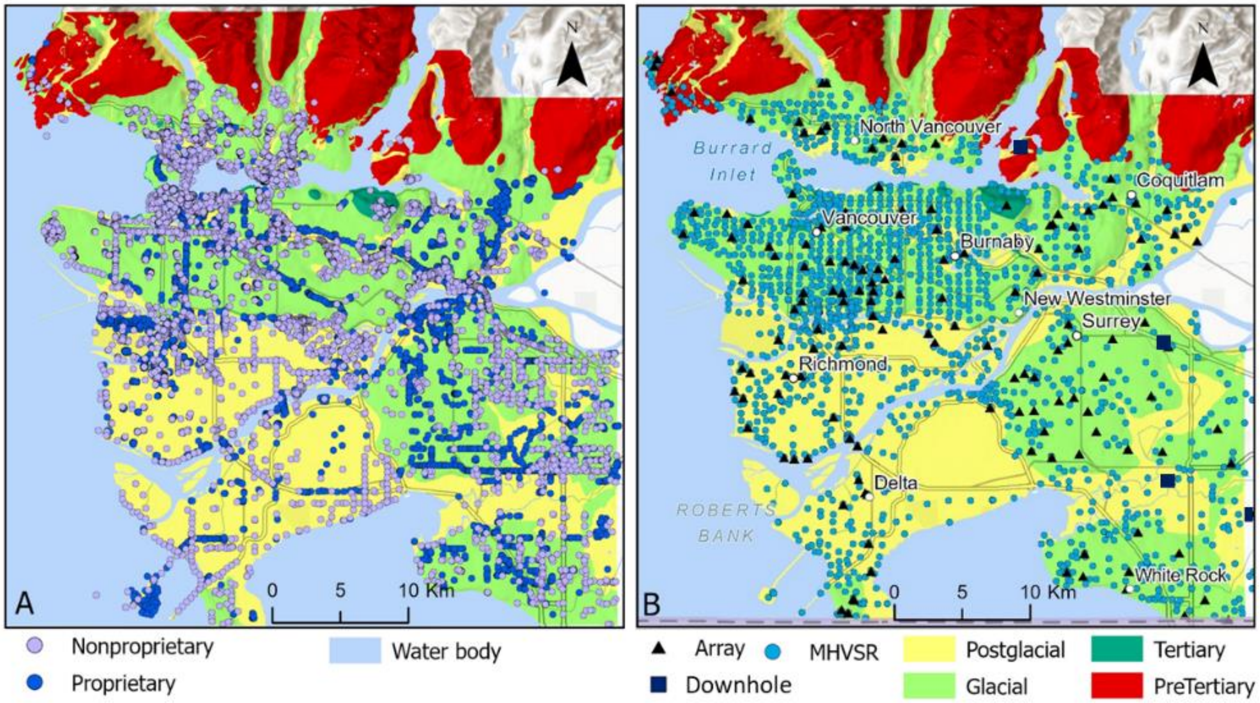

Figure 2. Geodata locations of the MVSMMP geodatabase from (a) proprietary and non-proprietary existing geodata sources, (b) non-invasive seismic testing (MHVSR and array sites) and downhole Vp and Vs logging in 4 existing boreholes, and (c) large-scale seismic array testing for deep velocity profiling at 6 select areas. Simplification of geologic mapping is shown in background.

MVSMMP Field Campaigns

The 1st field campaign (2018) focused on obtaining adequate spatial coverage within the western communities of the Metro Vancouver region. Available geodata as well as previous MHVSR measurements (obtained by the Univ. British Columbia Earthquake Engineering Research Facility from 2009-2012) were assessed to inform regions where additional data coverage was needed while active- and passive-source array testing were primarily co-located with strong motion instrument locations to characterize the subsurface conditions near the stations. A total of 10 field personnel was assembled and trained over 10 days with an overnight field campaign within Ontario by S. Molnar and A. Bilson Darko to perform the various non-invasive seismic testing data collection and analyses. All field data collection was accomplished in Metro Vancouver by the 10 field personnel over 30 days: 713 MHVSR sites and 44 multi-method seismic array sites (Figure 1). Active- and passive-seismic array testing was accomplished by 4 field personnel at 2 unique sites per day. A minimum of 2 field personnel performed single station MHVSR measurements per day. Simultaneously, 1 alternating field personnel performed initial data analyses of the collected data per day. In addition, project personnel simultaneously conducted observational field surveys of regional geologic features and steep slopes within specific regions (e.g., Burnaby Mountain, Fraser view, Sandy Cove, Deep Cove) to assess slope geology and morphology, presence of structural elements, fill, seepage, and runoff.

