SIGNIFICANCE OF GEODATABASE DEVELOPMENT FOR SEISMIC MICROZONATION IN METROPOLITAN VANCOUVER, CANADA

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Abstract

Southwestern British Columbia is situated over the active Cascadia subduction zone with shallow crustal, inslab and mega-thrust earthquakes occurring respectively in the shallow North American crust, subducting Juan de Fuca plate and the subduction interface. Earthquake shaking due to local site effects varies across the Metropolitan Vancouver region. Earthquake site classification is an established component of seismic microzonation by linking *insitu* shear wave velocity (Vs) depth profiling with site amplification. This work presents the arduous multi-year data compilation and harmonization process of geological, geophysical and geotechnical datasets from various agencies and their quality assessment to generate the most robust and comprehensive geodatabase for the region to date. We also generate preliminary geodatabase products, including maps showing depths to water table and the two major seismic impedance contrasts across Metro Vancouver. Geostatistics of important site effect metrics (Vs, fundamental frequency, etc.) are derived per major geologic unit from the geodatabase which can be used to improve site response modelling in future.

Keywords: Geodatabase; Seismic microzonation; Site effects; Site characterization; Shear wave velocity

1. Introduction

Metropolitan (Metro) Vancouver, a federation of 21 municipalities, one Electoral Area and one Treaty First Nation, lies in southwestern British Columbia, Canada, with a population of more than 2.5 million spanning an area 2700 km^2 (Fig.1). Around 420 earthquakes occur annually in southwest British Columbia at the northern extent of the Cascadia subduction zone [1], indicating that the region is seismically active as a result of the subduction of the oceanic Juan de Fuca plate beneath the North American plate at a rate of 2 to 4 cm/yr [2]. During the last 130 years, there have been ten moderate to large magnitude earthquakes within 250 kilometres of Vancouver [3]. The most recent large magnitude (M > 7) earthquake was the 1946 M7.3 shallow crustal event (15 km depth) under Vancouver Island. Crustal earthquakes result from compressional forces within the North American plate overriding the Juan De Fuca plate. Inslab events are common in the Strait of Georgia and Puget Sound, Washington. The 2001 M6.8 Nisqually earthquake was an inslab event (52km depth) in southern Puget Sound, northeast of Olympia, Washington, and widely felt in Victoria and Vancouver [4]. The largest magnitude earthquake occurred at the interface of the Cascadia subduction zone, producing a M9 in 1700 AD [5]. If similar large magnitude earthquakes occur today near Vancouver, the damage is predicted to be tens of billions of dollars [6]. Onur et al. [7] conducted risk assessments for Vancouver considering a M6.5 inslab event, and their analyses estimate an economic loss of $3.5 billion Canadian dollars (CAD). For a M9 Cascadia interface scenario, the Insurance Bureau of Canada [8] estimates $ 62 billion CAD in direct losses and $ 1.7 billion CAD in indirect losses.

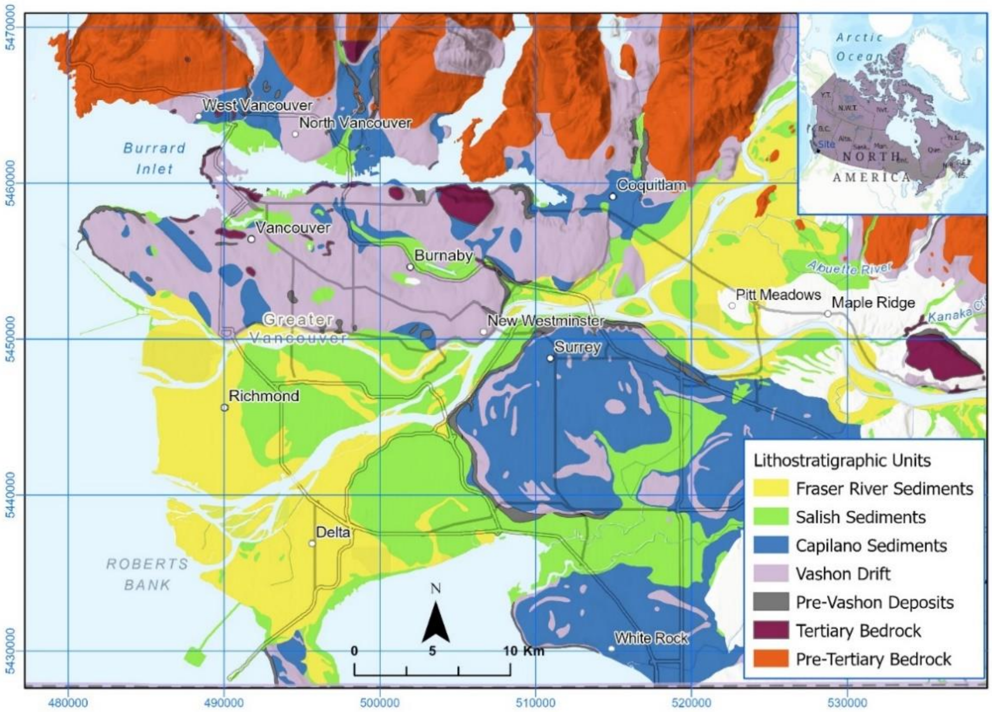

Fig. 1 – Quaternary geological map of Metro Vancouver (modified from Roddick [9]and Armstrong [10][11]). The additional Quaternary geologic unit that does not belong to the study area are shown in white.

