SURFICIAL GEOLOGY AND EARTHQUAKE HAZARD MAPPING, CHILLIWACK, BRITISH COLUMBIA (92G/1 & H/4)

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INTRODUCTION

Earthquake hazard mapping in British Columbia is currently being conducted by the Ministry of Energy, Mines and Petroleum Resources, in cooperation with the B.C. Resource Inventory Committee, the Provincial Emergency Program and Emergency Preparedness Canada. The program is coordinated by the Seismic Microzonation Task Group of the Resource Inventory Committee. To date, the program has included a compilation of earthquake hazard mapping standards and methods (Klohn-Crippen Consultants Ltd., 1994), a conference for land-use and emergency planners (Levson *et al.,* in preparation) and an earthquake hazard mapping pilot project in the Chilliwack area (Levson *et al.,* 1995). The latter project was started in August, 1994 and covers the District of Chilliwack and parts of the Fraser-Cheam Regional District (contained within NTS mapsheet 92H/4W south of the Fraser River and north of 49° 03' N lat.; Figure 1). Earthquake hazards in the Chilliwack area include landslides, liquefaction and amplification hazards, but only liquefaction hazards are discussed in this paper.

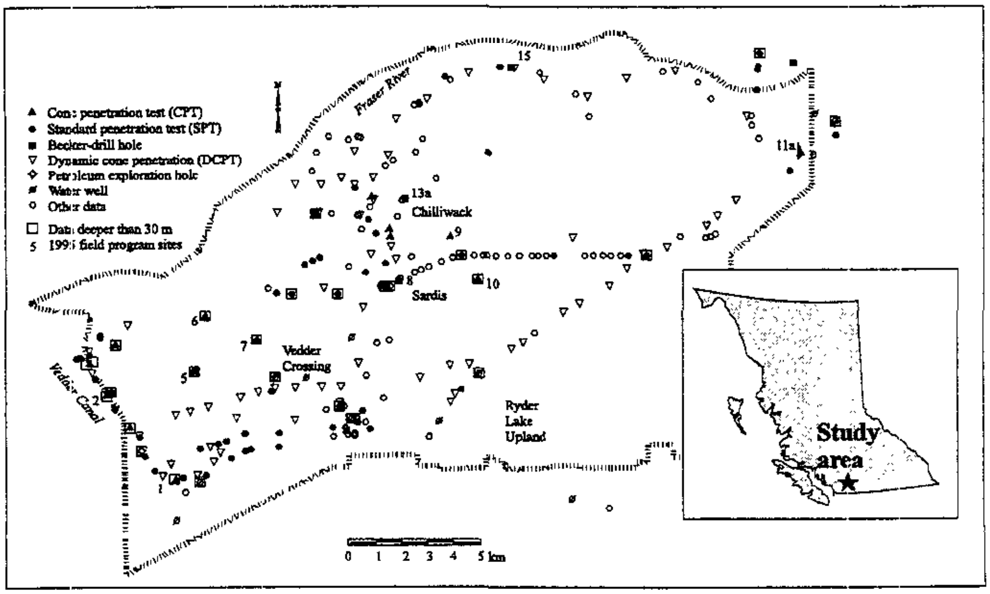

Figure 1. Distribution and type of geotechnical borehole data collected for the study area.

Earthquake hazard maps, or seismic microzonation maps, are detailed (generally 1:20 000 to 1:50 000 scale) maps that identify the relative potential for ground disturbance during an earthquake. Seismic microzonation is defined as "the process of determining absolute or relative seismic hazard at many sites accounting for the effects of geologic and topographic amplification of motion and of soil stability and liquefaction, for the purpose of delineating seismic microzones" (Earthquake Engineering Research Institute, Committee on Seismic Risk, 1984). Earthquake hazard maps are compiled from geologic and geotechnical data and reflect local site conditions, which in addition to earthquake source and magnitude, exert a major control on potential ground disruption. They identify regions that are expected to experience the same relative severity of earthquake hazard and they are used mainly for land-use and emergency planning and prioritizing structural upgrades.

