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# Seismic microzonation mapping of Greater Vancouver based on various site classification metrics

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The goal of the multi-year seismic microzonation mapping project for Greater Vancouver, British Columbia, Canada, is to produce seismic hazard maps inclusive of local site effects, in particular seismic hazard specific to one-dimensional site response and three-dimensional Georgia sedimentary basin amplification, as well as liquefaction and landslide hazard potential. We explore the variability in key seismic site characterization measures most often used for seismic microzonation mapping to evaluate the impact on mapping and communication of seismic microzonation of Greater Vancouver. This study focuses on the comparison of seismic microzonation maps of Greater Vancouver based on up to three seismic site term parameters and their associated classification schemes: 1) the time-averaged shear-wave velocity ( $V_s$ ) of the upper 30 m ( $V_{s30}$ ) and associated Canadian National Building Code (NBC) site class; 2)  $V_{s30}$ -based site classification proposed for the updated Eurocode 8; 3) site period ( $T_0$ ) determined from microtremor site amplification spectra; and 4) a hybrid site classification based on  $T_0$  and the average  $V_s$  and thickness of soil. 810  $V_{s30}$  and 2,200  $T_0$  values are determined to evaluate sub-regional differences in these important seismic site parameters in Greater Vancouver. We find that the seismic microzonation of Greater Vancouver depends on the chosen seismic site parameter ( $V_{s30}$ ,  $T_0$ , or a combination of parameters) and that classification schemes with greater class divisions are beneficial to communicating the great variability in seismic site conditions in Greater Vancouver. We recommend that either one hybrid classification map or two classification maps of  $V_{s30}$  and  $T_0$  together are required for effective communication of the seismic microzonation of Greater Vancouver.

## KEYWORDS

$V_{s30}$ , shear-wave velocity, ambient vibrations, seismic microzonation, site period, soil amplification, site classification, building code

## 1 Introduction

Seismic microzonation is a method for characterizing a region's seismic hazard due to local site conditions at a regional or municipal scale, often communicated in the form of a map or spatial GIS layer. Seismic microzonation maps identify and characterize seismically homogeneous behavior, such as zones with similar susceptibility to seismic site amplification, liquefaction, or slope instability. Seismic microzonation is a comprehensive process that involves three distinct stages: 1) estimating the regional seismic hazard that involves examining the geological environment, recorded and historical earthquake data, and fault activity in the area; 2) estimating the conditions of the regional seismic site, such as the material properties and dynamic response of the soil and

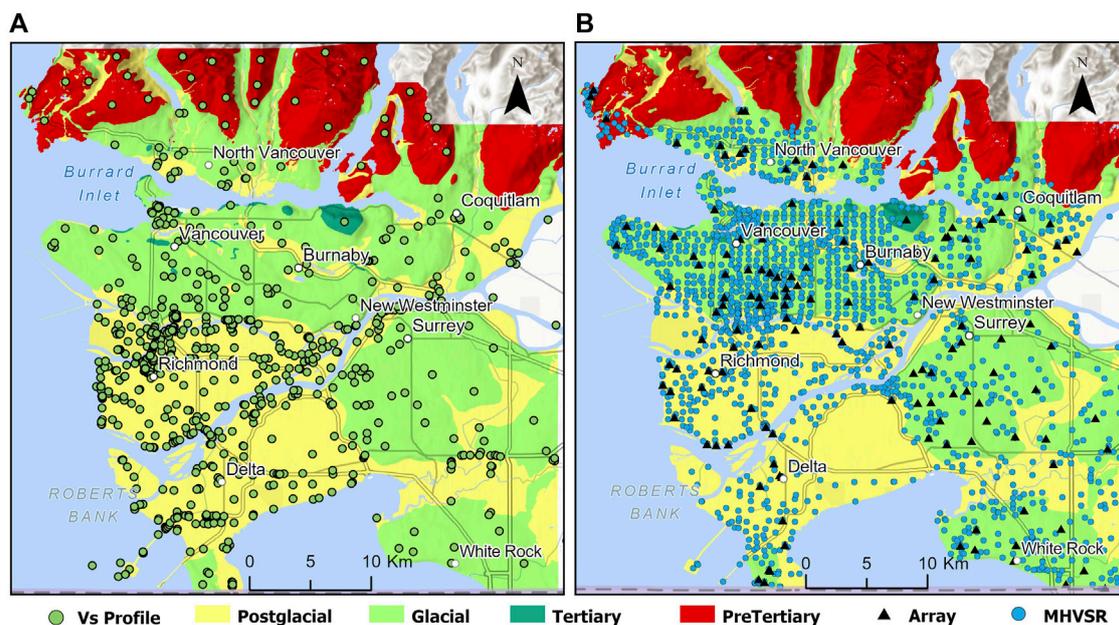
rocks, groundwater levels, geological substructure, and surface topography of the surrounding area; and 3) using the outcomes of stages 1 and 2 to perform seismic hazard analyses to predict seismic ground motions and site response at the ground surface. Intuitively, as the quality and quantity of *in situ* seismic site characterization data and spatial geodatasets in combination with technical seismic hazard analyses increase, the grade or level of seismic microzonation mapping increases. For example, a grade I seismic microzonation map uses lower quality and quantity of data and technical seismic analyses than grade III (TC4-ISSMGE, 1999; SM Working Group, 2015). Seismic microzonation maps are most directly used as input in seismic risk analyses. Thereby, they are beneficial to regional or local authorities in urban planning, emergency managers in response and recovery planning, and earthquake engineering professionals in seismic design, among others.

