REPORT
doi:10.26443/seismica.v3i2.1339

SEISMICA

Development and Comparison of 3D Seismic Geology and Shear-wave Velocity Models of Metro Vancouver

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Author contributions: *Conceptualization*: S.R Adhikari, S. Molnar. *Data Curation*: S.R. Adhikari. *Formal Analysis*: S.R Adhikari, S. Molnar. *Methodology*: S.R Adhikari, S. Molnar. *Software*: S.R Adhikari. *Validation*: S.R Adhikari, S. Molnar. *Visualization*: S.R Adhikari. *Writing – original draft*: S.R Adhikari. *Writing – review & editing*: S. Molnar.

Abstract This study presents a 3D regional modeling of seismic geology and shear wave velocity (Vs) in Metro Vancouver for seismic microzonation and hazard prediction. Leveraging an extensive geodatabase compiled from invasive and non-invasive in situ data, including lithological logs and seismic field data, we delineated four major geological units: Holocene post-glacial and Pleistocene inter/glacial sediments, and Tertiary sedimentary and Pre-Tertiary Coast Mountain plutonic rocks. Seismic geology model integrates the four primary geological formations, leveraging significant impedance-based surfaces derived from meticulously analyzed borehole stratigraphic logs and Vs depth profiles sourced from 2333 georecords, enhancing its depth and accuracy. Through a meticulous comparison with established interpreted geological cross-sections, we have reaffirmed the robustness and reliability of our seismic geology modeling approach. A numerical 3D "geotechnical layer" Vs model with 11 isovelocity surfaces was developed using 688 Vs depth profiles. Comparison with microtremor amplification spectra confirms our 3D models' reliable use in predicting site amplification. We find that the combination of local geology (thicknesses) and Vs information outperforms prediction in fundamental peak frequency compared to using only local geology combined with regional Vs information. Our study contributes to advancing understanding of seismic hazards in Metro Vancouver, highlighting the importance of incorporating localized seismic site conditions for precise regional seismic hazard assessments

Non-technical summary This study focuses on creating a three-dimensional model of the seismic geology beneath Metro Vancouver to better predict earthquake ground shaking and seismic-induced liquefaction and landslide hazards. From our development of a comprehensive geodatabase, we identified four main seismic geology units that are mapped in detail in our 3D seismic geology models. We evaluated our models by comparison of site amplification predicted numerically for sites in our models with that measured by ambient vibrations at these selected sites. This research enhances the understanding of subsurface seismic site conditions in Metro Vancouver and underscores the importance of considering local seismic conditions for accurate ground motion prediction

Production Editor:
Gareth Funning
Handling Editor:
Tiegan Hobbs
Copy & Layout Editor:
Théa Ragon

Signed reviewer(s):
Philippe Rosset

Received:
March 25, 2024
Accepted:
August 14, 2024
Published:
September 12, 2024

1 Introduction

The importance of 3D modelling lies in its capacity to provide a comprehensive representation of the Earth's subsurface complexities. 3D modelling enables geoscientists to capture the spatial complexities of geological and geophysical layer structures providing a more accurate portrayal of subsurface ground conditions. With the advancements in computer processing power and the development of enhanced geological software, there has been significant progress in the use of 3D modelling in the geoscientific fields. These developments brought profound changes in the approaches to acquiring, storing, processing, and displaying geological data for 3D geological models. Proper data collection and management are essential for any modelling environment. Various geological surveys around the world have developed databases for 3D modelling. For instance, Geoscience Australia has developed 3D structural and geological model inputs for Australia (Lemon and Jones, 2003), British Geological Survey models are based on a national cross-section fence diagram approach (Mathers et al., 2014), the Danish Geological Survey has developed Jupiter database containing borehole information, GERDA database consist of surface-near geophysics data and Oil and gas database known as FRISBEE (Sandersen et al., 2016), and the Netherlands Geological Survey built the Digital Information of the Dutch Subsurface (DINO) database consisting of 3D models of the upper 30 m of the subsurface (Stafleu et al., 2021). 3D geological models are being gradually utilized worldwide to support advanced analysis and decision-making for geotechnical (Culshaw, 2005), hydrogeological (Scharling et al., 2009), hydrocarbon (Ringrose and Bentley, 2015), and other geological investigations.

The conventional understanding of 3D geologic modelling typically adheres to the concept of a stratigraphic sequence, where layers are arranged based on basic ge-

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ologic principles (e.g., the law of superposition and, the law of lateral continuity). There has been progress in the approach to 3D modelling, transitioning from this geologic-rules-based approach with human expertise guiding the modelling decisions (Miller, 1993) to an explicit modelling approach using 2D cross-sectional interpretation along survey lines which permit more detailed and controlled representation of geological structures while leveraging user-defined rules and conditions. The more recent implicit modelling approach (Cowan et al., 2003) utilizes algorithms and mathematical functions to infer geological structures from available data without explicit user inputs. Based on geologically interpreted data and structural modelling, the software then employs mathematical functions, such as kriging and radial basis functions, to determine layer contacts (Cowan et al., 2003). In the modelling practices of the 1990s, conventional GIS platforms like MapInfo Pro (Kosuwan et al., 1999; Logan et al., 2006; Maxelon et al., 2009) and ArcInfo (Götzl et al., 2007; E.S.R.I., 1999; Stafleu et al., 2021), along with 3D modelling software, such as GOCAD (Mallet, 1992; Russell et al., 2019; de Kemp and Schetselaar, 2015), were commonly employed. However, contemporary 3D geological and groundwater modelling studies have transitioned to utilizing Seequent's LeapfrogGeo platform (Alcaraz et al., 2011), as highlighted by MacCormack et al. (2019).

In Canada, the Geological Survey of Canada initiated a surface trend evaluation in 1970, utilizing 3rd order polynomials for pluton geometry estimation (Agterberg and Chung, 1975). Methodologies for handling complex folding evolved from propagation approaches to implicit methods based on kriging and radial basis functions since the 1990s (De de Kemp et al., 2016). Notably, Schetselaar (2013) conducted 3D modelling of the Canadian Shield and orogenic belts for the estimation of regional geology and mineral deposit. Various projects that have utilized 3D modelling in Canada, including geological and hydrological modelling of the Dundas Valley (Marich et al., 2011), 3D wave propagation simulation in western Canada (Molnar et al., 2014), and a 3D geological model of the Paleozoic bedrock of southern Ontario (Carter et al., 2019), have enhanced groundwater, geology, and public safety geoscience initiatives. Canada is a leader in 3D geomodelling with the most advanced 3D mapping programs in Alberta (MacCormack and Banks, 2013), Saskatchewan (Card et al., 2010), and Manitoba (Matile et al., 2011), while Ontario has made significant progresses in both bedrock and surficial modelling efforts (Marich et al., 2011).

3D models are quite commonly used in the field of geology and mineral exploration (e.g., Lemon and Jones, 2003; Caumon et al., 2009; Berg et al., 2011; Guo et al., 2021), however there has been a shift of 3D modelling applications particularly towards seismic hazard assessments (e.g. Salsabili et al., 2020; Panzera et al., 2022). 3D models are now being generated and utilized with a primary focus on predicting site amplification or ground motion in the context of seismic hazards. Rosset and Chouinard (2008) initially introduced a four-layer model, utilizing borehole and seismic data to generate amplification factor and Vs30 maps for the island of Montreal. This method was later extended to encompass the entire metropolitan area of Montreal (Rosset et al., 2023). Nastev et al. (2016a) established a regional Vs30 model by combining a simplified five-layer 3D geology model of the St. Lawrence Lowlands, Canada (Parent et al., 2021) with 6000 statistically representative shear-wave velocity (Vs) values. Subsequently, Foulon et al. (2017) successfully developed a 3D geological model of Saguenay, Canada, and applied the regional average Vs value to each geological layer to develop the 3D by-product models in terms of key seismic site characterization measures (i.e., the time-averaged Vs of the top 30 meters, Vs30 and site period). Salsabili et al. (2021) developed a methodology for probabilistic regional 3D modelling of soil deposits with the main focus on considering soil type heterogeneity as the primary source of uncertainty in the city of Saguenay, Canada. Utilizing Leapfrog Geo modelling software, 3D seismic-related geology block models have been successfully generated for seismic microzonation mapping in the St. Lawrence Lowlands (Nastev et al., 2016b) and Saguenay (Salsabili et al., 2020; Foulon et al., 2017); the term seismic-related geology is used to convey that geologic layers (2D surfaces within the 3D model) are generated and associated or attributed with region-specific (geostatistical) average Vs estimates. All these endeavors collectively contribute to advancing our understanding of seismic characteristics in specific regions through sophisticated 3D geological modelling techniques.

This paper presents our 3D regional modelling of Metro Vancouver in terms of seismic geology (four major geologies and their three seismic impedance contrasts) and Vs that are generated for seismic microzonation and seismic hazard (ground motion, amplification) prediction purpose. To achieve the 3D modelling, we utilize the most comprehensive geodatabase assembled for the region to date (Adhikari, 2024; Adhikari et al., 2021). Given that our 3D models are tailored for seismic hazard purposes, the most suitable comparison method involves assessing its predictive accuracy concerning site amplification and its alignment with empirical amplification data. The primary objective of this study is to develop detailed 3D models (1 km depth) of Metro Vancouver's seismic site conditions suitable for future seismic hazard analyses, including prediction of ground motions and site amplification as well as for seismic microzonation purposes.

2 Setting

Metro Vancouver is situated in the southwestern part of the British Columbia province; surrounded by mountains, including the Cascade Mountains to the east and the Coast Mountains to the north. The Fraser River runs through the middle of Metro Vancouver. The city of Delta has the lowest elevation of 0 meters, while Black Mountain in West Vancouver has a maximum elevation of 1,220 meters. The area's slopes are steep in the north, especially along the North Shore of West and North Vancouver and gentle in the south, in the Fraser River delta and lowlands (Figure 1A). The geology of Metro Vancouver is quite variable and simplified to four major geologies of Holocene post-glacial and Pleistocene and older inter/glacial sediments, Tertiary Georgia basin sedimentary and Pre-Tertiary Coast Mountain plutonic rocks in Figure 1A.