PREVIOUS WORK

Earthquake hazard mapping has been completed and successfully applied in many countries throughout the world (Levson *et al.*, in preparation). Of particular relevance to British Columbia is recent mapping in Washington and Oregon (Grant *et al.*, 1991; Mabey and Madin, 1993; Mabey *et al.*, 1994; Palmer *et al.*, 1994). Excellent reviews of earthquake hazard mapping methods have been provided by Finn (1991, 1994) and Youd (1991).

Previous related studies in British Columbia include a liquefaction hazard map of the Lower Mainland region focusing on B.C. Hydro's infrastructure (B.C. Hydro, 1992; Watts *et al.*, 1992). A thorough review of earthquake hazards in British Columbia and methods of seismic microzonation mapping for land-use planning purposes was recently completed by Klohn-Crippen Consultants Ltd. (1994). Earthquake hazard mapping and its implications for land-use and emergency planning are discussed by Levson *et al.* (in preparation). A preliminary version of this paper, reporting on the Chilliwack pilot project, was provided by Levson *et al.* (1995). Studies related to microzonation mapping have also been recently conducted in the Lower Mainland by the Geological Survey of Canada (*e.g.* Clague *et al.*, 1992; Hunter *et al.*, 1993; Luternauer *et al.*, 1994). Armstrong (1980, 1984) described and mapped the surficial geology of the Chilliwack study area at a scale of 1:50 000. Groundwater studies have been conducted in the region by Halstead (1986) and Dakin (1994). Other relevant regional reports include a geological investigation of the Sumas Valley based on borehole data (Cameron, 1989) and a soil survey of the Chilliwack region (Comar *et al.*, 1962).

EARTHQUAKES IN BRITISH COLUMBIA

Southwestern British Columbia is a seismically active area subject to crustal, subcrustal and subduction earthquakes (Rogers, 1992, 1994). 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. Although a number of damaging earthquakes have occurred in British Columbia and in nearby Washington and Alaska in historic times, most occurred prior to extensive urban development. One of the more recent of these earthquakes, in 1965 in Seattle, caused $12 million in damage. The estimated potential economic impact of a similar (M 6.5) earthquake on the Lower Mainland alone is $14.3 to $32.1 billion (Munich Reinsurance, 1992).

MITIGATION

Earthquake hazard maps provide fundamental information for seismic hazard mitigation and they are critical tools for effective emergency and land-use planning. Current earthquake hazard mitigation programs in British Columbia are mainly site specific or focused on agency-specific facilities. In contrast, earthquake hazard maps can be used for regional seismic vulnerability assessments and they are a cost-effective way to prioritize mitigation efforts. They do not, however, replace the need for site-specific geotechnical evaluations for new construction. General applications of earthquake hazard maps to land-use and emergency planning include: 1) identification of areas with vulnerable lifeline systems (*e.g.* water, gas and power lines); 2) planning transportation and utility corridors; 3) setting priorities for seismic upgrading or remedial work on schools, hospitals, firehalls and other structures; 4) identifying good areas for new essential facilities (*e.g.* schools, hospitals, bridges, toxic waste containment facilities); 5) identifying areas requiring special study before development, or high-hazard areas with restricted development; 6) property insurance; 7) assessment of risk for financing new projects; 8) providing information on site effects for design of new structures; 9) establishing more stringent design requirements where needed (Klohn-Crippen Consultants Ltd., 1994).

The costs of earthquake hazard map production are relatively low compared to the costs of current seismic vulnerability studies and upgrading programs. For example, the British Columbia Ministry of Education has, in recent years, allocated about $30 million per year to seismic upgrading of schools. Similarly, from 1988 to 1994, B.C. Hydro, a leader in seismic hazard mitigation, spent about $18 million on electric system seismic strengthening (excluding dam safety) and about $4 million on seismic studies and research (Katrichak *et al.,* 1994). In comparison, a liquefaction susceptibility map covering parts of the Lower Mainland, (B.C. Hydro, 1992) cost about $110 000 to produce (Klohn-Crippen Consultants Ltd., 1994).

