Regional-scale Seismic Hazard Mapping of Metro Vancouver, British Columbia

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ICLR Friday Forum

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Seismic Hazards

Primary seismic hazard is propagation of seismic waves and resulting ground shaking

Secondary seismic hazards result from source (fault) rupture and ground shaking including coseismic uplift or subsidence, ground deformations, tsunami, etc.

Three seismic hazards are commonly addressed by Microzonation Mapping

1. **Shaking** hazard (shaking amplitude de/amplification relative to a reference ground condition)
2. Seismic-induced **Liquefaction** Hazard
3. Seismic-induced **Landslide** Hazard

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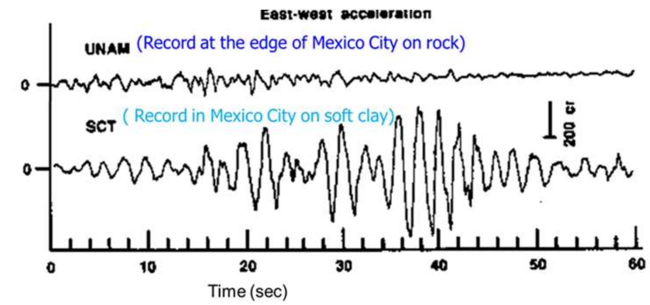
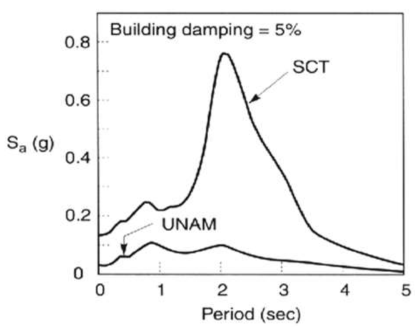
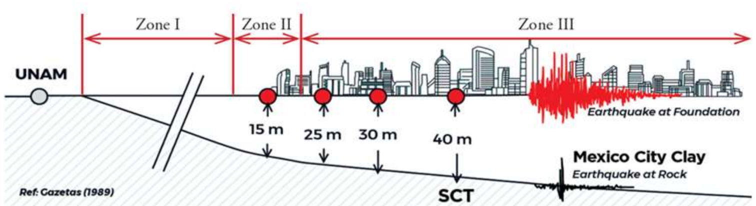
Seismic Hazard: Ground Motions or Shaking



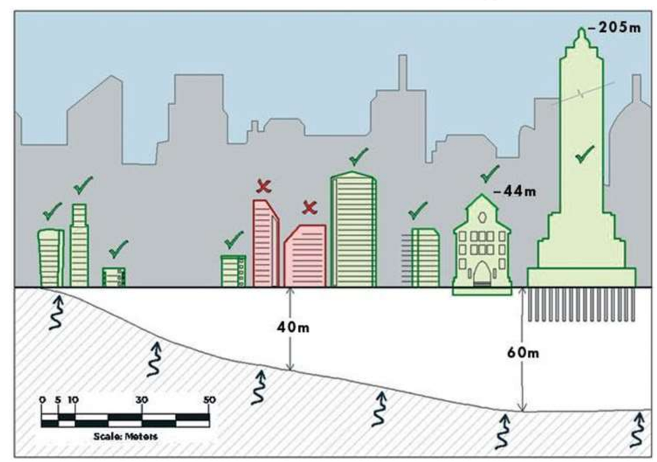




Ground shaking of the 1985 magnitude 8.0 Michoacan earthquake was amplified by soft clays under Mexico City.

Shaking amplitude was **5 times higher** on soft clay sites than rock sites at **2 second period**.

Led to collapse of 412 mid-height buildings (8-18 storeys) with a corresponding 2 second period.



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Seismic Hazard: Liquefaction

Liquefaction occurs when pore fluid pressures in a saturated granular soil increases and separates soil particles (lose contact with each other, lose shear strength) resulting in the soil behaving like a liquid.

2011 M 6.2 Christchurch, NZ earthquake

Liquefaction manifests or appears as:

- Sand boiling
- Ground cracking
- Ground settlement
- Lateral spreading
- Flow slides

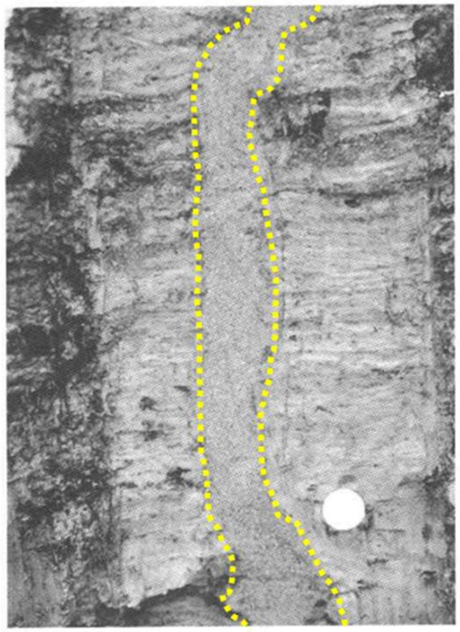

FIG. 13. Typical, steeply dipping sand dyke at site 1. The dyke cuts sharply through unit 1 mud. Coin is 24 mm in diameter.

- **12 paleo-liquefaction sites** in Metro Vancouver (Clague et al. 1992, 1997, 1998)
- 30-60% probability of liquefaction for a M8.9^{+} Cascadia interface earthquake *(Javanbakht et al. 2023)*

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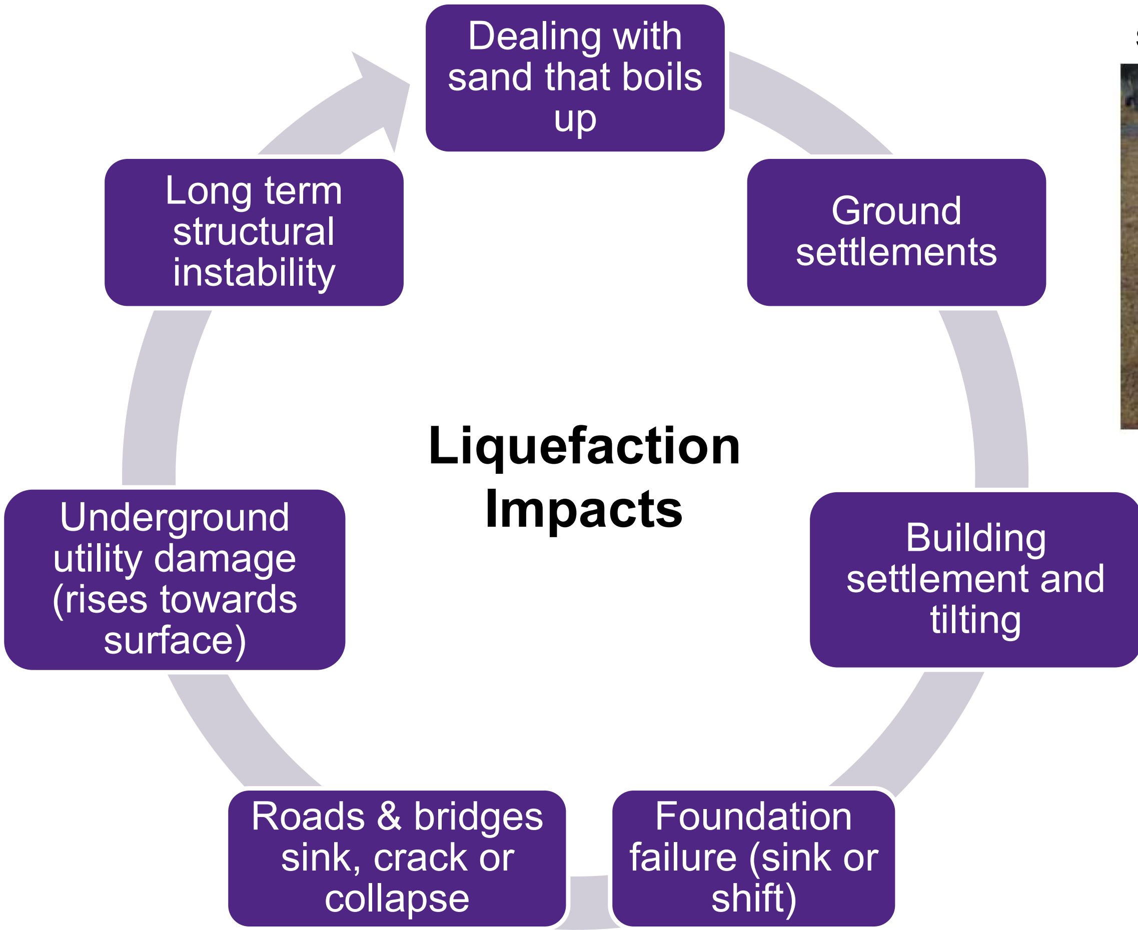

Sand boils, Nisqually wildlife refuge

Lateral spread, Capitol Lake

Examples of liquefaction effects that developed within minutes to hours after the 2001 M 6.8 Nisqually, Washington earthquake

Seismic Hazard: Landslides

Landslide is the movement of a mass of rock, debris, or earth (soil) down a slope.

"Landslide" is a general term.

- (Rock) Fall
- (Rock) Topple
- (Earth) Slide
- (Earth) Spread
- (Earth) Slump
- (Debris) Flow

- "Numerous" landslides on Vancouver Island following the 1946 M7.3 earthquake

The slide zone just below Landslide Lake from 1954 with Mount Colonel Foster above
(Patrick Guilbride photo)

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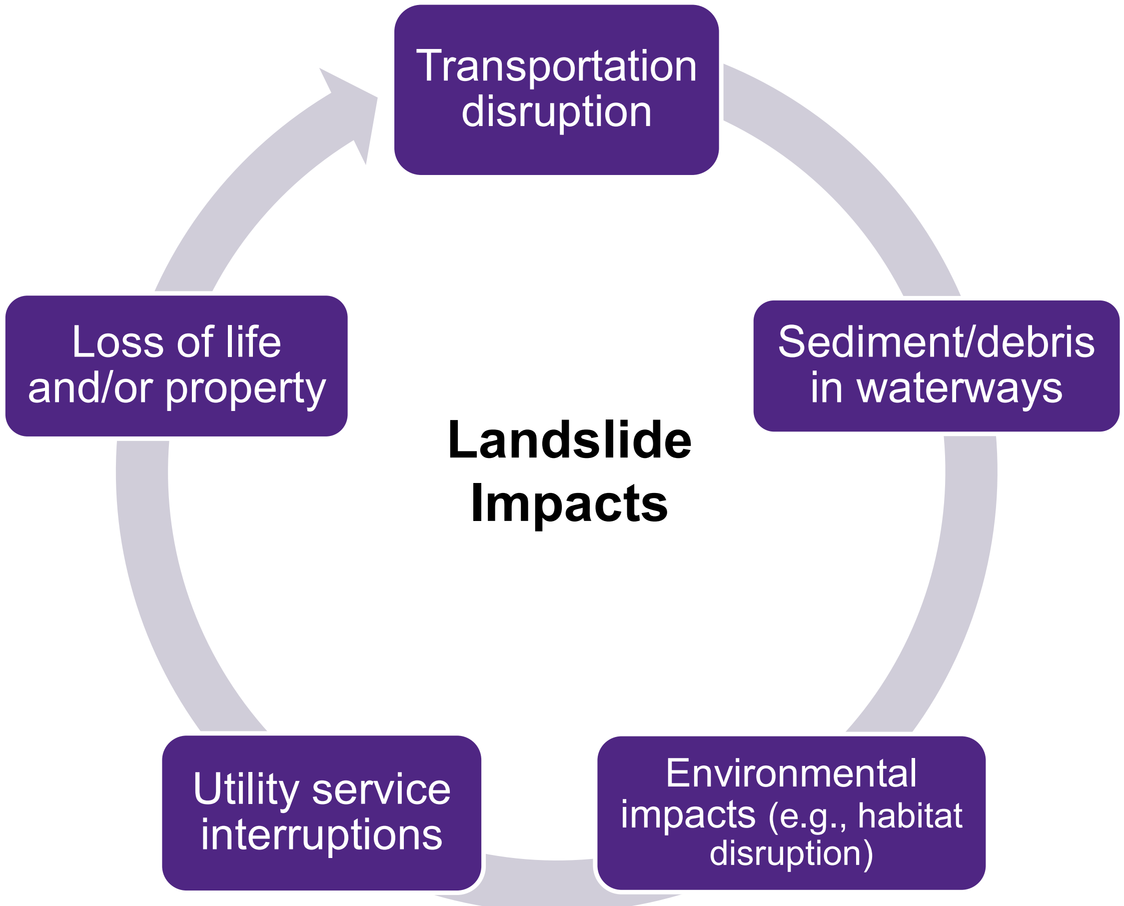

Earth Embankment Slide, Martin Way

Failed retaining wall, Hwy 101/Tumwater

Examples of landslide effects that developed within minutes to hours after the 2001 M 6.8 Nisqually, Washington earthquake

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Introducing the Project

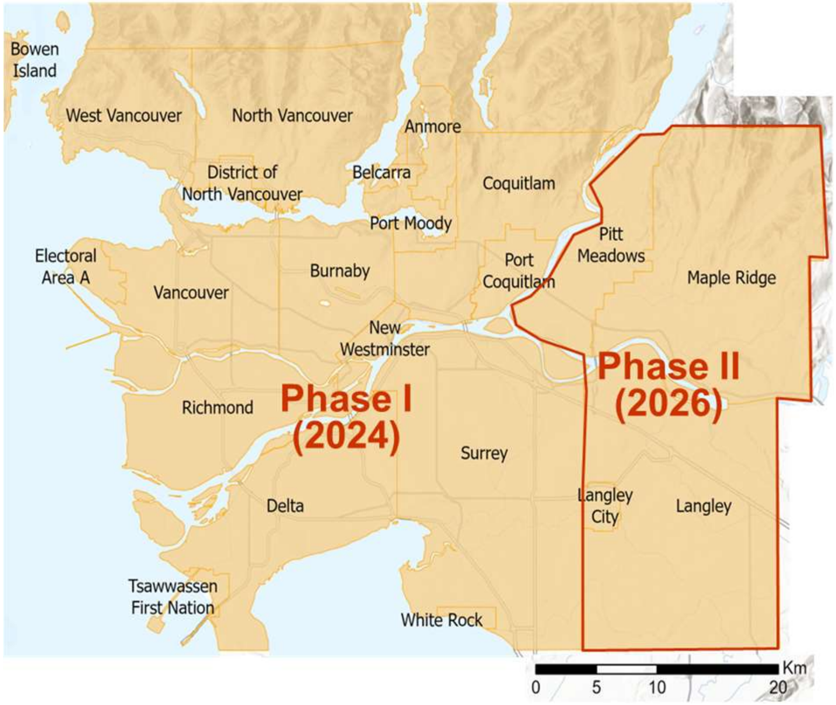
Metro Vancouver Seismic Microzonation Mapping Project (MVSMMP)

The MVSMMP is a multi-year research project to generate a suite of **region-specific seismic hazard maps**

Seismic microzonation maps display predicted variation in earthquake hazards due to local site conditions

The MVSMMP is led by the University of Western Ontario in collaboration with the Institute of Catastrophic Loss Reduction (ICLR) and with support from the British Columbia Ministry of Emergency Management and Climate Readiness (EMCR).

