GEOLOGICAL AND GEOTECHNICAL BASIS FOR SEISMIC MICROZONATION ASSESSMENTS ON THE CANADIAN WEST COAST

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ABSTRACT
The west coast of Canada is the most seismically active region in the country and ground conditions susceptible to earthquake-induced hazards are widespread. These conditions include: highly liquefiable fluvial, deltaic and beach sands; soft, Late Pleistocene, glaciomarine clays susceptible to amplification; and steep slopes with unconsolidated sediments prone to earthquake induced landslides. To help mitigate these hazards, seismic microzonation maps have been developed for landuse and emergency planning purposes by quantitatively assessing the hazards of different geologic units. Liquefaction hazard ratings are based on determinations of liquefaction potential (probability of liquefaction severity) and lateral displacement index. Amplification of ground motion hazards are evaluated using site classes defined by the U.S. National Earthquake Hazard Reduction Program. Slope instability hazards are assessed by combining the yield acceleration of representative slopes with the NBCC seismic model to estimate the probability of failure. The results of microzonation studies in three areas are summarized here.

RÉSUMÉ
La côte Ouest du Canada est la région sismique la plus active du pays, et les conditions de terrain favorables aux effets de sites sont très répandues. Ces conditions comprennent : les sables fortement liquéfiables fluviatiles, deltaïques, et littoraux; les argiles molles, tardi-Pléistocène, et glaciomarines susceptibles d'amplifier les vibrations; et les pentes abruptes formées de sédiments meubles pouvant être affectées par des glissements de terrain. Afin de contribuer à la réduction de ces aléas, des cartes de microzonage sismique ont été préparées pour l'aménagement du territoire et la planification des urgences, en évaluant de façon quantitative les aléas des différentes unités géologiques. La cotation de l'aléa dû à la liquéfaction est basée sur la détermination du potentiel de liquéfaction (probabilité de la gravité de la liquéfaction) et d'un indice de déplacement latéral. L'aléa dû à l'amplification des mouvements vibratoires est évalué en définissant différentes catégories de site conformément aux recommandations du "U.S. National Earthquake Hazard Reduction Program". L'aléa dû aux instabilités de pentes est défini en combinant l'accélération critique de talus représentatifs avec le modèle sismique proposé dans le Code national de construction du Canada (CNCC), ce qui permet d'estimer la probabilité de rupture. Les résultats d'études de microzonage effectuées dans trois secteurs sont résumés ici.

1. INTRODUCTION

Seismic microzonation maps, also referred to as earthquake hazard maps, are detailed maps that identify the relative potential for ground disturbance during an earthquake. Seismic microzonation is the process of determining absolute or relative seismic hazard due to the effects of hazards such as amplification of ground motion, slope instability and liquefaction. Earthquake hazard maps are compiled from geologic and geotechnical data that reflect local site conditions and which, in addition to earthquake source and magnitude, exert a major control on potential ground disruption. They depict the severity of earthquake hazard that is expected in a map unit relative to other units. Although the size and location of future earthquakes are difficult to predict, the behaviour of the soil at any one location relative to another can be estimated by evaluating local site conditions. Thus, although predictions of when and where the next earthquake will occur are not possible, areas that are susceptible to ground disruption during an earthquake can be identified. Empirical data from historical earthquakes show that damage is largely controlled by site characteristics, which can be readily mapped. Earthquake hazard maps based on site geology, therefore, can be used directly as a predictive planning tool. Specific applications of the hazard mapping include the development of emergency plans, regional land use plans and economic loss estimations.

In this paper, we review the approaches used in recent seismic microzonation mapping programs in southwest British Columbia, Canada. The relative potential for ground disturbance is quantified for each hazard so that assessments can be compared throughout the province on a standardized basis. Earthquake hazard maps are a cost-effective way to regionally assess vulnerable facilities and they provide fundamental information for developing seismic hazard mitigation policies. Mapping programs in British Columbia, since their inception, have been developed in cooperation with public planners and resource managers and emergency preparedness associations at regional, provincial and federal government levels. Liquefaction, amplification, and landslide hazard mapping programs in the Victoria, Chilliwack and Richmond regions are provided here as examples.

