USE AND DEVELOPMENT OF SEISMIC MICROZONATION MAPS IN BC

VERSION 1.0
PUBLISHED MAY 10, 2024
These Professional Practice Guidelines—Use and Development of Seismic Microzonation Maps in BC—were developed by Engineers and Geoscientists British Columbia (Engineers and Geoscientists BC) to guide professional practice related to the use and development of Seismic Microzonation (SM) Maps in British Columbia (BC), specifically for Ground Shaking, Liquefaction, and Landslide Seismic Hazards. 

These guidelines were first published in 2024 to complement the Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP), an initiative crafted and implemented by the Institute for Catastrophic Loss Reduction and the University of Western Ontario, and supported and funded by the BC Ministry of Emergency Management and Climate Readiness, to produce comprehensive Seismic Hazard Maps for the Metro Vancouver region of BC. These guidelines provide a common approach for using the MVSMMP and other SM Maps in BC and to also provide a common approach for carrying out SM Mapping Projects in BC. These guidelines are not intended to be prescriptive or provide exhaustive technical or systematic instructions; instead, they are intended to outline the framework for good professional practice for both the use and development of SM Maps.

These guidelines provide professional practice guidance to:

- Engineering/Geoscience Professionals—particularly Geotechnical Engineers of Record (GERs) and Structural Engineers of Record (SERs)—using SM Maps, by describing considerations for how and when they can be applied, and how to interpret and use the information provided in them.
- Engineering/Geoscience Professionals developing SM Maps, by identifying considerations for development and deliverables.
- Other related parties—including approving authorities, the public, and related industries—to introduce terminology and identify the role that SM Maps can play in the planning and operation of communities.

These guidelines describe expectations and obligations of professional practice in relation to the use and development of SM Maps to be followed at the time they were prepared. However, this is a living document that is to be revised and updated as required in the future, to reflect the developing state of practice.

The use and development of SM Maps is land-based work. Engineers and Geoscientists BC gratefully acknowledges First Nations who have been the caretakers and knowledge keepers of these lands since time immemorial. First Nations hold knowledge of and relationships with the land that contributes to and enhances SM Mapping Projects and the work that is done using the SM Maps and data.

Engineering/Geoscience Professionals and others involved in the development of SM Maps should collaborate with First Nations in alignment with the United Nations Declaration on the Rights of Indigenous Peoples (UN General Assembly 2007). As rights and title holders, it is important to recognize each Nations’ diverse knowledges, experiences, and relationships with the land and their territories.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>I</td>
</tr>
<tr>
<td>Abbreviations</td>
<td>VI</td>
</tr>
<tr>
<td>Symbols</td>
<td>VIII</td>
</tr>
<tr>
<td>Defined Terms</td>
<td>X</td>
</tr>
<tr>
<td>Version History</td>
<td>XIV</td>
</tr>
<tr>
<td>1.0 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Purpose of These Guidelines</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Role of Engineers and Geoscientists BC</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Introduction of Terms</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Scope and Applicability of These Guidelines</td>
<td>5</td>
</tr>
<tr>
<td>1.5 Acknowledgements</td>
<td>5</td>
</tr>
<tr>
<td>2.0 Roles and Responsibilities</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Common Forms of Project Organization</td>
<td>6</td>
</tr>
<tr>
<td>2.1.1 Mapping Project Team</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Responsibilities</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 Owner/Client</td>
<td>7</td>
</tr>
<tr>
<td>2.2.2 Mapping Professional</td>
<td>7</td>
</tr>
<tr>
<td>2.2.3 Local Community Governing Bodies</td>
<td>8</td>
</tr>
<tr>
<td>2.2.4 Geotechnical Engineer of Record</td>
<td>8</td>
</tr>
<tr>
<td>2.2.5 Structural Engineer of Record</td>
<td>8</td>
</tr>
<tr>
<td>3.0 Introduction to Seismic Hazards and Seismic Microzonation Mapping</td>
<td>10</td>
</tr>
<tr>
<td>3.1 Seismic Hazards</td>
<td>10</td>
</tr>
<tr>
<td>3.1.1 Hazards Commonly Addressed in Seismic Microzonation Mapping</td>
<td>10</td>
</tr>
<tr>
<td>3.1.2 Hazards Not Commonly Addressed in Seismic Microzonation Mapping</td>
<td>13</td>
</tr>
<tr>
<td>3.2 Overview of Seismic Hazards in BC</td>
<td>14</td>
</tr>
<tr>
<td>3.3 Seismic Microzonation Mapping</td>
<td>16</td>
</tr>
<tr>
<td>3.4 Introduction to Seismic Microzonation Map Levels</td>
<td>16</td>
</tr>
<tr>
<td>3.4.1 Level 1 Seismic Microzonation Maps</td>
<td>18</td>
</tr>
<tr>
<td>3.4.2 Level 2 Seismic Microzonation Maps</td>
<td>18</td>
</tr>
<tr>
<td>3.4.3 Level 3 Seismic Microzonation Maps</td>
<td>18</td>
</tr>
<tr>
<td>3.5 Risk Management in Seismic Microzonation Mapping</td>
<td>19</td>
</tr>
<tr>
<td>4.0 Use of Seismic Microzonation Maps</td>
<td>21</td>
</tr>
<tr>
<td>4.1 General Considerations for Use</td>
<td>21</td>
</tr>
<tr>
<td>4.2 Local Community Governing Bodies</td>
<td>22</td>
</tr>
<tr>
<td>4.2.1 Seismic Hazard Specific Considerations</td>
<td>23</td>
</tr>
<tr>
<td>4.2.2 Considerations for Regulatory Document Development</td>
<td>24</td>
</tr>
<tr>
<td>4.2.3 Emergency Management and Recovery</td>
<td>26</td>
</tr>
<tr>
<td>4.2.4 Seismic Hazard Mitigation Policy and Planning Examples</td>
<td>26</td>
</tr>
<tr>
<td>4.3 Geotechnical Engineering Professionals</td>
<td>27</td>
</tr>
<tr>
<td>4.3.1 General Considerations</td>
<td>27</td>
</tr>
<tr>
<td>4.3.2 Use of Ground Shaking Maps</td>
<td>28</td>
</tr>
<tr>
<td>4.3.3 Use of Liquefaction Maps</td>
<td>28</td>
</tr>
<tr>
<td>4.3.4 Use of Landslide Maps</td>
<td>29</td>
</tr>
<tr>
<td>4.4 Structural Engineering Professionals</td>
<td>30</td>
</tr>
<tr>
<td>4.4.1 General Considerations</td>
<td>30</td>
</tr>
<tr>
<td>4.4.2 Use of Level 1 Ground Shaking Maps</td>
<td>31</td>
</tr>
<tr>
<td>4.4.3 Use of Level 2 Ground Shaking Maps</td>
<td>31</td>
</tr>
</tbody>
</table>
List of Appendices

Appendix A: Authors and Reviewers

Appendix B: Examples of Seismic Microzonation Maps

Appendix C: History of Use and Development of Seismic Microzonation Maps in BC

Appendix D: Non-Invasive and Invasive vs Methods

Appendix E: Methods of Seismic Analysis of Soil Liquefaction

List of Figures

Figure 1: Diagrammatic Illustrations of the Major Amplification Effects Associated with Soft Soil Overlying Firm Ground or Bedrock (Modified from Hunter and Atukorala 2015) ........................................ 11

Figure 2: Tectonic Plate Setting of the West Coast of BC (Modified from Turner et al., 1998) ............. 15

Figure 3: Seismic Hazard Map Showing Peak Ground Acceleration with a Probability of Exceedance of 2% in 50 Years (Source: National Building Code of Canada 2020) .................. 15

Figure 4: Conceptual Illustration on How to Optimize the Use of Seismic Microzonation Maps in Seismic Risk Assessments .......................................................... 20

Figure 5: Formula to Assess the Amplification/De-amplification of Seismic Ground Motions due to Changes in Localized Topography (Source: Faccioli 1991) ........................................... 52

Figure 6: Published Correlations Between Peak Bedrock and Ground Surface Acceleration for Stiff Soils (Source: Seed and Idriss 1982) .......................................................... 56

Figure 7: Published Correlations Between Peak Bedrock and Ground Surface Acceleration for Soft Soils (Source: Idriss 1991) ................................................................. 57

Figure 8: Methodology for Calculation of $F_{liquefaction}$ for Seismic Microzonation Mapping Projects ................................................................................................. 66

Figure 9: Example Deaggregation of Peak Ground Acceleration ($X_{bd}$) for a Probability of 2% in 50 Years for Vancouver (City Hall) (Modified from Kolaj et al. 2023) 68
LIST OF TABLES

TABLE 1: SIMPLIFIED DEFINITIONS, EXAMPLES, AND APPLICATIONS OF COMMONLY USED TERMS FOR NON-SEISMIC HAZARD RISK MANAGEMENT, AS THEY RELATE TO SEISMIC HAZARDS ............................................. 3

TABLE 2: CONCEPT OF SEISMIC MICROZONATION MAP LEVELS .................................................................................................................. 17

TABLE 3: PRINCIPAL GEOTECHNICAL AND GEOPHYSICAL DATA TYPES USED IN SEISMIC MICROZONATION MAPPING, AND THEIR RELATION TO SHEAR WAVE VELOCITY ............................................................... 39

TABLE 4: CONCEPT OF SEISMIC MICROZONATION MAP LEVELS PARTICULAR TO GROUND SHAKING ................................................................. 54

TABLE 5: CONCEPT OF SEISMIC MICROZONATION MAP LEVELS PARTICULAR TO LIQUEFACTION ........................................................................ 62

TABLE 6: EXAMPLE RATINGS OF LIQUEFACTION SUSCEPTIBILITY FOR SEDIMENTARY DEPOSITS DURING STRONG GROUND SHAKING (RECREATED FROM YOUD AND PERKINS 1978) ............................................. 64

TABLE 7: EXAMPLE LIQUEFACTION HAZARD EVALUATION MATRIX ................................................................................................................. 70

TABLE 8: EXAMPLE LIQUEFACTION HAZARD RATINGS BY LIQUEFACTION POTENTIAL INDEX OR LIQUEFACTION POTENTIAL INDEX (G) .................................................................................................................... 70

TABLE 9: EXAMPLE LIQUEFACTION HAZARD RATINGS BY LIQUEFACTION SEVERITY NUMBER .................................................................................... 70

TABLE 10: CONCEPT OF SEISMIC MICROZONATION MAP LEVELS PARTICULAR TO LANDSLIDE ........................................................................ 74

TABLE 11: GEOLOGIC GROUP DESCRIPTIONS AND ASSUMED EFFECTIVE SHEAR-STRENGTH PARAMETERS (WIECZOREK ET AL. 1985) .................................................................................................................. 78

TABLE 12: EXAMPLE ASSIGNMENT OF GEOLOGICAL UNITS IN GLACIATED TERRAIN FROM THE SAINT-LAWRENCE LOWLANDS OF EASTERN CANADA (FARZAM ET AL. 2018) ..................................................... 78
<table>
<thead>
<tr>
<th>ABBREVIATION</th>
<th>TERM</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP</td>
<td>annual exceedance probability</td>
</tr>
<tr>
<td>BC</td>
<td>British Columbia</td>
</tr>
<tr>
<td>BCGS</td>
<td>British Columbia Geological Survey</td>
</tr>
<tr>
<td>BPT</td>
<td>Becker penetration test</td>
</tr>
<tr>
<td>CCP</td>
<td>comprehensive community plan</td>
</tr>
<tr>
<td>CPT</td>
<td>cone penetration test</td>
</tr>
<tr>
<td>CPTu</td>
<td>piezocone penetration test</td>
</tr>
<tr>
<td>CRR</td>
<td>Cyclic Resistance Ratio / Liquefaction Resistance</td>
</tr>
<tr>
<td>CSR</td>
<td>Cyclic Stress Ratio</td>
</tr>
<tr>
<td>DCPT</td>
<td>dynamic cone penetration test</td>
</tr>
<tr>
<td>DEM</td>
<td>digital elevation model</td>
</tr>
<tr>
<td>EMAP</td>
<td>Emergency Management Assistance Program</td>
</tr>
<tr>
<td>GER</td>
<td>Geotechnical Engineer of Record</td>
</tr>
<tr>
<td>GIS</td>
<td>geographic information system</td>
</tr>
<tr>
<td>GMM</td>
<td>Ground Motion Model</td>
</tr>
<tr>
<td>GSC</td>
<td>Geological Survey of Canada</td>
</tr>
<tr>
<td>GWELLS</td>
<td>British Columbia Groundwater Wells and Aquifers Database</td>
</tr>
<tr>
<td>LiDAR</td>
<td>light detection and ranging</td>
</tr>
<tr>
<td>LPI</td>
<td>Liquefaction potential index</td>
</tr>
<tr>
<td>LPT</td>
<td>large penetration test</td>
</tr>
<tr>
<td>LSN</td>
<td>Liquefaction severity number</td>
</tr>
<tr>
<td>MAM</td>
<td>microtremor array method</td>
</tr>
<tr>
<td>MASW</td>
<td>multichannel analysis of Surface Waves</td>
</tr>
<tr>
<td>MHVSR</td>
<td>microtremor horizontal to vertical spectral ratio</td>
</tr>
<tr>
<td>ABBREVIATION</td>
<td>TERM</td>
</tr>
<tr>
<td>--------------</td>
<td>------</td>
</tr>
<tr>
<td>MMASW</td>
<td>multimodal analysis of Surface Waves</td>
</tr>
<tr>
<td>MSF</td>
<td>(earthquake) magnitude scaling factor</td>
</tr>
<tr>
<td>MVSMMP</td>
<td>Metro Vancouver Seismic Microzonation Mapping Project</td>
</tr>
<tr>
<td>NBC</td>
<td>National Building Code of Canada</td>
</tr>
<tr>
<td>NEHRP</td>
<td>National Earthquake Hazards Reduction Program</td>
</tr>
<tr>
<td>NRCAN</td>
<td>National Research Council of Canada</td>
</tr>
<tr>
<td>OCP</td>
<td>official community plan</td>
</tr>
<tr>
<td>PGA</td>
<td>peak ground acceleration</td>
</tr>
<tr>
<td>PGV</td>
<td>peak ground velocity</td>
</tr>
<tr>
<td>PI</td>
<td>plasticity index</td>
</tr>
<tr>
<td>PSHA</td>
<td>probabilistic Seismic Hazard analysis</td>
</tr>
<tr>
<td>SASW</td>
<td>spectral analysis of Surface Waves</td>
</tr>
<tr>
<td>SCPT</td>
<td>seismic cone penetration test</td>
</tr>
<tr>
<td>SDPM</td>
<td>seismic displacement prediction model</td>
</tr>
<tr>
<td>SER</td>
<td>Structural Engineer of Record</td>
</tr>
<tr>
<td>SM</td>
<td>Seismic Microzonation</td>
</tr>
<tr>
<td>SPT</td>
<td>standard penetration test</td>
</tr>
<tr>
<td>SSI</td>
<td>site-specific investigation</td>
</tr>
<tr>
<td>SSRA</td>
<td>Seismic Site Response Analysis</td>
</tr>
<tr>
<td>TRIM</td>
<td>terrain resource information management</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>VSP</td>
<td>vertical seismic profiling</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>TERM</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>A</td>
<td>peak ground motion amplitudes</td>
</tr>
<tr>
<td>a_c</td>
<td>critical acceleration</td>
</tr>
<tr>
<td>a_max</td>
<td>maximum ground acceleration</td>
</tr>
<tr>
<td>C_e</td>
<td>correction for standard penetration test hammer energy ratio</td>
</tr>
<tr>
<td>C_n</td>
<td>Factor to normalize N_m to an effective overburden stress (σ' v0) of about 100 kPa</td>
</tr>
<tr>
<td>c'</td>
<td>effective cohesion intercept of Soil or rock</td>
</tr>
<tr>
<td>d</td>
<td>threshold displacement value</td>
</tr>
<tr>
<td>F_l or F(FS)</td>
<td>nonlinear function of FSliquefaction</td>
</tr>
<tr>
<td>f_0</td>
<td>Fundamental Site Frequency</td>
</tr>
<tr>
<td>f_s</td>
<td>sleeve friction</td>
</tr>
<tr>
<td>FSliquefaction</td>
<td>factor of safety against Liquefaction</td>
</tr>
<tr>
<td>g</td>
<td>acceleration due to gravity</td>
</tr>
<tr>
<td>h</td>
<td>the slope-normal thickness of the sliding mass</td>
</tr>
<tr>
<td>k_y</td>
<td>yield acceleration (coefficient)</td>
</tr>
<tr>
<td>K_w</td>
<td>correction factor for effective overburden stress (σ' v0)</td>
</tr>
<tr>
<td>m</td>
<td>the saturated proportion of the sliding mass</td>
</tr>
<tr>
<td>M_w</td>
<td>earthquake moment magnitude</td>
</tr>
<tr>
<td>N_m</td>
<td>standard penetration test (SPT) blow count measured in field testing</td>
</tr>
<tr>
<td>N_M</td>
<td>Number of representative cycles</td>
</tr>
<tr>
<td>q_c</td>
<td>cone penetration test (CPT) tip resistance</td>
</tr>
<tr>
<td>q_CLN</td>
<td>cone penetration test (CPT) tip resistance normalized to an effective overburden stress (σ' v0) of 100 kPa.</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>TERM</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>$r_d$</td>
<td>stress reduction coefficient</td>
</tr>
<tr>
<td>$S_a$</td>
<td>spectral acceleration</td>
</tr>
<tr>
<td>$T$</td>
<td>period</td>
</tr>
<tr>
<td>$T_0$</td>
<td>Fundamental Site Period</td>
</tr>
<tr>
<td>$T_s$</td>
<td>slope period</td>
</tr>
<tr>
<td>$u$</td>
<td>pore pressure</td>
</tr>
<tr>
<td>$V_P$</td>
<td>P-Wave velocity</td>
</tr>
<tr>
<td>$V_s$</td>
<td>Shear Wave velocity</td>
</tr>
<tr>
<td>$V_{s30}$</td>
<td>the time-weighted average Shear Wave velocity ($V_s$) from ground surface to 30 m depth</td>
</tr>
<tr>
<td>$w_{ij}$</td>
<td>a combined weighting term that represents uncertainties in $a_c$ and $T_s$</td>
</tr>
<tr>
<td>$Z_{s5}$</td>
<td>depth ($z$) to a Shear Wave velocity ($V_s$) of 2500 m/s. A common basin depth in Ground Motion Models (GMMs)</td>
</tr>
<tr>
<td>$Z_{10}$</td>
<td>depth ($z$) to a Shear Wave velocity ($V_s$) of 1000 m/s. A common basin depth in Ground Motion Models (GMMs).</td>
</tr>
<tr>
<td>$z$</td>
<td>depth below ground surface</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>slope angle</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Soil unit weight</td>
</tr>
<tr>
<td>$\gamma_w$</td>
<td>unit weight of water</td>
</tr>
<tr>
<td>$\Delta \phi_r$</td>
<td>difference in Cyclic Resistance Ratio (CRR) required and CRR available</td>
</tr>
<tr>
<td>$\phi^*$</td>
<td>effective friction angle</td>
</tr>
<tr>
<td>$\varepsilon_v$</td>
<td>volumetric strain</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Soil density</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>total overburden stress</td>
</tr>
<tr>
<td>$\sigma'_{vo}$</td>
<td>effective overburden stress</td>
</tr>
<tr>
<td>$\tau_{cyc}$</td>
<td>cyclic shear stress amplitude</td>
</tr>
</tbody>
</table>
The following definitions are specific to these guidelines. These words and terms are capitalized throughout the document.

<table>
<thead>
<tr>
<th>TERM</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplification/De-amplification</td>
<td>An increase (or decrease) in ground motion amplitude relative to nearby reference condition, commonly bedrock.</td>
</tr>
<tr>
<td>Authority Having Jurisdiction</td>
<td>The jurisdictional body with the authority to administer and enforce the British Columbia Building Code, the City of Vancouver Building By-law, the National Building Code of Canada (NBC), or a local building bylaw or code, as well as government agencies that regulate a particular function in a building.</td>
</tr>
<tr>
<td>Basin Effects</td>
<td>A subset of Earthquake Site Effects specific to wave interactions in a sedimentary basin.</td>
</tr>
<tr>
<td>Bylaws</td>
<td>The Bylaws of Engineers and Geoscientists BC made under the Professional Governance Act.</td>
</tr>
<tr>
<td>Code</td>
<td>The National Building Code of Canada (NBC), British Columbia Building Code, or the Vancouver Building By-law.</td>
</tr>
<tr>
<td>Consequence</td>
<td>An event or sequence of events that culminates in: 1. harm, injury, illness, or death to one or more persons; or 2. damage to the environment.</td>
</tr>
<tr>
<td>Cyclic Resistance Ratio (CRR)</td>
<td>The Cyclic Stress Ratio (CSR) to trigger a Liquefaction failure. Also known as Liquefaction Resistance.</td>
</tr>
<tr>
<td>Cyclic Stress Ratio (CSR)</td>
<td>The ratio of the cyclic shear stress amplitude ($τ_{cy}$) to the effective overburden stress ($σ_v$).</td>
</tr>
<tr>
<td>Earthquake Site Effects (1D, 2D, 3D)</td>
<td>An umbrella term that captures the effects of all Seismic Wave interactions that occur in the near surface due to Local Site Conditions. These include Ground Shaking, Liquefaction, and Landslide.</td>
</tr>
<tr>
<td>Engineering/Geoscience Professional(s)</td>
<td>Professional engineers, professional geoscientists, professional licensees engineering, professional licensees geoscience, and any other individuals registered or licensed by Engineers and Geoscientists BC as a “professional Registrant” as defined in Part 1 of the Bylaws.</td>
</tr>
<tr>
<td>Engineers and Geoscientists BC</td>
<td>The Association of Professional Engineers and Geoscientists of the Province of British Columbia, also operating as Engineers and Geoscientists BC.</td>
</tr>
<tr>
<td>Geotechnical Engineer of Record</td>
<td>The Registered Professional who is responsible for the geotechnical aspects of the design and associated field reviews for the subgrade support of the building or structure in a project, and issues Code letters of assurance for those items of direct responsibility.</td>
</tr>
<tr>
<td>Geoscience Data</td>
<td>Seismological, geological, geotechnical, and geophysical data.</td>
</tr>
<tr>
<td>TERM</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>------</td>
<td>------------</td>
</tr>
<tr>
<td>Gradational (Site)</td>
<td>Gradual change in Soil properties (e.g., an increase in Shear Wave velocity ( V_s )) with depth.</td>
</tr>
<tr>
<td>Ground Motion Model</td>
<td>Empirical, synthetic, and/or hybrid model to predict ground motions based on source, path (distance), and site condition terms, typically applicable to a particular seismotectonic setting.</td>
</tr>
<tr>
<td>Ground Shaking</td>
<td>Ground vibrations resulting from propagation of Seismic Waves.</td>
</tr>
<tr>
<td>Hazard</td>
<td>A set of conditions or an operational situation, including natural Hazards, that might lead to a Consequence.</td>
</tr>
<tr>
<td>Higher-Level Seismic Microzonation Maps</td>
<td>Level 2 or level 3 Seismic Microzonation Maps.</td>
</tr>
<tr>
<td>(High) Impedance Contrast</td>
<td>One or more sharp change(s) in Soil properties (e.g., increases in ( V_s )) with depth.</td>
</tr>
<tr>
<td>In-Situ/In Situ</td>
<td>Latin for “in place” or “at site.” Includes invasive or non-invasive field testing conducted at the site. Does not include geotechnical laboratory testing of samples retrieved from the site.</td>
</tr>
<tr>
<td>Landslide</td>
<td>The movement of earth material (i.e., Soil and rock) down sloping terrain due to gravity. While Landslides can occur due to various factors, the focus of these guidelines is on earthquake-triggered Landslides.</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>The phenomena of generation of excess pore water pressures due to seismic loading (or cyclic loading in a laboratory test) that lead to significant loss of strength and stiffness (softening) of saturated granular Soils.</td>
</tr>
<tr>
<td>Liquefaction Resistance</td>
<td>See Cyclic Resistance Ratio (CRR).</td>
</tr>
<tr>
<td>Local Community Governing Body</td>
<td>An Authority Having Jurisdiction, local authority (e.g., municipality, regional district, First Nation [including those who are self-governing, Treaty, Nisga’a Nation and non-Treaty Nations, and those who operate under the Indian Act or land codes]), or other public administration tasked with making decisions on legislative framework and providing services to their community, including but not limited to Hazard and community planning, permitting, asset management, and emergency management.</td>
</tr>
<tr>
<td>Local Site Conditions</td>
<td>The subsurface ground conditions of a particular site considering both geology and material properties.</td>
</tr>
<tr>
<td>Mapping Professional</td>
<td>The Engineering/Geoscience Professional who is professionally responsible for one or more Seismic Microzonation Maps, or an aspect of a Seismic Microzonation Map.</td>
</tr>
</tbody>
</table>
| Metro Vancouver Seismic Microzonation Mapping Project | A multi-year (2017–2024) research project that involves the assessment and mapping of:  
- Ground Shaking Susceptibility and Hazard (Amplification, Basin Effects, Site Class, Site Period)  
- Liquefaction Susceptibility and Hazard  
- Landslide Susceptibility and Hazard  
at a neighbourhood scale with an initial focus in the western communities of Metro Vancouver. |
<table>
<thead>
<tr>
<th>TERM</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Wave/P-Wave</td>
<td>A body or compressional wave in which particle motion is in the same direction as its wave propagation.</td>
</tr>
<tr>
<td>Professional of Record</td>
<td>The Engineering/Geoscience Professional who is professionally responsible for professional work, professional activities, or documents related to the engineering or geoscience practice.</td>
</tr>
<tr>
<td>Quaternary</td>
<td>The most recent geological time period, which began 2.58 million years ago and continues to the present. Consists of Pleistocene and Holocene epochs (The Geological Society of America, 2022).</td>
</tr>
<tr>
<td>Registrant</td>
<td>Means the same as defined in Schedule 1, section 5 of the Professional Governance Act.</td>
</tr>
<tr>
<td>Risk</td>
<td>A combination of two factors: 1. the severity of the anticipated Consequence resulting from a Hazard; and 2. the likelihood of a Hazard occurring and leading to a Consequence.</td>
</tr>
<tr>
<td>Seismic Hazard</td>
<td>Any Hazard resulting from an earthquake (Ground Shaking, Liquefaction, Landslide), often considering a certain level of shaking over a relevant time period or probability of interest.</td>
</tr>
<tr>
<td>Seismic Microzonation Map</td>
<td>A map depicting Seismic Hazards due to Local Site Conditions, as opposed to regional seismicity; can include either Seismic Susceptibility Maps or Seismic Hazard Maps.</td>
</tr>
<tr>
<td>Seismic Microzonation Mapping Project</td>
<td>An initiative to develop one or more Seismic Microzonation Maps.</td>
</tr>
<tr>
<td>(Seismic) Hazard Map</td>
<td>A map that conveys Seismic Hazard; requires input of seismic demand in addition to variation in the physical properties of shallow geological materials.</td>
</tr>
<tr>
<td>(Seismic) Susceptibility Map</td>
<td>A map that conveys Susceptibility to the Seismic Hazard due only to the variation in the physical properties of shallow geological material relevant to Seismic Hazard; does not depend on seismic demand or regional seismicity.</td>
</tr>
<tr>
<td>Seismic Risk</td>
<td>Any Risk resulting from a Seismic Hazard, often considering the vulnerability of the populations, buildings, and infrastructure.</td>
</tr>
<tr>
<td>Seismic Wave</td>
<td>A mechanical wave of acoustic energy generated from an earthquake. Seismic Waves vibrate (travel) through earth material as body waves (P-Waves and S-Waves) and Surface Waves (Raleigh and Love waves).</td>
</tr>
<tr>
<td>Sendai Framework</td>
<td>The United Nations' Sendai Framework for Disaster Risk Reduction is a document that outlines seven clear targets and four priorities for action to prevent new and reduce existing disaster Risks and has been adopted in Canada both provincially and federally.</td>
</tr>
<tr>
<td>ShakeMap</td>
<td>A map that depicts the distribution of Ground Shaking from an earthquake with a defined magnitude and location.</td>
</tr>
<tr>
<td>Shear Wave/Secondary Wave/S-Wave</td>
<td>A body wave in which particle movement is perpendicular to its wave propagation direction.</td>
</tr>
<tr>
<td>TERM</td>
<td>DEFINITION</td>
</tr>
<tr>
<td>------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Site Amplification/ De-amplification</td>
<td>Increase (or decrease) in Ground Shaking amplitude at a site relative to a nearby reference site condition, commonly bedrock.</td>
</tr>
<tr>
<td>Site Class</td>
<td>A classification system that considers a Soil’s propensity for Amplification or De-amplification of the intensity of surface ground motion propagating from underlying rock.</td>
</tr>
<tr>
<td>(Fundamental) Site Frequency</td>
<td>Inverse of Site Period.</td>
</tr>
<tr>
<td>(Fundamental) Site Period</td>
<td>Period of vibration of a site. Inverse of the Fundamental Site Frequency.</td>
</tr>
<tr>
<td>Seismic Site Response Analysis (SSRA)</td>
<td>Numerical prediction of earthquake Ground Shaking via time- or frequency-domain modelling of wave propagation through the Soil model.</td>
</tr>
<tr>
<td>Soil</td>
<td>All unconsolidated (unlithified) geological materials overlying bedrock.</td>
</tr>
<tr>
<td>Susceptibility</td>
<td>The conditional likelihood of a condition or situation that might produce a Consequence, given the occurrence of a trigger.</td>
</tr>
<tr>
<td></td>
<td>In the context of Seismic Microzonation Maps, Susceptibility is a function of the underlying topographic, geological, geotechnical, groundwater, land use, vegetation, and other causal factors for Landslides, Liquefaction, and Amplification, and is distinct from the triggering earthquake.</td>
</tr>
<tr>
<td>Structural Engineer of Record</td>
<td>An Engineering Professional with general responsibility for the structural integrity of the primary structural system of a building, and issues Code letters of assurance for those items of direct responsibility.</td>
</tr>
<tr>
<td>Surface Wave</td>
<td>Seismic Waves (e.g., Raleigh and Love waves) that travel near the ground surface in which the motion is primarily perpendicular to the wave front with radial and vertical motion. Wave amplitude decays strongly with depth.</td>
</tr>
</tbody>
</table>
## VERSION HISTORY

<table>
<thead>
<tr>
<th>VERSION NUMBER</th>
<th>PUBLISHED DATE</th>
<th>DESCRIPTION OF CHANGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>May 10, 2024</td>
<td>Initial version.</td>
</tr>
</tbody>
</table>
INTRODUCTION

Engineers and Geoscientists BC is the regulatory and licensing body for the engineering and geoscience professions in British Columbia (BC). To protect the public, Engineers and Geoscientists BC establishes, monitors, and enforces standards for the qualification and practice of its Registrants.

Engineers and Geoscientists BC provides various practice resources to its Registrants to assist them in meeting their professional and ethical obligations under the Professional Governance Act and Engineers and Geoscientists BC's Bylaws (the Bylaws). Those practice resources include professional practice guidelines, which are produced under the authority of Section 7.3.1 of the Bylaws and are aligned with Engineers and Geoscientists BC's Code of Ethics Principle 4.

Each professional practice guideline describes expectations and obligations of professional practice that all Engineering/Geoscience Professionals are expected to have regard for in relation to specific professional activities. Engineers and Geoscientists BC publishes professional practice guidelines on specific professional activities where additional guidance is deemed necessary. Professional practice guidelines are written by subject matter experts and reviewed by various industry groups before publication.

Having regard for professional practice guidelines means that Engineering/Geoscience Professionals must follow established and documented procedures to stay informed of, be knowledgeable about, and meet the intent of any professional practice guidelines related to their area of practice. By carefully considering the objectives and intent of a professional practice guideline, an Engineering/Geoscience Professional can then use their professional judgment when applying the guidance to a specific situation. Any deviation from the guidelines must be documented and a rationale provided. Where the guidelines refer to professional obligations specified under the Professional Governance Act, the Bylaws, and other regulations/legislation, Engineering/Geoscience Professionals must understand that such obligations are mandatory.

These Professional Practice Guidelines—Use and Development of Seismic Microzonation Maps in BC—provide guidance on professional practice for Engineering/Geoscience Professionals who use (e.g., Local Community Governing Bodies, Geotechnical Engineers of Record [GERs], and Structural Engineers of Record [SERs]) or develop (e.g., Mapping Professionals) Seismic Microzonation (SM) Maps.

1.0 INTRODUCTION

Engineers and Geoscientists BC is the regulatory and licensing body for the engineering and geoscience professions in British Columbia (BC). To protect the public, Engineers and Geoscientists BC establishes, monitors, and enforces standards for the qualification and practice of its Registrants.

Engineers and Geoscientists BC provides various practice resources to its Registrants to assist them in meeting their professional and ethical obligations under the Professional Governance Act and Engineers and Geoscientists BC's Bylaws (the Bylaws). Those practice resources include professional practice guidelines, which are produced under the authority of Section 7.3.1 of the Bylaws and are aligned with Engineers and Geoscientists BC's Code of Ethics Principle 4.

Each professional practice guideline describes expectations and obligations of professional practice that all Engineering/Geoscience Professionals are expected to have regard for in relation to the specific professional activity outlined in these guidelines by:

1. Describe expectations and obligations of professional practice that Engineering/Geoscience Professionals are expected to have regard for in relation to the specific professional activity outlined in these guidelines by:

Following are the specific objectives of these guidelines:

1. Describe expectations and obligations of professional practice that Engineering/Geoscience Professionals are expected to have regard for in relation to the specific professional activity outlined in these guidelines by:
- specifying tasks and/or services that Engineering/Geoscience Professionals should complete;
- referring to professional obligations under the Professional Governance Act, the Bylaws, and other regulations/legislation, including the primary obligation to protect the safety, health, and welfare of the public and the environment; and
- describing the established norms of practice in this area.

2. Describe the roles and responsibilities of the various parties involved in these professional activities. The document should assist in delineating the roles and responsibilities of the various parties, which may include Mapping Professional(s), the Local Community Governing Body, the GER, and the SER.

3. Define the skill sets that are consistent with the training and experience required to carry out these professional activities.

4. Provide guidance on how to meet the quality management requirements under the Professional Governance Act and the Bylaws when carrying out the professional activities identified in these professional practice guidelines.

5. Describe the limitations and appropriate uses of SM Maps.

1.2 ROLE OF ENGINEERS AND GEOSCIENTISTS BC

These guidelines form part of Engineers and Geoscientists BC’s ongoing commitment to maintaining the quality of professional services that Engineering/Geoscience Professionals provide to their clients and the public.

Engineers and Geoscientists BC has the statutory duty to serve and protect the public interest as it relates to the practice of professional engineering and professional geoscience, including regulating the conduct of Engineering/Geoscience Professionals. Engineers and Geoscientists BC is responsible for establishing, monitoring, and enforcing the standards of practice, conduct, and competence for Engineering/Geoscience Professionals. One way that Engineers and Geoscientists BC exercises these responsibilities is by publishing and enforcing the use of professional practice guidelines, as per Section 7.3.1 of the Bylaws.

Guidelines are meant to assist Engineering/Geoscience Professionals in meeting their professional obligations. As such, Engineering/Geoscience Professionals are required to be knowledgeable of, competent in, and meet the intent of professional practice guidelines that are relevant to their area of practice.

The writing, review, and publishing process for professional practice guidelines at Engineers and Geoscientists BC is comprehensive. These guidelines were prepared by subject matter experts and reviewed at various stages by a formal review group and the final draft underwent a thorough consultation process with various advisory groups and divisions of Engineers and Geoscientists BC. These guidelines were then approved by the Engineers and Geoscientists BC Board and, prior to publication, underwent final editorial and legal reviews.

Engineers and Geoscientists BC supports the principle that appropriate financial, professional, and technical resources should be provided (i.e., by the client and/or the employer) to support Engineering/Geoscience Professionals who are responsible for carrying out professional activities. These guidelines may be used to assist in the level of service and terms of reference of an agreement between an Engineering/Geoscience Professional and a client.
1.3 INTRODUCTION OF TERMS

See the Defined Terms.

A Seismic Hazard is any Hazard resulting from an earthquake (e.g., Ground Shaking, Liquefaction, Landslide), where a Hazard is a set of conditions or an operational situation that might lead to harm, injury, illness, or death to one or more persons or damage to the environment. Seismic Hazards are an input to Seismic Risk, which considers the vulnerability of the populations, buildings, and infrastructure. Table 1 provides simplified definitions, examples, and applications of select defined terms, as well as other commonly used terms for non-Seismic Hazard Risk management, as they relate to Seismic Hazards.

Table 1: Simplified Definitions, Examples, and Applications of Commonly Used Terms for Non-Seismic Hazard Risk Management, as They Relate to Seismic Hazards

<table>
<thead>
<tr>
<th>TERMINOLOGY</th>
<th>DEFINITION (SIMPLIFIED)</th>
<th>EXAMPLE / APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hazard</td>
<td>See Defined Terms for guideline specific definition. Generally, a set of conditions with the potential to cause harm to a person or damage to the environment.</td>
<td>Seismic Hazard is often depicted as the magnitude of the Consequence—for example displacement due to Landslide, settlement due to Liquefaction, Amplification due to Ground Shaking—and is commonly depicted for a statistical event aggregated for multiple sources (e.g., 1/2475 return period).</td>
</tr>
<tr>
<td>Demand</td>
<td>A term used to describe the loads (gravity or lateral) a structure must be designed to resist. Codes often describe how the structure or infrastructure is to be designed to resist the demand.</td>
<td>SERs and GERs work together to determine the seismic demand expected to be imparted on a structure due to Local Site Conditions. For example, Code-based accelerations, site-specific accelerations, or displacements due to settlement or Liquefaction can be calculated.</td>
</tr>
<tr>
<td>Risk</td>
<td>See Defined Terms for guideline specific definition. Generally, the product of severity and likelihood of Consequences.</td>
<td>Seismic Hazard needs to be combined with exposure (i.e., building and infrastructure inventory) and vulnerability datasets (e.g., age, type, and condition of the built environment) to determine Seismic Risk.</td>
</tr>
<tr>
<td>Probabilistic Map</td>
<td>A map that considers a variety of Hazards, weighted by respective probabilities.</td>
<td>Seismic Hazard Maps inherently are probabilistic maps, as the local seismicity component includes weighted probabilities of various earthquake locations, magnitudes, and earthquake types (crustal, in-slab, interface).</td>
</tr>
<tr>
<td>Hazard Map (Potential Map)</td>
<td>See Defined Terms for guideline specific definition. Generally, the likelihood and/or magnitude of a Hazard at a given location</td>
<td>Level 3 SM Maps are Hazard Maps in that they show the potential for a Seismic Hazard to occur, by taking Local Site Conditions and local seismicity into account. These SM Maps do not consider the potential for harm or damage; for that, a detailed Seismic Risk assessment must be done that considers the vulnerability of the population, buildings, and infrastructure.</td>
</tr>
<tr>
<td>TERMINOLOGY</td>
<td>DEFINITION (SIMPLIFIED)</td>
<td>EXAMPLE / APPLICATION</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| **Hazard Map** (Susceptibility Map) | - See Defined Terms for guideline specific definition.  
- Generally, the predisposition to be affected by a Hazard at a given location.                                                                                                                               | - Level 1 and level 2 SM Maps are Susceptibility Maps in that they depict the Susceptibility of Seismic Hazards based on Local Site Conditions but do not consider local seismicity.  
- Certain regions in BC are more susceptible to certain Seismic Hazards than others but the likelihood and severity of Consequence is dependent on local seismicity. For example, sites in Metro Vancouver may have the same Susceptibility to Amplification as those in Fort St. John, but the Ground Shaking Hazard is quite different. |
| **Vulnerability**                  | - Likelihood of damage or harm (e.g., to people, buildings, infrastructure, environment)  
- An Input to Risk.                                                                                                                                                                                                 | - Buildings located in higher seismic regions are generally more vulnerable to damage due to earthquakes and associated Seismic Hazards than those located in lower seismic regions.  
- Buildings that were designed to lower seismic loads (e.g., those designed to older Codes) are generally more vulnerable to damage due to earthquakes than those designed to higher seismic loads. |
| **Code**                           | - See Defined Terms for guideline specific definition.  
- Generally, a set of regulations that govern how structures and infrastructure are to be designed and, in some cases, constructed.                                                                                       | - Codes in BC have specific requirements for seismic design and are periodically updated to incorporate new design and construction techniques.  
- Understanding of seismicity and best practice in seismic design is continually evolving; as such, buildings and infrastructure designed to newer Codes tend to be inherently less vulnerable than those designed to previous versions of the same Code. |
1.4 SCOPE AND APPLICABILITY OF THESE GUIDELINES

These guidelines provide guidance on professional practice for Engineering/Geoscience Professionals who use and/or develop SM Maps. These guidelines are not intended to provide exhaustive technical or systematic instructions for how to carry out these activities; rather, these guidelines outline considerations to be aware of when carrying out these activities. Engineering/Geoscience Professionals must exercise professional judgment when providing professional services; as such, the application of these guidelines will vary depending on the circumstances.

Although these guidelines may provide thresholds above which professional involvement is specified as being required, Engineering/Geoscience Professionals must always use their professional knowledge, experience, and judgment to provide the appropriate level of service that is commensurate with the risk of their professional activities to public safety and/or the environment.