During the 2nd field campaign (2019), 4 University of British Columbia (UBC) undergraduate students were hired to supplement data collection and enable the 9-personnel project team to prioritize preliminary data analyses during the campaign. All fieldwork occurred within a 28-day period, with emphasis on collecting measurements to verify existing site effect boundaries (i.e., verify if mapped surficial geology polygon boundaries correspond to changes in seismic properties or MHVSR amplification response). For this reason, targeted microzonation (i.e., MHVSR measurements obtained within 10's to 100 m of each other), was accomplished in selected areas (False Creek, Burnaby Lake, Horseshoe Bay). Active- and passive-source array testing of 43 sites was accomplished to obtain continued coverage of the western Metro Vancouver communities, primarily outside of the geodata-populated Fraser River delta. A large array site (radii from 15 to 380 m) was accomplished in Delta to assess the possibility of retrieving dispersion estimates below the second MHVSR peak frequency (~0.8-1.0 Hz) [20]. This served as a feasibility study and informed the logistical planning of the 5th field campaign (discussed below). A 3-personnel team also performed geologic site checks of the available surficial geology mapping (validation) in combination with continued field observations of exposed geology and slope hazards. A total of 150 slope locations were visited and categorized based on their observed performance.

Following the addition of the municipality of Surrey and White Rock to the project scope, the 3rd field campaign in 2020 was planned to obtain adequate coverage and testing of site conditions in this sub-region. Due to travel restrictions from the global COVID-19 pandemic, the 2020 field campaign occurred in two phases. The first campaign phase focused on obtaining MHVSR measurements only, performed by 2 of the local UBC students (previously trained in 2019) over a 3-week period. When travel restrictions eased, the second campaign phase involved a 4-personnel project team performing targeted multi-method array measurements only for 2 weeks. The two-phase 2020 field campaign resulted in data acquisition of over 350 MHVSR and 20 array sites (Figure 1). In addition, array sites tested in 2018 and 2019 that had complex site conditions (e.g., lateral heterogeneity, sloping ground) were revisited to perform compression-wave and Vs refraction surveys for improved site characterization [21].

The 4th field campaign in 2021 targeted specific regions in the project's eastern most communities to better understand and resolve local seismic site conditions there. A 5-personnel project team performed the field campaign over a 3-week period. Denser MHVSR measurements were performed to map the thickness of Capilano sediments throughout the Nicomekl-Serpentine valley as well as co-locate measurements with existing downhole or SCPT locations with known depths to till and/or bedrock. Spatial coverage of MHVSR measurements was accomplished for the southeast Surrey region (including White Rock upland, Hazelmere area) and elsewhere for Sea Island and Iona Island. Multi-method array measurements were completed mainly in south Surrey as well as Tsawwassen and White Rock uplands. Vs refraction was performed at select sites to help constrain the inversion of array data at glacial sediment sites with likely velocity inversions [21]. To improve our knowledge of the seismic properties of glaciated sediments and rock units within the project region, 4 existing boreholes (two in Surrey, one each in Belcarra and Langley) from the provincial groundwater observation wells database were identified. Frontier Geosciences Inc. was sub-contracted to perform downhole compression-wave and Vs logging in these existing boreholes in collaborative support with the BC Ministry of Forests, Lands, and Natural Resources. Additional MHVSR and array measurements were co-located to these boreholes to calibrate the multimethod seismic testing at the sites.