The west coast of Canada has one of the highest earthquake risks in the country and is subject to large (M6-8) crustal and subcrustal earthquakes as well as very large (M9) subduction zone earthquakes (Rogers, 1994). Geologic evidence for past earthquakes is widespread in the region (Clague, 1996). The largest earthquake in Canada (M 8.1) occurred near the Queen Charlotte Islands in 1949. The 1946 earthquake (M 7.3) near Courtenay was the most destructive in western Canada. In addition, many highly populated areas in the region have ground conditions susceptible to earthquake-induced hazards such as liquefaction, amplification and slope instability. Much of the Greater Vancouver region, for example, is underlain by liquefiable deposits of the Holocene Fraser River delta. Likewise, glaciomarine clays susceptible to ground motion amplification are common in coastal areas on southern Vancouver Island. Earthquake-induced land sliding is also considered to be a particularly important seismic hazard in British Columbia because of the potential for causing severe damage to structures and extreme risk to human life, as demonstrated by historic and recent earthquakes in various parts of the world. These maps may be used by planners to determine, for example, what emergency routes, services and buildings might be impacted in various areas.

1.1 Previous Studies

A provincial seismic microzonation program was initiated in British Columbia in 1993 with the establishment of a Seismic Microzonation Task Group. The first objective was to develop standards and recommended procedures for seismic microzonation, also referred to as earthquake hazard mapping (Klohn-Crippen, 1994) and the second was to evaluate the usefulness of these maps for land use and emergency planning purposes (Levson et al., 1998a). Subsequently, a pilot project, evaluating liquefaction and ground-motion amplification hazards, was conducted in the Fraser River valley near Chilliwack (Levson et al., 1996a). The program included detailed geologic mapping, compilation of geotechnical data, field testing, subsurface geological modelling in a GIS, and production of liquefaction, amplification and generalized earthquake hazard maps for technical users and land use and emergency planners (Levson et al., 1996b). A similar program was later conducted in the Capital Regional District (Monahan and Levson, 1997, 2001; Monahan et al., 1998) and the Victoria earthquake hazard map series was published in the millennial year (Levson et al., 2000; Monahan and Levson, 2000; McQuarrie and Bean, 2000, Monahan et al., 2000a,b,c). In the last few years, the B.C. Ministry of Energy and Mines has been working with the Universities of Victoria and British Columbia on evaluations of earthquake hazards in the Richmond area, especially in relation to dyke stability along the Fraser River.

In addition to Canadian studies, seismic microzonation mapping also has been conducted in adjoining Pacific Northwest states, particularly Washington and Oregon (e.g. Mabey et al., 1994, 1997; Palmer et al., 1995; Madin and Wang, 2000a,b; Black et al., 2000). In these studies, evaluations of amplification, liquefaction, and landslide hazards, are commonly combined into one relative earthquake hazard map for planning purposes.

2. METHODS

The initial step in the British Columbia seismic microzonation programs has been the preparation of Quaternary geology maps that reflect the thickness and distribution of Quaternary stratigraphic units in the upper 20-30 m. Map units are defined on the basis of subsurface stratigraphy, geotechnical properties and geomorphic characteristics. Development of the maps requires collection and evaluation of large volumes of subsurface data including geotechnical borehole records, water well logs, and engineering drawings of excavations.

Hazard ratings for the microzonation maps are derived by applying consistent and quantifiable criteria to each Quaternary geology map unit as described below for three types of hazards.

2.1 Mapping Liquefaction Hazards

Liquefiable sediments are widespread in southwest British Columbia, especially in the Fraser River delta where a large percentage of the provincial population resides. The susceptibility of a site to liquefaction is dependent mainly on the density, grain size and age of the underlying deposits and the water table depth (e.g. Youd and Perkins, 1978). In our studies we assign hazard ratings to each geological map unit based on an analysis of these factors as well as quantitative analyses that combine estimates of liquefaction susceptibility using site characteristics (Seed et al., 1985) with probabilistic ground motions from the National Building Code of Canada (NBCC) seismic model. A depth weighting function, that is greatest at the surface and zero at 20 metres depth, is then applied to provide a measure of the severity of the liquefaction hazard in each map unit at the surface (PLS; Levson et al., 1995, 1998b). In the Richmond area, more detailed assessments of the liquefaction hazard along the river have been conducted by evaluating the potential for lateral displacement, using the methods of Zhang et al. (2001, 2002).