These guidelines provide guidance on the use and development of SM Maps for Engineering/Geoscience Professionals with a wide range of engineering and geoscience backgrounds. Engineering/Geoscience Professionals are required to stay informed of, knowledgeable about, and meet the intent of all applicable standards, policies, plans, and practices established by the government or by Engineers and Geoscientists BC, including professional practice guidelines, and are expected to read the guidelines in full.

It is recognized that non-Registrants may also refer to these guidelines. As such, some sections of these guidelines were written with that audience in mind.

The following reading is recommended for non-Registrants to obtain the most value from these guidelines:
- Section 3.0 Introduction to Seismic Hazards and Seismic Microzonation Mapping
- Section 4.1 General Considerations for Use.
- One or more of sections 4.2 Local Community Governing Bodies, 4.5 Building/Infrastructure Providers and Owners, or 4.6 Related Industries, depending on the user.

These guidelines form a consensus of good professional practice at the time they were produced but research and developments are ongoing; Engineering/Geoscience Professionals should keep apprised of new publications and practice trends.

An Engineering/Geoscience Professional's decision not to follow one or more aspects of these guidelines does not necessarily represent a failure to meet professional obligations. For information on how to appropriately depart from the practice guidance within these guidelines, refer to the Quality Management Guides—Guide to the Standard for the Use of Professional Practice Guidelines (Engineers and Geoscientists BC 2023a), Section 3.4.2.

1.5 ACKNOWLEDGEMENTS

Engineers and Geoscientists BC thanks all contributors involved in the development of these guidelines. See Appendix A: Authors and Reviewers for a full list of contributors. Authorship and review of these guidelines does not necessarily indicate the individuals and/or their employers endorse everything in these guidelines.

Engineers and Geoscientists BC also thanks the Institute of Catastrophic Loss Reduction, the University of Western Ontario, and the BC Ministry of Emergency Management and Climate Readiness for their input, technical expertise, and funding support.
2.0 ROLES AND RESPONSIBILITIES

2.1 COMMON FORMS OF PROJECT ORGANIZATION

2.1.1 MAPPING PROJECT TEAM

The makeup of a Seismic Microzonation (SM) Mapping Project team can vary widely depending on the scope of the project and the client, among other factors.

Since SM Mapping Projects typically involve the development of a suite of multi-disciplinary SM Maps, the SM Mapping Project team should consist of appropriately trained, multi-disciplinary Mapping Professionals, such as those with geology, geophysics, seismology, and engineering backgrounds. It is important to clearly outline the responsibilities of the various professionals involved and have one professional who is responsible for coordinating the work of others to make sure there are no gaps in scope.

The SM Mapping Project team may need to rely on others for scoping and/or consultation and engagement during the course of the project, such as the intended users of SM Maps (e.g., Local Community Governing Bodies, geotechnical engineers, structural engineers) and additional Mapping Professionals who provide independent and/or peer review services. Generally, only one Mapping Professional should be responsible for each SM Map, but they may delegate and directly supervise aspects of the work (see Section 6.1.3 Direct Supervision).

At the start of the SM Mapping Project, First Nations with traditional territories or treaty areas in the mapping project area should be engaged in alignment with the Declaration on the Rights of Indigenous Peoples Act. In addition, the SM Mapping Project Team should communicate with other Local Community Governing Bodies as well as industry partners and agencies, to share knowledge and data and to consult on any non-technical expectations or requests for the SM Mapping Project deliverables. Where permission is given, Indigenous knowledges should be incorporated and protected. For example, First Nations may request that culturally significant areas be clearly identified or be protected from viewing in public facing documents. Local authorities may request municipal or regional district boundaries be shown, and geotechnical and structural engineers may have requests related to map visuals.

SM Mapping Project teams should determine the expectations for scope and content at the outset or contract stage of the project, along with the schedule and expectations for draft and final deliverables, with their client and/or funders. SM Mapping Project teams should also communicate regularly with their client and/or funders, where applicable, on both progress (e.g., data collection, analysis, and mapping) and finances.

Lastly, SM Mapping Project teams may be required or inclined to host meetings, webinars, or workshops with First Nations communities, industry partners, colleagues, and others, such as the public, to share findings and progress to date. See Section 4.0 Use of Seismic Microzonation Maps for more information on the appropriate uses of SM Maps for various professionals and related parties.
2.2 RESPONSIBILITIES

This section outlines the responsibilities of the various professionals and related parties involved in the use and development of SM Maps and should be read in conjunction with the area-specific sections throughout the rest of these guidelines, which provide professional practice expectations and obligations of each professional and related party in more detail.

2.2.1 OWNER/CLIENT

The Owner/Client may be a federal or provincial government, Local Community Governing Body (including First Nations government), public building/infrastructure owner, or other organization, who commissions an SM Mapping Project. They are responsible for:

- retaining the appropriate Engineering/Geoscience Professional(s);
- setting clear expectations for the SM Mapping Project deliverables;
- determining which supporting documentation (e.g., reports) will be released with the SM Maps;
- understanding the limitations and appropriate uses of SM Maps; and
- retaining independent reviewer(s), where applicable.

2.2.2 MAPPING PROFESSIONAL

Mapping Professional is used throughout these guidelines as a collective term for an Engineering/Geoscience Professional who is professionally responsible for one or more SM Maps, or a portion of an SM Map. Generally, Mapping Professionals are responsible for:

- understanding data requirements and data collection methodologies, collecting data from appropriate sources, and clearly documenting the collected data, including the sources;
- correcting data points to natural ground, where applicable;
- determining the appropriate methodology for analysis and mapping;
- understanding the client’s project-specific expectations and requirements;
- where appropriate, consulting with SM Map users (e.g., Local Community Governing Bodies, First Nations, Indigenous organizations, geotechnical engineers, structural engineers) to collect any additional expectations or requests for the SM Mapping Project deliverables;
- where appropriate, determining expectations and allowing time for those who were engaged in early-stage consultation to review and provide feedback on how the expectations and requests were incorporated;
- documenting all assumptions and decisions related to data collection, analysis, and map development;
- determining and utilizing appropriate mapping visuals;
- showing active faults on the SM Map, where applicable;
- determining, documenting, and clearly presenting the appropriate limitations of and potential uses for the SM Map;
- developing surficial or Quaternary geological maps and/or Geoscience Data models, where applicable;
- making sure an independent review of the SM Map is done, where applicable;
- preparing a report (e.g., user guide, map notes, title block) to complement the SM Map;
- preparing a report to document a record of the process, any assumptions, and all decisions made; and
- coordinating with other Mapping Professionals involved in the SM Mapping Project, where applicable.
2.2.3 LOCAL COMMUNITY GOVERNING BODIES

As it relates to SM Maps, local authorities should:

- understand the limitations and suitable uses of SM Maps;
- understand that SM Maps do not replace the need for site-specific seismic or geotechnical field investigations;
- consider SM Maps in the development of official community plans (CCPs), zoning bylaws, permitting requirements, and other regulatory functions;
- where required, engage appropriately qualified Mapping Professionals to develop SM Maps; and
- where required, engage appropriately qualified Engineering/Geoscience Professionals to interpret SM Maps.

Local authorities must abide by legislation and regulations applicable to their work. Examples of legislation applicable to local authorities include the Community Charter, the Land Title Act, and the Emergency and Disaster Management Act. A review of the obligations related to such legislation is outside the scope of these guidelines.

First Nations and Treaty Nations have unique governance models and jurisdictional factors. Each Nation is distinct and will determine the appropriate use for their community; this could include considering SM Maps in the development of comprehensive community plans (CCPs), bylaws, and other regulatory functions.

2.2.4 GEOTECHNICAL ENGINEER OF RECORD

The Geotechnical Engineer of Record (GER) has overall responsibility for all geotechnical aspects of the design and associated field reviews for the subgrade support of the building or structure in a project. GERs primarily use SM Maps to gain information on the Local Site Conditions as well as to gauge the Susceptibility or potential of a particular Seismic Hazard; this information can be used to inform project scoping and approaches to obtain additional site-specific information.

The GER must meet the intent of all relevant professional practice guidelines applicable to their practice. As it relates to use of SM Maps, GERs are responsible for:

- understanding the limitations and appropriate uses of SM Maps;
- understanding that SM Maps do not replace the need for site-specific seismic or geotechnical field investigations;
- working with the Structural Engineer of Record (SER) to interpret the data presented in SM Maps, where applicable;
- working with Mapping Professionals to determine the desired output for new SM Maps, where applicable;
- where appropriate, engaging supporting registered professionals or specialists to provide supporting services, such as interpreting SM maps; and
- clearly documenting assumptions related to the use of SM Maps.

2.2.5 STRUCTURAL ENGINEER OF RECORD

The SER has overall responsibility for the design and field review of the primary structural system of a building. SERs primarily use SM Maps to gauge the Susceptibility or potential of a particular Seismic Hazard and whether the Code-based seismic ground motions are appropriate for a site, or whether more information would be beneficial.
SERs must meet the intent of all relevant professional practice guidelines applicable to their practice. As it relates to use of SM Maps, SERs are responsible for:

- understanding the limitations and appropriate use of SM Maps;
- understanding that SM Maps do not replace the need for site-specific seismic or geotechnical field investigations;
- working with GERs to interpret the data presented in SM Maps, where applicable;
- working with Mapping Professionals to determine the desired output for new SM Maps, where applicable;
- where appropriate, engaging supporting registered professionals or specialists to provide supporting services, such as interpreting SM Maps; and
- clearly documenting assumptions related to the use of SM Map.
3.0 INTRODUCTION TO SEISMIC HAZARDS AND SEISMIC MICROZONATION MAPPING

This section provides an introduction to, and background information on, Seismic Hazards and Seismic Microzonation (SM) Mapping in British Columbia (BC).

3.1 SEISMIC HAZARDS

A Seismic Hazard is any Hazard resulting from an earthquake (e.g., Ground Shaking, Liquefaction, Landslide), where a Hazard is a set of conditions or an operational situation that might lead to harm, injury, illness, or death to one or more persons or damage to the environment. Seismic Hazards are an input to Seismic Risk, which considers the vulnerability of the populations, buildings, and infrastructure.

An earthquake itself is caused when parts of the earth’s crust suddenly move relative to another along a fault plane, releasing energy in the form of Seismic Waves. Seismic Waves can pass within the body of the earth, called body waves and are categorized as either Primary Waves (P-Waves) or Secondary Waves (S-Waves or Shear Waves), or along the earth’s surface, called Surface Waves, and have the potential to result in Seismic Hazards.

3.1.1 HAZARDS COMMONLY ADDRESSED IN SEISMIC MICROZONATION MAPPING

The three Seismic Hazards most commonly considered in SM Mapping Projects are:

- Ground Shaking (Amplification)
- Liquefaction
- Landslides

3.1.1.1 Ground Shaking

Seismic ground motions—referred to in these guidelines as Ground Shaking—at a site on the earth’s surface is the result of three main components:

- source effects, including the earthquake magnitude and fault type;
- path effects, including the distance and the geological conditions between the source and the site; and
- Local Site Conditions, comprising the physical properties of the geological materials underlying the site, and the topography.

Amplification of seismic ground motion refers to the increase, or decrease, in Ground Shaking at a site relative to a nearby site condition, commonly, bedrock. Amplification is primarily caused by the differences in the velocity at which seismic Shear Waves travel through different geological materials near the earth’s surface. Consequently, the Shear Wave velocity ($V_s$) of near-surface geological materials is an important property to measure to...
determine the variation in Ground Shaking. Several types of Amplification can occur, but not all are usually considered in SM Maps (Hunter and Atukorala 2015).

These are (see Figure 1):
- broad-band Amplification;
- resonance Amplification;
- Basin Effects; and
- topographic Amplification.

Figure 1: Diagrammatic illustrations of the major Amplification effects associated with soft Soil overlying firm ground or bedrock (modified from Hunter and Atukorala 2015)
Broad-band Amplification occurs when the $V_s$ of the Soil is lower than that of the bedrock (Part A in Figure 1). As Shear Waves pass through the Soil and slow down, they increase in amplitude relative to nearby bedrock sites, thereby causing stronger Ground Shaking. This process is comparable to how ocean waves increase in height as they slow down approaching the shore. Broad-band Amplification can occur at all periods of ground motion. However, the amount by which Ground Shaking is amplified decreases as the amplitude of the incoming Seismic Waves increases, particularly for softer Soils. These effects are more pronounced at short periods of ground motions, which typically affect lower buildings, than at long periods, which typically affect taller buildings. The net effect for sites on thick deposits of soft Soils experiencing strong levels of incoming Seismic Waves is that short period ground motions may be less than those on nearby bedrock sites (i.e., de-amplified), whereas long period ground motions will be greater than on bedrock (i.e., amplified).

Resonance Amplification occurs when Shear Waves become trapped and reverberate in a Soil layer over a rigid base, such as bedrock (Part B in Figure 1). In this case, Amplification occurs at specific periods of ground motions, that are determined by the thickness and $V_s$ of the Soil layer. The Fundamental Site Period ($T_0$) and the Fundamental Site Frequency ($f_0$) are the period and frequency at which resonance occurs, respectively. The magnitude of Amplification of the $T_0$ is determined by the $V_s$ and density contrast between the Soil layer and underlying bedrock. Buildings and other structures that have the same natural period as the site are particularly affected by resonance Amplification.

Both broad-band and resonance Amplification are usually addressed in modern SM Maps. Amplification is estimated in geotechnical practice and SM Mapping Projects by conducting Seismic Site Response Analyses (SSRAs) or implementing Code-based procedures. SSRAs require detailed site-specific data and considerable effort to perform, and so are typically only carried out for critical projects or for select sites in an SM Mapping Project. Procedures in the current Code are based on correlations with the time-averaged $V_s$ from ground surface to 30 m depth ($V_{30}$). The National Earthquake Hazards Reduction Program (NEHRP) in the United States defined five Site Classes based on $V_{30}$ (Building Seismic Safety Council, 1994, 2003). $V_{30}$ and the NEHRP Site Classes are widely used in the Code and SM Maps, but do not directly account for resonance or other types of Amplification. In SM Maps, resonance Amplification is commonly represented by $T_0$.

Broad-band and resonance Amplification are 1D Earthquake Site Effects. However, Amplification can also occur due to the 2D or 3D subsurface geological structures, and these are referred to as Basin Effects (Kramer 1996; Hunter and Atukorala 2015; Part C in Figure 1). Basin Effects are complex, as they are dependent on the basin geometry and the direction of the incoming Seismic Waves, and are a subject of ongoing research. Amplification is the result of Seismic Waves being focused, for example over sediment-filled valleys and geologically young sedimentary basins, and De-amplification is the result of Seismic Waves being defocused, for example over buried hills. Amplification can also occur as a result of Surface Waves being generated along the edges of sedimentary basins and sediment-filled-valleys, where they constructively interfere with incoming Shear Waves (Part D in Figure 1). To date, the only Basin Effect considered in SM Mapping Projects has been Amplification, estimated by detailed computer modelling (Molnar et al. 2014a, 2014b).

Topographic Amplification occurs when Seismic Waves travel over hills and the tops of slopes, and the corresponding De-amplification occurs in valleys (Hough et al. 2010; Bard 2021). Topographic Amplification is complex, as it is dependent on the detailed site geology, the geometry of the topographic features, and the direction of the incoming Seismic Waves. It too is a subject of
ongoing research, and is not considered in most SM Mapping Projects, because predictive models for application on a regional basis have not yet been developed.

Amplification due to Basin Effects and topography can be equal to or greater than 1D types of Amplification that are traditionally considered in SM Mapping Projects. As such, SM Maps that do not depict these types of Amplification should be referenced with caution, and SSI should be pursued.

3.1.1.2 Liquefaction

Liquefaction is the process in which loose, saturated, cohesionless (e.g., granular) Soils—generally sands and low plasticity silts—lose significant strength and stiffness, and behave like a liquid during Ground Shaking. Liquefied sediments are unable to support the weight of structures built over them, which can cause aboveground or shallow structures to settle, and buried structures to float upwards or flow down a gentle slope or towards a body of water (Kramer 1996). Therefore, Liquefaction can cause significant damage to structures built on or in them. In SM Mapping Projects, Liquefaction can be qualitatively assessed by correlations with the sediment type, age, and depositional environment. Quantitative assessments are based on the amplitude of the incoming Seismic Waves and the Soil type and strength, as determined by In Situ and laboratory geotechnical testing. Quantitative assessment may consider only the likelihood that Liquefaction will be triggered, and may not consider the amount of vertical and lateral displacements caused by Liquefaction. Since the likelihood of Liquefaction increases with the amplitude of the incoming Seismic Waves, Amplification of ground motions can increase the likelihood of Liquefaction.

3.1.1.3 Landslides

Landslides are the downward movement of earth material (Soil and rock) along sloping terrain. Earthquake-triggered Landslides occur when Ground Shaking creates temporary stresses that exceed the strength of the earth materials that form the slope.

Topographic Amplification is an important contributor to seismically-induced Landslides. Landslides can occur on any terrain if the conditions are right and can cause significant damage and casualties to people and property.

3.1.2 HAZARDS NOT COMMONLY ADDRESSED IN SEISMIC MICROZONATION MAPPING

Though outside the scope of these guidelines, and not normally considered in SM Mapping Projects, Mapping Professionals and users of SM Maps should be aware of the following Hazards and how they might affect their site or scope of work:

- Co-seismic uplift or subsidence
- Ground rupture due to faulting
- Tsunamis
- Seiches

Co-seismic uplift or subsidence refers to the rapid vertical movement of a large area of the earth's surface during an earthquake and is a consideration in low-lying coastal areas (Clague 1996). Subsidence has the potential to cause flooding and therefore typically represents the greater Hazard of the two.

Instances of co-seismic uplift and subsidence close to one metre in magnitude were documented along the west coast of Vancouver Island and in south coastal BC approximately 300 years ago. In Puget Sound approximately 1000 years ago, co-seismic uplift and subsidence close to seven metres in magnitude was documented. These events are also documented in First Nations' oral histories and passed on through generations.

Ground rupture due to faulting occurs where movement on a fault at depth propagates to the surface causing visible, vertical, and/or lateral displacement of the earth's surface along the fault line. It has not been considered in SM Mapping Projects in BC because, until recently, none of the faults observed at surface had been known to be potentially active. However, some have been identified recently: the Leech River fault in and west...
of Greater Victoria; the Elk Lake fault, located in Saanich; and the Beaufort Range fault, located in central Vancouver Island near Port Alberni (Morell et al. 2017, 2018; Lynch 2017; McLeod 2021; Harrichhausen et al. 2021, 2022). More potentially active surface faults capable of causing ground rupture are likely to be identified in the future. Where potentially active faults can be accurately located, Mapping Professionals should consider showing them on the SM Map.

Tsunamis are ocean waves triggered by large-scale displacement of the sea floor, due to large earthquakes that occur near or under the ocean, volcanic eruptions, submarine Landslides, or by onshore Landslides in which large volumes of debris fall into the water. Tsunamis caused by earthquakes are a significant Seismic Hazard in coastal regions of BC, particularly as a result of earthquakes immediately offshore. Distant earthquakes can even cause tsunamis and damage to coastal communities, such as in Port Alberni from the 1964 Alaskan earthquake.

Seiches are standing waves in an enclosed body of water, such as a lake. They can be caused by earthquakes, wind, or submarine Landslides and can result in flooding along the shoreline of the enclosed body of water. Seiches are difficult to predict because they occur where long period waves match the natural oscillation period of the water body. They can be caused by distant earthquakes, as Seismic Waves from a very large earthquake can travel thousands of kilometres.

3.2 OVERVIEW OF SEISMIC HAZARDS IN BC

The current understanding of offshore plate tectonics resulting in Seismic Hazards in BC is depicted in Figure 2.

In Southwestern BC, Seismic Hazards result from the Cascadia Subduction zone, where the Juan de Fuca and Explorer Plates are being subducted, or thrust, beneath the North American Plate. This tectonic environment results in three different earthquake types, each with its own characteristics (i.e., the intensity of Ground Shaking, the magnitude, the distance to fault rupture, and the duration of Ground Shaking). The earthquake types (sources) are:

- Shallow crustal earthquakes that occur in the North America Plate, with depths typically 30 km or less.
- Deep in-slab earthquakes that occur in the subducting Juan de Fuca Plate, with depths typically at 30–60 km depth.
- Subduction interface earthquakes that occur at the interface of the North America and Juan de Fuca Plates.

In Northwestern BC, Seismic Hazards result from the strike-slip fault boundary between the Pacific and North America Plates, marked by the Queen Charlotte Fault. The Queen Charlotte Fault extends more than 500 km northward from the offshore region to the west of Vancouver Island, to the west of Haida Gwaii, to the southern extent of the Fairweather Chatham Strait-Denali fault systems of southeast Alaska (Riddihough and Hyndman 1991).

In Central and Eastern BC, away from the offshore plate tectonic boundaries, the historical seismicity consists of low and shallow crustal earthquakes. In northeast BC, there has been a recent increase in seismicity due to petroleum industry activity, primarily, hydraulic fracturing and wastewater injection.
In the Code, Seismic Hazard Maps show the regional variation in seismicity expressed as the amplitude of Ground Shaking that has a 2% probability of being exceeded in 50 years (1/2475 return period), on a specified $V_{S30}$. The Seismic Hazard Maps cover a range of ground motion measures, including spectral accelerations ($S_a$) at different periods, peak ground acceleration (PGA), and peak ground velocity (PGV). One of these Seismic Hazard Maps, depicting the variation in PGA across Canada, is shown in Figure 3. Details of the seismic model used to create this map are summarized below in Section 5.1.3.1 Data from Earthquakes.

Figure 2: Tectonic plate setting of the west coast of BC (modified from Turner et al., 1998)

Figure 3: Seismic Hazard Map showing peak ground acceleration with a probability of exceedance of 2% in 50 years (Source: National Building Code of Canada 2020)
3.3 SEISMIC MICROZONATION MAPPING

The effects of earthquakes vary considerably depending on Local Site Conditions, which can be identified using available geological and geophysical data. Although it is not possible to predict the exact timing or magnitude of earthquakes, it is possible to predict where the effects of earthquakes will be greater or lesser.

SM Maps depict variations in Local Site Conditions by subdividing an area into relatively homogeneous microzones, or areas of similar Seismic Hazard. Several different Seismic Hazards are usually considered in SM Mapping Projects; as such, no single SM Map can display all the Earthquake Site Effects. For this reason, SM Maps are usually prepared as suites of maps, with each map showing a different Seismic Hazard, or a different aspect of the same Seismic Hazard. See Appendix B: Examples of Seismic Microzonation Maps for a select list of possible SM Maps.

SM Maps can help inform regional planning, emergency planning, and post-disaster recovery planning. They can also be utilized for preliminary assessments, feasibility studies, conceptual designs, and project planning/scoping. SM Maps do not replace the need for site-specific seismic or geotechnical field investigations where these would normally be required.

SM Maps consider natural Hazards, and do not usually reflect human-made alterations to the ground surface. They also do not reflect non-natural Hazards, such as fires resulting from ruptured gas lines.

SM Maps depict Seismic Hazard, not Seismic Risk, but can be inputs to inform Seismic Risk assessments for a region, in combination with information on the distribution and vulnerability of the population, buildings, and infrastructure. Users and developers of SM Maps must understand the limitations of a particular SM Map and may need to source or develop other resources to suit their Hazard-assessment needs. SM Maps are highly technical documents that should be referenced with caution by the public.

SM Maps are based on interpretations of seismological, geological, geotechnical, and geophysical data (termed Geoscience Data), and are subject to revision as more data become available. Where these data are insufficient, mapping may then be based on local geological knowledge and geological principles.

For the reasons discussed above, it is important that users carefully review all accompanying reports for an SM Map, to ensure they understand the Seismic Hazards that are and are not included, the level of mapping detail, the uncertainties and limitations of the maps, and their appropriate uses. For more detail on the appropriate uses of SM Maps, see Section 4.0 Use of Seismic Microzonation Maps.

Although they have not been widely distributed, an extensive collection of SM Maps has been developed for BC, which can provide insight to the future development and application of SM Maps. The history of the use and development of SM Maps in BC, relevant recent advances in eastern Canada, and SM Maps produced to date in BC are shown in Appendix C: History of Use and Development of Seismic Microzonation Maps in BC.

3.4 INTRODUCTION TO SEISMIC MICROZONATION MAP LEVELS

SM Maps can be prepared at different levels of detail, depending on the objectives, budget, and time constraints of the SM Mapping Project. The concept of a three-level system was introduced by the Technical Committee for Earthquake Geotechnical Engineering (International Society of Soil Mechanics and Geotechnical Engineering) in 1993 and was updated in 1999. The definitions of each level have been revised for the purposes of these guidelines as described below and summarized in Table 2.
The increase in each SM Map level conveys the increasing quality and quantity, as well as the increasing complexity of technical analysis. The reliability and complexity of appropriate use of an SM Map increases with the increasing complexity of the SM Map itself.

It is beneficial to distinguish Seismic Susceptibility Maps and Seismic Hazard Maps. Seismic Susceptibility Maps show the variation in the physical properties of the local geological materials related to Seismic Hazards, such as $V_{30}$, but do not consider the local seismicity. Seismic Hazard Maps take local seismicity into account—based on the ground motions prescribed by the current national seismic model or similar models—in addition to the physical properties of the local geological materials. Seismic Hazard Maps provide the basis for comparing Seismic Hazards between areas of different seismicity, whereas Susceptibility Maps do not. For example, sites in Metro Vancouver may have the same Susceptibility to Amplification as those in Fort St. John, but the Ground Shaking Hazard is quite different.

At their simplest, the levels of SM Maps can be defined as follows. These levels are discussed further in Table 2 and sections 4.3.1 to 4.4.3 below.

1. Level 1 SM Maps are Susceptibility Maps. They rely primarily on surficial geological maps as their primary data source along with a limited amount of subsurface data.
2. Level 2 SM Maps can be either Susceptibility Maps or Hazard Maps. They are normally based on surficial geological maps and require a moderate amount of subsurface data.
3. Level 3 SM Maps are Hazard Maps. They require an abundance of advanced analyses and Geoscience Data and are based on detailed subsurface geological maps.

Table 2: Concept of Seismic Microzonation Map Levels

<table>
<thead>
<tr>
<th>Type of Map</th>
<th>LEVEL 1</th>
<th>LEVEL 2</th>
<th>LEVEL 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Statement</td>
<td>Level 1 SM Maps are Susceptibility Maps based on generalized correlations of Seismic Hazard with age, lithology, and the depositional environment of surficial geological materials. These maps are normally based on surficial geological maps, or proxies, and a limited amount of subsurface data.</td>
<td>Level 2 SM Maps are either Susceptibility Maps or Hazard Maps and require subsurface geological data to confirm the thicknesses of geological units and area-specific data on physical properties of geological materials. These maps are normally based on surficial geological maps and a moderate amount of subsurface data relevant to Seismic Hazards.</td>
<td>Level 3 SM Maps are Hazard Maps and require advanced analyses that are based on extensive Geoscience Data and simulations. These maps are normally based on detailed subsurface geological maps or models.</td>
</tr>
<tr>
<td>Complexity</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Scale</td>
<td>1:250,000 to 1:50,000</td>
<td>1:100,000 to 1:20,000</td>
<td>1:25,000 to 1:5,000</td>
</tr>
</tbody>
</table>
3.4.1 LEVEL 1 SEISMIC MICROZONATION MAPS

Level 1 SM Maps are Susceptibility Maps and are based on existing and readily available datasets. These datasets include surficial geological and geomorphological maps and reports, or topographic maps and digital elevation models (DEMs). Additional data may include that from historical earthquakes. Level 1 SM Maps may be based on generalized correlations of Susceptibility with Soil type, age, and depositional environment of the surficial geological deposits. Level 1 SM Maps may include some data on the physical properties of the local geological materials, but they are often too few or of low quality.

The scale of a level 1 SM Map may be in the range of 1:250,000–1:50,000. The time and effort required for a typical level 1 SM Map could take anywhere from several hours to several weeks or months to develop.

3.4.2 LEVEL 2 SEISMIC MICROZONATION MAPS

Level 2 SM Maps exist on a sliding scale between level 1 and level 3 SM Maps and can vary significantly depending on the quantity and quality of data used, as well as the complexity of the analysis done. Level 2 SM Maps incorporate area-specific data on the thickness and physical properties of the near-surface geological materials relevant to Seismic Hazards. They may be either Susceptibility Maps or Hazard Maps. Level 2 Susceptibility Maps can range in detail from those that rely on existing surficial geological maps to define the microzones, but with sufficient subsurface data to locally confirm sediment thicknesses and physical properties, to maps based on abundant subsurface data so that microzones better represent subsurface geological conditions. Level 2 Hazard Maps contain the same characteristics, but also include a simple or limited quantitative analysis of Seismic Hazards.

A level 2 SM Map may involve some detailed interpretation and spatial, numerical modelling, but will likely require a number of assumptions in areas without sufficient high-quality data. Level 2 SM Mapping Projects may involve the acquisition of new geophysical, geological, and geotechnical data.

The scale of a level 2 SM Map may be in the range of 1:100,000–1:20,000. A level 2 SM Map can take anywhere from several months to several years to develop.

3.4.3 LEVEL 3 SEISMIC MICROZONATION MAPS

Level 3 SM Maps are Hazard Maps. They rely on an abundance of Geoscience Data that permit the creation of maps that represent the subsurface geological conditions relevant to Seismic Hazards, as well as spatial, numerical Seismic Hazard analyses of the ground conditions to calculate the variation in Ground Shaking, or likelihood of Liquefaction or Landslides. The numerical analyses rely on sufficient quantity and quality of data, as well as site-specific multidisciplinary investigations and computer-based analyses performed with different numerical methods. Level 3 SM Maps generally require the acquisition of new geophysical, geological, and geotechnical data.

Level 3 SM Maps are typically carried out on areas characterized by high Seismic Hazard and/or economic and social relevance. The scale of a level 3 SM Map may be in the range of 1:25,000–1:5,000. A level 3 SM Map typically takes several years to develop, depending on the number and complexity of geological maps that need to be developed for predictor variables, in addition to the Hazard Maps themselves.
3.5 RISK MANAGEMENT IN SEISMIC MICROZONATION MAPPING

Although SM Maps represent Seismic Hazard rather than Seismic Risk, one of their primary objectives is to contribute to the reduction of Seismic Risk for human safety, buildings, infrastructure, and the environment, including related adaptation, mitigation, and emergency management planning activities. SM Maps should be combined with exposure (e.g., building and infrastructure inventory) and vulnerability datasets (e.g., age, type, and condition of the built environment) to determine the Seismic Risk (Hobbs et al. 2023). As a tool that supports Risk reduction, the success or failure of SM Maps can largely be judged by the degree to which their use aids in the reduction of human exposure to Seismic Risk and in societal recovery from a major earthquake. Seismic Risk reduction can be structural, for example, by upgrading or replacement of buildings and infrastructure, or non-structural, for example, by avoiding development in Hazardous areas and developing emergency response plans.

The following discussion uses an Ishikawa (fish bone) diagram approach to conceptually illustrate how to optimize the use of SM Maps in Seismic Risk assessments. Figure 4 shows an illustration of the following approach.

The main horizontal stem in the Ishikawa is the Seismic Risk itself and the vertical branch off this stem is a completed SM Map.

The first horizontal branch off the vertical SM Map branch represents Seismic Hazards that are not included in the project. SM Maps do not usually address all Seismic Hazards; as such, the Risks associated with these Hazards will not be analyzed and thereby will remain unchanged. Mapping Professionals should clearly document which Seismic Hazard(s) have been addressed in an SM Map, to reduce the chance of incorrect assumptions by users.

The second horizontal branch represents when SM Maps are not used to evaluate Seismic Risk. In this case, the exposure to Seismic Risk also remains unchanged. The negative consequences of ignoring available SM Maps are more than just financial, because the cost of producing the ignored SM Maps then effectively represents a misallocation of funds that could otherwise have been used to mitigate Seismic Risk by other means, such as site-specific mitigation projects. To avoid these consequences, Mapping Professionals should present the results in ways that are intelligible and useful to all users (Fyfe and Molnar 2020). The technical details in SM Maps are important, as are descriptions in everyday terms for non-technical users. Mapping Professionals should communicate directly with potential users over the course of the SM Mapping Project, not only to help users understand how the maps could be used, but also to gain insight into the users’ needs.

The third horizontal branch represents when SM Maps are misused or misinterpreted in Seismic Risk analyses, most commonly because the mapped Seismic Hazard is misinterpreted as Seismic Risk. In many cases, newer buildings located in high Hazard areas and built to the modern seismic Code provisions present less Risk than older buildings built to meet past seismic Code provisions. Understating Risk is more serious than overstating Risk because high Risk areas may remain unknown and therefore unremedied. However, the negative consequences of overstating Risk are more than just financial, as noted above, as they represent a misallocation of funds. Mapping Professionals should make appropriate recommendations for an SM Map’s uses clear to users—for example, on the SM Map or in the accompanying report—to avoid misunderstandings.

The final branch represents when SM Maps are used correctly, with an appropriate Seismic Risk assessment. In this case, the likelihood of Risk being misrepresented is lower, though it cannot be completely eliminated. While minimal with the appropriate use of SM Maps, the inherent limitations and potential for misrepresentation of SM Maps could
be the result of professional errors and/or omissions, or geological uncertainty. Professional errors and omissions can be addressed by quality management protocols, including checking and independent review. However, due to data limitations and the inherent variability of geological materials, geological uncertainty cannot be eliminated. Consequently, there will always be areas where Hazard, and implicitly, Risk, is understated or overstated. The extent to which this occurs can be reduced by preparation of Higher-Level SM Maps, which require more extensive Geoscience Data and detailed analysis. Mapping Professionals should clearly communicate the assumptions, limitations, and appropriate uses of SM Maps to users.

---

**Figure 4:** Conceptual illustration on how to optimize the use of Seismic Microzonation Maps in Seismic Risk assessments.
4.0 USE OF SEISMIC MICROZONATION MAPS

4.1 GENERAL CONSIDERATIONS FOR USE

To appropriately use Seismic Microzonation (SM) Maps, Engineering/Geoscience Professionals must understand the originally intended use, level of mapping, qualifications, and limitations of each SM Map, then apply professional judgment to determine the extent to which they should be used or relied upon in a particular situation. Users of SM Maps should:

- refer to any accompanying reports or supporting documentation to understand the assumptions and limitations of each SM Map;
- review the data types and sources, and the types of analyses conducted;
- review the spatial density of data points to assess the level of uncertainty inherent in the SM Map; and
- as required, seek help from other Engineering/Geoscience Professionals to understand and interpret the SM Map.

As discussed in Section 3.4 Introduction to Seismic Microzonation Map Levels, SM Maps can be prepared at different levels of detail, depending on the objectives, timeline, and budget constraints of the SM Mapping Project. They are prepared using data collected from sources of varying accuracy and spatial distribution. Users must understand that every SM Map is an interpretation of data and inherent uncertainties exist in each map due to the variation in the levels of geological mapping, the spatial distribution of different data sets, the quality of available data from previous investigations, and the interpretations of geological, geotechnical, and geophysical data.

SM Maps are subdivided into map units or microzones, which are areas with similar geological, Susceptibility, or Hazard characteristics. A map unit or microzone may consist of one or more polygons. The following should be considered when relying on the boundaries of polygons:

- Boundaries of map units are approximate and may include smaller unrecognized areas of other map units.
- Sites with unusual properties may exist within a map unit. Consequently, the conditions at a specific site could differ from those shown on SM Maps.
- Boundaries of geological map units and microzones are subject to revision as more data becomes available.
- The locations of sites providing subsurface geological, geotechnical, and geophysical data used to create the SM Map may be shown on Higher-Level SM Maps. Where these data are shown, uncertainty at a specific site may be qualitatively estimated by the user by the proximity to and local density of these subsurface data points, as well as the proximity to geological and other boundaries shown on the SM Map.

The locations of the Geoscience Data points used in SM Mapping Projects are commonly shown within the SM Maps, particularly in Higher-Level SM Maps. These data are used to represent conditions around the site where they were located, not just the site itself. Users...
must recognize that if these locations represent large construction projects, the data represent conditions at the site that existed prior to construction, and that the conditions at these sites are likely to have changed during construction, due to ground improvement, or excavation of basements or underground parking.

SM Maps do not usually directly consider the seismic stability of dams, dikes, or other large, engineered structures. For these sites, users of SM Maps should defer to SSIs.

If a Seismic Hazard is identified at a site, it does not mean that the site is unsuitable for use. It simply means that the Seismic Hazard should be confirmed and addressed.

SM Maps should be accessed and used in accordance with the applicable laws and regulations, ensuring compliance with copyright and intellectual property rights, while respecting the principles of licensing agreements, and any other legal framework and best practices (e.g., The First Nations Principles of ownership, control, access, and possession) that govern their distribution and use. In all cases, the source of information (the map's citation or its authors) should be cited or referenced. Since the data underlying the map development may evolve with time, it is also essential to identify the date the map was produced and, for electronic maps that are regularly updated, the date last accessed.

4.2 LOCAL COMMUNITY GOVERNING BODIES

Seismic Hazards are one of many natural Hazards in British Columbia (BC) that Local Community Governing Bodies should consider when planning land use and emergency response, developing policies, reviewing developments, and managing infrastructure.

Local Community Governing Bodies can use SM Maps to better understand the Susceptibility of a geographic area to Seismic Hazards. SM Maps are not Seismic Risk maps, as they do not contain information on the vulnerabilities of the population, buildings, and infrastructure, but they can be used as an input when conducting Seismic Risk assessments. An example of a Seismic Risk assessment is the City of Victoria’s Citywide Seismic Vulnerability Assessment (Ventura and Bebamzadeh 2016) that overlaid an SM Map with a generalized building inventory. See for more information on Seismic Hazard versus Seismic Risk as well as a discussion on the purpose and appropriate uses of SM Maps.

Planners, Engineering/Geoscience Professionals, emergency managers, and their colleagues, all have a role to play in reducing Seismic Risk through structural and non-structural means by applying tools, such as land use designations, official community plan (OCP) or comprehensive community plan (CCP) policies, capacity building measures, response plans, retrofit programs, bylaws, regulations and standards, and more. Where SM Maps exist, Local Community Governing Bodies should consider using them as the basis of Risk assessment.

However, SM Maps do not currently exist for all communities in BC. Where they do exist, Local Community Governing Bodies should consider making SM Maps and their supporting documentation available as open data. Where they do not exist, Local Community Governing Bodies should consider commissioning the development of them.

As the collection of geotechnical data is a resource intensive step in SM Mapping Projects, Local Community Governing Bodies should consider archiving geotechnical data and reports in their database as they are completed, to facilitate the development of future SM Maps.
The following guidance on the use of SM Maps for Local Community Governing Bodies may also be applicable to the use of other Hazard measurement and identification tools.

4.2.1 SEISMIC HAZARD SPECIFIC CONSIDERATIONS

As discussed in Section 3.1 Seismic Hazards, Ground Shaking, Liquefaction, and Landslide are the three most commonly mapped Seismic Hazards. The use of SM Maps in BC is relatively new, but consideration of natural Hazards in Local Community Governing Body planning and policy making is not. Many Local Community Governing Bodies have experience creating policies for other natural Hazards, such as floods and Landslides (not seismically-induced). First Nations communities have a deep understanding of natural Hazards and key environmental elements within their territories. The principles utilized in existing decision-making processes may be used when considering the Seismic Hazards presented in SM Maps as well.

The following sections describe the importance of considering each Seismic Hazard in policies, and how Local Community Governing Bodies might do so. For all Seismic Hazards, Local Community Governing Bodies should understand the Susceptibility and effects that could occur at a specific location, so that they can create policies and bylaws for building and infrastructure development, as well as an emergency response that best protects the life safety of people within their communities.

4.2.1.1 Ground Shaking

Assumptions about the geologic ground conditions are made to develop the Code-based seismic design spectrum. However, certain conditions that are prevalent in BC—namely, soft Soil over bedrock and deep basins—may cause Site Amplification at certain periods that exceeds what is estimated by the Code. If not understood and accounted for in structural design, buildings and infrastructure may underperform in the event of an earthquake. As such, Local Community Governing Bodies can develop policies based on the Seismic Hazards depicted in SM Maps that require site-specific information to be obtained and used by Engineering Professionals where Ground Shaking Susceptibility is high. Similarly, Local Community Governing Bodies can obtain information about Fundamental Site Periods ($T_s$) from SM Maps and use this to create zoning policies, with the understanding that short buildings are more susceptible to damage from short periods and that taller buildings are more susceptible to damage from long periods.

4.2.1.2 Liquefaction

If there is Liquefaction in an area, then it is typically widespread in that entire area. Therefore, it is generally not realistic to avoid developing buildings and infrastructure in those areas, as it often is for areas susceptible to Landslides or floods. However, Local Community Governing Bodies should consider creating policies and zoning bylaws whereby critical infrastructure is protected from the Liquefaction either by avoidance or by a selection of alternative alignment for critical linear infrastructure.

SM Maps can help Local Community Governing Bodies understand when a site-specific Liquefaction study would be beneficial, or should be required, prior to development. They can also help planners and Engineering/Geoscience Professionals get a sense of the effect of Soil amelioration, and opportunities for Seismic Risk mitigation, as well as help emergency managers consider the potential intensity of debris management in various areas.