20 local gov'ts, 10 First Nation communities, 1 electoral area



and First Nation communities of the Katzie, Kwantlen, Kwikwetlem, Matsqui, Musqueam, Squamish, Semiahmoo, and Tsleil-Waututh

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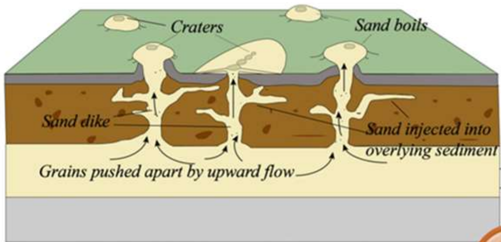
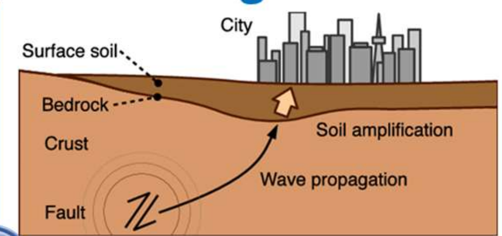
Liquefaction Hazard Potential

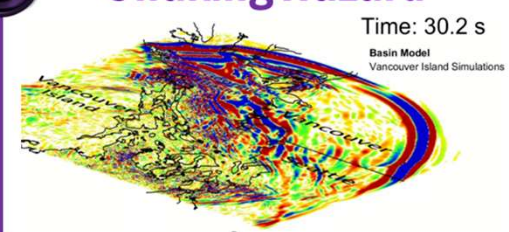


1D Soil Shaking Hazard



Landslide Hazard Potential

3D Basin Shaking Hazard



Why does Metro Vancouver need region-specific seismic hazard maps?

Metro Vancouver has the highest seismic risk in Canada

Level 3 Seismic Microzonation Maps

- Supersede Existing Level 1 and 2 SMMs of Local Communities
- Comprehensive and Equitable Regional Geodata
- Consistent State-of-the-Art Seismic Hazard Analyses
- Standardized Approach to SMM

Complex regional seismic hazard

- Cascadia (mega-thrust) interface fault earthquakes
- Deeper JdF plate inslab earthquakes
- Shallower NA plate crustal earthquakes

Paleo-liquefaction evidence but no strong earthquake recordings

Highly variable seismic site conditions

- Unconsolidated to glaciated sediments, Two rock types
- Elevations from 0 to over 1000 meters
- Max. depth to rock = 800 meters
- Basin within a Basin

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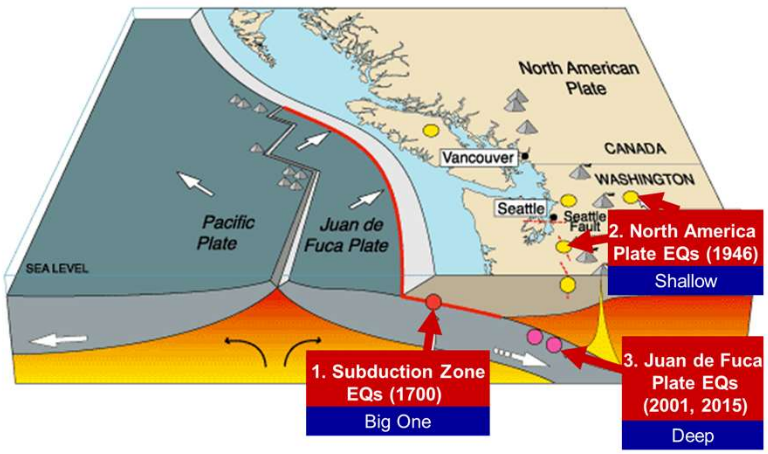
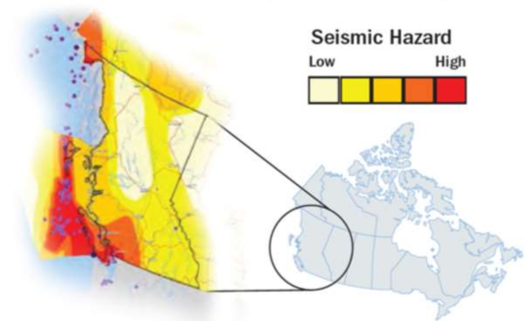


90% of **earthquakes** occur along active plate boundaries.
60% of Canada's earthquakes occur along BC's coast.



Source: Earthquakes Canada

Complex regional seismic hazard

- Cascadia (mega-thrust) interface fault earthquakes
- Deeper JdF plate inslab earthquakes
- Shallower NA plate crustal earthquakes

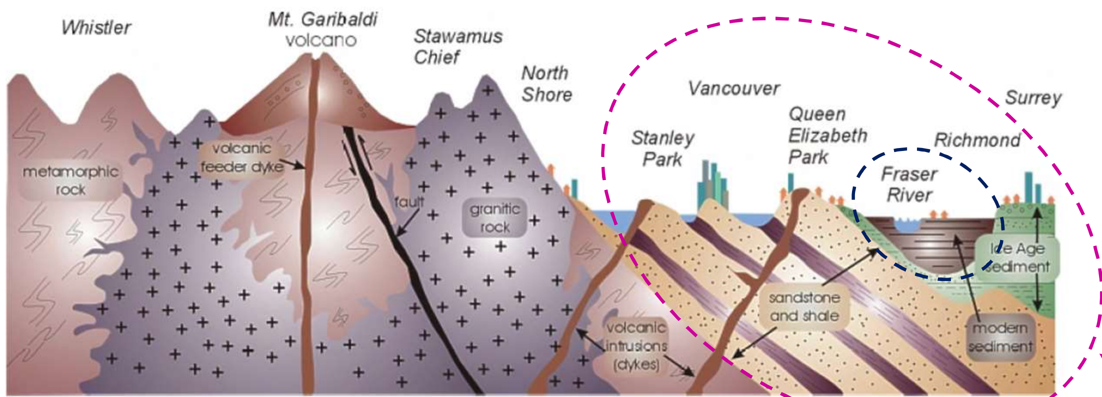
Regional seismic shaking ≈ earthquake occurrence rates

Average 475 year return period
10% probability of exceedance in 50 years
0.21% annual probability of exceedance

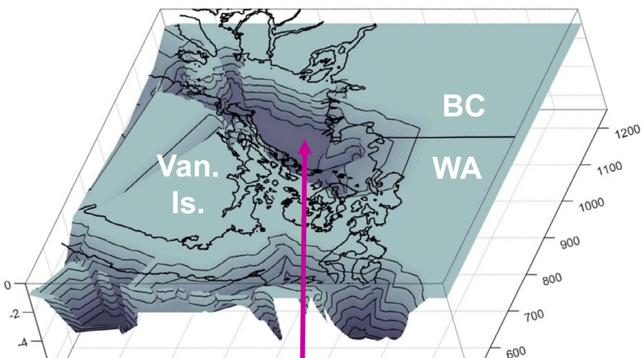
Average 2,475 year return period
2% probability of exceedance in 50 years
0.04% annual probability of exceedance

	475 year		2,475 year
Short period (PGA):	**0.19 g**	**2x**	**0.38 g**
Long period (2.0 s):	**0.07 g**	**2.5x**	**0.19 g**

for Vancouver City Hall (760 m/s)



Cartoon cross-section of the Earth below the Vancouver area showing the major rock types and the nature of their contacts.
https://www.cgenarchive.org/vancouver-rocks.html



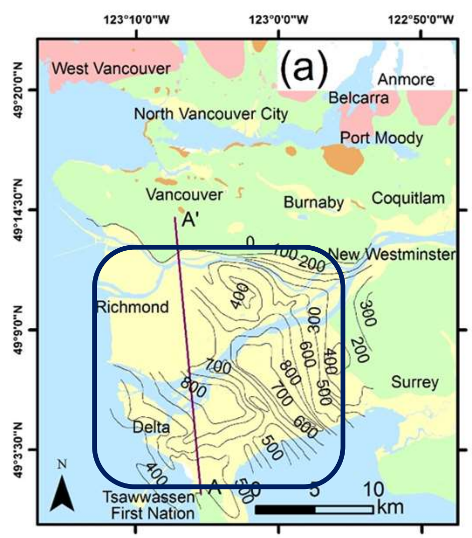
Georgia basin

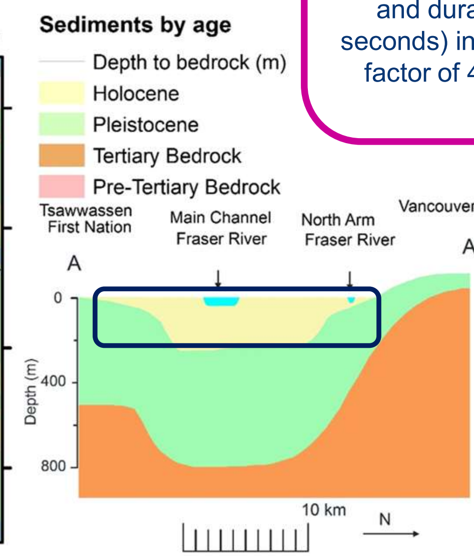
Late-Cretaceous sedimentary rock basin

Presence of the Georgia basin sedimentary rock basin increases the amplitude (intensity) and duration of long-period shaking (> 2 seconds) in Greater Vancouver by an average factor of 4 and 22 seconds longer shaking (Molnar et al. 2014).

Highly variable seismic site conditions

- Unconsolidated to glaciated sediments, Two rock types
- Elevations from 0 to over 1000 meters
- Max. depth to rock = 800 meters
- **Basin within a Basin**





Fraser River delta

Holocene deltaic basin

Soft sediments amplify earthquake shaking. Nonlinear soil response during strong shaking will lead to deamplification. Saturated sands may liquefy during strong shaking.

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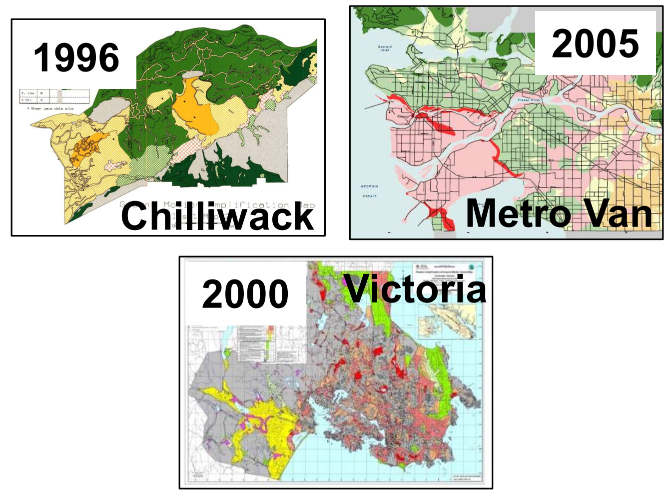
What are seismic microzonation maps?

Effects of earthquake shaking are not uniform due to variation in local site conditions

Seismic microzonation is the process of subdividing a seismically prone region into zones of similar {insert type of seismic hazard here}.

Seismic microzonation maps display predicted variation in earthquake hazards due to local site conditions.
Microzonation maps typically accomplished at urban or region scale



Previous SMM in southwest BC led by Vic Levson (BCGS) and Pat Monahan

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What are seismic microzonation maps?

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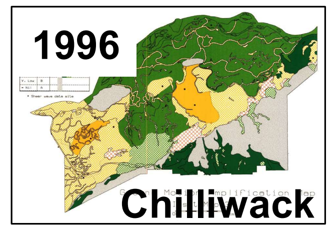
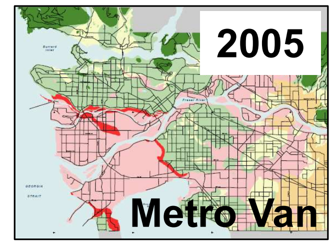
Microzonation maps typically accomplished at urban or region scale

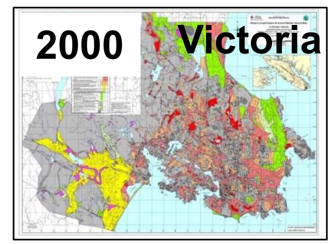
Maps offer a means to **communicate extensive and complex information** in a compact product and **play a critical role** in making this information **accessible to a variety of users**.

To produce seismic microzonation maps requires:

1. Subsurface geological, geophysical, geotechnical **data**
2. Sophisticated seismic hazard **analyses** and **numerical modelling**







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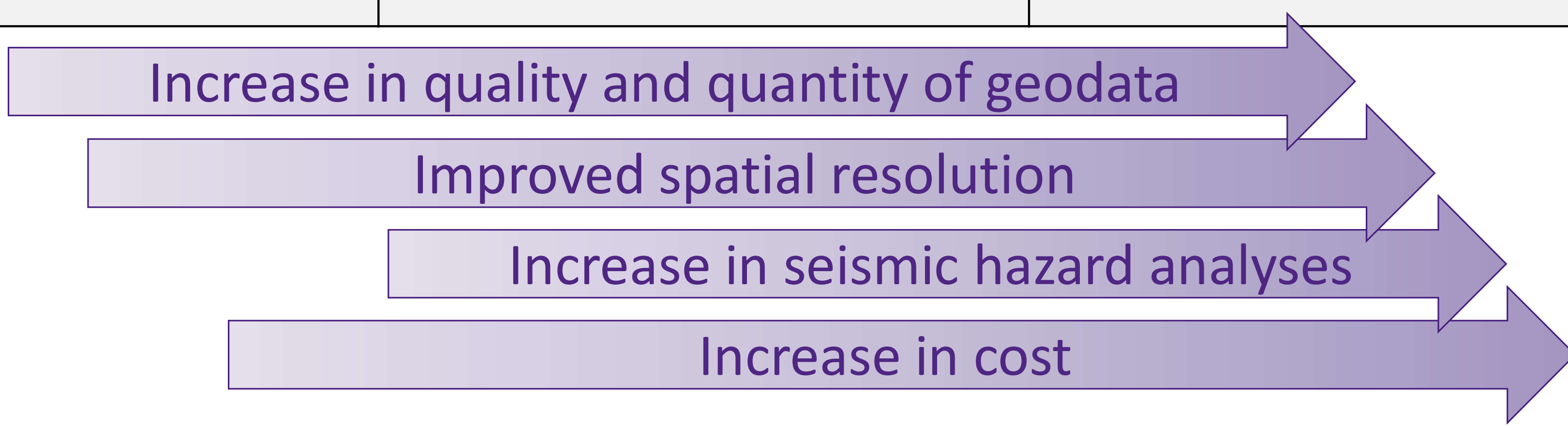
Levels of seismic microzonation mapping

Level 1	Level 2	Level 3
Susceptibility maps Surficial and remote sensing maps / spatial datasets. Remote sensing (topo) maps. Limited use of subsurface data.	**Susceptibility or Hazard Maps** Subsurface geological data and area-specific data on physical properties.	**Advanced analyses of Hazard** Extensive seismological and subsurface geological, geophysical and geotechnical data and simulations. Detailed subsurface maps and models.



Applications of Seismic Microzonation Mapping

A wide range of anticipated applications and end-users

- Technical experts:
  - **Earthquake engineering** professionals, stakeholders (**owners of critical or high consequence infrastructure**), and decision makers (**catastrophe modellers or risk analysts**)
  - Technical experts may utilize these map products as inputs to risk analysis to **inform disaster risk reduction, seismic design and retrofitting** or **improved understanding of regional variability** of potential earthquake ground motions for further detailed earthquake investigations and modelling.
- Intermediate users:
  - Decision makers (**emergency managers, land use planners, consultants, architects**) and other stakeholders (**re/insurers, building owners**);
  - May utilize these map products for **emergency response and recovery planning**, **land use planning** or **prioritizing seismic retrofit programs** (adaptation, mitigation, resilience, sustainability), or as inputs for **risk analysis**, **damage estimation**, or **loss calculations for the insurance industry**.
- Others:
  - **Educators to the general public** rely on the accurate communication of seismic hazard and risk information from both primary technical end users and intermediate non-technical end users to inform their personal decision-making (e.g., **developers, real estate agents, insurance agents, homeowners**).