From the four field campaigns (2018-2021), MHVSR measurements were performed at over 2,000 locations (Figure 2b) to obtain amplification frequency spectra and peak resonance frequencies and combined active- and passive-source surface wave array testing at over 125 locations (Figure 2b) to obtain fundamental-mode Rayleigh wave dispersion curves (Figure 3). See Molnar et al. [11] of this special session for depiction and discussion of the ~2200 lowest MHVSR peak frequency values (inferred as the inverse of site period) across western Metro Vancouver. Joint inversion of the fundamental-mode Rayleigh wave phase velocity dispersion curve with the MHVSR peak frequency(ies) was accomplished for each array site to determine the optimal Vs depth profile [e.g., 5, 20, 21]; eight personnel were involved in achieving joint inversion of the MHVSR and dispersion datasets for the over 125 array sites over a five-year duration. Figure 3 displays the fundamental-mode Rayleigh wave phase velocity dispersion curve extracted from the combined active- and passive-source seismic array testing accomplished at 123 seismic array sites across western Metro Vancouver. The presentation of dispersion curves in Figure 3 is in terms of spatial location (plot location corresponds to spatial layout in western Metro Vancouver) as well as the national building code of Canada seismic site class (colours correspond to classes C, D, and E) determined from the time-averaged shear-wave velocity of the upper 30 meters (Vs_{30}) calculated from the optimal Vs depth profile of the joint inversion. Figure 3 shows that dispersion estimates at all tested sites in western Metro Vancouver occur within 0.5 to 200 Hz; our consistent multi-method array testing (smallest MASW survey length was 11.5 m to the largest AVA array diameter of 60 m) typically provides reliable dispersion estimates within this frequency bandwidth. In Figure 3 frequency decreases along the x-axis, showing from left to right, lower velocity dispersion estimates at high frequencies (shallower depths) that increase with decreasing frequency (deeper depths). Sites with the lowest Rayleigh phase velocity dispersion estimates at the lowest frequencies (class E) have moderate-velocity (~400-500 m/s) estimates at their lowest frequency (base of velocity depth profile); the velocity of post-glacial sediments and their transition into moderate-velocity glacial till is measured. Site class E sites occur in lowland areas of Port Moody (grouped with Port Coquitlam and Coquitlam (PoCo)), the Fraser River delta (Richmond, Delta), and the Nicomekl-Serpentine valley (Surrey). Sites with low velocity dispersion estimates at mid-frequencies (class D) have velocities that reach between ~400 to ~1100 m/s at their lowest frequency (base of velocity profile); the velocity of post-glacial sediments and their transition into higher velocity glacial till or rock is measured. Class D sites are found throughout the western Metro Vancouver region. Sites with low velocity estimates limited to the highest frequencies (class C) exhibit moderate velocities (~400-700 m/s) that transition to high velocities (≥ 1000 m/s) at ~10 Hz or shallower depths (e.g., NorthShore, PoCo) to ≤ 1 Hz or deep depths (e.g., Surrey). Dispersion curves corresponding to seismic site class C show that velocities of surficial post-glacial sediments and glaciated sediments (variable thickness) and the transition to underlying rock is measured. Class C sites occur in glaciated upland regions (Vancouver, Burnaby, Surrey, Tsawwassen) and in the North Shore. The number of sites corresponding to class C to E generally decreases and results from the project's testing methodology, applying multi-method non-invasive seismic array testing outside of the Fraser River delta lowlands.