Earthquake hazards can be mapped at different levels of certainty, with the amount, quality and cost of information required generally increasing with each mapping level. For example, liquefaction hazard maps can be grouped into liquefaction susceptibility, liquefaction potential and liquefaction-induced ground displacement maps (Finn, 1994). Liquefaction susceptibility maps (level 1) are based on surficial geology data such as sediment type, geomorphologic characteristics, relative density, deposit age, water table depth and geologic or historical evidence of liquefaction. Liquefaction potential maps (level 2) indicate the probability of liquefaction actually occurring, by accounting for the expected intensity of seismic shaking (based on past records of earthquakes) as well as soil conditions. Liquefaction-induced ground displacement or lateral displacement maps (level 3) can be produced by accounting for ground movement (lateral spreading) on slopes and towards free faces such as river banks (Youd, 1991).

METHODOLOGY

The Chilliwack hazard mapping pilot program comprised several phases: 1) collection of existing geotechnical data; 2) surficial geology mapping at a scale of 1:20 000, focusing on the Fraser River valley and Ryder Lake upland area; 3) collection of new cone-penetration data and shear-wave data at several sites selected to fill gaps in the existing database; 4) input of surficial geology and geotechnical data into a geographic information system; 5) development of a three-dimensional geologic model for the area; 6) evaluation of liquefaction and amplification hazards at specific sites within the map area where good quality geotechnical data are available; and 7) integration of surficial geology and geotechnical data to produce an earthquake hazard map. Borehole data were compiled from private and public agencies including the District of Chilliwack, Chilliwack School Board, B.C. Ministry of Transportation and Highways, B.C. Hydro, B.C. Ministry of Environment (Water Management Division and Groundwater Section), Geological Survey of Canada, Department of National Defense, Public Works and Government Services Canada and geotechnical consultants. Further work on the project may include reflection seismic or ground penetrating radar lines in selected areas where borehole data are lacking or where specific problems need to be addressed. The methods used generally follow those recommended by the Seismic Microzonation Task Group (Klohn Crippen Consultants Ltd., 1994).

The methodology used for the collection of geotechnical data during the field component of the pilot project is described by ConeTec Investigations Ltd. (1995) and is summarized here. Seismic cone penetration test (SCPT) data were obtained using electric cones supplied by ConeTec Investigations Ltd. and deployed with a modified drill rig (MARL-10) operated by Mud Bay Drilling Co. Ltd. (Photo 1). Cone bearing (Qt), sleeve friction (Fs) and dynamic penetration pore pressure (Ut) data were collected at 5-centimetre intervals and recorded digitally. Time-based pore pressure and seismic shear-wave velocity measurements were also recorded every metre. Shear-wave traces were recorded and analyzed according to procedures described by Robertson *et al.* (1986). The spectral analysis of surface waves (SASW) method uses surface waves of the Raleigh type to evaluate the shear-wave velocity and shear modulus profiles of geotechnical sites and to infer soil parameters such as *in situ* density. The method is non-intrusive with both the source (vertical hammer impact) and receivers located on the ground surface. The Becker density test (BDT) uses a diesel hammer to drive a double-walled steel drill-casing into the ground. Blow counts were recorded for each 30.5 centimetres of penetration. The force of each blow was measured, using a pile driving analyzer (PDA), by the British Columbia Ministry of Transportation and Highways.