Three of five selected cross-sections of the simplified geology are also shown in Figure 1; these are interpreted geologic cross-sections by Rogers et al. (1998) and Clague et al. (1998) from the region's Quaternary geologic mapping of Armstrong and Hicock (1979, 1980). The youngest Holocene post-glacial deposits in the region are modern alluvial, deltaic and bog deposits. The Fraser River delta, south of Vancouver, is a topographically lowland region comprising deltaic silts and sands, with thickness up to 300 m (Rogers et al., 1998) as seen in Figure 1B. Pleistocene and older inter/glacial sediments are mostly composed of ice-compacted till and glaciomarine and glaciofluvial sediments (Luternauer et al., 1994). These sediments are exposed north and east of the Fraser River delta in upland areas. Beneath the Fraser River delta, the succession of Pleistocene and older sediments is as thin as 19 m beneath central Lulu Island (Figure 1C; Dallimore et al., 1995) and up to 500 m thickness under the centre of Fraser River delta (Figure 1D; Christian et al., 1994; Britton et al., 1995). The Holocene-Pleistocene sediment package overlies the Late-Cretaceous (Tertiary) Georgia basin sedimentary bedrock which pinches out (outcrops) along the North Shore and dips southward beneath Vancouver (Figure 1) reaching ~200 m depth north of the Fraser River delta and ~800 m beneath Richmond (Britton et al., 1995). Pre-Tertiary Coast Mountain plutonic igneous rocks are well exposed at the highest altitudes in northern Metro Vancouver. Drilling wells and geophysical investigations have revealed details about the extent, stratigraphy, and material properties of Quaternary deposits below the Fraser River delta. The overall subsurface architecture of the Fraser River delta is therefore dominated by two major seismic impedance contrasts between Holocene and Pleistocene and older sediments (seismic impedance contrast of ~1.5 to 3) and between Pleistocene and older sediment and Tertiary bedrock (seismic impedance contrast of ~2 to 3) (Hunter et al., 2016). The depths to these two major seismic impedance contrasts control the resonant frequencies of Fraser River delta sites and play a major role in its site amplification and earthquake site response (e.g., Assaf et al., 2022; Sirohey, 2022).

3 Regional Geodatabase

We gathered geological, geophysical, and geotechnical data to develop a comprehensive 3D geodatabase for the Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP, https://metrovanmicromap.ca). The Project's goal is to predict and map earthquake shaking de/amplification and seismic-induced liquefaction and landslide hazards. Development of this important regional geodata resource for seismic hazard prediction was documented previously (Molnar et al., 2023; Adhikari, 2024; Adhikari et al., 2021) and is summarized here.

Geodata compilation for the MVSMMP was accomplished via two independent but parallel avenues: (1) from previously collected available and private geodata sources, and (2) by performing in situ field-based multi-method non-invasive seismic testing across the region. In avenue 1, open geodata resources of the federal, provincial, and municipal governments were gathered first, then we requested and compiled private in situ geodata from 24 local geoconsultants, government agencies, stakeholder groups, and engineering firms. The most notable open source geodata resource is that of Hunter et al. (2016) which provides access to over 500 Vs depth profiles within the Holocene Fraser River delta area obtained over decades from seismic refraction, seismic cone penetration testing (SCPT), and downhole velocity profiling testing. In avenue 2, the MVSMMP facilitated supplementing avenue 1 geodata with multi-method non-invasive in situ seismic testing techniques, such as active-source seismic refraction and surface wave dispersion (e.g., multichannel analysis of surface waves (MASW) methods, and passive-source ambient vibration array (AVA) and microtremor horizontal to vertical (H/V) spectral ratio methods (MHVSR).

At over 120 locations of multi-method seismic field testing (AVA, MASW, and MHVSR), joint inversion of each site's fundamental-mode Rayleigh wave dispersion curve and site frequencies (f_{0HV}, and f_{1HV} when applicable) is accomplished to provide constrained Vs depth profiles with depth (Assaf et al., 2022; Boucher, 2022; Ladak, 2020). At over 2,300 locations, single station MHVSR testing provides amplification spectra and associated peak frequencies (Molnar et al., 2020; Sirohey, 2022). MHVSRs were calculated from 60-s time windowed microtremor recordings using the HVSRPy software by dividing the geometric mean spectrum of the horizontal component Fourier spectra by that of the vertical Fourier spectrum, both of which were smoothed using the Konno Omachi frequency filter (b value of 40; Sirohey, 2022). Each MHVSR Fourier amplification frequency spectrum provides peak frequencies and associated amplification related to seismic impedance contrasts; the default assumption is that the lowest H/V peak frequency (f_{0HV}) is a measure of the fundamental-mode site frequency (f_0, inverse of site period) (Molnar et al., 2022). Various distinct types of MHVSR amplification response are obtained across Metro Vancouver (Molnar et al., 2020; Sirohey, 2022). Rock and thin sediments sites in northern Metro Vancouver are characterized by flat MHVSR spectra (no f_{0HV}) or occurrence of f_{0HV} at very high frequencies (> 10 Hz), respectively. The succession of Pleistocene and older inter/glacial sediments present in upland areas of Vancouver, Burnaby, and Surrey, manifests as low and broad f_{0HV}. The Holocene Fraser River delta exhibits a very low f_{0HV} (~0.3 Hz) that is persistent throughout the delta due to the relatively great depth (> 200 m) to Tertiary Georgia basin sedimentary bedrock. Towards the edges of the Fraser River delta, a second peak frequency (f_{1HV}) occurs ~1 Hz and may exhibit amplification greater than that of A_{0HV} depending on the depth of the shallower Holocene-over-Pleistocene-sediments impedance contrast (Sirohey, 2022). Hence, the depths of the two significant seismic impedance contrasts beneath the

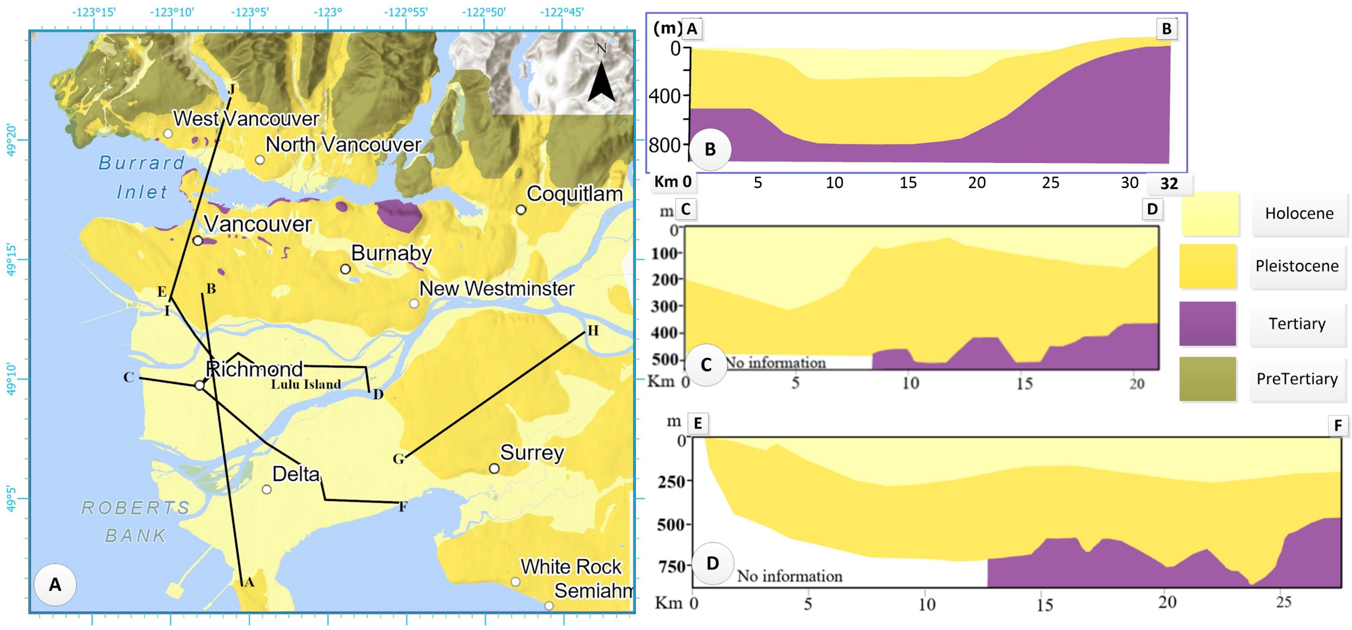

Figure 1 (A) Simplified geological map of Metro Vancouver draped over the regional digital elevation model with solid line depicting five selected cross-sectional profiles. Interpreted geological cross section for three cross-section profiles are shown in (B) north-south profile AB (modified from Rogers et al. (1998)), (C) west-east profile CD, and (D) northwest-southeast profile EF (modified from Clague et al. (1998)).

Fraser River delta leads to either single or double-peak H/V amplification as well as impacts each peak's amplification (Sirohey, 2022).

The MVSMMP geodatabase comprises ~15,000 locations of subsurface geodata including 688 Vs depth profiles and 2,375 MHVSR amplification spectra and associated peak site frequencies. Figure 2 depicts the quantity and location of the MVSMMP's geodata of relevance to this study. Figure 2A and Figure 2B shows locations of geological (lithology) datasets that are converted to estimates of depth to Pleistocene and older inter-glacial sediments (i.e., thickness of Holocene post-glacial sediments) and depth to rock (i.e., total Quaternary sediment thickness), respectively. Figure 2C and Figure 2D displays locations of seismic datasets: 688 locations of Vs depth profiles obtained from a variety of field methods and the project's multi-method seismic field-tested locations, respectively. This compiled geodatabase is a crucial and comprehensive resource of Metro Vancouver that offers a robust and current repository of geospatial data from which to predict seismic hazards.