The most ubiquitous seismic site term parameter in seismic hazard prediction is the time-averaged shear-wave velocity ( $V_s$ ) of the upper 30 m ( $V_{s30}$ ), first proposed by Borchardt (1994) and used to characterize five seismic site classifications (A–F), each based on a particular range of  $V_{s30}$  (e.g., class A corresponds to  $V_{s30} > 1,500$  m/s) (NEHRP, 1994). It is now a near-universal requirement for seismic design standards to use  $V_{s30}$ , which increases the precision and dependability of seismic design techniques, particularly for locations with diverse soil conditions (Castellaro et al., 2008; Borchardt, 2012; Myriam et al., 2018; Stanko and Markušić, 2020). In Canada,  $V_{s30}$  was adopted for seismic site classification in the 2005 National Building Code (NBC) (Adams and Halchuk, 2004) and maintained in the code until 2020 (NBCC, 2015). The recently adopted 2020 NBC permits the use of  $V_{s30}$  directly to determine seismic design ground motions when it is calculated from an *in situ* seismic field method (Kolaj et al., 2020); otherwise, the design ground motions are the maximum motion for the seismic site class based on *in situ* measurements of standard penetration test blow count ( $N$ ) or undrained shear strength ( $s_u$ ) averaged for the upper 30 m. The most recent American seismic design code (ASCE 7–22) maintains the use of seismic site classification based on  $V_{s30}$  with further refinement of the original five NEHRP classes to seven (addition of CD and DE classes). Although widely used, numerous authors have questioned the ability of  $V_{s30}$  to capture the complexity of site effects (Castellaro et al., 2008; Gallipoli and Mucciarelli, 2009; Lee and Trifunac, 2010) because it could mislead the amplification value for deep and low stiffness deposit laying on harder rock (sedimentary basin site) or for sites with a velocity profile that does not monotonically increase with depth. The lowest peak observable in an MHVSR curve ( $f_{0HV}$ ) is assumed to represent the fundamental resonant site frequency ( $f_0$ ) of the soil column.  $f_0$  is related to both the stiffness distribution in the subsurface and the depth of the seismic bedrock (Pitilakis et al., 2013; Pitilakis et al., 2019; Farrugia et al., 2018; Molnar et al., 2018). Zhao et al. (2006) developed a site period classification scheme from earthquake spectral ratios of 5% damped response spectra in Japan. Compared to the  $V_{s30}$ -based classification method, Zhao et al. (2006) discovered that their site period classification offered a more precise prediction of ground motion characteristics. Later, Di Alessandro et al. (2012) used Italian datasets to propose two additional site period classes to the Zhao et al. (2006) site

period classification. Recent efforts to utilize site frequency in the development of ground motion models (Hassani and Atkinson, 2016) and seismic site classification for earthquake design codes (Zhao et al., 2006; Pitilakis et al., 2013) indicate the growing popularity of  $f_0$  and accompanying shift away from the dominance of  $V_{s30}$  in seismic hazard analyses. Cultrera et al. (2021) ranked 24 distinct indicators of site classification based on a questionnaire survey and ranked them based on the responses of several experts in various domains. They found that  $f_0$ ,  $V_s$  depth profile,  $V_{s30}$ , and the depth of engineering and seismological bedrock are the preferred site indicators for effective seismic site characterization. A number of alternative seismic site classification schemes have been proposed, each based on a mix of several site characterization measures (Rodríguez-Marek et al., 2000; Di Giulio et al., 2020; Cultrera et al., 2021). A hybridized seismic site classification scheme based on multiple seismic site characterization measures [ $N$ ,  $s_u$ , plasticity index,  $f_0$ , soil thickness ( $h$ ), and average  $V_s$  to seismic bedrock ( $V_{sav}$ )] has been proposed for the revision of the Eurocode 8 seismic design code (Pitilakis et al., 2013; Pitilakis et al., 2019).

The earliest seismic microzonation studies in Canada resulted in  $V_{s30}$ -based NBC site class mapping for the municipalities of Victoria, BC (Monahan et al., 2000); Greater Vancouver, BC (Monahan, 2005); Ottawa, ON (Motazedian et al., 2011); and Montreal, QC (Rosset et al., 2015). There are fewer seismic microzonation maps in Canada based on site period (inverse of  $f_0$ ): Toronto (Mihaylov, 2011) and Québec City (Leboeuf et al., 2013). More recent Canadian seismic microzonation studies have produced multiple maps of various seismic site characterization measures, including site period ( $V_{sav}$ ,  $V_{s30}$ , or both; not NBC site class) and total sediment thickness maps with the development of 3D geomodels: the St. Lawrence Lowlands (Nastev et al., 2016) and Saguenay, QC (Salsabili et al., 2021). The ongoing Metro Vancouver seismic microzonation mapping project (Molnar et al., 2020) will produce a suite of high-quality (grade III) seismic microzonation maps to convey local seismic site conditions (e.g.,  $V_{s30}$ , site period, and post-glacial/glacial sediment thickness) and probabilistic seismic hazard maps depicting shaking (de)amplification and seismic-induced liquefaction and landslide hazard potential at 2% and 10% probability of exceedance in 50-year risk levels (considering ground motions with a 2,500- and 475-year recurrence interval, respectively). A comprehensive regional geodatabase of geological, geophysical (primarily seismic), and geotechnical spatial datasets and *in situ* field measurements has been compiled (Adhikari et al., 2021b) to achieve high-quality mapping, including over 10,000 lithology logs, 2,300 microtremor horizontal-to-vertical spectral ratio measurements (Sirohey, 2022), 1,380 cone penetration tests, 810  $V_s$  depth profiles, and 530 standard penetration tests.

In this study, we utilize the geodatabase compiled to achieve seismic microzonation mapping of Metro Vancouver, British Columbia, Canada (Adhikari et al., 2021b) to explore sub-regional differences in important seismic site term parameters ( $V_{s30}$ , site period) across 16 local municipalities, lands of 6 First Nations, and 1 Electoral Area of western Metropolitan Vancouver. Subsequently, we apply various site classification schemes based on  $V_{s30}$ , site period, or a hybrid combination of seismic site characterization measures in generating seismic microzonation



**FIGURE 1**

Simplified surficial geologic map (colors) with (A) locations of 810 Vs depth profiles (circles) from invasive and non-invasive field testing, and (B) further details of the non-invasive field testing in terms of ~2,200 MHVSR measurements (circles) and over 120 multi-seismic-method array tests (triangles) performed during the Metro Vancouver seismic microzonation mapping project.

maps of Greater Vancouver from which the impact of each scheme on communicating the region's seismic site characterization to technical and non-technical end users can be evaluated (Fyfe and Molnar, 2020).