If avoiding development in certain areas is not possible, Local Community Governing Bodies should consider creating policies and regulations that require prescriptive or performance-based Seismic Risk mitigation of the Seismic Hazard(s).
For example, Local Community Governing Bodies could require geotechnical and/or structural measures for buildings (e.g., ground improvement, raft slabs, or tied footings) and prescriptive design requirements (e.g., use of flexible joints and joint restraints for pipelines) for linear infrastructure.

4.2.1.3 Landslide

Landslides are typically localized but can cause significant damage to buildings and infrastructure when they occur. SM Maps help to identify the Susceptibility of areas to seismically-induced Landslides.

The likelihood of Landslides increases as the intensity and frequency of heavy rainfall increases (e.g., due to climate change). Mitigating features for seismically-induced Landslides may be effective for climate change induced Landslides, and vice versa. Common mitigation strategies include identifying the Hazard and developing steep slope Hazard development permit areas in OCPs, avoiding the Hazard through setbacks, and mitigating the Hazard with engineered structures (e.g., retaining walls and deep foundations).

4.2.2 CONSIDERATIONS FOR REGULATORY DOCUMENT DEVELOPMENT

While most governing legislation (e.g., the Community Charter) does not expressly require local authorities to consider Seismic Hazards, local authorities should strive to decrease the Seismic Risk to an acceptable level for land use and infrastructure planning. Reducing Seismic Risk can be done by reducing exposure to the Seismic Hazard (e.g., avoiding locating infrastructure and people in Hazard prone areas) or by reducing the vulnerability of the infrastructure to the Hazard (e.g., making structures less susceptible to damage). New Risks should be avoided where possible, and existing Risks should be reduced.

4.2.2.1 Seismic Hazard Planning and Policies

Local Community Governing Bodies have the ability to develop Seismic Hazard-specific requirements. To do this, as per the first principle of the Sendai Framework, the Seismic Hazard needs to be understood. SM Maps are a tool that Local Community Governing Bodies can use to improve knowledge of the relative Seismic Hazards across a jurisdiction and inform policies that strive to reduce overall Seismic Risk. The areas of highest Seismic Hazard on an SM Map should be targeted as a priority for more stringent policy, site-specific investigations (SSIs), regulations to reduce vulnerability, and thoughtful land use designations that reduce Risk. When considered alongside other datasets, such as the vulnerability of the population, buildings, and infrastructure, SM Maps can help Local Community Governing Bodies to understand existing Seismic Risk and to develop priorities and policies for retrofits and infrastructure renewal. Local Community Governing Bodies should consider how existing and new policies affect different populations and consider utilizing an analysis tool, such as Gender-based Analysis Plus.

The Local Government Act provides that OCPs should include policies that restrict use on land that is subject to high Hazard conditions and that OCPs can include development permit areas (DPA) for the protection of development from hazardous conditions. It is common for local authorities to establish and enforce policies related to DPAs for geological and flood Hazards. Local Community Governing Bodies can use information obtained from SM Maps to inform general policies (e.g., CCPs, OCPs, and DPAs) and should consider including requirements for site-specific information to be acquired before designs are completed and permits are granted.

Zoning regulations can restrict land-use to low-Risk activities for a particular Seismic Hazard, require additional studies to confirm acceptable Risk, and/or specify mitigative strategies to minimize Hazards or
Risks identified. Local authorities should consider adding policy wording and identifying SM Maps in OCPs so that they can be considered in rezonings to support the design of appropriate Hazard mitigation measures.

The state of practice surrounding the definition and mitigation of Seismic Hazards is evolving. Local Community Governing Bodies should consider periodically updating policies to suit the current state of practice and available resources.

4.22.2 Permitting/Regulatory

Local Community Governing Bodies may develop regulations requiring professionals to certify that land and buildings are safe for the intended use. In some legislation, those professionals are referred to as qualified professionals; these guidelines refer to them as Engineering Professionals. SSIs, Seismic Hazard, and/or Seismic Risk assessments may be required by Local Community Governing Bodies prior to the issuance of development permits, subdivision approval, rezoning approval, building permit issuance, and other regulatory phases. In the context of establishing permitting regulations for Engineering Professionals, Local Community Governing Bodies should consider developing and publishing guidance that defines when an SSI is required.

Geotechnical Engineers of Record (GERs) may use SM Maps as a starting point for scoping the level of geotechnical investigation required for a site. Local Community Governing Bodies can set out requirements for Seismic Hazard assessments and SSIs that GERs must fulfill when completing these reports. Where appropriate, local authorities can register restrictive covenants for specific Hazards with the GER’s report attached, to make sure that prospective purchasers and future landowners have this information readily available. This mechanism is most appropriate for new development.

4.22.3 Servicing Agreements

To accommodate growth, Local Community Governing Bodies can accept new infrastructure as part of development. Local Community Governing Bodies may look to SM Maps for information when developing servicing agreements and to Engineering Professionals when determining associated Risk tolerance levels. There are very few examples of publicly-stated Risk tolerance criteria. Therefore, the identified Risk tolerance conditions for subdivision and building permits should go through an engagement process with community members.

4.22.4 Community Engineering Standard Development

Many Local Community Governing Bodies establish engineering standards for new infrastructure within their jurisdiction. SM Maps should be considered in establishing these standards to mitigate Seismic Risk based on the spatially varying level of Hazard identified for the jurisdiction.

4.22.5 Asset Management

Reviewing Seismic Hazard exposure and Seismic Risk is an integral part of asset management, to assess the vulnerability and likelihood of infrastructure failure and the associated Consequences. SM Maps can be used alongside other Hazard and Risk information for high level asset planning to support the prioritization of critical infrastructure resilience assessments and to improve Risk-based renewal decisions.

SM Maps, coupled with an understanding of infrastructure vulnerability to Ground Shaking, Liquefaction, and Landslide, can help asset managers to identify where the highest likelihood of failure during a seismic event may be. Local Community Governing Bodies may consult with a Structural Engineer of Record (SER) to understand building or bridge performance, commensurate with the level of detail required when assessing the Risk of a
community's building stock or bridge inventory. Investment in assets—for example, by incorporating mitigation measures or relocating infrastructure to areas of lower Seismic Hazard—can reduce Seismic Risk.

See Section 3.5 Risk Management in Seismic Microzonation Mapping and Section 4.2.3 Emergency Management and Recovery for more information on Risk and emergency management, respectively.

4.2.3 EMERGENCY MANAGEMENT AND RECOVERY

Emergency management consists of mitigation, preparation, response, and recovery from emergencies (Emergency and Disaster Management Act). Local Community Governing Bodies are responsible for emergency management and recovery within their jurisdictions. Local authorities are required to adhere to the Emergency and Disaster Management Act. First Nations develop their own procedures and regulations regarding emergency management.

Regulated entities under the Emergency and Disaster Management Act must identify all reasonably foreseeable hazards and assess the extent of the Risk that each Hazard presents; the potential consequences for persons or property, or for objects or sites of heritage value, if an emergency occurs; and any prescribed matters. While SM Maps do not illustrate Seismic Risk, they provide a relative depiction of the anticipated intensity of the Seismic Hazard. SM Maps are appropriate for use in a regional or community-wide Seismic Hazard assessment. Areas with high Seismic Hazard or high Seismic Risk can be prioritized for mitigation, response, and recovery planning (or action).

Emergency managers should consider running simulation exercises to improve emergency preparedness for a given Hazard scenario, by utilizing SM Maps as input. As necessary, more response supplies and rapid damage assessors may be allocated to higher Seismic Hazard areas. Other information an emergency manager may require includes debris volumes, interruption of critical infrastructure, and estimates of casualties and injuries. These inputs and the results of the Hazard scenario analysis can assist in post-disaster recovery planning. When completing exercises for post-disaster response and recovery training, special consideration should be given to the identified high-Risk areas.

Another important role for all levels of government is the disclosure of Hazard-related information, as well as education campaigns, to help individuals and businesses prepare for Seismic Hazards.

4.2.4 SEISMIC HAZARD MITIGATION POLICY AND PLANNING EXAMPLES

There are a variety of approaches for Local Community Governing Bodies to consider in mitigating the Seismic Risk. Availability and use of public SM Maps has been limited to date, but it is anticipated that there will be an increase following the publication of the Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP) and these complementary guidelines. Local Community Governing Bodies should familiarize themselves with the following resources and examples, which may form the basis of or be inspiration to create or update their own SM Maps, bylaws, or Risk assessments.

- Professional practice guidelines such as the Professional Practice Guidelines—Landslide Assessments in British Columbia (Engineers and Geoscientists BC 2023).
- The City of Victoria undertook a Citywide Seismic Vulnerability Assessment (Ventura and Bebamzadeh 2016) in which existing SM Maps were overlayed with existing building databases and supporting infrastructure to estimate potential damage after an earthquake.
The District of North Vancouver has DRAs for wildfire and slope hazard and had a Seismic Risk profile completed in partnership with Natural Resources Canada (Journeay et al. 2015; Wagner et al. 2015). The District of North Vancouver also has land-use maps related to Landslide, Liquefaction, and Fire.

The City of Vancouver has implemented a number of policies within their bylaws to mitigate risk to the building stock. For example, per Table A-11.2.1.2.-B in the Vancouver Building By-law, existing buildings with less than 30% of seismic resistance (compared to seismic design requirements of the current Code) must be upgraded to have at least 50% seismic resistance (per the current Code).

The City of New Westminster has a bylaw that requires areas of known subsidence concern to verify the information provided on regional-scale maps and ensure SSIs are collected for the building design.

Indigenous Services Canada actively provides funding for First Nations, through their Emergency Management Assistance Program (EMAP), to develop emergency management plans, training, all-hazard assessments, and more. EMAP supports collaboration with other governments and agencies, recognizing that Hazards are often not isolated to one community.

The First Nations’ Emergency Services Society has evolved, since its beginnings in 1986 as the Society of Native Indian Fire Fighters of BC, to meet the growing diversity of emergency services needed on-reserve.

In the United States, the City of Seattle has a director’s rule that provides information and requires consideration for Basin Effects and the City of San Francisco has an all-Hazard resilience plan and seismic-specific building retrofit incentive programs.

Local Community Governing Bodies should keep up to date and familiarize themselves with other policies developed after the publication of these guidelines.

See Section 8.4 Related Documents and Resources for a list of other SM guidelines and a list of document and resources related to the use and development of SM Maps.

### 4.3 GEOTECHNICAL ENGINEERING PROFESSIONALS

GERs should have a high-level understanding of Seismic Hazards and SM Maps, as discussed in Section 3.0 Introduction to Seismic Hazards and Seismic Microzonation Mapping. GERs should understand the intent, assumptions, and limitations of any SM Map before relying on the information contained within, including the concept of suites of SM Maps and different SM Map levels, and the appropriate use of each as it relates to geotechnical engineering (see Section 4.1 General Considerations for Use). Specifically, GERs should be aware of the increasing quality of the maps that aligns with the increasing map levels as a result of increasing data quality, quantity, and density as well as increasing complexity of analysis to produce the calculated Seismic Hazard. The guidance in this section complements the guidance in Section 5.0 Development of Seismic Microzonation Maps and applies in principle regardless of whether an SM Map is labeled with a specific level.

#### 4.3.1 GENERAL CONSIDERATIONS

The guidance in this section for GERs using SM Maps is complementary to the Professional Practice Guidelines—Geotechnical Engineering Services for Building Projects (Engineers and Geoscientists BC 2021). SM Maps do not replace the need for an SSI or the need for a GER on a project. The existence of SM Maps does not drastically change the typical workflow of the GER, but it can simplify the investigation and design process by providing more detailed data at an earlier stage. SM Maps are appropriate for use in schematic design and may be considered for use in the early parts of the design development stage, prior
to obtaining site-specific information required for the detailed design and contract document phases. GERs should consider using SM Maps as early as the proposal stage of a project, to help in identifying Local Site Conditions and any associated Seismic Hazards. SM Maps are an improvement over historic Susceptibility or geological maps (e.g., GeoMap Vancouver) for Seismic Hazard assessment. GERs may use Seismic Susceptibility Maps to identify the need for an SSI of certain Seismic Hazards but should use Higher-Level SM Maps when available. The GER should document all sources of data used in their own work and clearly indicate any assumptions made.

GERs should obtain data at and around their site of interest that can aid in informing appropriate courses of further investigation. If the GER knows the type of Soil (sand, gravel, silt/clay, peat), depth to and type of bedrock, as well as the locations of existing Geoscience Data points, they can determine appropriate geophysical and geotechnical site investigation methods, locations, and initial estimates of depths of investigation required. Open-source data is available from the Geological Survey of Canada (GSC) (National Research Council of Canada [NRCAN] Geoscan website) and the MVSMMP.

4.3.2 USE OF GROUND SHAKING MAPS

Ground Shaking SM Maps can be utilized to obtain the Code-based Site Class or the time-weighted average Shear Wave velocity (V$_s$) from ground surface to 30 m depth (V$_s$30) and the T$_0$. The variations in V$_s$30 and T$_0$ anticipated at a given site should be assessed by comparing data from nearby sites. The V$_s$30 data established from the SM Maps for a given site should be compared against values determined from the Code and included in the geotechnical report along with their anticipated variations, for the SER to develop the response spectrum for the site and the resulting inertial loads on the structure. Utilizing the SM Map and/or its underlying Geoscience Data is equivalent to performing a desktop study and does not replace the need to conduct an SSI.

Level 3 Ground Shaking SM Maps developed using 1D Seismic Site Response Analysis (SSRA) account for local Soil conditions only and do not typically include Basin Effects or topographic Amplification/De-amplification that occurs at sites located near slopes and ridge tops. Basin Effects are only applicable for select regions in Southwestern BC. When required, the GER should assess topographic effects separately via numerical simulations. Basin Effects and topographic and Amplification/De-amplification should be considered in addition to the local Soil effects on ground motions.

Level 3 Ground Shaking SM Maps assume Gradational changes in the impedance of Soil layers (i.e., a gradual change in stiffness). The GER should undertake site-specific SSRAs for sites with High Impedance Contrast—impedance ratios or V$_s$ contrasts larger than three—or for sites comprising shallow Soils with a T$_0$ less than 0.3 and should not solely rely on the information provided in Ground Shaking SM Maps.

4.3.3 USE OF LIQUEFACTION MAPS

Liquefaction SM Maps do not depict Seismic Hazards from cyclic strain softening of plastic Soils. GERs should be cautious of Soils that are not liquefiable—either as presented on an SM Map or geomap, or inherently as a material—but are susceptible to experiencing progressive softening without experiencing Liquefaction and investigate and design accordingly. SM Maps also do not depict the beneficial effects of the presence of a hard crust below ground surface that acts to reduce the Consequences of Liquefaction.

Caution should be exercised when using information provided in Higher Level SM Maps for Liquefaction for sites located within 300 m from a shoreline or a riverbank or when a hard non-liquefiable Soil crust exists at ground surface, as SM Maps typically do not account for Liquefaction-induced ground displacements for sites.
The GER should undertake a site-specific assessment of Liquefaction effects when:

- A hard non-liquefiable Soil crust exists near the ground surface and the Liquefaction Hazard SM Map indicates a high Liquefaction potential index (LPI) (e.g., LPI > 15) or high Liquefaction severity number (LSN) (e.g., LSN > 30). See Table 8 and Table 9 for example Liquefaction Hazard ratings by LPI and LSN, respectively.
- The subject site underlain by liquefiable Soils is located within 300 m from a shoreline or a riverbank.
- Basin Effects are expected and the application requires the consideration of such effects.
- The application is out of the scope for the intended use of the SM Maps. It is noted that quantitative Liquefaction potential analysis (i.e., calculation of factor of safety against Liquefaction \( \text{FS}_{\text{liquefaction}} \)) is likely to consist of one Soil profile for an area of 5–25 km² in level 2 Liquefaction Hazard Maps and for an area of 1–5 km² in level 3 Liquefaction Hazard Maps. An SSRA is likely only conducted for level 3 Liquefaction Hazard Maps, with one Soil profile for an area of 25–100 km².
- The depth to groundwater is in excess of several metres and potentially liquefiable Soils may exist below 20 m depth.
- The quality and extent of available Soil data is questionable.

4.3.4 USE OF LANDSLIDE MAPS

The GER should be aware of the following limitations when it comes to use of Landslide SM Maps:

- Landslide SM Maps typically use simplified or generalized geological, groundwater, and slope models as inputs. The GER should recognize where Local Site Conditions are not in conformance with generalized or assumed conditions and use SSIs accordingly.
- Landslide SM Maps typically exclude Liquefaction-induced ground displacements, such as lateral spreads and flows of liquefied Soils on gentle Soil slopes. If the SSI reveals geological and groundwater conditions consistent with Liquefaction on or adjacent to sloping terrain, the GER should perform lateral-spread or flow failure analyses and account for these phenomena in project design.
- Landslide SM Maps consider regional water table data that may not accurately reflect the depth to groundwater table at a given site. Site-specific groundwater-level measurements should be part of an SSI where earthquake-triggered Landslides are credible.
- Most Landslide SM Maps exclude the slope instability associated with human-made over steepened slopes along roads and highways. The GER should identify cuts and fills that could produce Landslides adjacent to or beneath the site of interest and assess them as part of an SSI.
- Landslide SM Maps typically depict onshore Susceptibility or Hazard under the assumption of normal climatic conditions. They typically exclude the effects of an earthquake in combination with other potential Landslide triggers (e.g., flooding or extreme precipitation) and Landslides within and adjacent to water bodies (e.g., tsunami and associated run-up, inundation, and scour). The GER should consider these potential combined or secondary Hazards in an SSI.
- Landslide SM Maps typically portray areas where Landslide triggering is expected, but often exclude zones of retrogression. This retrogression might be expected upslope or behind the crest of slopes underlain by liquefiable or sensitive deposits subject to spreads or flows, and long-runout zones (e.g., beneath rockfalls, rock avalanches, debris flows, avalanches, and similar Landslide mechanisms). Where a site is adjacent to an earthquake-triggered Landslide Hazard, as shown on an SM Map, the GER should determine whether the Hazard has credible potential for nonlinear...
retrogression or long runout, and if so, whether the site falls within the potential zone of influence of those Hazards, as part of an SSI.

- Landslide SM Maps are typically constructed by calculations on a grid-cell basis. The GER should note where local variability (e.g., in slope angle \( \alpha \) or geology) might not be adequately represented by an input variable generalized to a specific map unit, and account for that variability in the interpretation and use of the SM Map.

- Higher Level SM Maps constructed using statistical techniques—as discussed in Section 5.4.4.3.2 Statistical Techniques—are based on relatively few earthquake-triggered Landslide inventories in settings analogous to BC; accordingly, the GER should treat these with caution.

- Level 2 and level 3 SM Maps constructed using empirical or semi-empirical seismic displacement prediction models (SDPMs)—as discussed in Section 5.4.4.3.3 Seismic Displacement Prediction Models—are often based on simple geological models that are not generally representative of natural slopes. The GER should use caution where site geological conditions are incompatible with the data sets informing SDPMs.

### 4.4 STRUCTURAL ENGINEERING PROFESSIONALS

SERs should have a high-level understanding of Seismic Hazards and SM Maps, as discussed in Section 3.0 Introduction to Seismic Hazards and Seismic Microzonation Mapping. SERs should understand the intent, assumptions, and limitations of any SM Map before relying on the information contained within, including the concept of suites of SM Maps and different SM Map levels, and the appropriate use of each as it relates to structural engineering (see Section 4.1 General Considerations for Use). Specifically, SERs should be aware of the increasing quality of the maps that aligns with the increasing map levels as a result of increasing data quality, quantity, and density as well as increasing complexity of analysis to produce the calculated Seismic Hazard. The guidance in this section complements the guidance in Section 5.0 Development of Seismic Microzonation Maps and applies in principle regardless of whether an SM Map is labeled with a specific level.

#### 4.4.1 GENERAL CONSIDERATIONS

SERs rely on the design response spectrum to determine the equivalent lateral design force that is applied to a structure under earthquake load combinations. The influence of Soil properties is included in the Code-based design response spectrum as well as other parameters obtained from site-specific studies or from SM Maps. While Ground Shaking SM Maps can provide good estimates of these parameters to then enable the development of a design response spectrum, they should not be used to reduce the loading compared to that developed based on detailed site-specific geotechnical studies.

Local Community Governing Bodies may utilize SM Maps in the development of policies and bylaws related to emergency management, community-wide seismic vulnerability assessments, and community planning (see Section 4.2 Local Community Governing Bodies). Local Community Governing Bodies may require the SERs or GERs to reference SM Maps in the development or building permitting stages of particular sites. Regardless of any referenced SM Map level in this requirement, SERs should generally be using SM Maps of the highest level available to them and should work with the GER to develop a common interpretation. Discussion with a seismologist may also be appropriate when interpretation of an SM Map or the underlying data is required.

When available, site-specific data resulting from field investigations by the GER should be used in preference to data obtained from SM Maps. Data obtained from a desktop study based on historical or proprietary nearby field investigations from the GER
may be preferential to an SM Map, for example, where data used in SM Map development is sparsely distributed or where certain geotechnical parameters are not included. Available Geoscience Data used to develop the SM Maps from open or online databases, proprietary databases, or obtained from SSIs at nearby sites with similar characteristics may also be beneficial in understanding the Local Site Conditions. This approach would be considered equivalent to a site-specific desktop study.

The content and level of detail in level 1, 2, and 3 SM Maps are described in Section 3.4 Introduction to Seismic Microzonation Map Levels. The following sections focus on use of the Ground Shaking SM Maps by SERs. Use of Liquefaction and Landslide SM Maps by SERs is less common and therefore not discussed in detail. However, many of the principles for appropriate use and coordination with other Engineering/Geoscience Professionals still apply.

### 4.4.2 USE OF LEVEL 1 GROUND SHAKING MAPS

Level 1 Ground Shaking SM Maps are Seismic Susceptibility Maps. They are low-level maps typically based on interpretations of existing and readily available Geoscience Data. Level 1 SM Maps are only appropriate for use during the conceptual or schematic design phases of a project, prior to obtaining the results of an SSI. Level 1 SM Maps can also be used by SERs when completing portfolio-style screening or to establish typical design criteria for a region. Level 1 SM Maps for Ground Shaking, Liquefaction, and Landslides can be used to determine general areas with higher Seismic Hazard levels and inform the SER where more detailed review is required.

Suites of level 1 Ground Shaking SM Maps may include a map from which the Code-based Site Class can be determined. This Code-based Site Class should generally be considered as an upper bound estimate of the Seismic Hazard; however, the SER should consider selecting the less favorable Site Class near map boundaries. Site Classes provided by the GER from an SSI should be used over those obtained from SM Maps. Level 1 SM Maps rely heavily on surficial geological maps that may not accurately describe the depths of the deposits, and this uncertainty should be considered when referring to level 1 SM Maps. For sites with High Impedance Contrast in the upper 30 m, SERs should exercise caution in relying solely on level 1 SM Maps as inputs for establishing the design spectrum. An SSI is recommended for High Impedance Contrast sites, and is required per the Code for buildings designed using seismic isolation on sites of Site Class D, E, or F and for sites with $V_{30}$ less than 360 m/s; an SSRA by the GER may be beneficial in such cases. Refer to Section 4.3 Geotechnical Engineering Professionals for more information.

Local Community Governing Bodies should keep up to date and familiarize themselves with other policies developed after the publication of these guidelines. See Section 8.4 Related Documents and Resources for a list of other SM guidelines and a list of documents and resources related to the use and development of SM Maps.

### 4.4.3 USE OF LEVEL 2 GROUND SHAKING MAPS

Level 2 SM Maps are typically Seismic Susceptibility Maps, but could also be Seismic Hazard Maps. Level 2 SM Maps exist on a sliding scale between level 1 and level 3 SM Maps and can vary significantly depending on the quantity and quality of data used as well as the complexity of the analysis done.

SERs can use level 2 SM Maps to obtain similar data as level 1 SM Maps, but with higher confidence of the information presented on such maps, since they are developed from additional detailed data sources and/or increased data sampling. In addition to providing Site Class, level 2 Ground Shaking SM Maps might also provide $V_{30}$ and the $T_o$. Level 2 Liquefaction and Landslide SM Maps might provide an improved indication of Susceptibility of those Seismic Hazards for consideration in developing preliminary schematic designs, but Seismic Hazards associated with Liquefaction and Landslide should
typically be further refined in consultation with the GER.

SERs should note that the Code strongly recommends the use of $V_{S30}$ over Site Class; therefore, level 2 SM Maps for $V_{S30}$, when available, should generally be used in preference to level 1 SM Maps for Site Class. Note that when Code-based Site Class data is utilized, each Site Class is defined as a range of $V_{S30}$ values; the lowest $V_{S30}$ number applicable to the range should be selected for all design calculations. Alternate values in the range may be appropriate for use in sensitivity studies.

Resonance Amplification and Basin Effects can have a detrimental impact on the seismic response of structures. Resonance Amplification occurs where $T_s$ is close to the period of the structure. Some level 2 SM Maps may be suitable to estimate the $T_s$, but the potential for resonance Amplification should be reviewed in consultation with the GER. SERs should use caution when relying on level 2 SM Maps for $V_{S30}$ for sites within a basin, as the true Site Amplification effects might not be clearly reflected. Basin Effects are dominant in areas where depth ($z$) to $V_5$ of 2500 m/s ($Z_{2s}$) is 3 km or more. Level 3 Ground Shaking SM Maps indicating basin Amplification factors may be available for selected period ranges, and such factors may be directly applied. Coordination with the GER to interpret the SM Map is strongly encouraged, as these basin Amplification factors only consider deep Basin Effects and may not accurately consider all possible influences from basins. Note that Basin Effects are partially accounted for in some of the Ground Motion Models (GMMs) in the 6th generation Seismic Generation Hazard model used to derive Seismic Hazard values in the NBC 2020.

Topographic Amplification effects can occur for sites located near slopes and ridge tops. These effects are not typically included within level 2 SM Maps. The applicability for these effects should be reviewed in consultation with the GER.

Where Seismic Hazard values for a region are not included in the Code data tables, the Local Community Governing Body does not publish such values, or localized values by latitude and longitude of the site are not available through the NRCAN Seismic Hazards Tools website for specific return periods, level 2 Seismic Hazard Maps may be used to obtain such information. Level 2 Seismic Hazard Maps are typically appropriate for use in schematic design and may be considered for use in early parts of the design development stage, prior to obtaining the site-specific information required for the detailed design and contract document phases. Level 2 SM Maps may also be appropriate for use in assessment studies that provide an indication of the potential need for seismic upgrading during planned construction or renovation work on existing buildings.

If using data obtained from an SM Map (e.g., $V_{S30}$) for early stages of design development, SERs should consider doing a sensitivity analysis to understand the effects of different inputs, in the event that the future SSI results in different, and more accurate, information than the SM Map. This is particularly important for existing buildings where early design decisions include whether seismic upgrading is required. Where the structural design results prove to be sensitive to the $V_{S30}$ value or other parameters, an SSI should occur sooner rather than later to avoid unnecessary rework. The need for the SER or GER to consider performing sensitivity analysis for variations in site parameters at the design development stage is often apparent from level 2 SM Maps, when the seismic parameter of interest rapidly changes within a small mapping area. Regardless of building type, an SSI should be conducted prior to the building permitting stage and this information should be relied upon as soon as it is available, negating the use of information from an SM Map.

When SSIs reveal significantly different Local Site Conditions than the available level 2 SM Maps, or the data collected for the SSI fills a spatial gap relative to the data used in the level 2 SM Map, the SER and GER are strongly encouraged to contribute any new Geoscience Data to an open database or repository so that it can be incorporated into future updates or
enhancements of the regional SM Maps. If required, the submitted data could be anonymized.

### 4.4.4 USE OF LEVEL 3 GROUND SHAKING MAPS

Level 3 SM Maps are Seismic Hazard Maps. They involve performing a Seismic Hazard analysis of the ground conditions (using level 1 and 2 Susceptibility SM Maps as input) to calculate Ground Shaking.

It is recommended that the GER be retained to assist in the interpretation of all level 3 SM Map data and, where appropriate, independently determine/verify the $T_0$ and its expected influence on the structure.

From level 3 Ground Shaking SM Maps, SERs can obtain the specific design response spectrum, or modification factors that apply to all or portions of the Code-based design response spectrum, based on the site’s $V_{s30}$. The results are applicable to sites with Gradational changes in impedance but not to High Impedance Contrast sites. Level 3 SM Maps may indicate that the design response spectrum for a site is lower or higher than the response determined through application of the Code. Where the level 3 spectrum is higher, this suggests that the Code is underestimating the demand on the structure and a more detailed assessment by the GER is required.

Where the level 3 spectrum is lower, the SER should design for the higher Code requirements unless an SSRA and other Soil modeling is completed by the GER, supported by appropriate levels of checking and independent review. Similarly, SERs can use level 3 SM Maps to get a better indication of Liquefaction effects, Basin Effects, $T_0$ effects, and Landslide effects, that may suggest the need for additional, detailed interpretation by the GER.

SERs should verify that the $T_0$ obtained from a level 3 SM Map is similar to that determined by an SSI, and carefully review significant differences with the GER. Differences may suggest that meaningful variations in subsurface conditions exist across the site, or that an SSRA is necessary to accurately determine how the subsurface conditions will affect the building response. GERs and SERs should compare the obtained $T_0$, $V_{s30}$, and/or Basin Effects determined from SM Maps with the results of any SSRA, and use professional judgment to determine the appropriate data to use. Knowing the $T_0$, the SER should consider designing the building to have an elastic building period greater than $2T_0$ in order to avoid the period of the structure from coinciding with the resonant state in the Soil column, as that condition could result in significantly more demand on the structure than otherwise designed for, which may lead to significant damage to or collapse of the building. For High Impedance Contrast sites, additional consultation with the GER to identify the influence of the building period and the $T_0$ of the upper Soils should be considered.

When SSIs reveal significantly different Local Site Conditions than the available level 3 SM Maps, or the data collected for the SSI fills a spatial gap relative to the data used in the level 3 SM Map, the SER and GER are strongly encouraged to contribute any new Geoscience Data information to the SM Map open database or repository for future improvements of regional SM Maps. If required, the submitted data could be anonymized.

### 4.4.5 ADDITIONAL CONSIDERATIONS

While the above discussion highlights the application of different SM Map levels to the traditional design phases of a construction project, the following additional considerations are required to successfully utilize data from SM Maps:

- Where Hazards are identified through reference to SM Maps, early involvement by a GER is recommended. SM Maps do not replace the need for an SSI or a GER.
- When a site-specific geotechnical report is not yet available and the SER is obtaining data from an SM Map for feasibility studies, conceptual design, or schematic design, the SER should consider using data that would result in a conservative design, especially when located near a mapping boundary. Designs may be later refined to reflect SSIs.
• For detailed design, the SER should refer to a site-specific geotechnical report for Code-based design parameters related to Site Class or $V_{30}$ and, if applicable, the $T_o$. Even in cases where a Local Community Governing Body provides recommendations based on an SM Map, it is important that an SSI and geotechnical report be prepared for the site.

• The SER should provide appropriate disclaimers related to their interpretation of the SM Maps used, as well as any limitations of the documents created under those interpretations and assumptions.

• SERs should exercise caution relying on information from SM Maps that were developed based on data collected or processed before human-made alterations were done to a site.

• The GER’s recommendation on Site Class and $V_{30}$ should take precedence over the use of the data presented in SM Maps. Code-based Seismic Hazard values (obtained from the NRCAN Seismic Hazards Tool) should be used unless the effects presented in the SM Maps are more conservative than the Code-based values. SM Maps do not present an opportunity to reduce the design requirements below minimum performance criteria specified in the governing Codes and standards. Furthermore, SM Map data should not be used as an opportunity to reduce design criteria below that recommended from site-specific geotechnical studies. The only situation in which it may be appropriate to reduce below the Code-specified values is when an SSRA is conducted by a qualified GER or where the qualified GER completes a review of the underlying data and assumptions used to produce the SM Map. The interpretation of data and analysis supporting a reduction in design requirements below the minimum Code requirements should be subject to an independent review. Refer to the Practice Advisory: Site Response Analysis and Site-Specific Response Spectra (Engineers and Geoscientists BC 2022).

• Design spectrum—in accordance with Code and using $V_{30}$ data—assumes that the site is a Gradational Site. For sites with High Impedance Contrast layers, Amplification or De-amplification of ground motions relative to the Code-based procedure can occur, depending on the $T_o$, the building period, and other factors. The SER should discuss with the GER if the use of an SSRA is appropriate.

• If the potential for Liquefaction at a site is established—through SM Maps or otherwise—the SER should work with a GER experienced in Liquefaction issues to assess the likelihood and severity of the Liquefaction Hazard. This should include the expected range of lateral and vertical Soil deformations and consider mitigation approaches through geotechnical methods, structural methods, or a combination of both. Recent studies indicate that the extent of lateral and vertical Soil deformations may be significantly higher for Site Class D and E sites located within 300 m of shorelines.

• If the potential for Landslides is identified through SM Maps, where structures are to be located on slopes or near abrupt changes in topography, or where water seepage or above ground drainage of water may increase the Hazards associated with slope stability, the SER should work with the GER and other design professionals to determine appropriate mitigation approaches.

4.5 BUILDING/INFRASTRUCTURE PROVIDERS AND OWNERS

SM Maps are highly technical documents that should be referenced with caution by the public. SM Maps define Susceptibility or potential of Seismic Hazards in an area and may be used to inform zoning and permitting policies, emergency management and recovery strategies, and appropriate approaches to geotechnical and structural designs. SM Maps should
not be used as a sole determinant for real estate or insurance decisions. For more information on appropriate use of SM Maps, see Section 4.1 General Considerations for Use.

SM Maps do not represent Seismic Risk, because Seismic Risk is also dependent on the type and condition of buildings and other infrastructure potentially subjected to that Seismic Hazard. See Section 4.2 Local Community Governing Bodies for further discussion.

4.5.1 INFRASTRUCTURE PROVIDERS AND OWNERS

Local Community Governing Bodies provide considerable additions to infrastructure, however, there are many other types of infrastructure providers in BC. Use of SM Maps by infrastructure providers and owners may be appropriate in the following activities:

- Developing design criteria that balances Seismic Risk with the investment, considering whether the Seismic Risk can be removed or accommodated in the design.
- Conducting a Seismic Risk assessment of critical or other priority infrastructure, and conducting community-wide or regional seismic vulnerability assessments.
- Informing investment decisions and criteria for retrofit or renewal.
- Determining Soil remediation best management practices, priorities, and applications.
- Informing preliminary design decisions for distributed assets, such as transportation infrastructure and those related to utilities or the energy sector.
- Scoping geotechnical investigations necessary for infrastructure design.

4.5.2 RESIDENTIAL AND COMMERCIAL USERS

Residential and commercial users may use SM Maps as an aid to:

- Inform purchase or location selection decisions based on relative geotechnical complexity and Seismic Hazard, understanding that structural design can be adapted to accommodate geotechnical issues.
- Determine appropriate insurance coverage.
- Establish seismic retrofit priorities.
- Create individual or family emergency response plans.

4.5.3 DEVELOPERS

Developers may use SM Maps as an aid to:

- Scope and understand the seismic complexity of structural and geotechnical investigations.
- Inform the cost of development.
- Understand the requirements for development permits.

4.6 RELATED INDUSTRIES

4.6.1 CATASTROPHIC HAZARD/RISK MODELLING

Catastrophe Hazard/Risk modelers may use SM Maps as an input to their proprietary Seismic Hazard and Seismic Risk models. Key components that are useful to modelers are assurances of an independent or peer review process, as well as the age and resolution of input data. Equally important components are the ease of access of the SM Maps and available guidance on how to use each SM Map. Generally, SM Maps can be used to:

- Support model updates or adjustments, such as economic loss estimates, debris clean up estimates, and supply chain impact analysis.
- Validate models, such as for sensitivity analyses to identify variances between the model vendors.
- Supplement or adjust Risk models, such as for portfolio management and development of insurance products and rates.
4.6.2 INSURANCE PROFESSIONALS

Insurance professionals may use Higher-Level SM Maps as an aid to:

- Inform insurance coverage for regions or buildings. However, SM Maps should not be used on their own to determine available or appropriate insurance coverage. Insurance professionals should engage the support of Local Community Governing Bodies, geotechnical engineers, and structural engineers to appropriately interpret and apply SM Maps.
- Develop or revise underwriting guides to establish appropriate limits, deductibles, and more.
- Develop Risk-scoring products and/or data layers that inform insurance pricing and support rate filings.
- Enhance portfolio management and monitoring by incorporating accumulation analyses based on SM Maps.
- Quantify defined deterministic loss scenarios for exposure to seismic events.
- Perform catastrophe Risk model validation, enhancement, and/or adjustment.
- Structure traditional reinsurance programs (i.e., catastrophe reinsurance) or alternative Risk transfer (i.e., catastrophe bond, industry loss warranty), where applicable.

4.6.3 REAL ESTATE PROFESSIONALS

Real estate professionals may use SM Maps as an aid to:

- Inform their clients of local Seismic Hazards in the area.
- Gauge insurability of specific properties.
- Inform their clients of future development opportunities, limitations, or restrictions (as per Local Community Governing Body requirements).
5.0 DEVELOPMENT OF SEISMIC MICROZONATION MAPS

The following sections provide guidance to Mapping Professionals that is generally applicable to the development of all Seismic Microzonation (SM) Maps, regardless of Seismic Hazard, as well as Seismic Hazard-specific guidance.

Engineering/Geoscience Professionals are reminded that, while the professional practice guidance in the following sections contain some technical information on the development of SM Maps, these guidelines do not replace or provide technical or systematic instructions for how to carry out these activities. Engineering/Geoscience Professionals must exercise professional judgment when providing professional services; as such, the application of these guidelines will vary depending on the circumstances.

5.1 GENERAL CONSIDERATIONS FOR DEVELOPMENT

The objective of SM Mapping Projects is to divide an area into microzones, where microzones are areas with similar geological, Susceptibility, or Hazard characteristics. During the development of SM Maps, it is necessary to curate, compile, and interpret both new and existing Geoscience Data that are relevant to the Seismic Hazard being mapped. Spatial mapping of the Geoscience Data is then required.

SM Maps can be produced at varying levels of detail, as described in Section 3.4 Introduction to Seismic Microzonation Map Levels. However, the variation in detail is not only in the complexity and sophistication in the technical analyses, which define the levels, but also in the mapping detail, based on the spatial density of the underlying data. Increased spatial density of Geoscience Data provides greater reliability in the spatial distribution of the specific Seismic Hazard parameter being mapped, whereas an increased sophistication of technical analysis provides more reliable and quantitative assessments of the Seismic Hazard itself. Usually, the levels of mapping detail should increase with the level of technical analysis, as the benefits of higher levels of seismological and geotechnical analysis are limited if not accompanied by an appropriate level of mapping detail.

The relative levels of these two factors should be made clear in SM Maps and accompanying reports, and should be released as part of the final SM Mapping Project deliverables, so that users are aware of the limitations of the SM Maps. Specifically, the report should indicate the Seismic Hazard and describe the specific aspects of those Seismic Hazards being addressed, such as:

- the amounts, types, and spatial distribution of data used;
- any fieldwork conducted;
- all details of the geotechnical and seismological analysis; and
- methodology and considerations, as described below.

The following sections discuss the general expectations and considerations for the development of SM Maps including mapping workflow, data requirements, data sources, mapping considerations, and human effects and other considerations.
5.1.1 MAPPING WORKFLOW

Before starting an SM Mapping Project, the following will need to be defined:

- the specific objectives of the SM Map;
- the SM Map level; and
- the SM Map scale.

The general mapping workflow is described in the following steps:

1. Data collection and compilation
2. Data reduction and interpretation
3. Spatial mapping

Specific details of the data and analyses required will vary with the specific Hazard(s) being addressed and level of SM Map intended. See sections 5.2 Ground Shaking, 5.3 Liquefaction, and 5.4 Landslide for Hazard-specific data requirements and methodologies.

5.1.1.1 Step 1—Data Collection and Compilation

The first step of SM Mapping Projects involves the collection and compilation of existing Geoscience Data and water level data from a variety of sources. The principal data types and sources are listed in Section 5.1.2 Data Requirements, and the sources and details are discussed in Section 5.1.3 Data Sources. The most important and commonly used geotechnical and geophysical data types, along with their relation to Shear Wave velocity (V$_s$), are summarized in Table 3.

As part of data collection and compilation, fieldwork may be required to acquire new or additional data, particularly for Higher-Level SM Maps where the quantity and quality of data are paramount.

Fieldwork activities may include:

- conducting geological fieldwork, including:
  - reconnaissance;
  - spot checking; and
  - mapping surficial geology and geomorphology;
- geotechnical field method testing, including:
  - borehole drilling with standard penetration tests (SPTs) and associated laboratory testing;
  - Becker penetration tests (BPTs); and
  - cone penetration tests (CPTs), including seismic cone penetration tests (SCPTs); and
- geophysical testing, including:
  - non-invasive methods, such as single station microtremor method recordings and active- and passive-source seismic array V$_s$ testing;
  - invasive methods, such as the acquisition of V$_s$ data from boreholes and CPTs; and
  - seismic reflection and refraction surveys.