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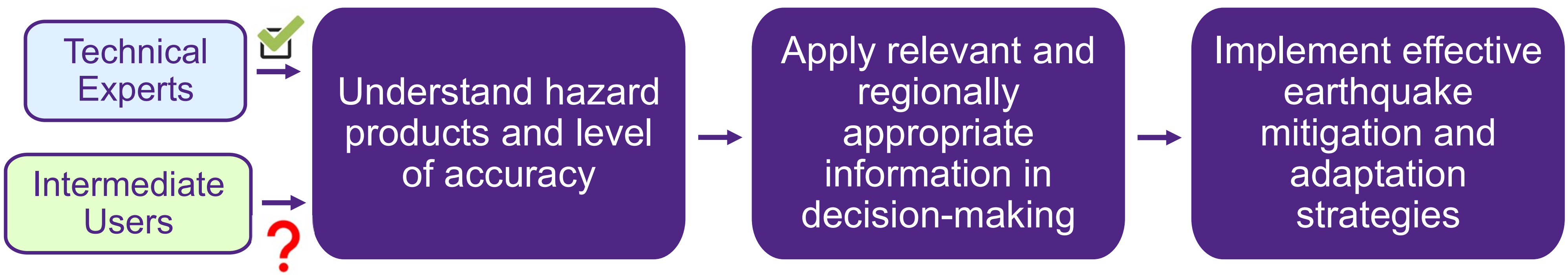
Applications of Seismic Microzonation Mapping

A wide range of anticipated applications and end-users

Seismic hazard and risk assessment *is one of the fields in which rigorous scientific work* ***can often be misinterpreted*** *if it is not translated to a proper language of the client or end-user because it* ***involves technical and non-technical (intermediate) users with very different backgrounds and expectations****.* *(Fyfe 2023)*



Fyfe (2023). Evaluation of Effectiveness in Seismic Microzonation Hazard Mapping in Canada: Communication, Use, Standardization and Levels, Western University, MSc Thesis, 9567.

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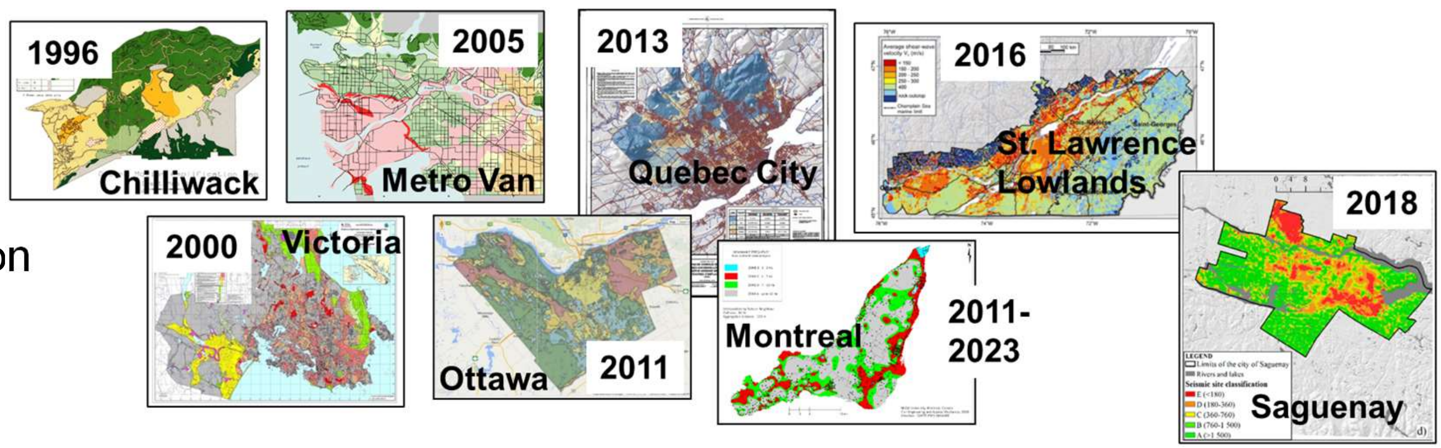
Some key facts about SMM in Canada

Hindrances to comprehension and use

1. There are no Canadian standards or guidelines for SMM
2. No existing SMMs in Canada are accessible in digital (GIS layer) form
3. Very few Level 3 SMM in Canada
   - All SMMs in Canada (12 regions) map seismic susceptibility (seismic site class, or Vs_{30} or site period).
   - Seismic-induced liquefaction or landslide hazard maps produced only for Victoria and Vancouver.

Little experience with access to (& use of) Level 3 SMMs in Canada

Regional Seismic Microzonation Maps



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Metro Vancouver Seismic Microzonation Mapping Project

Level 3 Seismic Microzonation Maps

- Supersede Existing Level 1 and 2 SMMs of Local Communities
- Comprehensive and Equitable Regional Geodata
- Consistent State-of-the-Art Seismic Hazard Analyses

How is this unique?

Level 3 maps are rare in Canada

Professional Practice

- Promote comprehension and use through professional practice standards

1. EGBC Technical Peer Review of project methodologies, analyses, and map outcomes
2. EGBC Professional Practice Guidelines *Development and Use of Seismic Microzonation Maps in British Columbia*

How is this unique?

There is no Canadian standard or guidelines for SMM

Communication and Engagement

- Promote comprehension and use through knowledge sharing

1. Include regular engagement opportunities **during** and after SMM project
2. Involve non-technical users in peer-review process

How is this unique?

Include opportunities for communication, consultation, and education

Multi-disciplinary and -experiential training leads to careers !

Multi-disciplinary
Geohazards,
Geology,
Seismology,
Geotechnical Engineering,
Geological Engineering,
Spatial Mapping

Multi-experiences
Practical experiences with month-long field campaigns, multi-method site investigations, state-of-the-art seismic hazard analyses, technical peer review, written and oral communication

~30 Individuals
Project Managers, Research Associates, Postdocs, PhD and MSc students, Undergrads, Research Assistants

Data Processing Manager (Expert Geophysics), **Exploration Geophysicist** (Fleet Space Technologies), **Geohazards Specialist** (AtkinsRealis), **Geotechnical Engineers** (GHD, Jacobs, WSP), **Geophysicists** (Municon West Coast, WSP), **Graduate GIS Technician** (Mott MacDonald), **Academic Researchers** (UWO), **Seismic Analyst** (Natural Resources Canada)

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List of MVSMMP Maps

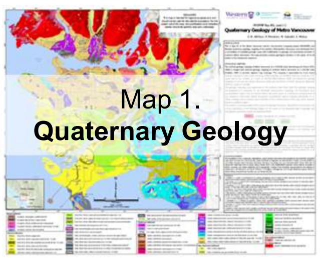
LEVEL 2

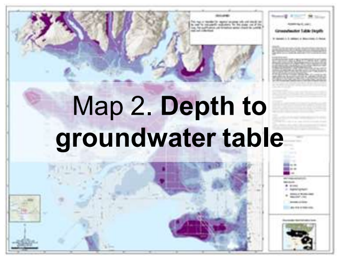
11 Maps!

All maps generated considering natural (non-engineered) ground conditions

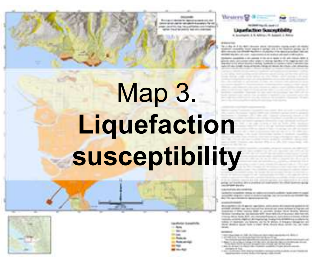
All map images shown are preliminary

Fundamental to many hazard types

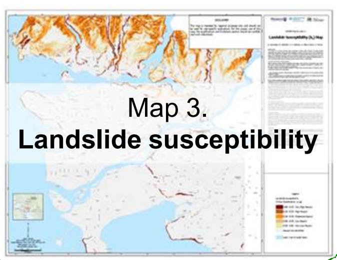




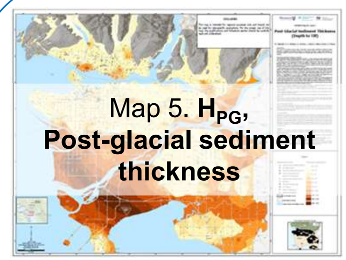
Liquefaction susceptibility

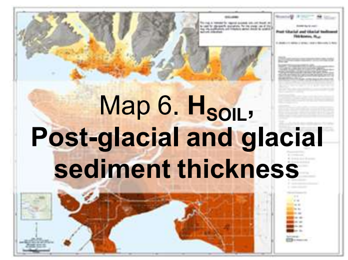


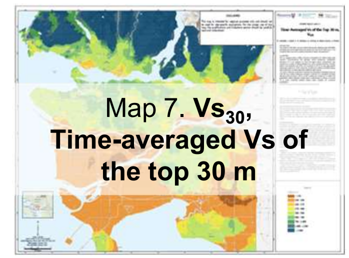
Landslide susceptibility

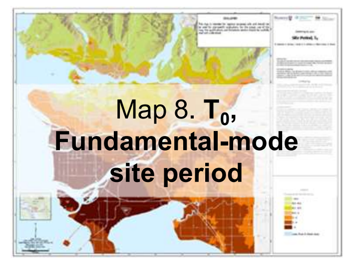


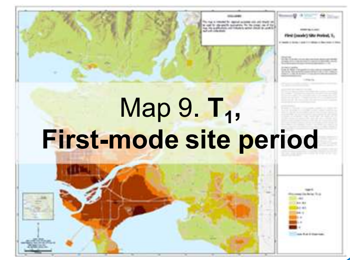
1D Soil Shaking Susceptibility



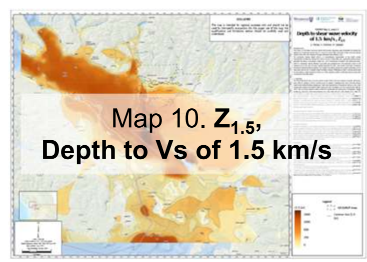


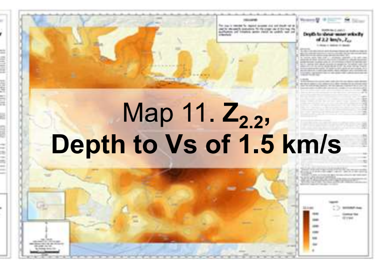






3D Georgia Basin Shaking Susceptibility





List of MVSMMP Maps

LEVEL 3

18 Maps!

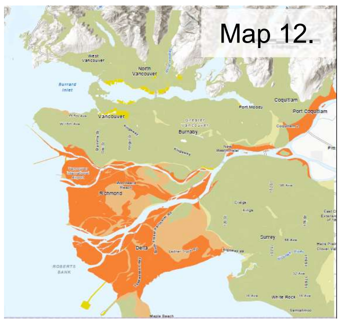
475 year return period
0.2% annual probability of exceedance

All map images shown are preliminary

*Maps are based on natural ground conditions only

Liquefaction Hazard Potential

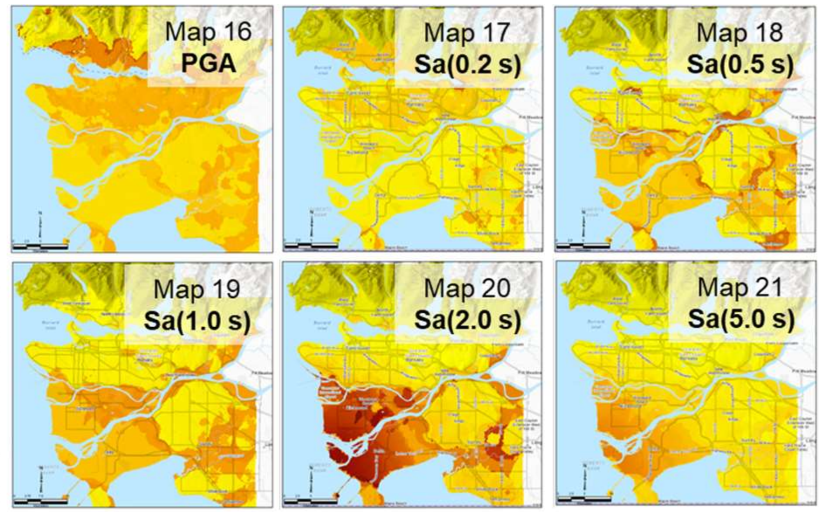
LPI_{ISH}	Liquefaction Hazard Potential
0-2	None to Very Low
2-5	Low
5-10	Moderate
10-15	High
15-25	Very high
> 25	Severe

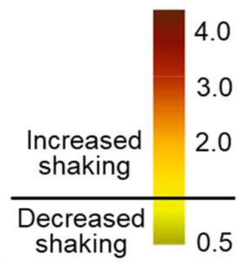


Landslide Hazard Potential

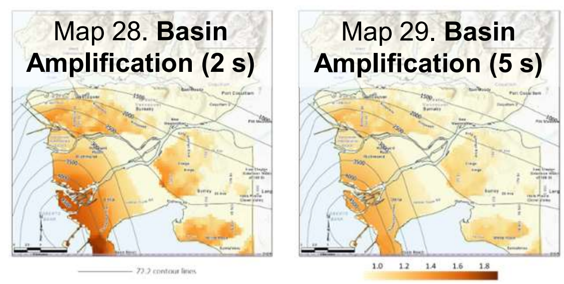
Sliding Disp. (cm)	Landslide Hazard Potential
< 1	Low
1-5	Moderate
5-15	High
> 15	Very High

1D Soil Shaking Hazard





3D Georgia Basin Shaking Hazard



List of MVSMMP Maps

18 Maps!

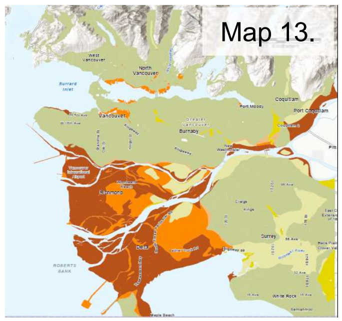
All map images shown are preliminary

2,475 year return period
0.04% annual probability of exceedance

*Maps are based on natural ground conditions only

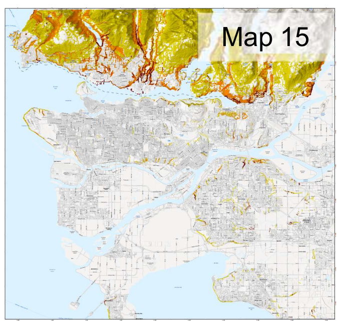
Liquefaction Hazard Potential

LPI_{ISH}	Liquefaction Hazard Potential
0-2	None to Very Low
2-5	Low
5-10	Moderate
10-15	High
15-25	Very high
> 25	Severe

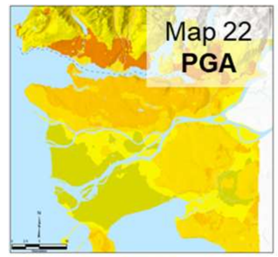


Landslide Hazard Potential

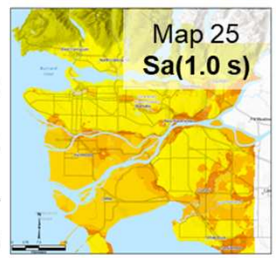
Sliding Disp. (cm)	Landslide Hazard Potential
< 1	Low
1-5	Moderate
5-15	High
> 15	Very High