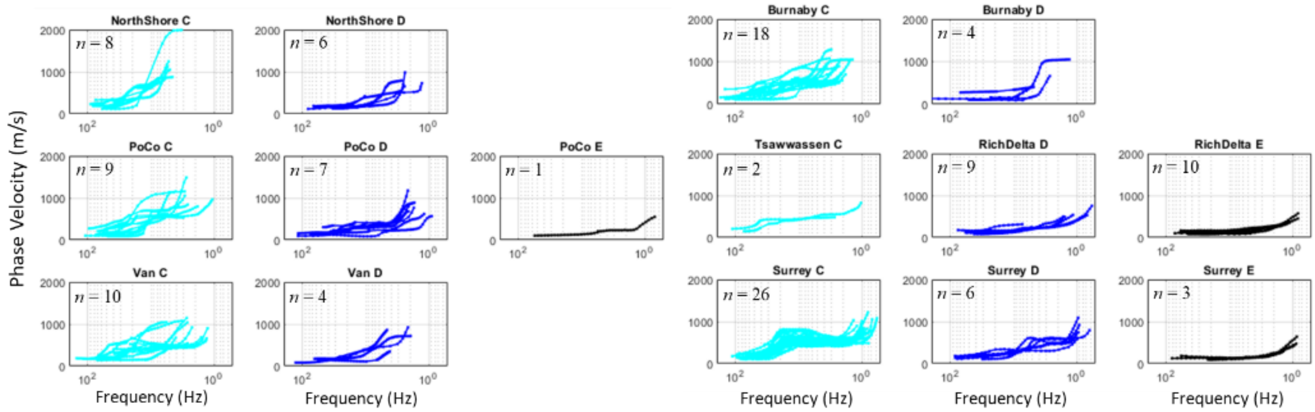

Figure 3. Fundamental-mode Rayleigh wave phase velocity dispersion curves at 123 array locations (see Fig. 2b) coloured according to Vs_{30} calculated from the optimal joint-inverted Vs depth profile (not shown): class C (760 ≤ Vs_{30} < 360 m/s) in cyan, class D (360 ≤ Vs_{30} < 180 m/s) in blue, and class E (Vs_{30} ≤ 180 m/s) in black.

A two-purpose 5th field campaign was performed by a 3-personnel team in 2022 over a 9-week period. Large-scale ambient vibration arrays of 0.5 to 2 km circumradii using 13 simultaneous recording seismometers were performed at 6 select areas to obtain low frequency (deep depth) dispersion estimates of the soil-till interface (Richmond, Ladner) and the till-rock interface (Burnaby, Coquitlam, Surrey, Vancouver) (Figure 4). The 13 seismometers were deployed in two circular arrays for simultaneous recording durations of up to 8 hours; all testing was accomplished over a 1-week period. The centre of each large array coincides with a multi-method seismic array site from a previous field campaign, i.e., the Vs depth profile will be extended to deeper depth at these six previous array sites, see Molnar et al. [11] for preliminary results. Following the completion of the six large-scale arrays for deep velocity profiling, an ambient noise tomography (ANT) survey was performed for two months which involved semi-permanent installation of 19 seismometers (14 short-period and 5 broad-band sensors) to densify the current seismometer networks and thereby improve resolution of a regional 3D Vs model [3]. These semi-permanent installation locations spanned the Lower Mainland, from Tsawwassen (southwest) to north of Lion's Bay (northwest) to Abbotsford and Mission (east). Preliminary 3D Vs modelling results from this ANT surveying is presented in Ghofrani et al. [3].