Data collection, including requests for First Nations' oral histories and knowledges, should follow the Nations' protocol and requirements (e.g., The First Nations Principles of ownership, control, access, and possession [OCAP]). First Nations may direct that these protocols and requirements apply to survey research, data collection, interpretation, and analysis, which are fundamental steps in SM Mapping Projects. Additionally, permission for site access should be obtained prior to collecting In-Situ measurements on First Nations reserves and lands. Engineering/Geoscience Professionals and others involved in the development of SM Maps should collaborate openly and inclusively with First Nations, recognizing the importance of their relationships and knowledge of their territories.
Table 3: Principal Geotechnical and Geophysical Data Types Used in Seismic Microzonation Mapping, and Their Relation to Shear Wave Velocity

<table>
<thead>
<tr>
<th>METHODS</th>
<th>MEASUREMENT</th>
<th>$V_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Penetration Test (SPT)</td>
<td>Blow count (N)</td>
<td>Empirical relations</td>
</tr>
<tr>
<td>Cone Penetration Test (CPT)</td>
<td>Tip resistance ($q_t$), sleeve friction ($f_s$), and pore pressure ($u$)</td>
<td>Empirical relations</td>
</tr>
<tr>
<td>Seismic Cone Penetration Test (SCPT)</td>
<td>$q_c$, $f_5$, and $V_s$</td>
<td>Direct measurement</td>
</tr>
<tr>
<td>Downhole</td>
<td>P-Wave velocity ($V_p$) and/or $V_s$</td>
<td>Direct measurement</td>
</tr>
<tr>
<td>Multichannel Analysis of Surface Waves (MASW)</td>
<td>High-frequency dispersion curve</td>
<td>Inversion to $V_s$</td>
</tr>
<tr>
<td>Microtremor Array Method (MAM)</td>
<td>Low-frequency dispersion curve</td>
<td>Inversion to $V_s$</td>
</tr>
<tr>
<td>Microtremor Horizontal to Vertical Spectral Ratio (MHVS)</td>
<td>Amplification spectrum (includes Fundamental Site Frequency [$f_0$])</td>
<td>Inversion to $V_s$</td>
</tr>
</tbody>
</table>

5.1.2 Step 2—Data Reduction and Interpretation

For all map levels, the second step of SM Mapping Projects involves data reduction and standardization, which may include:

- processing new geophysical data to obtain the Fundamental Site Period ($T_o$) and $V_s$;
- validating data and removing any unreliable data;
- removing or identifying the effects of human alterations to the ground surface, where applicable (see Section 5.1.5.1 Human Effects);
- providing geological interpretation, including the refinement of existing geological models or development of new ones;
- determining site-specific Seismic Hazard metrics for:
  - Ground Shaking (e.g., the time-weighted average $V_s$ from ground surface to 30 m depth [$V_{s30}$]),
  - Liquefaction (e.g., Liquefaction potential index [LPI], Liquefaction severity number [LSN]), and
  - Landslide (e.g., shear-strength parameters for slope stability);
- correlating the Seismic Hazard metrics with stratigraphy, geological conditions, or slope to generate $V_s$ models of the subsurface, Liquefaction models, and slope stability models; and
- developing intermediate SM Maps—such as subsurface geological maps, maps of water table depth and elevation, and slope maps from digital elevation models (DEMs)—that form the basis of the final SM Map deliverables.

For Higher-Level SM Maps, the Seismic Hazard must be determined during this second step. The predicted Seismic Hazard should be determined from numerical modelling, earthquake rupture models, or by adjusting Ground Motion Models (GMMs) using developed Amplification factors. The predicted Liquefaction and Landslide Hazards should be determined based on factor of safety or horizontal or vertical displacements.

These Seismic Hazard analyses must then be correlated with geological conditions and the following earthquake data:

- instrumentally recorded earthquake data, including Seismic Site Response Analyses (SSRAs);
- historic earthquake records, isoseismal maps, and reports of historical earthquake effects and damage;
- paleo-seismic evidence of Liquefaction and Landslides; and
- seismically-induced Landslide inventories.
5.1.1.3 Step 3—Spatial Mapping

SM Mapping Projects typically involve the creation of a suite of SM Maps. For each SM Map, the third and final step of SM Mapping Projects involves spatial mapping. Considerations for spatial mapping include:

- developing 3D physical-structure models based on compiled Geoscience Data;
- defining map units or contouring, including geostatistical Interpolation of the 3D data points (see Section 5.1.4.2 Contouring and Geostatistical Interpolation); and
- assigning Susceptibility or potential to geological or other map units.

Mapping Professionals should prepare a report (e.g., user guide, map notes, title block) to complement each SM Map, documenting the process, assumptions, and decisions made. Whether intended for distribution with the SM Maps or as records, the report should include:

- title;
- purpose or introduction;
- Seismic Hazard(s), including specific aspects of the Seismic Hazard(s), being addressed;
- methodology and considerations, including:
  - amounts, types, and spatial distribution of data used;
  - fieldwork conducted; and
  - details of geotechnical and seismological analysis;
- appropriate uses and limitations;
- relevant defined terms or acronyms;
- legend and, as appropriate, expanded legend;
- scale;
- references; and
- acknowledgements including, but not limited to:
  - Mapping Professional;
  - key contributors and reviewers;
  - funding sources; and
  - data sources.

5.1.2 DATA REQUIREMENTS

5.1.2.1 Level 1 Data Requirements

Level 1 SM Maps are based on surficial geological and geomorphological maps and generalized correlations of the age, lithology, depositional environment, and physical properties of the surficial geological materials with Seismic Hazard Susceptibility. The following data should be obtained for all SM Maps, unless noted otherwise:

- Published and proprietary geological reports and data.
- When available, reports of historical earthquake effects and damage, and paleo-seismic studies.
- Readily available remote-sensing datasets—including light detection and ranging (LiDAR) topographic slope maps (or DEMs), terrain classification maps, and water level data—are required for Landslide and Liquefaction SM Maps.
- Topographic slope data could be used as a proxy for \( V_{30} \) in Amplification mapping where other data are unavailable (Wald and Allen 2007; Allen and Wald 2007; Iwahashi and Pike 2007; Iwahashi et al. 2018). This approach is only suitable for low resolution level 1 SM Maps, and caution must be exercised when using it in British Columbia (BC) where the terrain has been shaped by multiple glaciations.

5.1.2.2 Level 2 Data Requirements

Higher-Level SM Maps require more diverse, detailed, or extensive, and area-specific datasets to define the thickness and extent of the various geological materials to quantify the Hazard. Level 2 SM Maps include both Seismic Susceptibility Maps and Seismic Hazard Maps with simplified assessments of seismic demand. Level 2 SM Maps are based on either surficial geological maps or maps representative of subsurface geological conditions relevant to Seismic Hazard and are prepared using subsurface Geoscience Data. In addition to the data required for
level 1 SM Maps, data required for level 2 SM Maps includes:

- Geological reports, studies, and cross-sections.
- Earthquake data, including reports of recent and historical earthquake effects and damage, paleoseismic studies, co-seismic landslide inventories, and for level 2 Seismic Hazard Maps, projected seismic ground motions (either deterministic or probabilistic, usually at 2% and 10% probability of exceedance in 50 years per the Code).
- MHVSR data for Amplification spectra and peak frequencies.
- Surficial and bedrock geological maps, including Soil and drift thickness maps.
- Borehole data, water well logs, and test data. Test data may include those obtained from:
  - Invasive field testing methods, such as:
    - Geophysical logging, particularly \( V_s \) logging, either downhole or cross hole.
    - SPTs, piezocene penetration tests (CPTus), SCPTs, BPTs, dynamic cone penetration tests (DCPTs), and vane shear tests.
    - Laboratory geotechnical testing of samples from boreholes, including grain size analyses, moisture content, Atterberg limits, Soil unit weight \( (\gamma) \), shear strength, consolidation, bender element, and the \( V_s \) of Soils, and sonic wave transmission testing of \( V_s \) and P-Wave Velocity \( (V_p) \), or compressive strength measurements of rock.
  - Non-invasive field testing methods, such as:
    - Single station microtremor method recordings for MHVSR Amplification spectra and peak frequencies.
    - Body-wave seismic reflection and refraction surveys for velocity models.
    - Active- and passive-source seismic array testing (e.g., MASW, MAM) for dispersion curve analysis and inversion to \( V_s \) models.
- Any other geophysical data that can provide useful information on the shallow and deep geological structure, such as those from resistivity, electromagnetic, ground penetrating radar, deep seismic reflection, and gravity surveys (Hunter and Crow 2015).

5.1.2.3 Level 3 Data Requirements

Level 3 SM Maps require extensive subsurface geoscience data. In addition to the data required for level 1 and level 2 SM Maps, level 3 SM Maps require the inclusion of the input seismic demand for the chosen reference site condition, either in terms of a single measure of ground intensity (e.g., peak ground acceleration [PGA]) or appropriately scaled earthquake time histories for numerical Ground Motion Models (GMMs). Time histories for Ground Shaking and Landslide mapping should be scaled and/or matched to select source-based target response spectra at 2% and 10% probability of exceedance in 50 years. For Liquefaction mapping, time histories should be scaled to the Code-based PGA at 2% and 10% probability of exceedance in 50 years. Other probabilities of exceedance could also be considered for critical infrastructure. Mapping Professionals should work with the client and the Local Community Governing Body(ies) to determine any project-specific expectations and requirements.

5.1.3 Data Sources

Mapping Professionals should use professional judgment to assess the validity and reliability of data and only use the data that makes sense; for example, some newer data points may invalidate others.

Mapping Professionals should collect as much geoscience data as possible and should supplement existing data with new data where required.
Geoscience Data that should be collected includes:

- data from earthquakes;
- geologic and topographic maps and related datasets;
- subsurface geological and geotechnical data, including:
  - geotechnical borehole and test hole logs, and associated laboratory test data;
  - water well logs;
  - petroleum industry well data; and
  - other types of subsurface data; and
- geophysical data, including:
  - MHVSR;
  - $V_s$ and related seismic methods (including $V_p$ methods); and
  - other geophysical methods.

5.1.3.1 Data from Earthquakes

Mapping Professionals should collect local historic earthquake recordings in the form of time-series and waveforms, as they provide the most direct evidence of local ground motions and relative Seismic Hazards. The following are resources to obtain earthquake recordings:

- The Canadian National Seismic Network of the Government of Canada operates a network of stations at which seismometer and accelerometer data are recorded; these data are available via Earthquakes Canada. Most of these stations are installed on outcropping rock and thereby cannot be used to understand Local Site Conditions. The installation of both seismograph and accelerometer instruments permits accurate measurement of weak to strong Ground Shaking.
- The BC Ministry of Transportation and Infrastructure operates a strong motion network on the ground, as well as on highway and road structures. Data are available via the BCSIMS website.
- Various other public and private agencies operate seismic networks in southwestern BC, including BC Hydro.

Generally, strong motion networks are deployed for the purpose of understanding spatial variation in ground motion across a region and are deployed on a range of Local Site Conditions, so therefore are suitable for SM Mapping Projects. However, Ground Shaking resulting from an earthquake must be relatively strong in order to be accurately recorded by an accelerometer network.

Based on data from strong motion networks, the variation in seismic site response due to local geological conditions has been documented for sites in Greater Vancouver and Greater Victoria (Cassidy et al. 1997; Rogers et al. 1998; Cassidy and Rogers 1999, Atkinson and Cassidy 2000, Cassidy and Rogers 2004; Molnar et al. 2004a; Jackson et al. 2017; Assaf et al. 2018; Assaf et al. 2022).

Furthermore, Molnar and Cassidy (2006) demonstrated that spectral ratios from earthquakes and ambient noise (microtremors) are similar. Variation in site response from microtremor recordings has been documented for Victoria and south-central Vancouver (Onur et al. 2004; Sirohey 2022) and many locations on Vancouver Island and the Sea to Sky highway corridor (Molnar et al. 2006). The MHVSR method is described below in Section 5.1.3.4.1 Microtremor Horizontal to Vertical Spectral Ratio.

Mapping Professionals should also consider collecting qualitative earthquake data, such as:

- Earthquake felt and/or damage intensity reporting, such as:
  - Earthquakes Canada’s “Did You Feel It” reporting.
  - Community Internet Intensity Maps, a form of empirical SM Maps.
- Earthquake damage reports from historic earthquakes, and paleo-seismic data.
- ShakeMap products—produced by the United States Geological Survey (USGS) or others—that
provide spatial interpolation of both earthquake recordings and earthquake intensity reporting.

- First Nations histories, knowledges, and sciences.

5.1.3. Geologic and Topographic Maps and Related Datasets

Surficial geological data relevant to an SM Mapping Project in BC that should be collected includes:

- Published surficial and Quaternary geologic maps, prepared and/or hosted by:
  - Geological Survey of Canada (GSC);
  - British Columbia Geological Survey (BCGS); and
  - Government of British Columbia (MapPlace 2).

- Terrain inventory and terrestrial ecosystem maps, for example, those hosted by:
  - British Columbia iMapBC; and
  - Government of Canada’s Terrain Inventory Mapping (TIM).

- Soil maps, which can be useful in preparing or augmenting surficial geological maps, for example, those hosted by:
  - Government of British Columbia’s Soil Information Finder Tool.

- Bedrock geological maps, prepared by the GSC and BCGS, that can be used to outline areas of thick Quaternary sediments, where surficial geological maps are unavailable.

- Physical models of the Georgia Basin (Stephenson 2007; Stephenson et al. 2017) from the USGS.

- Topographic data, which can provide basic data for Seismic Hazard analysis, particularly for Landslides, but can also be used to interpret surficial and subsurface geological conditions, as many surficial geological units and their boundaries have distinct topographic and geomorphic expression. The following are sources:

  - Published surficial and Quaternary geologic maps, prepared and/or hosted by:
    - Geological Survey of Canada (GSC);
    - British Columbia Geological Survey (BCGS); and
    - Government of British Columbia (MapPlace 2).

  - Terrain inventory and terrestrial ecosystem maps, for example, those hosted by:
    - British Columbia iMapBC; and
    - Government of Canada’s Terrain Inventory Mapping (TIM).

  - Soil maps, which can be useful in preparing or augmenting surficial geological maps, for example, those hosted by:
    - Government of British Columbia’s Soil Information Finder Tool.

  - Bedrock geological maps, prepared by the GSC and BCGS, that can be used to outline areas of thick Quaternary sediments, where surficial geological maps are unavailable.

  - Physical models of the Georgia Basin (Stephenson 2007; Stephenson et al. 2017) from the USGS.

  - Topographic data, which can provide basic data for Seismic Hazard analysis, particularly for Landslides, but can also be used to interpret surficial and subsurface geological conditions, as many surficial geological units and their boundaries have distinct topographic and geomorphic expression. The following are sources:
5.1.3.3 Subsurface Geological and Geotechnical Data

The acquisition of new data for an SM Mapping Project is usually limited due to cost, particularly with borehole and associated test data. However, large datasets of borehole data can be assembled by collecting existing data from geotechnical and scientific investigations. Acquisition of new data usually focuses on geophysical data rather than borehole data, as they are less represented in existing geotechnical datasets.

Existing subsurface data sources include those of scientific agencies such as the GSC, BCGS, Geoscience BC, and university engineering and geoscience departments, primarily in technical publications or theses. Larger volumes of data, primarily from geotechnical investigations, can be acquired from public or private agencies. Public agencies—including the BC Ministry of Transportation and Infrastructure, the Department of National Defense, BC Hydro, municipal governments, school boards, hospitals and health authorities, and universities and colleges—generally have larger datasets than private agencies. However, few public agencies archive their geotechnical data systematically, so Mapping Professionals should be prepared to refer to the geotechnical consulting firms that did the work to obtain the data. Furthermore, most existing geotechnical datasets, including those from public agencies, are considered proprietary. These data can be laborious to collect and require formal or informal agreements on how the data can be shared or presented.

5.1.3.3.1 Geotechnical Borehole and Test Hole Logs

Geotechnical borehole and test hole logs associated In-Situ and laboratory test data are generally considered the best subsurface data for SM Mapping Projects because they provide essential data for stratigraphic interpretation and analysis of Seismic Hazards. Additionally, the lithologies are typically professionally and consistently described. However, it should be noted that the quality of borehole logs varies with the type of drilling and the frequency of sampling. Continuously cored boreholes provide the most reliable stratigraphic data. Regardless of the quality of the individual borehole or test hole data, Mapping Professionals should understand that existing logs are likely to be unevenly distributed across a SM Mapping Project area and may vary in detail and accuracy.

In-Situ geotechnical tests are primarily SPTs, CPTs, CPTus, DCPTs, BPTs, and vane shear tests. Laboratory tests include grain size analyses, moisture content, Atterberg limits, Soil unit weight (γ), shear strength, consolidation, bender element, and V₅ of Soils; as well as sonic wave transmission testing of V₅ and V₆, or compressive strength measurements of rock, where available.

CPT data are notably valuable for the continuous and detailed records of water level data and their use in detailed stratigraphic interpretation. A particular benefit of a CPT compared with an SPT is its repeatable nature.

In addition to laboratory tests, V₅ data can be acquired in geotechnical boreholes and combined with CPTs (SCPTs) for stratigraphic interpretation. These methods are discussed further in Section 5.1.3.4 Shear Wave Velocity, P-Wave Velocity, and Related Seismic Methods and Appendix D2: Invasive Vs Data Collection Methods.

In some cases, geophysical logs may have been run in existing boreholes and can be used for lithology identification, stratigraphic correlation, determination of physical properties and water saturation, and the accurate definition of stratigraphic boundaries.

In cases where new borehole data are acquired during an SM Mapping Project, all logs should include a Soil type and stratigraphic description for Soils, as well as rock lithology and rock quality designation, weathering, and joint properties for rock.
5.1.3.3.2 Water Well Logs

Water well logs provide lithological and stratigraphic data, as well as water level data. These data are available through the BC Groundwater Wells and Aquifers Database (GWELLS). Water well logs are copious and useful, but Mapping Professionals should be aware of the following potential sources of error:

- Well logs are prepared by individuals with a range of technical backgrounds, experience, and expertise, and lithological terms are often used inconsistently. Mapping Professionals should verify the use of various terms by comparing logs from nearby wells, and by comparing logs described by the same driller.
- Location uncertainties and errors are common. In many cases, the location of a water well within a particular site is unknown. Though rare, large-scale errors of up to several hundred kilometres have been reported. Mapping Professionals should check the location accuracy using the reported street or community address.
- Because surface elevations are not usually reported in GWELLS, Mapping Professionals must rely on DEMs or topographic maps to estimate surface elevations, and thereby derive water level elevations. In areas of topographic relief, elevation uncertainty can be magnified by location uncertainty.
- Mapping Professionals should check the GWELLS website for a link to the original well record, to verify the accuracy and completeness of the record in the database.

5.1.3.3 Petroleum Industry Well Data

Petroleum industry well data, particularly geophysical logs, are an important data source for deeper stratigraphic horizons that are poorly sampled by other methods. These data are in the public domain in BC and are available from the BC Oil and Gas Commission and commercial sources.

Historically, operators have paid little attention to the upper few hundred metres in a well and therefore, those lithological sample descriptions may be poor or non-existent; however, all petroleum wells in BC must now have a gamma ray log to surface through the surface casing and may also have a neutron log. Mapping Professionals may be interested in these logs, as they are useful indicators of lithology and porosity, respectively, and can be interpreted to provide depth to bedrock data in areas where the Quaternary deposits are thick (Schlumberger 1991; Hickin et al 2008).

A common limitation is that the gamma ray signal is attenuated in the uppermost 10–30 m by conductor pipe, so where the bedrock occurs within this interval, only the maximum depth to bedrock is known (Monahan et al. 2022). Deeper intervals in petroleum wells usually have sample descriptions and are logged with a variety of geophysical logs, including:

- resistivity logs, for fluid saturations;
- acoustic logs, for Vp;
- density logs, for lithology and porosity; and
- gamma ray and neutron logs, for lithology and porosity.

5.1.3.4 Other Types of Subsurface Data

Other types of subsurface data may be locally available and provide important constraints on subsurface geology, particularly from community records. For example, in Greater Victoria, drawings of excavations for water and sewer lines commonly show where bedrock was encountered, providing local confirmation of shallow bedrock.

5.1.3.4 Geophysical Data

Geophysical data are important components of Higher-Level SM Maps, particularly seismic body wave, Surface Wave, and microtremor data for determining Vp profiles, T0, and geological structure. While some relevant geophysical data may be acquired while collecting geotechnical borehole data or from technical publications, acquisition of new geophysical data is typically required.
5.1.3.4.1 Microtremor Horizontal to Vertical Spectral Ratio

MHVSR data are an essential component of Higher-Level SM Maps. They can be acquired quickly and cost effectively, provide an efficient means of obtaining a dense volume of data that relate to both seismic site response and subsurface geology across an SM Mapping Project area, and are particularly useful for interpretation in those parts lacking other forms of subsurface data. Molnar et al. (2022) provide a detailed discussion on acquisition and interpretation.

The MHVSR method is used in Ground Shaking Hazard mapping and is starting to be used for Landslide Hazard assessment and geological mapping. Where there is a High Impedance Contrast, the average MHVSR provides a direct measure of $f_0$ or $T_0$. In Canada, glaciation has led to sufficiently High Impedance Contrasts such that the MHVSR method is generally applicable. The $T_0$ from MHVSR can be used to estimate the depth of the impedance boundary using the quarter wavelength rule (Joyner et al. 1981), although local calibrations may be required. In some cases, a measured MHVSR curve may be used as a proxy of weak Site Amplification.

The single station MHVSR method involves recording ambient noise (microtremors) using a single three-component seismometer (Molnar et al. 2022). A sufficient number of time windows to evaluate statistics, and therefore reliability, of the MHVSR are required. For short period sites (< 1 s), microtremor recordings of approximately 15–30 minutes are often sufficient, whereas for long period sites (> 1 s), recordings of one hour or more may be required. If the microtremor recording does not result in a reliable MHVSR curve, the recording should be repeated with a longer duration and/or on a different recording surface, away from local seismic sources.

Microtremor data from multiple seismometers in a 2D array can be used to estimate the $V_s$ profile at a site; this is the MAM.

5.1.3.4.2 Shear Wave Velocity, P-Wave Velocity, and Related Seismic Methods

$V_s$ data are also an essential component of SM Mapping Projects, particularly for Ground Shaking and Liquefaction assessments.

Mapping Professionals should utilize available guidelines and publications to understand the various $V_s$ data acquisition methods and select the one most suitable for their purposes. Guidelines published by GSC (Hunter and Crow 2015), and special issues of the Bulletin of the Seismological Society of America (introduction by Kaklamanos et al. 2021) and the Journal of Seismology (introduction by Yong et al. 2022) are particularly useful. For all methods, data acquisition and processing should be done by appropriately experienced professionals.

$V_s$ acquisition methods can be either invasive or non-invasive. Although the results are broadly similar (Molnar et al. 2010), invasive $V_s$ methods have been generally considered more reliable than non-invasive methods, because the sensor passes through the materials being measured (Hunter and Crow 2015). Furthermore, depth resolution is better in invasive methods, so that $V_s$ data can be correlated more confidently with stratigraphy for development of $V_s$ models or for Liquefaction assessments. In Liquefaction assessments, the use of non-invasive $V_s$ profiles, in which $V_s$ is averaged over thick intervals, requires the addition of lithologic data from boreholes, and still may not have sufficient resolution. However, blind comparison studies have shown that averaged $V_s$ parameters are comparable within and between invasive and non-invasive methods (Asten et al. 2022; Garofalo et al. 2016a, 2016b; Cornou et al. 2006; Stephenson 2017; Boore and Asten 2008).

Invasive methods are both more expensive and logistically complex, as sites must be checked for underground services, and not all sites are accessible due to concerns by surface owners. The costs and
Logistics of drilling for invasive testing can be avoided if pre-existing cased holes can be accessed for downhole V_s logging (Monahan et al. 2019, 2022).

The most used invasive V_s methods are SCPT and downhole logging by the vertical seismic profiling (VSP) method. Non-invasive V_s methods are body wave reflection and refraction methods, Surface Wave dispersion methods, and the single station microtremor method.

Mapping Professionals should note that multi-method approaches are increasingly being used and recommended for seismic site characterization and SM Mapping Projects (Molnar et al. 2020; Stephenson et al. 2022). An example of a multi-method approach is combining direct V_s profiling with MAM or MASW to retrieve lower and higher frequency data, respectively. Another example is the joint inversion of the combined MAM and MASW data with the T_0 to provide a well-resolved V_s profile to the resonator depth for each site (Molnar et al. 2020; Assaf et al. 2022).

2D seismic reflection profiling techniques, using both P-Waves and S-Waves, are now widely used in shallow investigations, including microzonation studies (Pullan et al. 2015; Hunter et al. 2022). They show the lateral changes in subsurface geological conditions in addition to providing V_s and V_p data. Seismic refraction profiling for shallow geotechnical investigations also shows lateral changes in subsurface geological conditions. Seismic reflection and refraction data may be available in technical publications or be acquired as part of the geotechnical data search.

Seismic reflection and refraction profiling has been widely used in the petroleum industry for deep structural and stratigraphic interpretation. Such data may be locally available from petroleum companies, industry data brokers, or government sources for interpretation of basin structure in basin Amplification studies.

Distributed acoustic sensing is an emerging method that uses pre-existing fibre-optic cables to record ground motions from both earthquakes and microtremors, and has the potential to provide dense networks of site response and V_s data profiles in urban environments (Yang et al. 2022).

Mapping Professionals should refer to Appendix D1: Non-invasive V_s Data Collection methods for an overview of different non-invasive and invasive V_s methods and the referenced material to determine which method(s) are appropriate for their SM Mapping Project.

5.1.3.4.3 Other Geophysical Methods

Other geophysical methods include, but are not limited to:

- Electromagnetic, resistivity, ground penetrating radar, and microgravity, which are commonly used in geotechnical and groundwater investigations. These methods can provide information about sediment thickness, water saturation, and variations in subsurface structure, particularly at large complex sites. Although these surveys will likely not be conducted as part of an SM Mapping Project, they could be acquired as part of the data collection for the project.

- Gravity and airborne magnetic surveys, which are commonly conducted for regional investigations of deep geological structures, may provide further information on basin structure in microzonation studies. These data could be available from resource industry or government sources.

5.1.3.5 Data Compilation and Acquisition in the Metro Vancouver Seismic Microzonation Project: a Level 3 Example

A cost-effective approach to compiling V_s and other relevant Geoscience Data to build a 3D database for the Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP) involved capitalizing on existing data in the region and performing non-invasive seismic testing to supplement and fill data gaps. Compilation of public and proprietary geological,
geophysical, and geotechnical data began with available open-source and online datasets (federal and provincial government agencies) and then moved to curating proprietary data from solicitation of contractors, consultants, public and private agencies, and municipal engineering and geographic information system (GIS) departments. In total, more than 12,000 borehole logs, 800 Vs soundings, and 1389 CPTs were obtained from these sources.

The project applied a multi-method approach to obtaining new constrained Vs profiles from non-invasive seismic testing (Assaf et al. 2022). At 123 selected sites, MAM tests were performed, in combination with active-source MASW testing, to retrieve lower and higher frequency dispersion data, respectively. The MAM test involved seven three-component seismometers deployed in four circular arrays of different radii. From the total of 28 single station microtremor recordings obtained, a site-average MHVSR was calculated. Joint inversion of the combined MAM and MASW dispersion curve with f0 or T0, of the MHVSR was performed to obtain the constrained Vs profile for each site.

The locations of the 123 array sites required an open space with a 30 m radius or more and thus were primarily located in community parks or school playing fields. The target of the 123 array sites was to measure Vs outside of the Fraser River delta, where over 500 Vs recordings had been performed previously by the GSC and others, and to constrain Vs structure of the glaciated upland areas of Vancouver, Burnaby, Surrey, Tsawwassen, North Vancouver, Deep Cove, and Horseshoe Bay. Most geotechnical boreholes in these upland areas were shallow and failed to provide stiffness measures deeper than a few metres. Application of these non-invasive seismic methods is typically not recommended on sloping ground, which violates the 1D site condition assumption of the testing methods. Consequently, both field techniques (Shear Wave refraction testing along with the MAM, MASW, and MHVSR testing) and analysis techniques were developed (Boucher 2022) to obtain Vs profiles for sites with complicated surface and subsurface geometry and/or low velocity zones.

Single station MHVSR data were acquired at 2370 sites to provide a dense grid of f0 or T0 measurements, both in areas where other subsurface data are abundant or sparse (Molnar et al. 2020; Sirohey 2022).

In addition, Vs and Vp VSP logs and gamma ray logs were run in four provincial groundwater observation wells to depth between 15 and 81 m. These wells are located in the eastern parts of the SM Mapping Project area, where invasive Vs data was sparse.

5.1.4 MAPPING CONSIDERATIONS

SM Maps are a type of subsurface geoscience map, because they implicitly represent the variation in geological conditions and associated material properties with depth relevant to Seismic Hazards, commonly between 10 and 30 m, but in some cases much deeper. The Geoscience Data supporting the mapping can vary from the use of surficial geological or topographic maps only, to extensive Geoscience Datasets that are used to create maps more representative of subsurface geological conditions. Surficial geological maps are an important starting point in SM Mapping Projects, and can be used for level 1 SM Maps on their own, using the mapped geological units to define microzones. However, surficial geological maps do not necessarily fully represent the subsurface geological conditions deeper than a few metres. For level 2 SM Maps, subsurface data and quantitative analysis should be used to confirm thicknesses and physical properties. Seismic Hazard Susceptibility is assigned based on generalized correlations with the age, lithology, and depositional environment of the surficial geological map units, as well as slope and water table data for Landslide and Liquefaction.

Although they are not suitable on their own for Higher-Level SM Maps, surficial geological maps provide useful information, particularly in parts of the mapped area where subsurface data are sparse.
Where surficial geological maps are unavailable, Mapping Professionals should consider including the development of surficial geological maps in the scope of the SM Mapping Project. Furthermore, existing surficial geological mapping can be enhanced by shaded relief models from DEMs, particularly from those based on LIDAR.

Where direct measures of seismic site conditions—such as microtremor $T_o$, $V_{50}$, or Liquefaction Hazard indices—are sufficiently closely spaced, these data points can be contoured directly. This approach has been taken in Amplification Susceptibility mapping in Oakland, California (Holzer et al. 2006). However, with the exception of microtremor data, such conditions are currently not typical, so borehole and other subsurface data are required to map subsurface geological conditions relevant to Seismic Hazard.

Different approaches to mapping can be taken depending on the geological complexity of the SM Mapping Project area, types of Seismic Hazards being considered, and the level of SM Map. Some examples are listed below, but others are possible:

- Preparation of new subsurface geological maps with geological map units defined in terms of thickness and physical properties of specific stratigraphic units relevant to Seismic Hazard indices ($V_{50}$ or Liquefaction Hazard).
- Using a locally developed $V_s$ model of the shallow geological units derived from limited $V_s$ data to estimate the $V_s$, $V_{50}$, and $T_o$ in multiple boreholes where $V_s$ and microtremor data are unavailable. This approach can provide a large volume of data points suitable for contouring. Because $V_s$-SPT correlations are lithology dependent, caution is recommended, unless they are locally developed or validated.
- Contouring depth to bedrock from borehole data where $V_s$ data demonstrate a correlation between depth to bedrock, $V_{50}$, and $T_o$.
- Conducting seismic slope stability analyses on typical slopes using representative shear strength data to build a slope stability model.

and applying this model to topographic slope maps (derived from topographic maps or DEMs) and surficial geological maps to map the Seismic Hazard.

- On Higher-Level SM Maps, the locations of all subsurface data points used should be shown, either on the map or as a layer in a digital product, to provide a visual qualitative guide to the uncertainties of the mapping at a specific location. Where new geological maps representative of subsurface geological conditions are prepared as part of an SM Mapping Project, Mapping Professionals should consider making the geological maps available as part of the final deliverable. The geological maps can assist Engineering/Geoscience Professionals using the maps understand the factors leading to the interpretations made in the SM Maps, often have value for other geological studies, and are usually better starting points for future SM Mapping Projects than the final SM Maps themselves.

Mapping Professionals should consider compiling Geoscience Data in three dimensions as a point cloud or in models (Nastev et al. 2016; Salsabili et al. 2021). Development of 3D block models of seismic geology or impedance layers is becoming more common (St. Lawrence Lowlands, Nastev et al. 2016; Saguenay, Quebec, Salsabili et al. 2021; Metro Vancouver, Adhikari et al. 2023; Ghofrani et al. 2023). Geostatistical relationships of the measured seismic site conditions within the geologic model or 3D seismic geology model may be used to predict an appropriate grid for contouring the seismic site condition. See Section 5.1.4.2 Contouring and Geostatistical Interpolation for factors to be considered in contouring Geoscience Data.
5.1.4.1 Remote-sensing Mapping Approaches

There are a variety of Seismic Hazard mapping approaches that are based solely on available remote-sensing datasets and associated maps. All remote-sensing approaches are an approximation of the In-Situ seismic site condition, measured by various geophysical and geotechnical field methods. SM Maps developed using remote-sensing datasets typically corresponds to level 1.

Ground Shaking Susceptibility mapping most often involves the mapping of $V_{30}$. Allen and Wald (2007) developed a method of $V_{30}$-based Site Class (Amplification) mapping using correlations of topographic slope with $V_{30}$, with adjustments for different tectonic settings. The coarse pixel size, approximately 1 km, and generalized nature of this approach restricts its use to low resolution level 1 SM Maps where other data are sparse. However, this approach has been further modified by applying terrain classification models at finer resolution (Iwasaki and Pike 2007; Iwasaki et al. 2018), and merging with $V_{30}$ SM Maps prepared using more direct $V_{s}$ measurements (Heath et al. 2020).

Remote-sensing based Liquefaction and Landslide SM Maps use the same readily available remote-sensing datasets and maps as Amplification SM Maps—surface topography and surficial geological maps—but also require an approximation of the ground’s saturation, often accomplished from remote-sensing datasets/maps of things such as vegetation cover and precipitation totals.

5.1.4.2 Contouring and Geostatistical Interpolation

Contouring irregularly distributed data points is a useful way to represent the spatial variation in geological conditions and Seismic Hazard in map form, but there are important considerations. Geostatistical interpolation methods are useful for contouring dense or large datasets of a particular parameter, where the density of data points is higher than the spatial variation of the contoured parameter. These methods can also be used to statistically assess uncertainty and display it in map form. However, with the exception of densely spaced geophysical datasets, it is important to recognize that all contour maps are interpretations. The reliability of the interpretation increases by increasing the coverage of data points used, particularly in regions where the parameter varies over short spatial scales, as well as consideration of additional, sometimes unquantified, relevant data. Examples of such data that could be used to inform contouring include:

- Surface and subsurface geological boundaries from existing or new geological maps or geophysical data.
- Topographic boundaries that reflect geological changes (e.g., breaks in slope).
- Geomorphic boundaries (e.g., arcuate sloughs or oxbows delineating floodplain deposits of different ages).
- Minimum values (e.g., in mapping the thickness of a geological unit, boreholes that do not fully penetrate the geological unit being mapped constrain the minimum thickness at that point).
- Maximum values (e.g., in cases where the log for the upper part of borehole is unavailable or unreliable, such as where an old water well has been deepened, and the log for the original hole is not available, and in oil and gas wells, where conductor pipe in the upper 10–30 m obscures the response of geophysical logs). For a geological boundary within that interval, such as the top of bedrock, the top of the logged interval provides a maximum possible depth to that boundary (Monahan et al. 2022).
- Subsurface data from sites that lack the quantified parameter, but have similar geological characteristics as sites that do.
- Known geological relationships, trends, and models.
These considerations apply not only to maps that show contours directly, but also to maps in which map units are defined in terms of having properties greater or lesser than a specific numerical threshold, such as thickness of a particular lithology.

5.1.5 HUMAN EFFECTS AND OTHER CONSIDERATIONS

5.1.5.1 Human Effects

SM Maps are generally intended to represent the natural Hazard, and typically do not consider human alterations to ground conditions. A common case of human alteration is fill over natural ground. Since the data collected at a specific site are used to represent the Hazard in the surrounding area, Mapping Professionals should correct any data collected at a site with fill over natural ground to the natural ground and water table conditions before calculating Hazard indices. Failure to do so may produce unconservative results, particularly for Liquefaction. See Section 5.3 Liquefaction for more information.

However, Mapping Professionals should include some areas of human alteration where information is available and may be particularly important or useful to planners and other users. Such alterations may include, but are not limited to:

- Artificial shoreline fills (e.g., port facilities and reclaimed land), which can be particularly susceptible to Liquefaction and earthquake damage.
- Fills of small stream valleys within urban areas (e.g., sites infilled as part of urban levelling programs), which often represent localized bands of increased Liquefaction Hazard.
- Artificially over-steepened slopes (e.g., along major thoroughfares), which often represent areas of increased Landslide Hazard.
- Large excavations, such as abandoned gravel pits.

5.1.5.2 Other Considerations

For Liquefaction and Landslide assessments, water table elevations are key input data. It is important to note that water table elevation data should be used in SM Mapping Projects, rather than the water depth data, as variability in topography will impact the results. Where borehole logs report water depth, Mapping Professionals should convert the depth to elevation. Where borehole logs do not report water levels, Mapping Professionals should contour surrounding water table elevation data to determine the gradient. See Section 5.1.4.2 Contouring and Geostatistical Interpolation.

For boreholes in which elevations are unknown, surface elevation can be estimated using DEMs, particularly those based on LiDAR data. However, DEMs can have up to a few metres of error, and larger errors can be introduced if locations are uncertain, particularly in areas of topographic relief. This is particularly true for water well logs in BC, on which elevations are not consistently reported. See Section 5.1.3.3 Water Well Logs.

In Liquefaction assessments, Mapping Professionals should ensure that water levels reported on water well logs are relevant to the shallow deposits being evaluated, not deeper confined aquifers. Mapping Professionals should be aware of these uncertainties and use professional judgment to determine whether data and results are reasonable.

Due to limited data, ground rupture has not been considered in SM Mapping Projects in BC to date. However, where potentially active faults can be accurately located, Mapping Professionals should consider showing them on the SM Map. Not all areas of Seismic Hazard need to be represented by polygons on a map.

Narrow linear features could be shown as lines, such as minor stream courses, along which liquefiable deposits may be present.
5.2 GROUND SHAKING

5.2.1 GENERAL

This section provides guidance on Amplification/De-amplification effects, caused by Earthquake Site Effects.

Seismic Waves change in amplitude and frequency as they propagate upwards towards the ground surface. The stiffness, strength, and damping properties of the various geological materials along the path of wave propagation in the near surface environment influences these changes, and potentially leads to Amplification/De-amplification of motions. The magnitude of Amplification/De-amplification varies depending on the frequency and intensity of Ground Shaking, as well as the properties of the subsurface.

Mapping Professionals should estimate the Amplification/De-amplification effects of ground motions using either Code-based procedures or by carrying out an SSRA. SSRAs require detailed information on Soil stratigraphy, the dynamic properties of the geological materials, and any seismic ground motions that are applicable for the site. This involves conducting site-specific investigations (SSI), supplemented with specialized laboratory testing of representative Soil samples and the collection of published data. The effort required to conduct an SSRA is considerable and is therefore typically only carried out for critical projects or for select representative sites in an SM Mapping Project.

When using the procedures specified in the Code, the time-weighted average $V_{50}$, which is an index of Seismic Hazard, should be used.

In addition to the stiffness, strength, and damping properties of the overburden Soils, local topography of a site also influences the changes to the Seismic Waves. Convex surface topography amplifies ground motion amplitudes, due to wave reflections and wave trapping (focusing), such as at the top of a mountain. Conversely, concave surface topography de-amplifies the ground motions (de-focusing). Amplifications/De-amplifications due to changes in localized topography or slope configurations can be assessed using a simplified formula, such as that shown in Figure 5.

Sites that are located above a young, deep sedimentary basin—with sedimentary rocks overlying an igneous and/or metamorphic basement and where depth ($z$) to $V_s$ of 2,500 m/s is in excess of about 3 km ($z > 3$ km)—can experience an increase in the amplitude of Ground Shaking, changes to frequencies, and a longer duration of Seismic Waves from trapped waves and the resulting reverberations within the basin. These effects are known as Basin Effects and may result in De-amplification of high frequency motions and Amplification of low frequency motions.

$$A_2 = \frac{A_1}{\phi_1}$$

where $A_1$ and $A_2$ are the peak ground motion amplitudes at points 1 and 2; and $\phi_1$ and $\phi_2$ are the angles at points 1 and 2.

Figure 5: Formula to assess the Amplification/De-amplifications of seismic ground motions due to changes in localized topography (Source: Facciolli 1991)
Basin Effects also impact ground motions near the edges of buried bedrock valleys or basins, where the thickness of Soil cover is low. This results in a complex interaction between Surface Waves and Shear Waves that can cause large Amplifications in ground motions. Basin Effects on ground motion predictions are a subject of active research in many seismically active geographical regions. Basin Effects can be in the order of 10–200% of the Code-based Amplification at long periods (T), where T > 1 s. Basin Effects should be considered in Higher-Level SM Maps, though this has been uncommon to date (Wirth et al. 2018). As Basin Effects have shown to slightly de-amplify high frequency ground motions, they should be quantified using 3D SSRA methods.

Some of the GMMs incorporated in the 6th generation Seismic Hazard model contain specific terms that can approximately account for Basin Effects; these are ZL0 (depth [z] to V5 = 1,000 m/s) for crustal earthquakes and Z2.5 (depth [Z] to V5 = 2,500 m/s) for subduction earthquakes. Routine location-specific Seismic Hazard calculations carried out using the National Research Council of Canada (NRCAN) Hazard calculator do not include Basin Effects; instead, NRCAN uses default values for Zl0 and Z2.5. However, some implicit account of basin Amplification effects are present in the long-period Hazard estimates, because those GMMs that lack basin terms contain observations made in basins where basin Amplification is expected.