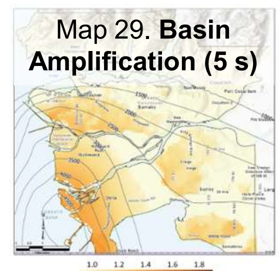
1D Soil Shaking Hazard



4.0
3.0
Increased shaking
2.0
Decreased shaking
0.5



3D Georgia Basin Shaking Hazard



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Outline

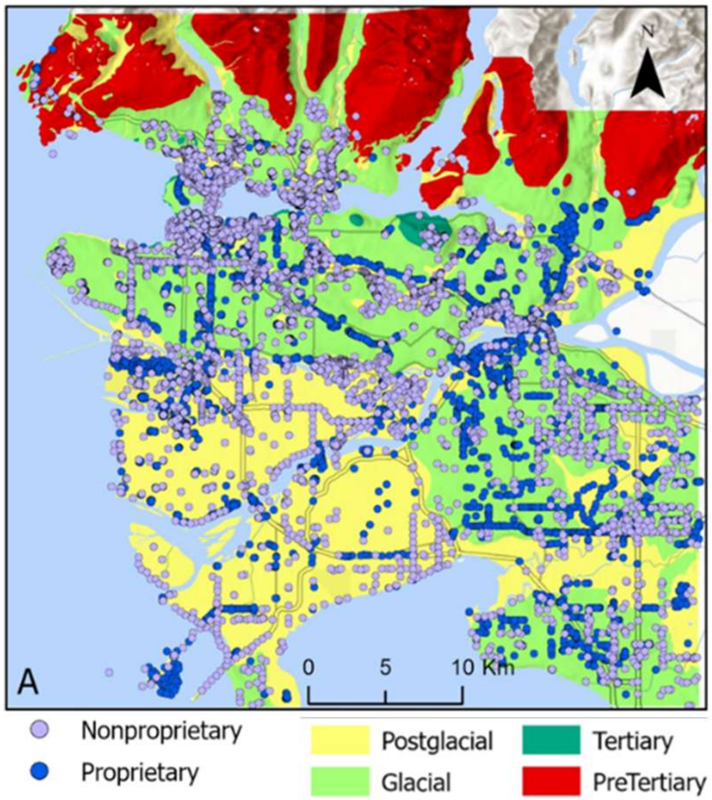
- Introduction to the Metro Vancouver SMM project
- Background on seismic microzonation mapping
- Key outcomes of the Metro Vancouver SMM project
- Achieving Level 3 seismic microzonation mapping
    1. Lots of Data
    2. Creating the 29 maps: shaking hazard, liquefaction hazard, and landslide hazard
    3. Engagement, Communication, Education, and Training
- EGBC Professional Practice Guidelines for *Development and Use of SMMs in British Columbia*
- Applications specific to the insurance industry
- How to access the project's maps and datsets

Comprehensive Regional Geodatabase

for Seismic Site Characterization, Development of Regional 3D Velocity Models, and Site-Specific Seismic Hazard Analyses

The MVSMM Project geodatabase consists of over 15,000 unique geodata locations

1. Non-Proprietary geodata was compiled from available online (open data) government sources
   - e.g., ~500 velocity depth profiles of the Geological Survey of Canada (Hunter et al. 1998, 2016)
2. Proprietary geodata compiled from 24 local governments, stakeholder groups, engineering firms, and geoconsultants via data sharing agreements when applicable
   - Primarily *in situ* invasive field testing data (S/CPT, downhole, SPT) and some geotechnical laboratory testing of samples



Molnar et al. 2020; Adhikari et al. 2021; Molnar et al. 2023; Adhikari, 2024

Comprehensive Regional Geodatabase

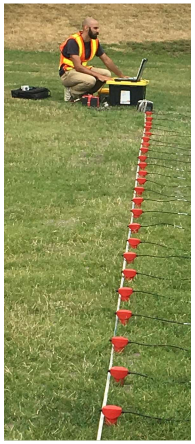
for Seismic Site Characterization, Development of Regional 3D Velocity Models, and Site-Specific Seismic Hazard Analyses

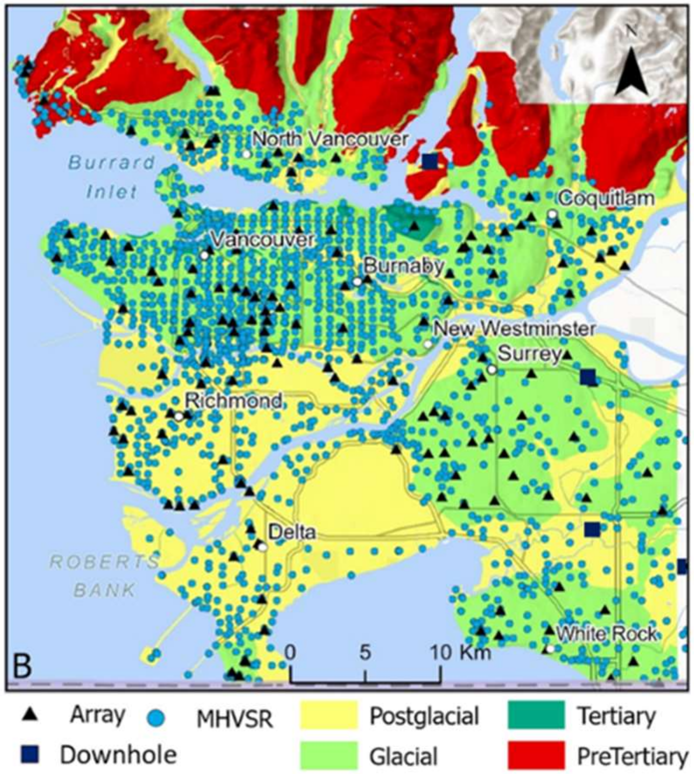
3. Multi-method *in situ* non-invasive seismic field testing approach over 5 field campaigns (2018-2022)

- Single-station microtremor horizontal to vertical spectral ratio (**MHVSR**) testing **over 2,300 locations** at an average ~800 meter spacing
- Combined active- and passive-source **surface wave array testing** (MASW and AVA) at **over 120 locations**
- Joint inversion of site peak frequencies and combined Rayleigh wave dispersion curve to obtain Vs depth profile model

- Cost effective for achieving spatial coverage and improved geodata equity across the region

Multiple invasive and non-invasive geodatasets are needed to measure the great variety of seismic site conditions





Molnar et al. 2020; Adhikari et al. 2021; Molnar et al. 2023; Adhikari, 2024

Achieving Level 3
Seismic Microzonation Mapping

Shaking Hazard Mapping

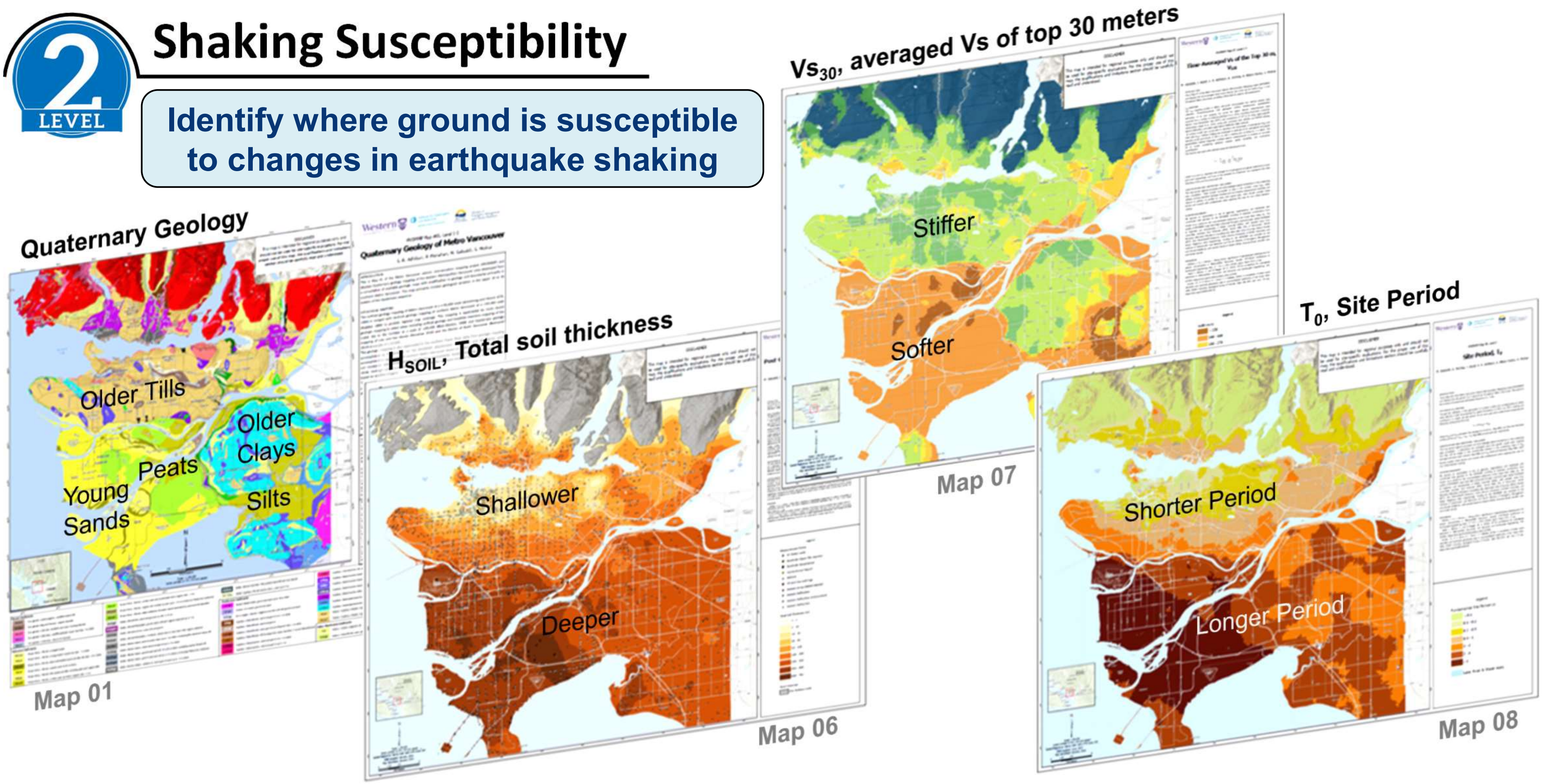
Earthquake shaking de/amplification inclusive of
1D site and 3D sedimentary basin effects

Assaf et al. (2022), Assaf (2022) PhD Thesis, Adhikari & Molnar (2023), Assaf et al. (2023a, b), Ghofrani et al. (2023), Adhikari (2024) PhD Thesis, Adhikari & Molnar (submitted), Adhikari et al. (submitted), Ojo et al. (submitted)

Shaking Susceptibility

2 LEVEL

Identify where ground is susceptible to changes in earthquake shaking

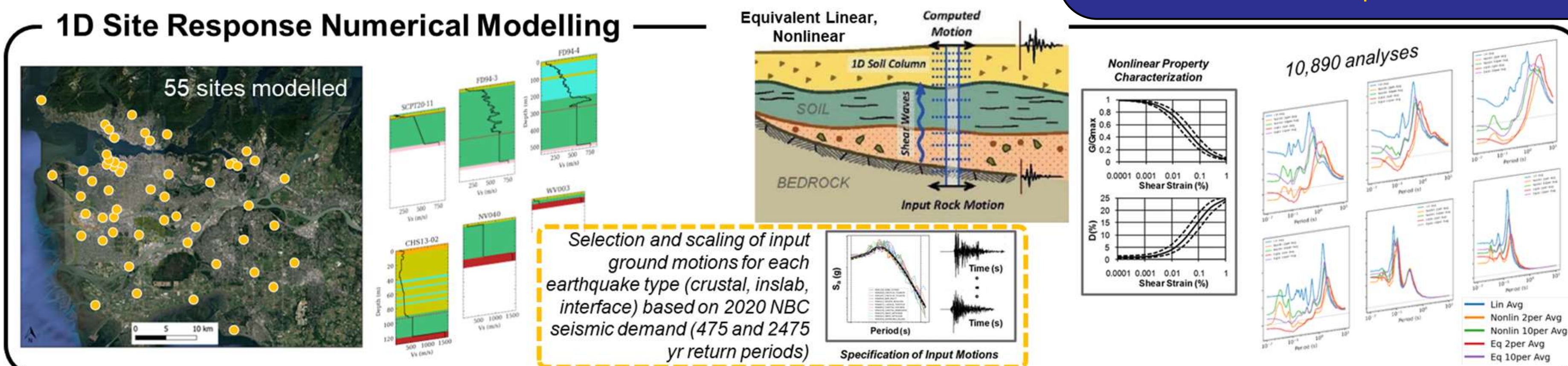


3 LEVEL — Shaking De/Amplification Hazard

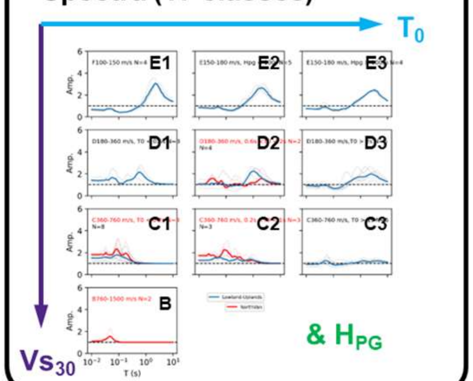
How much will the ground de/amplify earthquake shaking?