4 3D Modeling Methodology

We employ implicit modelling techniques for 3D model creation that utilize Radial Basis Functions (RBF). RBFs are real-valued functions that for a set of specified data points consider the values of each associated datum point to ensure that a linear combination of these basic functions meets the interpolation requirements (Wright, 2003). The interpolated value is most influenced (weighted) by nearby location points and less by further location points and at a certain distance there is no influence according to Tobler's first law of geography (Sui, 2004; Waters, 2018). 3D model values are primarily controlled by the quality of input data (control points) and the spatial modelling methodology followed during the modelling process (e.g., Gaussian RBF interpolation). In this study, we employ the most extensive geodatabase developed for Metro Vancouver to date as part of the MVSMMP (Adhikari, 2024) to achieve 3D regional modelling of Metro Vancouver. By utilizing the MVSMMP's geodatabase of borehole stratigraphic logs and depth estimates of major seismic impedance(s), we seek to develop a 3D model of the significant seismic-impedance-based geologic surfaces. The crucial step in this 3D modelling process involves constructing seismic geology interfaces between the four major geologies in the region to identify the significant impedance boundaries between seismically similar geologic layers. Additionally, we use Vs depth profiles obtained from both invasive and non-invasive in situ seismic testing to develop a 3D "geotechnical layer" Vs model. The "geotechnical layer" terminology is used by seismologists to convey the near surface (uppermost grid cells) of a regional 3D community velocity model that is typically developed for physics-based ground motion prediction via earthquake wave propagation simulations; the 3D Vs model developed in this study for Metro Vancouver is a higher (lateral and vertical) resolution 3D model based on local in situ geodata and will be merged into (supersede) the uppermost cells of an existing regional 3D velocity model of southwest British Columbia (Ghofrani et al., 2023).

We choose to use Seequent's Leapfrog Geo (version 2021.1.0) platform to achieve the 3D seismic geology and "geotechnical layer" Vs modeling. The Leapfrog Geo platform generally requires three input files for 3D modelling: (1) collar files that include geographic coordinates and a unique ID for each collar position, (2) sur-

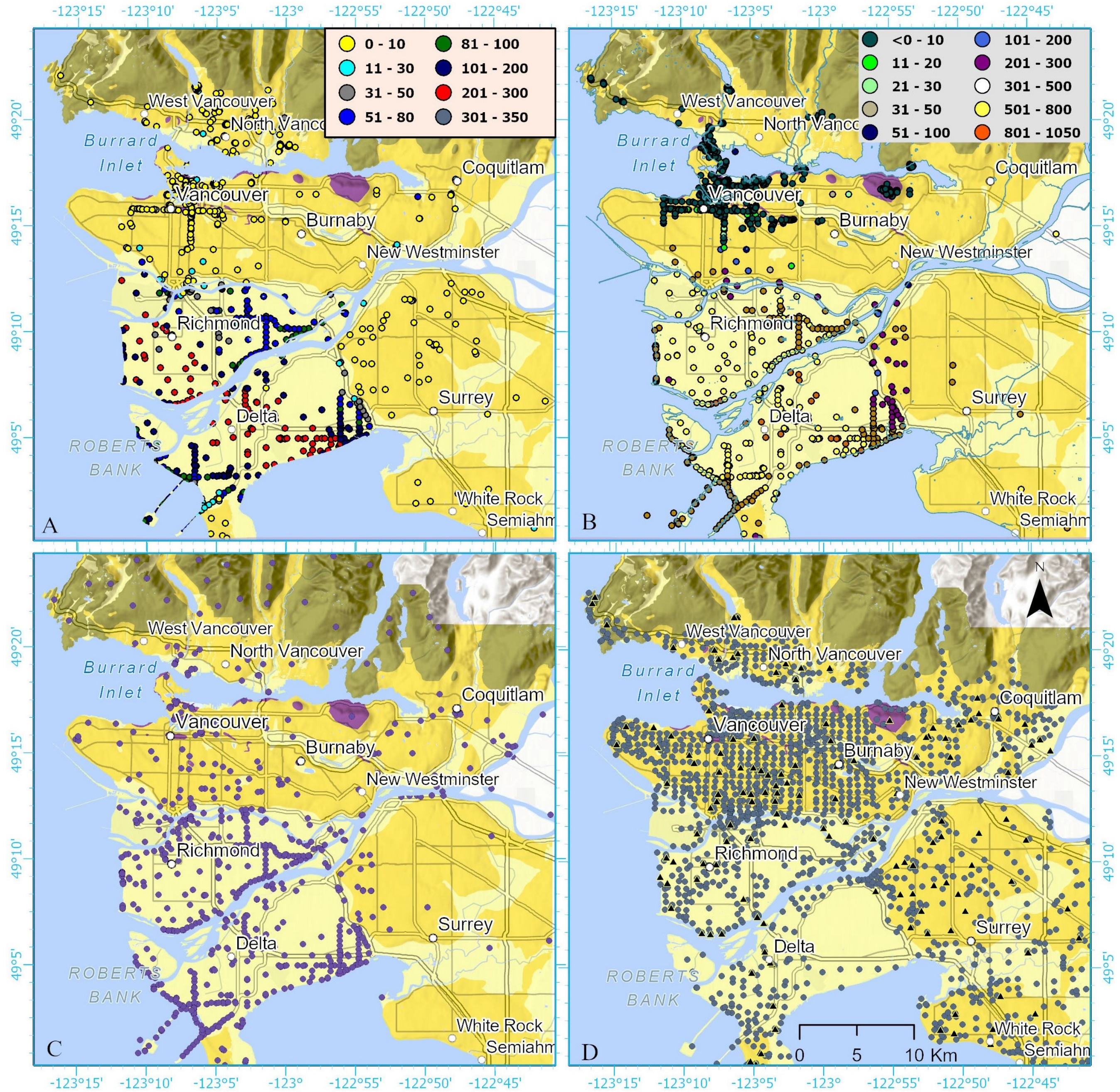

Figure 2 (A) Location (symbols) of geodata overlaid on the simplified geology map of Metro Vancouver (shading as in Figure 6-1). Depicted location relate to (A) depth to Pleistocene and older inter/glacial sediments, (B) depth to rock, (C) locations of Vs depth profiling from a variety of field methods, and (D) over 120 multi-method seismic field-testing location (triangles) and 2,375 single station MHVSR measurement locations (circles).

vey files that specify depth, azimuth, and inclination of each collar's data, and (3) lithology files with lithology (seismic geolgy model) or Vs (Vs model) as a function of depth. . Details of developing 3D seismic geology and Vs models specific to Metro Vancouver are described in the following sub-sections. Surface topography is input from a high-resolution (1-m contoured) Digital Elevation Model (DEM) from GeoBC's LidarBC provincial online repository (https://lidar.gov.bc.ca/). This DEM is then used to intersect the upper surface of each developed 3D block model.

4.1 3D Seismic Geology Block Model

We utilize the extensive geodatabase from the MVSMMP to construct a 3D seismic geology block model of Metro Vancouver featuring the four main geologies and their significant impedance-based surfaces. The input dataset to develop the 3D seismic geology block (layered) model are the depth intervals at which each of four main geologies occur as obtained from borehole stratigraphic logs, interpreted geologic cross-sections, and Vs depth profiles. Examples of these lithologic input files are provided in Supplemental Tables 1 and 2. The northern boundary of the Late-Cretaceous Georgia basin sedimentary basin occurs north of Vancouver, with sporadic pockets of outcropping Georgia basin sedimentary rocks found in northern Metro Vancouver along the North Shore. We classify all bedrock in and beneath the Northshore as Pre-Tertiary Coast Mountain plutonic igneous rocks and all rocks south of Burrard Inlet as Late-Cretaceous Georgia basin sedimentary bedrock.

Depth intervals of the four main geologies are retrieved from 2,333 borehole lithology logs or depth profiles in the MVSMMP geodatabase covering depths ranging from tens of meters to hundreds of meters. Boreholes that do not reach depths of Pleistocene till or bedrock are excluded. 550 boreholes were drilled by consulting companies and obtained from proprietary site investigation reports. The remaining 1,780 boreholes were obtained from public open-source Geologic Survey of Canada open files (e.g., Belanger and Harrison, 1976; Mustard and Roddick, 1992; Luternauer and Hunter, 1996) and drilled water well reports of the BC groundwater wells and aquifers online repository (https://apps.nrs.gov.bc.ca/gwells/). For each borehole stratigraphic log of the MVSMMP database, the first occurrence of Pleistocene till or diamictite is designated as the depth of Pleistocene and older inter/glacial sediments. For the boreholes in the Fraser River delta where Pleistocene and older inter/glacial sediments were drilled into, but bedrock was not reached, we consistently added an additional 10 m to the depth of Pleistocene and older inter/glacial sediments to ensure the Leapfrog Geo software will build the surface top of Pleistocene sediments between drillholes with measured depth of Pleistocene. If geologic bedrock is present (either Tertiary Georgia basin sedimentary rock or Pre-Tertiary Coast Mountain rock) then its depth is recorded as the depth of bedrock. Additional borehole lithology sources in the MVSMMP geodatabase include depths to Pleistocene sediments and bedrock obtained from 12 oil & gas exploration wells (Gordy, 1988; Hannigan et al., 1998) and 15 previous 1D geologic interpretations by Armstrong (1984) and 32 "virtual" logs of the four main geologies depth intervals visually retrieved at select locations along interpreted geological cross-sections of Clague et al. (1998). To enhance the realistic spatial variability of the region's four main geologies, virtual borehole logs are introduced that capture selected locations of outcropping Pleistocene sediments and bedrock with support from a compilation of geology mapping (Adhikari et al., 2024) to improve interpolation precision. For example, 30 virtual logs are used to demarcate the occurrence of Coast Mountain plutonic rocks in northernmost Metro Vancouver. In addition to borehole lithology logs, geophysical logs of the MVSMMP database are reviewed to obtain depth intervals of the four main geologies. Depth to bedrock estimates aligned with the Pleistocene-Tertiary unconformity are obtained from 126 km of seismic reflection surveying in the Fraser River delta (Britton et al., 1995). We also include estimated depths to Pleistocene till and bedrock provided by J. Hunter (pers. comm. 2016) from the GSC's over 500 Vs depth profiles (Hunter et al., 2016). For 120 multi-method non-invasive seismic field-testing sites acquired by the MVSMMP, the depths of Pleistocene till and bedrock are obtained from the inverted minimum misfit Vs profile when Vs exceeds 400 m/s and 1,000 m/s respectively and accompanied by an abrupt increase in Vs (Assaf et al., 2022).