Earthquake research worldwide shows that damage is significantly higher on unconsolidated soil than rocks. The 1985 M8.1 Mexico City earthquake is a classic example of damage occurring 100's of kilometres from the earthquake source due to increased earthquake shaking in the city's soft lake bed deposits [12]. Site effects result from local geological conditions. For example, one-dimensional (1D) earthquake site amplification occurs from vertical propagation of shear waves upward through the soil column due to reduced seismic impedance towards the surface and may also result from resonance within the soil when overlying a rigid base. How seismic waves are altered by subsurface geology is mainly dependent on seismic impedance, material damping, and nonlinear behaviour of the soil. Linear 1D site amplification is mainly controlled by the seismic impedance contrast (Vs and density of soil and in the underlying layer), and the fundamental resonance site frequency, f_0 (inverse of site period), which depends on the soil's average Vs and its thickness. In 2005, the National Building Code of Canada (NBCC) adopted the use of Vs_{30} (the time-averaged Vs of upper 30 meters at a site) for earthquake site classification [13], and in the upcoming 2020 NBCC, Vs_{30} is used directly (not site class) to predict ground motions [14]. Thus, an understanding of local geology and 1D site amplification (e.g., seismic site class or Vs_{30}) is essential to assess earthquake hazards accurately. Metro Vancouver includes the Fraser River delta (Fig.1), which is the most significant delta in North America. This delta consists of Holocene sands, silts, clays and peat, which were deposited over Pleistocene glacial tills and interglacial sediments over Tertiary sedimentary rocks and older Coast Mountain crystalline rocks [15].

Table 1 – Summary of Quaternary geologic units in Metro Vancouver.

Stratigraphy	Lithostratigraphy	Units	Age	Deposits	Material
Holocene	Fraser River sediments	Fa	Very recent	River channel	Sand
		Fb	Holocene	Overbank	Sand & silt
		Fc	Holocene	Overbank	Silt / Silty clay
		Fd	Holocene	Deltaic	Mostly Sand
		Fe	Holocene	Estuarine	Sand/silt/clay
	Salish sediments	SAa	<800yrs	Landfill	Variable
		SAb	Holocene	Bog	Peat
		SAc	Holocene	Bog	Peat
		SAd	Holocene	Bog	Organic loam
		SAe	Holocene	Bog	Peat
		SAf	Very recent	Marine shore	Sand
		SAg	Holocene	Marine beach	Coarse sand
		SAh	Holocene	Channel fill	Sand and clay
		SAi	Holocene	Mountain stream	Gravel
		SAj	Holocene	Mountain stream	Sand & gravel
		SAk	Holocene	Channel fill	Sand & gravel
Pleistocene	Capilano sediments	Ca	11ka-14ka	Raised beach	Sand & gravel
		Cb	11ka-14ka	Raised beach	Coarse sand
		Cc	11ka-14ka	Raised deltaic	Stoney clayey
		Cd	11ka-14ka	Marine	Silty clay
		Ce	11ka-14ka	Marine	Gravel & sand
	Vashon Drift	VCa	13ka-18ka	Glacial	Glacial till
		VCb	13ka-18ka	Glacial	Glacial till
		Va	13ka-18ka	Glacial	Lodgement till
		Vb	13ka-18ka	Glacio fluval	Sand & gravel
	PreVashon	Pv	18ka-29ka	Channel fill/Glacio	Quadra sand
Tertiary	Tertiary	Sandstone, Siltstone, Shale, Conglomerate, and minor volcanic rock			
PreTertiary	PreTertiary	Mesozoic bedrock, including Granite & associated felsic igneous rock			

Seismic microzonation studies, to assess local geological variations and their impact on seismic hazards, have been performed for Canada's highest seismic risk cities: Ottawa, Ontario [16], Vancouver [17] and Victoria, British Columbia [18], and Montreal [19] and Québec City [20], Quebec. Microzonation maps of the St. Lawrence Lowlands region spanning Ottawa to Quebec City [21] present the regional variation in Vs_{30} or site period. Similarly, in Toronto, Ontario [22] and Nanaimo, British Columbia [23], preliminary efforts have been accomplished towards mapping seismic amplification hazard, primarily in terms of site period. In each of these regions, the regional Quaternary geology combined with soil measure of importance to 1D site amplification (e.g., Vs, soil thickness, fundamental site frequency or site period) were required to produce the seismic microzonation maps. However, the quantity of 1D site amplification measures and their types of *insitu* site investigation methods vary significantly. Currently, there are no standardized guidelines for seismic microzonation in Canada.