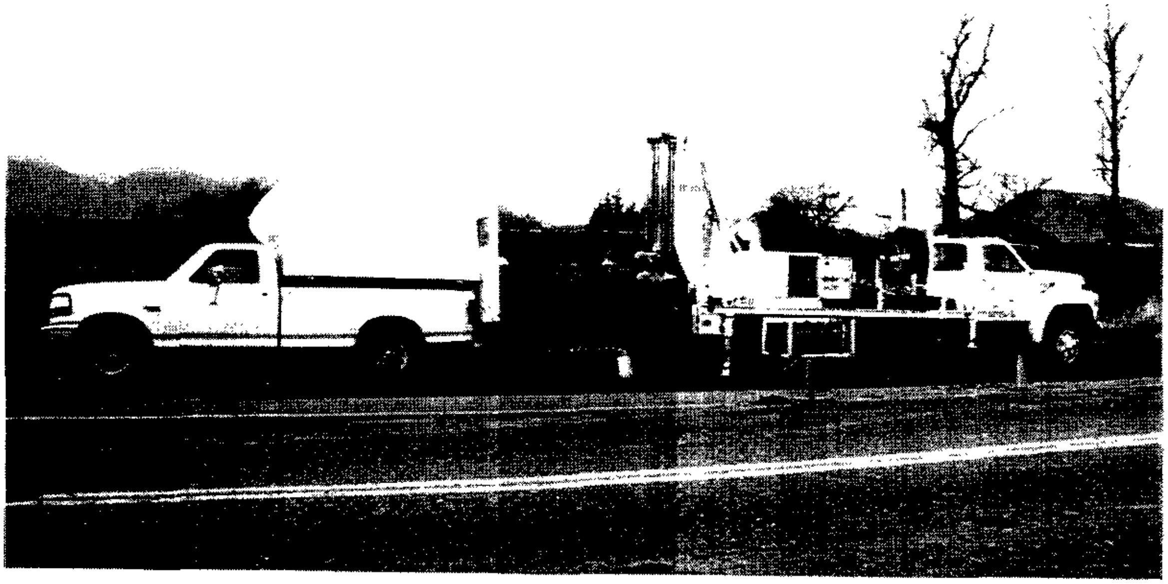

Photo 1. Seismic cone penetration test in progress on Luckakuk Way, south of Chilliwack, showing ConeTec SCPT data-recording truck (left), Mud Bay drill rig (right) and Trans-Canada Highway (background).

GEOTECHNICAL DATABASE

The geotechnical database for the Chilliwack area consists of over 1700 test holes, including approximately 250 holes with standard penetration test (SPT) data, 50 with cone penetration test (CPT) data, 200 with dynamic cone penetration test (DCPT) data, 60 with Becker penetration test (BPT) data and a few sites with shear-wave data (Figure 1). Drill holes are concentrated along the Trans-Canada Highway, in the Chilliwack, Sardis and Vedder Crossing areas, along the Fraser River and Vedder Canal dikes and along B.C. Hydro's main transmission line (Figure 1). An additional 700+ water-well logs are available for the area; about 70 of the deeper wells were selected to fill in gaps in the data (Figure 2). The geotechnical database includes information on the following: sediment type, grain-size distribution, moisture content, depth to bedrock, stratigraphy, penetration test data, Atterberg (liquid and plastic) limits, shear-wave velocity and other seismic data, shear strength, water table and piezometric pressure. The database also includes accurate location information for each geotechnical hole or data collection site, the agency that collected the data, the client and the date of collection.

GEOTECHNICAL DRILLING PROGRAM

Seismic cone penetration tests (SCPT) were conducted at eight different locations (Figure 1). A typical example of the results produced from a SCPT test, including cone bearing (Qt), sleeve friction (Fs), friction ratio (Rf) and pore pressure (U) data, is provided in Figure 3, together with an interpretive log of the site. Sands and gravelly sands, fining upwards to silts in the upper 5 metres of the profile, are interpreted to represent alluvial fan deposits. They overlie floodplain silts and clayey silts (at 5-10 m depth) and older Fraser River alluvium (below 10 m depth).