Leapfrog Geo allows users to create a 3D geological model by interpolating between data points to represent geological features in three dimensions. This is typically achieved using implicit modeling techniques, which define geological boundaries based on mathematical functions rather than explicit surfaces. The software automatically generates a volumetric grid, using geological boundaries and contacts between different lithological units from boreholes using RBFs to efficiently interpolate the scalar fields describing implicit geologic surfaces (Krajnovich et.al, 2020). We input our dataset of the depth intervals of the four main geologies (Holocene and Pleistocene sediments, and Tertiary and PreTertiary rocks) into the Leapfrog Geo platform to develop the 3D seismic geology block model (Figure 3). A contact surface chronology method that follows the geologic law of superposition (younger geologic units are overlaid on older units) is used to develop the continuous isosurfaces of the seismic impedance contrasts between the four main geologies. Use of the 'drilling only' option (in the boundary filter and 'snap to data' options) snaps the surface to the drillhole data and thereby honours all of the input 'drillhole' data. The single pass isosurfacing was enabled to efficiently create the 3D model in one pass. We set our 3D seismic geology block model resolution to 100 m laterally in building the geology surfaces within the 3D model volume (1000 m max. depth) to optimise processing performance, a constraint imposed by the capabilities of the computer's clock speed. A regional high-resolution DEM is input to adjust the elevations of the 3D seismic geology model's block (layer) surfaces to mimic the natural topography of the ground surface devoid of vegetation and structures.

We compared all our results with the cross sections from Clague et al. (1998), Figure 1, and found them to be consistent. However, only one example is shown here in Figure 4A for brevity. We visualize the east-west cross-sectional CD profile in the northern Fraser River delta (Figure 1A) from our seismic geology block model in Figure 4A; this cross-section's interpreted geology from Clague et al. (1998) was shown in Figure 1C. The 21 drillhole logs along the CD profile include the 9 drillhole logs used by Clague et al. (1998) to accomplish their cross-section interpretation; our seismic geology block model includes 12 additional drillhole logs along this cross-sectional profile that were not available to Clague et al. (1998). Figure 4A serves as visual confirmation that every input drillhole record is honoured in constructing the 3D seismic geology model. The credibility of our 3D model's implicit mathematical approach is showcased by comparing the great similarity of our 3D model's CD cross-section in Figure 4A with that of the traditional expert-based geologic-rules approach in Figure 1C. The Holocene post-glacial Fraser River delta sediments thin eastward (mid-way along the CD cross-section) where depth to Pleistocene till is known to be a minimum of 19 m along a northwest-southeast trending ridge of Pleistocene sediments (Figure 1C and Figure 4A). The presented evidence suggests that the 3D

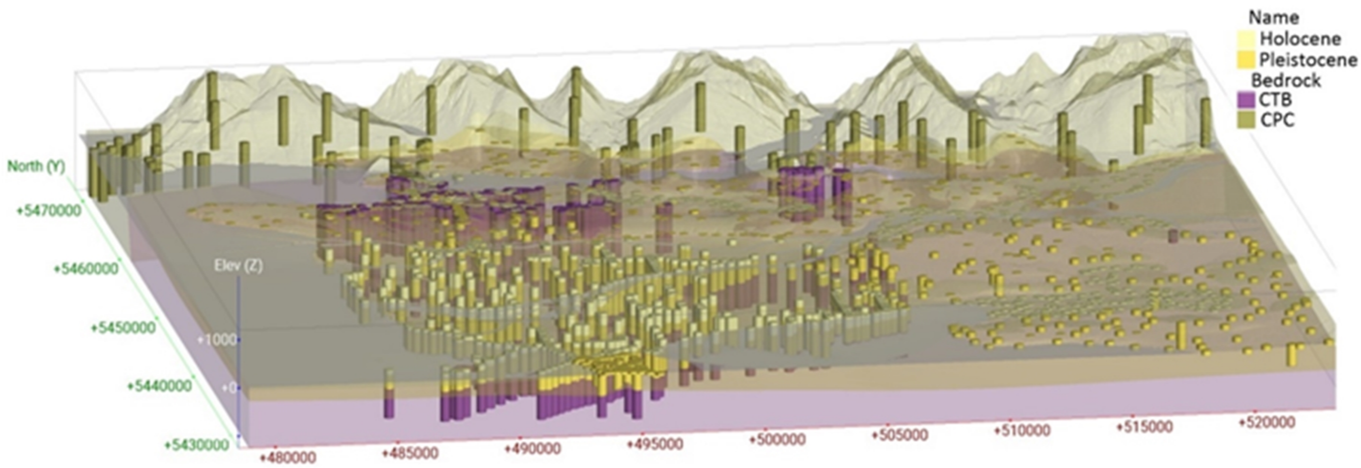

Figure 3 Screen capture image of the 3D seismic geology block model within Leapfrog Geo (axes report UTM coordinates in meters); the four main geology block layers are shaded and shown with transparency to reveal the input 'drillhole' data (circular columns shaded based on the corresponding geology's depth interval).

seismic geology block model faithfully represents the underlying geology of the area.

4.2 3D "Geotechnical Layer" Vs Model

We use the extensive geodatabase from the MVSMMP to construct a 3D "geotechnical layer" Vs model of Metro Vancouver. A 3D numerical Vs model is created independently of the categorial (geology) data. The input dataset to develop this 3D Vs model are the 688 Vs depth profiles obtained from both invasive and non-invasive in situ seismic testing covering depths ranging from tens of meters to hundreds of meters. Downhole and SCPT testing obtained from proprietary site investigation reports provide a total of 156 "direct Vs measurement" Vs depth profiles. From the MVSMMP's multi-method non-invasive seismic field testing, 117 Vs depth profile models are obtained from joint inversion of each site's fundamental-mode Rayleigh wave dispersion curve and site frequencies ($f_{0\mathrm{HV}}$, and $f_{1\mathrm{HV}}$ when applicable). The remaining 410 Vs depth profiles are obtained from Hunter et al. (2016) which consists of 85 SCPT, 50 downhole, 95 surface refraction, and 180 wide-angle seismic reflection Vs profiles constrained to the Fraser River delta area.

The depth distribution of Vs is less constrained in the eastern section of the region, particularly in Surrey and Coquitlam, owing to a lack of available Vs data (Figure 2C). Hence, the Vs depth distribution in this area is strongly controlled by the MVSMMP's Vs datasets of downhole Vs profiling (two locations) and inverted Vs profiles at 37 multi-method non-invasive seismic field-testing sites (Figure 2D). To enhance the spatial coverage of the Vs depth distribution in the region, we include an additional 10 virtual Vs depth profiles in the Coast Mountains. The Vs depth profile for this representative rock site condition is obtained from compilation of in situ Vs profiling methods at several Coast Mountains sites (S. Molnar, pers. comm., 2021).

The input Vs depth profiles include the depth interval of each Vs "measurement"; a reminder that some in situ methods directly measure the interval Vs (e.g., downhole, SCPT) while others indirectly predict the interval Vs (e.g., seismic refraction, inversion of dispersion curves). We input our dataset of the depth intervals of measured Vs into the Leapfrog Geo platform to develop the 3D "geotechnical layer" Vs model. A numerical Vs model is generated by Leapfrog Geo using global RBF spheroidal interpolation. The spheroidal variograms provide a smooth and gradual transition between data points, enhancing their accuracy in predicting values across the entire spatial domain (Seequent, 2019). We define the spheroidal variogram range based on a value equal to twice the maximum spacing (4000 m) of input Vs depth profiles to capture meaningful spatial correlation between them. Additionally, we also set the variogram's nugget parameter at 5% of the sill value; a small nugget (5% of the sill) ensures the model primarily reflects the larger-scale Vs spatial correlation rather than random fluctuations due to measurement errors and micro-scale heterogeneities . To visualize the 3D Vs model, we instruct the software to delineate boundaries in space where consistent Vs values are present, i.e., isocontours of Vs. We choose 12 discrete Vs ranges between < 100 and > 2500 m/s (Figure 4B). Essentially the 3D numerical Vs model is generated into a Vs block model with 11 horizons or 12 Vs layers. A high-resolution regional DEM is used to alter the heights of the 3D "geotechnical layer" Vs model's block (layer) surfaces to imitate the natural topography of the ground surface devoid of vegetation and structure.