How much will the ground increase or decrease earthquake shaking given the regional seismic demand over a mean return period of 475 or 2475 years

1D Site Response Numerical Modelling

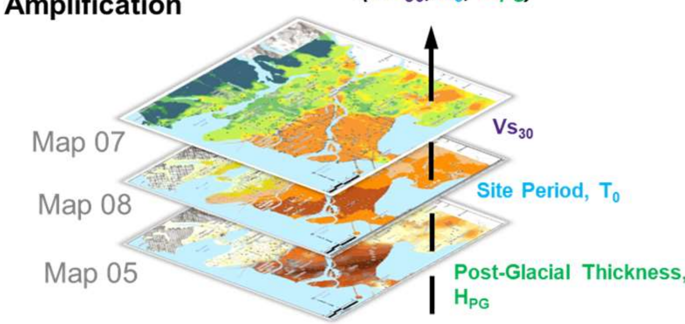


Grouping Amplification Spectra (17 classes)

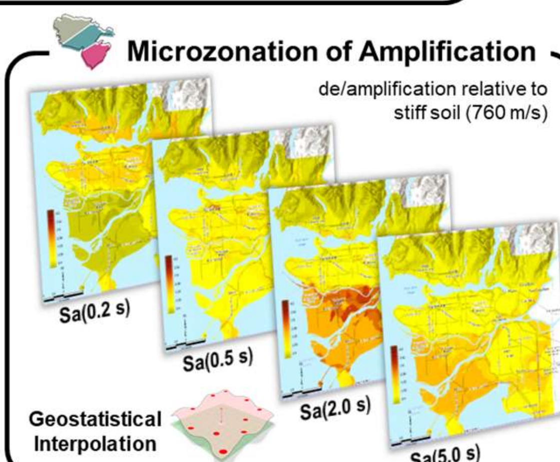


Regional Mapping of Amplification

$= f(Vs_{30}, T_0, H_{PG})$



Microzonation of Amplification



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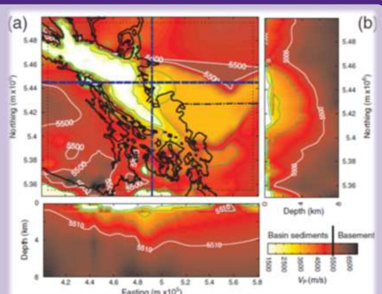
Plus… 3D sedimentary basin effects

- Presence of the deep and wide Georgia sedimentary basin affects long wavelengths and thereby shaking at long periods (> 2 sec) (*Molnar et al. 2014a, b; Ghofrani and Molnar 2019*)

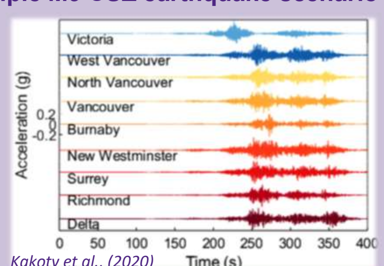
~6400 locations within Metro Vancouver
*8 crustal scenarios
*6 inslab scenarios
*32 interface scenarios
= ***320,000*** **synthetic ground motions**

3D Wave Propagation Numerical Modelling

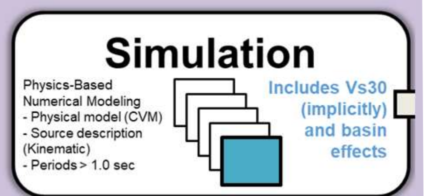
Physical structure (velocity) model of the Georgia basin

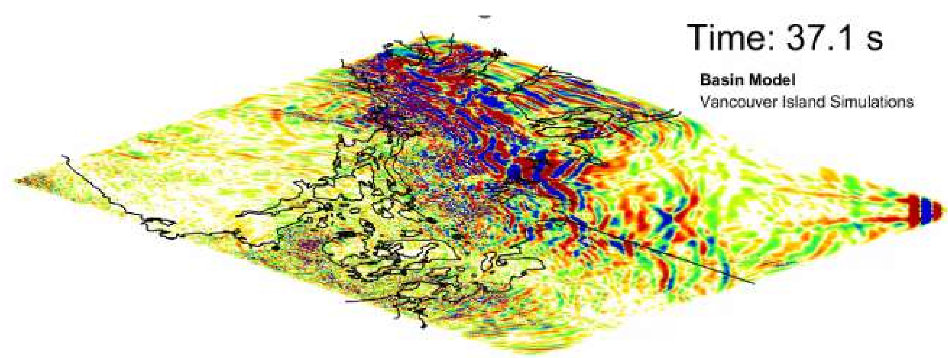


Sample M9 CSZ earthquake scenario



Kakoty et al., (2020)





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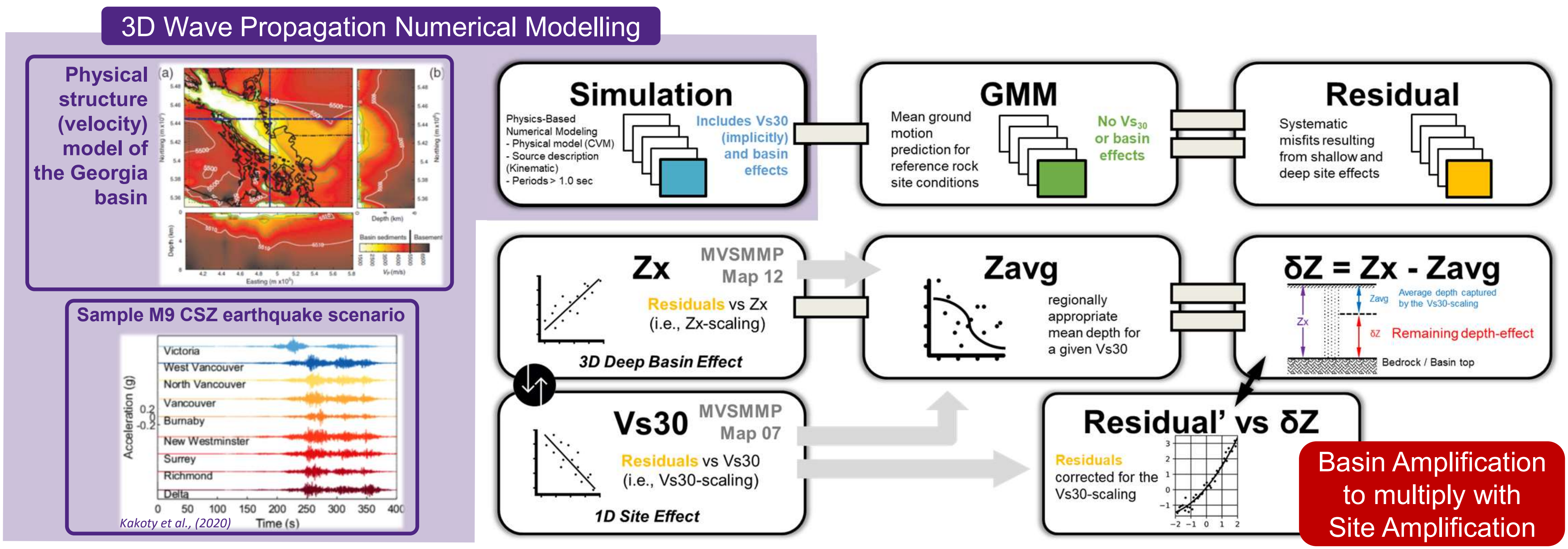
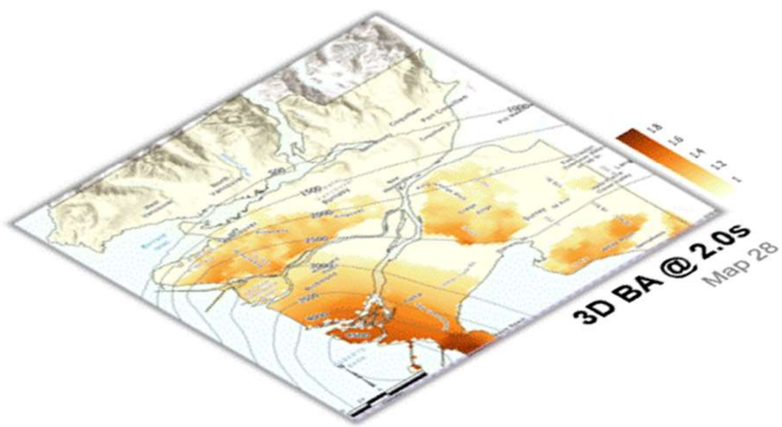
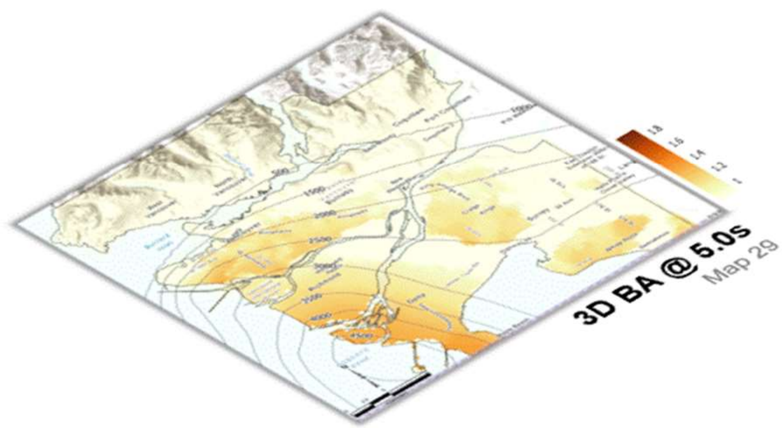


All map images shown are preliminary

Plus… 3D sedimentary basin effects





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3 LEVEL

Shaking De/Amplification Hazard

All map images shown are preliminary

[redacted]

10% Prob. Exceedance in 50 yrs, 475 yr return period

2% Prob. Exceedance in 50 yrs, 2475 yr return period

Achieving Level 3
Seismic Microzonation Mapping

Liquefaction Hazard Mapping

Javanbakht (2023) PhD Thesis, Javanbakht et al. (2022), Javanbakht et al. (2023a, b), Javanbakht et al. (submitted)

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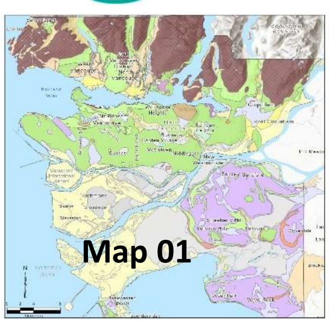
Liquefaction Hazard Mapping

Level 1	Level 2	Level 3

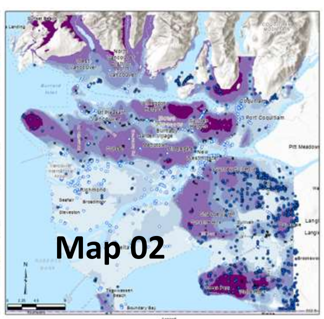
Identify if/where natural ground is susceptible to liquefaction

Considers the local soil resistance (how sandy, how saturated)

1 LEVEL — Qualitative Approach



Quaternary Geology



Groundwater Table Depth

Liquefaction Susceptibility Rating

FEMA-Hazus-MH5.1
Technical Manual (2022)

- Geologic Age
- Depositional Env.
- Material type
- Depth to GWT

(Youd & Perkins 1978)

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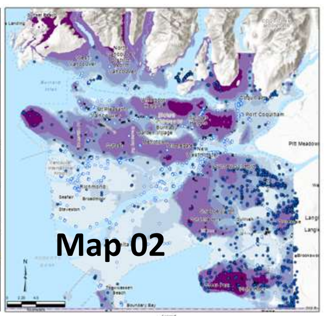
Liquefaction Susceptibility Mapping

LEVEL 1 Qualitative Approach

Quaternary Geology



GWT

Liquefaction Susceptibility Rating

FEMA-Hazus-MH5.1
Technical Manual (2022)

- Geologic Age
- Depositional Env.
- Material type
- Depth to GWT

LEVEL 2 Quantitative Data & Analyses

Measures of Soil Resistance from Regional Geodatabase

- SPT(z) and CPT(z) measurements with depth
- Thickness of liquefiable layers (H_{cr})
- Average cyclic resistance ratio (CRR)

Initial

Final

Table 1. Liquefaction susceptibility rankings for each mapped geologic unit

Units	Geological Age	Depositional Environment	Deposit and Material Type	Liquefaction Susceptibility (Y&P78)	Number of insitu data	Thickness average (m)	CRR average	Liquefaction Susceptibility (this study)
Recent Sedimets								
NG,An,f	< 500 yrs	Anthropogenic (An)	Undifferentiated fill (f) containing sand, gravel, till, crushed stone 1 to 10m thick	Very High	54	13.1	0.198	Very High
NG,BS,o	Holocene	Bog and Swamp (BS)	Undifferentiated organic (o) deposits, consists of fine sand slit and clay deposit in lakes	High	0	-	-	High
NG,C,Tl	Post last Glaciation	Colluvial (C)	Colluvial landslide (l) and mass-wasting deposits. Unconsolidated sediments. Rock fragments in a matrix of boulder, gravel, sand silt and minor clay	Moderate	0	-	-	Moderate
NG,C,T	Post last Glaciation	Colluvial (C)	Apron or talus (T) scree deposits, Rubble and block accumulation at the bottom of steep slopes 1 to 10 m thick	Moderate	0	-	-	Moderate
NG,C,u	Post last Glaciation	Colluvial (C)	Colluvium veneer (v) < 3m thick, Thin and discontinuous cover of slope wash material, containing matrix of boulders, gravel, sand, silt usually up to 3m thick	Moderate	0	-	-	Moderate

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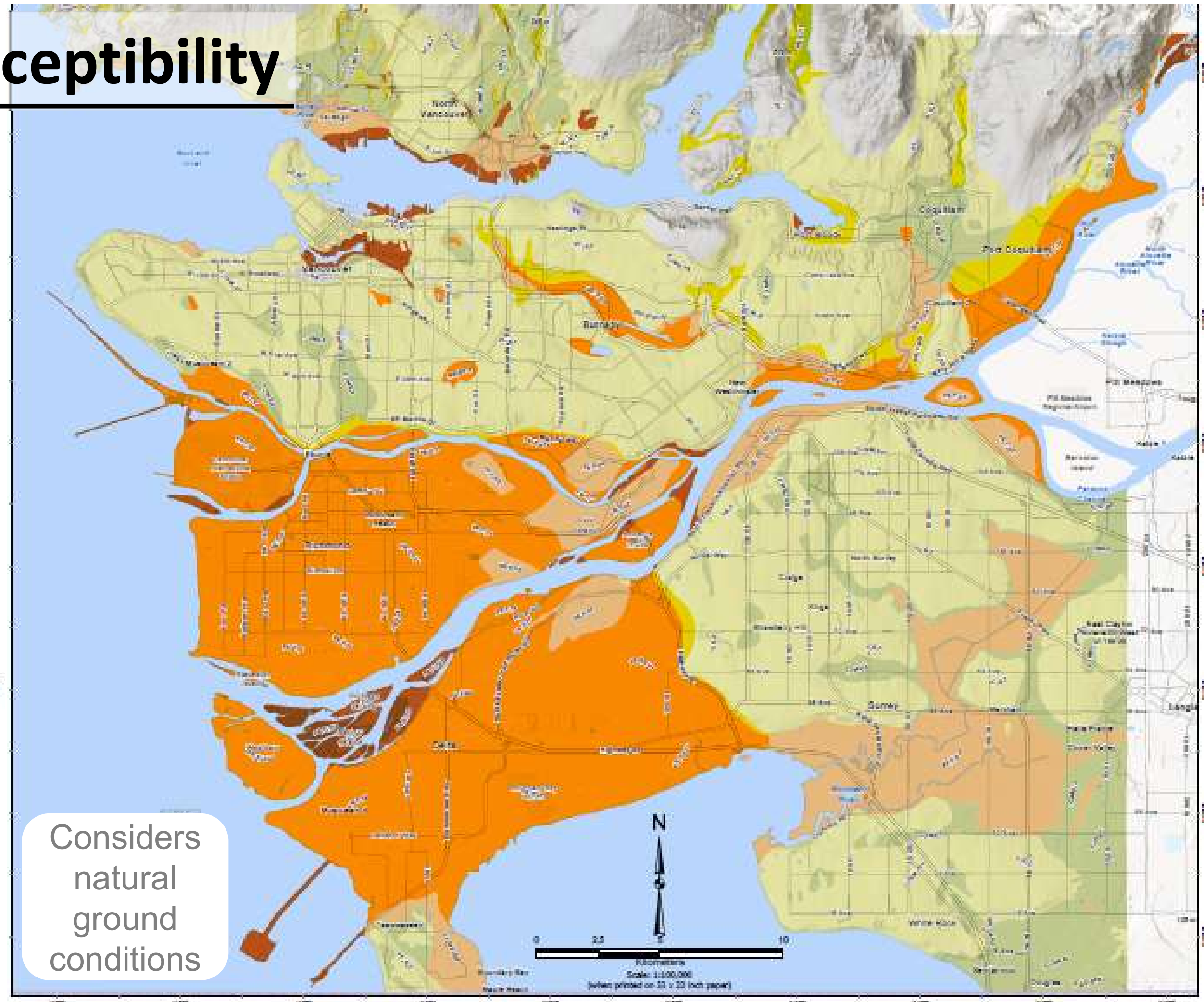
LEVEL 2