This paper documents our multi-year effort and methodology in assembling and developing a robust and comprehensive geodatabase for the Metro Vancouver seismic microzonation mapping project [24] [25]. We examine the statistics of particular geodata (e.g., Vs per geological unit) to update the existing Vs model for all regional geologic units [26] with our more comprehensive geodatabase. We provide preliminary geodatabase products in this paper to inform or generate seismic microzonation mapping, including regional maps showing depth to the groundwater table and depths to the two major seismic impedance contrasts, i.e., depth to glaciated sediments, and seismic (Tertiary and older) bedrock. Another example of a preliminary geodatabase product is documenting geostastistics of fundamental site frequency for each major geological unit. The comprehensive geodatabase of Metro Vancouver described in this paper will be used to develop accurate subsurface geomodels for earthquake ground motion, liquefaction and landslide hazard prediction.

2. Geological Setting

The local geology of Metro Vancouver is simplified here (Fig. 1 and Table 1) into major geological events and units. Before 140 million years ago, volcanic islands and marine basins formed the rocks presently underpinning Metro Vancouver. Between 140 and 95 million years ago, these rocks were buried, metamorphosed, and intruded by granodiorite plutons. Early Cretaceous granitic rocks and Late Cretaceous sedimentary rocks are locally exposed in North Vancouver, West Vancouver and Vancouver [27]. At 70 million years ago, the Coast Plutonic Complex started to erode by streams and rivers, which transported gravel, sand, mud, and plant debris to form the sedimentary Georgia Basin, a large depression between the northern Coast Mountains and the southern Cascade Mountains.

The Quaternary sediments in Metro Vancouver overlie the irregular, glacially scoured bedrocks of Tertiary or Pre-Tertiary rocks. Three major glaciations occurred with interglacial cycles during the Quaternary Period, with the Fraser Lowland formed primarily in the last major Fraser glaciation (~13,000 years ago or kilo annum, ka). Southwest of the Coast Mountains, thick accumulations of proglacial sand (Quadra Sand) were deposited between 29 ka and 19 ka years ago around Vancouver, West Vancouver and North Vancouver. Proglacial deposits were covered by till and gravelly ice-contact sediments (Vashon Drift) between 19 ka and 13 ka. The average thickness of Vashon drift in a glacial, glaciofluvial and glaciolacustrine deposits is 25 m, 60 m and 80 m, respectively [28]. At the close of the last Fraser glaciation (~13 ka), sea level was as much as 120 m higher and Capilano sediments (glaciomarine silt and clay) were deposited over the Vashon till unit. Thick glaciers did not override these Capilano sediments. The thickness of Capilano sediments in marine and glaciomarine depositional environments are around 15 m, thinning to 8 m in fluvial channels [28]. Holocene Salish sediments start deposition between 12 ka and 10 ka. Salish sediments include alluvial fan, organic, lacustrine, coarse-grained alluvial and deltaic deposits of smaller rivers that formed in post-glacial time. The thickness of Salish sediments in the marine shore is 8 m, whereas in fluvial, lacustrine, and bog deposits is around 20 m [28]. The Fraser River, which developed after the ice left the low-lying land some 8 ka to 10 ka years ago, began depositing sands, silts, and clays forming the Holocene Fraser River delta [28]. The Fraser River deposits are divided into bottom sets, foreset, and topset deposits. The bottom set deposits are dominated by silt and clay and have a maximum thickness of 120 m. Foreset deposits are up to 165 m thick and are primarily sandy silt. Topset deposits consist of 8-30 m thick sand[26]. The maximum Tertiary sedimentary bedrock depth is ~1000 m beneath the Fraser River delta [29].

3. Comprehensive Regional Geodatabase

Seismic microzonation hazard mapping requires a significant amount of geodata, including geological, geophysical and geotechnical measurements of subsurface ground conditions or samples. Essential types of geodata for earthquake shaking (amplification) hazard mapping include seismic velocities, density, fundamental site frequency, and nonlinear soil behaviour (e.g. shear modulus reduction and damping curves, stress-strain hysteresis model). Other geodata, including water table depth, cone penetration testing (CPT), surface topography, and soil cohesion and friction angle, are essential for seismically triggered landslide and liquefaction hazard prediction. A comprehensive regional geodatabase of subsurface ground conditions across Metro Vancouver is not available currently. The vital objective of developing a comprehensive geodatabase for Metro Vancouver is to document each geological unit's material properties to aid in robust regional seismic microzonation mapping. Table 2 summarizes the in situ data collection methods and their data types incorporated into the Metro Vancouver geodatabase. We began assembling our geodatabase [25]in 2017 by compiling publicly available geological, geophysical, geotechnical data and maps of surficial geology for the Metro Vancouver area.

