Liquefaction susceptibility mapping derived from terrain mapping; experience on a linear project in British Columbia, Canada

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Earthquake-triggered liquefaction and its attendant ground-movement hazards (e.g. buoyancy, subsidence, lateral spreading) may threaten linear infrastructure. Such infrastructure often traverses a range of physiographic, geologic and seismic settings, with varying liquefaction potential. Liquefaction susceptibility maps and the distribution of seismic hazard are typically combined to screen areas for more detailed geotechnical investigations of liquefaction potential. We applied several liquefaction susceptibility classification systems, including Youd and Perkins (1978), to airphoto-based, medium-scale (1:20,000) terrain maps completed in general accordance with Howes and Kenk (1997) for a proposed natural gas pipeline corridor across northern British Columbia, Canada. We compare these maps against site-specific geotechnical and geophysical data to generate statistics relating liquefaction susceptibility categories to the expected thickness of loose, saturated, cohesionless soil. We conclude that medium-scale mapping is reliable for preliminary design level screening, with potential for improvement through larger scale mapping and the compilation of additional subsurface and mapping data.

RÉSUMÉ
La liquéfaction déclenchée par des tremblements de terre, ainsi que les mouvements de sol qui en découlent (e.g. la subsidence ou la diffusion latérale) peuvent menacer les infrastructures linéaires. Une telle infrastructure traverse souvent une multitude de terrains ayant des paramètres physiographiques, géologiques et sismiques différents, avec un potentiel de liquéfaction plus ou moins grand. Les cartes de susceptibilité à la liquéfaction et la répartition des risques sismiques sont généralement combinées pour cibler des zones ou conduire des études géotechniques plus détaillées sur le potentiel de liquéfaction. Le long d'un corridor proposé pour un pipeline de gaz naturel, nous avons appliqué plusieurs systèmes de classification, incluant celui de Youd et Perkins (1978), en se basant sur l'étude des photographies aériennes à une échelle moyenne (1:20000), selon la démarche proposée par Howes et Kenk (1997). Nous comparons ces cartes avec les données géotechniques et géophysiques spécifiques à ces sites pour générer des statistiques concernant la susceptibilité à la liquéfaction, ainsi que l'épaisseur prévue de dépôts de sol pulvérulent lâches et saturés. Nous concluons que la cartographie à moyenne échelle est fiable pour le dépistage préliminaire au niveau de la conception, avec un potentiel d'amélioration, grâce à la cartographie à plus grande échelle et à la compilation de données de sous-surface et de cartographie supplémentaires.

1 INTRODUCTION

British Columbia (BC) in western Canada has variable geology, physiography, climate and seismicity. Long linear infrastructure in BC, including highways, railways, power transmission lines and oil and gas pipelines may cross a diverse range of terrain and climate, with exposure to a spectrum of geohazards. Seismic geohazards, including strong shaking, co-seismic landslides, fault displacement and liquefaction, are an important subset of geohazards, and are most prevalent in areas of elevated seismicity. In BC, seismic hazard is highest near the coast in proximity to the Cascadia Subduction Zone, Queen Charlotte Fault, and associated structures. This paper examines the topic of seismic liquefaction, which may occur where seismic loading is sufficiently high and subsurface conditions are such that liquefaction may occur given strong enough shaking (i.e. liquefaction *susceptibility*).

Liquefaction can cause differential settlement, buoyancy of buried structures, or lateral movement associated with lateral spreading or flow failure. Determining the locations, extent and severity of liquefaction effects along a long linear corridor presents a considerable engineering challenge. This is due in part to the variability of seismic hazard, and in much greater measure to the variability in ground conditions. For long linear facilities, it is generally impractical to characterize this variability with sufficient resolution to understand precise behaviour at all locations. Designs must often be generalized or interpolated from conditions known at specific, sometimes widely-spaced, locations where subsurface data are available.

This paper presents a procedure used to develop liquefaction susceptibility maps for linear corridors in BC. The work was based on terrain mapping completed in general accordance with Howes and Kenk (1997). This work was completed to identify areas along linear corridors that are susceptible to seismically triggered liquefaction.