## 2 Greater Vancouver seismic site condition

Greater Vancouver lies within the Late Cretaceous to Early Tertiary Georgia basin filled with south-dipping sedimentary rocks that overlie Mesozoic plutonic rocks exposed in the Coast Mountains (Monger and Journeay, 1994). A simplified geologic map of the western Greater Vancouver study area is shown in Figure 1. The youngest Holocene post-glacial deposits in the region are modern alluvial, deltaic, and bog deposits with near surface Vs of 115–175 m/s, respectively (Assaf, 2022). The Fraser River Delta, beneath the cities of Richmond and Delta, is a topographically lowland region comprising deltaic silts and sands, with a thickness of up to 300 m (Rogers et al., 1998). The Fraser River Delta sediments exhibit an expected power law Vs depth ( $z$ ) relationship, with Vs of ~70 m/s at the surface to ~320 m/s at 90 m depth (Hunter and Christian, 2001). A thick Pleistocene succession (maximum of 500 m) of glacial and interglacial sediments underlies the Fraser River Delta's center (Christian et al., 1994; Britton et al., 1995) and thereby has complex changes in sediment types vertically at individual sites and laterally between them. These Pleistocene sediments are mostly composed of Ice-compacted sediment (till) at surface or near the surface across most of Vancouver, Burnaby and Surrey (Luternauer et al., 1994). We group the former as glacial

sediments and the latter as post-glacial, as they were never glacially overridden (Figure 1). Glacial sediments have a range of Vs that increases with depth from ~490 m/s at the surface to ~800 m/s at 50 m depth in upland Vancouver, Burnaby, and Surrey areas and from 375 m/s (base of Holocene) to 550 m/s (200 m deeper) beneath the Fraser River Delta (Assaf, 2022). Pleistocene post-glacial sediments have a  $V_{Sav}$  of ~250–265 m/s (Assaf, 2022). The Quaternary sediment package overlies the Late-Cretaceous Georgia basin sedimentary bedrock and pinches out to the north, from a maximum thickness of 800–1,000 m beneath the Delta to only several meters at the edge of the post-glacial Fraser River Delta (Britton et al., 1995). Tertiary sedimentary rocks have Vs as low as ~650 m/s in the near surface, increasing to over 1,200 m/s at 40 m depth, and Tertiary rock Vs increases from ~575 to 1,525 m/s, from 445 to 605 m depth beneath the Fraser River Delta (Assaf, 2022). Mesozoic plutonic igneous rocks are exposed along the North Shore (north of Burrard Inlet) at the highest altitudes. In the near shore, the  $V_{Sav}$  of these crystalline fractured rocks is ~1,600 m/s and increases to over 2,000 m/s by ~40 m depth (Assaf, 2022). In general, there are two major seismic impedance contrasts at depth between post-glacial and glacial units and between post-glacial or glacial and rock units.

Figure 1 displays geodata locations of the Metro Vancouver microzonation study's geodatabase (Adhikari et al., 2021b), including 810 Vs depth profiles (Figure 1A), ~2,200 MHVSR measurements, and over 120 multi-method-seismic array test locations (Figure 1B). The geodatabase is developed from two main data sources: 1) from previously collected open and private geodata sources, with the private geodata shared by 24 municipalities, organizations, or consultants, and 2) by

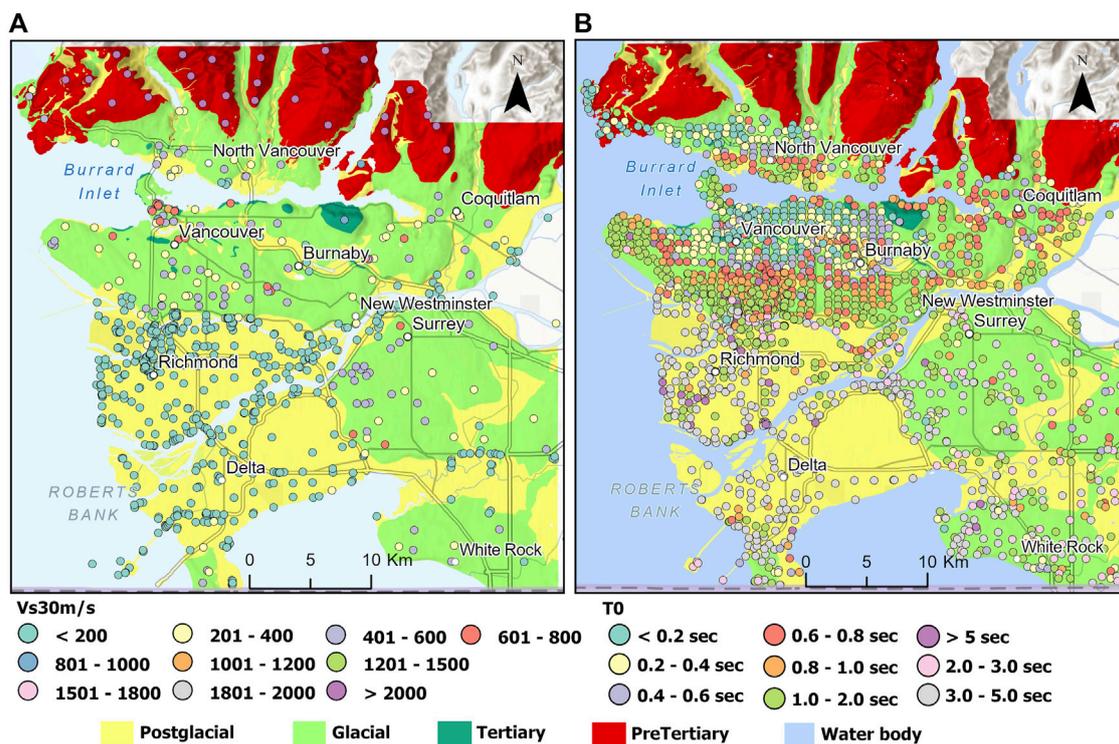


FIGURE 2

(A) Locations of  $V_{s30}$  obtained from 810 Vs profiles and (B) site period obtained from MHVSR data overlaid on the surficial geological map of the study area.