Liquefaction Susceptibility

Identify where natural ground is susceptible to liquefaction

Liquefaction Susceptibility
- None
- Very Low
- Low
- Moderate
- Moderate-High
- High
- Very High



Considers natural ground conditions

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Liquefaction Hazard Mapping

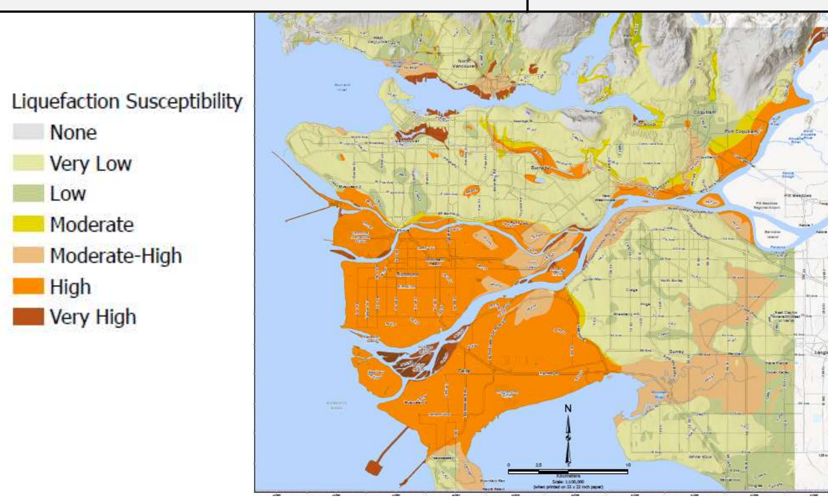
Level 1	Level 2	Level 3

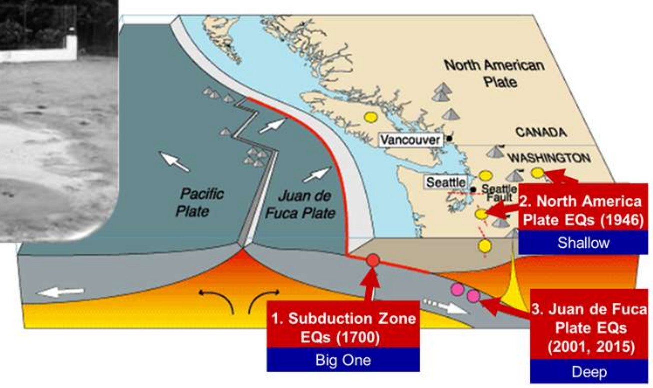
Identify if/where natural ground is susceptible to liquefaction

Considers the local soil resistance (how sandy, how saturated)

But will the natural ground liquefy given the regional seismic hazard?

Consider both the local soil resistance WITH the earthquake shaking that would occur over a mean return period of 475 or 2475 years





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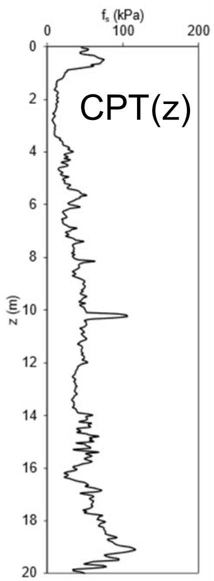
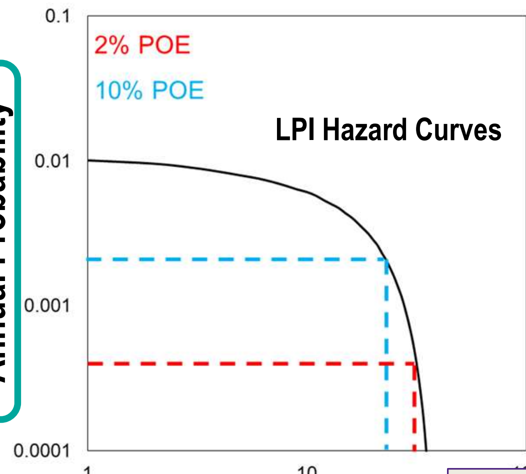


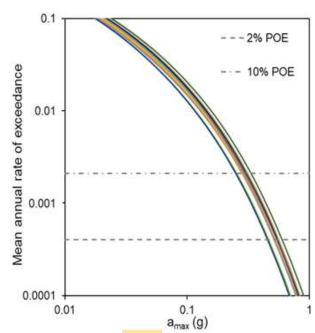
$$\text{Factor of Safety}_L = \frac{\text{Cyclic Resistance Ratio (CRR)}}{\text{Cyclic Stress Ratio (CSR)}}$$

Liquefaction Potential Index

$$LPI = \int_0^{20} F_L . w(z)dz$$



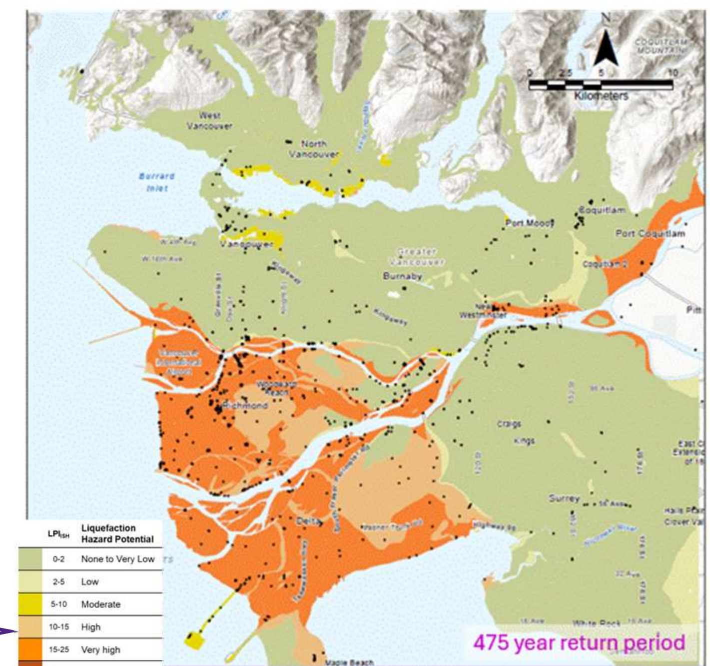
PSHAs using 6th Generation Canadian Seismic Hazard Model (2020 NBC)



~1075 sites

$$\lambda_{LPI} = \sum_{j=1}^{N_{M_w}} \sum_{i=1}^{N_{a_{max}}} P\left(LPI > lpi | a_{max_i}, M_{w_j}\right) \Delta\lambda_{a_{max_i}, M_{w_j}}$$

LEVEL 3 Seismic-Induced Liquefaction Hazard Potential Maps



Hazard rating based on correlation of LPI with worldwide observed seismic-induced liquefaction effects

Achieving Level 3
Seismic Microzonation Mapping

Landslide Hazard Mapping

Yeznabad (2021) PhD Thesis, Yeznabad et al. (2021), Yeznabad et al. (2022), Yeznabad et al. (2024), Yeznabad et al. (in prep.)

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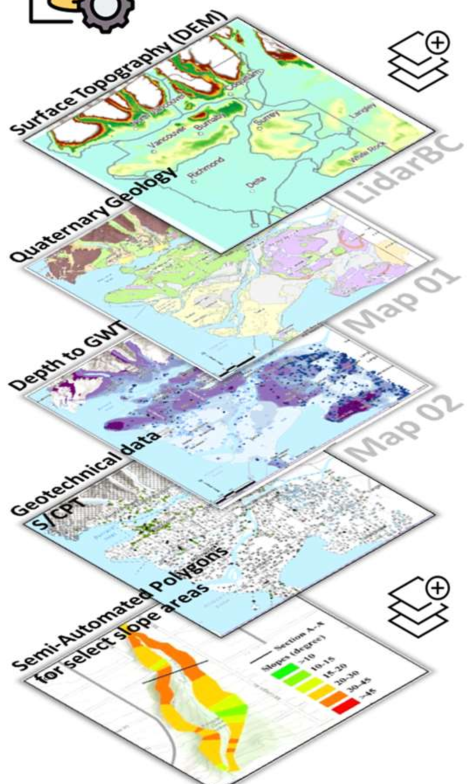
Landslide Susceptibility Mapping

Data Compilation and Processing



Landslide Susceptibility Rating

LEVEL 1

FEMA-Hazus-MH5.1

Technical Manual (2022)

- **Table 4.15** Landslide Susceptibility of Geologic Groups
- **Table 4.16** Lower Bounds for Slope Angles and Critical Accelerations for Landsliding Susceptibility
- **Table 4.17** Critical Accelerations (Ky) for Susceptibility Categories

Yeznabad (2021)

Slope Stability Analysis

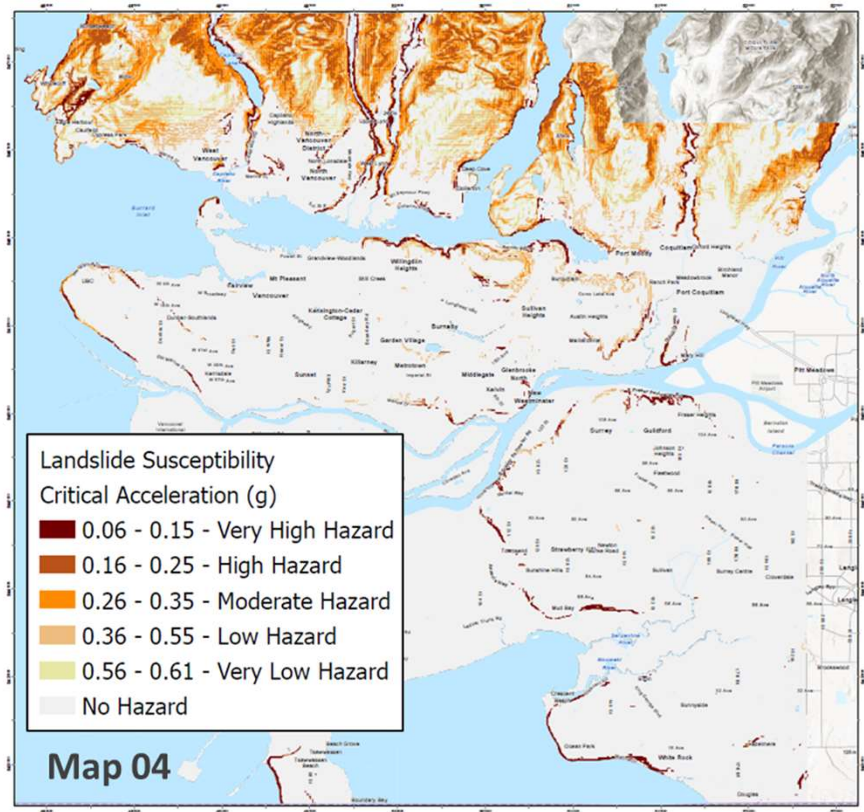
~216 models

2D Numerical Models for groupings of representative slope height (H) and slope angle ($\alpha > 10^0$) to calculate yield acceleration.

LEVEL 2

Yeznabad (2021)

Landslide Susceptibility



$$FS = \frac{c'}{\gamma \, . \, t \, . \, \sin\alpha} + \frac{\tan\Phi'}{\tan\alpha} - \frac{\gamma_{\omega} \, . m \, . \tan\Phi'}{\gamma \, . \tan\alpha}$$

$$k_y = \frac{(FS - 1)g}{(\tan\Phi' + 1/\tan\alpha)}$$

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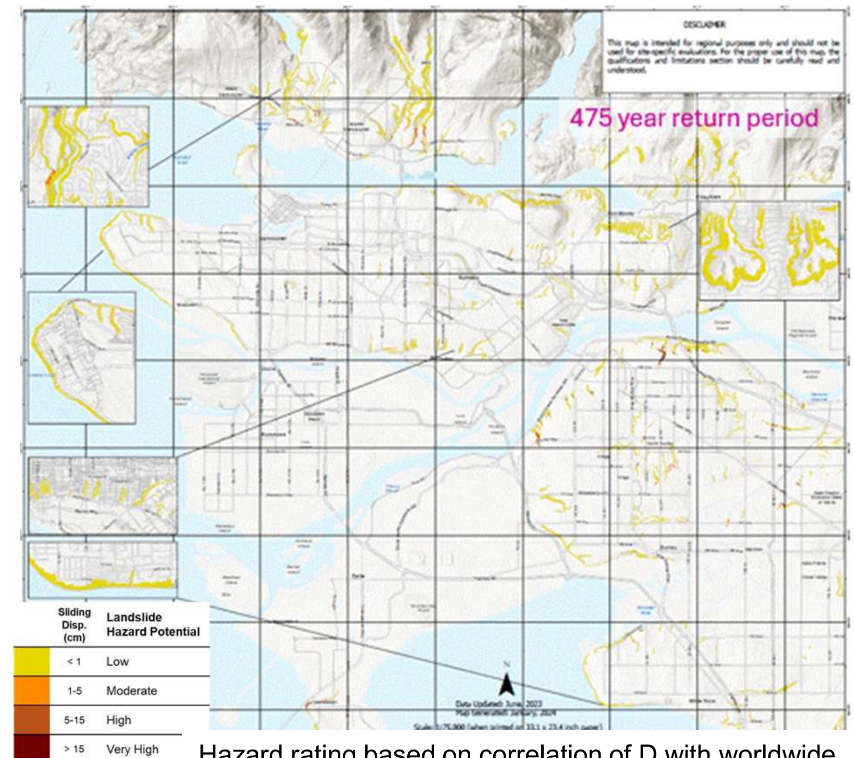
LEVEL 3

Seismic-Induced Landslide Hazard Potential Maps

$$\lambda_D = \iint P\left(D > x \middle| GM_z, M_j, Ky\right).P(GM_z).P\left(M_j \middle| GM_z\right).dz.dj$$



Hazard rating based on correlation of D with worldwide observed seismic-induced landslide effects

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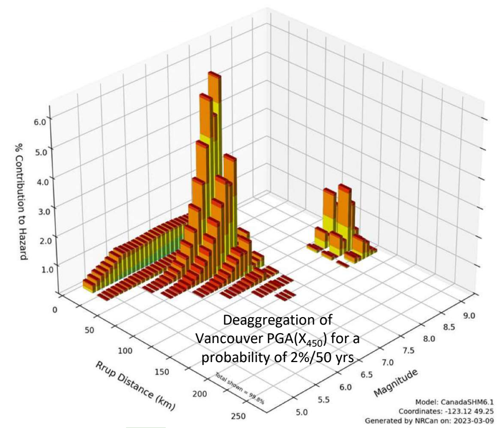
NBCC 2020 Seismic Hazard