The literature includes several approaches to regional-scale liquefaction susceptibility mapping. The present work relies most heavily on core principles from Youd and Perkins (1978). In their work, qualitative liquefaction susceptibility is based on the type and age of the deposit. The landform, or type of deposit, governs the likelihood that loose, cohesionless soils could be present. The age of the deposit affects the likelihood that such saturated cohesionless soils could liquefy during adequate seismic loading, given that liquefaction resistance increases with age due to various processes (e.g. consolidation or cementation). The Youd and Perkins (1978) susceptibility classification, reproduced in Table 1, considers liquefaction susceptibility *assuming* that shallow groundwater is present (i.e. the stratum is saturated).

Table 1. Liquefaction susceptibility of sedimentary deposits during strong seismic shaking. Reproduced from Youd and Perkins (1978).

Type of deposit	General distribution of cohesionless sediments in deposits	Likelihood that cohesionless sediments when saturated would be susceptible to liquefaction			
		< 500 yr	Holocene	Pleistocene	Pre-Pleistocene
Continental deposits					
River channel	Locally variable	Very high	High	Low	Very low
Flood plain	Locally variable	High	Moderate	Low	Very low
Alluvial fan and plain	Widespread	Moderate	Low	Low	Very low
Marine terraces and plains	Widespread	---	Low	Very low	Very low
Delta and fan-delta	Widespread	High	Moderate	Low	Very low
Lacustrine and playa	Variable	High	Moderate	Low	Very low
Colluvium	Variable	High	Moderate	Low	Very low
Talus	Widespread	Low	Low	Very low	Very low
Dunes	Widespread	High	Moderate	Low	Very low
Loess	Variable	High	High	High	Unknown
Glacial Till	Variable	Low	Low	Very low	Very low
Tuff	Rare	Low	Low	Very low	Very low
Tephra	Widespread	High	High	?	?
Residual soils	Rare	Low	Low	Very low	Very low
Sabkha	Locally variable	High	Moderate	Low	Very low
Coastal Zone					
Delta	Widespread	Very high	High	Low	Very low
Estuarine	Locally variable	High	Moderate	Low	Very low
Beach - High wave energy	Widespread	Moderate	Low	Very low	Very low
Beach - Low wave energy	Widespread	High	Moderate	Low	Very low
Lagoonal	Locally variable	High	Moderate	Low	Very low
Foreshore	Locally variable	High	Moderate	Low	Very low
Artificial fills					
Uncompacted fill	Variable	Very high	---	---	---
Compacted fill	Variable	Low	---	---	---

Iwasaki et al. (1982) examined liquefaction susceptibility on the basis of topographic position. In their classification (see Table 2), groundwater levels are implicitly considered in each susceptibility class: low-lying ground is more likely to be saturated than upland terrain.

Levson et al. (1996) compiled a test hole database and large-scale surficial geological mapping to infer typical groundwater conditions and geotechnical properties of a subset of deposit types. Table 3 relates surficial geology, typical grain size distribution, typical groundwater levels, and qualitative liquefaction susceptibility classes for Chilliwack, BC. Their key changes from the Youd and Perkins (1978) classification system included:

- Subdividing alluvial fans into coarse-grained fans at the mouths of steep mountain streams, and fine-grained alluvial fans farther from mountain sources.
- Considering likely water table elevations.
- Limiting deposit types and ages to those present in the study area.

Monahan et al. (2000) mapped liquefaction hazard for Greater Victoria, BC, as a combination of quantitative liquefaction susceptibility inferred from test hole data, and liquefaction opportunity defined by the probabilistic seismic hazard. Holocene sands and modern anthropogenic fills were assigned high to very high liquefaction hazard ratings. Early Holocene postglacial sediments with a high sand content and shallow groundwater had low to moderate liquefaction hazard ratings. Other map units, including glaciomarine clays, tills, colluvium, and bedrock had low to very low liquefaction susceptibility.

Palmer et al. (2004) modified the Youd and Perkins (1978) susceptibility framework to suit existing geologic mapping across Washington State. Changes included:

- Adding glaciofluvial and glaciolacustrine deposit types to the susceptibility classification system, and differentiating between advance outwash, recessional outwash, and outburst flood deposits.
- Eliminating the “very high” susceptibility class, because the surficial geological mapping did not have the resolution to subdivide units into Holocene and <500-year age classes.
- Differentiating between coastal and inland eolian deposits on the basis of likely groundwater levels.
- Assigning no susceptibility to peat and bedrock.
- Differentiating between coarse-grained and fine-grained alluvial fans.

These various approaches have been considered in developing an appropriate methodology for inferring liquefaction susceptibility at the regional scale for use on linear projects across northern BC.