We visualize the east-west cross-sectional CD profile in the northern Fraser River delta (Figure 1A) from our 3D "geotechnical layer" Vs model in Figure 4B. The 11 Vs surface horizons of this Vs model (Figure 4B) are independent of 3D seismic geology block model (Figure 4A) developed in section 4.1 but both models express similar seismic site conditions. Overall lower Vs Holocene post-glacial sediments occur in western Richmond and span depths of ~20 to hundreds of meters across the norther Fraser River delta. In western Richmond, the shallowest depth to Pleistocene till (i.e., Vs > 400 m/s) is observed spatially in both 3D models, although the exact location along the profile differs slightly. Depths

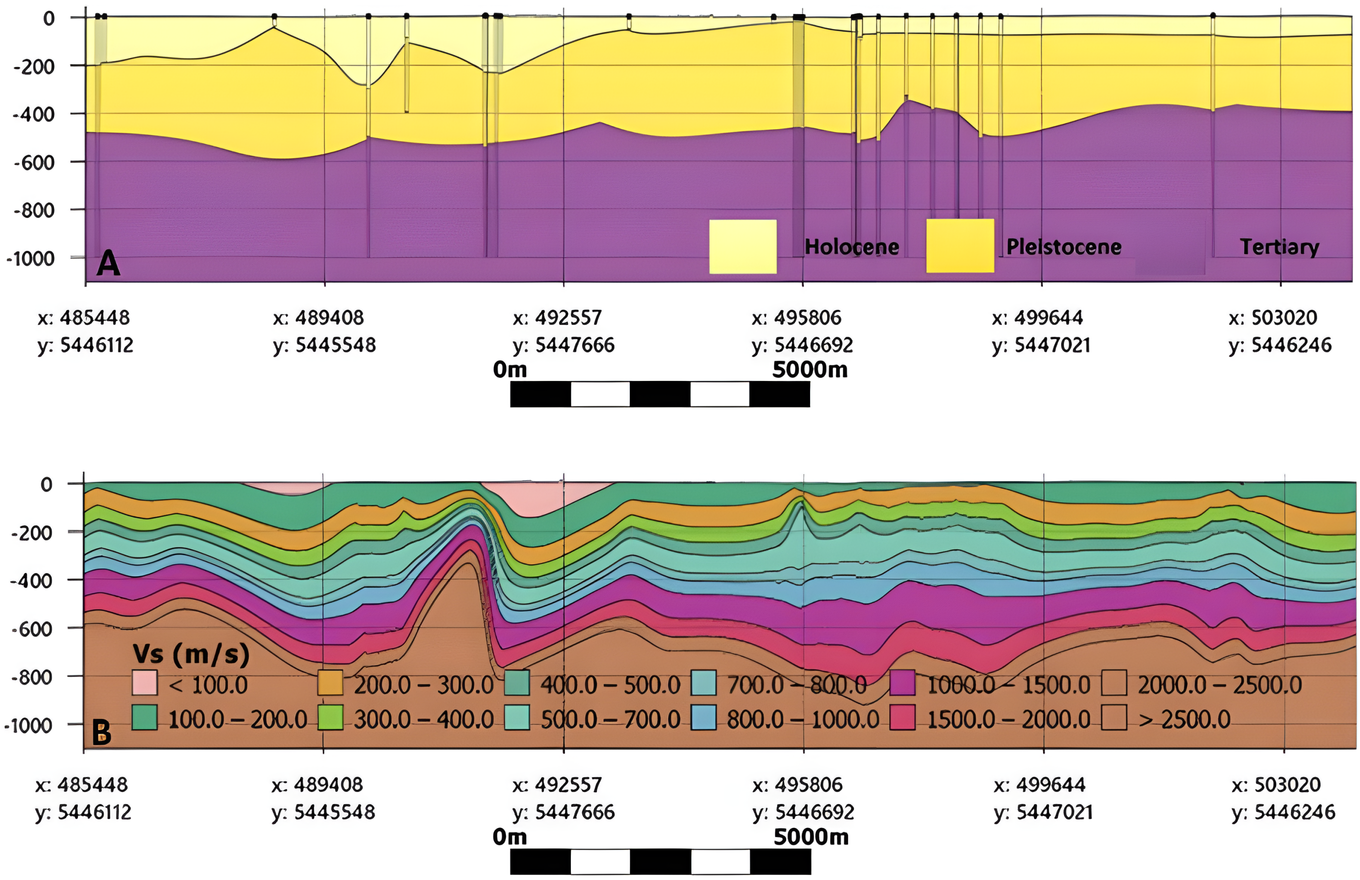

Figure 4 Visualization of the (A) seismic geology block model and (B) "geotechnical layer" Vs model along the east-west trending CD cross-section in the northern Fraser River delta (see Figure 1A for location of this cross-section). In (A), locations of 'drillhole' data are indicated by a black circle at surface and vertical black lines depict the drillhole's lithology.

of Pleistocene sediments and Tertiary bedrock in Figure 4A are similar to the 400-500 m/s and 1000-1500 m/s Vs layers in Figure 4B, respectively, as expected.

5 Evaluation of 3D Models

The evaluation of a 3D geomodel is a key step in determining the legitimacy and reliability of the model's depiction of subsurface ground conditions and geophysical parameters. We seek to evaluate our 3D models via comparison of the independently measured microtremor H/V amplification by the MVSMMP with theoretical site amplification predicted from 1D layered Vs models extracted from the 3D models. For this evaluation purpose, we compare theoretical site amplification with the empirical H/V amplification at select MHVSR locations along four selected cross-sectional profiles (Figure 1). MHVSR locations are selected within a 300 m distance of the four selected cross-sections. The theoretical site amplification is predicted as the Fourier transfer function for vertically propagating plane shear waves given each layered 1D Vs model according to reflectivity theory as implemented in Bard and Gariel (1986) and source code in the Geopsy software package (Wathelet et al., 2020).

At each selected MHVSR site (e.g., Figure 5A), we extract the thickness of each geology unit (layer depth) from the 3D seismic geology block model (e.g., Figure 5B) and the 1D Vs model from the 3D "geotechnical layer" Vs model (e.g., Figure 5C). For each geologic layer, the average Vs is calculated by averaging Vs values from the 1D Vs model over the relevant geology unit's depth interval and applied as that layer's uniform velocity. Thus, a layered 1D Vs model is developed at each MHVSR location from the 3D seismic geology and Vs models; termed amplification model M. We also compare the 3D seismic geology (thickness) model, independent of the 3D Vs model, by using the regional average (one std. deviation) Vs for the given geology layer as determined in Adhikari (2024) from the MVSMMP geodatabase: 239 (87) m/s for Holocene sediments, 543 (140) m/s for Pleistocene and older sediments, and 1500 (~600) m/s for rock; termed the general amplification model G.

In this way, direct comparison of the theoretical site amplification predicted by these two versions of layered 1D Vs models developed from the 3D models is possible with that of the empirical MHVSR amplification (e.g., Figure 5D). Agreement in f_{0HV} or f_0 is most sensitive to agreement in sediment layer thicknesses, whereas agreement in A_{0HV} is most sensitive to agreement in Vs; noting agreement in empirical H/V and theoretical 1D site amplification is an ongoing area of active research (Molnar et al., 2022). Thus, we concentrate on the evaluation of the 3D model's performance in predicting 1D site amplification compared to measured MHVSR amplification in terms of the absolute and percentage change in f_{0HV} only and not A_0 or am-

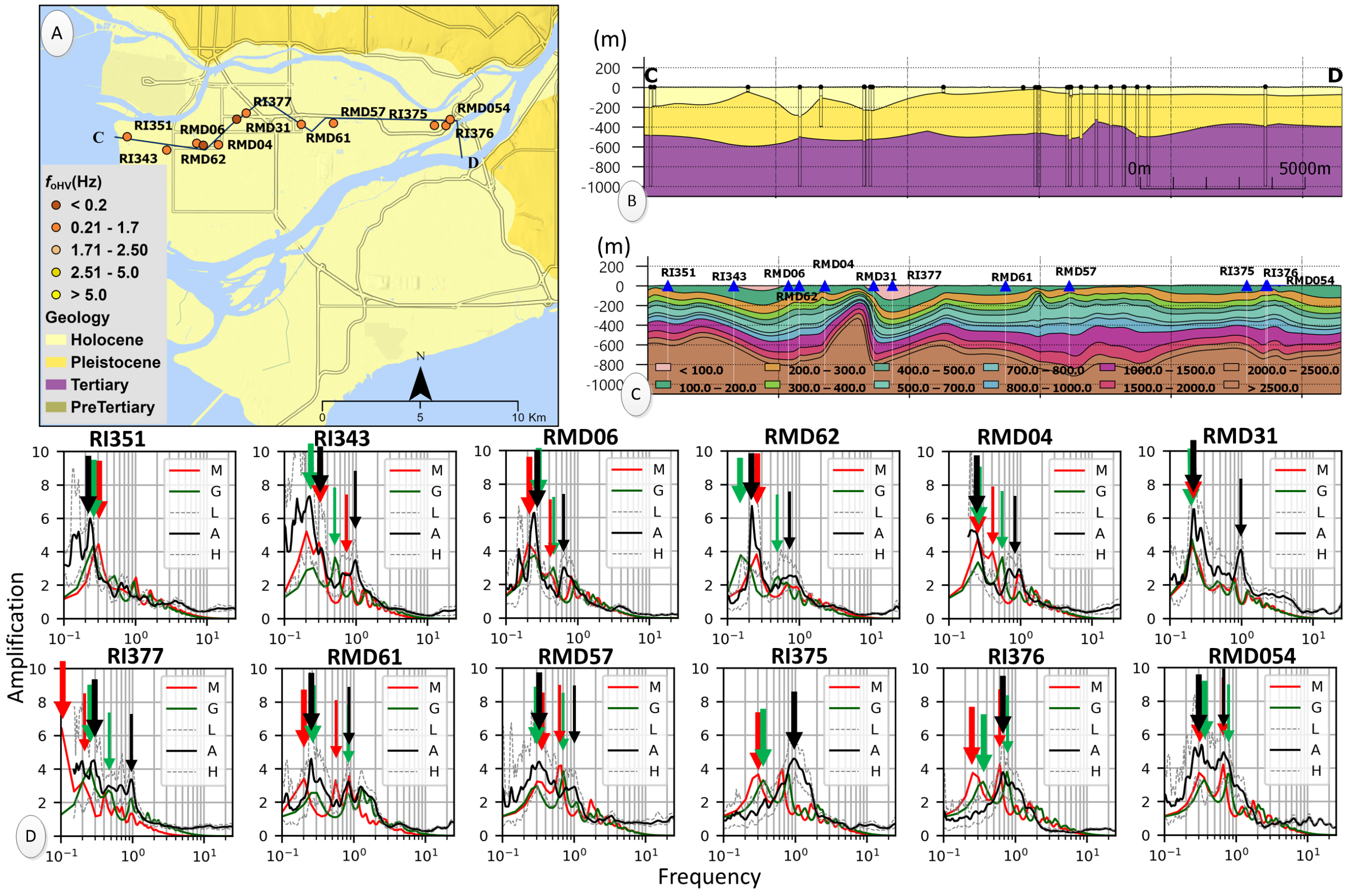

Figure 5 (A) Metro Vancouver simplified geology map showing C-D, the east-west trending cross-section profile with selected MHVSR locations (circles coloured according to f_{0HV}). (B) C-D cross-sectional view of the 3D seismic geology block model; locations of 'drillholes' as in Figure 4A and don't correspond to MHVSR locations. (C) C-D cross-sectional view of the 3D "geotechnical layer" Vs model; blue triangles correspond to MHVSR locations. (D) For the 12 selected MHVSR locations, (the measured average MHVSR "A" as black line and L,H are one standard deviation shown by dashed lines) is compared with the theoretical site amplification of model M (red line) and model G (green line); thick arrows point to f_{0HV}, and thin arrows point to f_{1HV}.

plification level of the full spectrum. The fundamental peak frequency is selected manually from each empirical and theoretical amplification spectrum with the criterion that A_{0HV} must be > 2.