Seismic ground motions caused by earthquakes consist of waves of varying frequencies and amplitudes. High-frequency ground motions have short periods of oscillation and low-frequency ground motions have long periods of oscillation. It is important to note that, typically, Amplification decreases as the intensity of Ground Shaking and stiffness of Soil increase. These effects are more pronounced at high frequencies or short periods. Consequently, at strong levels of Ground Shaking on sites located on thick deposits of soft Soils, the amplitude of high-frequency ground motions may be less than those on nearby bedrock sites (De-amplification) and the amplitude of low-frequency ground motions may be greater than those on nearby bedrock sites (Amplification). When the T0 is close to the dominant period of the earthquake input ground motion, there can be considerable Amplification of ground motions at the surface due to resonance.

Amplification is commonly estimated by correlations with V30, with Amplification factors generally increasing as V30 decreases at low Ground Shaking intensities. V30 and Site Class are widely used in the Code and SM Maps, but do not directly account for resonance or other types of Amplification. As resonance effects are important in structural design, Mapping Professionals should develop T0 maps in SM Mapping Projects.

Table 4 outlines expectations and considerations for the three Ground Shaking SM Map levels. Each level is discussed in more detail in the following sections. See Appendix B: Examples of Seismic Microzonation Maps in BC for a select list of possible SM Maps.
Table 4: Concept of Seismic Microzonation Map Levels Particular to Ground Shaking

<table>
<thead>
<tr>
<th>Type of Map</th>
<th>LEVEL 1 MAP</th>
<th>LEVEL 2 MAP</th>
<th>LEVEL 3 MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Statement</td>
<td>- Level 1 Ground Shaking SM Maps are qualitative to semi-quantitative Susceptibility Maps and are based on generalized correlations of Seismic Hazard with age, lithology, and the depositional environment of surficial geological materials. These maps are normally based on surficial geological maps, or proxies, and a limited amount of subsurface data.</td>
<td>- Level 2 Ground Shaking SM Maps contain basic quantitative analyses of Susceptibility or potential. They are developed using subsurface geological data to confirm the thicknesses of geological units, area-specific data on physical properties of geological materials, and use either surficial or subsurface geological maps.</td>
<td>- Level 3 Ground Shaking SM Maps contain advanced analyses of Seismic Hazard, based on extensive subsurface geological, geophysical, and geotechnical data, and simulations. They are normally based on detailed subsurface geological maps or models.</td>
</tr>
<tr>
<td>Data Required</td>
<td>- Surficial geological maps, topographic maps or DEMs, and historical earthquake data. - No test data required.</td>
<td>- Surficial or subsurface geological maps, topographic maps or DEMs, and historical earthquake data. - Test hole, In Situ and lab tests, Vₙ and MHVSR data also required.</td>
<td>- Detailed subsurface geological Maps, topographic Maps or DEM, and historical earthquake data. - Extensive test hole, In-Situ and lab tests Vₙ and MHVSR data also required.</td>
</tr>
<tr>
<td>Map</td>
<td>- A generalized correlation of Site Class, Tₜ, or V₃₀ with age, lithology, and depositional environment of surficial geological materials or topographic slope.</td>
<td>- A correlation of surficial or subsurface geology with Site Class, V₃₀, Tₜ, measured and/or estimated from regional Vₙ model(s). - Comparison with observed ground motions.</td>
<td>- A correlation of subsurface geology with Site Class, V₃₀, Tₜ, measured and/or estimated from regional Vₙ model(s), Ground Shaking levels from 1D, 2D, and 3D SSRA, and Basin Effects. - Comparison with observed ground motions.</td>
</tr>
</tbody>
</table>
5.2.2 THE STATE OF PRACTICE OF GROUND 
SHAKING MAPPING IN BRITISH 
COLUMBIA

The earliest SM Map on Amplifications in BC was prepared by Vilho Wuorinen in 1974 following the magnitude 7.3 earthquake that occurred in 1946 on Vancouver Island. Wuorinen prepared an SM Map for Victoria by correlating surficial geology with estimates of Ground Shaking felt and damage that occurred. The Mapping Professionals reviewed newspaper articles, conducted interviews with approximately 450 people who felt the earthquake, and assigned perception-based modified mercalli intensity scales to different areas. This was combined with data on overburden Soils, collected from surficial geological maps, approximately 700 borings, and 450 Soil profiles collected from the City of Victoria. This effort resulted in an SM Map for Victoria that could be considered level 1 or level 2.

In the mid-1990s, the Seismic Microzonation Task Group of the Resource Inventory Committee of the Government of BC (now Resources Information Standards Committee [RISC]) carried out a preliminary microzonation assessment for BC that included Ground Shaking (Hollingshead and Watts 1994). The study was carried out at a time when the Code addressed Amplification Earthquake Site Effects via the foundation factor, which was loosely defined based on Soil conditions underlying a site. The study focused on establishing Amplification of peak horizontal bedrock acceleration as a function of the Soil type descriptions established by Seed and Idriss (1982) and for soft Soils established by Idriss (1991). This study resulted in an SM Map for British Columbia that represents Ground Shaking (approximately level 1), applicable for short period responses, and an accompanying report. It is stated in the report that a Higher-Level SM Map could be developed by considering V₅ measurements.

Although V₃₀ is currently widely used in the Code as one of the variables to estimate Amplification/De-amplification effects, it lacks the ability to capture the differences in response between shallow sites with High Impedance Contrasts and sites with uniform or Gradational changes. The measured V₅ profile of a site is important when assessing site response, as opposed to an average V₃₀ or the Site Class. Alternatives to V₃₀ or Site Class that include a combination of V₅ and T₀ may need to be introduced in future Code revisions, to better define Ground Shaking effects for a wide range of site conditions.

Direct measurement of Ground Shaking from moderate to large earthquakes, combined with geological models and geotechnical characterization of Soils, provide the most useful data to assess Amplification/De-amplification effects due to Ground Shaking. Over the past several decades, a large number of digital and interfaced seismographs have been deployed in the region to monitor Ground Shaking from earthquakes. The Amplification of ground motions resulting from several earthquakes have been assessed and documented (Cassidy et al 1997; Cassidy and Rogers 1999; Atkinson and Cassidy 2000; Jackson et al 2017). Although the Ground Shaking data that is currently available from such instrument arrays is limited to low levels of Ground Shaking (i.e., generally < 0.05 g, where g is the acceleration due to gravity), Ground Shaking data from future moderate to large earthquakes would constitute a significant database to better assess site response and Amplification effects.

Ground Shaking Susceptibility Maps based on V₃₀ were prepared for Chilliwack and Victoria by the BCGS in 1996 and 2000. In 2015, the GSC prepared Amplification Maps for the District of North Vancouver that are based on V₃₀ (Wagner et al 2015). SM Maps have been developed and are being used in other high Seismic Risk regions in Eastern Canada, such as Ottawa, Montreal, and Quebec City. See Appendix C: History of Use and Development of Seismic Microzonation Maps in BC for more details.

5.2.3 LEVEL 1 GROUND SHAKING MAPS

Level 1 Ground Shaking SM Maps are Susceptibility Maps and should consist of:
surficial geological maps (or proxy, such as topographic slope) demarcating different Soil types/stiffnesses;
- simplified charts correlating peak bedrock accelerations to ground surface accelerations expected at a site; and
- regional \( V_{S30} \) maps developed based on empirical correlations with surficial geology and/or topographic slopes.

The intensity of Ground Shaking, or the seismic demand, is approximately represented by the peak bedrock acceleration estimated for the site. Amplification/De-amplification effects may only be given for the peak bedrock acceleration, which is a limitation of level 1 Ground Shaking SM Maps. Relationships correlating bedrock acceleration to ground surface acceleration for varying Soil types and profiles are shown in Figure 6 and Figure 7.

![Figure 6: Published correlations between peak bedrock and ground surface acceleration for stiff Soils (Source: Seed and Idriss 1982)](image-url)
These simplified charts do not provide detailed information on the Amplification of ground motions anticipated at different periods. Additionally, the Soil and bedrock descriptions are qualitative and lack quantitative estimates of Local Site Conditions, such as $V_{30}$. Generally, soft Soil sites have $V_s$ lower than 180 m/s, stiff and deep cohesionless Soil sites have $V_s$ varying from 180–760 m/s, and rock sites have $V_s$ varying from 760–1500 m/s and higher.

Level 1 Amplification SM Maps are useful to Mapping Professionals when dealing with sites that lack site-specific $V_s$ measurements, such as in less populated regions of the province.

### 5.2.3.1 Methodology

Level 1 Ground Shaking SM Maps should be developed by collecting information on surficial geology, type and consistency of Soils underlying the site, and $V_s$ of geological materials (established via empirical correlations or regional geological models). Surficial geological maps are available from the GSC. Existing $V_s$ maps are highly localized and limited.

### 5.2.3.2 Ground Information Data Requirements

Level 1 Ground Shaking SM Maps require information on type, consistency, and depth of overburden Soils underlying a given site or an area. See Section 5.1.2 Data Requirements.

### 5.2.3.3 Mapping Parameters and Procedures

Soil type and stiffness descriptions are the primary parameters used in level 1 Ground Shaking SM Maps. Soil type descriptions are obtained from surficial geological maps, whereas Soil stiffness variations are established via In-Situ measurement of $V_s$ at discrete locations. $V_s$ should be used as a direct In-Situ measurement to evaluate Soil stiffness:

$$\text{shear modulus } [G] = \text{mass density } \times V_s$$  \[\text{Formula 1}\]

The typical $V_s$ for different Soil types/densities are given in Section 5.2.3 Level 1 Ground Shaking Maps.
5.2.3.4 Applications and Examples

Amplification SM Maps developed according to the procedures recommended in the mid-1990s by the Seismic Microzonation Task Group (Hollingshead and Watts 1994), such as the Ground Shaking SM Maps developed for Victoria in 2000, are examples of level 1 Ground Shaking SM Maps.

Amplification Susceptibility Maps developed based on Site Class (or Vs30) using generalized correlations with surficial geological units (Wills et al. 2000) or topographic slope (Wald and Allen 2007; Allen and Wald 2007) are additional examples of level 1 Ground Shaking SM Maps.

5.2.4 LEVEL 2 GROUND SHAKING MAPS

Level 2 Ground Shaking SM Mapping Projects should include Vs30 and T0 maps where data have been collected and mapped via In-Situ measurements at discrete locations. Most Amplification Hazard Maps completed to date in Canada are correlations with Site Class and Amplifications (approximately level 2 Ground Shaking SM Maps).

An SM Map of Vs30 is indicative of Ground Shaking Susceptibility and is independent of the seismic demand at a given site.

A T0 SM Map is independent of the seismic demand and is a useful indicator of high Ground Shaking resulting from resonance effects in detailed Soil-structure interaction analyses.

5.2.4.1 Methodology

Level 2 Ground Shaking SM Maps should be developed based on a collection of In-Situ Vs and T0, or f0, measurements for the region of interest. Where existing data is limited, Mapping Professionals may need to collect additional Vs and T0 data to develop level 2 Ground Shaking SM Maps. In the absence of In-Situ measurements, empirical correlations with penetration resistance measurements can be used.

A quantitative Code-based ground Amplification/De-amplification assessment for a given site requires a Vs profile, from which an estimate of Vs30 can be derived. When using the NRCAN Hazard calculator that corresponds to the 6th generation Seismic Hazard model, it should be noted that these values do not consider topographic and Basin Effects or the effects of Soil softening and/or Liquefaction due to cyclic loading.

5.2.4.2 Ground Information Data Requirements

Vs30 measurements should be established via In-Situ measurements of V, using geophysical investigations, such as downhole or cross hole Vs, measurements, or MASW. Mapping Professionals should collect In-Situ site-specific measurements of Vs rather than rely on correlations. However, where In-Situ Vs measurements are not available, Vs should be estimated via seismic data (e.g., MAM), reliable SPT, CPT, equivalent SPT established from BPTs and published/accepted correlations, or from a Vs model of the shallow subsurface geological units.

SPT should be established from energy measurements and meet the requirements of ASTM D1586 Standard Test Method for SPT and Split-Barrel Sampling of Soils and BPTs (or instrumented BPTs) should be carried out in overburden Soils. Vs data can also be established using seismic refraction and reflection geophysical surveys. The depth accuracy of these measurements when using these techniques should be sufficient to establish Vs30 for a given site.

For sites in Metro Vancouver, Vs profiles, including spatial and depth variations, are contained in 3D geomodels that have been developed by coding available measurements using the LeapFrog platform.

T0 should be established via MHVSR measurements carried out in dense arrays.

Data may consist of measurements taken at limited and unevenly spaced locations. The data in between locations should be interpolated by contouring. See Section 5.1.4.2 Contouring and Geostatistical Interpolation.
5.2.4.3 Mapping Parameters and Procedures

The fundamental mapping parameters used for level 2 SM Maps are $V_{S30}$ and $T_0$. For sites where these data are lacking, but where stratigraphy is known and/or reliable penetration resistance data are available, these parameters should be estimated from $V_5$-SPT (or equivalent) correlations or a $V_5$ model of the shallow geological units, reliable measurements of standard or equivalent SPT penetration measurements, and Soil stratigraphy information.

Mapping Professionals should have an independent review conducted of their Higher-Level SM Map(s). See Section 6.1.8 Documented Independent Review of High-Risk Professional Activities or Work.

5.2.4.4 Applications and Examples

Structural Engineers of Record (SERs) use $V_{S30}$ as a fundamental input parameter to establish site-specific acceleration response spectra to assist in base shear calculations for structural design. The use of the SM Maps depicting $V_{S30}$ should only be used for conceptual and preliminary design and analysis of structures. Detailed structural design should use site-specific measurements of $V_{S30}$.

5.2.5 LEVEL 3 GROUND SHAKING MAPS

Level 3 Ground Shaking SM Maps incorporate the seismic demand and are Seismic Hazard Maps. SM Maps should be provided for at least two levels of seismic demand—one corresponding to 1/475 return period ground motions and the other corresponding to 1/2475 return period ground motions.

The level 3 Ground Shaking Mapping Projects should consist of the following:

- Maps showing Amplification/De-amplification resulting from Basin Effects established via 3D geological models and wave propagation analysis of the region. The results should be presented in terms of basin Amplification/De-amplification factors to be applied on top of the Site Amplifications/De-amplifications established either via Code-based methods using $V_{S30}$ or 1D SSRA methods described above. The basin Amplification factors are relevant only in areas where $Z_{2.5} > 3$ km.

5.2.5.1 Methodology

Level 3 Ground Shaking SM Maps should contain detailed information compiled from numerous 1D, 2D, and 3D numerical simulations carried out for select sites and for select region(s).

Maps showing 1D Amplification/De-amplification of ground motions should be developed by carrying out SSRAs at select locations distributed throughout the SM Mapping Project area. The locations should represent a range of Soil profiles that exist in the region. SSRAs should be carried out using crustal, in-slab, and interface scenario spectra that are compatible with ground motion time histories developed for a reference ground condition (e.g., $V_{S30} = 760$ m/s). The analyses should be appropriate for the level of Ground Shaking anticipated and take into consideration the nonlinear Soil response.

The Basin Effects should be estimated via region-specific 3D computer models. In the absence of such models, Basin Effects may be estimated using the GMMs with appropriate $Z_{2.0}$ and $Z_{2.5}$ values.

5.2.5.2 Ground Information Data Requirements

Level 3 SSRAs require detailed information on Soil stratigraphy and parameters that characterize the dynamic response of each Soil layer, such as dynamic shear moduli, stress-strain variations, or modulus reduction and damping curves, and input ground motions that are applicable for the site for each return period of interest.
Analysis of Basin Effects require estimates of depths to $V_s = 2,500 \text{ m/s}$ for the region of interest. Consistent with the definitions in Section 3.4 Introduction to Seismic Microzonation Map Levels, for an SM Map to be level 3, it should be based on subsurface geological mapping relevant to Seismic Hazard; surficial geological maps are inadequate as they do not represent depths and thicknesses well. New subsurface geological mapping is often required for level 3 SM Mapping Projects.

3D basin Amplification/De-amplification analyses should include:

- basin-wide 3D velocity models (e.g., Pacific Northwest Community velocity model);
- scenario earthquake-source rupture models that are input to 3D wave propagation algorithms and require high-performance parallel computing; and
- appropriate nonlinear Soil models.

5.2.5.3 Mapping Parameters and Procedures

Mapping parameters for level 3 Ground Shaking SM Maps should include ground motion Amplification/De-amplification effects due to propagation of Seismic Waves within the near surface zones established via 1D and/or 2D wave propagation models and topographic and Basin Effects expressed as separate factors established via 2D and 3D wave propagation models.

Mapping Professionals should have an independent review conducted of their Higher-Level SM Map(s). See Section 6.1.8 Documented Independent Review of High-Risk Professional Activities or Work.

5.2.5.4 Applications and Examples

Level 3 Ground Shaking SM Maps are uncommon, as they require considerable time, effort, data, and expertise in 3D modelling. The available examples of level 3 SM Maps are those prepared for the MVSMMP (University of Western Ontario 2023).

5.3 LIQUEFACTION

5.3.1 GENERAL

Liquefaction is the process in which loose, saturated, cohesionless (e.g., granular) Soils lose significant strength and stiffness, and behave like a liquid during Ground Shaking. When the Soil is saturated with water during an earthquake, the water in the Soil cannot drain quickly enough under the rapid earthquake loading. Instead, the water pressure in the Soil increases rapidly and effectively suspends sand particles. This causes a near-complete loss of shear strength and stiffness of the Soil, which results in a failure or collapse of structures founded above or around the Soil. It also causes lateral spreading ground displacements or settlements, which results in sands being ejected to the surface, as a surface manifestation of Liquefaction.

These guidelines focus on the triggering of Liquefaction in granular Soils. The Consequences of Liquefaction are outside the scope of these guidelines, except for the LSN, which predicts the major manifestation of Liquefaction at the ground surface and is calculated from volumetric strains ($\varepsilon_v$) of Soils after Liquefaction occurs.

Susceptibility to Liquefaction is largely dependent on sediment material, depositional environment, distribution, and deposition age. The shallower the Liquefiable layer is, the more effect it will have on the surface. Deeper Liquefaction from a very strong earthquake event is possible, but is outside the scope of these guidelines. For the purposes of these guidelines, Liquefaction susceptible Soils are those within 20 m of the ground surface that include:

- sands (0–12\% of fines with particle size < 0.075 mm);
- silty or clayey sands with 12–50\% of fines and a plasticity index (PI) of < 5\%;
- gravelly sands (12–50\% of gravels) or sandy gravels (12–50\% sands); and
- non-plastic silts (50–100\% of fines and PI < 5\%).
However, it is recognized that cyclic failure can also occur in plastic Soils (Wang 1979; Idriss and Boulanger 2008; Finn 1998). A more descriptive terminology for cyclic failure of plastic Soils (silts or clayey silts), containing 100% fines and with relatively high PI (PI > 10%), is cyclic strain softening (Idriss and Boulanger 2008), as it places more emphasis on the structural breakdown of the material under cyclic loading than on buildup or rise of water pressure in Soil. However, the quantitative analysis of cyclic strength or resistance—Cyclic Resistance Ratio (CRR)—of plastic Soils is outside the scope of these guidelines and typical Liquefaction SM Maps.

Mapping Professionals should consider the natural ground condition—that is, ground that does not contain human modifications, including ground densification, fill placement, or human-made structures such as dikes, buildings, bridges, and dams—when developing Liquefaction SM Maps. Because of the effects of overburden stress on Liquefaction Hazard, geotechnical test holes drilled on top of flood-protection dikes with thick fills (> 3 m) should not be used for Liquefaction assessment of surrounding natural ground that is at a lower ground level than the dikes. In addition, Liquefaction maps should not be used to evaluate the vulnerability of existing dikes. However, geotechnical data obtained at drill holes on building sites or on dikes with a few metres (< 3 m thick) of fill over natural ground may be used if the effect of the fill is removed. Elsewhere, in areas of extensive fills (e.g., shoreline facilities), the fills should be identified, mapped, and evaluated, as these fills represent the new normal ground conditions in these areas.

Table 5 outlines expectations and considerations for the three Liquefaction SM Map levels. Each level is discussed in more detail in the following sections. See Appendix B: Examples of Seismic Microzonation Maps in BC for a select list of possible SM Maps.

5.3.2 THE STATE OF PRACTICE OF LIQUEFACTION MAPPING IN BRITISH COLUMBIA

Existing Liquefaction SM Maps for various areas in BC were developed prior to the development of GSC’s 5th (2015) and 6th (2020) generation Seismic Hazard models (Halchuk et al. 2016; Kolaj et al. 2020). As such, these maps were based either purely on surficial geological maps (approximately level 1 SM Maps), or on Liquefaction analyses in which contribution to Liquefaction Hazard was considered to be dominated by the crustal earthquakes (approximately level 2 SM Maps). During the development of the Liquefaction Hazard Map of Greater Victoria (Monahan et al. 2000), it was concluded that the Liquefaction Hazard is generally not widespread in the Victoria area, although it was recognized that there is the potential for a very large (approximately Magnitude 9) earthquake on the Cascadia subduction zone west of Vancouver Island. Since the development and adoption of the 5th and 6th generation Seismic Hazard models by GSC, more areas in Greater Victoria are now considered to have Liquefaction Hazard; as such, existing SM Maps should be referenced with caution. Currently, Liquefaction Hazard Maps do not include Basin Effects.

It is noted that, in addition to unique Seismic Hazard in BC, the Soil conditions of particularly thick liquefiable sand, silty sand layers, and shallow groundwater table in some regions are contributing factors to Liquefaction Hazard.
<table>
<thead>
<tr>
<th>Type of Map</th>
<th>LEVEL 1 MAP</th>
<th>LEVEL 2 MAP</th>
<th>LEVEL 3 MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Statement</td>
<td>- Seismic Susceptibility Map</td>
<td>- Seismic Susceptibility Map or Seismic Hazard Map</td>
<td>- Seismic Hazard Map</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>General Statement</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 Liquefaction SM Maps are qualitative to semi-quantitative Susceptibility Maps and are based on generalized correlations of Seismic Hazard with age, lithology, and the depositional environment of surficial geological materials. They are developed using surficial geological maps, or proxies, and a limited amount of subsurface data.</td>
<td>Level 2 Liquefaction SM Maps contain basic quantitative analyses of Susceptibility or potential. They are developed using subsurface geological data to confirm the thicknesses of geological units and area-specific data on physical properties of geological materials and use either surficial or subsurface geological maps.</td>
<td>Level 3 Liquefaction SM Maps contain advanced analyses of Seismic Hazard, based on extensive subsurface geological, geophysical, and geotechnical data, and simulations. They are normally developed based on detailed subsurface geological maps or models.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data Required</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Surficial geological maps, topographic maps or DEMs, and historical earthquake and Liquefaction data.</td>
<td>Surficial or subsurface geological maps, topographic maps or DEMs, and historical earthquake and Liquefaction data.</td>
<td>Detailed subsurface geological maps, topographic maps or DEMs, and historical earthquake and Liquefaction data.</td>
<td></td>
</tr>
<tr>
<td>Water level data.</td>
<td>Water level data, In Situ (e.g., CPT and SPT) and lab tests, and V_s data.</td>
<td>Water level data, extensive test hole, In-Situ (e.g., CPT and SPT) and lab tests, and V_s data.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Map</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A generalized correlation of Seismic Hazard with age, lithology, and depositional environment of surficial geological materials.</td>
<td>A depth to, and thickness of, susceptible deposits or factor of safety-based analyses (LPI or equivalent), seismic demand Cyclic Stress Ratio (CSR) based on a simplified method (without SSRA, using regional maximum ground acceleration (a_{max})), correlation of Seismic Hazard with geological units defined using surficial or subsurface geological maps.</td>
<td>A factor of safety-based analyses (LPI or equivalent), seismic demand CSR based on a simplified method and SSRA, correlation of Seismic Hazard with geological units defined using surficial or subsurface geological maps, Liquefaction Resistance (CRR) based on subsurface Soil data.</td>
<td></td>
</tr>
</tbody>
</table>
5.3.3 LEVEL 1 LIQUEFACTION MAPS

Level 1 Liquefaction SM Maps depict the Susceptibility of a site to Liquefaction that is related mostly to the geological and ground water conditions.

5.3.3.1 Methodology

Level 1 Liquefaction SM Maps are created by qualitatively subdividing the map area into seismically homogeneous microzones based on the existing surficial geological and subsurface geophysical/geotechnical data. Liquefaction Susceptibility ratings of Soils are assigned primarily based on the depositional and formation environments and their ages.

An example rating of Liquefaction Susceptibility, based on age and depositional environment of sedimentary deposits, was presented in Youd and Perkins (1978) and is cited in Table 6.

The criteria in the table applies to sites where water table depths are less than 10 m and the surficial sediment deposits are thicker than 10 m. Since these criteria are generic, Mapping Professionals should take the geological history of BC into account, particularly the effects of pleistocene glaciation, and should also consider referring to the BC-specific Liquefaction Susceptibility matrices published in Levson et al. (1998) and Quinn et al. (2015).

5.3.3.2 Ground Information Data Requirements

As discussed in Section 5.1.2 Data Requirements, Mapping Professionals should use existing and readily available data for level 1 SM Maps including, but not limited to:

- surficial geological maps and topographic maps;
- historical earthquake and Liquefaction data; and
- when available, SPT, CPT, V, and borehole stratigraphic data, to determine groundwater tables and thickness of Liquefaction susceptible Soil layers.

Although seismic demand is not explicitly addressed in level 1 SM Maps and quantitative calculation of factor of safety against Liquefaction is not required, Mapping Professionals should be aware of the general seismicity of the region they are mapping.

5.3.3.3 Mapping Parameters and Procedures

A level 1 Liquefaction SM Map should include a Liquefaction Susceptibility evaluation matrix. An example matrix can be found in Maps of Quaternary Deposits and Liquefaction Susceptibility in the Central San Francisco Bay Region, California (USGS 2006). Similar to the ratings used in Youd and Perkins (1978), the Susceptibility ratings in these maps and matrix are very low, low, moderate, high, and very high. However, this matrix does not account for the effects of Pleistocene glaciation that is unique to BC. Mapping Professionals should consider referencing the BC-specific Liquefaction Susceptibility matrices published in Levson et al. (1998) or Quinn et al. (2015).

5.3.3.4 Applications and Examples

Level 1 Liquefaction SM Maps are often based on generalized correlations of Susceptibility with the types, depositional environments, and ages of surficial geological deposits and water table depth (Youd and Perkins 1978).

An example level 1 Liquefaction SM Map was developed by Turner et al. (1998), which was based on surficial geological maps developed by Armstrong and Hicock (1979, 1980).
### Table 6: Example Ratings of Liquefaction Susceptibility for Sedimentary Deposits During Strong Ground Shaking (Recreated from Youd and Perkins 1978)

<table>
<thead>
<tr>
<th>TYPE OF DEPOSITS</th>
<th>GENERAL DISTRIBUTION OF COHESIONLESS SEDIMENTS IN DEPOSITS</th>
<th>LIKELIHOOD THAT COHESIONLESS SEDIMENTS, WHEN SATURATED, WOULD BE SUSCEPTIBLE TO LIQUEFACTION (BY AGE OF DEPOSIT)</th>
<th>&lt; 500 YEAR</th>
<th>HOLOCENE</th>
<th>PLEISTOCENE</th>
<th>PRE-PLEISTOCENE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Continental Deposits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River channel</td>
<td>Locally variable</td>
<td>Very high</td>
<td>High</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Flood plain</td>
<td>Locally variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Alluvial fan and plain</td>
<td>Widespread</td>
<td>Moderate</td>
<td>Low</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Marine terraces and plains</td>
<td>Widespread</td>
<td>–</td>
<td>Low</td>
<td>Very Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Delta and fan-delta</td>
<td>Widespread</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Lacustrine and playa</td>
<td>Variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Colluvium</td>
<td>Variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Talus</td>
<td>Widespread</td>
<td>Low</td>
<td>Low</td>
<td>Very Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Dunes</td>
<td>Widespread</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Loess</td>
<td>Variable</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Unknown</td>
<td></td>
</tr>
<tr>
<td>Glacial till</td>
<td>Variable</td>
<td>Low</td>
<td>Low</td>
<td>Very low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Tuff</td>
<td>Rare</td>
<td>Low</td>
<td>Low</td>
<td>Very low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Tephra</td>
<td>Widespread</td>
<td>High</td>
<td>High</td>
<td>Unknown</td>
<td>Unknown</td>
<td></td>
</tr>
<tr>
<td>Residual Soils</td>
<td>Rare</td>
<td>Low</td>
<td>Low</td>
<td>Very low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Sebka</td>
<td>Locally variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>(b) Coastal Zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delta</td>
<td>Widespread</td>
<td>Very high</td>
<td>High</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Esturine</td>
<td>Locally variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>High energy wave beach</td>
<td>Widespread</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Low energy wave beach</td>
<td>Widespread</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Lagoonal</td>
<td>Locally variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
<tr>
<td>Fore shore</td>
<td>Locally variable</td>
<td>High</td>
<td>Moderate</td>
<td>Low</td>
<td>Very low</td>
<td></td>
</tr>
</tbody>
</table>

#### 5.3.4 LEVEL 2 LIQUEFACTION MAPS

Level 2 Liquefaction SM Maps can be either enhanced Susceptibility Maps that require more data and analysis compared with Level 1 SM Maps, or Hazard Maps that consider the effect of Seismic Hazard by adopting the simplified method for Liquefaction analysis.

#### 5.3.4.1 Methodology

Building on the analysis of surficial geological maps that is required for the development of level 1 SM Maps, the development of level 2 SM Maps should include analyses of subsurface geological, geophysical, and geotechnical data.
A level 2 Liquefaction Susceptibility Map should present groundwater levels, depths and thickness of Liquefaction susceptible deposits or layers, and the correlation of Susceptibility with geological map units or microzones defined using surficial or subsurface geological data. A Liquefaction Hazard Map should involve application of seismic force demand and calculation of factor of safety against Liquefaction ($F_{S\text{liquefaction}}$).

$F_{S\text{liquefaction}}$ for the representative Liquefaction susceptible layer can be calculated using either the simplified method (Seed and Idriss 1971) or the SSRA method. When using either method, $F_{S\text{liquefaction}}$ is calculated as follows in Formula 2:

$$F_{S\text{liquefaction}} = \frac{CRR_\sigma}{CSR_{M7.5}} = \frac{CRR_\sigma K_\sigma}{CSR / MSF}$$

[Formula 2]

where
- $CRR$ is the Cyclic Resistance Ratio;
- $CSR$ is the Cyclic Stress Ratio;
- $CRR_\sigma$ is $CRR$ corrected for effective overburden stress in a Liquefaction analysis;
- $CSR_{M7.5}$ is CSR normalized for earthquake moment magnitude ($M_w$) of $M_w = 7.5$;
- $K_\sigma$ is the correction factor for effective overburden stress ($\sigma'_vo$); and
- $MSF$ is the earthquake magnitude scaling factor for $M_w$.

Corrections are needed so that the $CRR$ and the seismic load intensity are consistent at the In-Situ effective overburden stress ($\sigma'_vo$) of the layer and for $M_w = 7.5$ (i.e., 15 cycles).

There are a variety of industry-accepted procedures for calculating $F_{S\text{liquefaction}}$, each with their own set of pros and cons. In 2010—on the recommendation of an ad hoc committee of the Earthquake Engineering Research Institute—a comprehensive assessment of the state of the art and practice was initiated and completed by the US National Academies of Sciences, Engineering, and Medicine. The study was carried out by a committee of 12 engineers and scientists, with inputs from external reviewers and experts around the world. Mapping Professionals are encouraged to read the final report of this study (US National Academies 2021) to better understand the applications and limitations of each of the industry-accepted procedures. These procedures include:

- SPT-based on Youd et al. (2001)
- SPT-based on Idriss and Boulanger (2008) and Boulanger and Idriss (2012, 2014)
- SPT-based on Cetin et al. (2004)
- CPT-based on Robertson and Wride (1998), as recommended by Youd et al. (2001)
- CPT-based on Idriss and Boulanger (2008) and Boulanger and Idriss (2014, 2016)
- CPT-based on Moss et al. (2006)
- $V_s$-based on Andrus and Stokoe (2000), as recommended by Youd et al. (2001)
- $V_s$-based on Kayen et al. (2013)

Mapping Professionals should familiarize themselves with each of these procedures and use professional judgment to determine the best approach for their SM Mapping Project, considering the scope of work, client expectations, geologic conditions, and available data. Regardless of which methodology is chosen, Mapping Professionals should document and be prepared to defend their selection. They should consider verifying results against other procedures but should not mix and match procedures.

The following sections, as well as Appendix E: Methods of Seismic Analysis of Soil Liquefaction, describe considerations for determining the appropriate methodology for an SM Mapping Project. Figure 8 outlines the various methodologies for calculating $F_{S\text{liquefaction}}$. 
Figure 8: Methodology for calculation of $F_{S_l i q u e f a c t i o n}$ for Seismic Microzonation Mapping Projects

5.3.4.1.1 Considerations for Selecting SPT, CPT, or $V_s$ Procedures

An SPT-based procedure is the most common method used to calculate $F_{S_l i q u e f a c t i o n}$. It is one of the earliest developed methods and is the basis of most empirical equations. However, the quality of historical and existing SPT data can vary greatly and is therefore less reliable than CPT data. Mapping Professionals should consider conducting periodic checks to verify the quality and reliability of SPT data and/or using SPT data and procedures in combination with CPT data and procedures.

For SPT-based procedures to calculate $F_{S_l i q u e f a c t i o n}$, Youd et al. (2001) is considered the basis of all industry-accepted procedures. The Youd et al. (2001) procedure was accepted by a consensus of 20 industry experts at the time of its publication. Since then, some of the authors have completed more studies and developed alternative procedures. Idriss and Boulanger (2008) considered more SPT data and developed adjustment factors (MSF and others), which were subsequently updated in 2012 to incorporate equations for probabilistic analysis (Boulanger and Idriss 2012). Cetin et al. (2004) included an adjustment factor for depth ($r_d$) from SSRAs and also included equations for probabilistic analysis.
A CRT-based procedure is another common method used to calculate $F_{\text{liquefaction}}$. A CRT-based procedure is newer and typically more reliable and repeatable than an SPT-based procedure, as it can accurately measure ground soil resistance at the point of testing (i.e., the CPT tip resistance $q_c$).

The earliest CRT-based procedure accepted by the industry was by Robertson and Wride (1998) and was recommended in Youd et al. (2001) as an alternative to the SPT-based procedure. However, the Robertson and Wride (1998) procedure hasn't been updated since its publication and is no longer commonly used in BC. The Idriss and Boulanger (2008) procedure considered more CPT data and used its own adjustment factors (MSF and others). The Moss et al. (2006) procedure included an adjustment factor for depth $t_d$ from SSRAs and also included equations for probabilistic analysis. The Boulanger and Idriss (2016) procedure was updated to include CRT-based equations for probabilistic analysis.

$V_s$-based procedures are considered to have limited accuracy (Idriss and Boulanger 2008) for calculating $F_{\text{liquefaction}}$ because they are the least sensitive to changes in soil relative density. However, the $V_s$-based procedure represents an alternative for characterizing the CRR of gravelly soils where it is not possible to get reliable SPT or CPT data. This is because $V_s$ is directly correlated to liquefaction triggering potential, and conversion to an equivalent SPT blow count is not required.

In addition to the $V_s$-based method, liquefaction hazard for gravelly soils can also be evaluated using field instrumented BPTs (Ghafghazi et al. 2017a).

For additional discussion on the calculation of CRR and CSR, as well as the variability in results of different methods, see Appendix E1: Information for the Calculation of Soil Liquefaction Resistance, Appendix E2: Information for the Calculation of Cyclic Ratio, and Appendix E3: Variability of Results Using Simplified Methods, respectively.

### 5.3.4.1.2 Considerations for Selecting Deterministic or Probabilistic Approaches

Prior to the 5th generation probabilistic seismic hazard model—the probabilistic seismic hazard analysis (PSHA) released in 2015 by the GSC (Halchuk et al. 2016)—the GSC only considered the M7-cluster of earthquakes; this does not represent the full scope of seismic hazards in BC as currently understood.

Notably, the key change in the 6th generation seismic hazard model (Adams et al. 2019; Kolaj et al. 2020) is the addition of four rupture earthquakes and the probabilistic treatment of ground shaking hazards in the Cascadia subduction zone to include the M9 interface and the M7 crustal and in-slab earthquakes. Both clusters are shown in Figure 9.

The two common methods for seismic analysis of liquefaction in BC are the deterministic one-cluster (M7) method and the fully probabilistic method, based on Kramer and Mayfield 2007. However, while the deterministic one-cluster method was considered suitable for the previous Code and GSC seismic models, since the publication and adoption of the 6th generation seismic hazard models in the NBC 2020, it is no longer considered appropriate for the west coast of BC. Using the M7-cluster alone or the M9-cluster alone to calculate CSR will severely underestimates the seismic demand (and ultimately the Liquefaction Hazard) at a site in Metro Vancouver. To be in conformance with the Code, both clusters must be used to calculate CSR. However, in areas where the M9-cluster has no impact to seismic site response, the use of the deterministic one-cluster method can continue.

Recognizing that the fully probabilistic method requires significant time and resources to complete and is typically only used for academic SM Mapping Projects, a two-cluster probabilistic method is proposed (Wu 2017, 2018, 2021) as a practical solution for the unique tectonic environment in BC.
Figure 9: Example deaggregation of peak ground acceleration ($X_{50}$) for a probability of 2% in 50 years for Vancouver (city hall) (modified from Kolaj et al. 2023)

Expectations for using this method are described in Appendix E: Methods of Seismic Analysis of Soil Liquefaction. This method may be used to develop level 2 Liquefaction Susceptibility Maps and may be combined with an appropriate reference Seismic Hazard level (e.g., 1/475 return period or 1/2475 return period) to develop seismically-induced Liquefaction Hazard Maps. If utilizing other seismic analysis methodologies, Mapping Professionals should consider also conducting an analysis using this two-cluster method to compare results. The results of any comparison done should be presented in the SM Map's accompanying report.

5.3.4.2 Ground Information Data Requirements

In addition to that listed under Section 5.3.3.2 Ground Information Data Requirements for level 1, Mapping Professionals should collect and analyze the following data for level 2 SM Maps:

- Water level data, test holes, In Situ (particularly CPT and SPT) and lab tests, $V_s$, and borehole stratigraphic data.
- Surficial and subsurface geological, geotechnical, and geophysical data.
- $a_{max}$ values from GSC 2020 Seismic Hazard models.
### 5.3.4.3 Mapping Parameters and Procedures

A level 2 Liquefaction SM Map should include a Liquefaction Susceptibility evaluation matrix, as described in Section 5.3.3 Level 1 Liquefaction Maps and a legend that characterizes the liquefiable layers.

A Liquefaction Hazard Map should be based on the calculation of Liquefaction Hazard for one representative 20 m deep Soil profile, in an area appropriate to the variability of subsurface geological conditions (5–25 km² in most cases). Liquefaction can occur within one layer or in multiple layers at different depths within the Soil profile. Level 2 Liquefaction analysis for the Soil profile should be carried out at the appropriate Seismic Hazard level (e.g., 1/2475 return period) and should include:

- The determination of \( F_{\text{liquefaction}} \) for a single layer in the Soil profile (i.e., calculating one \( F_{\text{liquefaction}} \) on the most liquefiable layer).
- The calculation of \( F_{\text{liquefaction}} \) for all liquefiable layers at different depths in the Soil profile. The overall Liquefaction Hazard of the Soil profile should be determined based on the weighted sum of \( F_{\text{liquefaction}} \), using the procedure described below.

Mapping Professionals should consider utilizing a Liquefaction Hazard evaluation matrix, such as the example provided in Table 7.

While the example Liquefaction Hazard matrix in Table 7 intuitively demonstrates the Liquefaction severity of a site using five classifications, the matrix can be somewhat difficult to apply when developing a Liquefaction Hazard Map, as it does not explicitly account for the importance of the depth of liquefiable layer(s). Alternative, more sophisticated, evaluations for Liquefaction Hazard include the LPI, LPI\(_{\text{ISH}}\), and the LSN.

LPI is the oldest and most widely used index for calculating the Liquefaction Hazard. It is an integration function of \( F_{\text{liquefaction}} \) over depths of the 20 m Soil profile.

For reference, one formula for calculating LPI (Iwasaki et al. 1981; Holzer et al. 2006) is:

\[
LPI = \int_{0}^{20} F_l \times (10 - 0.5 \times z) \times dz
\]

where \( z \) is depth in metres and \( F_l \) is a nonlinear function of \( F_{\text{liquefaction}} \).

Building on the original LPI framework, LPI\(_{\text{ISH}}\) considers the effect of a non-liquefiable cap layer on Liquefaction induced surface manifestation. For reference, one formula for calculating LPI\(_{\text{ISH}}\) (Maurer et al. 2015) is:

\[
LPI_{\text{ISH}} = \int_{0}^{20} F(FS) \times \frac{25.56}{z} \times dz
\]

where \( z \) is depth in metres; and \( F(FS) \) is a nonlinear function of \( F_{\text{liquefaction}} \).

The last commonly used index of Liquefaction is the LSN, which is based on Liquefaction induced ground volumetric strains (\( \varepsilon \)), or deformations. For reference, one formula for calculating LSN (Tonkin and Taylor 2013) is:

\[
LSN = 1000 \int_{0}^{20} \frac{\varepsilon_z}{z} \times dz
\]

where \( \varepsilon_z \) is the volumetric strain in percent (%).