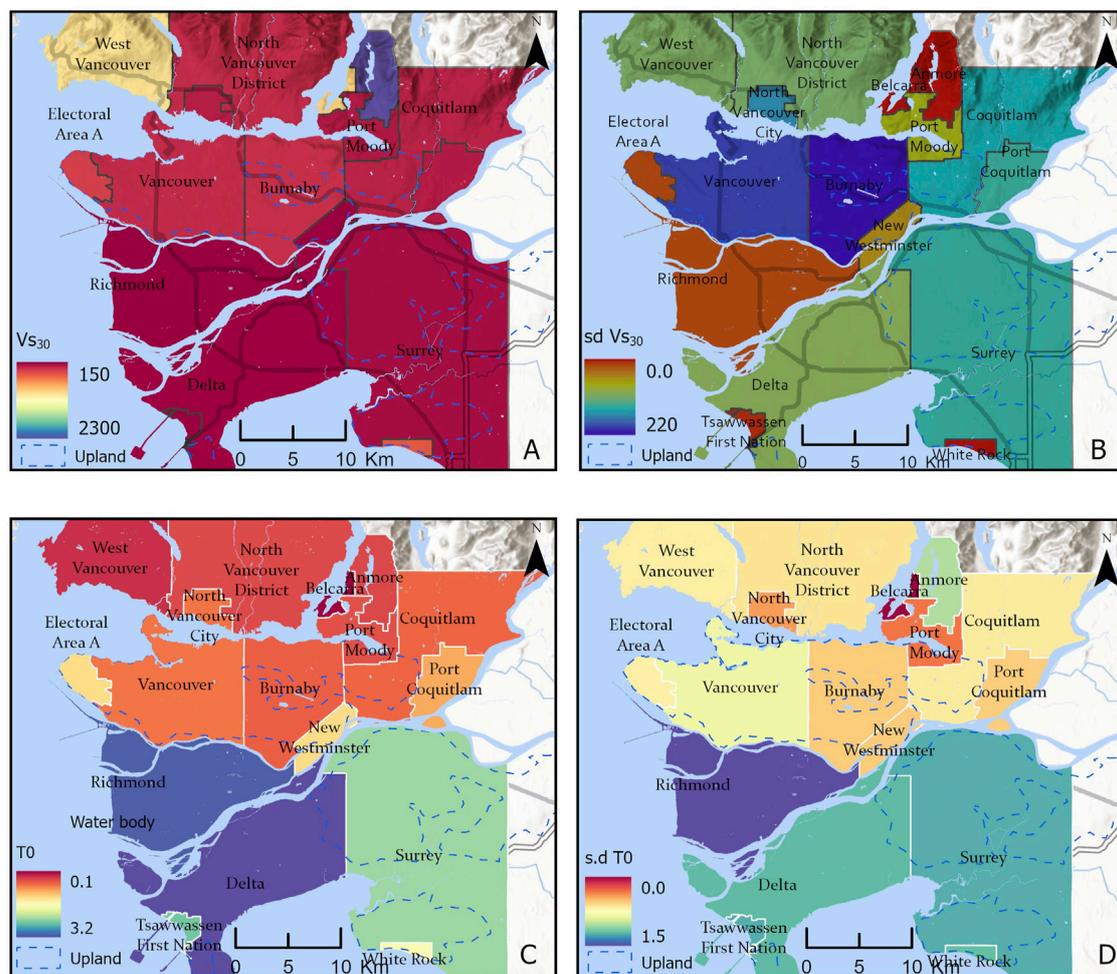
performing *in situ* field-based multi-method non-invasive seismic testing throughout the region annually between 2018 and 2021. The non-invasive seismic field methods include single-station microtremor measurements (Molnar et al., 2022) performed at a 600- to 1,000-m grid spacing across the study area (Figure 1B) to obtain amplification spectra and site peak frequencies ( $f_{0HV}$  and higher frequency peaks  $f_{1HV}$  and rarely  $f_{2HV}$ ) (Sirohey, 2022), combined active-source multi-channel of surface waves (MASW) and passive-source microtremor array method (MAM) array testing to obtain fundamental-mode Rayleigh wave dispersion estimates for joint inversion with MHVSR peak frequency(ies) ( $f_{0HV}$  and  $f_{1HV}$ ) to obtain Vs depth profiles (Ladak, 2020; Assaf et al., 2022; Boucher, 2022) and compression-wave velocity and Vs refraction surveys at selected sloping ground sites (Boucher, 2022).

### 3 Spatial variation of $V_{s30}$ and site period

Two main seismic site classification measures,  $V_{s30}$  and site period, can be readily obtained from the Vs depth profile (Figure 1A) and MHVSR (Figure 1B, circles) databases, respectively.  $V_{s30}$  is calculated as the time-averaged Vs over the upper 30 m [i.e., 30 m divided by the summation of travel times ( $h/V_s$ ) of each layer in the depth profile]. For Vs profiles shallower than 30 m, we use an extrapolation model specific to the Vs data of Metro Vancouver developed by Assaf et al. (2022) and based on Dai et al. (2013) functional form to estimate  $V_{s30}$ . To fill spatial data gaps and

increase spatial coverage, we utilize other *in situ* field-based measurements to supplement additional  $V_{s30}$  values. Assaf et al. (2023) developed an empirical relationship to convert CPT measurements to Vs for Fraser River Delta sediments ( $z < 90$  m). We use this relationship to predict Vs depth profiles for 365 CPT logs in the Fraser River Delta. A representative Vs depth profile of the upper 30 m for Coast Mountain plutonic igneous rocks of the North Shore developed from multiple invasive and non-invasive field methods (private consulting data of the second author) is used to estimate  $V_{s30}$  at 25 selected locations of outcropping rock in the study area. Figure 2A displays the locations of 810  $V_{s30}$  values calculated from *in situ* Vs or converted CPT-converted Vs depth profile data.