2.2 Mapping Amplification of Ground Motion Hazards

Relative ground motion amplification hazard ratings are estimated for each geological map unit on the basis of site classes for susceptibility to amplification, defined by the National Earthquake Hazard Reduction Program (NEHRP). Shear wave velocity data were collected for different surficial geology units using data from seismic cone penetration tests and spectral analysis of surface waves (c.f. Robertson et al., 1992). The NEHRP site classes are defined primarily on the basis of the average shear-wave velocity in the upper 30 m of the underlying soil and rock (Building Seismic Safety Council, 1994; Finn, 1994). Unit assignments are calibrated using geotechnical data and shear wave velocity information from seismic cone penetration tests and other subsurface investigation methods.

2.3 Seismic Slope Stability Hazards

Slope instability hazards are assessed by determining the yield acceleration of typical slopes, considering slope angles and strengths of the geological units present. Yield accelerations are then combined with the probabilistic seismic model to estimate the probability of slope failure. In the Victoria area, for example, seismic slope hazard mapping was based on a compilation of existing subsurface data, previous slope stability assessments, bedrock geology, surficial geology, topographic data, airphoto interpretation, and field observations (McQuarrie and Bean, 2000). Slope stability analyses were performed on representative slopes in different types of geological materials to determine the static factor of safety and acceleration levels that would cause slope failure. The slope instability hazard was found to be greatest along sea cliffs with exposed sediments and along valleys and gullies deeply incised into these deposits. Similar to the approach used to assign liquefaction hazard ratings, the probability of slope failure was estimated for soil slopes by combining the yield acceleration with NBCC probabilistic ground motions. For rock slopes, most of which are relatively stable in the region, the hazard rating was assigned using mainly qualitative criteria (McQuarrie and Bean, 2000).

3. CHILLIWACK MICROZONATION MAPS

The first microzonation mapping program in British Columbia was initiated in 1994 in the Fraser River valley near Chilliwack. The study area includes a number of communities and is a critical corridor in the Lower Mainland that supports the Trans-Canada Highway, B.C. Hydro's Main Transmission Line, and the Fraser River and Vedder Canal dykes. Liquefaction and amplification hazards were selected for consideration. The first step in the mapping program was the compilation of existing geotechnical borehole data from private and public agencies and geotechnical consultants. The resulting database includes information on sediment type, stratigraphy, depth to bedrock, moisture content and a variety of geotechnical characteristics (e.g. penetration test data, liquid and plastic limits, shear wave velocity, shear strength, water table). The database includes over 2400 testholes concentrated in the vicinity of highways, rail lines, communities, dykes and power lines. New high quality geotechnical data were collected as part of the field investigations to supplement the existing data. Seismic cone penetration tests (SCPT's) were conducted at sites with sandy or silty soils, and Becker penetration tests and spectral analysis of surface waves (SASW) tests were conducted at locations in gravel rich areas to assess the liquefaction susceptibility of these deposits.

Surficial geology mapping was integrated with geotechnical borehole data to produce a subsurface geological model of the area. The Fraser River floodplain, which dominates the area, is underlain by about 50 metres of sand and gravel interbedded with silt and peat that is interpreted to represent a prograding deltaic and overlying fluvial sequence. These deposits are underlain by Holocene and/or earlier glaciomarine silts, clays and sands that locally extend to depths of over 400 metres. The Fraser River floodplain deposits pass laterally into Holocene lacustrine sands, silts and clays in the Sumas Valley. Gravels deposited in an alluvial fan where the Chilliwack-Vedder River enters the Fraser Lowland are over 35 metres thick at the mountain front and have prograded over older deposits in the Sumas and Fraser River valleys. A large area of landslide debris that overlies glaciogenic deposits and is capped by up to 10 metres of soft silt, peat and marl, occurs in the eastern end of the study area. Upland areas are mantled by glacial deposits and locally are capped by up to several metres of loess.

The next step in the program was the compilation of a chronostratigraphic surficial geology map. Data collected for each map unit included information on the type, geomorphic characteristics, age, genesis and thickness of surficial sediment that dominates each map unit. Surficial geology and geotechnical data were then digitized and inputted into a GIS. Quantitative hazard evaluations were conducted at specific sites within the map area where good quality geotechnical data were available.

