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Metro Vancouver Landslide Hazard Mapping

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ABSTRACT

The methodology to obtain the first probabilistic seismic landslide hazard mapping for Metro Vancouver is presented. Newmark's sliding block analogy is adopted to calculate seismic sliding displacement (D) values for slopes. Seismic hazard source zones and their reoccurrence parameters will be calculated based on the 6th generation national seismic hazard model (2020 National Building Code of Canada) to derive probabilistic displacement values for slopes at 2% and 10% probability of exceedance in 50 years risk levels based on probabilistic seismic hazard analysis (PSHA). This paper presents probabilistic seismic landslide hazard mapping based on the 5th generation national seismic hazard model (2015 building code). Slope identification and geometrical properties (slope angle, height) are determined in a novel semi-automated manner using a LiDAR-based digital elevation model (1 m elevation contours) for the Greater Vancouver area. Identified slopes are divided into multiple polygons based on slope curvature and assigned the corresponding mapped surficial geology unit. 2D limit equilibrium slope stability models are developed to estimate the yield acceleration (k_y) values for every slope polygon based on the geometry and geology unit information contained in every polygon. Considering the probabilistic seismic hazard in the region and the developed k_y map, probabilistic D values are determined for slopes units from which the first probabilistic landslide maps for the region are generated at both 2% and 10% probability of exceedance in 50 years risk levels. The developed seismic landslide maps demonstrate that Capilano sediments in Surrey and North Vancouver have the highest landslide hazard level with some slope areas observed to have high and very high hazard category at the 2% probability of exceedance in 50 years risk level. Although the plutonic Coast Mountains form steep slopes in northwestern Greater Vancouver, performed analysis demonstrates a low seismic landslide hazard level for identified slope units.

Keywords: Greater Vancouver, seismic landslide, Newmark analogy, slopes, probabilistic displacement

INTRODUCTION

In the last 150 years, over 600 people in Canada have lost their lives to landslides and the west coast province of British Columbia (BC) has experienced the most landslide-related fatalities considering its mountainous terrain and unique physiography ([1]). Earthquake-induced landslides are of particular interest for the Lower Mainland of southwestern BC. The 1946 magnitude (M) 7.3 central Vancouver Island earthquake, triggered more than 300 landslides over an area of about 20,000 km^2 ([2]), and the 2001 M 6.8 Nisqually, Washington, inslab earthquake (52 km depth) caused more than $34.3 million USD of landside damage [3]. Specific to seismic-induced landslides, there have been no recorded deaths within BC in the past century; although a rockfall related to the 1946 Vancouver Island earthquake caused a large wave in Lake Name leading to a casualty from a cap-sized boat [4]. With increasing population and the expansion of communities into and onto more mountainous terrain, the risk, in contrast to the hazard, is increasing.

A minimal degree of seismic landslide mapping for the Metro Vancouver region has been accomplished to date. The Geological Survey of Canada (GSC) depicted earthquake shaking, liquefaction, and landslide hazards in their GeoMap Vancouver poster [8]. This poster product depicts crude landslide hazard highlighting areas where slope angles are > 20° and shading circular zones where rain-induced slope failures had occurred within the 20th-century. A landslide susceptibility map was produced by the GSC for the District of North Vancouver [9] as part of a multi-hazard risk assessment for the selected region. However, a comprehensive seismic landslide hazard map for Metro Vancouver based on potential earthquake loading is currently not available and the mentioned maps do not include the intensity of ground motions from the various earthquake sources in the region.

Nowadays, engineering approaches for regional landslide mapping (i.e. physically-based numerical modeling) with the application of slope stability analyses have been intensively conducted (e.g.,[10]). In the engineering approach, regional landslide maps are commonly based on Newmark's analogy to estimate rigid sliding block displacements (e.g.,[11]) where the region seismic hazard is incorporated in assessments through intensity measures (IMs, e.g., peak ground acceleration, PGA). Newmark's sliding block method assumes that the soil mass within the failure zone behaves as a rigid block, which may slide on the inclined plane. The block has a yield or critical acceleration (k_y), defined as the acceleration required to overcome basal resistance and initiate sliding. Stemming from the rigid sliding block analogy of Newmark, several seismic displacement prediction models (SDPMs) are available in the literature (e.g., [12,13]). These SDPMs estimate the slope's seismic displacement considering flexibility of the sliding mass (i.e., depth of failure included in f_s) and are based predominantly on western North American earthquake ground motions. The SDPMs use ground motion IMs, k_y, and the predominant frequency of the sliding mass (f_s) to predict the seismic displacement (D) of slopes. SDPMs predictions have been commonly adopted to develop seismic landslide maps and predict the locations of earthquake-triggered landslides in different regions (e.g., [10]).

In the current study, the probabilistic solution of Newmark's sliding block analogy presented in Yeznabad et al. [14] and the simplified predictive regression models developed by Yeznabad et al. [15] are employed to determine the probabilistic displacement values for slopes with different k_y and f_s values across the southern Lower Mainland. To specify suitable k_y and f_s values for slope units, the geometrical and strength characteristics are needed. Therefore, geologic, topographic, and geotechnical datasets are compiled and evaluated to constrain k_y and f_s values. High-resolution surface topography is used to generate mapped slope units which are semi-automated user-defined polygons constructed for sloping ground to capture the slope angle and height values. The geotechnical and geologic information is used to determine stratigraphy, shear strength parameters, and depth to groundwater for slopes in different geological units across the region. The compiled slope geometries and material properties are utilized to perform multiple two-dimensional (2D) limit equilibrium analyses. The 2D limit equilibrium analyses ensure the static stability of slopes and determine k_y and f_s values based on failure characteristics of the various slopes investigated. Probabilistically calculated displacements are assigned to corresponding slope units depending on their location (i.e., input ground motion and site class) and slope-specific properties (k_y and f_s). The determined probabilistic seismic slope displacements are converted to landslide hazard categories to achieve regional seismic landslide hazard mapping for western Metro Vancouver. The developed seismic landslide maps delineate slope areas coloured according to their probabilistic seismic sliding displacement hazard category at a 2% and 10% probability of exceedance (PE) in 50 years risk level based on the 5th generation national seismic hazard model (2015 National Building Code of Canada, NBCC). Efforts are ongoing to update the probabilistic landslide hazard mapping based on the 6th generation national hazard model (2020 NBCC) consistent with other probabilistic seismic microzonation maps of the Metro Vancouver seismic microzonation mapping project (https://metrovanmicromap.ca, Molnar et al.[16])

Probabilistic solution for seismic sliding displacements of slopes in the southern Lower Mainland of BC