Figure 5A shows the 12 MHVSR locations and their associated f_{0HV} along the east-west trending CD cross-section across the northern Fraser River delta (Lulu Island); f_{0HV} is also indicated in each MHVSR amplification spectrum using a thick black arrow in Figure 5D. Comparison of the two versions of theoretical site amplification spectra as well as with the empirical H/V amplification spectra for the 12 MHVSR locations along cross-section CD are shown in Figure 5D. This C-D cross-section is an ideal example to convey the observed trend in amplification spectra detected in the Fraser River delta (as discussed in section 6.3). In the west, the Holocene deltaic sediments are thickest (Holocene-Pleistocene seismic impedance contrast is deepest) and the low frequency f_{0HV} peak (~0.3 Hz) dominates (e.g., sites RI351 to RMD04). Around mid-way along profile C-D, the Holocene deltaic sediments thin significantly (Holocene-Pleistocene seismic impedance contrast shallows to ~20 m) causing the secondary f_{1HV} peak to increase in amplification (most apparent at RMD31). In the east, the Holocene sediments are approximately half as thick as in the west and the frequencies at which f_{0HV} and f_{1HV} occur are more similar (i.e., RI375, and RMD054) and may manifest as a broadened single peak (i.e., RI375, and RI376) due to either merging of these resonance frequencies or dominance of the secondary resonance frequency. Overall, the theoretical site amplification spectra of the two model versions are able to reproduce the observed amplification response at the 12 MHVSR sites. Both models M and G tend to slightly overpredict f_0 in the west (i.e., RI351 and RMD04) while model M is slightly better at predicting f_0 in the east (i.e., RMD57 and RMD054).

Figure 6 and Supplementary Table 3 reports the absolute and percentage change in f_0 of the two model versions in comparison to f_{0HV} for the 12 MHVSR sites. Both models tend to slightly overpredict f_{0HV} in the west while model G is slightly better at predicting f_{0HV} in the east. The greatest discrepancy between f_0 and f_{0HV} occurs at sites RI375 and RI376. On average, f_0 is predicted within ~20% of f_{0HV} by either model. The most site-specific model M in terms of layer thicknesses and Vs does not consistently provide the greatest agreement in theoretical site amplification with empirical H/V am-

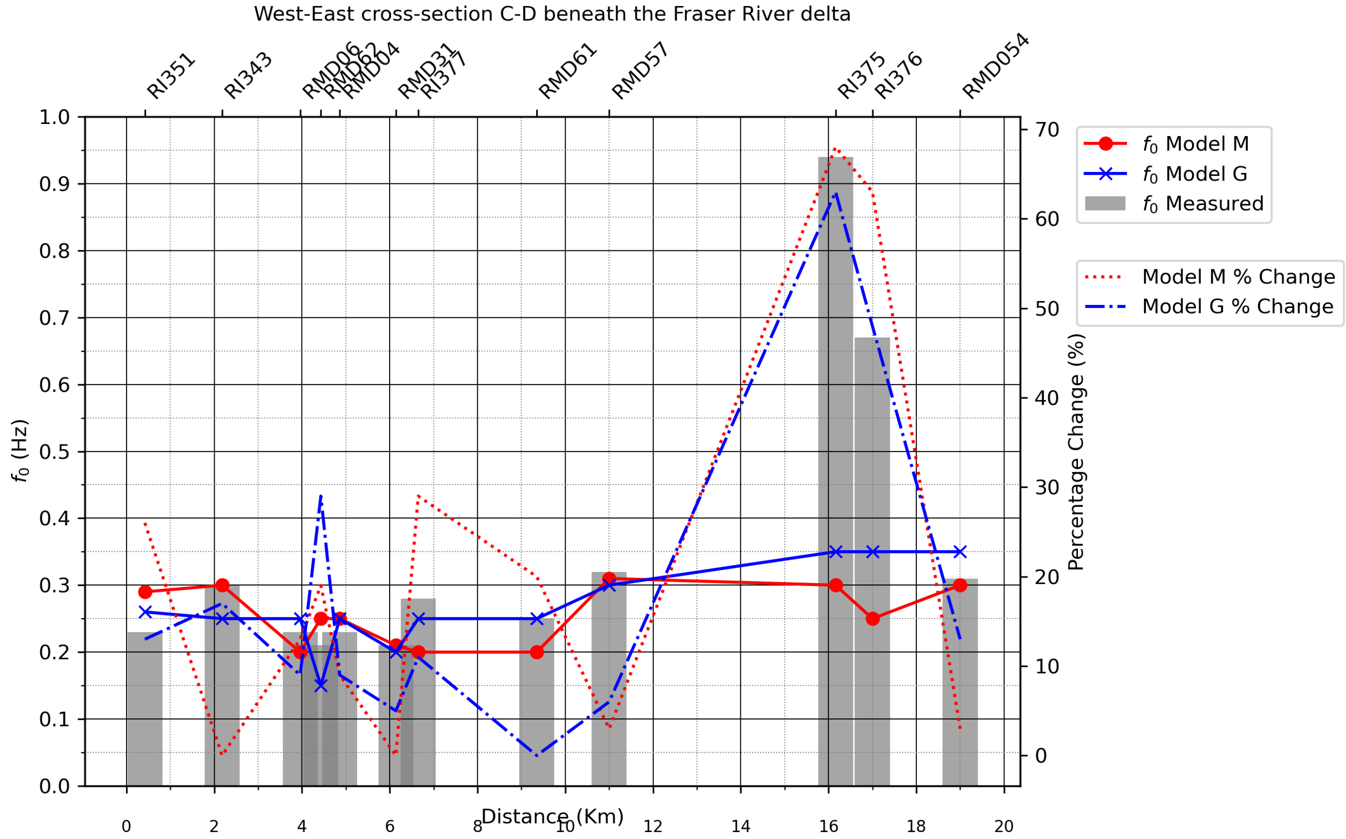

Figure 6 Evaluation of $f_{0(HV)}$ for 12 sites along West-East cross-section C-D beneath the Fraser River delta.

plification in comparison to the more general model G with site-specific layer thicknesses combined with regional average Vs estimates.

The Northwest-Southeast cross-section E-F (Figure 7) spans from the Fraser River delta edge in southern Vancouver to its southeast margin. Figure 7B and Figure 7C convey that the thickness of Holocene sediments increases rapidly at the delta edge (VNC25 to RI400) and the combined Quaternary sediment succession is greatest in the southwest (DE1353 to DTA14). This overall trend from northwest to southeast across the Fraser River delta is consistent in both theoretical site and empirical H/V amplification spectra (Figure 7). There is greater variability in f_{0HV} in the northwest at the delta edge (VNC25 to RI400) compared to consistent f_{0HV} dominance at southeast sites (DE1353 to DTA14) in the deep delta. Dominance of f_{0HV} between 0.6 to1 Hz occurs when Holocene sediments are thinnest (e.g., VNC25, and RI400) and is notably best expressed by model M at RI400. In the central delta, both f_{0HV} and f_{1HV} are prominent in the central delta (RMD33 to DE1353) and both models predict A_{0HV} better than A_{1HV}, noting model M predicts higher A0 than model G and in better agreement with A_{0HV}. Consistent f_{0HV} dominance in the southeast delta (DTA15 to DTA14) is predicted by both models and again model M slightly outperforms model G amongst these four sites. In terms of f_{0HV} (Supplemental Table 4 and Supplementary Figure 1), both models have difficulty in predicting the rapid f_{0HV} changes in the northwest while model M is slightly better at predicting f_{0HV} in the delta's centre and southeast margin compared to model G. For the delta as a whole (cross-sections C-D, and E-F), model M slightly outperforms model G and confirms that model M's greater local accuracy in both Vs and major seismic impedance depths is beneficial to predicting earthquake site amplification and hazards.

For the southwest-northeast trending G-H cross-section (Figure 8) across the Surrey uplands, the measured data at SUR35 and SUR36 (Figure 8D) exhibits the same broadened f_{1HV} peak as sites near the Fraser River delta edge (e.g., RI375, and RI400). From SUR607 to SUR85, only a low frequency f_{0HV} is observed characteristic of the seismic impedance contrast between Pleistocene sediments and Tertiary rock as appropriate in the Surrey uplands with negligible post-glacial sediments present. At SUR587, as we descend from the uplands back down to the shoreline, the measured data exhibits significant amplification of the broadened f_{0HV} peak indicating that Vs at this site is very low. Overall model M is better able to predict transition in the site amplification from the southwest into the central uplands (varying f_0) compared to model G (Supplemental Table 5 and Supplementary Figure 2). The similarity in amplification suggests that the impedance contrast is accurate which implies that the models effectively include the thickness of the geological layers. Neither model includes very low Vs at SUR587 to predict the high A_{0HV} amplification, but they accurately estimate depths of the major impedance contrast(s), resulting in a matching peak frequency.