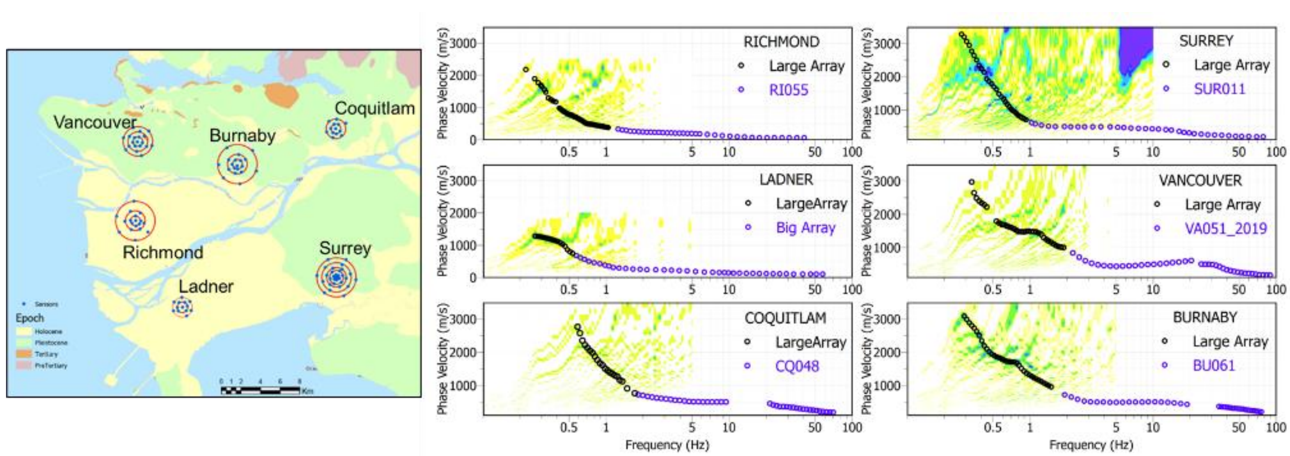

Figure 4. (left) Locations of 6 selected large-scale array testing sites are shown by 13 seismometer locations (blue circles) of the 1 to 4 km diameter (red circle) circular arrays. (right) Fundamental mode Rayleigh wave phase velocity dispersion estimates of the large arrays (black circles) from modified spatial autocorrelation dispersion analysis (yellow (low count) to purple (high count) colour scale) and previous smaller arrays (purple circles).

TANGIBLE PROJECT OUTCOMES

Open Data Site

Geodata acquired by the MVSMMP, and geodatabases developed by the MVSMMP, will be shared publicly via an open data site hosted by the Western Libraries Geospatial Hub (https://western-libraries-geospatial-hub-westernu.hub.arcgis.com/) and/or the BC government ClimateReadyBC hazard and mapping tools data site (https://climatereadybc.gov.bc.ca/) by the project end date (Figure 1). Links to the online open data resources will be made available at the project website, https://metrovanmicromap.ca. Data sharing agreements of proprietary data will be honoured, either anonymized prior to sharing, or only project-processed interpretation of the original proprietary data will be shared (e.g., Vs_{30} is shared but not the proprietary Vs depth profile). The 3D block models of seismic impedance layering and Vs (1 km depth; "geotechnical layer") and updates to the 3D regional community velocity model (60 km depth) [these models are described in [3]) will also be shared at the open data site.

Maps (geospatial data layers) generated by the MVSMMP will be shared publicly at the same open data site as the geodata(base) hosted by the Western Libraries Geospatial Hub and/or ClimateReadyBC by the project end date. Links to project maps will be made available at the project website. Users will have the ability to interact with the maps online, prior to downloading the maps for printing (e.g., PDF file) or for viewing on the end-users operating system (e.g., digital version to view with ArcMap).

It is expected that the suite of over 20 seismic microzonation maps developed by the MVSMMP will include ~9 seismic hazard susceptibility maps and ~12 probabilistic seismic hazard maps depicting shaking, liquefaction, or landslide hazard at 2% or 10% probability of exceedance risk levels.

Seismic Hazard Susceptibility Maps

Maps (geospatial data layers) that show subsurface ground conditions in terms of relevant and useful seismic hazard metrics have been produced, primarily as input to probabilistic seismic hazard (shaking, liquefaction, landslide) analyses. These map products do not depend on seismic shaking level and will not change when a new national seismic hazard model (new building code motions) are released, thereby termed as seismic hazard *susceptibility* maps. The planned seismic hazard susceptibility maps are: (1) liquefaction susceptibility and (2) landslide susceptibility, and maps showing measures relevant to seismic shaking susceptibility including (3) Vs_{30} and likely (4) geologic-unit-average Vs, (5) site period, (6) post-glacial soil thickness (depth to glacial till), (7) drift thickness (depth to seismic rock), (8, 9) basin depth terms, $Z_{1.5}$ and/or $Z_{2.5}$ (depth, Z, to Vs of 1.5 or 2.5 km/s, respectively). Note a seismic site class map can be produced from the Vs_{30} values but is not recommended; dissemination and access to mapped Vs_{30} values rather than site class are more impactful to evolving seismic hazard analysis and building code seismic site designation practice.