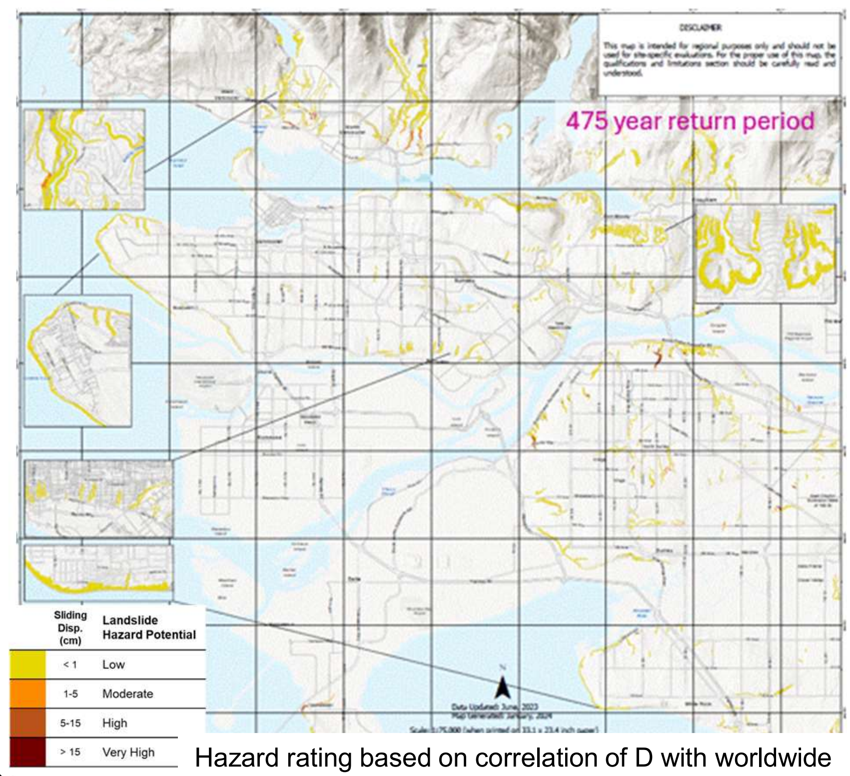


Kolaj et al., (2023)

$$\lambda_D = \iint P\left(D > x | GM_z, M_j, Ky\right) . P(GM_z) . P\left(M_j | GM_z\right) . dz . dj$$

All map images shown are preliminary

LEVEL 3 Seismic-Induced Landslide Hazard Potential Maps



Hazard rating based on correlation of D with worldwide observed seismic-induced landslide effects

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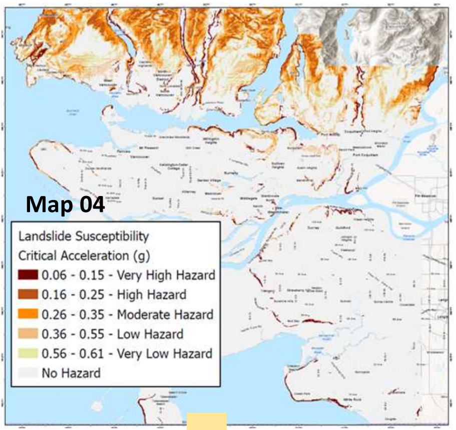
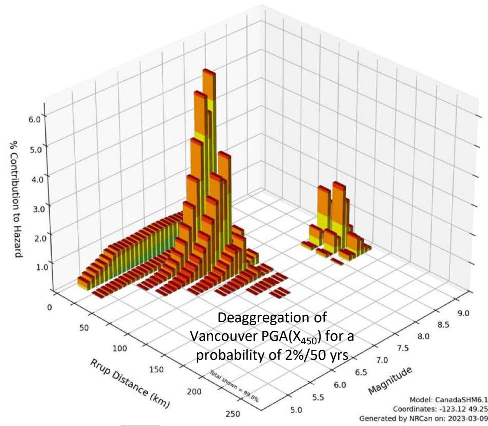
Landslide Susceptibility (*Ky*)



NBCC 2020 Seismic Hazard



Kolaj et al., (2023)

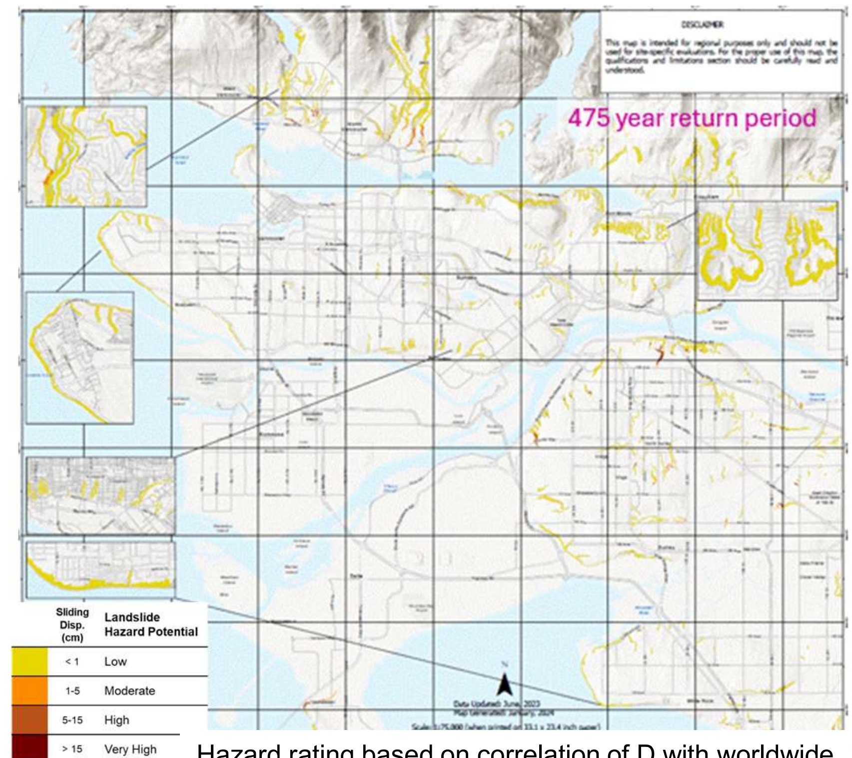
$$\lambda_D = \iint P(D > x|GM_z, M_j, Ky).P(GM_z).P(M_j|GM_z).dz.dj$$

Seismic Displacement Prediction Models (SDPMs)

$$\ln D = f(\mathrm{Ky}, \mathrm{PGA}, \mathrm{M}) \pm \varepsilon$$

All map images shown are preliminary

LEVEL 3 Seismic-Induced Landslide Hazard Potential Maps



Hazard rating based on correlation of D with worldwide observed seismic-induced landslide effects

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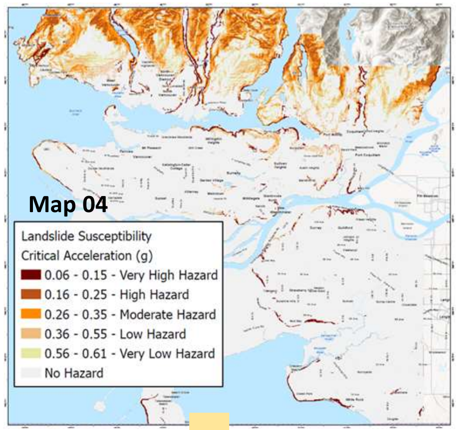
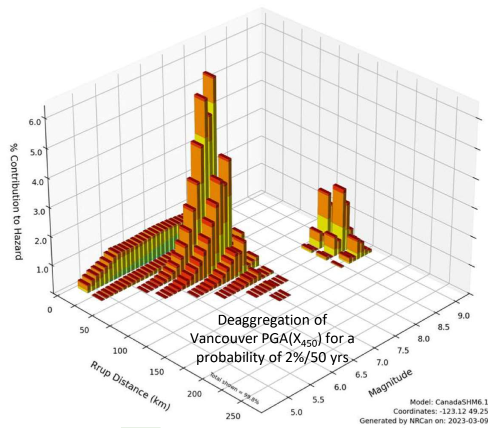
Landslide Susceptibility (*Ky*)



NBCC 2020 Seismic Hazard



Kolaj et al., (2023)

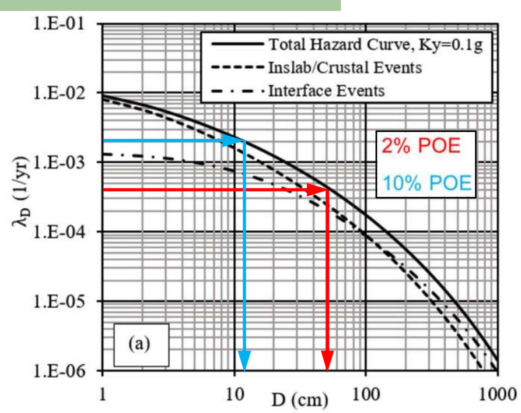
$$\lambda_D = \iint P(D > x|GM_z, M_j, Ky).P(GM_z).P(M_j|GM_z).dz.dj$$

Seismic Displacement Prediction Models (SDPMs)

$$\ln D = f(\text{Ky}, \text{PGA}, \text{M}) \pm \varepsilon$$

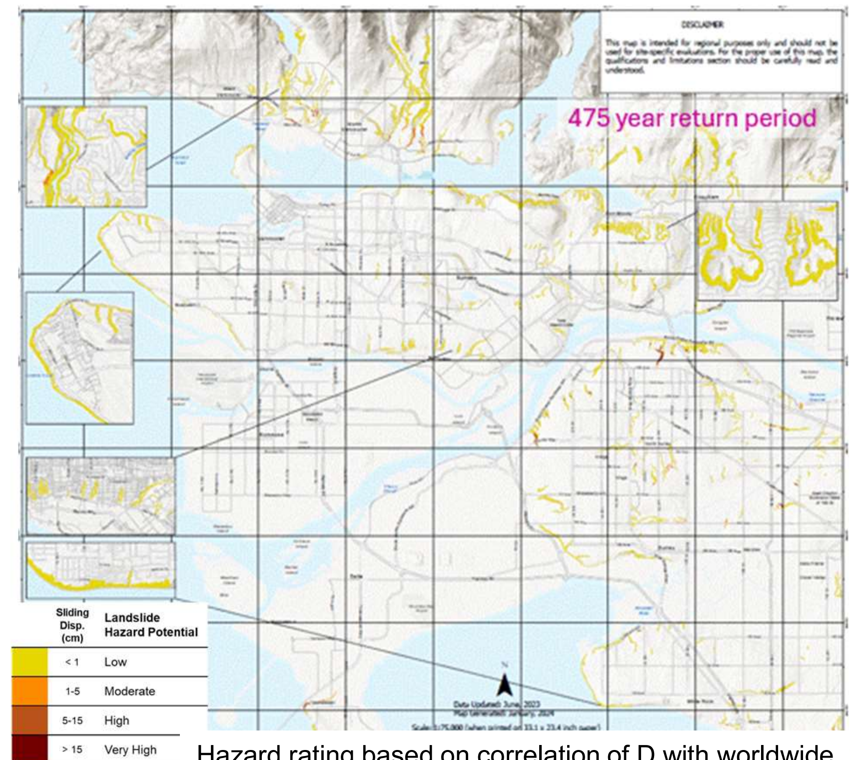
Sliding Displacement Hazard Curves

$$\lambda_{D,Total} = \lambda_{D,Crustal/Inslab} + \lambda_{D,Interface}$$



All map images shown are preliminary

LEVEL 3 Seismic-Induced Landslide Hazard Potential Maps



Hazard rating based on correlation of D with worldwide observed seismic-induced landslide effects

Outline

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Engagement, Communication, Education and Training

Molnar et al. (2023)

Metro Vancouver is exposed to earthquake hazards

↓

Updated seismic hazard maps inform engineers and decision makers

↓

Traditional hazard metrics are not intuitive to non-technical users

↓

Hazard must be presented appropriately for all users

↓

Stakeholder and End-User Engagement

2017-2019 — Initial project communication & request for geodata

2019-2020
1. Half-day workshop with map exercises
2. Online questionnaire about SMMs in Canada

Online questionnaire survey, Jan. – Jun. 2020

- 54 questions designed to gather:
  - Respondents' seismic hazard knowledge and experience
  - Seismic microzonation mapping experience
  - Respondents' interpretations of existing Canadian seismic microzonation maps
  - Preferred proxies/metrics for communicating seismic hazard
- 58 responses analyzed
  - Over 100 responses collected; 58 sufficient for analysis
- Respondents are classed as "creators" or "end-users" of seismic hazard information
  - Classified as "technical" (n=38) or "non-technical" (n=20) for comparison

Fyfe & Molnar (2020), Fyfe (2023)

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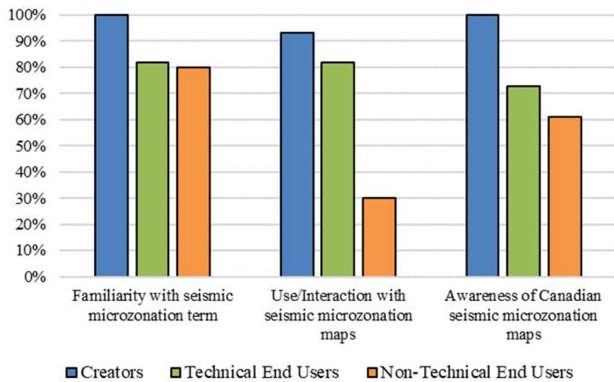
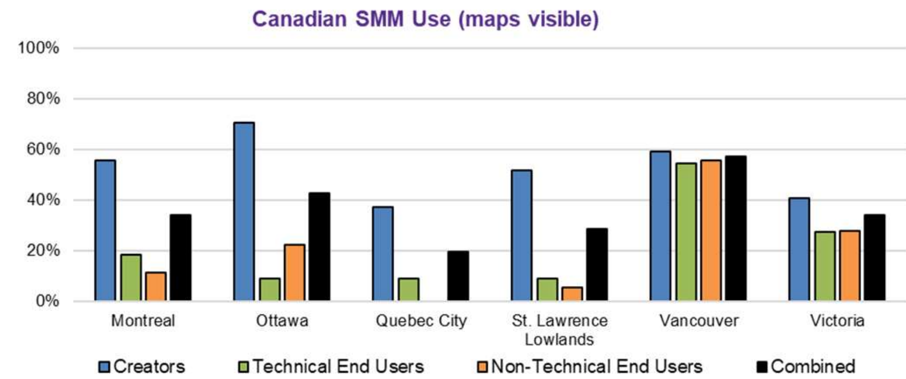
Online Questionnaire Survey, 2020

- Satisfaction with existing hazard maps and earthquake preparedness:
  - Most respondents report that they are **not satisfied with the level of seismic hazard mapping available** in Canada and many professionals feel **underprepared for a significant earthquake** in their region
- Familiarity with seismic microzonation mapping and existing Canadian studies:





- Map Interpretation Testing – respondents asked to interpret existing Canadian SM maps:
  - **Technical respondents** were **more successful** in answering interpretation questions correctly
  - **Clear, informative legends promote successful interpretation** by all users
  - **Overlays** of measurement locations or data points (e.g. Ottawa-Gatineau) or landslide and liquefaction hazard ratings (e.g. Victoria composite map) **confused many users**

Fyfe & Molnar (2020), Fyfe (2023)

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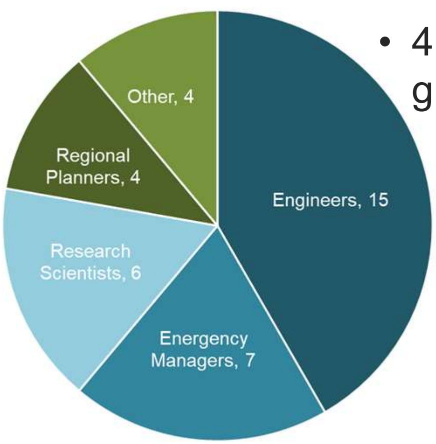
Engagement, Communication, Education and Training

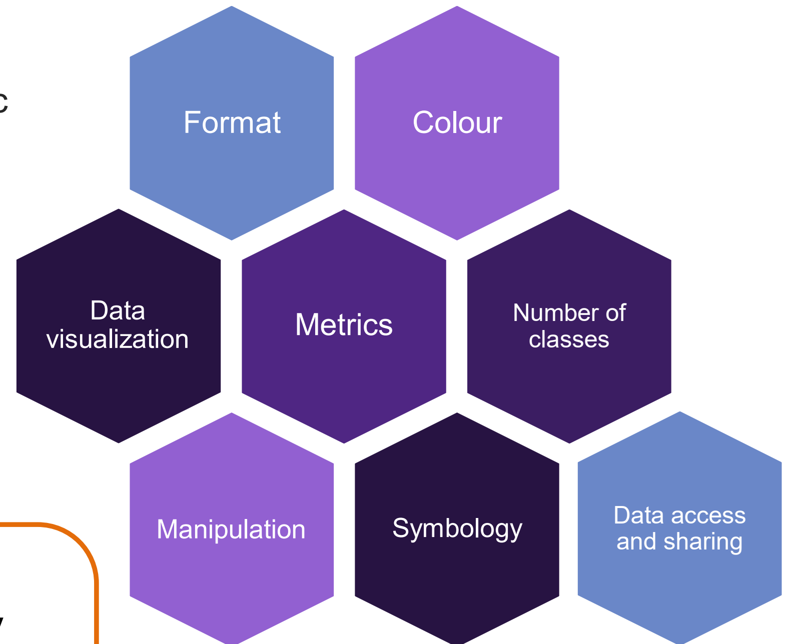
- Stakeholder engagement workshop, Dec. 2, 2019
  - Comparison of draft seismic hazard maps to gather participants' metric and formatting preferences
  - Create an opportunity for stakeholders to interact
  - Forum to express opinions & concerns
  - Obtain stakeholder involvement *during* the project's progression



- 36 in-person participants
- 4 map comparison exercises completed by groups of mixed-professionals

Outcomes

- Non-technical audience does not readily understand the technical aspects of seismic hazard and related metrics.
- Standardization of SMM needed.
- Digital data and maps wanted.