Sirohey (2022) developed a multi-peak picking algorithm to determine the peak site frequencies for the single-station microtremor measurements of the Metro Vancouver microzonation study (Figure 1B). The MHVSR curve is calculated for each time window of the microtremor recording using HVSRPy (Cox et al., 2020), and a modified agglomerative hierarchical clustering routine (Di Alessandro et al., 2016) is used to compile clusters of MHVSRs with similar curve shape (i.e., edit inconsistent MHVSR curves from consistent MHVSR curves). The end-user selects the most appropriate MHVSR cluster based on visual comparison with the plotted Fourier amplitude spectra. Peak frequencies are determined for all individual curves, as well as the mean and 10th and 90th percentile curves. Then, statistics about the peak frequency values and their amplification are calculated based on the matched peaks from the individual windows to determine if



**FIGURE 3**  
Maps of the (A) mean  $V_{s30}$  and (B) its one standard deviation and (C) mean site period and (D) its one standard deviation for 17 local communities in Greater Vancouver.

SESAME's two reliability and six clear peak criteria (Bard, 2008) are met. In this study, the lowest frequency peak of the over 2,200 average MHVSR curves is inverted as an estimate of the site period (Figure 2B).

Prior to using existing seismic site classification schemes in the following section, we evaluate the spatial variation of  $V_{s30}$  and site period across Greater Vancouver in terms of their average and one standard deviation variation for 17 local communities (Figure 3, Table 1). Although this mapping does not use seismic microzonation (zones defined by similarity of  $V_{s30}$  or site period), it is a form of seismic microzonation map useful for communicating with local communities or conveying the communities in which the acquisition of *in situ*  $V_{s30}$  could reduce 2020 NBC design ground motions (Adhikari et al., 2021a). In general, the lowest  $V_{s30}$  ( $180 \pm 60$  m/s) and longest site periods ( $3.1 \pm 1.5$  s) occur in the cities of Richmond and Delta, as expected for the Fraser River Delta lowlands. The glaciated uplands of Vancouver, Burnaby, and Surrey have higher  $V_{s30}$  values with a greater variance ( $442 \pm 170$  m/s) as expected, whereas the average site periods are moderate-to-long (0.7–2.3 s, Table 1), indicating that

these stiffer glacial sediments are relatively thick. For Surrey, the site period (depth to Georgia basin sedimentary rock) is consistent with the neighboring Delta even with  $\sim 100$  m elevation gain of glacial uplands, and for Vancouver and Burnaby, site periods decrease northward (Figure 2B) toward the northern limit of the Georgia sedimentary rock basin (Burrard Inlet, North Shore, or both). Communities constrained to north and eastern shorelines (e.g., City of North Vancouver, Port Moody, and Port Coquitlam) have an average  $V_{s30}$  and site period that is relatively low and moderate, respectively (Table 1), related to soft sediments that are thicker than 30 m. Communities that are further north and with higher elevations (outcropping Coast Mountain plutonic rocks) have the highest  $V_{s30}$  and shortest site periods.

## 4 Application of various seismic site classifications

We select and apply four seismic site classification schemes based on  $V_{s30}$ ,  $T_0$ , or a hybrid combination of seismic site

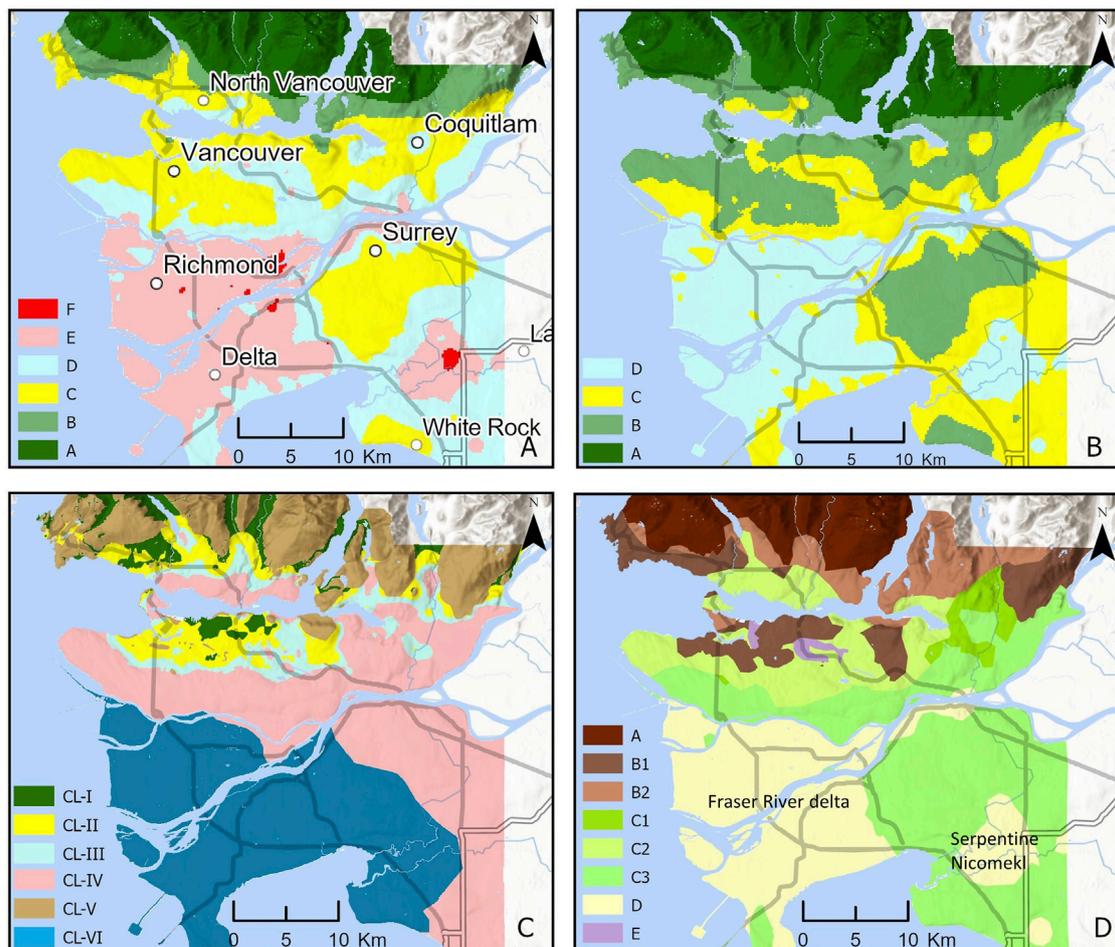
TABLE 1 Average and one standard deviation (SD) of  $V_{s30}$  and  $T_0$  (inverse of  $f_{0HV}$ ) for 17 local communities in Greater Vancouver.