Probabilistic Seismic Hazard Maps

The Metro-Vancouver-specific probabilistic seismic hazard maps are developed using the 6th national seismic hazard (6NSHM) model (2020 National Building Code) at 2% and 10% probability of exceedance risk levels [8, 9, 10]. The 6NSHM includes areal and fault seismic sources, defined by their geometry and reoccurrence parameters, and associated ground motion models (GMMs) to predict surface ground motions based on seismicity of the 6NSHM sources (i.e., earthquake magnitude, source-to-site distance, Vs_{30} site term). Seismic sources of the 6NSHM within ~200 km of Vancouver include areal source zones that capture seismicity within the overriding North American continental and subducting Juan de Fuca and Explorer tectonic plates, and active fault sources that capture seismicity of the Cascadia subduction zone interface thrust fault and the Devil's Mountain – Leech River Valley fault system. The project did not update the source model or the GMMs of the 6NSHM.

For shaking (de/amplification) hazard mapping, the project uses the seismic design ground motions of the 6NSHM to select and scale input earthquake waveforms (two reference site conditions; Vs_{30} of 760 m/s and 1500 m/s) for one-dimensional (1D) site response analysis at 51 selected locations to develop a site effects (de/amplification) model specific to seismic site conditions in Metro Vancouver that modifies the 2020 NBC motions inclusive of local site conditions [8]. Long periods (> 1 s) in the developed region-specific site (de)amplification model are modified to reflect deep Georgia basin amplification in southwestern Metro Vancouver (e.g., Richmond, Delta, Tsawwassen) determined from 3D wave propagation simulations of large magnitude scenario earthquakes [3]. The shaking (de/amplification) hazard map is not produced from using the 6NSHM in combination with the region's spatial distribution of Vs_{30} because the inherent site amplification model within each GMM of the 6NSHM may not be appropriate to Metro Vancouver site conditions and soil nonlinear behaviour; the purpose of seismic microzonation mapping [11] is to replace non-region-specific (ergodic) models with region-specific (non-ergodic) models. The 6NSHM does not use/activate basin depth terms in the GMMs and thereby does not explicitly incorporate amplification related to the Georgia sedimentary basin that underlies Metro Vancouver and the Georgia Strait. Amplification hazard maps, displaying spatial variation in the factor adjustment of the 6NSHM motions at 2% and 10% probability of exceedance in 50 years risk levels, are expected to be produced at ~5 spectral periods (e.g., PGA, SA(0.2), SA(1.0), SA(2.0), SA(5.0)), totaling 10 maps.

For liquefaction hazard mapping, peak ground acceleration (PGA) of the 6NSHM at 5 select Vs_{30} values and 16 sites is used to predict liquefaction potential index (LPI) and liquefaction severity number (LSN) at over 800 *in situ* cone penetration test and Vs depth profile locations [9]. For landslide hazard mapping, seismic-induced sliding displacement prediction equations for crustal, inslab, and interface earthquakes are integrated into the 6NSHM probabilistic seismic hazard analysis to predict seismic-induced sliding displacements (as a function of yield acceleration, slope angle and height, and groundwater table elevation) at 16 select periods [10]. Probabilistic liquefaction and landslide hazard potential maps at 2% and 10% probability of exceedance in 50 years risk level will be produced, displayed as qualitative hazard ratings based on LPI and seismic-induced displacement, respectively.

Seismic Microzonation Mapping Guidelines

The Metro Vancouver seismic microzonation mapping project revived development of professional practice guidelines of seismic microzonation mapping in British Columbia [11], led by the Engineers and Geoscientists of British Columba (EGBC). These guidelines are intended to complement the MVSMMP and provide a common approach for carrying out seismic microzonation mapping projects in British Columbia, as well as a common approach for using seismic microzonation maps in the province. The guidelines are written and organized to be useful to a variety of end-users – 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. For further details, see the last conference paper of this special session [11].