The existing approaches to estimate D values can be classified as 1) deterministic 2) pseudo-probabilistic, and 3) probabilistic approaches [17]. In a deterministic approach, only a limited number of earthquake scenarios (Magnitude (M), source to site distance (R)) is considered. On the other hand, a pseudo-probabilistic approach accounts for the uncertainty of GMs ($\varepsilon_{\mathrm{GM}}$) through PSHA, however, SDPMs' uncertainty (ε_{D}) is ignored. Nonetheless, the displacement in the probabilistic approach is calculated by accounting for uncertainties in D predictions and earthquake ground motions by considering all possible earthquake scenarios. This method employs the full GM hazard curve and different SDPMs with their variabilities (i.e., both of $\varepsilon_{\mathrm{GM}}$ and ε_{D}) to perform a probabilistic sliding displacement analysis. The outcome of a probabilistic approach is a displacement hazard curve, which provides the annual rate of exceedance, λ_{D}, for the desired level of D. The probabilistic approach for calculating D rationally remedies the shortcomings of deterministic and pseudo-probabilistic approaches. However, it is computationally demanding and has been thus far applied only in certain regions such as Southern California [7].For the Metro Vancouver region, Yeznabad et al. [14,15] has investigated the probabilistic solution of seismic sliding displacements and it will be implemented in this study for regional mapping of seismic landslides in Metro Vancouver.

Three earthquake source types contribute to the seismic hazard in the Metro Vancouver region: (1) shallow crustal earthquakes of the continental North American plate, (2) deeper inslab earthquakes of the subducting oceanic Juan de Fuca plate, and (3) subduction interface earthquakes of the Cascadia subduction zone's thrust fault off the west coast of Vancouver Island. The resulting ground motion parameters (e.g., PGA) from these earthquake sources are adopted by SDPMs to calculate the probabilistic displacement hazard curves for different slopes in the area. Different SDPMs were previously reviewed and the probabilistic solution for the seismic displacement of slopes in Metro Vancouver was provided [14,15] using Bray and Macedo's (BM) updated SDPM for the combined effect of crustal and inslab events (crustal_inslab) [18] and Bray et al.'s (BMT) SDPM for interface events [12], respectively. The recent update of SDPMs is presented in Bray and Macedo [19] where separate SDPMs are offered for interface and inslab events. These SDPMs are developed based on enlarged earthquake databases and are following local guidelines of Metro Vancouver [20,21] concerning seismic landslide assessments. The same model parameters are involved in both SDPMs regardless of earthquake source type: the slope's k_y, sliding mass's initial (fundamental) frequency (f_s), earthquake magnitude (M), and the ground motion's spectral acceleration (SA) at a degraded frequency of sliding mass. Considering adopted SDPMs, Yeznabad et al. [14] calculates the mean annual rate of sliding displacement (D) exceedance for a given threshold level:

$$\lambda_{D,Total} = \lambda_{D,crustal\_inslab} + \lambda_{D,interface}. \quad (1)$$

where λ_D is the mean annual rate of sliding displacement (D) exceedance for a given threshold level (x). Based on equation 1, the total mean annual rate of exceedance for a specific level of sliding displacement ($\lambda_{D,Total}$) will be the sum of the mean annual rate of exceedances for combined crustal_inslab events ($\lambda_{D,crustal\_inslab}$) and interface events ($\lambda_{D,interface}$). The $\lambda_{D,Total}$ values and its variation in Greater Vancouver is investigated in Yeznabad et al. [15]. Herein, in consistence with NBCC, 2% PE in 50 years hazard level will be adopted to evaluate the probabilistic D values in the Lower Mainland. Correspondingly, D denotes the probabilistic seismic displacement of slopes for 2% PE in 50 years hazard level. To obtain D values across Metro Vancouver in a computationally-efficient manner, a regression model was adopted from Yeznabad et al. [15] which directly predicts D values only based on location, k_y, and f_s values of a slope without the need to perform PSHA and displacement calculations. This regression model was established based on the D values of ten different sites in the southwest of BC considering a wide range of k_y values, soil profiles covering different site classes (i.e., classes A-E), and different natural frequencies of sliding mass (i.e., f_s=0.3, 0.75, 1.5, 3, 5, 7.5, 15, 30 Hz and PGA for rigid block). In this predictive model D value for a site of interest in Metro Vancouver is obtained by

$$D = X_1 \exp(X_2\, k_y) + X_3 \exp(X_4\, k_y) \quad (2)$$

where X_1 to X_4 are the model constants for the desired level of k_y and can be calculated based on the location of the slope with the following equation

$$X_i = a_i + b_i(R_x) + c_i(R_y) \quad (3)$$

a_i, b_i, and c_i are regression coefficients and R_x and R_y are longitudinal (R_x) and latitudinal (R_y) distances from the reference site in the southwest end of Greater Vancouver (i.e., Tsawwassen, 49.002°N, 123.09°W). The coefficients a, b and c in Equation 3 can be obtained based on f_s and site class of a slope unit (from [22]) and will be used to obtain X_i coefficients of Equation 2. Having Equation 2 and k_y value for a slope unit across the Metro Vancouver, the probabilistic based D value for 2% PE in 50 years hazard level can be determined efficiently, which is of significant advantage for mapping purposes. Having D values for every slope polygon, corresponding hazard level can be assigned based on available guidelines for displacement levels in the literature. This study adopts the displacement categories recommended in Table 1. The D values presented in Table 1 are mainly used for shallow failures mapping [23] and can be conservative for deeper failures. In absence of exclusive threshold values for deep failures, Table 1 is used for both shallow and deep failures. Based on the adopted threshold values for D shown in Table 5-1, the D values in the range of 0-15 cm will have low to high hazard levels and a slope with D >15 cm will have a very high seismic landslide hazard level.

Table 1. Adopted landslide hazard categories implemented in this study [23].

Hazard category	Sliding displacement (cm)
Low	0-1
Moderate	1-5
High	5-15
Very high	>15

Seismic landslide mapping methodology

Figure 1 illustrates the proposed framework to determine k_y values and compute probabilistic D for slopes within the region considering probabilistic seismic loading at 2% and 10% PE in 50 years hazard levels. Surface topography and compiled geology and geotechnical information are integrated to constrain k_y and f_s for regional slopes (part A in Figure 1); k_y and f_s are characteristics of stabilizing factors against seismic landslide failure in Newmark's analogy. The probabilistic framework discussed in section 2.1 (see part B in Figure 1) considers the probable seismic hazard and ground motion IMs as the destabilizing factor to determine D for k_y values of interest. Within that probabilistic framework, the k_y values and ground motion IMs are input to the BM and BMT SDPMs to compute D levels and later to obtain the seismic landslide hazard level.