Figure 9 presents the south to north I-J transect span-

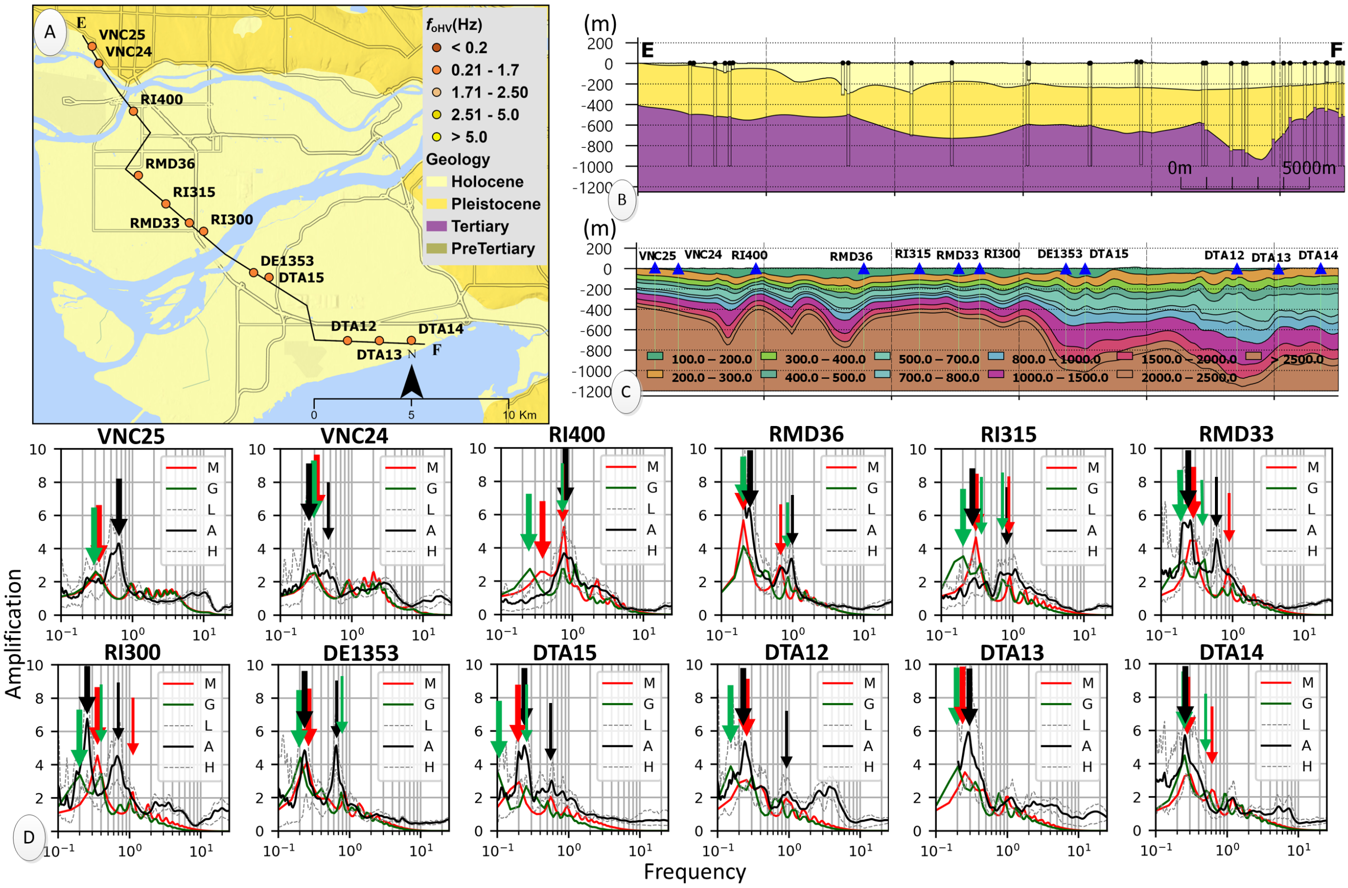

Figure 7 Same as Figure 5 for northwest- southeast trending EF cross-section profile.

ning from the edge of the Fraser River delta (VQ06, and VP06) across the Vancouver uplands (VO07 to VJ08), downtown Vancouver (RAN1555), and headward along the Capilano valley on the North Shore (NV212 to NVD23). For sites across the Vancouver uplands (VP06 to VJ08), consistent low amplification is observed due to the stiffer Pleistocene and older sediment ground conditions and f_{0HV} increases northward due to the shallowing bedrock depth. For these sites, both models underpredict f_{0HV} (Pleistocene sediments are too thick) and model M's amplification is too high (Vs at sites VL07 and VJ08 are too low, Supplemental Table 6 and Supplementary Figure 3).

In downtown Vancouver (RAN1555), Tertiary bedrock is within tens of meters of surface (edge of the Georgia sedimentary rock basin) and Pleistocene-age postglacial (Capilano) sediments may be present with variable thickness. Both model's (near) flat site amplification accurately express this transitional edge of the sedimentary rock basin. Although the rapid transition to very low Vs sediments on the North Shore (observed H/V amplification at NV212) is not present in either model, both models are able to predict the observed H/V response at NV237 in terms of f_{0HV} and its amplification (Supplemental Table 6). For the remaining sites headward along the Capilano valley, high amplification at high frequencies is observed indicative of relatively thin and low Vs sediments (i.e., shallow impedance contrasts) and is not captured by either model as these are more local responses than the model can capture. Rather, both models can only express the general transition from occurrence of Pleistocene and older sediments (f_0 ~0.7 to 1 Hz) to Coast Mountain igneous rock (no amplification). Evaluation of the 3D model's performance in terms of the absolute and percentage change in $f_{0(HV)}$ (Figure 6 and Supplemental Tables 3 to 6 and Supplementary Figure 1 to 3) demonstrates that using merely the regional average Vs paired with the 3D model soil thicknesses (model G) is less accurate than using more local Vs and soil thickness estimates (model M). The utilization of model M is justified based on its superior performance in predicting measured MHVSR amplification compared to model G. The developed 3D models are able to predict f_{0HV} with greatest accuracy (within 20-30%) in the Fraser River delta (profiles C-D and E-F) as well as the Surrey uplands (profile G-H). The deeper and less locally varying seismic impedance contrast between Pleistocene and older sediments and Tertiary sedimentary bedrock is well captured in the 3D modelling. Local variations (e.g., very low Vs sediments present along shorelines) and rapidly changing site conditions (e.g., North Shore) are poorly captured in the 3D modelling, leading to generally poor prediction of f_{0HV} (e.g., over 50% error for profile I-J).

6 Conclusion

This study developed 3D regional modelling of Metro Vancouver in terms of seismic geology and "geotechnical layer" Vs models for seismic microzonation and seis-

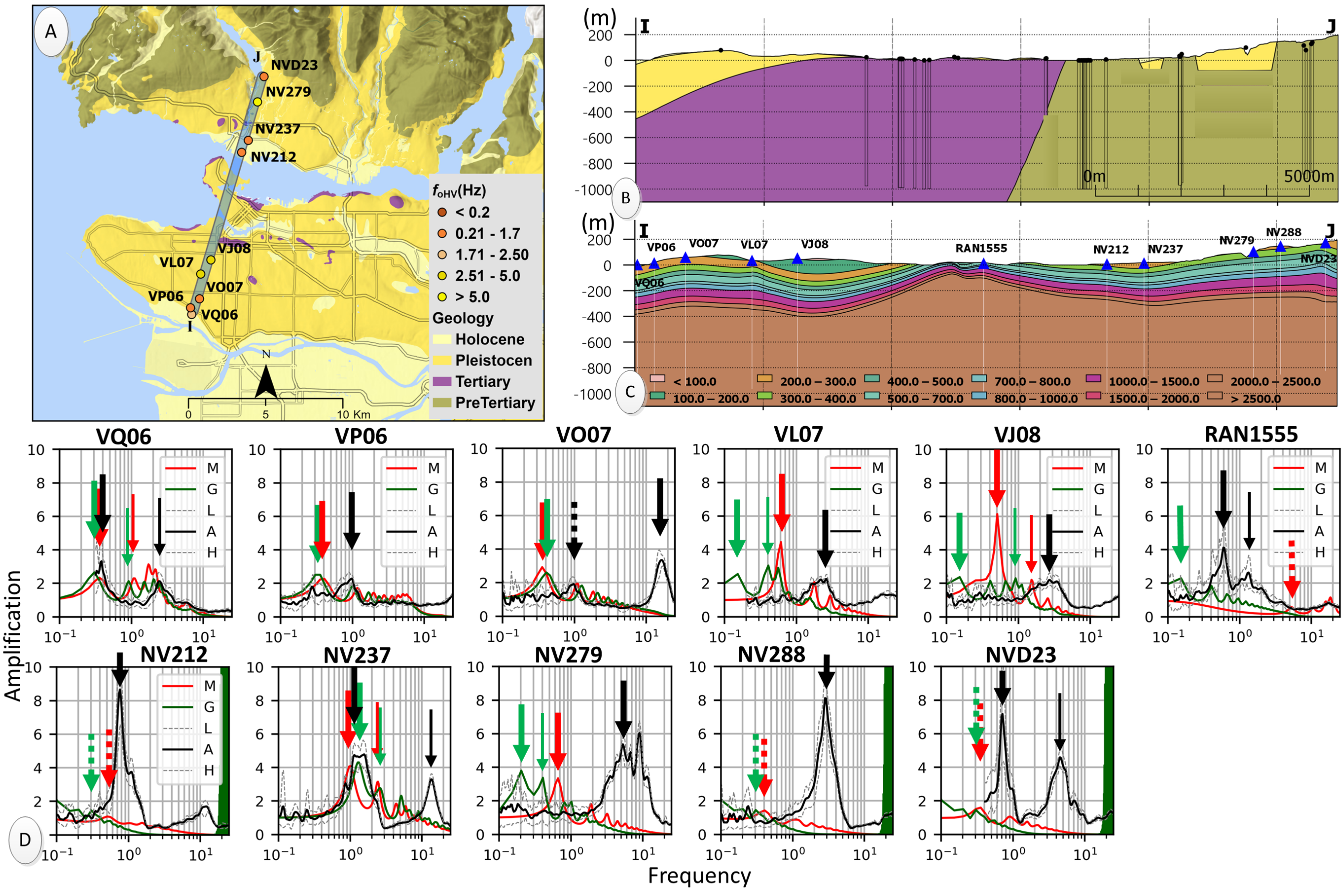

Figure 8 Same as Figure 5 for southwest-northeast trending GH cross-section profile. Dashed arrows are used to indicate peak frequencies that do not meet the amplification > 2 criterion.

mic hazard prediction purposes. We utilize the most extensive geodatabase compiled for the region to date (Adhikari, 2024; Adhikari et al., 2021) to accomplish the 3D modeling. This geodatabase has been compiled from in situ invasive logging and penetration methods from various public and private data sources supplemented by abundant multi-method non-invasive seismic field data collection across the region. Through a systematic analysis of over 1,200 lithological logs and existing interpreted geologic 2D cross-sections present in the geodatabase, we successfully delineated a seismic geological block model in the region consisting of four major geologies: Holocene post-glacial and Pleistocene inter/glacial sediments, and Tertiary sedimentary and Pre-Tertiary Coast Mountain plutonic rocks. Additionally, utilizing 688 Vs depth profiles, we constructed a numerical 3D Vs model with 11 isovelocity surfaces. This work is conducted in the Seequent LeapfrogGeo modeling platform, utilizing fundamental datasets as inputs for the modeling process. Geostatistical spatial interpolation techniques are employed to create these two 3D models.