In general, Liquefaction Hazard measured using LPI\(_{\text{ISH}}\) or LSN carries more weight from shallow liquefiable layers, compared to the LPI measurement. Examples of Liquefaction Hazard ratings by LPI or LPI\(_{\text{ISH}}\) and LSN are shown in Table 8 and Table 9. All tables in this section are examples and should be reviewed for applicability and adapted, as necessary, prior to use.

Mapping Professionals should have an independent review conducted of their Higher-Level SM Map(s). See Section 6.1.8 Documented Independent Review of High-Risk Professional Activities or Work.
Table 7: Example Liquefaction Hazard Evaluation Matrix

<table>
<thead>
<tr>
<th>TOTAL THICKNESS (m) OF LIQUEFACTION SUSCEPTIBLE LAYERS WITHIN 20 m DEPTH</th>
<th>&lt; 2.0</th>
<th>2-10</th>
<th>&gt; 10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSliquefa</td>
<td>H</td>
<td>VH</td>
<td>VH</td>
</tr>
<tr>
<td>0.8-1.0</td>
<td>M</td>
<td>H</td>
<td>VH</td>
</tr>
<tr>
<td>1.0-1.2</td>
<td>L</td>
<td>M</td>
<td>H</td>
</tr>
<tr>
<td>1.2-1.5</td>
<td>VL</td>
<td>L</td>
<td>M</td>
</tr>
<tr>
<td>&gt; 1.5</td>
<td>VL</td>
<td>VL</td>
<td>L</td>
</tr>
<tr>
<td>VH</td>
<td>Very High Liquefaction Hazard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>High Liquefaction Hazard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>Moderate Liquefaction Hazard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Low Liquefaction Hazard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VL</td>
<td>Very Low Liquefaction Hazard</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Example Liquefaction Hazard Ratings by Liquefaction Potential Index (LPI) or LPI$_{ISH}$

<table>
<thead>
<tr>
<th>LPI OR LPI$_{ISH}$</th>
<th>LIQUEFACTION HAZARD USING LPI</th>
<th>LIQUEFACTION HAZARD USING LPI$_{ISH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Very Low</td>
<td>No surficial manifestations of Liquefaction</td>
</tr>
<tr>
<td>0 &lt; LPI $\leq$ 5</td>
<td>Low</td>
<td>No to minor surficial manifestations of Liquefaction</td>
</tr>
<tr>
<td>5 &lt; LPI $\leq$ 15</td>
<td>High</td>
<td>Moderate surficial manifestations of Liquefaction</td>
</tr>
<tr>
<td>LPI $&gt;$ 15</td>
<td>Very High</td>
<td>Severe surficial manifestations of Liquefaction</td>
</tr>
</tbody>
</table>

Table 9: Example Liquefaction Hazard Ratings by Liquefaction Severity Number (LSN)

<table>
<thead>
<tr>
<th>LSN RANGE</th>
<th>LIQUEFACTION HAZARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 $&lt;$ LSN $\leq$ 10</td>
<td>None to little manifestations of Liquefaction</td>
</tr>
<tr>
<td>10 $&lt;$ LSN $\leq$ 20</td>
<td>Minor manifestations of Liquefaction</td>
</tr>
<tr>
<td>20 $&lt;$ LSN $\leq$ 30</td>
<td>Moderate manifestations of Liquefaction</td>
</tr>
<tr>
<td>30 $&lt;$ LSN $\leq$ 40</td>
<td>Moderate to severe manifestations of Liquefaction</td>
</tr>
<tr>
<td>40 $&lt;$ LSN $\leq$ 50</td>
<td>Major manifestations of Liquefaction</td>
</tr>
<tr>
<td>LSN $&gt;$ 50</td>
<td>Severe damage, extensive manifestations of Liquefaction</td>
</tr>
</tbody>
</table>
5.3.4.4 Applications and Examples

The following are examples of level 2 Liquefaction SM Maps in BC:

- Preliminary Relative Earthquake Hazard Map of the Chilliwack Area (Levson et al. 1996c).
- Relative Liquefaction and Ground Motion Amplification Hazard Maps of Greater Victoria (Monahan et al. 2000b).
- Liquefaction Hazard Map of Richmond, BC (Monahan et al. 2010b).

The Liquefaction Susceptibility Map of Greater Vancouver for use by BC Hydro (Watts et al. 1992) was prepared at a greater level of complexity than the other SM Maps on the above list. Although it is primarily based on surficial geological maps by Armstrong and Hicock (1979, 1980), the SM Map was developed with considerations of seismic force demand (i.e., the calculated probabilities of Liquefaction in 50 years based on a 1/475 return period). The Richmond SM Map (Monahan et al. 2010b) was based on a subsurface geological map (Monahan et al. 2010a) using an extensive database of borehole data and quantitative Liquefaction analyses. This SM Map considered probabilities of Liquefaction in 50 years at 278 sites, and related age to Liquefaction Susceptibility. This study included the depth weighted sum of probabilities of Liquefaction.

5.3.5 LEVEL 3 LIQUEFACTION MAPS

Level 3 Liquefaction SM Maps depict Liquefaction Hazard and are developed by performing analyses required for level 2 SM Maps at more locations and incorporating the SSRA method within the SM Mapping Project area.

5.3.5.1 Methodology

For the development of level 3 SM Maps and to differentiate Liquefaction Hazards within the map area, Liquefaction analyses for calculation of a depth profile of CSR should be based on seismic force demand, calculated by:

- a simplified method (e.g., the two-cluster probabilistic method) for at least one profile in an area of 1–5 km², and
- an SSRA for one Soil profile in an area of 25–100 km².

Mapping Professionals should determine the appropriate number of analyses and/or area each analysis represents based on the variability of subsurface geological and geotechnical conditions within the SM Mapping Project area. Fewer analyses are needed for an area with less variability.

Within the 20 m deep Soil profiles, multiple values of $FS_{liquefaction}$ should be calculated as required to characterize the Liquefaction Hazard at different depths. Subsequently, the overall Liquefaction Hazard at the site location should be determined based on the weighted sum of $FS_{liquefaction}$ using the procedures described in Section 5.3.4.3 Mapping Parameters and Procedures for level 2.

Mapping Professionals should consider including separate maps that show the depth to the top of the liquefiable layer (from sea level or grade) and the Liquefaction Hazard under earthquake Ground Shaking at a lower Seismic Hazard level (e.g., 1/475 return period) to convey the areas that are most likely to liquefy. When both the simplified method and an SSRA method are used for level 3 SM Maps, Mapping Professionals should integrate the results of the two methods to generate a unified Liquefaction Hazard Map by applying a weighting factor of 0.5 to each of the two methods.

A Liquefaction analysis of a site using an SSRA typically involves the following steps:

1. Characterization of Seismic Hazard and geotechnical data (e.g., groundwater table, CPT tip resistance normalized to an effective overburden stress $\sigma'_{ov}$ of 100 kPa [$G_{CM}$], normalized SPT blow count $[(N_i)_{60}^\text{CM}]$ for sandy
Soils, fines content for silty sands) that are relevant to the analysis.

2. Determination of CRR for the Soils that are identified to be vulnerable to Liquefaction within 20 m depth.

3. Determination of seismically-induced CSR for each Liquefaction susceptible layer, using the two-cluster probabilistic method. For the calculation of Seismic Hazard values, the analysis model for the 1D Soil profile should include an elastic base and have a $V_s$ value that is also used in the GSC Seismic Hazard model (Kolaj et al. 2020). The input ground motions should be applied as outcropping motions in the analyses. Detailed methodology for an SSRA is provided in Appendix E5: Calculation of Cyclic Stress Ratio From a Seismic Site Response Analysis.

4. Calculation of factor of safety against Liquefaction for each Liquefaction susceptible layer at the appropriate Seismic Hazard level.

It is recognized that epistemic uncertainties exist in CRR and CSR calculations, as there is no consensus on the single method to be used. As such, Mapping Professionals may adopt multiple methods for the calculation of CRR and/or CSR and account for the epistemic uncertainties by using weighting factors for each of the methods applied.

5.3.5.2 Mapping Parameters and Procedures

Level 3 SM Maps should be supported by an extensive database and detailed subsurface geological mapping. In addition to that listed under Section 5.3.4.2 Ground Information Data Requirements for level 2, Mapping Professionals should collect or develop, when required, and analyze the following data for level 3 SM Maps:

- Extensive water level data, test holes, In Situ (particularly CPT and SPT) and lab tests, $V_s$, and borehole stratigraphic data.
- Extensive surficial and subsurface geological, geotechnical, and geophysical data.
- Seismic Hazard values from GSC 2020 Seismic Hazard models that include deaggregation results of the M7- and M9-cluster earthquakes, if utilizing the two-cluster methodology.

Mapping Professionals should also develop the input earthquake ground motion records for SSRA. The intensity of these motions should be consistent with the Seismic Hazard level of the SM Map. Further guidance regarding input ground motions is provided in Appendix E5: Calculation of Cyclic Stress Ratio From a Seismic Site Response Analysis.

5.3.5.3 Applications and Examples

Level 3 Liquefaction SM Maps should include a report that presents the following information:

- The details of any new investigations (e.g., geophysical surveys, borehole data, and CPT, SPT, or $V_s$ data) and any laboratory tests performed.
- Methodology for the SSRA, including earthquake ground motion records and computer software adopted for the analysis.
- Methodology for the development of level 3 SM Maps, including the procedures for dealing with the two-cluster earthquakes that are unique to BC.
- In addition to or included in the report, level 3 SM Maps should be accompanied by a Liquefaction Hazard evaluation matrix or Liquefaction Hazard ratings (see Table 7–Table 9).

Mapping Professionals should have an Independent review conducted of their Higher-Level SM Map(s). See Section 6.1.8 Documented Independent Review of High-Risk Professional Activities or Work.

5.3.5.4 Applications and Examples

Level 3 SM Maps for Metro Vancouver were developed for the MVSMMP. These SM Maps include probabilistic contributions to Liquefaction Hazard from both the Cascadia subduction earthquakes (in-
5.4 LANDSLIDE

5.4.1 GENERAL

A Landslide is the movement of Soil and/or rock down sloping terrain. An earthquake can trigger a Landslide if Ground Shaking creates temporary stresses that exceed the strength of the earth materials that form a slope. This section provides guidance on mapping earthquake-triggered Landslide Susceptibility or Hazard.

Susceptibility refers to the conditional likelihood of a slope experiencing permanent ground displacement as a Landslide, given the occurrence of a trigger, such as sufficiently strong Ground Shaking. Susceptibility is a function of slope angle ($\alpha$), shear strength of geological materials, groundwater conditions, land use, and vegetation patterns, among other factors.

Hazard refers to the frequency or probability at which an earthquake-triggered Landslide is expected to occur on a slope. A Hazard Map integrates Susceptibility and Seismic Hazard across a map area.

Case-history data (Keefer 2002) suggests that earthquake-triggered Landslides can occur on terrain steeper than:

- one degree for flow slides and translational block sliding;
- five to seven degrees for pre-existing slumps and block slides;
- 15 degrees for disrupted translational Soil slides where pre-existing Landslides are absent; and
- $\geq$ 15 degrees for slides and falls of rock.

Lateral spreads and flows of liquefied Soil can occur on gentle slopes (as low as 0.5 degrees), but are not generally addressed in SM Maps.

Ridge top cracking, spreading, or shattering—that is, ground failure or cracking on ridge tops due to topographic Amplification—may or may not be related to Landslides (Griggs et al. 1991; Nolan and Weber 1998) and is also not normally considered in SM Mapping Projects.

Table 10 outlines expectations and considerations for the three Landslide SM Map levels. Each level is discussed in more detail in the following sections. See Appendix B: Examples of Seismic Microzonation Maps in BC for a select list of possible SM Maps.

These guidelines outline expectations and obligations for the development of earthquake-triggered Landslide SM Maps with respect to the onshore effects of an earthquake under normal climatic conditions, and do not address Landslides within water bodies or the effects of an earthquake in combination with other potential Landslide triggers, such as flooding or extreme precipitation. Where coincident triggers or submarine Landslides have a meaningful impact on the study area, Mapping Professionals should develop methodologies to assess and map those Hazards and their effects. For example, the potential for submarine Landslides to trigger tsunamis—and the resulting run-up or inundation zones—should be mapped where that Hazard exists.

The focus of these guidelines is on Landslides that occur during or immediately following the occurrence of strong Ground Shaking. Changes in Susceptibility or Hazard that persist after the cessation of Ground Shaking—for example, delayed failure, ongoing Landslide creep, and changes in Landslide rate associated with ground damage and fracturing from Ground Shaking—are excluded.

The inclusion of the effects of human modification of the landscape on Landslide SM Maps should be considered, depending on the available information and the mapping objectives. Earthquake-triggered Landslides may be affected locally by the placement of fills and excavation of cuts around slopes with Susceptibility to earthquake-triggered Landslides. See Section 5.1.5.1 Human Effects.
<table>
<thead>
<tr>
<th>Type of Map</th>
<th>LEVEL 1 MAP</th>
<th>LEVEL 2 MAP</th>
<th>LEVEL 3 MAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Statement</td>
<td>- Seismic Susceptibility Map</td>
<td>- Seismic Susceptibility Map or Seismic Hazard Map</td>
<td>- Seismic Hazard Map</td>
</tr>
<tr>
<td>Data Required</td>
<td>Surfacial geological maps and slope data (topographic maps or DEMs), historical earthquake and Landslide data, and satellite images and/or air photos.</td>
<td>Surfacial or subsurface geological maps and high-resolution slope data, historical earthquake and Landslide data, and satellite images and/or air photos.</td>
<td>Detailed subsurface geological Maps and high-resolution slope data, historical earthquake and Landslide data, and satellite images and/or air photos.</td>
</tr>
<tr>
<td>Map</td>
<td>Infinite-slope failure mode determination of yield acceleration ($k_v$) using generalized correlation of shear strength with age and lithology of surficial geological materials.</td>
<td>Infinite-slope failure mode or pseudostatic limit-equilibrium analyses determination of $k_v$. May include a simplified integration of Seismic Hazard to map probability of Landslide triggering.</td>
<td>Probability of Landslide triggering or exceeding displacement thresholds, 2D numerical modelling to calculate displacements, and area-specific shear-strength data.</td>
</tr>
</tbody>
</table>
5.4.2 THE STATE OF PRACTICE OF LANDSLIDE MAPPING IN BRITISH COLUMBIA

In comparison with the other Seismic Hazards discussed above—Ground Shaking and Liquefaction—very few Landslide SM Maps have been completed in Canada.

Earthquake-triggered Landslide Hazard was mapped across the Greater Victoria area by McQuarrie and Bean (2000), who performed limit-equilibrium factor of safety analyses to map the distribution of Landslide Hazard. This is approximately a level 2 SM Map.

The public record, through various environmental permitting processes, contains examples of earthquake-triggered Landslide Hazard Maps along proposed infrastructure projects. A recent example is the mapping of earthquake-triggered Landslide Hazard using the expected displacement under a 1/2475 return period ground motion along the proposed Trans Mountain Expansion Project, between Edmonton, Alberta, and Burnaby, BC (Trans Mountain Pipeline ULC 2013). That study combines terrain map depictions of near-surface Soil deposits and drainage class, regional-scale geological mapping, average slope angle ($\alpha$) within mapped terrain polygons, and the distribution of Ground Shaking Hazard, to generate SM Maps of expected slope displacement. This is approximately a level 2 SM Map.

The MVSMMP developed level 2 and level 3 Landslide Hazard Maps. The level 2 pseudo-probabilistic SM Map identifies slopes where displacement is expected to exceed 0.15 m under seismic loading consistent with a 1/2475 return period ground motion, by constructing a slope-unit-based $k_s$ map for the region (Yeznabad et al. 2019). The level 3 SM Map is a fully probabilistic integration of Ground Shaking and slope displacement prediction models (Yeznabad et al. 2023a).

5.4.3 LEVEL 1 LANDSLIDE MAPS

Level 1 Landslide SM Maps depict the Susceptibility of terrain to earthquake-triggered Landslides. Landslide Susceptibility may be described qualitatively, using descriptive classes such as very low, low, moderate, high, or very high, or quantitatively, as a spatial distribution of critical acceleration ($a_c$) which is defined as the value of horizontal acceleration at which a Landslide is expected to initiate.

Level 1 SM Maps are based on the distribution of earth materials, slope angle ($\alpha$), Soil moisture conditions, and proxies for various contributing factors. Mapping Professionals should define simple rules to delineate susceptible terrain and/or simple Landslide mechanisms to calculate $a_c$ across the study area.

Level 1 SM Maps do not consider the triggering mechanism (i.e., Ground Shaking). Level 1 SM Maps usually focus on Landslide initiation, but where expected mechanisms are consistent with long runout or retrogression, the extents of these zones should be considered by Mapping Professionals.
5.4.3.1 Methodology

For level 1 SM Maps, Mapping Professionals should develop a rubric that defines qualitative Susceptibility classes or an algorithm that calculates the $a_L$ values. The rubric should relate shear strength to surficial geological deposits, incorporate knowledge of typical static slope failure mechanisms, and incorporate groundwater conditions within the study area.

Mapping Professionals should consider using the methodology adopted in the U.S. Federal Emergency Management Agency's HAZUS model (2022), as described in Section 5.4.3.3 Mapping Parameters and Procedures. This methodology leverages methods pioneered in California by Wieczorek et al. (1985) and Wilson and Keefer (1985). It assumes an infinite-slope mechanism for all slope failures. If Mapping Professionals use a similar approach, they should modify the methodology to suit the geological conditions in the region they are mapping.

5.4.3.2 Ground Information Data Requirements

The minimum data required for level 1 Maps are:

- Surficial and bedrock geological maps at scales generally between 1:250,000 and 1:25,000.
- Topographic or digital elevation data, as provided by the Canadian Digital Elevation Dataset, at a nominal resolution of 0.75 arc-seconds (approximately 23 m north-south by 11–16 m east-west spacing in most of British Columbia). Higher-resolution maps—for example, terrain resource information management (TRIM) or LiDAR—should be used where available. Mapping Professionals should construct slope-angle maps from these data using standard GIS software tools.
- Satellite imagery and/or aerial photographs.
- Water level data or assumptions. Mapping Professionals should use one of the following approaches:
  - Make a conservative assumption of wet conditions everywhere (i.e., an earthquake occurs at a time of year when near-surface Soils are saturated).
  - Relate assumed groundwater levels to topography (i.e., assume shallow groundwater in valleys, basins, and other topographic lows) and proximity to watercourses and waterbodies, provided the available groundwater-level or well data supports this assumption.
  - Obtain or construct a groundwater-level map in settings where the hydrogeological setting is sufficiently well understood, and the interpreted map is supported by available groundwater-level or well data. Mapping Professionals should solicit the input of a groundwater consultant for the development of a groundwater model.

Where applicable, other proxies for the Susceptibility of terrain to earthquake-triggered Landslides should be considered, depending on geological setting. Examples include:

- proximity to watercourses where glaciomarine flow slides are expected (Quinn 2009);
- rock-strength, slope, and elevation proxies for topographic Amplification (Dunham et al. 2022); and
- topographic relief and unevenness (Chen et al. 2022).

5.4.3.3 Mapping Parameters and Procedures

To construct a level 1 SM Map that displays earthquake-triggered Landslide Susceptibility in qualitative or descriptive classes, Mapping Professionals should establish rules that define Susceptibility classes based on geological unit, slope angle ($\alpha$), groundwater conditions, and other relevant predictor variables and proxies mapped across the study area. Rules should be established that cover the range of expected Landslide types within a study area. Examples of such rules might include:

- Assigning higher Susceptibility to earthquake-triggered rock falls and slides where bedrock
exposures above a threshold angle for initiation are present (e.g., cliffs).

- Defining Susceptibility classes for shallow translational slides based on slope angle ($\alpha$) and expected rock or Soil type.
- Assigning higher Susceptibility to existing Landslides, slopes with landforms consistent with past Landslides, or slopes with similar geotechnical conditions as those hosting Landslides.
- Assigning higher Susceptibility to human-made modified terrain (e.g., large cuts and fills).
- Assigning higher Susceptibility for expected glaciomarine deposits based on position below the maximum relative sea level or proximity to watercourses (Quinn 2009; Farzam et al. 2018).

Mapping Professionals may group geological units by expected shear strength properties, for example, by distinguishing between dominantly fine-grained and coarse-grained Soil deposits. Bedrock grouping might consider:

- depositional setting (e.g., differentiating between fine-grained and coarse-grained clastic sedimentary bedrock);
- the presence of known weak lithologies (e.g., clay, shale, or bentonite); and
- the geological structure (e.g., pervasive fractures in strong bedrock, sheared planes, or surfaces).

Considerable local knowledge of the origin and typical geotechnical properties of Soil and bedrock units within the study area is required.

To construct a level 1 SM Map of $a_c$, Mapping Professionals should assign the representative effective friction angle ($\phi^*$) and the effective cohesion intercept ($c^*$) values to geological units within the SM Mapping Project area. An example that assigns shear-strength values to three geologic groups, which has been widely adopted for use in the U.S. Federal Emergency Management Agency’s HAZUS model (2022), is provided in Table 11.

The example shear strength values are based on Soil and bedrock units that occur around California’s San Francisco Bay Area; accordingly, Mapping Professionals should use typical shear strength properties of geological units present in BC that are distinct from those present in California. Specifically, Mapping Professionals should consider the strength properties of glacial and periglacial Soil deposits, and generally stronger bedrock that withstood repeated glaciations. Mapping Professionals should also consider dynamic shear strength parameters for Soils that are brittle or exhibit strain softening behaviour. For example, they should identify the predominantly fine-grained Soils that could exhibit undrained behaviour under seismic loading, and consider applying more rigorous analysis to those deposits. Oversimplification of dynamic shear strength conditions may lead to unconservative results.

An example of geologic group assignments in glaciated terrain is provided by Farzam et al. (2018), who developed a Susceptibility model for earthquake-triggered Landslides and rock falls in the Saint-Lawrence Lowlands of eastern Canada, as shown in Table 12.

It is expected that the application of the parameters in Table 11 will, in general, produce a conservative estimate of $a_c$ for level 1 Landslide SM Maps. In some cases, especially in steeper terrain, the parameters in Table 11 will not meet static equilibrium, and the factor of safety will be less than 1.0.

Wilson and Keefer (1985) propose a minimum $a_c$ value of 0.05 g, arguing that slopes with smaller calculated $a_c$ values are subject to instability triggered by more frequent climatic or anthropogenic phenomena.
Table 11: Geologic Group Descriptions and Assumed Effective Shear-Strength Parameters (Wieczorek et al. 1985)

<table>
<thead>
<tr>
<th>GEOLOGIC GROUP</th>
<th>DESCRIPTION</th>
<th>EFFECTIVE SHEAR-STRENGTH PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Strongly cemented rocks</td>
<td>35°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.4 kPa</td>
</tr>
<tr>
<td>B</td>
<td>Weakly cemented rocks and Soils</td>
<td>35°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>Argillaceous rocks and Soils, including existing Landslides</td>
<td>20°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

Table 12: Example Assignment of Geological Units in Glaciated Terrain From the Saint-Lawrence Lowlands of Eastern Canada (Farzam et al. 2018)

<table>
<thead>
<tr>
<th>LITHOLOGY</th>
<th>GEOLOGIC GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial deposits (tills, gravels, sands, clays, and silts reworked)</td>
<td>B</td>
</tr>
<tr>
<td>Colluvial and mass-wasting deposits (clays and silts reworked)</td>
<td>C</td>
</tr>
<tr>
<td>Eolian deposits (sands)</td>
<td>B</td>
</tr>
<tr>
<td>Glaciofluvial deposits (sands and gravels)</td>
<td>B</td>
</tr>
<tr>
<td>Glaciolacustrine deposits (clays)</td>
<td>C</td>
</tr>
<tr>
<td>Anthropogenic deposits</td>
<td>C</td>
</tr>
<tr>
<td>Lacustrine deposits (silts)</td>
<td>B</td>
</tr>
<tr>
<td>Marine deposits (mostly clays)</td>
<td>C</td>
</tr>
<tr>
<td>Organic deposits (mostly peats and plant residues)</td>
<td>C</td>
</tr>
<tr>
<td>Bedrock</td>
<td>A</td>
</tr>
<tr>
<td>Till—glacial deposits</td>
<td>B</td>
</tr>
<tr>
<td>Undifferentiated deposits</td>
<td>C</td>
</tr>
</tbody>
</table>
Once shear strength units are assigned, Mapping Professionals can calculate $a_c$ from shear strength, slope angle ($\alpha$), and assumed groundwater conditions. Mapping Professionals may assume an infinite-slope failure mode. This approach is generally appropriate at a screening level, given that global case histories are dominated by landslides with shallow translational failure modes (Keefer 1984, 2002). Under this assumption, $a_c$, for dry and wet conditions, respectively, is calculated as follows (Wieczorek et al. 1985):

$$a_c = g \left( \frac{c'}{\gamma h} + \cos \alpha \tan \phi' - \sin \alpha \right)$$

[Formula 6]

$$a_c = g \left( \frac{c'}{\gamma h} + \left( 1 - \frac{m \gamma_w}{\gamma} \right) \cos \alpha \tan \phi' - \sin \alpha \right)$$

[Formula 7]

where $a_c$ is the critical acceleration of the slope (in units of g); $g$ is the standard acceleration due to gravity (equal to 9.81 m/s$^2$); $c'$ is the effective cohesion intercept of the Soil or rock (kPa); $\phi'$ is the effective friction angle of the Soil or rock (in degrees); $\alpha$ is the slope angle (in degrees); $h$ is the slope-normal thickness of the sliding mass (in m); $m$ is the saturated proportion of the sliding mass (a value between 0 and 1); $\gamma$ is the unit weight of Soil (kN/m$^3$); and $\gamma_w$ is the unit weight of water (equal to 9.81 kN/m$^3$).

As a supplement, Mapping Professionals should perform an assessment of runout or retrogression potential and identify such regions as requiring further study.

The level 1 methodology does not discriminate between displacement magnitude, only whether triggering is credible. Even where the model predicts ground movement, displacement magnitude might be small enough to be non-detectable or to have limited potential for damage to facilities of interest. Development of Higher-Level SM Maps should be considered where the potential for damage is sensitive to displacement magnitude.

### 5.4.3.4 Applications and Examples

Level 1 Landslide SM Maps have been produced for Metro Vancouver for the MVSMMP (Yeznabad et al. 2023b).

GeoMap Vancouver includes a level 1 Landslide SM Map that shows slopes with high angles (> 20°) and locations of previous landslides. This Susceptibility Map is for landslides in general, and does not discriminate between the triggering mechanisms (e.g., earthquakes, precipitation, freeze thaw, snowmelt).

A Landslide Susceptibility Map (approximately level 1) incorporating maps of surficial geology, slope angle ($\alpha$), and groundwater level was constructed by the GSC as part of a Seismic Risk study for the District of North Vancouver (Wagner et al. 2015).

### 5.4.4 LEVEL 2 LANDSLIDE MAPS

Level 2 Landslide SM Maps represent an intermediate level of data and analysis between level 1 SM Maps (Susceptibility Maps) and level 3 SM Maps (probabilistic Hazard Maps). Deliverables consistent with level 2 may be enhanced Susceptibility Maps, deterministic seismic displacement Hazard Maps, or pseudo-probabilistic displacement Hazard Maps.
5.4.4.1 Methodology

Level 2 Landslide SM Maps incorporate region-specific geotechnical, geological, hydrological, hydrogeological, and topographic data, and should be developed using one of the following general methodologies (Massey et al. 2022):

- Use region-specific shear-strength datasets and/or pseudostatic limit-equilibrium slope stability modelling to replace the simplified strength and mechanistic assumptions deployed in Level 1 SM Mapping Projects with physics-based models (McQuarrie and Bean 2000).
- Use statistical methods—bivariate methods like weights-of-evidence (Chung and Leclerc 2003), multivariate methods like logistic regression (Nowicki-Jessee et al. 2018), or machine-learning techniques—to combine predictor variables into a map showing relative probability of earthquake-triggered slope instability.
- Use heuristic methods—where expert judgement informed by earthquake-triggered Landslide occurrence in past earthquakes is applied to geomorphologic map information—to assign qualitative Susceptibility ratings to distinct map units.

Deterministic SM Maps depict displacement in a representative scenario earthquake. Mapping Professionals should subdivide the study area into representative map units (defined by comparable slope angle \( \alpha \) and geological conditions). For each slope unit or cell, Mapping Professionals should combine the following:

- A ShakeMap—depicting the Ground Shaking from an earthquake—with a defined magnitude and location.
- One or more seismic displacement prediction models (SDPMs). These semi-empirical models provide estimates of ground displacement magnitude, probability of non-zero ground displacement, or conditional probability of exceeding a threshold displacement level. Inputs to these models are Ground Shaking experienced at site (typically PGA or spectral acceleration \( S_a \)), \( \alpha \), of the slope, and earthquake magnitude and fundamental slope or slide period, where required.

- Pseudo-probabilistic maps are similar to deterministic maps, in that the objective is to generate and depict displacement. However, instead of a scenario ShakeMap, the input seismic loading condition is a map of Ground Shaking at a specified Seismic Hazard level (e.g., a 1/2475 return period). Seismic Hazard deaggregations may be required to obtain magnitude values as inputs to some SDPMs.

5.4.4.2 Ground Information Data Requirements

Level 2 Susceptibility Maps can be constructed using the minimum level 1 data, plus the following, as available and where relevant to the selected methodology:

- Regional-scale (1:250,000–1:25,000) surficial and bedrock geological maps.
- Higher-resolution slope maps, derived from TRIM or LiDAR data.
- Structural geological data for bedrock slopes.
- Landslide inventories, with attributes that allow for the determination of trends in slide mechanism and depth with respect to geological map units, slope, and other proxies. Satellite images and aerial photographs should be considered when constructing a Landslide inventory.
- Shear-strength data from boreholes with lithologic logs and In Situ shear strength testing (e.g., SPT and vane shear), CPT/SCPT data, and/or laboratory shear-strength testing of representative Soil and rock samples.
Map coverage depicting additional candidate predictor variables or proxies, such as:
- stream networks;
- groundwater levels;
- land use and vegetation;
- proxies for soil moisture (e.g., water well data, proximity to streams and shorelines, topographic wetness index, topographic concavity); and
- fault lines, to compute distance-to-closest-fault maps, as a proxy for off-fault ground deformation (Massey et al. 2022).

Remote-sensing or earth-observation proxies for the preceding candidate predictor variables, such as synthetic aperture radar derived ground surface displacement maps.

Level 2 displacement Hazard Maps require the following:

- A map of the slope period (T). Mapping Professionals should begin by estimating T from slope or slide height and Vₙ, as described by Bray (2007), for slopes expected to have relatively uniform Vₙ profiles. Slide height should be determined from geological analysis (e.g., reviews of existing Landslide inventories for typical mechanisms and depths in comparable geological settings, back-analysis of representative slopes, or subsurface investigations at representative locations). Mapping Professionals should consider In-Situ measurements of Tₒ at slopes associated with elevated failure consequence or geological complexity.

- Tolerable or target displacement threshold, which depends on the elements at Risk. Mapping Professionals should consider implementing a tolerable displacement of 0.15 m for SM Maps intended to inform life safety Risk of general building stock. This tolerable displacement value is intended as a guide, based on experience with residential wood-frame construction, and is not intended to preclude Mapping Professionals from selecting another value they deem appropriate. Industrial facilities, critical facilities, or lifeline infrastructure might have smaller tolerable displacements and Mapping Professionals should consult the applicable design guidelines—for example, American Society of Civil Engineers 2005, Honegge 2017, and International Atomic Energy Agency 2005—or the engineering designs of each affected facility.

- For deterministic displacement Hazard Maps, ShakeMaps depicting the distribution of Ground Shaking for prescribed earthquake scenarios, defined by source location and magnitude.

- For pseudo-probabilistic displacement Hazard Maps, maps of Ground Shaking at a specified exceedance rate, with source magnitudes defined by Seismic Hazard deaggregations.

### 5.4.4.3 Mapping Parameters and Procedures

The following sections describe methodologies for level 2 SM Mapping Projects. Mapping Professionals should select a methodology based on available information for the SM Mapping Project area and the intended use of the SM Map. The following methodologies are described:

- Region-specific Shear-strength/Physics-Based Model
- Statistical Techniques
- Seismic Displacement Prediction Models
- ShakeMaps
- Probabilistic Seismic Hazard Assessments

Mapping Professionals should have an independent review conducted of their Higher-Level SM Map(s). See Section 6.1.8 Documented Independent Review of High-Risk Professional Activities or Work.
In a region-specific shear strength model, mapped bedrock and soil units are attributed with values of unit weight ($\gamma$), effective friction angle ($\phi'$), and effective cohesion intercept ($c'$). Saturation can be assumed or mapped based on local groundwater information or geological experience.

Mapping Professionals should begin by assuming an infinite-slope failure mode for most slopes. However, at pre-existing landslides, where instability is controlled by bedrock structure, or where slides and falls of rock are credible, Mapping Professionals should replace the infinite-slope assumption with kinematic or limit-equilibrium slope stability models consistent with regional geological conditions and expected modes of failure.

This method was used by Harp et al. (2006), who obtained shear-strength test data from geotechnical consultants to estimate average shear-strength values for Seattle-area soil and rock units and applied an infinite-slope model to compute static factor of safety. Subsequent work by Allstadt and Vidale (2012) used these same shear-strength values to construct a seismic landslide hazard map for Seattle, using an assumed infinite-slope model.

Mapping Professionals may choose to replace a refined physics-based model for landslide susceptibility with one based on statistical techniques, such as logistic regressions or various machine-learning models. These methods are highly complex and are beyond the scope of these guidelines. An example of the applications of these methods is the global model developed by USGS (Nowicki-Jessee et al. 2018), where susceptibility to landslides is represented as the part of the model that comprises geological, topographic, hydrologic, hydrogeologic, and other terrain and climatic proxy variables. Mapping Professionals are cautioned that the limited availability of earthquake-triggered landslide inventories in geological settings analogous to BC limits the training and validation data available for statistically rigorous regressions.

Mapping Professionals should select a permanent displacement estimation model that incorporates information about both the experienced earthquake Ground Shaking (expressed as PGA or $S_n$, peak ground velocity [$PGV$], Arias intensity, magnitude, or other metrics), and the susceptibility of slopes to earthquake-triggered landslides (expressed as $a$).

Recent, widely accepted displacement models that Mapping Professionals should consider using are the semi-empirical displacement relationships proposed by Bray and Macedo (2019) for shallow crustal earthquakes and Bray et al. (2018) for subduction zone events. These relationships build upon Newmark's (1965) simple sliding-block model, by incorporating magnitude as a proxy term for the duration of strong ground shaking, referencing the $T_s$, and fitting parameters to both simulated and observed landslide slope displacements. Mapping Professionals should consider that these relationships were developed from simple geological models (typically embankment slopes, not natural slopes) and therefore should be used with caution on natural terrain. Mapping Professionals should establish an upper limit of calculated displacement for the region of interest, above which it should be assumed that displacement is nonlinear. These regions should be highlighted for the application of more detailed models in the development of the level 3 SM Map, and/or for Engineering Professionals to consider in planning site-specific studies.

Mapping Professionals should consider other predictive models, either to account for geological complexity or to check results using the relationships described above. Of note, relationships proposed by Ambraseys and Menu (1988) have been used on major recent linear infrastructure projects in southern BC.
Mapping Professionals should consider calibrating or supplementing the results of SDPMs with 2D numerical displacement models where geological conditions and expected Landslide mechanisms are complex. These models are most effectively used where geotechnical and groundwater conditions have been determined through site-specific subsurface or geophysical investigations.

5.4.4.3.4 ShakeMaps

ShakeMaps are maps of Ground Shaking expected or experienced in specific earthquake scenarios with defined source locations and magnitudes. Mapping Professionals should obtain ShakeMaps directly from the NRCAN or USGS archives, or develop custom ShakeMaps using suitable GMMs. ShakeMaps should reference GMMs consistent with the current Code Seismic Hazard model (Adams et al. 2019), unless available seismological information supports the selection of different models, or new models applicable to the study area become available. GMMs should be specific to the source type—crustal, in-slab, or interface—and should consider Soil, Basin Effects, and topographic Amplification, as described in Section 5.2 Ground Shaking.

Intensity measures should include PGA and Sa at periods consistent with the range of intact and degraded T5 in the region of interest.

Mapping Professionals should consider the impact of different source types by selecting representative scenarios from each source type, where those are relevant to the SM Mapping Project area.

5.4.4.3.5 Probabilistic Seismic Hazard Assessments

Pseudo-probabilistic displacement SM Maps require ground motion predictions and representative magnitudes derived from a PSHA. Mapping Professionals should use the following:

- maps depicting Ground Shaking Hazard at a prescribed exceedance rate (e.g., 1/2475 return period) at periods consistent with the range of intact and degraded T5 across the study area; and
- earthquake magnitudes derived from deaggregations of the Ground Shaking Hazard, specific to the source type and T5.

The distribution of Ground Shaking should be informed by Soil, basin, and topographic Amplification, as described in Section 5.2 Ground Shaking.

Mapping Professionals should use a current regional or national seismic model that covers the study area of interest, for example, the current Code Seismic Hazard model (Adams et al. 2019). Mapping Professionals should replace available models with a project-specific PSHA where new information regarding source or Ground Motion Models is expected to appreciably affect the results.

5.4.4.4 Applications and Examples

McQuarrie and Bean (2000) constructed a Susceptibility Map for Greater Victoria, BC, based on limit-equilibrium analyses on representative slopes, with shear-strength parameters obtained from a database of values obtained from local geotechnical consultants. The resulting shear-strength values were related to 1:20,000 surficial geological map units (Monahan and Levsen, 2000) and topographic Amplification, as described in Section 5.2 Ground Shaking.

Bedrock slopes with structural controls on stability were treated qualitatively.

5.4.5 LEVEL 3 LANDSLIDE MAPS

Level 3 Landslide SM Maps are fully probabilistic earthquake-triggered Landslide Hazard Maps, combining Susceptibility and seismicity. They depict the spatial distribution of expected frequency of exceeding a threshold displacement level.
5.4.5.1 Methodology

The general methodology for a level 3 Landslide SM Map involves subdividing the map area into representative map units, and for each, computing the annual rate of exceedance of a threshold displacement value \( d \) as follows in Formula 8 (Yeznabad et al. 2021):

\[
\lambda_d = \int_M \int_0^\infty P(D > d | S_a, M, a_c) P(M | S_a) \Delta \lambda(S_a) d(S_a)
\]

[Formula 8]

where \( \lambda_d \) is the annual rate of exceedance of a threshold displacement value, \( d \); \( P(D > d | S_a, M, a_c) \) is the SDPM, or the conditional probability of exceeding displacement \( d \), given spectral acceleration \( S_a \) at the degraded \( T_s \), earthquake magnitude \( M \), and critical acceleration \( a_c \); \( P(M | S_a) \) represents the contribution to the total Hazard from each magnitude increment, obtained from Seismic Hazard deaggregation; and \( \Delta \lambda(S_a) \) represents the mean rate density of \( S_a \).

An expanded form of the calculation that allows for uncertainty in \( a_c \) and \( T_s \) to be treated as epistemic in a logic-tree approach (Macedo et al. 2017 and 2020) is per Formula 9 as follows:

\[
\lambda_d = \sum_{i=1}^{n_a} \sum_{i=1}^{n_T s} \int_M \int_0^\infty P(D > d | S_a, M, a_c, T_{s i}) \times P(M | S_a) \Delta \lambda(S_a) d(S_a) W_{ij}
\]

[Formula 9]

where \( T_s \) is the initial fundamental period of the sliding mass; \( P(D > d | S_a, M, a_c, T_{s i}) \) is the SDPM given \( S_a \), \( M \), \( a_c \), and \( T_s \); and \( W_{ij} \) is a combined weighting term that represents uncertainties in \( a_c \) and \( T_s \).

Mapping Professionals should select SDPMs that are consistent with the study area's seismicity and expected Landslide mechanisms. These are described in Section 5.4.3.3 Mapping Parameters and Procedures.

The result is a displacement Hazard curve at each map unit, in which uncertainties in both Seismic Hazard and conditional displacement probability are fully considered.

5.4.5.2 Ground Information Data Requirements

In addition to the level 2 SM Map inputs described in Section 5.4.3.2 Ground Information Data Requirements, level 3 SM Maps require the following:

- Susceptibility, as derived from geological, geotechnical, slope, groundwater, surface water, and other relevant predictor variables;
- fundamental site period (\( T_s \)); and
- tolerable displacement for facilities or infrastructure of interest.

Level 3 Landslide SM Maps should use a level 3 Ground Shaking model that incorporates Soil, Basin Effects, and topographic Amplification, as described in Section 5.2.5 Level 3 Ground Shaking Maps.

Level 3 Landslide SM Maps require appropriate seismic source and Ground Motion Models as an input. Mapping Professionals should consider using either the current national seismic model (Kola et al. 2020), or a site-specific model that incorporates more recent Seismic Hazard knowledge. A range of Seismic Hazard curves representing the full range of uncertainty should be developed at each location (map unit) within the region of interest. These should be constructed using PSHA software (e.g., OpenQuake).
5.4.5.3 Limitations

This methodology is limited to predictions of relatively small slope displacements and is not applicable to mechanisms, such as flow failure, lateral spreads, rock/soil avalanche, or rock fall, which behave nonlinearly under large displacement. If nonlinear behaviour is expected, experienced displacement may exceed predicted displacement by several orders of magnitude. Mapping Professionals should flag these regions for GERs to conduct a site-specific study.