To evaluate the stability of sloping grounds and estimate the k_y value for polygons (Figure 1-A), surficial and Quaternary geologic mapping for western Metro Vancouver [24–26] is utilized in this study. Major geologic units include: Capilano (C) sediments (divided into five sub-units Ca to Ce), combined Vashon drift and Capilano sediments sub-units (VCa, VCb), Vashon drift (Va, Vb), and Pre-Vashon deposits (eight sub-units PVa -h, and UPV). Geologic bedrock is divided into two simple categories in this study: Tertiary (T) rocks including Late-Cretaceous and younger sedimentary rocks of the Georgia basin and Pre-Tertiary (PT) rocks including Coast Mountain and Cascade rocks to the north and south respectively. For the scope of this work, the formations were sorted into 8 geologic groups as listed in Table 2 with their descriptions. Ca and Cb units and V and PV units are considered a single unit for the purpose of the current work based on geological similarity and availability of geodata for these units. Further separating the present geologic units into other sub-units would require a more detailed geotechnical knowledge for each sub-unit, which in some cases is not available.

In regional seismic landslide assessment based on slopes' displacement, the study area is commonly divided into a raster grid and each grid cell/pixel is assumed as a rigid block to compute each portion of the slope raster's yield acceleration based on the infinite slope model (e.g., [10]). The assumption of an infinite slope limits the regional assessment to shallow types of slope failures and neglects the slope geometry (e.g., the slope height is not considered). Additionally, the performed analysis will be considerably affected by the size of pixels. Moreover, a rational estimate of the slope height (difference in elevation from slope crest and toe in meters) cannot be provided using the pixel approach since automated rasterization produces pixels that are located with no concern for the toe and crest of slopes. Therefore, in the current study, the rasterization of the topography is avoided and high-resolution topographic data for Metro Vancouver are adopted to construct accurate semi-automated slope polygons. The novel semi-automated method is developed to generate slope polygons that adhere to the high-resolution elevation contours (not a grid cell or pixel), and within each polygon the slope terrain characteristics are homogeneous. In this approach, high-resolution LiDAR imaged topographic data for Metro Vancouver are transformed into high-resolution elevation 1-m contoured (e.g., Figure 2a) datasets. Later, the slope polygons are developed considering the topographic features and following the geometry of ravines and cliffs. For every polygon the angle and height values for the detected sections in the ravines and cliffs are calculated from digital elevation model (DEM) and are used to assign the slope height (H) and angle (α) values to the incorporating polygon as a slope unit (Figure 2d). As shown in part A of Figure 1, the resultant angle and height values for every slope polygon along with ground water table (GWT) levels are the geometrical information that is required with the shear strength parameters to calculate k_y values.

For the required GWT map, more than 4000 static GWT recordings available on the official website of Government of BC [27] and about 500 GWT records available in compiled local geotechnical reports are adopted. The resultant points have been interpolated using the Empirical Bayesian kriging to obtain the GWT depth for slope units. DEM is also considered as an explanatory variable raster in correlation with GWT for better predictions in hilly regions. Having geometrical information (i.e., slope angle, height and GWT) for every slope unit, to calculate the factor of safety in static condition (FS) and k_y for seismic assessments, we will need to have shear strength parameters for soil layers with every polygon.

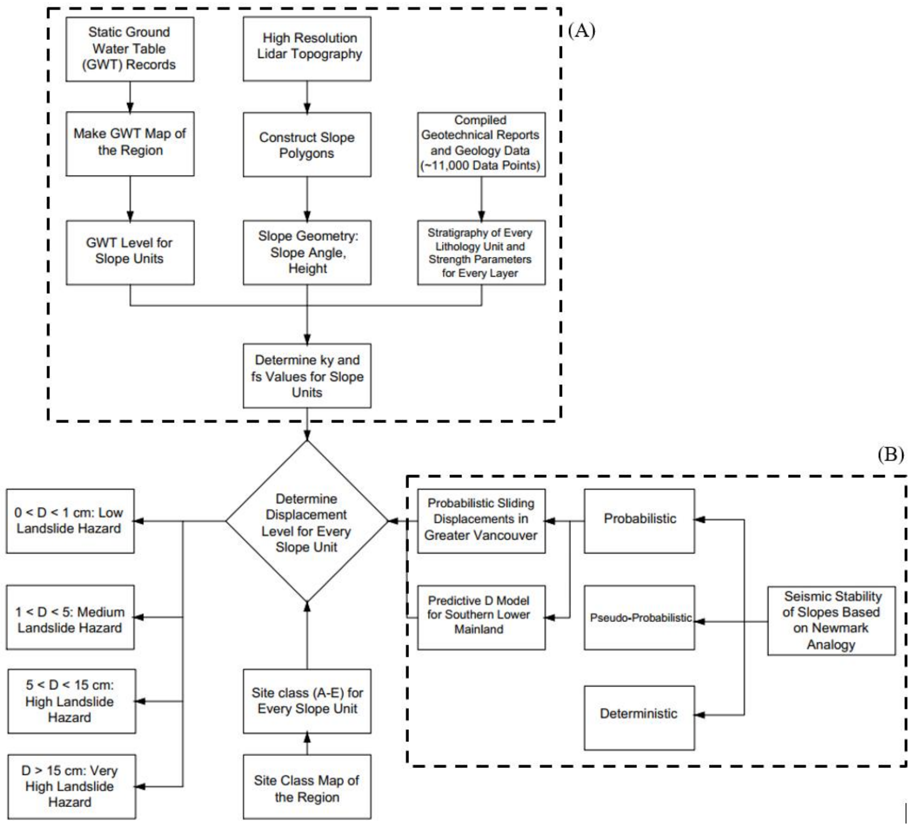

Figure 1: Framework for predicting probabilistic displacements and landslide hazard for western Metro Vancouver slopes. Box A includes calculation of k_y and f_s (stabilizing characteristics) based on slope geometry. Box B includes regional probabilistic seismic hazard ground motions (destabilizing factor) to predict D levels at either 2% or 10% PE in 50 years.