Table 2 – Summary of geodata methods (and their data types) relevant to seismic microzonation mapping.

***In situ* field testing methods**		**Geotechnical laboratory testing methods**
Invasive methods	**Non-Invasive methods**	
Boreholes (Stratigraphy, Water table)	Seismic refraction survey (Vp, Vs)	Grain size (% of gravel, sand and fines)
Standard Penetration Test, SPT (Blow count)	Ambient Vibration Array, AVA (Low-frequency dispersion curve)	Atterberg limits (Plasticity index, PI)
Cone Penetration Test, CPT (Tip resistance, sleeve friction) Seismic Cone Penetration Test, SCPT (with Vs)	Spectral analysis of surface wave, SASW; Multi-Channel Analysis of Surface Waves, MASW (High-frequency dispersion curve)	Bender Element test (Vs)
Down/Cross hole velocity profiling (Vp, Vs)	Microtremor horizontal-to-vertical spectral ratio, MHVSR ($f_{\#HV}$ and $A_{\#HV}$)	Direct shear test (soil cohesion, friction angle)

Federal, provincial, municipal governments and the Geological Survey of Canada provide multiple open access resources (e.g., topographical and geological maps [10], water logs, geological and geophysical records [30]). These datasets were downloaded and compiled to generate the geodatabase. We also requested government agencies, stakeholder organizations, engineering firms, local geo-consultants and municipalities in the region to share their proprietary geodata. However, this method of data acquisition required the development of a data-sharing agreement with multiple user-selected options. The geodata provided was mainly in the form of *insitu* invasive methods (e.g. borehole stratigraphy, CPT, downhole seismic, seismic cone penetration test (SCPT)), and laboratory testing methods of discrete soil samples. We began supplementing the geodatabase with *insitu* non-invasive testing methods in 2018; the microtremor horizontal to vertical spectral ratio (MHVSR) method [25] provides resonance peaks $f_{\#HV}$ (f_{0HV} is assumed as f_0) and is a reasonable proxy for 1D site amplification, ($A_{\#HV}$), and active-source multichannel analysis of surface waves (MASW) and passive-source ambient vibration array (AVA) methods that provide surface wave dispersion estimates. During the last three annual field campaigns, we performed MHVSR measurements at over 1,700 locations (approx. 600 by 600 m grid) and surface wave dispersion measurements at over 100 locations. Figure 2 shows all geodata locations according to the data method within our compiled geodatabase, effective March 6, 2021.

Conversion of all the compiled maps, files and reports (in digital and paper form) into our digital geodatabase occurred in three phases. In Phase I, we focused on providing a 'high-level summary' of the geodata within each file or report to ascertain what we had and where. To create this, we assigned a unique file identifier for each file or report, extracted a single representative location (geo-coordinates) for all the geodata within the report, and tabulated the year of commencement, data type, technique used and the total depth of measurement. Likewise, whether the report included liquefaction or landslide assessment was also tabulated using Yes or No. Phase I was accomplished primarily in Microsoft Excel. Data that did not have geographic coordinates were georeferenced with the support of Google Earth Pro [25] by comparing the provided location map in the report with the corresponding Google Earth location using the report's address. Multiple measurements within a single report were often located together using a single coordinate. As a result of tabulating simple metrics like the data method and maximum depth, we could begin to query and visualize geodata locations across the region in Phase I. We collected 480 reports from different agencies which provide relevant information of ~11,000 geodata locations in the region (Fig. 2). Three undergraduate students were hired part-time to accomplish our Phase I geodatabase compilation.