Mapping Professionals should consider the potential for variable response, in terms of slope instability, associated with human-made over steepened slopes along roads and highways. These are typically not captured at level 2 SM Map scales for geological and slope input parameters to level 3 models. Mapping Professionals should highlight areas where cuts and fills could produce potentially damaging landslides. This is useful information for emergency planners considering critical communication routes during an emergency. Mapping Professionals should acknowledge the potential for changing conditions in human-modified areas and apply appropriate qualifiers, for example, by documenting those existing at the time of SM Map preparation.

Mapping Professionals should consider identifying waterbodies surrounded by landslide-prone slopes as being susceptible to secondary Hazards such as seiches/tsunamis and flooding.

Lastly, Mapping Professionals should have an independent review conducted of their Higher-Level SM Map(s). See Section 6.1.8 Documented Independent Review of High-Risk Professional Activities or Work.
6.0 QUALITY MANAGEMENT IN PROFESSIONAL PRACTICE

6.1 ENGINEERS AND GEOScientISTS
BC QUALITY MANAGEMENT REQUIREMENTS

Engineering/Geoscience Professionals must adhere to applicable quality management requirements during all phases of the work, in accordance with the Engineers and Geoscientists BC’s Bylaws and quality management standards.

To meet the intent of the quality management requirements, Engineering/Geoscience Professionals must establish, maintain, and follow documented quality management policies and procedures for the following activities:

- Use of relevant professional practice guidelines
- Authentication of professional documents by application of the professional seal
- Direct supervision of delegated professional engineering or professional geoscience activities
- Retention of complete project documentation
- Regular, documented checks using a written quality control process
- Documented field reviews of engineering or geoscience designs and/or recommendations during implementation or construction
- Where applicable, documented independent review of structural designs prior to construction
- Where applicable, documented independent review of high-risk professional activities or work prior to implementation or construction

Engineering/Geoscience Professionals employed by a Registrant firm are required to follow the quality management policies and procedures implemented by the Registrant firm, as per the Engineers and Geoscientists BC’s permit to practice program.

6.1.1 USE OF PROFESSIONAL PRACTICE GUIDELINES

Engineering/Geoscience Professionals are required to comply with the intent of any applicable professional practice guidelines related to the engineering or geoscience work they undertake. As such, Engineering/Geoscience Professionals must implement and follow documented procedures to ensure they stay informed of, knowledgeable about, and meet the intent of professional practice guidelines that are relevant to their professional activities or services. These procedures should include periodic checks of the Engineers and Geoscientists BC website to ensure that the latest versions of available guidance are being used.

In particular, as it relates to the land-based work of SM Mapping Projects, Engineering/Geoscience Professionals should familiarize themselves with, and meet the intent of, guidelines and programs related to equity, diversity, and inclusion, and truth and reconciliation with Indigenous Peoples including, but not limited to, Engineers and Geoscientists BC’s Equity Diversity, and Inclusion Initiative and Engineers Canada’s Guideline on Indigenous Consultation and Engagement.
For more information, refer to the Quality Management Guides—Guide to the Standard for the Use of Professional Practice Guidelines (Engineers and Geoscientists BC 2023a), which also contains guidance for how an Engineering/Geoscience Professional can appropriately depart from the guidance provided in professional practice guidelines.

6.1.2 AUTHENTICATING DOCUMENTS

Engineering/Geoscience Professionals are required to authenticate (seal with signature and date) all documents, including electronic files, that they prepare or deliver in their professional capacity to others who will rely on the information contained in them. This applies to documents that Engineering/Geoscience Professionals have personally prepared and those that others have prepared under their direct supervision. In addition, any document that is authenticated by an individual Engineering/Geoscience Professional must also have a permit to practice number visibly applied to the document. A permit to practice number is a unique number that a Registrant firm receives when they obtain a permit to practice engineering or geoscience in BC. Failure to appropriately authenticate and apply the permit to practice number to documents is a breach of the Bylaws.

Engineering/geoscience information (e.g., data, analyses, interpretations) contained in Seismic Microzonation (SM) Maps may be relied upon by Engineering/Geoscience Professionals to inform their preliminary design decisions, and by Local Community Governing Bodies to inform policies, zoning bylaws, asset management decisions, emergency management response plans, and more. As such, it is important for Mapping Professionals to authenticate the deliverables (e.g., all SM Maps and accompanying reports) to indicate to users that they are complete for their intended use and may be relied upon. Intermediate SM Maps—such as subsurface geological maps, maps of water table depth and elevation, and slope maps from digital elevation models (DEMs)—that form the basis of the final SM Map deliverables should also be authenticated. While all contributors should be acknowledged in the development of each SM Map, only one Mapping Professional should authenticate each SM Map. Mapping Professionals are reminded that non-PDF documents can be authenticated using the PDF/A-3 function in ConsignO Desktop.

Users of SM Maps should cite any SM Maps relied upon for their own scope of work, document all relevant assumptions and interpretations, and authenticate their final deliverable.

For more information, refer to the Quality Management Guides—Guide to the Standard for the Authentication of Documents (Engineers and Geoscientists BC 2023b).

6.1.3 DIRECT SUPERVISION

Engineering/Geoscience Professionals are required to directly supervise any engineering or geoscience work they delegate. When working under the direct supervision of an Engineering/Geoscience Professional, an individual may assist in performing engineering or geoscience work, but they may not assume responsibility for it. Engineering/Geoscience Professionals who are professional licensees engineering or professional licensees geoscience may only directly supervise work within the scope of their license.

When determining which aspects of the work may be appropriately delegated using the principle of direct supervision, the Engineering/Geoscience Professional having ultimate responsibility for that work should consider:

- the complexity of the project and the nature of the risks associated with the work;
- the training and experience of individuals to whom the work is delegated; and
- the amount of instruction, supervision, and review required.
Careful consideration must be given to delegating field reviews. Due to the complex nature of field reviews, Engineering/Geoscience Professionals with overall responsibility should exercise judgment when relying on delegated field observations, and should conduct a sufficient level of review to have confidence in the quality and accuracy of the field observations. When delegating field review activities, Engineering/Geoscience Professionals must document the field review instructions given to a subordinate. See Section 6.1.6 Documented Field Reviews During Implementation or Construction.

Most Higher-Level SM Mapping Projects involve the development of a suite of Maps by a team of appropriately trained, multi-disciplinary Mapping Professionals. It is important to clearly outline the responsibilities of the various professionals involved in the development and have one professional responsible for coordinating the work of others to make sure there are no gaps in scope. Generally, only one Mapping Professional should be responsible for each Map, though they may rely on Supporting Registered Professionals or delegate to, and directly supervise, any non-professionals aiding with certain aspects of the work. Those professionals—Mapping Professionals and the Supporting Registered Professional(s)—remain professionally responsible for the final SM Map and any delegated work done under their direct supervision.

For more information, refer to the Quality Management Guides—Guide to the Standard for Direct Supervision (Engineers and Geoscientists BC 2023c).

6.1.4 RETENTION OF PROJECT DOCUMENTATION

Engineering/Geoscience Professionals are required to establish and maintain documented quality management processes to retain complete project documentation for a minimum of ten (10) years after the completion of a project or ten (10) years after an engineering or geoscience document is no longer in use.

These obligations apply to Engineering/Geoscience Professionals in all sectors. Project documentation in this context includes documentation related to any ongoing engineering or geoscience work, which may not have a discrete start and end, and may occur in any sector.

Many Engineering/Geoscience Professionals are employed by Registrant firms, which ultimately own the project documentation. Engineering/Geoscience Professionals are considered compliant with this quality management requirement when reasonable steps are taken to confirm that (1) a complete set of project documentation is retained by the organizations that employ them, using means and methods consistent with the Engineers and Geoscientists BC Bylaws and quality management standards; and (2) they consistently adhere to the documented policies and procedures of their organizations while employed there.

Engineering/Geoscience Professionals should familiarize themselves with the First Nations Principles of training and resources related to ownership, control, access, and possession of First Nations information. These principles apply to survey research, data collection, interpretation, and analysis, which are fundamental steps in SM Mapping Projects.

For more information, refer to the Quality Management Guides—Guide to the Standard for Retention of Project Documentation (Engineers and Geoscientists BC 2023d).

6.1.5 DOCUMENTED CHECKS OF ENGINEERING AND GEOSCIENCE WORK

Engineering/Geoscience Professionals are required to perform a documented quality checking process of engineering and geoscience work, appropriate to the risk associated with that work. All Engineering/Geoscience Professionals must meet this quality management requirement.

The checking process should be comprehensive and address all stages of the execution of the engineering or geoscience work. This process would normally
Checking is an important part of SM Mapping Projects from data collection through analysis and mapping. First, Mapping Professionals must verify the accuracy of the data obtained by checking location accuracy and that the information collected at each data point makes sense compared with those collected nearby. In collecting and choosing to utilize data, Mapping Professionals should consider how data collection techniques, and even what data was collected, may have changed over time, and should make sure that any existing data obtained is appropriate for use.

Similarly, Mapping Professionals must decide the appropriate methodology to use for analysis and mapping, including which software to use. They must understand the input and output of software, making sure the results make sense and avoiding the “black box effect,” for example, by inputting variations of the data to see how the results change (sensitivity analysis). Additionally, they should periodically validate the software and conduct checks with other software to verify solutions.

For more information, refer to the Quality Management Guides—Guide to the Standard for Documented Checks of Engineering and Geoscience Work (Engineers and Geoscientists BC 2023e).

6.1.6 DOCUMENTED FIELD REVIEWS DURING IMPLEMENTATION OR CONSTRUCTION

Field reviews are reviews conducted at the site of the construction or implementation of the engineering or geoscience work. They are carried out by an Engineering/Geoscience Professional or a subordinate acting under the Engineering/Geoscience Professional's direct supervision (see Section 6.1.3 Direct Supervision).

Field reviews enable the Engineering/Geoscience Professional to ascertain whether the construction or implementation of the work substantially complies in all material respects with the engineering or geoscience concepts or intent reflected in the engineering or geoscience documents prepared for the work.
For more information, refer to the Quality Management Guides—Guide to the Standard for Documented Field Reviews During Implementation or Construction (Engineers and Geoscientists BC 2023f).

6.1.7 DOCUMENTED INDEPENDENT REVIEW OF STRUCTURAL DESIGNS

Engineering Professionals developing structural designs are required to engage an independent review of their structural designs. An independent review is a documented evaluation of the structural design concept, details, and documentation based on a qualitative examination of the substantially complete structural design documents, which occurs before those documents are issued for construction or implementation. It is carried out by an experienced Engineering Professional qualified to practice structural engineering, who has not been involved in preparing the design.

The Professional of Record must conduct a risk-assessment after conceptual design and before detailed design to (1) determine the appropriate frequency of the independent review(s); and (2) determine if it is appropriate for the independent reviewer to be employed by the same firm as the Professional of Record, or if the independent reviewer should be employed by a different firm.

The risk-assessment may determine that staged reviews are appropriate; however, the final independent review must be completed after checking has been completed and before the documents are issued for construction or implementation. Construction must not proceed on any portion of the structure until an independent review of that portion has been completed.

For more information, refer to the Quality Management Guides—Guide to the Standard for Documented Independent Review of Structural Designs (Engineers and Geoscientists BC 2023g).

6.1.8 DOCUMENTED INDEPENDENT REVIEW OF HIGH-RISK PROFESSIONAL ACTIVITIES OR WORK

Engineering/Geoscience Professionals must perform a documented risk assessment prior to initiation of a professional activity or work, to determine if that activity or work is high risk and requires a documented independent review.

If the activities or work are deemed high risk, and an independent review is required, the results of the risk assessment must be used to (1) determine the appropriate frequency of the independent review(s); and (2) determine if it is appropriate for the independent reviewer to be employed by the same firm as the Professional of Record, or if the independent reviewer should be employed by a different firm.

The documented independent review of high-risk professional activities or work must be carried out by an Engineering/Geoscience Professional with appropriate experience in the type and scale of the activity or work being reviewed, who has not been involved in preparing the design.

The documented independent review must occur prior to implementation or construction; that is, before the professional activity or work is submitted to those who will be relying on it.

As discussed in Section 3.5 Risk Management in Seismic Microzonation Mapping, SM Maps are a risk reduction tool that can have an indirect effect on the life safety of the public, as they inform policies, retrofit prioritization, emergency management responses, and more. Seismicity and understanding Seismic Hazards is an evolving area of practice. Mapping Professionals should stay up to date and apply the latest practices and information available to their SM Mapping Project.
However, when information and practices are new—for example, collecting different types of data or collecting data by innovative means, conducting different analyses, utilizing different methodologies for mapping—it is particularly important to have both Independent Reviews and detailed Checks (see Section 6.1.5 Documented Checks of Engineering and Geoscience Work) conducted of the work to ascertain that procedures are appropriately applied and all assumptions, inputs, and outputs for analyses make sense.

For SM Mapping Projects comprising multiple SM Maps, Mapping Professionals should consider using an independent review panel comprised of at least three Mapping Professionals with a broad range of experiences to cover geological mapping, seismic/geotechnical site assessment, In Situ seismic testing, Seismic Hazard determination, ground motion characterizations, mathematical modeling and simulation, spatial interpolation, and mapping geographic information system (GIS) methodologies. One member of the independent review panel should coordinate all the reviews to make sure there are no gaps in scope.

Generally, a Type 2 Independent Review is appropriate for Higher-Level SM Maps and suites of SM Maps, and a Type 1 Independent Review is appropriate for level 1 SM Maps.

Independent Reviews for SM Maps may be viewed as a hybrid between traditional independent reviews, documented checking, and peer review (see the Professional Practice Guidelines—Peer Review [Engineers and Geoscientists BC 2022]) to provide an independent, objective, technical review of all aspects of the SM Mapping Project.

For more information, refer to the Quality Management Guides—Guide to the Standard for Documented Independent Review of High-Risk Activities or Work (Engineers and Geoscientists BC 2023h).

6.2 OTHER QUALITY MANAGEMENT REQUIREMENTS

Engineering/Geoscience Professionals must also be aware of any additional quality management requirements from other sources that are relevant to their work, which may include but are not limited to:

- legislation and regulations at the local, regional, provincial, and federal levels;
- policies of authorities having jurisdiction at the local, regional, provincial, and federal levels;
- agreements and service contracts between clients and Engineering/Geoscience Professionals or their firms; and/or
- standards for engineering or geoscience firms, particularly those that apply to quality management system certification, such as the ISO 9000 family.

Engineering/Geoscience Professionals should assess any areas of overlap between the Engineers and Geoscientists BC quality management requirements and the requirements of other applicable sources. If the requirements of different sources overlap, Engineering/Geoscience Professionals should attempt to meet the complete intent of all requirements.

Where there are conflicts between requirements, Engineering/Geoscience Professionals should negotiate changes or waivers to any contractual or organizational requirements which may conflict with requirements of legislation, regulation, or the Engineers and Geoscientists BC Code of Ethics. No contractual obligation or organizational policy that may apply to an Engineering/Geoscience Professional on a particular project will provide justification or excuse for breach of any of the Engineering/Geoscience Professional's obligations under any legislation, regulation, or the Engineers and Geoscientists BC Code of Ethics. Where such conflicts arise and cannot be resolved, Engineering/Geoscience Professionals should consider seeking legal advice from their own legal...
advisers on their legal rights and obligations in the circumstances of the conflict, and they may also seek practice advice from Engineers and Geoscientists BC on any related ethical dilemma that they may face in the circumstances.

6.3 PRACTICE ADVICE

Engineers and Geoscientists BC provides their Registrants and others with assistance addressing inquiries related to professional practice and ethics.

Practice advisors at Engineers and Geoscientists BC can answer questions regarding the intent or application of the professional practice or quality management aspects of these guidelines.

To contact a practice advisor, email practiceadvisor@egbc.ca.
7.0 PROFESSIONAL REGISTRATION AND EDUCATION, TRAINING, AND EXPERIENCE

7.1 PROFESSIONAL REGISTRATION

Engineering/Geoscience Professionals have met minimum education, experience, and character requirements for admission to their professions. However, the educational and experience requirements for professional registration do not necessarily constitute an appropriate combination of education and experience for the development of Seismic Microzonation (SM) Maps. Professional registration alone does not automatically qualify an Engineering/Geoscience Professional to take professional responsibility for all types and levels of professional services in this professional activity.

It is the responsibility of Engineering/Geoscience Professionals to determine whether they are qualified by training and/or experience to undertake and accept responsibility for carrying out the development of SM Maps (Engineers and Geoscientists BC’s Code of Ethics, Principle 2).

7.2 EDUCATION, TRAINING, AND EXPERIENCE

The development of SM Maps, as described in these guidelines, requires minimum levels of education, training, and experience in many overlapping areas of engineering and geoscience.

Engineering/Geoscience Professionals who take responsibility for SM Maps (Mapping Professionals) must adhere to the second principle of the Engineers and Geoscientists BC’s Code of Ethics, which is to “practice only in those fields where training and ability make the Registrant professionally competent” and, therefore, must evaluate their own qualifications and must possess the appropriate education, training, and experience to provide the services.

The level of education, training, and experience required of Mapping Professionals must be adequate for the complexity of the project. Engineering/Geoscience Professionals in training or other delegates must be supervised by Mapping Professionals. This section describes indicators that Engineering/Geoscience Professionals can use to determine whether they have an appropriate combination of education and experience.

Note that these indicators are not an exhaustive list of education and experience types that are relevant to development of SM Maps. Satisfying one or more of these indicators does not automatically imply competence.

7.2.1 EDUCATION INDICATORS

Certain indicators show that Engineering/Geoscience Professionals have received education that might qualify them to participate professionally in the development of SM Maps. Educational indicators are subdivided into formal education (such as university
or engineering school) and informal education (such as continuing education).

Formal educational indicators include having obtained or completed one or more of the following:

- A doctorate, masters degree, or postgraduate diploma in geoscience, geotechnical engineering, or earthquake engineering or a related engineering/geoscience field from an accredited engineering or geoscience program.
- An undergraduate degree complimented with 5 years of experience developing SM Maps under the direct supervision of a Mapping Professional.
- Informal educational indicators include having participated in or undertaken one or more of the following, with a focus on seismicity, geoscience, Ground Shaking, Liquefaction, or Landslide:
  - Training courses facilitated by the Engineering/Geoscience Professional’s employer.
  - Continuing education courses or sessions offered by professional organizations (such as Engineers and Geoscientists BC).
  - Conferences or industry events.
  - A rigorous and documented self-study program involving a structured approach that contains materials from textbooks and technical papers.

Users of SM Maps can have a wide range of backgrounds, depending on their area of practice. It is not expected that users of SM Maps have the detailed educational background as described above for Mapping Professionals.

However, they should have a high-level understanding of Seismic Hazards and related terminology, as well as Seismic Microzonation Mapping, including the methodology to create SM Maps and their limitations of use. Users should consider working with an appropriately trained Engineering/Geoscience Professional to use SM Maps that are beyond their expertise.

### 7.2.2 EXPERIENCE INDICATORS

Certain indicators show that Engineering/Geoscience Professionals have an appropriate combination of experience that might qualify them to participate professionally in the development of SM Maps.

Experience indicators include having completed one or more of the following for an extended duration (greater than one year) and/or as an Engineering-in-Training (EIT)/Geoscientist-in-Training (GIT):

- Participated in the development of SM Maps under the direct supervision of an Engineering/Geoscience Professional, with an appropriate combination of education and experience.
- Participated in past projects or academic or industry working groups, working alongside Mapping Professionals and/or academic researchers to develop a sufficient knowledge of Seismic Hazards commonly addressed in SM Maps.
- Performed probabilistic Seismic Hazard analyses.
- Used the latest available national seismic model for the SM Map region.
- Conducted seismic site characterization field methods and/or Soil testing in the field or geotechnical laboratory, respectively.
- Conducted field slope assessments for Landslide SM Maps.
- Modelled and analyzed Seismic Hazards (e.g., ground motion prediction, numerical modelling).
- Developed lower-level SM Maps (prior to Higher-Level SM Maps).
- Have awareness of, or participated in, Seismic Hazard Mapping activities within Canada (e.g., seismicity and Site Amplification task group, national Standing Committee for Earthquake Design).
- Developed geological maps.
8.0 REFERENCES AND RELATED DOCUMENTS

Documents and legislation cited in the main guidelines appear in Section 8.1 Legislation, Section 8.2 References, and Section 8.3 Codes and Standards; documents cited in the appendices appear in the reference list at the end of each corresponding appendix.

Related documents and resources that may be of interest to users of these guidelines but are not formally cited, though may be mentioned elsewhere in this document, appear in Section 8.4 Related Documents and Resources.

8.1 LEGISLATION

Professional Governance Act [SBC 2018], Chapter 47.
Declaration on the Rights of Indigenous Peoples Act [SBC 2019], Chapter 44.
Emergency and Disaster Management Act [Bill 31-2023]
Indian Act [RSC 1985], Chapter 1-5.
Local Government Act [RSBC 2015], Chapter 1.
Land Title Act [RSBC 1996], Chapter 250.

8.2 REFERENCES


https://ascelibrary.org/doi/10.1061/%28ASCE%291090-0241%282004%29130%3A12%281314%29. 26 pp.


https://pubs.geoscienceworld.org/ssa/bssa/article-abstract/111/2/1110/594201/Paleoseismic-Trenching-Reveals-Late-Quaternary?.redirectedFrom=fulltext. 28 pp.


https://az659834.vo.msecnd.net/eventaircancprod/production-venuewest-public/h0a0a58db4b45f169c0ea256bcaff5d8. 10 pp.


http://cmscontent.nrs.gov.bc.ca/geoscience/PublicationCatalogue/GeoscienceMap/BCGS GM2000-03.pdf

Amplification of Seismic Ground Motion Hazard Mapping for the Fort St. John - Dawson Creek Area.


Quinn P. 2009. Large Landslides in Sensitive Clay in Eastern Canada and the Associated Hazard and Risk to Linear Infrastructure. Queen’s University. [accessed 2023 December 20].


https://ascelibrary.org/doi/10.1061/%28ASCE%291090-0241%282001%29127%3A10%2817%29. 16 pp.


8.3 CODES AND STANDARDS


8.4 RELATED DOCUMENTS AND RESOURCES

OTHER SEISMIC MICROZONATION (SM) GUIDELINES

- The International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) Manual for zonation on seismic geotechnical hazards, published in 1999. In this manual, three SM levels were identified according to three increasing territorial scales and level of complexity.

- The Republic of Türkiye's *Seismic Microzonation for Municipalities Manual* by the World Institute for Disaster Risk Management, published in 2004. This manual has three chapters. The first provides an overview of the methodology, defines terms related to earthquake engineering, and describes principle earthquake effects; the second describes the SMSM procedures, including data acquisition, map preparation, and recommendations for zone-associate building regulations; and the third provides guidance for the application of SM Maps in the process of municipal land use management.

- In 2008, the Conference of Regions and Autonomous Provinces of Italy and the Civil Protection Department published the *Indirizzi e criteri per la Microzonazione Sismica*. In 2015, the updated *Guidelines for Seismic Microzonation* were published. These guidelines are an Italian national reference document for studies to estimate the Seismic Risk of a territory. They utilize three levels for SMSM studies and describe the principles and elements for basic studies and for applications in land and emergency planning.

- *Guidelines for Evaluating and Mitigating Seismic Hazards in California* published by the California Geological Survey in 2008. The objectives of these guidelines are to assist in the evaluation and mitigation of earthquake related Hazards for projects within designated zones of required investigations and to promote uniform and effective statewide implementation of the evaluation and mitigation elements of the *Seismic Hazards Mapping Act* [1990, Chapter 7.8].

OTHER RELATED DOCUMENTS AND RESOURCES

General

- Metro Vancouver Seismic Microzonation Mapping Project.
- First Nations Land Management Resource Centre's *Land Codes*.
- United Nations Office for Disaster Risk Reduction's *Sendai Framework*.
- Engineer's and Geoscientists BC's *Equity, Diversity, and Inclusion Initiative*.
- Engineers Canada's *Guideline on Indigenous Consultation and Engagement*.
- *Indigenous Peoples and Lands*.

From, or related to, Section 4.0 Use of Seismic Microzonation Maps

- First Nations Information Governance Centre's *The First Nations Principles of OCAP*.
- Government of British Columbia's *Hazard, Risk and Vulnerability Analysis (HRVA) Tool*.
- District of North Vancouver's *Wildfire Hazard Development Permit Area (DPA)*.
- District of North Vancouver's *Slope hazard development permit area (DPA)*.
- City of New Westminster's *Geotechnical Report & Soil Investigation Requirements*. 

PROFESSIONAL PRACTICE GUIDELINES

USE AND DEVELOPMENT OF SEISMIC MICROZONATION MAPS IN BC
• Indigenous Services Canada’s Emergency Management Assistance Program.
• First Nations’ Emergency Services Society of BC’s Core Programs.
• City of Seattle Department of Construction and Inspections’ Director’s Rule X-2018.
• City and County of San Francisco OneSF’s Hazards and Climate Resilience Plan.
• City of Calgary’s Calgary Disaster Risk Explorer.
• Natural Resources Canada’s RiskProfiler.
• Fraser Valley Regional District’s A bylaw to establish regulations regarding floodplain management (bylaw 1669, 2022).
• District of Squamish’s Floodplain Management (bylaw 2751, 2021).
• Natural Resources Canada’s GEOSCAN.

From, or related to, Section 5.0 Development of Seismic Microzonation Maps

• Earthquakes Canada’s Canadian National Station Book Index.
• British Columbia Ministry of Transportation and Infrastructure’s Smart Infrastructure Monitoring System (BCSIMS webpage).
• Earthquakes Canada’s Report a felt earthquake (“Did You Feel It”) webpage.
• Earthquakes Canada’s About Community Internet Intensity Maps.
• British Columbia Geological Survey’s Publications.
• Government of British Columbia’s MapPlace 2.
• Government of British Columbia’s iMapBC.
• Government of Canada’s Terrain Inventory Mapping (TIM) Detailed Polygons with Short Attribute Table Spatial View.
• Government of British Columbia’s BC Soil Information Finder Tool.
• Government of British Columbia’s Topographic Maps.
• Government of Canada’s High Resolution Digital Elevation Model (HRDEM) – CanElevation Series.
• LidarBC’s Open LIDAR Data Portal.
• Government of British Columbia’s Historical Air Photo Index Map Viewer.
• Government of British Columbia’s Air Photos.
• The University of British Columbia’s Air Photo Request webpage.
• National Resources Canada’s National Air Photo Library.
• Government of British Columbia’s Groundwater Wells and Aquifers’ (GWELLS) Well Search.
# 9.0 Appendices

**Appendix A: Authors and Reviewers**

**Appendix B: Examples of Seismic Microzonation Maps**

**Appendix C: History of Use and Development of Seismic Microzonation Maps in BC**
- C1: History of use and development of seismic microzonation maps in BC
- C2: Existing BC seismic microzonation maps
- C3: References

**Appendix D: Non-Invasive and Invasive Vs Methods**
- D1: Non-invasive Vs data collection methods
- D2: Invasive Vs data collection methods
- D3: References

**Appendix E: Methods of Seismic Analysis of Soil Liquefaction**
- E1: Information for the calculation of soil liquefaction resistance
- E2: Information for the calculation of cyclic stress ratio
- E3: Variability of results using simplified methods
- E4: The two-cluster probabilistic method for calculating cyclic stress ratio unique to BC
- E5: Calculation of cyclic stress ratio from a seismic site response analysis
- E6: References
APPENDIX A: AUTHORS AND REVIEWERS

Engineers and Geoscientists BC thanks all contributors involved in the development of these guidelines. All contributors are presented in alphabetical order by last name within their respective section.

AUTHORS

Upul Atukorala, Ph.D, P.Eng.
Tamsin Mills
Sheri Molnar, Ph.D.
Patrick Monahan, Ph.D., P.Geo.
Matthew Osler, P.Eng.
John Sherstobitoff, P.Eng.
Carlos Ventura, P.Eng., FEC
Guoxi Wu, Ph.D., P.Eng.
Martin Zaleski, P.Geo.

REVIEWERS

Amanda Broad
Trevor Carey, Ph.D.
John-Carlos Carvajal, Ph.D., P.Eng.
John Cassidy, Ph.D.
John Clague, Ph.D., P.Geo.
Heather Crow, P.Eng.
Jason Dowling, P.Eng.
Micah Hilt
Tiegan Hobbs, Ph.D.
Alireza Javanbakht, Ph.D. Candidate
Paul Kovacs
Albert Leung, Architect AIBC
Jennifer Lotz
TJ MacDonald
Melissa McCabe
Roberto Olivera, Ph.D., P.Eng.
Charmaine Pflugrath
Lee Rowley, P.Eng.
Sergio Sepulveda, Ph.D.
Daniel Stevens
Thuraisamy Thavaraj, P.Eng.
Chris Weech, P.Eng.
APPENDIX B: EXAMPLES OF SEISMIC MICROZONATION MAPS IN BC

SUPPORTING GEOLOGICAL MAPS

- Topographic maps
- Topographic slope maps
- Shaded relief map from digital elevation model (DEM), including light detection and ranging (LiDAR)
- Surficial geological map
- Quaternary geology map
- Depth to bedrock, or bedrock structure contour map
- Depth to base normally consolidated section map (i.e., depth to till or post-glacial sediment thickness), or structure contour of base of normally consolidated map
- Water table depth or structure contour (elevation) map
- Maps showing the locations and types of subsurface data points used in mapping (may also be presented on other maps)

GROUND SHAKING MAPS

- $V_{S30}$ map (time-weighted average Shear Wave velocity [$V_s$] from ground surface to 30 m depth)
- $V_s$ average of Soil map (time-averaged and above bedrock), or $V_s$ average of specific stratigraphic intervals map (e.g., post glacial Soil)
- Fundamental Site Period ($T_o$) or other resonant peaks map
- Holocene or post-glacial sediment thickness map (depth to first Impedance Contrast)
- Pleistocene or total sediment thickness (depth to seismic bedrock) map
- Peak ground acceleration (PGA) map for different return periods or scenarios
- Peak ground velocity (PGV) map for different return periods or scenarios
- A map of spectral acceleration ($S_a$) at different frequencies, for different return periods or scenarios
- Depth to $V_s$ of 1000 m/s or 2500 m/s map
- Basin Amplification, PGV, and specific frequencies for different return periods or scenarios map
LIQUEFACTION MAPS

- Liquefaction Susceptibility Map
- Thickness (isopach) of liquefiable deposits map
- Thickness (isopach) of non-liquefiable deposits overlying liquefiable deposits map
- Probability of Liquefaction for different return periods or scenarios map
- Probability of Liquefaction severity maps
- Liquefaction Hazard Map for different return periods or scenarios
- Vertical or lateral displacement map for different return periods or scenarios
- Average factor of safety of liquefiable deposits map for different return periods or scenarios
- $\Delta q$ map, the difference in Cyclic Resistance Ratio (CRR) required and CRR available, for different return periods or scenarios

LANDSLIDE MAPS

- Topographic slope map
- Landslide inventory map
- Landslide Susceptibility ($k_s$) Map
- Landslide Hazard Map (probability of seismically-induced Landslide triggering) for different return periods or scenarios
- Landslide displacements map

COMPOSITE HAZARD MAPS

- Showing two or more Seismic Hazards in a simplified form, as a reference for more detailed maps
APPENDIX C: HISTORY OF USE AND DEVELOPMENT OF SEISMIC MICROZONATION MAPS IN BC

INTRODUCTION

Although they have not been widely distributed, British Columbia (BC) has a long history with Seismic Microzonation (SM) Mapping Projects, that can provide insight to the future development and application of SM Maps. Recent developments in Eastern Canada are also discussed in the following sections. The SM Maps produced to date in BC are shown in Appendix C2: Existing BC Seismic Microzonation Maps.

EARLY MAPPING AND DATA ACQUISITION

The first SM Map in BC was prepared for the City of Victoria by Wuorinen (1974, 1976); this map focused on the Amplification of Ground Shaking. Correlations were made between the intensity of ground motions observed by residents during the 1946 Vancouver Island earthquake and local ground conditions, using historical maps and borehole data. It was found that the lowest intensities occurred where bedrock is shallower than 3 m, and the highest intensities occurred in major fills and former swamps, where Soil thicknesses are the greatest. This project involved the preparation of geological maps showing the depth to bedrock.

By the 1980s, the techniques to measure Ground Shaking and Liquefaction Hazards were sufficiently well established for development of SM Maps. SM and related seismic studies were initiated by the Geological Survey of Canada (GSC), consulting engineering firms, and the BC Geological Survey (BCGS). The GSC initiated geological and geophysical studies in the Fraser River delta and adjoining uplands that resulted in the acquisition of a large volume of Shear Wave velocity (V), geological, and geophysical data that contributed significantly to subsequent SM studies (Hunter et al. 1998, 2016; Clague et al. 1998). Additionally, using this data, preliminary Amplification Susceptibility Maps were prepared by Hunter and Christian (2001) and Hunter et al. (2002).

A Liquefaction Susceptibility Map (approximately level 1) of the Lower Mainland was included in the GSC Geomap Vancouver for use by the general public (Turner et al. 1998). This map was a simplified version of the surficial geological maps of the area, created by Armstrong and Hicock (1979, 1980) and Armstrong (1980a, 1980b).

BC Hydro and Klohn-Crippen Consultants Ltd. prepared a Liquefaction Hazard Map (approximately level 2) for Greater Vancouver to assess the vulnerability of the BC Hydro infrastructure; a summary was published by Watts et al. (1992). This map used existing surficial geological mapping by Armstrong and Hicock (1979, 1980) as a geological base, and quantified the probability of Liquefaction at
70 sites. Other SM Maps have been prepared by consulting firms for public and private agencies; however, most are not publicly available.

BRITISH COLUMBIA GEOLOGICAL SURVEY
SEISMIC MICROZONATION MAPPING PROGRAM
1994-2010

In 1993, the BCGS initiated a program for developing SM Maps by contracting Klohn-Crippen Consultants Ltd. to review current methodologies in North America and to prepare guidelines for Liquefaction and Amplification Hazard Mapping (Hollingshead and Watts 1994). Subsequently, BCGS developed detailed SM Maps (approximately level 2) for Chilliwack, Greater Victoria, and Richmond (Levson et al. 1996b; McQuarrie and Bean 2000; Monahan and Levson 2000; Monahan et al 2000a, 2000b, 2000c, 2010a, 2010b). In these SM Mapping Projects, existing surficial geological maps were deemed inadequate in representing the geology of the shallow subsurface. New subsurface geological maps were prepared, each requiring the collection and interpretation of several thousand geotechnical and other test hole logs from third parties (Levson et al. 1996a, 1996b; Monahan and Levson 2000, 2003; Monahan et al. 2010a, 2010b). The BCGS also acquired new V5 data.

The Amplification Susceptibility was represented by the time-weighted average Shear Wave velocity (V,) from ground surface to 30 m depth (V30) and the National Earthquake Hazards Reduction Program (NEHRP) Site Classes, based on applying V, models of the shallow geological materials to the borehole data. The Liquefaction Hazard was represented by the probability of Liquefaction severity, a Hazard metric proposed by Klohn-Crippen (Building Seismic safety Council 1994, 2003; Levson et al. 1996a, 1998). The Landslide Hazard was considered only in the Greater Victoria project (McQuarrie and Bean 2000), using limit-equilibrium factor of safety analyses to map the Landslide Hazard (see Section 5.4 Landslide for details on this methodology).

In the Chilliwack and Greater Victoria SM Mapping Projects, where more than one Hazard was mapped, a composite Hazard Map, summarizing all of the Hazards was also prepared.

Molnar (2003) and Molnar et al. (2004b) compared the Greater Victoria Amplification Site Class map with the intensity of Ground Shaking reported in felt reports from the 2001 Nisqually earthquake, and found general consistency between predicted and observed relative variation in Ground Shaking. Subsequently, a simplified version of the Greater Victoria Site Class map was prepared to assist prioritization of schools for retrofits in the Ministry of Education's Seismic Mitigation Program, which also required data on the type, age, and condition of the school buildings (Monahan 2005a; Taylor et al. 2006). Later, this map was used as a layer in seismic vulnerability and Risk assessments of the building stock and lifelines in Greater Victoria (Zaleski 2014; Ventura and Bebamzadeh 2016). Risk and damage estimates were determined by considering the effects of earthquakes on different types and ages of structures located on different Soil conditions.

LATER SEISMIC HAZARD AND SEISMIC MICROZONATION MAP DEVELOPMENTS

In the late 1990s and early 2000s, recordings of nearby moderate to strong earthquakes by seismographs deployed by the GSC and others were used to demonstrate the variability in site response due to Local Site Conditions in Greater Vancouver and Victoria (Cassidy et al. 1997; Rogers et al. 1998; Cassidy and Rogers 1999, 2004; Atkinson and Cassidy 2000; Molnar et al. 2004a). In particular, high Amplifications were confirmed in the Fraser delta, with the greatest Amplifications occurring due to resonance over the thin Soils at the delta margin. It was found that the Amplification varied with frequency, with De-amplification being observed at high frequencies, which are relevant to low-rise structures.
The Government of BC's Seismic Mitigation Program also included the preparation of an Amplification Susceptibility Map (approximately level 1 or level 2) of the Lower Mainland, showing NEHRP Site Classes (Monahan 2005b; Taylor et al. 2006). This map was primarily based on the surficial geological mapping by Armstrong and Hicock (1979, 1980) and Armstrong (1980a, 1980b), but incorporated data from the BCGS projects. Site Class assignments were derived from a $V_s$ model of the Quaternary deposits of southwestern BC, based on $V_s$ data acquired by the GSC, BCGS, and other sources (Monahan and Levson 2001; Taylor et al. 2006). This map also included a zone of high Amplification around the margins of the Fraser delta, where the potential for resonance Amplification had been determined by recent earthquakes, as noted above. This map was always recognized as being insufficient for the needs of Greater Vancouver as a whole, a need currently being met by the Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP) (Molnar et al. 2020).

In the mid-2000s, researchers from the GSC and the Universities of Victoria and British Columbia began collecting microtremor data from ambient noise (Onur et al. 2004; Molnar and Cassidy 2006; Molnar et al. 2006, 2007, 2010, 2014b). These investigations confirmed the applicability of these techniques to determine site response, including Fundamental Site Frequency ($f_0$), Fundamental Site Period ($T_0$), and estimate $V_s$ profiles. A significant database of microtremor data was collected for use in subsequent microzonation studies (e.g., the MVSMMP). These techniques are described in Section 5.1.3.4.1 Microtremor Horizontal to Vertical Spectral Ratio.

At the same time, Molnar (Molnar 2011; Molnar et al. 2014a, 2014b) investigated basin Amplification due to the structure of the Late Cretaceous and Tertiary Georgia Basin underlying the Lower Mainland. Numerical models were prepared for several shallow and deep earthquakes under several different scenarios. The seismic modelling was based on a modified geological and geophysical model prepared by Stephenson (2007) for the area above the subducting Juan de Fuca Plate from northern California to BC. This model has since been updated (Stephenson et al. 2017).

In 2014, the GSC prepared a detailed Seismic Hazard and Seismic Risk study of the District of North Vancouver (Journeay et al. 2015; Wagner et al. 2015). The Seismic Hazards addressed included Liquefaction, Amplification, and Landslides. Susceptibility and Hazard Maps (approximately level 2) were prepared for each Hazard. For Amplification, a $V_{500}$ map was included. In addition to assessments of the Seismic Hazards, the study also examined the effects of the earthquake scenarios on people and society, buildings and lifelines, and the economy. Instead of using existing surficial geological mapping of the area (Armstrong and Hicock 1979, 1980), a detailed surficial geological map was prepared for this project by Bednarski (2014).

In 2017, a comprehensive level 3 SM Mapping Project for Metro Vancouver was initiated by Western University and Emergency Management and Climate Readiness BC (Molnar et al. 2020). Susceptibility and Hazard Maps were prepared for Ground Shaking, Liquefaction, and Landslides. Basin Amplification was also addressed. This project used an extensive database of existing public and proprietary test hole data, existing and new microtremor data, and existing and new $V_s$ data. The new $V_s$ data was acquired by microtremor, Surface Wave, and downhole methods, and included geophysical techniques to refine the physical model of the Georgia Basin. In combination with new and existing surficial and subsurface geological mapping, these data were used to build a database of regional 3D Geoscience Data for Metro Vancouver.
RECENT DEVELOPMENTS IN EASTERN CANADA

Recent SM Mapping Projects in Ottawa, Montreal, Quebec City, and the St Lawrence Lowlands have focused on Amplification Susceptibility, represented by $V_{s30}$, Site Class, and $T_o$ maps, using approaches similar to those used in BC (Chouinard and Rosset 2007; Hunter et al. 2010; Motazedian et al. 2010, 2011, 2020; Leboeuf et al. 2013; Perret and Lamarche 2013; Perret et al. 2013; Rosset et al. 2015; Nastev et al. 2016). $V_s$ models of the shallow subsurface developed from newly acquired $V_s$ data were applied to extensive compilations of borehole data to map the Amplification Susceptibility. These maps are currently being used for land use and emergency response planning.