2D slope stability modelling with data-driven shear strength parameters to determine the static factor of safety and k_y

Assessing shear strength parameters is admittedly a subjective process [28,29]; however, several sources of data (e.g., different geotechnical field measurements) and approaches (e.g., different empirical equations to process the data) are adopted to provide reasonably consistent results. In this study, a comprehensive geodatabase is compiled from local practicing engineers and regulatory communities and consists of 194 Standard Penetration Tests (SPT) and 40 Cone Penetration Tests (CPT) measurements along with two reports with documented shear strength measured values. Moreover, the shear strength values assigned for geologic units in Seattle, Washington [30,31] were used as a supplementary source due to significant geological similarity with western Metro Vancouver is listed in Table 2 per geology unit. To obtain shear strength parameters, the CPT measurements are processed using CPeT-IT software. Further, SPT measurements are sorted based on their corresponding geology unit and are processed using NOVO-SPT software to obtain soil shear strength parameters. The resulting shear strength values from SPT and CPT measurements are averaged and assigned to geological units based on two criteria: stratigraphic information of geological units (from Geology maps) and bore log readings of field measurements need to match and that the 2D limit equilibrium slope models need to retain static stability for slopes in the region. For stratigraphic specifications of geological units, the descriptions provided in regional geology maps and geological information for the Metro Vancouver region offer four generic stratigraphic profiles for the sloping grounds in the region: (1) the Capilano sediments (Ca-e) overlaying V/PV and PT/T bedrock, respectively; (2) the Vashon Capilano (VC) sediments overlaying V/PV and PT/T bedrock, respectively; (3) V/PV sediments overlying PT/T bedrock, and finally (4) PT/T (bedrock exposure). The thickness of the top surficial layers (e.g., the thickness of Cd over V/PV)) varies across the region and the adopted thickness levels herein (shown in Table 2) are the highest values reported in geologic documentation that can lead to conservative estimation of FS and k_y values.

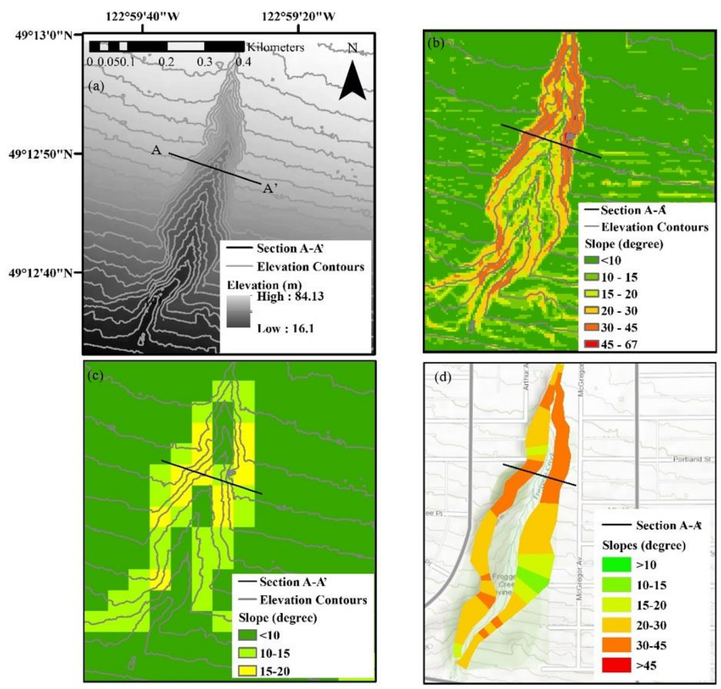

Figure 2. (a) Elevation data and contours (10 m interval) for a sample ravine in south Burnaby. Automatically generated raster of slopes with pixel size of (b) 5 m, and (c) 50 m. (d) Semi-automated slope units generated in this study to capture slope geometry values.

For shear strength parameters, in the initial iteration of the 2D limit equilibrium models, the average shear strengths from SPT, CPT and geotechnical reports are assigned. The strengths values are then adjusted where needed based on reported values from Seattle [30,31] to preserve the documented differences in strengths between units. The last constraint on assigning shear strengths to geologic units is the static stability of the 2D slope models, which simply means that the slope parameters are updated (if necessary) to ensure the slope is not moving before the shaking occurs. To maintain the static stability for every H-GWT group while avoiding increasing shear strength values beyond realistic levels, as suggested by Jibson et al. [28], the shear strength values of the statically unstable units are increased incrementally until all slopes less than 60 degrees are statically stable. A minimal factor of safety of 1.01, barely above equilibrium, was assigned for the unstable slope units steeper than 60°. Table 2 reports shear strength values assigned to the geologic units.

To estimate the FS and k_y values, having stratigraphy and shear strength parameters, sets of 2D numerical slope stability modeling are developed based on limit equilibrium method and adopting Spencer procedure in Slide software. For every slope unit in a specific geological unit, there will be fixed stratigraphy and shear strength parameters (Table 2), and α, H, and GWT depth as geometrical variables. For the geometrical variables, 6 different H and GWT levels per geology unit (listed in Table 3) are used to group the slope units in the region and evaluate FS and k_y values in a computationally affordable manner. By adopting this strategy, there will be a maximum of 36 groups of H and GWT values for every geology unit with varying slope angles (α) within the unit (e.g., H2GW2 means slope with 2 m height and groundwater table at 2 m).

Table 1. Geologic units adopted in this study with their stratigraphic specifications, available geotechnical measurements, and interpreted shear strength values. Shear strength parameters are denoted by c for cohesion (kPa) and φ for friction angle (degrees) for drained condition and Su (kPa) for undrained strength of cohesive soils. The predominant frequency of the sliding mass (fs) is recorded from performed 2D slope stability (limit equilibrium) analyses.

Geologic Unit		**Stratigraphy**		**Number of data points**			**Φ degrees**	**C (kPa)**	**Su (kPa)**	**f_s (Hz)**
		Description	**Thickness**	**SPT**	**CPT**	**Reported values**				
Capilano Sediments: Raised marine,	**Ca/Cb**	Raised marine and beach sediments, poorly sorted **sand to gravel**	Up to 10 m for Ca; up to 5 m for Cb	34	2	-	39	25	-	7.5 Hz for Ca; for Cb, 3 and 5 Hz are selected for H30GW2 and H20GW2