From these data, an earthquake-induced liquefaction hazard map of the study region and an amplification of ground motion hazard map were completed using the procedures described above. The liquefaction hazard was presented as the probability of liquefaction occurring in a 50 year period and includes a measure of severity of surface disruption (PLS) which is a function of the depth and thickness of each liquefiable unit. The amplification hazard is presented using the NEHRP classification. Hazard ratings are shown in relative terms (e.g. high, medium, low) but are based on quantifiable data. The hazard assessments are commonly shown as a range of hazard ratings, due to natural geological variability within units. The two maps were constructed separately but landuse and emergency planners in the region requested that they be simplified into a composite hazard map. This was accomplished by defaulting to the highest hazard rating within any one map unit, rather than attempting to assign relative hazard weightings to the two different hazards and then combine the weightings into a composite rating. The resulting map is both conservative and relatively simple for planners to use as it shows only the highest hazard rating for each map unit. The original data from the two hazard assessments are retained, however, as the liquefaction and amplification hazard maps are provided as insets on the composite map (Levson et al., 1996b).

4. VICTORIA EARTHQUAKE HAZARD MAP

Earthquake hazard map units in the Greater Victoria region are largely derived from a Quaternary geology map showing the thickness and distribution of Quaternary stratigraphic units in the area (Monahan and Levson, 2000). This map is based on air photo interpretation, detailed topographic maps and subsurface geological and geotechnical data including over 5000 geotechnical borehole logs, several hundred water well logs, nearly 3000 engineering drawings for municipal sewer and water lines, and data from a shear-wave and seismic cone penetration testing program. The map was produced as an initial step in evaluating earthquake hazards in the region and geological map units were defined in part to reflect their susceptibility to hazards such as ground motion amplification.

The Victoria region is characterized by a complex and highly variable distribution of soil types. For example, rock is often exposed at the surface directly adjacent to thick (up to 30 m) Late Pleistocene, glaciomarine, soft clays. In low areas, the clays are commonly capped by Holocene peats or beach sands, and in elevated sites they grade up into stiff desiccated clay. Late Wisconsinan till, older Pleistocene sediments and late-glacial, deltaic glaciofluvial gravels also are common.

The composite Victoria area map (Monahan et al., 2000a; Fig. 1) shows the relative susceptibility of soils in the Greater Victoria area to three of the most important earthquake hazards in the region: amplification of ground motion, liquefaction, and earthquake-induced slope instability hazards. The map was compiled using the methods described above for each of the three hazards. Since amplification of ground motion is the regionally dominant hazard, the map colours reflect this hazard and various types of cross-hatching are used to illustrate the locally significant effects of liquefaction and landslide hazards.