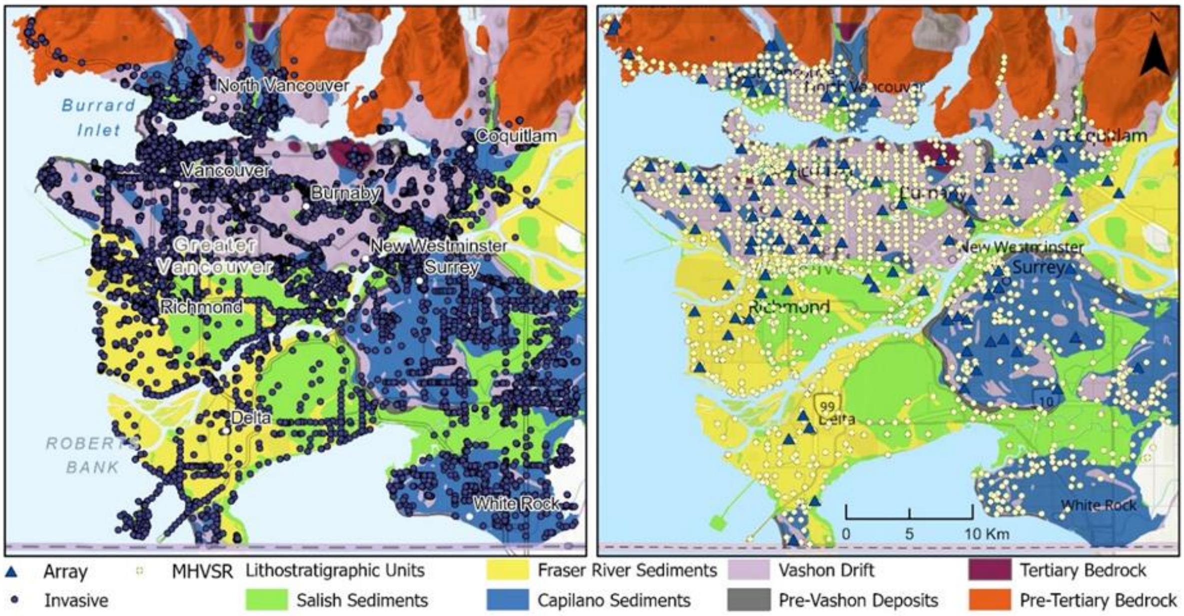

Fig. 2 – Location of subsurface geodata from various invasive measurements and geotechnical testing (left panel) and non-invasive measurements (right panel).

In Phase II, we began extracting the geodata itself from the compiled maps, files and reports into our digital geodatabase. A dedicated part-time Research Assistant was hired to accomplish Phase II for the sake of consistency rather than relying on registered students' sporadic output. The variability in data methods and how data were measured requires a standard format or representation in the geodatabase, thus we populated data within our geodatabases according to the Electronic Transfer of Geotechnical and Geoenvironmental Data format of the Association of Geotechnical and Geo-Environmental Specialists (AGS) [31]. As a result of our considerations for consistency, we develop a standardized data transfer file format for the invasive tests (e.g., borehole stratigraphy, SPT, CPT, Vs, water table) and laboratory tests (e.g., grain size distribution, plasticity index, and moisture content) based on the AGS guideline.

Figure 3 shows the organizational structure of our standardized data file formatting appropriate to *insitu* invasive method attributes. Data are populated in the geodatabase based on each invasive test location providing the HoleID (borehole or well log) as the unique identifier. This unique identifier is spatially referenced by UTM easting and northing (EPSG: 26910) and ground elevation of the hole location. All invasive testing data conducted within each borehole is linked within our geodatabase using the unique HoleID identifier. For example, if stratigraphic logging and SPT testing are conducted within a single borehole, HoleID will be the same for both the geologic information and SPT blow counts for that particular borehole. Each type of invasive testing data are tabulated according to depth (m) in a separate associated Comma Separated Value (CSV) text file, linked by HoleID in our geodatabase. Likewise, suppose further laboratory testing (e.g. grain size, moisture content, plasticity index) is conducted on discrete soil samples within the borehole, the unique HoleID remains the same for each sample with the laboratory test data tabulated in a separate CSV data file. Figure 3 summarizes all possible invasive testing data and their associated separate file linked to the unique HoleID. Our described geodatabase architecture achieves data harmonization amongst various geologic, geophysical and geotechnical datasets; the multiple file formats and SI units are not directly comparable with each other because the data come from different methods or sources.