APPLICATION TO INDUCED SEISMIC STUDIES

With the increase in seismic activity due to hydraulic fracturing by the petroleum industry, the techniques have been applied to the Montney hydrocarbon play in Northeast BC by Geoscience BC. An initial Amplification Susceptibility assessment was based on a compilation of existing surficial geological maps, with Site Class estimates assigned to map units on the basis of borehole and new $V_s$ data (Monahan et al. 2019). A follow-up SM Mapping Project (approximately level 2) focusing on the Fort St. John-Dawson Creek part of the play area considered resonance in addition to Site Class, based on $V_s$ profiles and site response data from induced earthquakes. The project involved the preparation of a map more representative of subsurface conditions, which required acquisition of additional borehole and $V_s$ data (Monahan et al. 2022).
### Table C-1: Existing Seismic Microzonation Maps In BC

<table>
<thead>
<tr>
<th>AREA</th>
<th>PUBLISHED BY</th>
<th>DATE</th>
<th>MAP TYPES</th>
<th>REPORT NUMBER/MAP NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chilliwack</td>
<td>BC Geological Survey</td>
<td>1996</td>
<td>Surficial Geology</td>
<td>Open File 1996-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Composite Hazard, Liquefaction, and Amplification Hazard, Facies to 20 m depth</td>
<td>Open File 1996-25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Quaternary Geology</td>
<td>Geoscience Map 2000-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Liquefaction, Amplification, and Seismic Slope Stability</td>
<td>Geoscience Map 2000-3</td>
</tr>
<tr>
<td>Lower Mainland</td>
<td>9th Canadian Conference on Earthquake Engineering</td>
<td>2005</td>
<td>Amplification</td>
<td>Soil Hazard Map of the Lower Mainland of British Columbia for Assessing the Earthquake Hazard due to Lateral Ground Shaking</td>
</tr>
<tr>
<td>Richmond</td>
<td>BC Geological Survey</td>
<td>2010</td>
<td>Quaternary Geology</td>
<td>Geoscience Map 2010-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Liquefaction Hazard</td>
<td>Geoscience Map 2010-3</td>
</tr>
<tr>
<td>District of North Vancouver</td>
<td>Geological Survey of Canada</td>
<td>2014</td>
<td>Surficial Geology</td>
<td>Canadian Geoscience Map 203</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2015</td>
<td>Report</td>
<td>Open File 7677</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Amplification, Liquefaction, Slope Instability, Building and Infrastructure Damage, Casualty Estimates, Economic Impact</td>
<td>Open File 7816</td>
</tr>
<tr>
<td>Fort St. John- Dawson Creek</td>
<td>Geoscience BC</td>
<td>2022</td>
<td>Surficial Geology, Depth to Bedrock, Amplification</td>
<td>Report 2022-05</td>
</tr>
</tbody>
</table>


https://ostrnrcan-dostmncan.canada.ca/entities/publication/adf24f77-f8f2-4cce-a4a3-337240242bca.


Molnar S.E. 2011. Predicting earthquake ground shaking due to 1D soil layering and 3D basin structure in SW British Columbia, Canada. PhD Dissertation, University of Victoria. 150 pages.


PROFESSIONAL PRACTICE GUIDELINES
USE AND DEVELOPMENT OF SEISMIC MICROZONATION MAPS IN BC

VERSION 1.0
Amplification of Seismic Ground Motion Hazard Mapping for the Fort St. John-Dawson Creek Area, Northeastern British Columbia.


https://cmscontent.nrs.gov.bc.ca/geoscience/PublicationCatalogue/GeoscienceMap/BCGS_GM2O10-03.pdf. 1 sheet.


APPENDIX D: NON-INVASIVE AND INVASIVE V\textsubscript{s} METHOD

Shear Wave velocity (V\textsubscript{s}) data are an essential component of Higher-Level Seismic Microzonation (SM) Maps. The Geological Survey of Canada (GSC) published the guidelines *Shear wave velocity measurement guidelines for Canadian seismic site characterization in soil and rock* (Hunter [ed.] and Crow [ed.] 2015) for V\textsubscript{s} data acquisition and site characterization methods; Mapping Professionals are referred to it for further details and guidance. More recent collections of papers on site characterization and V\textsubscript{s} data acquisition have been published in special issues of the *Bulletin of the Seismological Society of America* (introduction by Kaklamanos et al. 2021) and the *Journal of Seismology* (introduction by Yong et al. 2022).

D1: NON-INVASIVE V\textsubscript{s} DATA COLLECTION METHODS

Non-invasive V\textsubscript{s} data collection methods provide efficient and cost-effective means of obtaining large amounts of V\textsubscript{s} data, and are normally an important part of a Higher-Level SM Mapping Projects. A variety of methods are available, such as (Hunter and Crow 2015):

- seismic reflection and refraction methods;
- Surface Wave methods; and
- microtremor methods.

SEISMIC REFRACTION AND REFLECTION METHODS

Seismic refraction and reflection methods record either S-Wave or P-Wave data, and can be conducted In-Situ to produce a 1D V\textsubscript{s}-depth profile (V\textsubscript{s} versus depth plot) or along a line to generate a 2D profile showing lateral changes in the subsurface geology (Hunter et al. 2015, 2022). The latter is more costly and usually requires specialized equipment.

S-Wave refraction for 1D V\textsubscript{s}-depth profiles has been widely used in Seismic Hazard studies but should be used with caution. Important limitations are that it records low amplitude events (and so is depth-limited), results are sensitive to dipping subsurface horizons, velocity reversals cannot be reliably recorded, and thin layers may not be detected. These limitations can result in erroneous velocity-depth plots.

S-Wave reflection for 1D V\textsubscript{s}-depth profiles can be performed together with seismic refraction 1D profiles at a site to provide complementary data for interpretation. Reflection can image deeper horizons than refraction, but refraction can provide more velocity data. In Ottawa, Mapping Professionals found that reflection data were more useful at thick Soil sites in providing V\textsubscript{s}-depth data to the base of the soft post glacial marine sediments. Conversely, refraction data were more useful at thin Soil sites in providing V\textsubscript{s} estimates of glacial deposits and bedrock (Motazedian et al. 2011).

Seismic reflection 2D profiling techniques, using both P-Waves and S-Waves, are now widely used in shallow investigations, including SM studies, because
they provide both \( V_s \) and P-Wave velocity (\( V_p \)) data and show the lateral changes in subsurface geological conditions (Pullan et al. 2015; Hunter et al. 2022). These methods involve multiple profiles in a linear array, and may require sophisticated recording equipment. Consequently, they are more laborious and costly than ID methods. S-Wave profiling methods have higher resolution than P-Wave methods, due their lower velocity and shorter wavelength, and are unaffected by dry intervals or water-saturated sediments with dissolved gas (Pullan et al. 1998).

Seismic refraction profiling for shallow geotechnical investigations also shows lateral changes in subsurface geological conditions, and these data may locally be acquired as part of the geotechnical data search. Under some conditions, Surface Wave data, recorded in the course of seismic refraction profiling, can be processed to estimate \( V_s \)-depth plots (C. Candy, personal communication, July 29, 2022).

Seismic reflection and refraction profiling has been widely used in the petroleum industry for deep structural and stratigraphic interpretation. Such data may be locally available from petroleum companies, industry data brokers, or government sources, for interpretation of basin structure in basin Amplification studies.

**SURFACE WAVE METHODS**

Surface Wave methods typically measure the velocity of Rayleigh waves at different frequencies (Phillips 2015). Since the velocity of Rayleigh waves is close to that of Shear Waves, and their frequency is related to depth, Rayleigh wave velocity-frequency data can be modelled to estimate \( V_s \) changes with depth. Several methods have been developed, all of which involve a Surface Wave source and a linear array of geophones. The main limitations are that they do not measure \( V_s \) directly, resolution diminishes with depth, and the modelling solutions may be non-unique. The tests should be conducted on level ground and where the subsurface geological conditions are laterally homogeneous.

The following methods are available:

- **Continuous Surface Wave testing**, which uses a vibratory source to generate Surface Waves, and produces good resolution for shallow depth (Weemees and Woeller 2015a). However, the depth of penetration is usually less than 15 m.
- **Spectral analysis of Surface Waves (SASW)** testing, which uses two or more geophones that are moved during the test to record Rayleigh waves (Weemees and Woeller 2015b). Sources range from sledgehammers to bulldozers, and depth of penetration can exceed 30 m with larger Shear Wave sources.
- **Multichannel analysis of Surface Waves (MASW)** testing, which addresses the contribution of all recorded modes of ground motion to produce more accurate and reliable \( V_s \)-depth profiles than the other Surface Wave methods, which typically target only the fundamental mode of ground vibration for their analysis (Lefebvre and Karray 2015).

**MICROTREMOR METHODS**

**Microtremor Array Method**

Microtremor array method (MAM) is similar to the single station microtremor method described in Section 5.1.3.4.1 Microtremor Horizontal to Vertical Spectral Ratio, but differs in that it uses multiple seismometers in a 2D, circular array to record ambient noise (microtremors) and estimate the variation in \( V_s \) with depth (Claprood 2015a, 2015b; Molnar 2015). The analysis assumes ambient noise is dominated by Surface Waves, and estimates \( V_s \) in the same way as Surface Wave methods. This method can
be efficiently conducted in conjunction with single station microtremor horizontal to vertical spectral ratio (MHVSR) recordings and should be used as part of Higher-Level SM Mapping Projects.

**Ambient Noise Tomography**

Ambient noise tomography is a technique that uses ambient noise to investigate $V_s$ variations deeper in the earth’s crust than the MAM. It can be used in SM Mapping Projects to map the extent and $V_s$ structure of deep sedimentary basins (Shapiro et al. 2005; Delorey and Vidale 2011; Nicolson et al. 2012). As in the MAM, the noise is assumed to be dominated by Surface Waves. An array of broad-band seismometers is deployed with a spacing in the order of kilometres, and ambient noise is recorded for a number of months, to record lower frequencies. The data can be processed to estimate the average $V_s$ between seismometers at different periods, which represent different depths, and then integrated to develop a $V_s$ model for the area down to several kilometres.

**Distributed Acoustic Sensing**

Distributed acoustic sensing is an emerging method that uses pre-existing fibre-optic cables to record ground motions from both earthquakes and ambient noise, and has the potential to provide dense networks of site response and $V_s$ data profiles in urban environments (Yang et al. 2022).

**D2: INVASIVE $V_s$ DATA COLLECTION METHODS**

Invasive $V_s$ methods are typically more expensive and logistically complex than non-invasive methods, but are generally considered more reliable. The principal invasive $V_s$ data collection methods are:

- **Seismic cone penetration tests (SCPTs)** (Weemees and Woeller 2015c), which are considered the most reliable method, as the sensor is in direct contact with the Soil, minimizing Soil disturbance compared to drilling.

SCPTs are routinely conducted in geotechnical investigations, and potentially available as part of the geotechnical data search. The principal disadvantage is that they are limited in how deep they can be pushed without a drill-out (usually a few tens of metres), and they cannot usually penetrate very dense Soil, gravel, or rock, and so are unsuitable for investigating large Impedance Contrasts and rock velocities.

- **Downhole $V_s$ logging in boreholes, such as:**
  - Vertical seismic profiling (VSP) logging is the most common downhole method (Arsenault et al. 2015). It involves a surface source of Shear Waves and a downhole receiver. Shear Wave arrival times are recorded at specified intervals, usually 0.5–1 m. P-Wave data are commonly recorded as well. This method requires a cased hole in Soil, but an uncased hole is acceptable in rock.
  - Full waveform acoustic logging employs a downhole tool with both source and receivers to obtain both $S$-Wave and $P$-Wave data (Crow 2015). Full waveform logs are suitable for deeper, uncased, and fluid filled holes, but not for Soils in cased holes. Full waveform acoustic logging is widely used in petroleum wells.
  - Suspension logging is another downhole technique for logging both Shear Wave and P-Wave data. The downhole tool includes both source and receiver and can be run to depths of 600 m. This system can be run in both cased and uncased holes, although the results are better in cased holes (Geovision).
  - Cross hole methods employ a downhole Shear Wave source in one borehole and downhole receivers in one or more adjacent boreholes (Sincennes 2015; Candy and Hillman 2015). Cross hole methods produce the highest quality results but are costly and typically reserved for critical projects. This method determines the horizontal $V_s$, whereas the vertical $V_s$ is more relevant to...
seismic studies, because Seismic Waves approach vertically. Consequently, these data should be compared with vertically recorded invasive data to assess their reliability. Although cross hole methods are not likely to be conducted as part of an SM Mapping Project, such data may be obtained in the course of collecting data from other sources.

- Where $V_s$ logging of new or existing boreholes is conducted, Mapping Professionals should consider running additional geophysical logs for lithology identification, stratigraphic correlation, determination of physical properties and water saturation, and definition of stratigraphic contacts. Logs commonly run in cased shallow boreholes include gamma ray, conductivity, magnetic Susceptibility, and density (Crow and Hunter 2015).

- Acoustic logs from petroleum wells measure $V_p$ and are a potential indirect source of $V_s$ data for deep horizons (from $V_s$–$V_p$ correlations) in wells where full waveform acoustic logs were not run.


APPENDIX E: METHODS OF SEISMIC ANALYSIS OF SOIL LIQUEFACTION

E1: INFORMATION FOR THE CALCULATION OF SOIL LIQUEFACTION RESISTANCE

SOIL LIQUEFACTION RESISTANCE

The Soil Liquefaction Resistance (CRR) of saturated clean sands (median particle size from 0.075-4.75 mm) can be measured by laboratory testing using reconstituted samples prepared to a target relative density. It has been found (see Figure E-1) that CRR of clean sands (with fines less than 5%) increases with relative density, and under the same relative density, the cyclic shear stress amplitudes (τ cyc) decrease with more cycles of the shear stresses applied in the testing.

Because Liquefaction is triggered by multiple cycles of shear stresses, CRR of Soils is represented using both the τ cyc and the number of cycles for uniform stresses (constant amplitude) to trigger a Liquefaction failure. Cyclic Stress Ratio (CSR) refers to the ratio of the τ cyc to the effective overburden stress (σ’ vo) at which the sample is under cyclic shearing (CSR = τ cyc / σ’ vo). Although Soil would liquefy at various combinations of CSR and number of cycles, the CRR (or CSRiS) is defined by CSR at σ’ vo of approximately 100 kPa to cause Liquefaction in 15 cycles.

CRR of sands has been derived from field performance of Soils under various levels of historical earthquakes and can be plotted by one of the methods discussed in Section 5.3.4 Level 2 Liquefaction Maps. In general, sands with (Njeo > 30 are considered dense and generally not liquefiable and sands with (Njeo < 10 are generally loose and highly susceptible to Liquefaction, where (Njeo is the normalized standard penetration test (SPT) blow count.

Figure E-1: Liquefaction resistance trend curves for clean sands: (a) Cyclic Stress Ratio and number of cycles to Liquefaction; (b) Cyclic Resistance Ratio (CSRiS) and (Njeo (Source: Wu 2015)
At a given relative density or \(N_{s0}\), sandy soils containing greater than 5% of fines (particle size < 0.075 mm) are known to have higher CRR than clean sands with less than 5% of fines (Youd et al. 2001).

CRR for granular soils includes two groups of soils:
1. sandy soils (sands, silty or clayey sands, non-plastic silts); and
2. gravelly soils (gravelly sands or sandy gravels).

Non-plastic silts, containing 100% fines but with very low plasticity (such as plasticity index [PI] < 5%), are considered to behave under cyclic loading in a similar manner as sands. The CRR of non-plastic silts is evaluated as sandy soils with a correction on fines content.

The following sections outline specific considerations for calculating CRR for sandy soils and gravelly soils, respectively.

**CALCULATING SOIL LIQUEFACTION RESISTANCE FOR SANDY SOILS**

The most commonly used relationships to predict CRR from SPT blow count are those proposed by Youd et al. (2001), Cetin et al. (2004), and the Idriss and Boulanger procedure (2008; 2012; 2014). To use the simplified method appropriately, adjustment factors applied in calculating CRR and CSR should be consistent with those used in the development of the CRR curves or relationships. Mapping Professionals should not mix and match adjustment factors across different procedures.

The normalized SPT blow count, \(N_{s0}\), is calculated in Formula E-1:

\[
(N_{s0})_{se} = N_{m} \times C_{n} \times C_{e} \times \text{other factors}
\]  

**where**
- \(N_{m}\) is the SPT blow count measured in field testing;
- \(C_{n}\) is the factor to normalize \(N_{m}\) to an effective overburden stress \(\sigma'_{vo}\) of about 100 kPa;
- \(C_{e}\) is the correction for SPT hammer energy ratio; and
- other factors include corrections for borehole diameter, SPT rod length, and SPT samplers (with or without liners).

Using Youd et al. (2001), the CRR for M7.5 earthquakes can be estimated from the curves provided in Figure E-2. It is usually recommended that the SPT Clean Sand Base Curve be used, with correction for fines content. There are similar plots for cone penetration test (CPT) and Shear Wave velocity (V_s). For silty or clayey sands, the CRR normally increases with the content of fines. \((N_{s0})_{se}\) for silty or clayey sands should be corrected for the fines content prior to being applied to Figure E-2 for the calculation of CRR (Youd et al. 2001).

For determining the CRR of sandy soils, soil field density data collected from CPTs are generally more applicable than those from SPTs because of the greater repeatability of CPT data over a large area. CPT data has a number of advantages for assessment of liquefaction hazard, including that it provides a nearly continuous profile of penetration resistance over depth. Instead of using \(N_{s0}\), the CPT method uses the CPT tip resistance \((q_{c})\) normalized to \(\sigma'_{vo}\) of about 100 kPa \((q_{c,vo})\) for calculation of CRR.

The most commonly used relationships to predict CRR from \(q_c\) are those developed by Robertson and Wride (1998), as recommended in Youd et al. (2001), Moss et al. (2006), and the Idriss and Boulanger procedure (2008; 2014). See Figure E-3.

Like \((N_{s0})_{se}\) for the SPT method, \(q_{c,vo}\) for the CPT method should be corrected for fines content, prior to being applied to Figure E-3 for calculation of CRR. CRR typically increases with increased fines content.
In the absence of either SPT or CPT data, Mapping Professionals should consider using the V₅ method for the calculation of CRR of sandy and gravelly Soils that are uncemented Holocene-aged. Mapping Professionals should apply the Andrus and Stokoe (2000) correlation in Youd et al. (2001) or the 15% probability curve in Kayen et al. (2013), as shown in Figure E-4. The V₅-based procedure is typically less reliable than the SPT and CPT methods because the correlation between small-strain stiffness and large-strain Liquefaction has limited accuracy.

Figure E-2: Standard penetration test clean-sand Cyclic Resistance Ratio (CSRₑ) with data from Liquefaction case histories (Source: Youd et al. 2001)
Figure E-3: Cone penetration test clean-sand Cyclic Resistance Ratio (CSRmt) with data from Liquefaction case histories (Source: Idriss and Boulanger 2008)
In summary, the CPT-based method is considered the most suitable method for Liquefaction SM Mapping Projects in British Columbia (BC). However, the SPT-based method could be applicable and adopted when reliable data are available in the SM Mapping Project area. The $V_s$-based method should only be used when CPT and SPT data are not available, or for gravelly Soils.

CALCULATING SOIL LIQUEFACTION RESISTANCE FOR GRAVELLY SOILS

Due to the high permeability of gravel and its ability to dissipate pore water pressure quickly, unless completely confined, gravels (particle size from 4.75–75 mm) are not usually vulnerable to Liquefaction. However, gravelly sands or sandy gravels are potentially liquefiable.

The determination of CRR for gravelly Soils is more challenging than for sandy Soils. SPT and CPT measurements in gravelly Soils are generally not a reliable representation of CRR, because the large size gravels distort the Soil stress fields in these tests and thus misleadingly increase the penetration resistance.

The CRR for gravelly Soils may be evaluated by field Becker penetration tests (BPTs) (Youd et al. 2001) or by field large penetration tests (LPTs). However, improvements to the LPT and BPT test procedures and their conversion to equivalent SPT blow counts are still needed for these methods to be considered reliable means of assessing CRR (National Academies 2021). If the BPT method is used, a field instrumented BPT rig in which energy delivered to the sampler is measured should be used (Ghafghazi et al. 2017b). $V_s$ represents an alternative for characterizing the CRR of gravelly Soils. As $V_s$ is directly correlated to Liquefaction triggering potential, conversion to an equivalent SPT blow count is not required (Andrus and Stokoe 2000). See Figure E-4.
E2: INFORMATION FOR THE CALCULATION OF CYCLIC RATIO

SEISMICALLY-INDUCED CYCLIC STRESS RATIO

For Liquefaction analysis, seismic load in a Soil element (or layer) is represented by time history of \( \tau_{uv} \) imposed by Ground Shaking. The Cyclic Stress Ratio (CSR) should be calculated by using the simplified procedure (Seed and Idriss 1971) or from a Seismic Site Response Analysis (SSRA). The calculation of CSR using the simplified procedure requires the maximum ground acceleration \( (a_{\text{max}}) \) (see Section 5.2 Ground Shaking), the depth of groundwater table, and the depth to the Soil layer. An SSRA also requires the use of the input ground motions developed for the site and dynamic properties (e.g., \( V_J \)) of the Soils.

Per the Code, Seismic Hazard models by GSC (Kolaj et al. 2020) and their results must be used to derive \( a_{\text{max}} \) or input ground motions for the calculation of CSR. The magnitude 9 (M9) subduction interface earthquakes must be considered in Metro Vancouver and on Vancouver Island, and be treated separately from the non-interface magnitude 7 (M7) crustal and subduction in-slab earthquakes. An example calculation of combining seismic demand from the M9- and M7-clusters of earthquakes using the two-cluster probabilistic approach is provided in Appendix E4; The Two-Cluster Probabilistic Method for Calculating Cyclic Stress Ratio Unique to BC.

SIMPLIFIED PROCEDURE FOR CALCULATION OF CYCLIC STRESS RATIO

Using the simplified procedure with CRR relationships discussed above, the amplitude of CSR should be calculated from Formula E-2:

\[
\text{CSR} = 0.65 \frac{\sigma_{vo}}{\sigma'_{vo}} \frac{a_{\text{max}}}{g} r_d
\]

[Formula E-2]

where

- \( a_{\text{max}} \) is the maximum ground acceleration in m/s²;
- \( g \) is the gravitational acceleration in 9.81 m/s²;
- \( \sigma_{vo} \) and \( \sigma'_{vo} \) are the total and effective overburden stresses, respectively; and
- \( r_d \) is the stress reduction coefficient.

The calculation of CSR requires Soil unit weight (\( \gamma \)), groundwater table, \( a_{\text{max}} \), and \( r_d \).

When using the Youd et al. (2001) procedure, Mapping Professionals should apply average values of \( r_d \) using Formulas E-3-a and E-3-b:

\[
r_d = 1 - 0.00765 \ z \quad \text{for} \ z < 9.15 \text{ m, and}
\]

[Formula E-3-a]

\[
r_d = 1.174 - 0.0267 \ z \quad \text{for} \ 9.15 \text{ m} < z < 23 \text{ m}
\]

[Formula E-3-b]

where \( z = \) depth below ground surface in m.

The seismic load intensity, represented by \( \text{CSR}_{M,5} \) and used in calculation of the factor of safety against Liquefaction (\( FS_{\text{liquefaction}} \)), includes both the CSR amplitude and the CSR duration; the latter is reflected by the earthquake moment magnitude (\( M_w \)) associated with the \( a_{\text{max}} \) used in Formula E-1. The CSR at \( M_w \) is normalized to \( \text{CSR}_{M,5} \) using the earthquake magnitude scaling factor (MSF) \( (\text{CSR}_{M,5} = \frac{\text{CSR}}{\text{MSF}}) \).

In the early work by Seed and Idriss (1982), earthquakes with a magnitude of 7.5 were considered to have a number of representative cycles (\( N_m \)) equal to 15. Thus, \( M_w = 7.5 \) and \( N_m = 15 \) was used as the reference parameter for earthquake magnitudes or for laboratory cyclic tests, respectively, for which CRR and CSR for Liquefaction analysis are normalized to.

Table E-1 shows a comparison of the lower-bound and upper-bound values of MSF in Youd et al. (2001) at a few select \( M_w \).
Table E-1: Earthquake Magnitude Scaling Factor Values Recommended by Youd et al. (2001)

<table>
<thead>
<tr>
<th>MAGNITUDE, MW</th>
<th>LOWER-BOUND VALUES</th>
<th>UPPER-BOUND VALUES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSF = ((\frac{M_w}{7.5})^{-2.56})</td>
<td>(EQUATION NOT AVAILABLE)</td>
</tr>
<tr>
<td>6</td>
<td>1.76</td>
<td>2.1</td>
</tr>
<tr>
<td>6.5</td>
<td>1.44</td>
<td>1.6</td>
</tr>
<tr>
<td>7</td>
<td>1.19</td>
<td>1.25</td>
</tr>
<tr>
<td>7.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>8</td>
<td>0.84</td>
<td>0.8</td>
</tr>
<tr>
<td>8.5</td>
<td>0.72</td>
<td>0.65</td>
</tr>
<tr>
<td>9.0</td>
<td>0.55</td>
<td></td>
</tr>
</tbody>
</table>

Note:

(i) MSF for \(M_w = 9.0\) is extrapolated from the values recommended by Youd et al. (2001), not provided directly.

It is recognized that the use of MSF represents areas of uncertainty in the simplified procedure for the calculation of Liquefaction Hazard, especially when the calculation is associated with applications that involve large magnitude earthquakes. In Youd et al. (2001), MSF values were not available for \(M_w\) greater than 8.5. Boulanger and Idriss (2014) extended MSF values to \(M_w = 9\). However, it is cautioned that recommendations on MSF from the recent studies for large magnitudes (M9) need to be vetted by the profession for their practical application (National Academies 2021).

When using the Youd et al. (2001) procedure to develop Liquefaction SM Maps in BC, Mapping Professionals, should apply the mean values of MSF (i.e., the average of the lower and upper bound values in Table E1). For the Cascadia subduction interface earthquakes with \(M_w = 9\), they should use MSF of 0.55, assuming an extrapolation of the data in the table to \(M_w = 9\).

E3: VARIABILITY OF RESULTS USING SIMPLIFIED METHODS

Part A of Figure E-5 compares the three SPT-based CRR curves. The Cetin et al. (2004) curve plots below the curves of the Youd et al. (2001) and Idriss and Boulanger (2008) curves, which means that method is generally more conservative. This apparent significant difference between the three methods can partly be explained by the way in which the database was analyzed by Cetin et al. (2004). However, Boulanger et al. (2012) present a discussion of the data points that control the position of the curve and through that, cast doubt on the validity of the eight key points in the Cetin et al. (2004) curve on the following grounds:

- incorrect assignment of Liquefaction or no Liquefaction of four points;
- significant numerical errors between the \(r_5\) values used to develop their correlations; and
- \(r_5\) values computed using their applicable equation for four others.
Another explanation was provided by Cetin to the twelve-member committee (National Academies 2021) that suggests the differences in the Cetin et al. (2004) and Idriss and Boulanger (2008) CRR relationships are due primarily to differences in $r_e$ and $K_o$.

Griffiths and Cox (2012) used the three SPT-based methods to analyze three case studies to find that the three methods did not provide significantly different $F_{S_{liquefaction}}$ in the upper 20 m of the Soil profiles and that the Idriss and Boulanger procedure typically yields the highest factor of safety at depth, generally 5–15% higher than the others. However, the differences were much greater at SPT raw blow counts greater than 23. This was attributed to the fact that Idriss and Boulanger procedure made use of higher $K_o$ values and, more significantly, higher $C_{ml}$ values. At depths greater than 20 m, however, the $F_{S_{liquefaction}}$ evaluated using these methods diverges. National Academies (2021) presents another comparison of $F_{S_{liquefaction}}$ at a single site using the CRR relationships in Figure E-4 and Figure E-5 and their respective adjustment factors ($r_a$ and MSF). The results of the comparison study, shown in Figure E-6, seem to suggest that the Youd et al. (2001) procedure is preferred for the SPT-based procedure, the Idriss and Boulanger (2008) is preferred for the CPT-based procedure, and a large difference in results exists between the Andrus and Stoke (2000) and the Kayen et al. (2013) methods for the $V_s$-based procedure.

Mapping Professionals should familiarize themselves with all of these approaches for calculating $F_{S_{liquefaction}}$, as well as studies outlining the variability and conservatism of each, to make the most informed decision on which approach to use.

![Figure E-5: Comparison of selected Cyclic Resistance Ratio predictive relationships: (a) Standard Penetration Test blow count relationships; (b) Cone Penetration Test tip resistance relationships (Source: National Academies 2021)](image)
Figure E-6: $\text{FS}_{\text{liquefaction}}$ versus depth for different Cyclic Resistance Ratio relationships (for a site having a fines content of 5%, and with $N_{60} = 10$, $q_c = 5$ MPa, earthquake $M = 7.5$, and $a_{max} = 0.1$ g) using: (a) standard penetration test-based methods; (b) cone penetration test-based methods (Source: National Academies 202)
E4: THE TWO-CLUSTER PROBABILISTIC METHOD FOR CALCULATING CYCLIC STRESS RATIO UNIQUE TO BC

FULLY PROBABILISTIC LIQUEFACTION HAZARD ANALYSES

For project-specific research works, a fully probabilistic approach that includes uncertainties in the earthquake Ground Shaking, the CRR of the Soil, and the different empirical Liquefaction triggering models is used for Liquefaction Hazard analysis. This is because evaluation of Liquefaction Hazards based on just one Seismic Hazard level (e.g., 1/2475 return period), as is common in current geotechnical engineering practice, provides an incomplete measure of actual Hazards. Where deterministic Liquefaction Hazard analysis can only provide $F_{\text{liquefaction}}$ associated with the specific level of ground motions, probabilistic Liquefaction Hazard analyses can directly predict the return periods of the $F_{\text{liquefaction}}$ levels themselves.

Fully probabilistic procedures for evaluating Liquefaction Hazard have been developed since 2003 (Marrone et al. 2003). Kramer and Mayfield (2007) and others described a probabilistic analysis procedure in a performance-based design framework for evaluating Liquefaction Hazard. This approach generates $F_{\text{liquefaction}}$ Hazard curves that account for all $a_{\text{max}}$ levels and all earthquake magnitudes that contribute to the $a_{\text{max}}$. Kramer and Mayfield (2007) showed that application of conventional Liquefaction Hazard evaluation procedures produced very different Liquefaction Hazards at the same sites, with the return period of Liquefaction varying by a factor of two or more.

The fully probabilistic method (Kramer and Mayfield 2007) for generating SM Maps employs the use of advanced computational methods for its implementation and may not be suitable for all SM Mapping Projects, due to time and budget constraints.

Where the fully probabilistic method is not a viable approach, Mapping Professionals should use the two-cluster probabilistic method outlined in the section below to calculate the CSR.

TWO-CLUSTER PROBABILISTIC METHOD UNIQUE TO BRITISH COLUMBIA SEISMIC ZONES FOR CALCULATING CYCLIC STRESS RATIO

Due to the large difference in the MSF between the interface earthquakes (M9) and the non-interface earthquakes (M7) in BC, the seismic source zones are grouped into two clusters, the M7-cluster and the M9-cluster, as shown in Figure E-7.

In the two-cluster probabilistic method proposed by Wu (2017, 2018, 2021), CSR Hazard curves are calculated for each cluster by the conventional method used by geotechnical engineers in BC prior to 2015 (i.e., before the GSC Hazard model included the M9-cluster of earthquakes). This two-cluster probabilistic method provides a practical approach to combining seismic Liquefaction Hazard using the Hazard values for crustal, in-slab, and interface sources published by Halchuk et al. (2016) and by GSC (Kolaj et al. 2020). When applying the two-cluster probabilistic method, the calculation of CSR is done for multiple probability levels of ground motions.
The two-cluster probabilistic method to construct CSR Hazard curves is comprised of the following steps:

Step A: Calculation of response spectra for annual exceedance probability (AEP) of 0.0004–0.0001 Ground Motions.

1. Transfer the OpenQuake input files of the GSC 2020 seismic source characterization model into two new files (to create two separate earthquake source zones, one for the M7-cluster and the other one for the M9-cluster) so that the response spectra from the Cascadia interface earthquakes are obtained separately from the non-interface earthquakes.

2. Run OpenQuake using the new input files and obtain the Seismic Hazard curves (AEP versus Sa) at all periods interest (e.g., PGA 0.1 s, 0.2 s, 0.3 s, 0.5 s, 1 s, 2 s, 5 s, 10 s) and the location of interest (e.g., 123.10W, 49.17N for the example presented below) for the interface earthquake sources (the M9-cluster).

3. Repeat the above step to obtain the Seismic Hazard curves for the non-interface earthquake sources (M7-cluster).

4. The AEP values in the calculation of Seismic Hazard curves should contain a minimum of 0.0004, 0.00035, 0.0003, 0.00025, 0.0002, 0.00015, and 0.0001; however, more points may be used to increase the accuracy.

Step B: Calculation of CSR.

1. Calculate the CSR value at all AEPs using Formula E-1 for the M7-cluster and M9-cluster. In the example below using the simplified procedure, only the PGA values are required as input in this step. However, when the SSRA method is adopted, the spectral accelerations (Sa) for all periods are needed for developing the input ground motion time histories.

2. Construct a CSR Hazard curve using the CSR values at all AEPs for each of the M7- and M9-clusters. Then, construct the all-source CSR Hazard curve from all earthquakes by adding the curves from the M7-cluster and M9-cluster at each CSR.
AN EXAMPLE

The above procedure for probabilistic calculation of CSR is shown in Table E-2 and Figure E-8. The PGA values in Table E-2 are calculated for the 6th generation Seismic Hazard model, which are performed using OpenQuake (version 3.0) (GEM 2008) and the input files distributed with Open File 8630 (Kolaj et al. 2020). The input files were modified (Wu 2022) to create separate earthquake source zones for the M7- and M9-clusters. As shown in Part A of Figure E-8, combining the two PGA Hazard curves for the M7- and M9-clusters gives an all-source PGA value of 0.48 g for the 1/2475 return period. This PGA value agrees well with 0.475 g that would be calculated from the NBC 2020 Seismic Hazard Tool (NRC 2021).

Using the simplified procedure for the calculation of CSR described above, the CSRm7.5 Hazard curves for the M7- and M9-clusters are calculated, using MSF = 1.22 for M7 and MSF = 0.55 for M9 (see comments on MSF in Appendix E2: Information for the Calculation of Cyclic Ratio. As shown in Part B of Figure E-8, an all-source CSRm7.5 Hazard curve is obtained by combining the two CSRm7.5 Hazard curves. Then, reading off the all-source curve, an all-source CSRm7.5 value of 0.52 is obtained for the 1/2475 return period. The M9-cluster contribution to the all-source CSRm7.5 at the 1/2475 return period is larger than the M7-cluster. Using CSRm7.5 from the M7-cluster alone or the M9-cluster alone would severely underestimate the seismic demand (CSRm7.5) and, ultimately, the Liquefaction Hazard at this site in Metro Vancouver.

The finalization of CSR calculations should include determination of CSR Hazard curves that properly consider Seismic Hazard contributions from the crustal, in-slab, and interface earthquake sources.

**Table E-2: Example Probabilistic Calculations of Cyclic Stress Ratio (CSRm7.5) at Depth of 5 m for Richmond Site #81 (123.10W 49.17N) (V_{S30} = 450 m/s, Water Table at 1.0 m Depth, Soil Unit Weight [γ] of 19.6 kN/m^3) (source: Wu 2022)**

<table>
<thead>
<tr>
<th>AEP(1) FOR M7(3)</th>
<th>PGA(2)(G) FOR M7</th>
<th>CSRm7.5 FOR M7</th>
<th>AEP(1) FOR M9(4)</th>
<th>PGA(2)(G) FOR M9</th>
<th>CSRm7.5 FOR M9</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000040</td>
<td>0.457</td>
<td>0.3920</td>
<td>0.000040</td>
<td>0.204</td>
<td>0.3874</td>
</tr>
<tr>
<td>0.000035</td>
<td>0.480</td>
<td>0.4115</td>
<td>0.000035</td>
<td>0.218</td>
<td>0.4147</td>
</tr>
<tr>
<td>0.000030</td>
<td>0.507</td>
<td>0.4352</td>
<td>0.000030</td>
<td>0.235</td>
<td>0.4462</td>
</tr>
<tr>
<td>0.000025</td>
<td>0.540</td>
<td>0.4630</td>
<td>0.000025</td>
<td>0.256</td>
<td>0.4866</td>
</tr>
<tr>
<td>0.000020</td>
<td>0.581</td>
<td>0.4985</td>
<td>0.000020</td>
<td>0.282</td>
<td>0.5366</td>
</tr>
<tr>
<td>0.000015</td>
<td>0.640</td>
<td>0.5484</td>
<td>0.000010</td>
<td>0.373</td>
<td>0.7097</td>
</tr>
</tbody>
</table>

**Notes:**

1. AEP is the annual exceedance probability;
2. PGA is the peak horizontal ground acceleration (i.e., amax used in the simplified procedure for calculation of CSR);
3. M7 is for crustal and in-slab earthquakes; and
4. M9 is for interface earthquakes.
Figure E-8: Example two-cluster probabilistic calculations for Richmond site #81 (123.10W 49.17N): (a) peak ground acceleration Hazard curves; (b) $\text{CSR}_{M7.5}$ Hazard curves (source: Wu 2022)
E5: Calculation of Cyclic Stress Ratio From a Seismic Site Response Analysis

It is appropriate to use an SSRA to estimate CSR if the \( r_g \) factors used in the development of the CRR curve are unbiased relative to the values expected at liquefaction sites. Therefore, an SSRA should only be employed for the computation of the seismically-induced CSR in conjunction with the CRR relationships developed using the same methodology (National Academies 2021).

When using an SSRA, CSR at a depth is calculated using Formula E-4:

\[
CSR = 0.65 \frac{\tau_{cyc,\text{max}}}{\sigma_{v0}}
\]

where \( \tau_{cyc,\text{max}} \) is the maximum of cyclic shear stress amplitude and \( \tau_{cyc} \) at the depth calculated from the SSRA.

Seismic Site Response Analysis

An SSRA should be performed with the following considerations:

- Use a 1D Soil profile analysis for a level ground site or a 2D finite element dynamic analysis (for geometric effect) for a sloping-ground site (slopes at steeper than 5H:1V).

- Include reduction of shear modulus from \( G_{\text{max}} \) and increase of Soil material damping as shear strains increase, where \( G_{\text{max}} = \rho V_s^2 \) and \( \rho \) is the Soil density. Note that the reduction of Soil shear modulus (stiffness) with increasing shear strains is more significant for gravels than for sands, and more severe for sands than for clays. The hysteretic (or material) damping ratio is less than 5% at low levels of shear strain, but it increases with increasing strain levels. The maximum damping ratios are about 25% for gravels and sands, and in the order of 20% for clays and silts (Seed et al. 1986). The Soil nonlinear effect with increasing Ground Shaking should be considered (Seed et al. 1986), which could be carried out:
  - using the equivalent linear method (Idriss et al. 1974) in SHAKE (Schnabel et al. 1972) or in DEEPSOIL (Hashash et al. 2016);
  - using a nonlinear method (Finn et al. 1977) in DEEPSOIL or in VERSAT-1D (WGI 2021) for the simulation of hysteretic stress-strain loops of Soils under cyclic loadings. A nonlinear analysis is considered more appropriate than the equivalent linear analysis when the Ground Shaking level is high (e.g., \( a_{\text{max}} > 0.4 \) g); or
  - when VERSAT-1D is used for a nonlinear SSRA, using a total stress approach without including the effect of seismically-induced pore water pressures on Soil stiffness and damping.

- Include an elastic base in the 1D Soil column and apply the input ground motions as outcropping motions. The \( V_s \) applied to the elastic base should be compatible with that used in developing the input ground motions. For example, firm-ground free-field motions developed for \( V_s \) of approximately 560 m/s would be applied to a Soil column having a \( V_s = 560 \) m/s in the ground immediately below the Soil column. A rigid base model should be used if the input ground motions are measured within the base of the model (e.g., the borehole motions measured by seismographs installed at 30 m below the ground surface). The motions should be applied in the model where they are measured on site.

- Use input ground motions developed separately for M9-cluster and M7-cluster, where applicable, with the following considerations (see also Appendix E4: The Two-Cluster Probabilistic Method for Calculating Cyclic Stress Ratio Unique to BC.
  - Calculation of Seismic Hazard values (PGA and \( S_a \) at various periods) for the M9-cluster and M7-cluster using the GSC Seismic...
Hazard model (Kolaj et al. 2020) and \( V_s \) of the elastic base.

- Development of the M9 and M7 input ground motions corresponding to the Seismic Hazard values for M9-cluster and for M7-cluster, respectively.

- Use of a total of 7-11 earthquake ground motion records for the M9-cluster.

- Use of a total of 7-11 earthquake ground motion records for the M7-cluster.

When developing the input ground motions for an SSRA as part of an SM Mapping Project, for a Seismic Hazard level of 1/2475 return period for high seismic zones, Mapping Professionals should consider using the 1/5000 return period response spectra for the M9 interface earthquakes and the 1/5000 return period response spectra for the M7 non-interface earthquakes according to the work by Wu (2021).
https://ascelibrary.org/doi/10.1061/%28ASCE%291090-0241.82009-3A11%282016%29%20resistance%20curves%20were%20established,Dobry. 10 pp.


https://repository.lib.ncsu.edu/server/api/core/bitstreams/d9124cd1-53e4-4ea3-9870-b3f017759170/content. 8 pp.