2 TERRAIN MAPPING

2.1 Northern BC Geology

The western Canadian landscape is dominantly influenced by the effects of repeated Pleistocene glacial advances and retreats. Successive glaciations have tended to scour, re-work, and re-deposit most unconsolidated materials from preceding glaciations, so that most surficial deposits represent deposition by the most recent cycle of advance and retreat. However, some locations preserve deposits from earlier Pleistocene glaciations or channels and fans that pre-date these glaciations (e.g. Fulton 1976).

The Fraser Glaciation is the most recent episode of Cordilleran glaciation. Its maximum extent occurred around 17,000 years before present (BP) (Porter and Swanson 1998). Retreat was relatively rapid. In the southern and central British Columbia interior, ice cover had retreated to about today’s conditions by 11,400 years BP, although stagnant valley ice persisted in some locations (Clague and James 2002). Some valleys in the rain shadow east of the Coast Ranges were ice free before 13,000 years BP (Souch 1989, Ryder et al. 1991).

2.2 Terrain Mapping Methods

The BC Terrain Classification System (Howes and Kenk 1997) was employed to map surficial geology and terrain stability along a project corridor. Mapping was typically at 1:20,000 scale, relying primarily on soft copy stereo air photos and supported by LiDAR topography. Terrain mapping was ground truthed through helicopter and ground reconnaissance, with ground observations being made in approximately 10% of all mapped polygons.

Terrain was classified by genesis, surface expression, depositional process, drainage class, and expected depth to bedrock. Composite terrain units contain more than one surficial material proportionally or stratigraphically. We placed each terrain polygon into one of three typical bedrock-depth classes (<1 m, 1-3 m, and >3 m). We assigned a drainage class that references grain size and topographic position to each polygon (RIC 1996).

In some cases, important genetic information with implications for liquefaction susceptibility may not be contained within a terrain symbol. For example, the classification system contains no symbols to explicitly distinguish between advance and recessional outwash, ice-contact, or outburst flood deposits. A geomorphologist would characterize all these as glaciofluvial; however, an advance outwash would probably be compacted through ice loading and less susceptible to liquefaction; whereas recessional, outburst flood, or ice-contact deposits would not be compacted and thus more susceptible to liquefaction.

2.3 Age of Terrain Units

Howes and Kenk (1997) provide guidance on relating terrain to age or activity level, based on surficial material type and process symbols. Most terrain units have been placed into age classes similar to those proposed by Youd and Perkins (1978) based on our understanding of glacial chronology.

A <500 year, or modern, age was assigned to:

- Modern waterbodies, including lakes, river channels, and terrain below the high-tide mark.
- Anthropogenically modified terrain.
- Peat and bog deposits.
- Fluvial deposits with an “active” qualifier.
- Lacustrine deposits within modern lakes.

Holocene age was assigned to:

- Lacustrine deposits outside modern lakes.
- Marine deposits above the high-tide mark.

Terrain formed by depositional processes that began when glaciers receded from the area and continues through the present was assigned “Holocene to modern” age. Terrain that falls into this category includes:

- Colluvium and talus.
- Postglacial fluvial deposits, except those with an “active” qualifier or within modern channels.
- Eolian surficial materials.

Pleistocene age was assigned to:

- Till.
- Glaciolacustrine deposits.
- Glaciofluvial deposits.
- Glaciomarine deposits.

Table 2. Liquefaction microzonation based on topography. From Iwasaki et al. (1982).

Topography	Susceptibility
Present river bed, old river bed, swamp, reclaimed land, interdune lowland	Likely
Fan, natural levee, sand dune, flood plain, beach, other plains	Possible
Terrace, hill, mountain	Unlikely

Table 3. Liquefaction susceptibility of Chilliwack region soils. From Levson et al. (1996).

Surficial Geology	Age	Distribution	Sediment Type	Water Table	Liquefaction Susceptibility
River channel	Very recent	Along rivers and streams	Sand and gravel	At surface	High to very high
Fraser alluvium	Holocene	Widespread on flood plain	Sand, silt, and gravel	Near surface	Moderate to high
Sandy alluvial fan	Holocene	Lower Vedder River fan	Sand, silty sand, and gravelly silty sand	Variable	Moderate to high
Gravelly alluvial fan	Holocene	At mouth of mountain streams	Gravel, sand, and silty sand	Variable	Low to moderate
Alluvium with near surface fines	Holocene	Abandoned channels and other lows on flood plain	Silt, clay, and organics over sand and gravel	At surface	Low to moderate
Bog	Holocene	Widespread	Peat and organic silts	At surface	Nil at surface
Lacustrine deposits	Holocene/Late Pleistocene	Sumas Valley, Vedder Canal area	Sand, silt, and/or clay	Near surface	Low to high
Eolian	Holocene	Small areas, Ryder Upland	Silt and sand	Variable	Low to high
Till	Pleistocene	Ryder Upland	Diamicton	Variable	Very low
Glaciofluvial	Pleistocene	Ryder Upland	Gravel and sand	Variable	Very low
Bedrock	Pre-Pleistocene	Mountainous areas	Rock	Variable	None