| City                     | Mean $V_{s30}$ (m/s) | $V_{s30}$ SD (m/s) | $V_{s30}$ count (count/km <sup>2</sup> ) | Mean $T_0$ (sec) | $T_0$ SD (sec) | $T_0$ count (count/km <sup>2</sup> ) |
|--------------------------|----------------------|--------------------|--|------------------|----------------|--------------------------------------|
| Anmore                   | 2,310                | —                  | 4 (0.12)                                 | 1.0              | 1.5            | 9 (0.28)                             |
| Belcarra                 | 971                  | —                  | 1 (0.08)                                 | 0.1              | —              | 1 (0.08)                             |
| Burnaby                  | 353                  | 218                | 26 (0.27)                                | 0.7              | 0.6            | 216 (2.23)                           |
| Coquitlam                | 301                  | 147                | 22 (0.17)                                | 0.8              | 0.7            | 124 (0.96)                           |
| Delta                    | 200                  | 98                 | 218 (0.56)                               | 3.2              | 1.2            | 211 (0.54)                           |
| Electoral Area A         | 407                  | 18                 | 4 (0.05)                                 | 1.3              | 0.7            | 81 (1.01)                            |
| New Westminster          | 188                  | 52                 | 15 (0.82)                                | 1.3              | 0.5            | 37 (2.02)                            |
| North Vancouver City     | 280                  | 161                | 6 (0.35)                                 | 0.8              | 0.4            | 30 (1.77)                            |
| North Vancouver District | 331                  | 108                | 26 (0.15)                                | 0.6              | 0.7            | 118 (0.67)                           |
| Port Coquitlam           | 275                  | 134                | 10 (0.29)                                | 1.0              | 0.6            | 45 (1.30)                            |
| Port Moody               | 269                  | 75                 | 2 (0.06)                                 | 0.6              | 0.3            | 34 (1.04)                            |
| Richmond                 | 168                  | 19                 | 293 (1.10)                               | 3.1              | 1.5            | 357 (1.35)                           |
| Surrey                   | 224                  | 136                | 87 (0.24)                                | 2.3              | 1.2            | 317 (0.87)                           |
| Tsawwassen First Nation  | 161                  | 8                  | 4 (0.32)                                 | 2.5              | 1.2            | 25 (2.00)                            |
| Vancouver                | 334                  | 196                | 141 (1.03)                               | 0.8              | 0.8            | 683 (4.98)                           |
| West Vancouver           | 1,071                | 104                | 18 (0.18)                                | 0.4              | 0.8            | 81 (0.81)                            |
| White Rock               | 526                  | -                  | 1 (0.07)                                 | 1.7              | 1.2            | 12 (0.84)                            |

characterization parameters ( $V_{sav}$ ,  $T_0$ ,  $h$ ) to develop and compare various site classification maps for Greater Vancouver. The  $V_{s30}$ -based seismic site designation of the 2020 NBCC (CCBFC and NRCAN, 2022) (Supplementary Table S1 in the electronic supplement) defines six site classes based on  $V_{s30}$  ranging from  $>1,500$  m/s (class A) to  $\leq 140$  m/s (class F). Similarly, Eurocode 8 (CEN, 2004; 2021) has four classifications based on  $V_{s30}$  ranges (Supplementary Table S2 in the electronic supplement) that span from  $>800$  m/s (class A) to  $<180$  m/s (class D). The site classification scheme of Di Alessandro et al. (2012) defines seven classes based on site period ranges that span  $<0.2$  s (class I) to  $\geq 0.6$  s (class IV) with higher classes V–VII corresponding to HVSR amplification spectra morphology (e.g., flat HVSR and multiple peaks). In the Di Alessandro et al. (2012) classification scheme, the flat MHVSR response of rock and rock-like conditions of the North Shore corresponds to class V, and the double peak MHVSR response in the Fraser River Delta (Sirohey, 2022) corresponds to class VI. Finally, we utilize a hybrid seismic site classification scheme ( $V_{sav}$ ,  $T_0$ , and  $h$ ) proposed for revisions to Eurocode 8 by Ptilakis et al. (2019) (Supplementary Table S4 in the electronic supplement). The  $V_{sav}$  and  $h$  spatial datasets are calculated from the  $V_s$  profile (Figure 2A) and total (post-glacial and glacial) sediment thickness (from over 10,000 lithology logs, not shown), respectively. We have not compiled and calculated the average of other soil properties for the upper 30 m (e.g.,  $N_{60}$  and  $s_u$ ). Therefore, we do not assign a seismic site class according to the other soil properties in this study. In addition, we are unable to incorporate classifications that are based on information other than the seismic

site term parameters used in this study [i.e., Eurocode 8 class E and class X from Ptilakis et al. (2019) are ignored].

Figure 4 shows seismic microzonation maps for the four selected seismic site classification schemes, and an interpolation of the site classification data points is achieved using empirical Bayesian kriging. Table 2 reports the percentage of the area assigned by each site class in terms of the Greater Vancouver region's area, which is further sub-divided in terms of each simplified geology unit's area (outcropping rock, glacial or post-glacial sediments; see Figure 2). When the 2020 NBCC site classification based on  $V_{s30}$  is used (Figure 4A), classes A and B are only found in Greater Vancouver's higher elevation rock and thin soil over rock zones in the North Shore, which covers ~24% of the region (Table 2). Class C relates to the upland portions of Vancouver, Burnaby, Surrey, and White Rock that have been glacially overridden and covered with glacial debris, as well as the transition from class B at a higher elevation to the shoreline (e.g., the southern North Shore). Site class D regions typically consist of sites at a lower elevation with tens of meters of deep post-glacial sediments. However, they also cover a larger area than anticipated in Surrey, Burnaby, and Vancouver. The majority of Greater Vancouver corresponds to classes C (26%) and D (26%) (Table 2). Class E (23% of Greater Vancouver, Table 2) is generally confined to the Fraser River Delta and Serpentine–Nicomekl valley lowlands, where  $V_s$  is lowest. Site class F is present in only 1% of the region (Table 2) as small patches in Richmond, Delta, and the Serpentine–Nicomekl valley. The dominance of harder site classes A and B corresponds to outcropping rock geology areas of the



**FIGURE 4**

Spatial distribution of seismic site class based on  $V_{s30}$  in the (A) 2020 NBCC, (B) Eurocode 8, (C) site period, and (D) a hybrid site classification proposed in revisions to Eurocode 8.