deltaic, and fluvial deposits										and 15 Hz is selected for other HGWT groups.
	Cc	Raised deltaic and channel fill, medium **sand to cobble gravel**	Up to 15 m	17	5	-	38	40	-	7.5 Hz for H20GW15, H20GW25, H30GW15 and H30GW25 groups and 5 Hz for other groups
	Cd	Marine and glaciomarine **silt loam to clay loam** with minor sand and silt	Up to 30 m (thickens west to east)	15	-	-	34	15	110	1.5 Hz for all groups except: H10GW25 groups with 5 Hz and H20GW25and H30GW0 with 3 Hz.
	Ce	Marine **silt loam to clay** loam with minor sand, silt and stony glaciomarine	Up to 60 m	4	12	-	36	20	100	1.5 Hz for all groups except: H5GW0, H10GW0 and H10GW2 with 0.75 Hz.
Vashon drift and Capilano Sediment	**VC**	Glaciomarine and marine deposits similar to **Cd**	Up to 10 m	100	17	1	36	30	100	3 Hz for all groups, except 5Hz for H10GW(2, 15) groups and 1.5 Hz for H30GW(0,2,5) groups
		Lodgement and minor flow **till**, lenses and interbeds of sub-stratified glaciofluvial sand to gravel	Up to 35 m				39	50	-	
Vashon and Pre-Vashon deposits	**V/PV**	**Till**, glacial and ice-contact deposits; glacial, nonglacial and glaciomarine sediments (for PV)	-	16	4	2	39	75	-	5 Hz for all groups, except 7.5 Hz for H30GW(10,15,25) groups
Tertiary Bedrock	**T**	Sandstone, siltstone, shale, conglomerate; the top 2 m highly weathered at some locations	2 m (weathered depth)	8	-	-	38	38	-	-
Pre-Tertiary Bedrock	**PT**	Mesozoic bedrock including granite and associated rock types	-	-	-	-	-	-		-

Table 2. Slope height (H) and ground water table (GWT) categories adopted in this study to group different slope units for each geologic unit.

Slope height level (m)	**Height group (m)**	**GWT depth (m)**	**GWT depth group (m)**
< 1	0	< 2	0
$1 \leq H \leq 2$	2	$2 \leq GWT < 5$	2
$2 < H \leq 5$	5	$5 \leq GWT < 10$	5
$5 < H \leq 10$	10	$10 \leq GWT < 15$	10

$10 < H \leq 20$	20	$15 \leq GWT < 25$	15
$H > 20$	30	$25 \leq GWT$	25

After assigning the shear strength parameters, the k_y value is computed for every slope angle value in each H-GWT group using 2D limit equilibrium models and the results are plotted to construct yield acceleration curves (examples are shown in Figure 3; see chapter 5 in ref. 53 for all k_y curves). In these plots, the horizontal axis incorporates the range of slope in a specific H-GWT group and is normalized using the following equation:

$$\alpha^* = \frac{\alpha - \alpha_{min}}{\alpha_{max} - \alpha_{min}} \quad (4)$$

where α_{max} and α_{min} are the maximum and minimum slope values in a certain H-GWT group and α is the adopted value for the 2D modeling. In 2D models, normally at least three different α levels from the range of slope angles are considered per H-GWT group (e.g., α_{max}, α_{min}, α_{mean}) and for wider slope ranges more points were used to capture k_y variation with slope angle in each H-GWT group. As seen in Figure 3, the maximum k_y value considered herein is 0.65 g; this value is adopted from a previous study [15] where it was observed that in Metro Vancouver slopes with $k_y > 0.65$ g will have zero displacements (Low hazard level) regardless of their location and specifications. From Figure 3, it is observed that in general, k_y values generally decrease for higher GWT levels, taller slopes, and steeper angles. The k_y graphs will be used to interpolate the k_y value for the slope angle of desire in different geology and H-GWT units. Besides the k_y value, f_s is determined based on observations from the 2D limit equilibrium models for every H-GWT group in geology units as well. The failure mode (average depth of the sliding block) in the 2D models depends on slope geometry (i.e., α, H, GWT) as well as stratigraphy and material strength properties. Bray and Macedo [12,18] proposed that f_s normally can be estimated using the expression $f_s = V_s/4h$ for the case of a relatively wide potential sliding mass that is either shaped like a trapezoid or a segment of a circle where its response is largely one dimensional. In this equation, h is the average height of the potential sliding mass and V_s is the average shear wave velocity of the sliding mass. To solve for f_s, h and V_s of the sliding mass must be known or measured. An average Vs value for different geological units is adopted herein from Monahan and Levson's [32] study. The h value is also determined from the implemented 2D numerical slope stability modeling and the slope's slip surface. If the average slope height encompasses two different geology units (e.g., passes through Ca and V/PV, discussed in section 3.3), then the average V_s of two different geology units is considered for f_s estimations. Since the probabilistic solution and simplified predictive equations for D were developed for discrete f_s levels (Section 2.1), the selected f_s values for geology units and H-GWT groups are conservatively rounded to the discrete values and are listed in Table 2 for different geology units. For T bedrock, based on geological information and geotechnical measurements only the top weathered materials (up to 2 m) are prone to landslides (e.g., in Northern edge of Burnaby Mountain) and therefore, a commonly used surficial infinite slope analogy is adopted to estimate factor of safety (FS) and k_y values for T bedrock. Based on this analogy, the FS and k_y values are calculated by [10,29]

$$FS = \frac{c}{\gamma \, . \, t \, . \, \sin\alpha} + \frac{\tan\varphi}{\tan\alpha} - \frac{\gamma_w \, . \, m \, . \, \tan\varphi}{\gamma . \, \tan\alpha} \quad (5)$$

$$k_y = \frac{(FS-1)\, g}{(\tan\varphi + 1/\tan\alpha)} \quad (6)$$

where γ is the unit weight of the sliding mass in kN/m^3, t is the failure surface depth (normal to the slope) in meters, γ_w is the unit weight of water in kN/m^3, c is the soil cohesion in kPa and m is the percentage (value between 0 and 1) of failure thickness that is saturated (i.e., saturation ratio). For this study, we have taken t = 2 m and solved the above equation in dry (m=0) and wet (m=1) conditions for slope units with GWT > 2 m and GWT ≤ 2 m, respectively. The resulting k_y curves for T bedrock are shown in Figure 3-c. For PT rocks, the strength parameters across the region are still poorly characterized for the lack of direct data on the superficial deposits. Therefore, a more generic method is adopted here which is recommended in the Hazus-MH Earthquake Technical Manual [33] and was previously implemented in landslide susceptibility map for the District of North Vancouver [9]. In this method, for strongly cemented rocks such as PT, a landslide susceptibility level is assigned depending on the slope angle of raster data on a scale of I to X, with I and X being the least and most susceptible, respectively. The yield acceleration is then assigned for the respective geologic and groundwater conditions and the slope angle based on the values offered in this method (Table 4). To avoid calculating the occurrence of landslide for very low or zero slope angles and yield accelerations, lower bounds for slopes angles and yield accelerations are implemented. The lower bound of slope angles are 15° and 10°, for dry and wet conditions, respectively. The resulting yield acceleration curves for PT are shown in Figure 3-d, which could be interpolated to obtain k_y value for different slope values of the PT unit. For the complete ky curved from 2D limit equilibrium models, refer to Yeznabad [34].