3 LIQUEFACTION SUSCEPTIBILITY MAPPING

Liquefaction susceptibility ratings were assigned to terrain polygons using the correlations listed in Table 4. The terrain classifications were checked against available LiDAR and Google Earth™ imagery.

Terrain with high susceptibility to liquefaction includes:

- Modern waterbodies, including rivers, lakes, and oceans
- Postglacial fluvial deposits
- Modern lacustrine deposits
- Colluvial deposits on slopes less than 15°
- Eolian deposits.

Terrain with moderate susceptibility to liquefaction includes:

- Postglacial lacustrine deposits
- Postglacial marine deposits

Terrain with low liquefaction susceptibility includes:

- Glaciofluvial deposits
- Glaciolacustrine deposits
- Glaciomarine deposits
- Colluvial deposits on slopes 15° and steeper (i.e. talus)
- Till

Terrain is not susceptible to liquefaction if bedrock is at or within 1 m of ground surface. Peat is generally not liquefiable (Palmer et al. 2004), but where present, is often a thin cover on saturated ground. The liquefaction susceptibility of the underlying material, where given in the terrain symbol, was assigned to terrain covered with peat. Otherwise, peat was assigned variable susceptibility.

The liquefaction susceptibility of anthropogenically modified terrain depends on whether it is a cut, loose fill, or compacted fill. These were assigned variable susceptibility, pending site-specific evaluation. Variable susceptibility was also assigned to the few polygons that did not meet any criteria described above.

Table 4. Proposed liquefaction susceptibility classification system for northern BC

Deposit Type	Age[1]	Liquefaction Susceptibility	Terrain Map Units
Waterbodies	M	High	Waterbody as the only surficial material or with peat as the secondary material
Fluvial, Glaciofluvial	M to H	High	Fluvial deposits as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
	P	Low	Glaciofluvial deposits as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
Lacustrine, Glaciolacustrine	M	High	Waterbody with lacustrine deposits
	H	Moderate	Lacustrine deposits as the main surficial material, or beneath peat or a veneer
	P	Low	Glaciolacustrine deposits as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
Marine, Glaciomarine	H	Moderate	Marine deposits as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
	P	Low	Glaciomarine deposits as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
Dunes	M to P	High	Eolian deposits as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
Talus	M to H	Low	Colluvium as the main surficial material, or beneath peat or a veneer, or with waterbody deposits; on >15° slopes
Colluvium	M to H	High	Colluvium as the main surficial material, or beneath peat or a veneer, or with waterbody deposits; on <15° slopes
Till	P	Low	Till as the main surficial material, or beneath peat or a veneer, or with waterbody deposits
Bedrock	All	None	Bedrock and weathered rock at surface, or a veneer with subsurface bedrock or no subsurface material specified, or peat over bedrock
Anthropogenic	M	Varies	Anthropogenic deposits, not as a veneer
Peat and bogs	M	Varies	Bogs without underlying material specified

Note 1. M = modern; H = Holocene; P = Pleistocene

4 PREDICTIVE CAPABILITY OF LIQUEFACTION SUSCEPTIBILITY MAPPING

Liquefaction susceptibility mapping has been compared to subsurface information obtained from borehole drilling and in-situ penetration testing.

Table 5 summarizes borehole data for each liquefaction susceptibility category. The data illustrate the relative likelihood of encountering "loose, saturated, cohesionless" soils in each category. Recorded blowcounts (i.e. SPT "N") have been corrected for hammer energy (i.e. through measurement of delivered energy for the different drill rigs in different lithologies and at different depth ranges), overburden pressure and fines content. Penetration values were corrected as $(N1)_{60\text{-}cs}$, the clean sand equivalent, energy-corrected and overburden-corrected blowcount, which is commonly used in liquefaction triggering analyses (e.g. Idriss and Boulanger 2008). Table 5 records the number of boreholes within each category where soils with $(N1)_{60\text{-}cs}$ less than 5, 10 or 15 were observed for some non-zero thickness. These data provide an indication of the relative spatial frequency of loose and very loose, saturated, cohesionless soils for each liquefaction susceptibility category.