North Shore, classes C and D correspond dominantly to glaciated geology upland areas, and classes E–F dominate post-glacial geology present at shorelines and in the Fraser River Delta lowlands (Table 2). We note that a significant percentage of classes B and D also occurs in glacial and post-glacial geology areas, respectively.

Figure 4B shows the  $V_{s30}$ -based seismic site classification of Greater Vancouver according to Eurocode 8. Overall, this is very similar in zonation to the  $V_{s30}$ -based classification of the 2020 NBCC (Figure 4A) but with different  $V_{s30}$  ranges (see Supplementary Tables S1, S2) and, thereby, a general one classification shift higher. Class A rock conditions occupy 21% of Greater Vancouver, constrained to the North Shore, according to the Eurocode 8 classification scheme (Table 2). Eurocode 8 site classes B and C dominate the Greater Vancouver area, encompassing 28% and 27% of the region, respectively (Table 2). The softest Eurocode 8 site class D covers 24% of Greater Vancouver. Overall, the wider  $V_{s30}$  scale of the 2020 NBC classification (Figure 4A) is more appropriate than the Eurocode 8's  $V_{s30}$  scale for the end-member site condition variance in Greater Vancouver (from soft post-glacial sediments to outcropping glaciated hard rocks).

Figure 4C displays the seismic site classification of Greater Vancouver based on the predominant site period determined from microtremor average horizontal-to-vertical spectral ratios. This site period classification scheme apparently results in a different seismic microzonation pattern compared to  $V_{s30}$  (Figures 4A, B). The site period is controlled by  $V_{sav}$  and  $h$ . Class V (flat HVSR) is assigned to only outcropping rock areas and encompasses 17% of the region (Table 2). Short-period classes I (<0.2 s) and II (0.2–0.39 s) occur predominately in glaciated geology areas, in the transition zone between North Short outcropping rocks and the shoreline, as well as in northern Vancouver and Burnaby, where rock is relatively shallow yet comprises only 12% of Greater Vancouver. Long-period class IV ( $\geq 0.6$  s) and multiple peak class VI dominate the region (65%). Class IV is dominated by glacial geology in southern Vancouver and Burnaby, as well as Surrey, where these stiff glacial sediments are thick. In general, the site periods of the Fraser River Delta lowlands are significantly long ( $>2$  s, Figure 2B) and may require the addition of a new site class category(ies). Di Alessandro et al.'s (2012) addition of class VI (multiple peaks) is applicable to a significant area of Greater Vancouver (32%), where two peak frequencies are observed in MHVSRs due to the shallower

**TABLE 2 Percentage (%) of each site class's area within the Greater Vancouver region and its percentage (%) in terms of simplified geology unit [outcropping rock (R), glacial (G), and post-glacial (PG) sediments, as shown in Figure 2].**

| Class                       | Region | R  | G  | PG | Class                    | Region | R   | G   | PG  |
|-----------------------------|--------|----|----|----|--------------------------|--------|-----|-----|-----|
| NBCC 2020                   |        |    |    |    | Eurocode 8               |        |     |     |     |
| A                           | 16     | 11 | 3  | 2  | A                        | 21     | 14  | 5   | 2   |
| B                           | 8      | 4  | 3  | 1  | B                        | 28     | 3   | 23  | 2   |
| C                           | 26     | 2  | 22 | 2  | C                        | 27     | 0   | 16  | 11  |
| D                           | 26     | 0  | 16 | 10 | D                        | 24     | 0   | 2   | 22  |
| E                           | 23     | 0  | 2  | 21 | E                        | —      | —   | —   | —   |
| F                           | 1      | 0  | 0  | 1  | Pitilakis et al. (2019a) |        |     |     |     |
| Di Alessandro et al. (2012) |        |    |    |    | A                        | 12     | 9   | 2   | 1   |
| CL-I                        | 5      | 0  | 3  | 2  | B1                       | 9      | 4   | 4   | 1   |
| CL-II                       | 7      | 0  | 6  | 1  | B2                       | 7      | 4   | 2.5 | 0.5 |
| CL-III                      | 6      | 0  | 5  | 1  | C1                       | 3      | 0.5 | 2   | 0.5 |
| CL-IV                       | 33     | 0  | 23 | 10 | C2                       | 11     | 0   | 9   | 2   |
| CL-V                        | 17     | 17 | 0  | 0  | C3                       | 32     | 0   | 23  | 9   |
| CL-VI                       | 32     | 0  | 8  | 24 | D                        | 25     | 0   | 2   | 23  |
| CL-VII                      | —      | —  | —  | —  | E                        | 1      | 0   | 0.5 | 0.5 |

post-glacial and glacial impedance contrast and the deeper glacial and Georgia basin rock impedance contrast.

Figure 4D displays the application of the hybrid-based site classification scheme (Pitilakis et al., 2019) using  $V_{sav}$ ,  $T_0$ , and  $h$ . Again, a different seismic microzonation map pattern is apparent, but there are similarities in select areas with zonation patterns based solely on  $V_{s30}$  or site period classification (i.e., hybridization). Higher site classes (A–C1) constrained to the northern study area are consistent with thinner sediment thicknesses (shallower depth to rock). Classes B1 and B2 occur in transition zones from classes A to C1-3 in the North Shore and in northern Vancouver and Burnaby, dominated by shallow rock and glacial geology. Overall, the need for these two classifications (zones) also occurs in  $V_{s30}$  and site period metrics (Figures 4A, B). Classes C2 and C3 occur primarily in glacial geology areas in southern Vancouver and Burnaby, as well as Surrey. The division of these two classes is not controlled by  $V_{sav}$  (200–450 m/s) but by site period (shorter than 1.5 and 1.8 s, respectively) and  $h$  (20–60 m and >60 m, respectively). Overall, these hybrid classes (C2 and C3) are beneficial in subdividing the longer site period class IV area (compared to Figure 4C). The Fraser River Delta (Richmond and Delta) and Serpentine–Nicomekl valley (between Surrey and White Rock) lowlands correspond to class D. This relatively homogeneous classification (one zone; Figures 4C, D) is likely appropriate, although we are used to the two  $V_{s30}$ -based classifications (Figures 4A, B) simply because the  $V_{s30}$  of Fraser River Delta sediments is close to the 2020 NBC DE class boundary of 180 m/s (microzonation does not need two zones). Classes C1 (thick stiff sediments) and E (thin, soft sediments) are constrained to zones in northeastern Greater Vancouver (4% of the region, Table 2) that are

not apparent from only  $V_{s30}$  and site period classifications. This highlights the benefit of a hybrid site classification scheme to further subdivide zones based on stiffness and  $h$  (useful to differentiate thin and thick zones of both soft and stiff sediments).