Seismic Landslide Hazard Mapping

Figure 4 shows the k_y map for slope units in the region. Considering k_y, f_s, and the seismic site class (adapted from Monahan [32]) for every slope unit, the D values are calculated based on Equations 2 & 3. The R_x and R_y values for every slope unit are calculated based on units' centroid coordinates from the Tsawwassen seismic hazard reference site. Finally, Table 1 is used to interpret the calculated D values and assign the suitable landslide hazard level for every slope unit.

An example of probabilistic seismic landslide hazard mapping of western Metro Vancouver at 2% PE in 50 years is shown in Figure 5 based on the 5^{th} generation national seismic hazard model (2015 NBCC). Figure 5 indicates that the most significant landslide hazard (with the largest displacement) is generally associated with moderate-to-steep slopes with Capilano sediments. This high landslide hazard is a combination of factors: cohesive clay-rich Capilano sediments in Surrey exhibit undrained behavior and deep failures due to the high GWT in combination with f_s as low as 1.5 Hz (as discussed in Yeznabad et al.[14,15]); these slopes are exposed to the higher probabilistic seismic hazard in southwestern-most Metro Vancouver. The undrained behavior of the thick cohesive material (up to 30 m in unit Cd and 60 m in unit Ce; Table 2) in Surrey and East Delta, can make even gentle slopes experience a deep failure which leads to concerns of significant landslide volume and hazard mitigation implications in these regions.

In northern Metro Vancouver (West Vancouver to Coquitlam), steep slopes (> 35°) of Capilano sediments experience a significant hazard in some localities, e.g., North Vancouver where Capilano sediments are categorized as seismic site class D. However, the lower GWT level in the North Vancouver neighborhoods, more distance from the high hazard zone of the southwest in Metro Vancouver, and less cohesive material in their Capilano sediments (i.e., Cc and Cb deposits) make the slopes more stable compared to Surrey and Eastern Delta slopes. Contrarily for V/PV and VC deposits of Vancouver and Burnaby, not only does the higher strength of material result in larger k_y values but also the material's frictional behavior results in relatively shallow failure modes with higher f_s values which are of less concern regarding the resultant seismic sliding displacement levels. Furthermore, the calculations show that the PT rocks have very low seismic landslide hazard as they are associated with lower GWT levels due to their higher elevation and lower input ground motions than southwestern Metro Vancouver. However, the younger T rocks are prone to weathering and their surficial deposits can slide downwards in some regions including the northern part of Burnaby and edges of Burnaby Mountain.

Limitations

There are multiple limitations in the current study which should be considered for proper implementation of the seismic landslide maps presented in this study. First, the adopted methodology based on Newmark sliding block is a proxy to evaluate seismic stability of slopes with limitations as outlined in the literature (e.g.,[11]). Further, failures induced by liquefaction (i.e., flow failure and lateral spreading) was not addressed in the current work as it will be addressed as part of the liquefaction hazard analysis for the Metro Vancouver seismic microzonation mapping project (MVSMM). Moreover, although the developed probabilistic sliding displacement solution aimed to capture the uncertainty of multiple influencing parameters, the scale of the problem and uncertainties associated with multiple input parameters (such as shear strength parameters (c, φ), slope geometry (α, h, GWT) and, uncertainties associated with 2D slope stability analysis, i.e., limit equilibrium methods), will make the maps appropriate for regional (not site-specific) applications such as land-use planning and the development of major infrastructure and lifelines. The shear strength parameters assigned in this study should be considered as the peak strength values that represent the higher end of the range of probable strength variation within a given geologic unit since they are the values required to maintain stability in the steepest of slopes in that unit. Although deterministic peak strength values and k_y levels are adopted in this study, the variation of shear strength parameters in regional mapping is inevitable due to the inherent uncertainty of the geotechnical properties in slope stability analysis, especially for such a large-scale regional problem.

The epistemic uncertainty associated with SDPMs is also not considered in this study since there are a limited number of available and applicable SDPMs. Our developed probabilistic seismic landslide hazard map is intended for end-users to understand the earthquake-induced slope failures (landslide) hazard level considering the expected seismic demand at a 2% or 10% PE in 50 years risk level and the sliding resistance of the geologic units within the slopes given their geometrical specifications and degree of saturation. Earthquake engineering professionals should use the maps to identify and/or prioritize locations for detailed, site-specific seismic-induced landslide assessment.

The probabilistic seismic landslide hazard maps derived in this work do not provide landslide distribution estimates for a specific earthquake event. The probabilistic approach for landslide hazard mapping is similar to national seismic hazard (ground motion) maps obtained from PSHA. As recorded ground motions from a single earthquake do not validate a probabilistic ground motion hazard map, observations of earthquake-induced landslides from a single earthquake do not validate probabilistic seismic landslide hazard maps. However, observations of earthquake-induced landslides during previous earthquakes can validate the predictive displacement models used in the probabilistic approach. Further, other causative triggers for landslides especially rain-induced landslides for Metro Vancouver and their combined effect with earthquakes or following intense wildfire seasons need evaluation in future research studies.

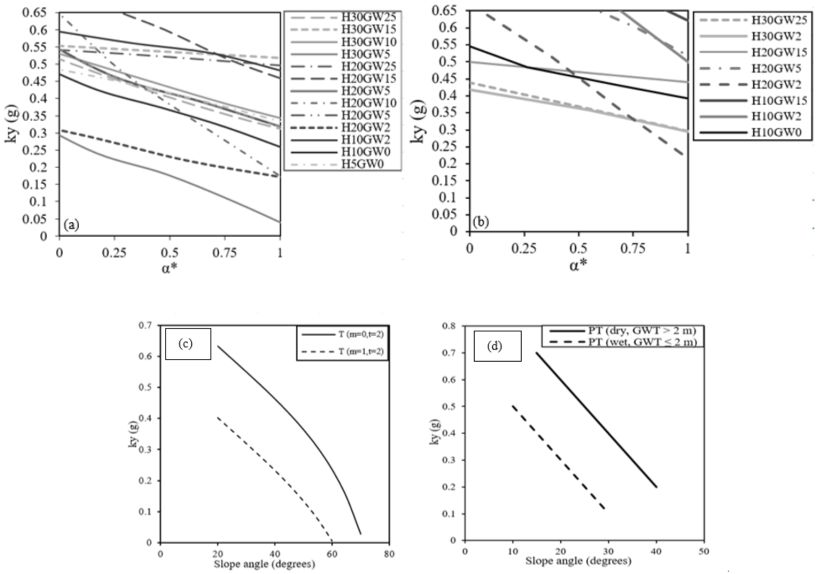

Figure 3. k_y curves from 2D slope modelling for the selected H-GW groups of the regional geologic units: (a) Ca, (b) Cb, (c) T, and (d) PT.