The credibility of our 3D model's implicit mathematical approach is evident from comparison with existing interpreted geologic cross-sections generated by the traditional expert-based geologic-rules approach. The 3D "geotechnical layer" Vs model is independent of the 3D seismic geology block model but both models express similar seismic site conditions. These comparisons emphasize the robustness and reliability of our modeling methodology to faithfully represent the underlying seismic site conditions of the area.

We further compare our 3D models via comparison of the independently measured microtremor H/V amplification with theoretical site amplification predicted from 1D layered Vs models extracted from the 3D models. A layered 1D Vs model is developed at each MHVSR location from the 3D seismic geology and Vs models; termed amplification model M. Additionally, we compare the 3D seismic geology model independently of the 3D Vs model by utilizing the regional average Vs for each seismic geology layer; termed the general amplification model G. We concentrate on evaluating the 3D model's performance in predicting 1D site amplification compared to measured MHVSR amplification in terms of the absolute and percentage change in f_{0HV}. For the Fraser River delta sub-region, model M exhibits slight superiority over model G. Similarly in Surrey, model M demonstrates a superior ability to predict the transition in site amplification from the southwest of the Fraser River delta to the central glaciated uplands compared to model G. Regarding the Northshore area, both models exhibit an underprediction of f_{0HV}, with model M showing excessive amplification. For sites further upstream along the Capilano Valley, there is notable high-frequency amplification, suggesting the presence of thin and low Vs sediments with shallow impedance contrasts. However, neither model adequately captures

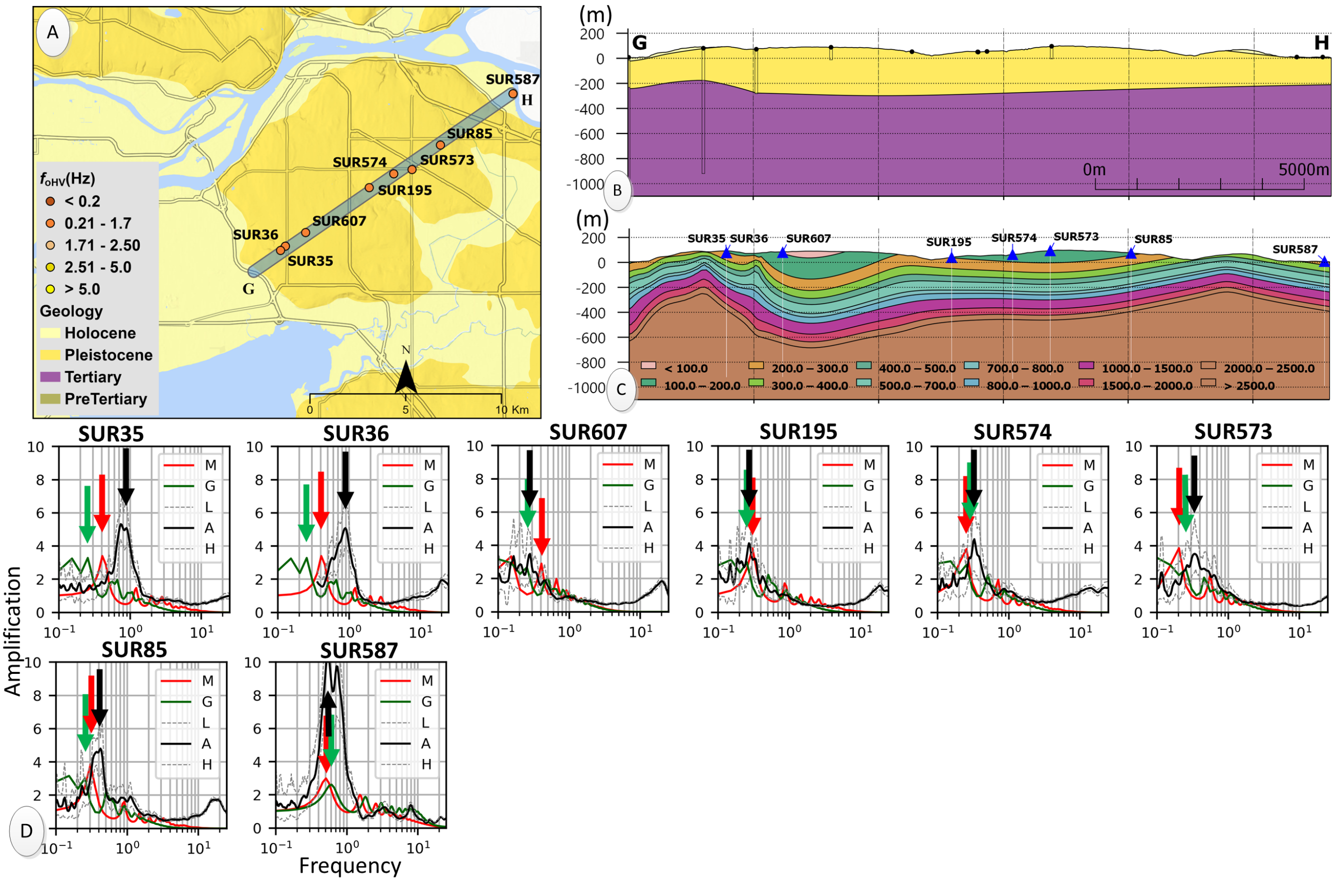

Figure 9 Same as Figure 5 for south-north trending I-J cross-section profile. Dashed arrows are used to indicate peak frequencies that do not meet the amplification > 2 criterion.

these localized responses, as they are beyond the regional models' capacity for detailed representation of localized seismic site conditions. Overall evaluation of the 3D model's accuracy, in terms of absolute and percentage changes in f_{0HV}, indicates that utilizing the regional average Vs along with 3D model soil thicknesses (model G) is less precise compared to incorporating more localized Vs and soil thickness estimates (model M).

Further improvements to this study's 3D "geotechnical layer" Vs model of Metro Vancouver are underway including conversion of the over 2200 MHVSR location's f_{0HV} and f_{1HV} to depths of rock and glaciated sediments, respectively, using correlative relationships developed from the MVSMMP geodatabase. Integration of a 3D "geotechnical layer" Vs model of Metro Vancouver is planned within our Community Velocity Model (CVM) of southwest British Columbia to improve resolution at shallow (< 1 km) depths and thereby future 3D wave propagation simulations and generation of synthetic ground motions (Ghofrani et al., 2023).

Acknowledgements

We are grateful to the 24 agencies, organizations and/or persons that shared their geodata for the Metro Vancouver seismic microzonation mapping project. The geodatabase is curated and managed by Sujan Raj Adhikari (first author) with Alex Bilson Darko (Project Manager), and the support of Jamal Assaf (PhD, Civil & Env. Engineering), Ranjana Ghimire and Rozhan Raoufi (Research Assistants), and part-time by University of Western Ontario (UWO) students Andrew Beney, Jacob Edgett, Tyler Beattie, and Congxi Zhu. Vs profiling of the multi-method non-invasive field data was accomplished primarily by Jamal Assaf (PhD, Civil & Env. Engineering), Christopher Boucher (MSc, Geophysics), Sameer Ladak (MSc, Geophysics), Magdalena Kapron (MSc, Geophysics) and Natalia Gómez Jaramillo (MSc, Geophysics), under the supervision of Alex Bilson Darko and Sheri Molnar. The manuscript was improved from feedback by Dr. Philippe Rosset and an anonymous reviewer. Project funding was provided by the Institute of Catastrophic Loss Reduction with support from the BC Ministry of Emergency Management and Climate Readiness.

7 Data and code availability

Digital data within the compiled Metro Vancouver seismic microzonation mapping project's database used in this study is provided by different organizations through data sharing agreements. The open data collection of Hunter et al. (2016) which provides over 500 Vs(z) collected by the Geological Survey of Canada using invasive and field methods is included in this study's geodatabase. Lithologic information from drilled water wells was retrieved at the BC groundwater wells and aquifers online repository (https://apps.nrs.gov.bc.ca/gwells/). A high-resolution digital Elevation Model (DEM) for the study region is downloaded from GeoBC's LidarBC provincial online repository (https://lidar.gov.bc.ca/). Leapfrog Geo (version 2021.1.0) and ArcGIS Pro 3.2.0 are provided by the University of Western Ontario. MATLAB® (R2023a) and Python plotting routines are used to generate Figures. Datasets of the Metro Vancouver Seismic Microzonation Mapping Project will be communicated at the project's website (https://metrovanmicromap.ca/products/) and uploaded to the project's online data repository (https://borealisdata.ca/dataverse/MVSMMP). The replication dataset of this publication is available at https://doi.org/10.5683/SP3/C1XMXF.

8 Competing interests

The authors have no competing interests.

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