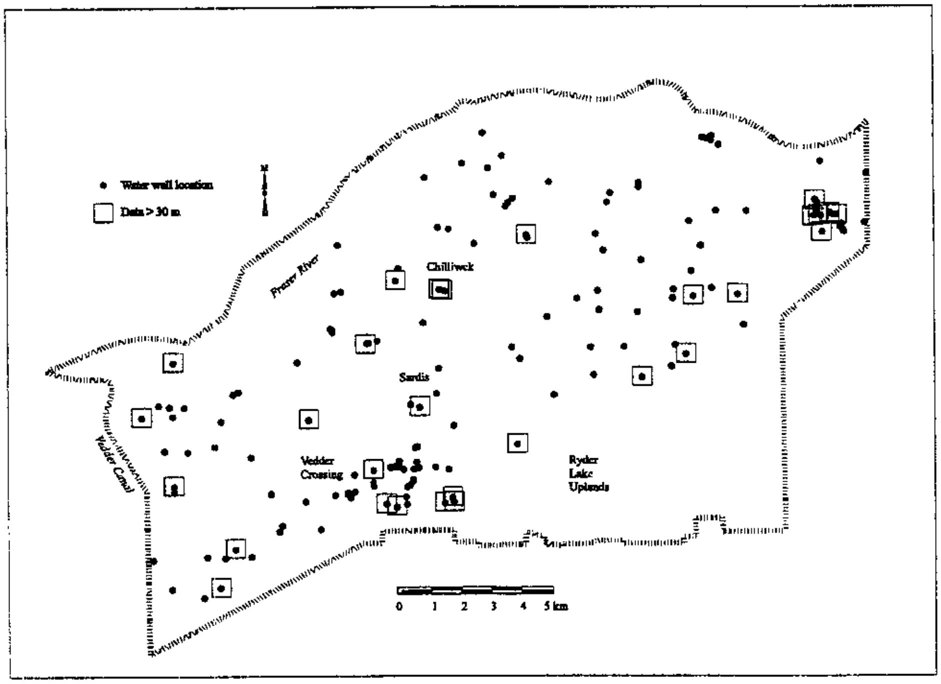

Figure 2. Distribution of water-well boreholes in the study area.