Table 3. The methodology adopted to estimate ky level for PT rocks; susceptibility levels are estimated based on slope angle and GWT, and later, the ky is assigned for them.

		Slope Angle in degrees					
		0-10	**10-15**	**15-20**	**20-30**	**30-40**	**>40**
DRY (GWT > 2 m, below level of sliding)	Susceptibility level	None	None	I	II	IV	V
	k_y (g)	-	-	0.6	0.5	0.35	0.3
WET (GWT ≤ 2 m)	Susceptibility level	None	III	VI	VII	VIII	VIII
	k_y (g)	-	0.4	0.25	0.2	0.15	0.15

Conclusions

The MVSMM project [35] has developed the first set of probabilistic seismic-induced landslide hazard maps for western Metro Vancouver based on seismic sliding displacements considering the expected seismic demand at a 2% and 10% probability of exceedance in 50 years risk level based on the 5th generation national seismic hazard model (2015 NBCC). This paper summarizes the EGBC peer-reviewed methodology [36] to determine probabilistic seismic sliding displacements for western Metro Vancouver. In this work, based on detailed topographic information for the region, a novel semi-automated approach to construct slope units that consider the topographic patterns of the region and offer improved estimations of slopes geometry (i.e., slope angle and height values) was implemented. Moreover, geological, and geotechnical information are compiled and reviewed to consider shear strength and ground water levels for different slope units. Assumptions regarding the rigidity of the slope units are avoided by implementing 2D limit equilibrium modeling for slope units in different geology units and k_y and f_s values are estimated.

The displacement levels based on the probabilistic solution of the Newmark sliding block analogy for Metro Vancouver are assigned to slope units. The probabilistic approaches presented represent rational methods to evaluate earthquake-induced landslide hazards. Importantly, these methods incorporate the uncertainties related to ground motion prediction and sliding displacement predictions and are easily implemented on a regional scale for hazard mapping using simplified regression models. The generated seismic landslide hazard map illustrates zones with high seismic landslide hazards especially in Capilano sediments of Surrey and North Vancouver. The Pre-Tertiary rocks of North Vancouver with steep slopes at higher elevations, are safe considering the seismic landslide hazard based on the methodology adopted in this study. The next step towards developing improved methods for seismic landslide hazard mapping is accurate assessments of the prediction models for sliding displacement. This work is planned for the near future with adopting recent updates of SDPMs [19] and considering variation in regional ky values.

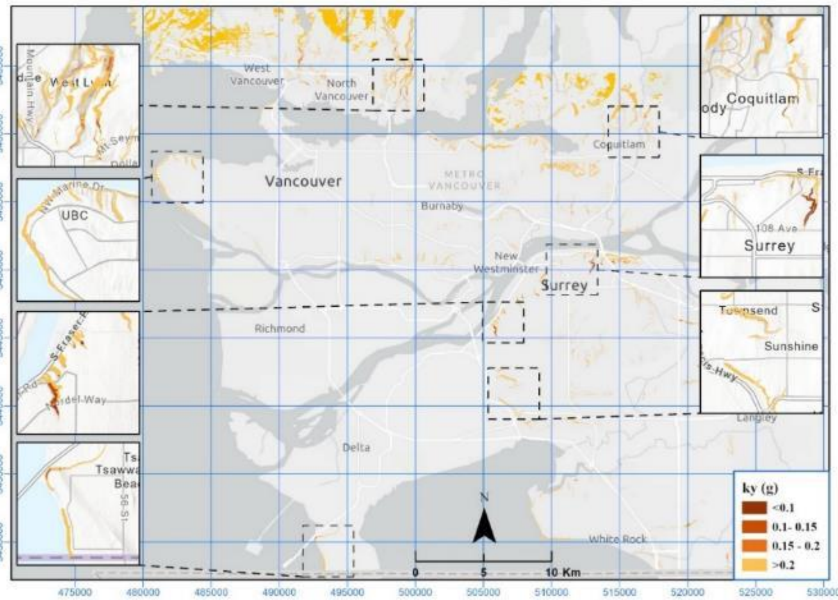

Figure 4. Map of yield acceleration levels for generated slope units in the region.

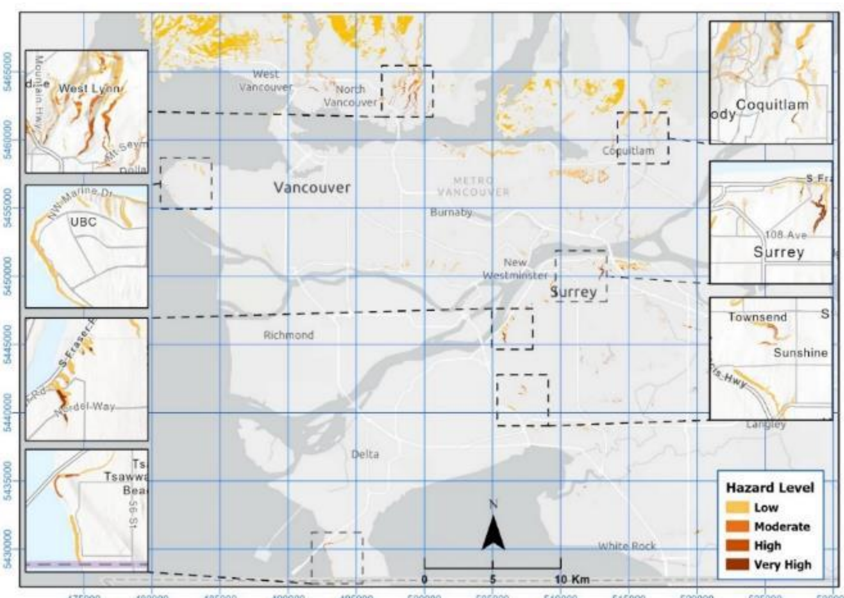

Figure 5. Metro Vancouver seismic landslide hazard map based on probabilistic sliding displacement at 2% PE in 50 years.

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REFERENCES

[1] Blais-Stevens A, Behnia P, Castagner A. Historical landslides that have resulted in fatalities in Canada (1771-2018).

Atlas Canada, Atlas Canada Ref Outl Map Ser 6434 2018:2 sheets. https://doi.org/10.4095/296421.

[2] Blais-Stevens A. Historical landslides in Canada resulting in fatalities (1771-2018) 2019.

[3] Clague JJ. The Earthquake Threat in Southwestern British Columbia: A Geological Perspective. Nat Hazards 2002;26:7–34. https://doi.org/10.1023/A:1015208408485.