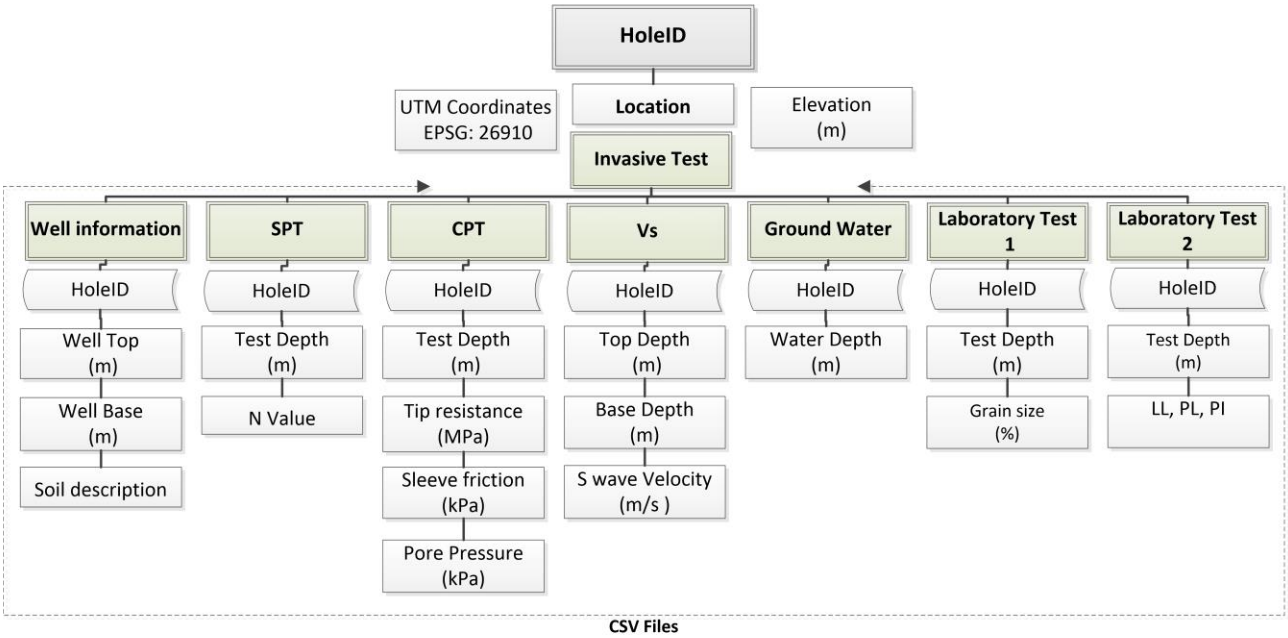

Fig. 3 –Example of geodatabase architecture related to an invasive method and their compiled data (metrics).

In Phase III, non-invasive measurements (MHVSRs and seismic array surveys) collected during our three consecutive field surveys (Fig. 2 shows their locations) are uploaded into the geodatabase using our own developed unique identifiers for each measurement location. The attribute table for each non-invasive test consists of spatial location (UTM coordinates, elevation), MHVSR peak ($f_{\#HV}$) and amplification ($A_{\#HV}$) and Vs depth profile and Vs_{30} from the inverted dispersion curve of the seismic array survey, which are also saved in CSV file for further analysis.

We also perform quality control of all geodata populated within the geodatabase. The ambiguous or incomplete geodata is flagged into two groups named "helpful" and "unhelpful," and the both groups will not be used for further analysis unless some associated data is found in that area. Our use of flags maintains knowledge of the geodata's existence for the region but conveys they are not reliable for our microzonation mapping purpose. We then transfer the digital geodatabase (CSV files) into the ArcGIS [32] environment for further data processing, interpolation and visualization.

All three Phases of geodatabase development are ongoing. When we receive a new report, it enters to Phase I summary, then the relevant geolocation's detail attributes (data) are extracted in Phase II. The 4th field campaign is scheduled for the summer of 2021, which will be processed under Phase III work. We are planning to continue compiling data into the geodatabase until Fall 2022, at which time the geodatabase will be considered complete to generate the Metro Vancouver seismic microzonation mapping project's analysis and map products in 2023.

3.1 Regional geostatistics of shear wave velocity as geodatabase product

Shear wave velocities are available with depth from invasive (Category I) and non-invasive (Category II) methods across Metro Vancouver; see Table 2 for the list of individual methods. Our comprehensive geodatabase enables an update and improvement in the geostatistics (e.g., mean and one standard deviation) of the Vs depth profile within each geologic unit in Metro Vancouver. For demonstration, we plot all measured Vs (1 m depth increments) in the Holocene (both Salish and Fraser River sediment) unit in Figure 4 [33]. Median Vs depth profiles are calculated from Vs values for Category I, Category II, or both.

Overall, the median Vs depth profiles are similar regardless of the data method, noting that non-invasive methods over-predict Vs compared to invasive methods in the upper 10 m. A power law gradient Vs model is also determined by regression of the Vs measurements. Outliers are eliminated using Chauvenet's criterion [34].

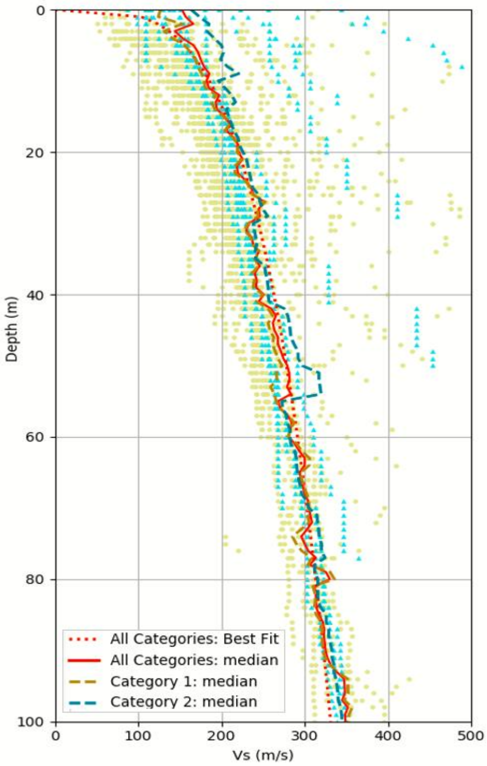

Fig. 4 – Median Vs profile for Holocene sediments.