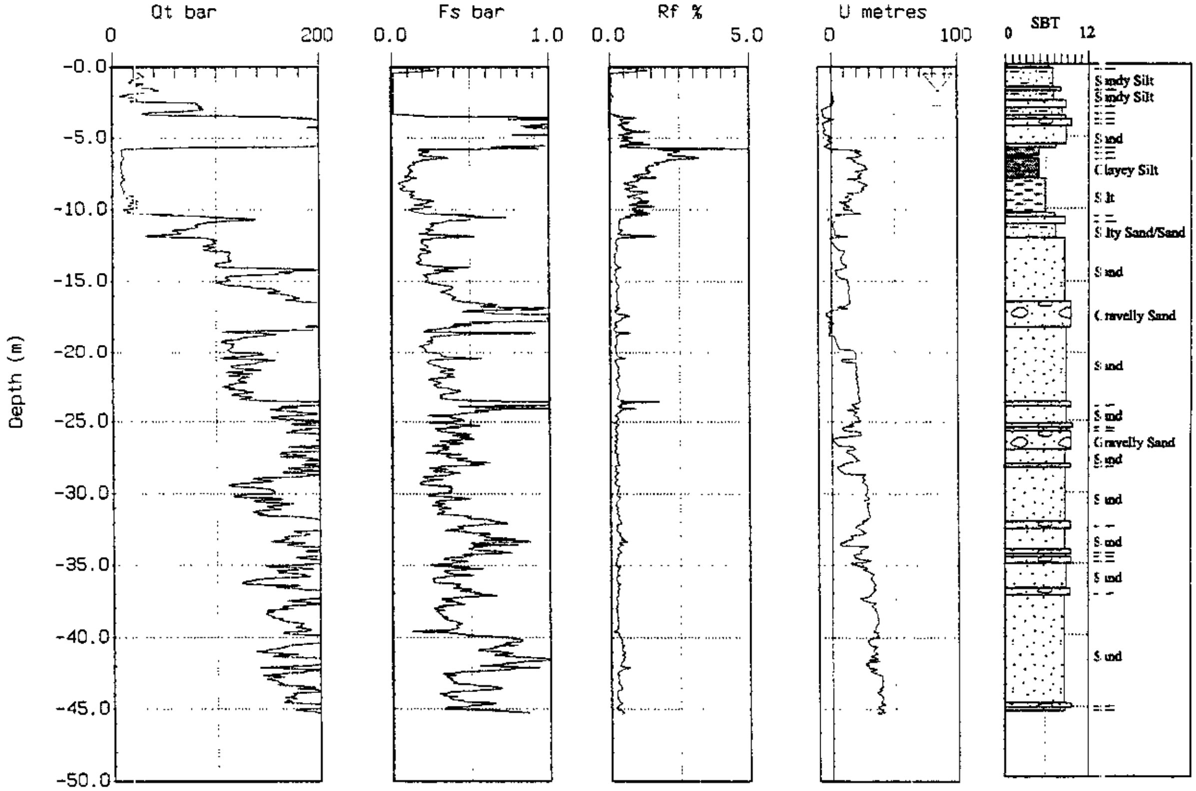

Figure 3. Cone penetration test results from location 7 (Figure 1) showing cone bearing (Qt), sleeve friction (Fs), friction ratio (Rf), pore pressure (U) and soil behavior type (SBT; after Robertson and Campanella, 1988). Alluvial fan sediments in the upper 5 metres of the profile overlie floodplain silts and clayey silts (at 5-10 m depth) and older Fraser River alluvium (below 10 m depth).

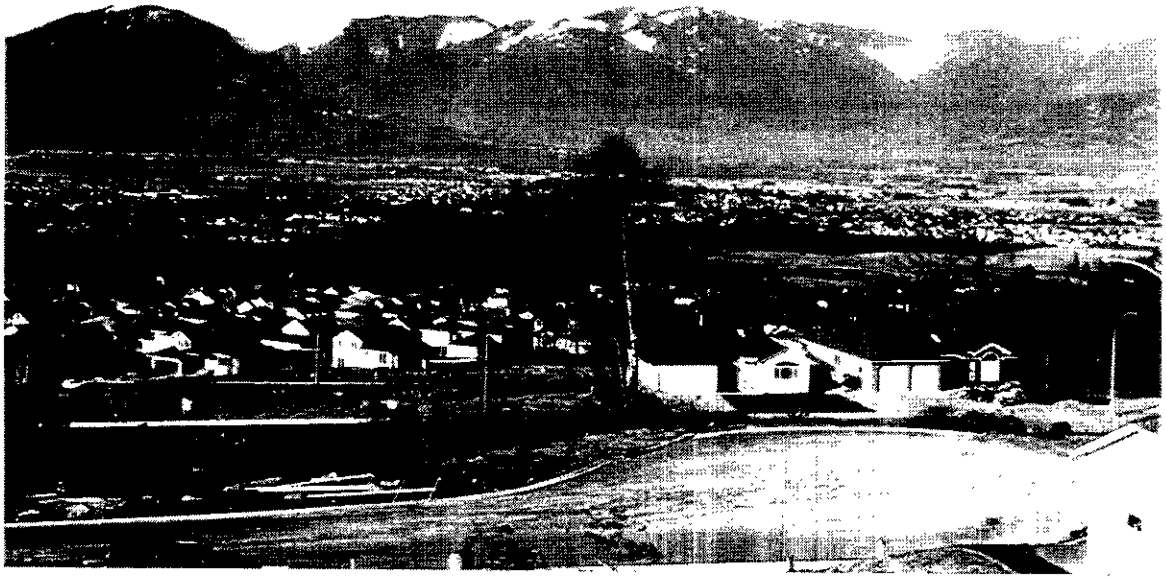

Photo 2. View from the edge of the Vedder Upland northwestward across the Vedder River alluvial fan (foreground) and the Fraser River floodplain (centre). Mountains in background are outside the study area, north of the Fraser River.