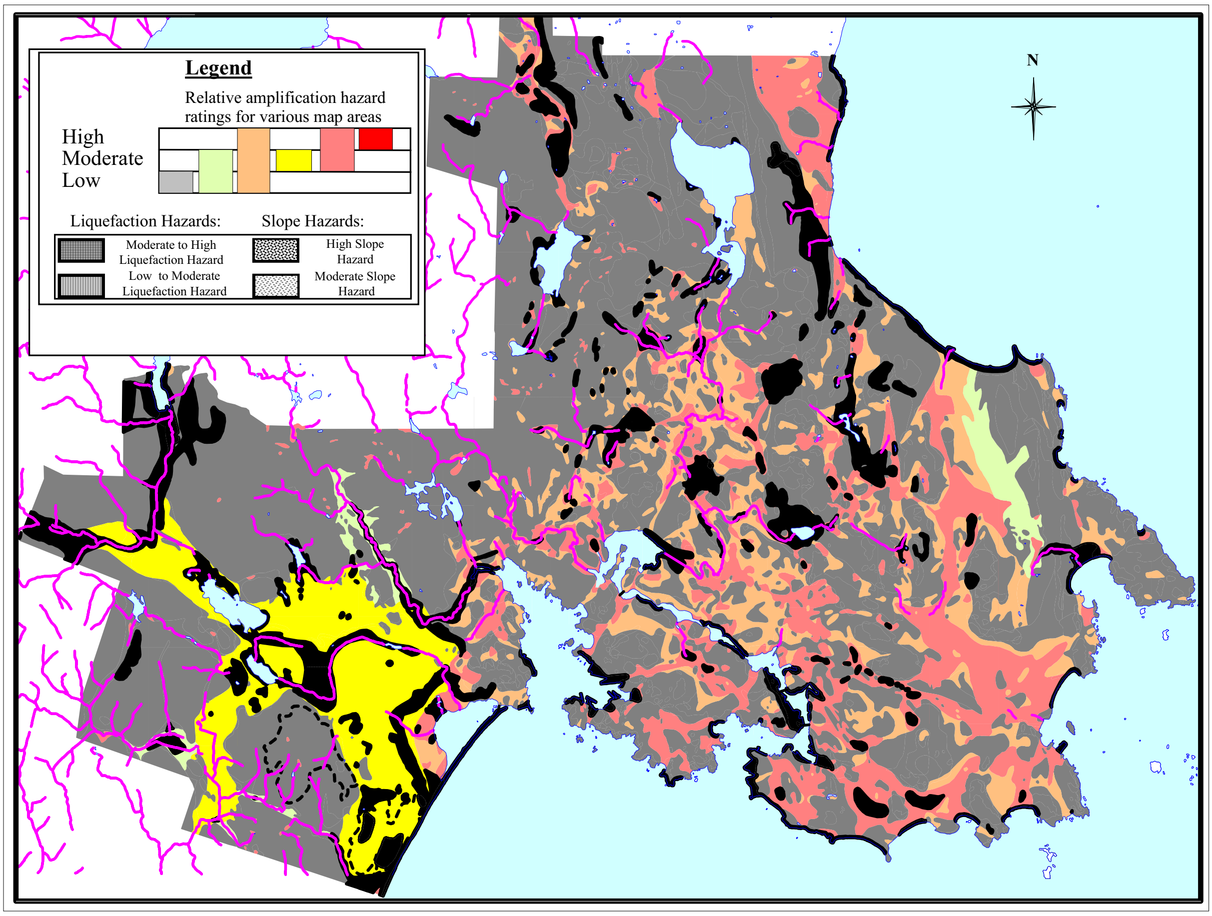

Figure 1. Simplified earthquake hazard map of the greater Victoria region (modified from Monahan et al., 2000a) produced for land use and emergency planning purposes. The map shows mainly the ground motion amplification hazard (in colours) but areas with moderate to high liquefaction and slope hazards are shown with cross-hatching and stippling, respectively.

5. RICHMOND LIQUEFACTION AND DYKE STUDIES

The most recent applications of our microzonation work include evaluations of liquefaction hazards in the City of Richmond and of the seismic stability of river and sea dykes. The latter study was initiated in order to estimahe most recent applications of our microzonation work include evaluations of liquefaction hazards in the City of Richmond and of the seismic stability of river and sea dykes. The latter study was initiated in order to estimate the potential deformation that the dykes would experience due to liquefaction during a major earthquake. The dykes provide flood protection to Richmond and other cities in the region built on Holocene deposits of the Fraser River delta. Earthquake hazards in the delta region are exasperated by the potential for widespread flooding that might occur following an earthquake if the loose sandy delta sediments under the dykes liquefied and, in a worse case, failed catastrophically. Liquefaction and possible resultant lateral displacements are the principal earthquake hazards that could potentially affect the dykes.

The City of Richmond is situated entirely on deposits of the Fraser River delta, which has been prograding out into the Strait of Georgia since the last glaciation ended approximately 13,000 years ago (Clague et al., 1998). The deltaic sediments overlie dense Pleistocene sediments that were overridden by glaciers. These dense materials provide firm ground for foundations where they occur at the surface, such as in much of Vancouver, Burnaby and Surrey. However, in the Fraser delta, the depth to the Pleistocene deposits generally exceeds 100 metres and reaches a maximum known depth of 300 metres at Richmond City Hall.