CONCLUSIONS

The Metro Vancouver seismic microzonation mapping project 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. This paper presents the development of a comprehensive geodatabase specific to seismic hazard prediction for the MVSMMP. Pre-existing geodata, primarily invasive *in situ* geodata, are compiled from various public and ~24 private data sources. In addition, field campaigns of multi-method non-invasive seismic testing were accomplished to supplement the geodatabase, including: (1) single-station microtremor method testing at ~2,200 locations to obtain amplification frequency spectra and peak resonance frequencies, (2a) combined active- and passive-source surface wave array testing at over 120 locations to obtain Rayleigh wave dispersion curves (inverted jointly with peak frequencies to obtain the shear-wave velocity (Vs) depth profile resolved to major impedance contrast(s) in the upper hundreds of meters) and (2b) extended to significant depth (~2 km) from large-aperture surface wave array testing, (3) Vs refraction surveying for select sites with sloping ground, and (4) downhole compression-wave and Vs logging in 4 existing water wells.

The developed geodatabase enables data-driven seismic site characterization across the Metro Vancouver region, including descriptive statistics of geodata, region-specific predictive relationships, 1D soil column to 3D regional-volume modelling, and generation of seismic-hazard-input susceptibility maps (e.g., Vs_{30}, $Z_{1.5}$, site period, post-glacial sediment thickness, landslide or liquefaction susceptibility). It is expected that the suite of over 20 seismic microzonation maps developed by the MVSMMP [8, 9, 10] will include ~9 seismic hazard susceptibility maps and ~12 probabilistic seismic hazard maps at 2% or 10% probability of exceedance risk levels. Additionally, the geodatabase acquired and developed by the MVSMMP provides a starting point for a geodata repository which will serve as a key reference for practicing engineers and geoscientists within the region for future seismic hazard studies.

ACKNOWLEDGMENTS

We are grateful to the various government agencies and 24 municipalities, agencies and consulting firms that provided geodata for this project. The geodatabase is managed by Sujan Raj Adhikari (PhD, Earth Sciences) with Alex Bilson Darko (Project Manager) and the support of Ranjana Ghimire and Rohzan Raoufi (Research Assistants) and University of Western Ontario (UWO) students Andrew Beney, Jacob Edgett, Tyler Beattie, and Congxi Zhu. Non-invasive measurement field campaigns were organized and led by Sheri Molnar (2018, 2019, 2022) and Alex Bilson Darko (2018-2022) with measurements collected and processed by UWO students: Sujan Raj Adhikari, Jamal Assaf (PhD, Civil Engineering), Chris Boucher (MSc, Earth Sciences), Meredith Fyfe (MSc, Earth Sciences & Env. Sustainability), Aamna Sirohey (MSc, Earth Sciences), Sameer Ladak (MSc, Earth Sciences), Natalia Gómez Jaramillo (MSc, Earth Sciences), Magdalena Kapron (MSc, Earth Sciences) with field support from Ali Fallah Yeznabad (PhD, Civil Engineering), Alireza Javanbakht Samani (PhD, Earth Sciences), Thomas Foulon (U. Waterloo) and undergraduate University of British Columbia summer students Azhar Izman and Youssef Shaaban (2019-2020) and Rachel Choboter and Christie Tsang (2019). 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] Molnar, S., J. Assaf, A. Sirohey, S. R. Adhikari (2020). “Overview of local site effects and seismic microzonation mapping in Metropolitan Vancouver, British Columbia, Canada.” *Engineering Geology*, 270, 105568.

[2] Adhikari, S.R., Molnar, S., and Wang, J. (2021). “Significance of geodatabase development for seismic microzonation in Metropolitan Vancouver, Canada”. *In* 17th World Conference on Earthquake Engineering, Sendai, Japan, 12 pg.

[3] Ghofrani, H., 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." In *CCEE-PCEE Conference Proceedings*, Vancouver, BC, Canada, Paper 257, 12 p.

[4] Yeznabad, A. (2021). "Probabilistic seismic landslide mapping of western Metro Vancouver, British Columbia." University of Western Ontario, Dept. Civil & Env. Engineering, PhD Thesis, https://ir.lib.uwo.ca/etd/8345/

[5] Assaf, J. (2022). "Seismic Site Characterization and Response of Metro Vancouver." University of Western Ontario, Dept. Civil & Env. Engineering, PhD Thesis, https://ir.lib.uwo.ca/etd/9035/.