[4] Mathews WH. Landslides of central Vancouver Island and the 1946 earthquake. Bull Seismol Soc Am 1979;69:445–50.

[5] Washington geological survey. Geologic Risk for Washington State. 2016.

[6] Rogers GC, Hasegawa HS. A second look at the British Columbia earthquake of June 23, 1946. Bull Seismol Soc Am 1978;68:653–76.

[7] The website of Government of Canada. Vancouver Island Earthquake (1946) 2017. https://science.gc.ca/eic/site/063.nsf/eng/97253.html.

[8] Turner RJW, Clague J, J, Groulx BJ, Journeay J, M. GeoMap Vancouver, geological map of the Vancouver Metropolitan area. 1998. https://doi.org/10.4095/209909.

[9] Wagner CL, Journeay J, M, Hastings NL, Prieto JA. Risk map atlas: maps from the earthquake risk study for the District of North Vancouver. vol. 7816. 2015. https://doi.org/10.4095/296439.

[10] Saygili G, Rathje EM. Probabilistically based seismic landslide hazard maps: An application in Southern California. Eng Geol 2009;109:183–94. https://doi.org/10.1016/j.enggeo.2009.08.004.

[11] Rathje EM, Wang Y, Stafford PJ, Antonakos G, Saygili G. Probabilistic assessment of the seismic performance of earth slopes. Bull Earthq Eng 2014;12:1071–90. https://doi.org/10.1007/s10518-013-9485-9.

[12] Bray JD, Macedo J. Procedure for Estimating Shear-Induced Seismic Slope Displacement for Shallow Crustal Earthquakes. J Geotech Geoenvironmental Eng 2019;145:1–13. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002143.

[13] Saygili G, Rathje EM. Empirical Predictive Models for Earthquake-Induced Sliding Displacements of Slopes. J Geotech Geoenvironmental Eng 2008;134:790–803. https://doi.org/10.1061/(ASCE)1090-0241(2008)134:6(790).

[14] Yeznabad AF, Molnar S, El Naggar MH. Probabilistic solution for the seismic sliding displacement of slopes in Greater Vancouver. Soil Dyn Earthq Eng 2021;140:106393. https://doi.org/https://doi.org/10.1016/j.soildyn.2020.106393.

[15] Yeznabad AF, Molnar S, El Naggar MH, Ghofrani H. Estimation of probabilistic seismic sliding displacement and pseudo-static coefficients (k15) for seismic stability assessment of slopes in the southern Lower Mainland, British Columbia. Soil Dyn Earthq Eng 2022;161:107364. https://doi.org/10.1016/j.soildyn.2022.107364.

[16] S. Molnar, A. Bilson Darko, H. Ghofrani, S. Adhikari MS. The Metro Vancouver seismic microzonation mapping project: Overview and multi-method approach to regional geodatabase developmento Title. CCEE-PCEE, 2023, p. Paper 258, 8 p.

[17] Rathje EM, Saygili G. Probabilistic Seismic Hazard Analysis for the Sliding Displacement of Slopes: Scalar and Vector Approaches. J Geotech Geoenvironmental Eng 2008;134:804–14. https://doi.org/10.1061/(asce)1090-0241(2008)134:6(804).

[18] Bray JD, Macedo J, Travasarou T. Simplified procedure for estimating seismic slope displacements for Subduction Zone Earthquakes. J Geotech Geoenvironmental Eng 2018;144:1–13. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001833.

[19] Bray JD, Macedo J. Performance-based seismic assessment of slope systems. Soil Dyn Earthq Eng 2023;168:107835. https://doi.org/10.1016/j.soildyn.2023.107835.

[20] APEGBC, Association of BC Forest Professionals. Guidelines for Professional Services in the Forest Sector - Terrain Stability Assessments 2010:25.

[21] VanDine D. Risk management, Canadian technical guidelines and best practices related to landslides: a national initiative for loss reduction. 2012. https://doi.org/10.4095/289863.

[22] Monahan P. Soil hazard map of the lower mainland of British Columbia for assessing the earthquake hazard due to lateral ground shaking. Monahan Pet Consult 2005;9.

[23] Jibson RW. Methods for assessing the stability of slopes during earthquakes-A retrospective. Eng Geol 2011;122:43–50. https://doi.org/10.1016/j.enggeo.2010.09.017.

[24] Armstrong JE, Hicock SR. Surficial geology, Vancouver, British Columbia. 1979. https://doi.org/10.4095/108876.

[25] Armstrong JE. Vancouver geology. Geol Assoc Canada Cordilleran Sect 1990.

[26] Armstrong JE, Hicock SR. Surficial geology, New Westminster, West of Sixth Meridian, British Columbia. 1980. https://doi.org/10.4095/108874.

[27] The official website of Government of BC. Groundwater Wells and Aquifers 2016. https://apps.nrs.gov.bc.ca/gwells/.

[28] Jibson RW, Michael JA. Maps showing seismic landslide hazards in Anchorage, Alaska. US Geological Survey Reston, VA, USA; 2009.

[29] Duncan JM, Wright SG, Brandon TL. Soil strength and slope stability. John Wiley & Sons; 2014.

[30] Harp EL, Michael JA, Laprade WT. Shallow landslide hazard map of Seattle, Washington. Landslides Eng. Geol. Seattle, Washington, Area, Geological Society of America; 2008. https://doi.org/10.1130/2008.4020(04).

[31] Savage WZ, Morrissey MM, Baum RL. Geotechnical properties for landslide-prone Seattle; area glacial deposits. 2000. https://doi.org/10.3133/ofr00228.

[32] Monahan P, Levson V. Development of a shear-wave velocity model of the near-surface deposits of southwestern British Columbia, Canada. Fourth Int Conf Recent Adv Geotech Eathquake Eng Soil Dyn 2001:1–12.

[33] Federal Emergency Management Agency (FEMA). Multi-Hazard Loss Estimation Methodology, Earthquake Model, Hazus-MH 2.1, Technical Manual. Washington, D.C.: 2013.

[34] Fallah Yeznabad A. Probabilistic seismic landslide mapping for western Metro Vancouver, British Columbia. University of Western Ontario, 2021.

[35] Molnar S, Bilson Darko A, Ghofrani H, Adhikari S, Salsabili M. The Metro Vancouver seismic microzonation mapping project: Overview and multi-method approach to regional geodatabase development. CCEE-PCEE, 2023, p. 8.

[36] Molnar S, DenToom A, Assaf J, Sirohey A, Boucher C, Gomez Jaramillo N, et al. Metro Vancouver seismic microzonation mapping: Advancements and guidelines. CCEE-PCEE, 2023, p. 9.