The deltaic sediments can be grouped into “topset” and “foreset” deposits (Clague et al., 1998; Monahan, 1999). Topset deposits form the uppermost (i.e. shallowest) 12 to 30 metres of the deltaic sequence and were deposited on the delta plain in river channel, tidal flat and floodplain environments. The topset deposits in the Fraser River delta consist of a thick lower massive sand layer, a middle layer of interbedded sands and silts, and an upper layer of laminated and organic silts (Figure 2). The massive sand was deposited in bars and islands in active river channels. Where the sand is shell-bearing, we interpret it to have been deposited by channels crossing a tidal flat environment, analogous to the modern Main Channel of the Fraser. The massive sand is locally overlain by interbedded sands and silts interpreted to be abandoned or intermittently active channel-fill deposits. The middle layer of interbedded silty sands and sandy silts also are shell bearing and extensively burrowed by marine organisms. This layer is interpreted to have been deposited in a tidal flat environment. The uppermost laminated and organic silts were probably deposited in a tidal marsh. Foreset deposits, consisting of interbedded and interlaminated silts and sands, underlie the topset sequence and were deposited on the delta slope beyond the river mouth. The foreset deposits generally slope to the west at approximately 7 degrees (Monahan, 1999). This is consistent with upper part of the modern delta slope, which slopes seaward at a similar angle.

5.1 Liquefaction analysis

The liquefaction susceptibility of the deltaic sediments has been estimated by analyzing CPT data using the procedures recommended by Robertson and Wride (1998) and modified by Youd and Idriss (2001). In their approach, the CPT data are used to calculate the “cyclic resistance ratio” (CRR), which is the resistance of the sediments to liquefaction. The CRR is then compared to the “cyclic stress ratio” (CSR), which represents the force imparted by the earthquake. Results show that CSR is commonly greater than CRR, in the massive sand layers that underlie the region. This conclusion is consistent with other studies, which concluded that the massive sand layer is the principal contributor to the liquefaction hazard in the delta (e.g. Watts et al., 1992). Standard penetration test (SPT) data, processed in a similar manner as the CPT data according to procedures defined by Youd and Idriss (2001), generates similar results. Sands deposited in channel environments, such as these have been, are generally looser than sands deposited on beaches (de Mulder and Westerhoff, 1985). Denser layers that locally occur in the lower part of the massive sand close to the river mouth may have been densified by wave loading.

The layer of interbedded sands and silts in the topset is shown by the CPT analyses and laboratory tests to include both liquefiable and non-liquefiable beds. The silts are locally susceptible to liquefaction due to burrowing by marine organisms that mixed the silts with sand, thus reducing their overall clay content. The organic silts of the topset sequence are typically too clay-rich to liquefy.

The foreset sequence consists of interbedded and interlaminated sands and silts. The CPT-based liquefaction analysis indicates that, like the topset sands and silts, both liquefiable and non-liquefiable layers occur. Numerous samples of silty beds from the foreset have been analyzed in the Fraser River delta, and are they are typically too clay-rich (>15% clay) to liquefy although rarely they may be marginally liquefiable. Because the grain size of silts generally decreases with depth in the delta, deep foreset silts are thought to be non-liquefiable.

For the purposes of comparing the liquefaction hazard at different sites, we use the PLS calculated by estimating the layer-by-layer probability of liquefaction. We have also calculated the “lateral displacement index” (LDI), a parameter defined by Zhang et al. (2001, 2002) to estimate the potential lateral displacements that could occur due to liquefaction. Detailed assessments were conducted at a number of sites along the Fraser River channels. The lateral displacement was calculated according to Equation 1 (Zhang et al., 2001):

$$\text{Lateral displacement} = 5 * (FFR)\ 0.7 * LDI \qquad [1]$$

LDI is the lateral displacement index and FFR is the “free face ratio” (slope height over distance to the river bottom determined from detailed, bathymetric survey data). LDI was calculated using quantitative geotechnical data at 164 locations and analyzed using the procedures of Robertson and Wride (1998) and Youd and Idriss (2001). The earthquake stresses were calculated using an earthquake magnitude of 7 and an acceleration of 0.3g (30% of the force of gravity), or the acceleration due to the 500 year earthquake amplified by a factor of 1.5, as recommended by Byrne and Anderson (1991). The results of the lateral displacement calculations were compared with detailed computer-based earthquake simulations and dynamic stability analyses conducted at a number of sites using the programs TARA-3 and TARA-3FL (Finn et al., 1986). The potential for lateral displacement varies significantly in the study area and reflects mainly the slope of the sides of the river bed and the Quaternary geology, with the hazard being greatest along steep erosional reaches adjacent to young paleochannel sands. The results of these studies are being used for earthquake mitigation purposes such as prioritization of river dyke seismic upgrades.