Figure 4 shows that the median Vs profile of Holocene sediments in Metro Vancouver varies from 100 m/s to ~300 m/s in the upper 60 m. In the upper 30m, Vs is generally less than 250 m/s in Holocene sediments. The range in Vs for Pleistocene glacial deposits (not shown) is 300 m/s to 610 m/s [33].

3.2 Groundwater information as a geodatabase product

Water table depth is crucial for evaluating groundwater sources and predicting seismic hazards, such as liquefaction assessment and lateral spreading. To produce interpolated maps of various metrological, climatic and groundwater estimations, researchers have used cokriging [35] techniques. Cokriging analysis determines a value z at each grid node based on a weighted linear combination of two dependent variables with n samples.

$$z = \sum_{i=1}^{n} \lambda_i z_i + \sum_{j=1}^{n} \beta_j t_j \tag{1}$$

where λ_i and β_j are weight (varies between 0 and 100%) assigned to the primary and secondary sample, respectively, and z_i and t_j are primary and secondary regionalized variables at a given location with the same units.

We calculate water table depth (below ground surface) as the summation between the water table and topographic elevation (both referenced to sea level). Hence, we generate an interpolated regional map of water table depth in meters (Fig. 5) from ~ 2,500 known groundwater elevation (primary variable) and 1 m LiDAR DEM (topography) elevations (secondary variable) using the cokriging interpolation technique provided in Eq 1. Water table depth is very close to the surface in Delta and Richmond because of the low-lying ground near sea level.