[6] Fallah Yeznabad, A. S. Molnar, H. El Naggar, H. Ghofrani (2022). "Estimation of probabilistic seismic sliding displacement and pseudo-static coefficients (k15) for seismic stability assessment of slopes in the southern Lower Mainland, British Columbia." *Soil Dynamics and Earthquake Engineering*, 161, 107364.

[7] Assaf, J., S. Molnar, H. El Naggar (2023). "CPT-Vs correlations for post-glacial sediments in Metropolitan Vancouver", *Soil Dynamics and Earthquake Engineering*, 165, 107693.

[8] Assaf, J., H. Ghofrani, M. H. El Naggar, S. Molnar (2023). "Metro Vancouver Seismic Hazard Mapping Inclusive of 1D Site and 3D Basin Effects." In *CCEE-PCEE Conference Proceedings*, Vancouver, BC, Canada, Paper 284, 8 p.

[9] Javanbakht, A., J. Assaf, M. Salsabili, A. Sadrekarimi, H. Ghofrani, S. Molnar (2023). "Metro Vancouver Liquefaction Hazard Mapping." In *CCEE-PCEE Conference Proceedings*, Vancouver, BC, Canada, Paper 275, 10 p.

[10] Yeznabad, A., H. Ghofrani, M. H. El Naggar, S. Molnar (2023). "Metro Vancouver Landslide Hazard Mapping." In *CCEE-PCEE Conference Proceedings*, Vancouver, BC, Canada, Paper 289, 12 p.

[11] Molnar, S., 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." In *CCEE-PCEE Conference Proceedings*, Vancouver, BC, Canada, Paper 288, 9 p.

[12] Assaf, J., A. Sirohey, H. Ghofrani, S. Molnar (2022). "Compilation and systematic processing of earthquake and microtremor HVSR amplification at Metro Vancouver strong-motion stations." Metro Vancouver Seismic Microzonation Mapping Project, Report 22-05, 38 p., ISSN 2816-602.

[13] Sirohey, A. (2022). "Soil amplification and peak frequencies from thousands of passive seismic measurements across Metro Vancouver, British Columbia, Canada." University of Western Ontario, Dept. Earth Sciences, MSc Thesis, https://ir.lib.uwo.ca/etd/8810/

[14] Assaf, J., S. Molnar, H. El Naggar (2018). "Comprehensive earthquake site amplification assessment for Greater Vancouver." *In 71st Canadian Geotechnical Conference Proceedings*, Edmonton, Alberta, October 2018, 8 p.

[15] Molnar, S., Cassidy, J. F., Olsen, K. B., Dosso, S. E., & 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.

[16] Ghofrani, H., and S. Molnar (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 CCEE proceedings*, June 17-20 2019, Quebec City, 8 pg.

[17] Javanbakht Samani, A., S. Molnar, A. Sadrekarimi, H. Ghofrani (in review). "Estimation of historical earthquake-induced liquefaction in Fraser River delta using NBCC 2020 GMPEs in deterministic and probabilistic frameworks." *Earthquake Spectra*, EQS-23-0001.

[18] Gomez Jaramillo, N., S. Molnar, H. Ghofrani (2023). "Searching for Empirical Nonlinear Site Response Applicable to Greater Vancouver, British Columbia." *Seismological Research Letters*, 94, 2B, 1264.

[19] Hunter, J. A., R. A. Burns, R. L. Good, and C. F. Pelletier (1998). "A Compilation of Shear Wave Velocities and Borehole Geophysics Logs in Unconsolidated Sediments of the Fraser River Delta." Geological Survey of Canada Open File Report 3622 (CD ROM), revised in 2016.

[20] Assaf, J., S. Molnar, M. H. El Naggar, A. Sirohey (2022). "Seismic site characterization in Fraser River Delta in Metropolitan Vancouver", *Soil Dynamics and Earthquake Engineering*, 161, 107384.

[21] Boucher, C. (2022). "Approaches to model non-uniqueness and site complexity for non-invasive shear-wave depth profiling." University of Western Ontario, MSc Geophysics Thesis, https://ir.lib.uwo.ca/etd/9005.