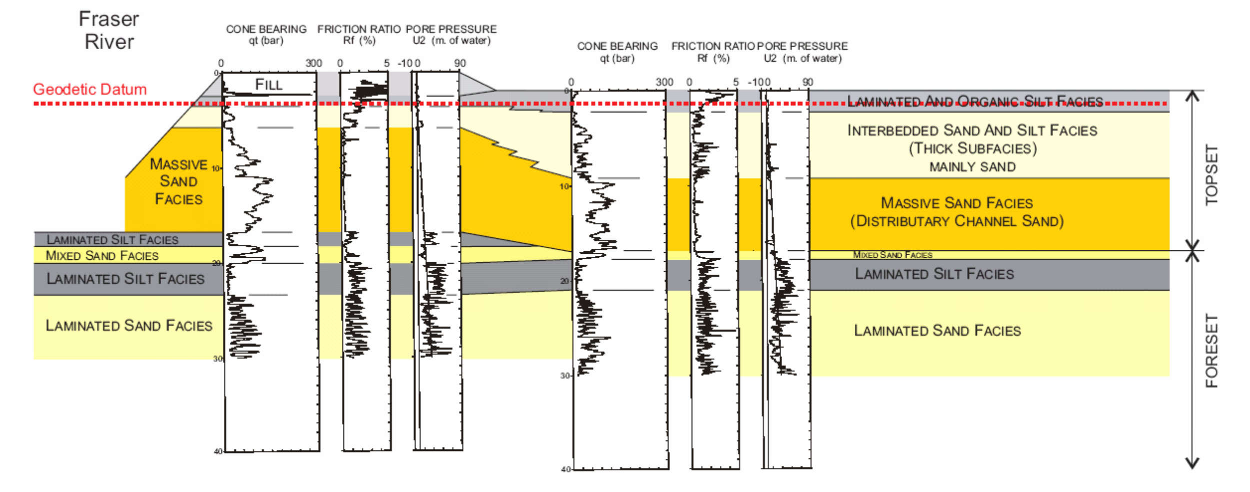

Figure 2. Schematic cross-section along the Fraser River through a river dyke drawn from cone penetration test data. Note the variable thickness of the massive sand facies (channel sands) and overlying sand and silt facies (abandoned channel-fill deposits).

6. CONCLUSIONS

Earthquake hazard maps derived from Quaternary geology and geotechnical data are an effective tool for identifying liquefaction, amplification and landslide hazards for landuse and emergency planning purposes. Along the west coast of North America, microzonation studies have become a standard component of emergency preparedness programs. Geological units susceptible to one or more hazards are identified and detailed hazard assessments are conducted at representative sites within each unit. The evaluations and resultant ranking schemes are quantifiable and therefore they can be consistently applied across wide regions. The maps can be prepared for technical or non-technical users. Applications of microzonation maps include identification of vulnerable lifeline systems, setting realistic insurance rates, prioritizing seismic retrofitting, developing earthquake loss estimations, and selecting low hazard areas for locating emergency organization facilities.

Earthquake hazards are quantified using a variety of analyses including assessments of liquefaction potential, liquefaction severity, lateral displacement, dynamic stability, shear wave velocity, and yield acceleration determinations. Quantification is also provided by combining evaluations with the National Building Code of Canada seismic model to give probabilistic assessments and by applying site classes defined by the U.S. National Earthquake Hazard Reduction Program.

Liquefaction hazards are found to be highest in areas underlain by fluvial and deltaic sands, Holocene beach sands, and in artificial fills. Young river alluvium and channel sands in the topset sequence of the Fraser River delta are of particular concern as are loose sediments and fill that commonly underlie port facilities and other shoreline developments. Amplification hazards are greatest in areas underlain by thick deposits of soft, Late Pleistocene glaciomarine clay. Sediments of this type are common on the west coast of Canada where late glacial sea levels were commonly 100 or more metres higher than present. In the greater Victoria area, soft clays pose an amplification hazard in many developed areas, particularly where they are capped by peat and organic soils in low-lying depressions. Earthquake induced slope hazards are common where steep exposures of unconsolidated sediments occur, such as along sea cliffs and incised stream valleys and gullies.

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