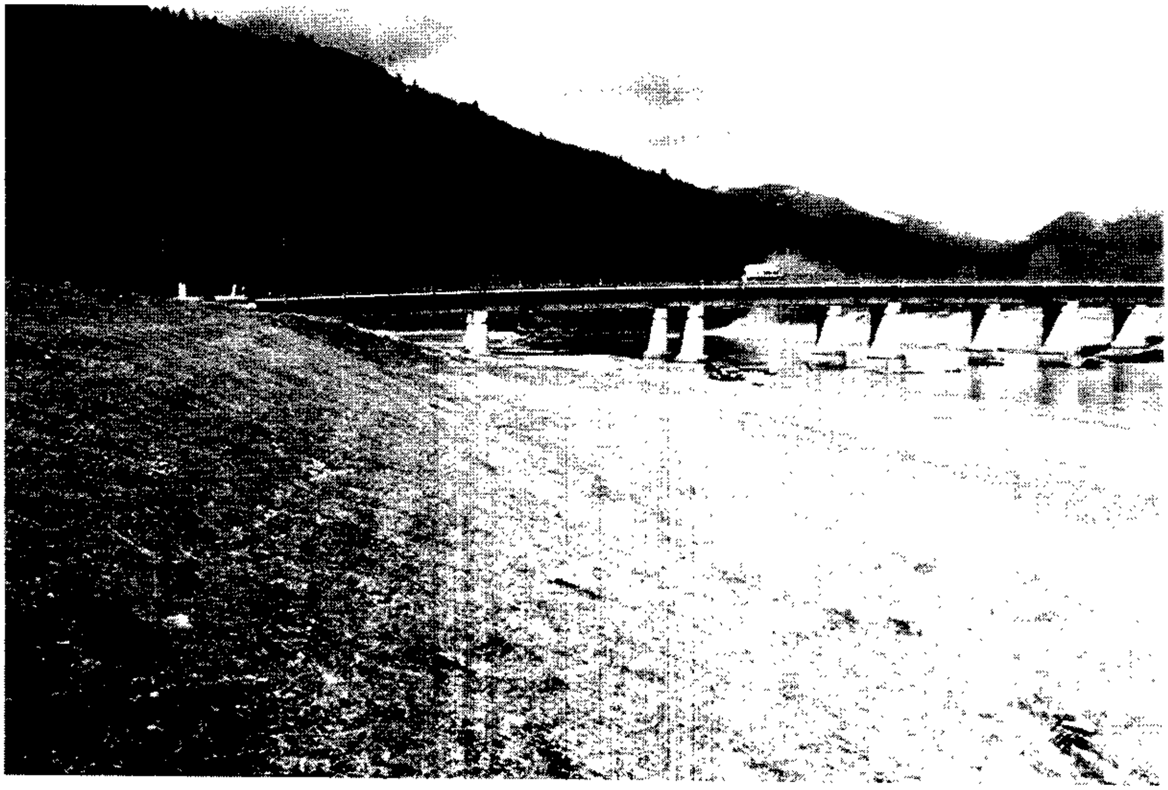

Photo 3. Trans-Canada Highway bridge over the Vedder River canal. Canal dikes (west embankment shown on left) are the highest in British Columbia and protect a large part of the Fraser River valley from flooding.

Spectral analysis of surface waves (SASW) and Becker penetration test (BDT) data were acquired to assess the liquefaction susceptibility of three gravel-rich areas, where conventional CPT or SPT equipment could not be used. Open Becker tests were conducted at two of these sites (8 and 13a) to penetrate the near-surface gravels and allow for deeper SCPTs. Complete results of the program are provided by ConeTec Investigations Ltd. (1995).

SURFICIAL GEOLOGY

Figure 4 is a chronostratigraphic surficial geology map of the study area, compiled at a 1:20 000 scale using existing information sources, aerial photographic mapping and field confirmation. Data collected for each map unit include: type of sediment, grain-size characteristics, thickness, age, genesis, subsurface stratigraphy and hydrogeologic, geotechnical and geophysical properties. Geological analysis and interpretation of the surficial geology data include an assessment of data quality, description of the relationship of map units with the subsurface stratigraphy and geological interpretation.