Fyfe & Molnar (2020), Fyfe (2023)

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From Engagement to Communication and Education

Molnar et al. (2023)

Metro Vancouver is exposed to earthquake hazards

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Stakeholder and End-User Engagement

2017-2019
Initial project communication & request for geodata

2019-2020
1. Half-day workshop with map exercises
2. Online questionnaire about SMMs in Canada

2022-2024
Engineers and Geoscientists of British Columbia (EGBC)
1. Technical & Non-Technical Peer Review
2. Professional Practice Guidelines

EGBC webinar coming soon!

2023
1. Canadian-Pacific Conference of Earthquake Engineering (CCEE-PCEE) Special Session
2. Panel Discussion at Understanding Risk BC
3. Project update and feedback on liquefaction maps

2024
Education and Training sessions for planners, insurance industry, and local governments and First Nation communities

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EGBC Professional Practice Guidelines

Molnar et al. (2023)

Development and Use of Seismic Microzonation Maps in British Columbia

The intent of these guidelines is to:

- Provide a **common approach for development** of seismic microzonation maps in British Columbia
- Provide a **common approach for use** of seismic microzonation maps in BC
- Inspire the effective use of new and existing microzonation maps

The intended audiences for these guidelines are:

● Local governments & First Nations & Treaty Nations ● Structural engineers ● Geotechnical engineers ● Liquefaction mapping professionals ● Landslide mapping professionals ● Ground shaking mapping professionals ● Others (e.g., infrastructure owners, insurers)

Table of Contents:

ENGINEERS & GEOSCIENTISTS BRITISH COLUMBIA

EGBC Professional Practice Guidelines
Use of Seismic Microzonation Maps in British Columbia

Applications for Structural and Geotechnical Engineers:

- To gauge variability in regional-scale seismic hazards
- Inform regional-scale scoping-to-risk studies (e.g., linear infrastructure)
- Inform project scoping, feasibility, and schematic designs
- Indicate where more site-specific information is required for detailed design and aid in conversations with clients (going above or beyond current design codes; performance-based design; resilience)

Applications for Local Governments, First Nations, &/or Treaty Nations:

- Inform hazard & urban planning and permitting policies
  - Including professional involvement and additional site-specific information
- Inform asset management and emergency response and recovery plans
  - Input to Risk analyses, Retrofit priorities, Flag emerg. response challenges, etc.
- Indicate where more site-specific information would be valuable

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Use of the MVSMMP Seismic Microzonation Maps

Applications for Insurance Industry:

- Serve as inputs / updates to include in seismic risk and loss analyses
  - Access will come from the industry's integration of our project map results and data into NEW cat models; Ask for these region-specific updates to be included in Cat Models used by your company
- Earthquake shaking will occur everywhere in Metro Vancouver → General uptake of earthquake (shaking) insurance is important for all of Metro Vancouver
- Seismic hazard maps (shaking, liquefaction, landslide) for TWO return periods are available
    - Financial risk assessments are based on 475 year return period
    - Seismic design of new buildings and bridges (national building and bridge codes) are based on 2475 year return period
  - Areas that have a greater than moderate hazard rating considering the lower shaking intensity (shorter 475-yr return period) should be **prioritized**.
    - Beneficial to compare hazards maps for the two different return periods (two levels of seismic demand or shaking intensity)

Use of the MVSMMP Seismic Microzonation Maps

Applications for Insurance Industry: Brokers (marketability, insurance policies)…

- Shaking hazard maps show where and how much shaking (for particular spectral period) will be increased or decreased based on underlying natural ground condition. → Prioritize / develop specialized policies for areas where earthquake shaking is expected to be increased.
  - North part of Metro Vancouver will experience increased shaking at shorter periods (damage to shorter or smaller structures and acceleration-sensitive nonstructural components).
  - Southwest part of Metro Vancouver will experience increased shaking at longer periods (damage to taller or longer structures and displacement-sensitive nonstructural components).
  - See basin amplification maps (2 and 5 s) for areas where damage to tallest and longest structures and displacement-sensitive nonstructural components may occur.
- Liquefaction and landslide hazard potential maps identify areas where liquefaction and landslides will be triggered (occur) when shaking exceeds the considered return period's shaking intensity. → "Additional earthquake insurance coverage" or "additional living expenses" would be most applicable in these identified areas.

Use of the MVSMMP Seismic Microzonation Maps

Applications for Insurance Industry: Underwriters (risk profiling)…

- Seismic risk assessments that do not incorporate the seismic hazard improvements resulting from this project's near decade effort in understanding the regional seismic hazard of Metro Vancouver are **outdated (does not include the most up-to-date regional seismic hazard data and information)**.
- The project's regional shaking hazard maps are based on better site information (several parameters; the national seismic hazard model uses only one parameter) and more detailed site information (sufficient regional spatial density) than national seismic hazard mapping and current seismic design codes. This improved regional-scale hazard mapping needs to be included in seismic risk analyses to understand the predicted impact to structural damage and thereby loss estimation.
- Current national seismic hazard mapping and site-specific engineering design does NOT include increased shaking intensities at long periods based on the 3D Georgia basin. **These regional maps are the only information source (currently) that includes this regional-scale basin effect.**
- In very general terms, liquefaction and landslides hazards are more concentrated (particular areas or zones) than shaking hazard; liquefaction and landslide hazards do not occur everywhere.

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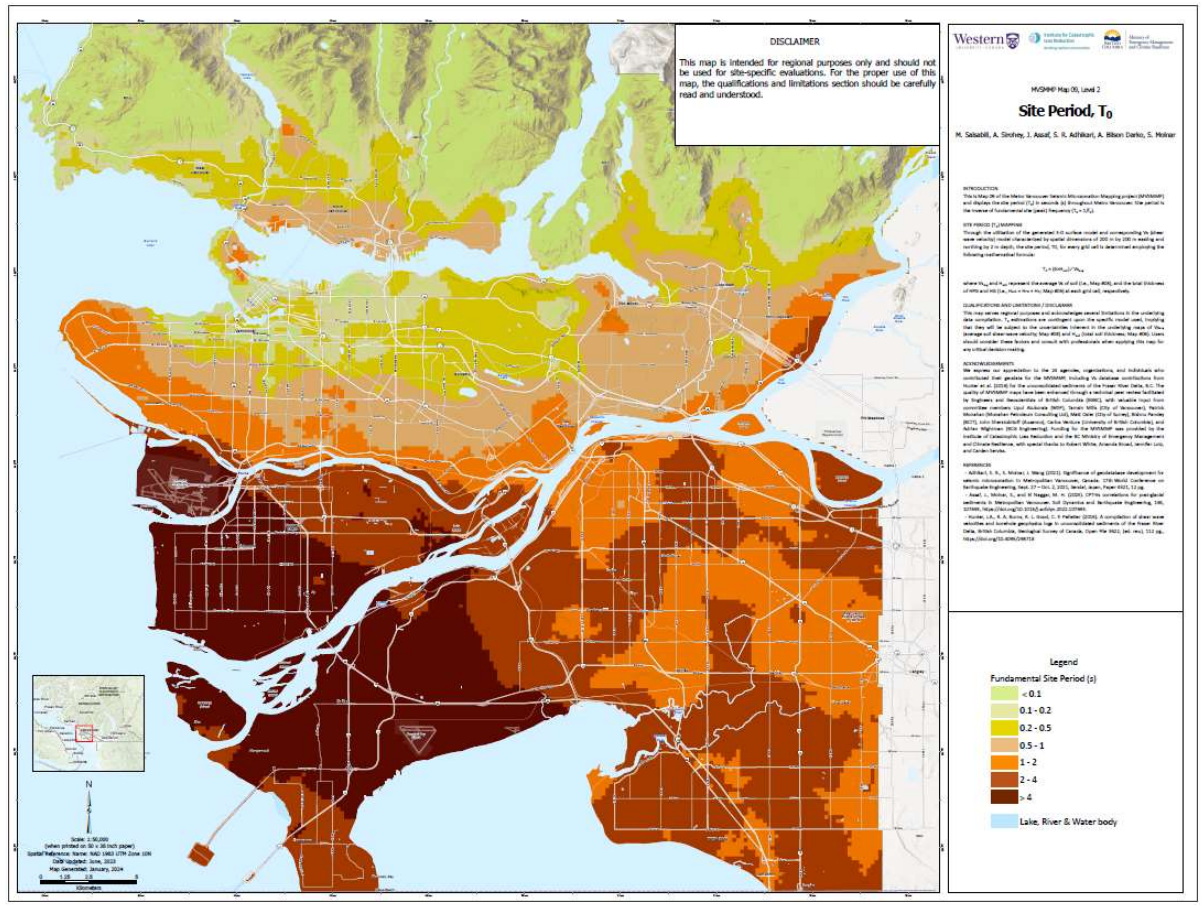
1. Published Maps

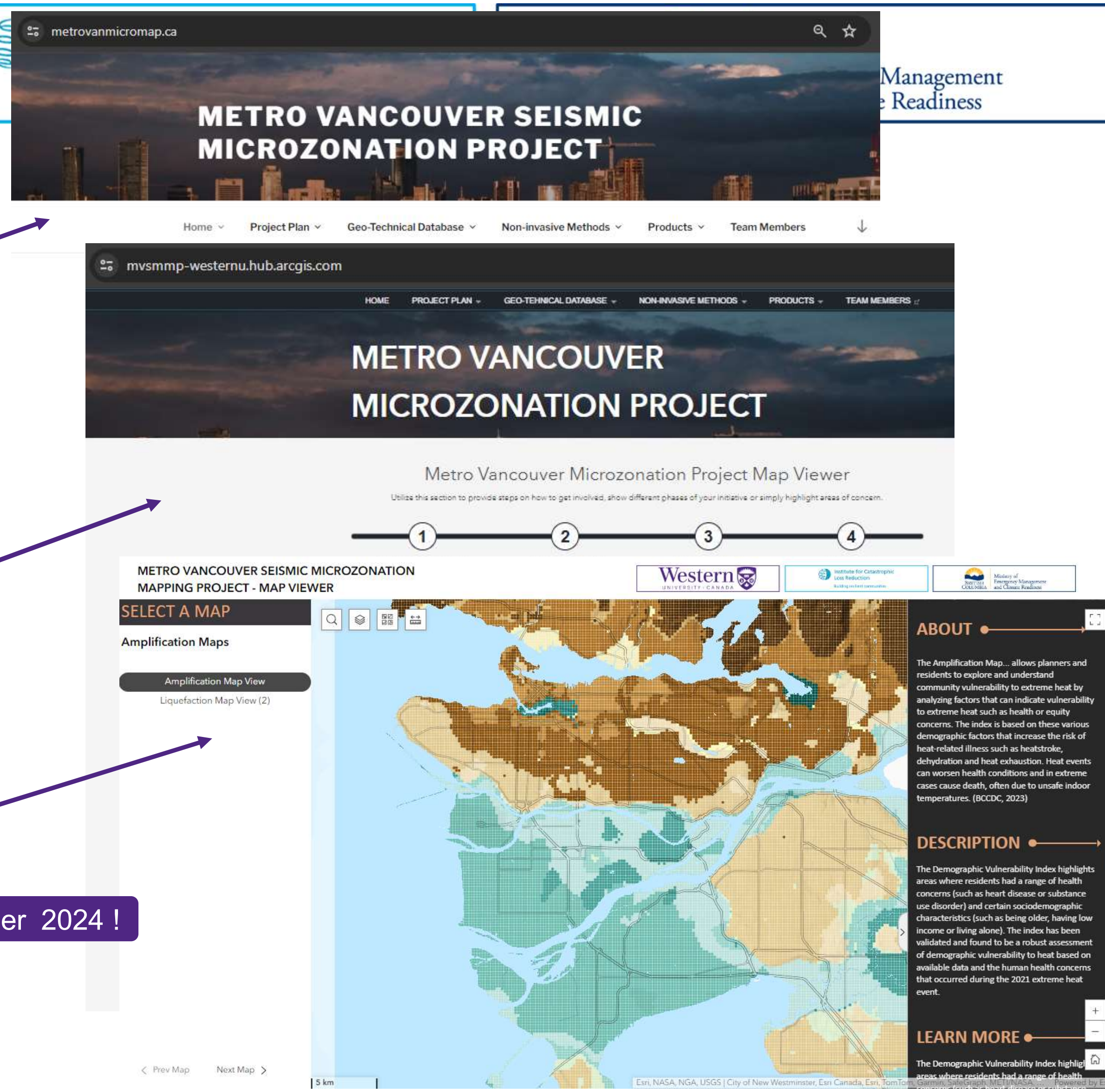
- Design of map sheets including:
  - (on left) The Map and Disclaimer (left)
  - (on right) Map Title, Authors, Explanation, Qualifications and limitations, Acknowledgements, References, and Recommended Citation. And Legend with sufficient text.
- Iterative improvements to this map sheet presentation from engagement consultations (2019, 2023) and technical peer review (2022-2024).
- PDF file format



2. Open Access

- Project website
  - Products
    - Publications list and links
    - Presentations list and links
    - Engagement and Training Events list and links
  - Open Data webpage
    - With links to **Published Maps** (Map sheets, PDF format) Coming summer 2024 !
    - Access to online Map Viewer experience
      - Links to digital **ArcGIS Files** with embedded attribute tables (map **data** values) Coming summer 2024 !
    - With links to **Geodatabase** files

Coming ~Fall 2024 !



Metro Vancouver Seismic Microzonation Mapping Project (2017 - 2026)

Release of Seismic Hazard Maps for western Metro Vancouver: **July 2024**

Seismic Microzonation Mapping of eastern Metro Vancouver: **2024 to 2026**

Release of Seismic Hazard Maps for eastern Metro Vancouver: **Late 2026**

https://metrovanmicromap.ca

Contact: Sheri Molnar, smolnar8@uwo.ca