In Table 6, liquefaction susceptibility categories have been grouped into two simplified classes: 1. "None" and "Low;" and 2. "Water," "Variable," "Moderate" and "High." "None" has been grouped with "Low" because one hole in a "None" polygon had non-zero thickness of loose soil. Examination of that individual borehole suggests it was an outlier, located at the boundary between a "None" and "High" polygon. Larger scale mapping would likely have placed that borehole more correctly within the "High" susceptibility area; however, such errors are to be expected at 1:20,000 scale.

No boreholes were completed in “Moderate” susceptibility polygons, which comprise only a very small proportion (i.e. 0.5%) of the mapping area. These polygons have been conservatively grouped with the “High” susceptibility. As noted earlier, waterbodies (included as “Water” in Table 5 and Table 6) belong in the “High” susceptibility category and have thus been grouped in the same class. The “Variable” category has been conservatively grouped along with “High” since it represents a very small proportion (i.e. 0.5%) of the map area and each “Variable” polygon requires site-specific consideration.

Table 5. Comparison of borehole data with liquefaction susceptibility mapping

Liquefaction Susceptibility	Proportion of Map Area	Number of Boreholes	Number of Boreholes having non-zero thickness of soil below the groundwater table with:			Number of boreholes with no $(N_1)_{60\text{-}cs} < 15$
			$(N_1)_{60\text{-}cs} < 5$	$(N_1)_{60\text{-}cs} < 10$	$(N_1)_{60\text{-}cs} < 15$	
Water	0.9 %	7	6	6	6	1
Variable	0.5 %	1	1	1	1	0
None	18.7 %	5	1	1	1	4
Low	69.5 %	28	1	3	10	18
Moderate	0.5 %	0	0	0	0	0
High	10.0 %	13	5	8	9	4
Totals:		**54**	**14**	**19**	**27**	**27**

Table 6. Summarized expectation of low $(N_1)_{60\text{-}cs}$ for Liquefaction Susceptibility Classes derived from terrain mapping

Simplified Liquefaction Susceptibility Classes	Proportion of Map Area	Number of Boreholes	Number of Boreholes having non-zero thickness of soil below the groundwater table with:			Number of boreholes with no $(N_1)_{60\text{-}cs} < 15$
			$(N_1)_{60\text{-}cs} < 5$	$(N_1)_{60\text{-}cs} < 10$	$(N_1)_{60\text{-}cs} < 15$	
1. None and Low	88.2 %	33	2 (6%)	4 (12%)	11 (33%)	22 (67%)
2. Water, Variable, Moderate and High	11.8 %	21	12 (57%)	15 (71%)	16 (76%)	5 (24%)

5 DISCUSSION

The results presented in the previous section show that liquefaction susceptibility mapping based on terrain mapping can serve as an initial basis for distinguishing between areas with lower or higher likelihood to contain soils susceptible to liquefaction, given adequate seismic load. The results distinguish clearly for very loose soils (i.e. $(N1)_{60\text{-}cs} < 5$), where the higher susceptibility categories have roughly 10 times the probability of non-zero thickness for $(N_1)_{60\text{-}cs} < 5$ at a random point location (i.e. 57% versus 6%). The absence of loose (i.e. $(N1)_{60\text{-}cs} < 15$), saturated soils is about three times more likely (67% versus 24%) in the lower susceptibility classes than in the higher susceptibility classes.

The probabilities shown in Table 5 and Table 6 have been used as inputs in project-wide qualitative geohazard risk assessment. In many areas, the differences in probability were sufficient to support decisive risk classification. In certain other cases, the assessed risk was too close to decision thresholds, given the inherent uncertainties in the assessment. In these cases, larger scale terrain interpretation was necessary to refine the interpretations, and in selected cases subsurface data would be necessary to support a decisive interpretation. Notwithstanding these limitations, the mapping approach was useful in focussing attention to areas meriting more detailed attention on the basis of either ground conditions or seismic load.

The interpretations in this paper are based on a limited dataset and would benefit from additional subsurface and susceptibility map data from other projects in BC.

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