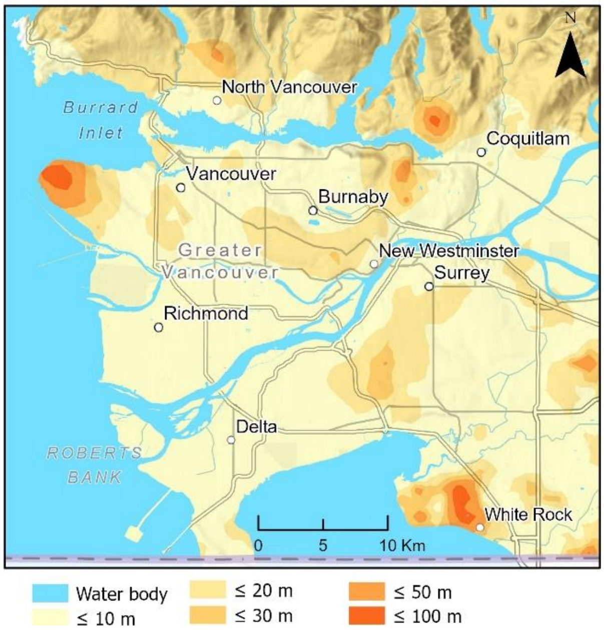

Fig. 5 – Map of predicted ground water depth

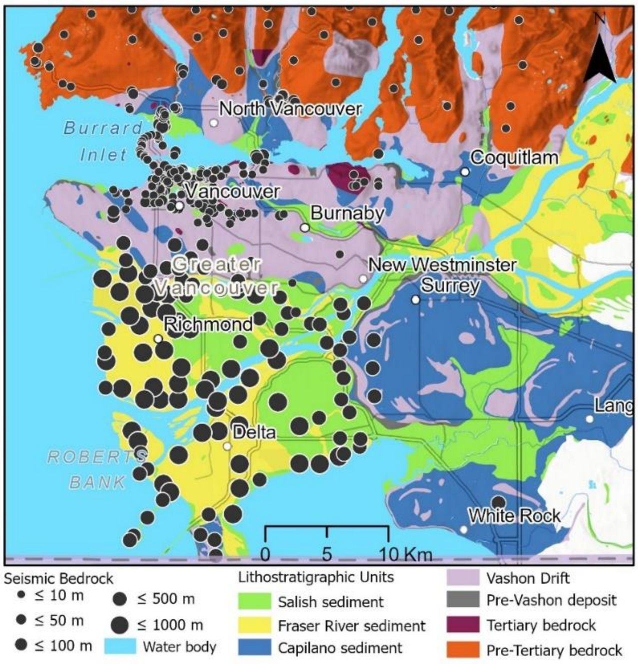

Fig. 6 – Locations showing depth to seismic bedrock

3.3 Depths to glacial till and seismic bedrock as a geodatabase product

The depths to the two major seismic impedance contrasts, glacial till and seismic bedrock, are important to earthquake shaking (amplification) prediction and mapping. Depth to glacial till and/or seismic bedrock is extracted and tabulated as secondary geodatabase products from each applicable geodata within the geodatabase. Figure 6 shows geodata locations and their associated depth to seismic bedrock (Vs >650 m/s); these locations are a mixture of measured and inferred seismic bedrock depths. The geologic bedrock type itself, Tertiary sedimentary rock or Coast Mountain plutonic rock, varies within our seismic bedrock definition; in general, Tertiary sedimentary bedrocks thin towards the north and are not present along the North Shore. Depths to seismic bedrock in Vancouver, Burnaby and Surrey uplands are in the tens of meters compared to hundreds of meters below the Fraser River delta in Richmond and Delta. Similarly, Pleistocene glaciated till thickness (not shown) in Vancouver is about 5 m, and more than 275 m in Delta and Richmond.

3.4 Geostatistics of fundamental site frequency as a geodatabase product

We have conducted a total of ~1,777 MHVSR measurements across Metro Vancouver. Each MHVSR peak of stratigraphic origin, $f_{\#HV}$, is extracted and tabulated within our geodatabase [25] [36]. The lowest MHVSR peak frequency (f_{0HV}) is a measure of the fundamental-mode resonance site frequency (f_0). We compile the geostatistics in f_{0HV} (Fig. 7) for each major geologic unit in the region. The median f_{0HV} is 0.26 Hz for Fraser River sediments, 0.85 Hz for Salish sediments, 1.65 Hz for Capilano sediments, 1.48 Hz for Vashon drift sediments, 1.18 Hz for Pre-Vashon sediments, and 6 Hz for Tertiary and Pre-Tertiary rock sites. Hence there is a correlation between the stiffness of the geological material and its resonant frequency. These results highlight variability in site effects across Metro Vancouver.

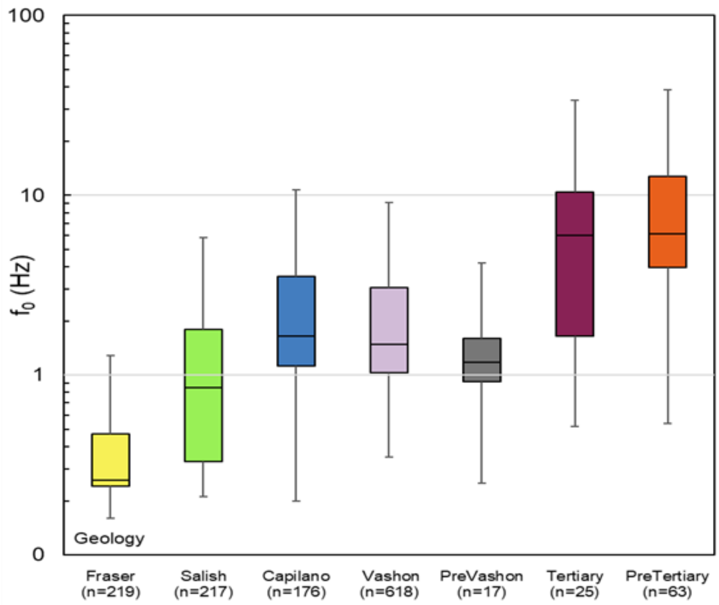

Fig. 7 – Geostatistics (boxplot) of f_{0HV} for each major geologic unit.

4. Conclusions

This paper documents our methodologies in compiling and developing a robust and comprehensive geodatabase of invasive and non-invasive datasets relevant to regional seismic microzonation hazard mapping. We compiled geodata from nearly 11,000 invasive method locations obtained from a variety of public and private sources. We compiled these files and reports over three years and hired part-time personnel to tabulate basic information about the geodata (Phase I) and then extracted the geodata itself (Phase II) in a standardized format. An appropriate geodatabase architecture is developed to harmonize the various geological, geophysical and geotechnical datasets collected from various agencies. Additionally, we supplemented the geodatabase with our extensive non-invasive testing performed during one-month field campaigns in each of the past three years. Compilation and development of the geodatabase are ongoing over the remaining two years, with a fourth and possible fifth field campaign to collect additional non-invasive data. We provided examples of preliminary products from the compiled geodatabase (effective to March 6, 2021). The geostatistics (mean or median and standard deviation) of particular metrics including Vs depth profiles and f_{0HV}, are provided in Figure 4 and 7 binned by each major geologic unit in the region. Other metrics or measures, including depth of water table and depth to major seismic impedance contrasts, are examined in terms of their spatial distribution as either point locations or interpolated here using cokriging techniques to demonstrate future seismic microzonation mapping products. Regional seismic microzonation mapping products, including earthquake (amplification), shaking, liquefaction and landslide hazard, are being developed in consultation with the Association of Professional Engineers and Geoscientists of British Columbia (EGBC) and regional stakeholders [37].

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