## 5 Conclusion

A seismic microzonation study is underway for 16 municipalities, lands of 6 First Nations, and 1 Electoral Area in western Metro Vancouver. A comprehensive regional geodatabase has been compiled to achieve Metro Vancouver seismic microzonation mapping. This comprehensive geodatabase of *in situ* site characterization datasets has been compiled from *in situ* invasive logging and penetration methods from various public and classified data sources supplemented by abundant multi-method non-invasive seismic field data collection across the region. Seismic site characterization measures, such as  $V_s$  depth profiles,  $f_{OHV}$ , and borehole lithology, are compiled in the regional geodatabase from which key seismic site term parameters ( $V_{sav}$ ,  $V_{s30}$ ,  $T_0$ , and  $h$ ) can be determined. In this study, 810  $V_{s30}$  values are determined from *in situ*  $V_s$  depth profiles and the conversion of CPT logs to  $V_s$  profiles via a region-specific empirical relation. Over 2,200  $T_0$  values are determined from the lowest peak frequency of microtremor horizontal-to-vertical spectral ratio curves. We evaluated the average and one standard deviation variation of  $V_{s30}$  and  $T_0$  for 17 local communities in Greater Vancouver to explore sub-regional differences in these seismic site term parameters. In northern Greater Vancouver, Pre-Tertiary Coast Mountain rocks are outcropping at the highest elevations and correspond to the highest  $V_{s30}$  (>1,500 m/s) and shortest site periods (<0.2 s). In contrast, the lowest  $V_{s30}$  and longest site periods are an average of 180 m/s and 3.1 s, respectively, in the Fraser River Delta and Serpentine–Nicomekl valley lowlands.

Subsequently, we applied four site classification schemes based on  $V_{s30}$ ,  $T_0$ , or a hybrid combination of seismic site characterization measures ( $V_{sav}$ ,  $T_0$ , and  $h$ ) to evaluate each scheme's impact on communicating the region's seismic site characterization. We found that both  $V_{s30}$ -based seismic site classification schemes, 2020 NBCC and Eurocode 8, result in a similar classification pattern (microzonation), but there is an overall shift to a higher site class when applying Eurocode 8. The 2020 NBC classification's wider  $V_{s30}$  scale is more appropriate for the end-member site condition variance in Greater Vancouver. We found that a site-period-based classification results in a different zonation pattern compared to  $V_{s30}$ . Our use of the site-period and amplification spectra classification scheme of Di Alessandro et al. (2012) with seven classes is beneficial to subdivide long-period sites (>0.6 s, class IV) with a single resonance peak from those with a second resonance peak (multi-peak, class VI), particularly in the Fraser River Delta lowlands. This could also be achieved by modifying or adding a new class to the Di Alessandro et al. (2012) scheme to differentiate the very long site periods of the Fraser River Delta lowlands (>2 s) (i.e., site periods are much longer than 0.6 s in Greater Vancouver). Finally, when a hybrid site classification scheme is used to perform seismic microzonation mapping, a different classification pattern is apparent but with similarities in select areas to mapping based solely on  $V_{s30}$  or site period classification.

Regardless of the classification scheme, we found that outcropping rock areas are equally well-identified on the North Shore, and such classification corresponds to ~20% of the Greater Vancouver region. The transition from outcropping rock to lowland areas is also consistently mapped into two classifications or zones by either  $V_{S30}$  or  $T_0$ . This results from classification schemes with four or more classes; however, it indicates that this discretization of classes is necessary to capture rapid variation in underlying seismic site conditions. The use of a hybrid site classification scheme with seven classes aids in subdividing glacial geology with different thicknesses and, thereby, site periods and glacial and post-glacial sediments that are thick and thin, respectively. The single site term parameter classification schemes ( $V_{S30}$  or  $T_0$ ) encapsulate these three cases into one class;  $V_{S30}$  cannot differentiate between these cases, and the four classes defined by site period ranges are too coarse. We also conclude that site period and hybrid classification schemes that categorize the Fraser River Delta lowlands as a single zone are more appropriate than a  $V_{S30}$ -based classification scheme with a class boundary serendipitously at the average  $V_{S30}$  of the Fraser River Delta lowlands (~180 m/s). This study provides a thorough understanding of seismic site characteristics in Greater Vancouver from the evaluation of seismic microzonation maps based on  $V_{S30}$ , site period, or hybrid-based seismic site classification approaches. We conclude that, at a minimum, the 2020 NBCC  $V_{S30}$  and site period maps together or the hybrid classification map needs to be produced to fully communicate the variability and range of local seismic site conditions in the region and, thereby, the susceptibility to seismic hazard shaking. Although the generation and comparison of all three maps provided benefit to understanding local seismic site conditions in this study, the minimum number of maps to effectively communicate seismic hazards inclusive of local site effects to technical and non-technical end users is sought.

## Data availability statement

Datasets that support the findings of this study will be made available through the Metro Vancouver Seismic Microzonation Project website at <https://metrovanmicromap.ca>. Requests to access the datasets should be directed to SM, [smolnar8@uwo.ca](mailto:smolnar8@uwo.ca).

## Author contributions

SA: conceptualization, writing—original draft, investigation, software, and data curation. SM: conceptualization, writing—review and editing, and resources. JW: review and editing. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2023.1221234/full#supplementary-material>

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