The surficial geology of the area is dominated by the Fraser River floodplain which is overlain by a large alluvial fan in the southwestern part of the map area where the Chilliwack-Vedder River enters the Fraser River valley (Photo 2). The alluvial fan deposits become more sandy, less gravelly and thinner towards the fan margins (Figure 3). The Chilliwack-Vedder River system historically has been prone to large floods and has been extensively channelized and diked, the lower canal dikes being the largest in British Columbia (Photo 3). A number of smaller alluvial and colluvial fans and a large landslide deposit (known as the Cheam slide) extend out onto the Fraser Valley from the mountains to the southeast (Figure 4). This large area of landslide debris, overlies glaciogenic deposits and is capped by up to 10 metres of soft silt, peat and marl. The western edge of the study area is dominated by lacustrine silts, sands and clays (Figure 4). Upland areas, such as the Ryder Lake upland, are mantled by glacial deposits and locally are capped by a few metres of loess. Several tens of metres of Pleistocene silt, sand and gravel underlie till, in the upland area southeast of Vedder Crossing, known as Promontory Heights.

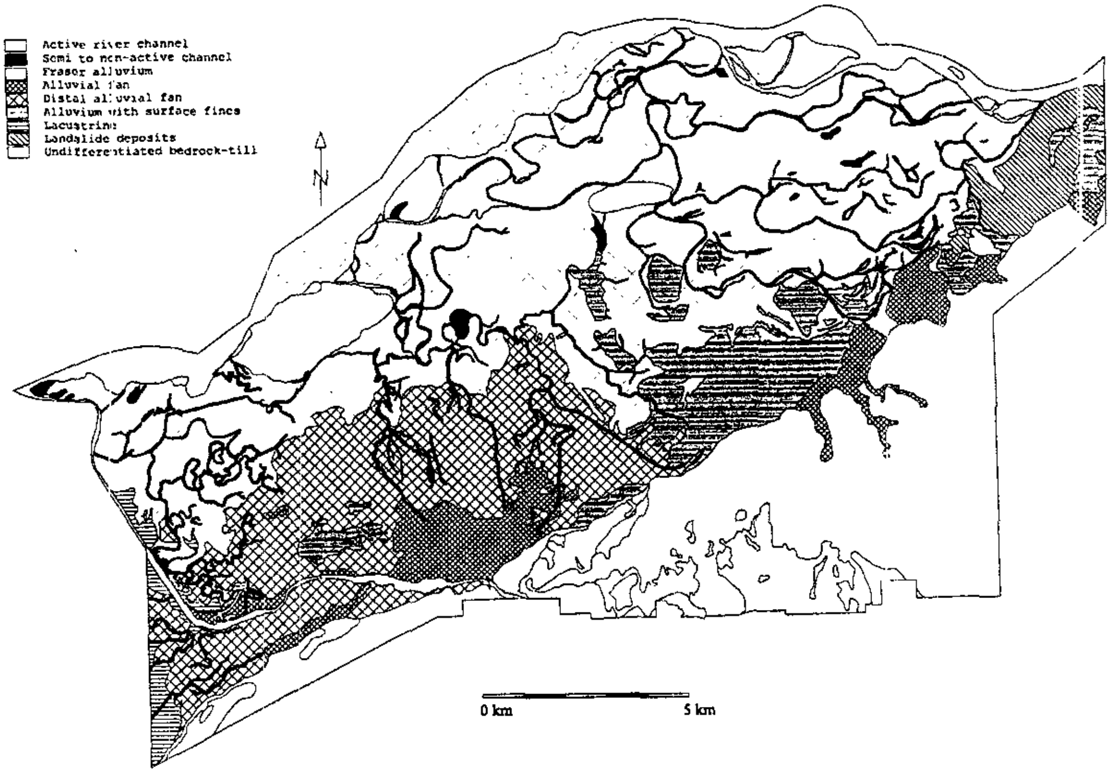

Figure 4. Generalized surficial geology of the study area.

The Fraser River lowland is characterized by numerous semi-active channels and abandoned sloughs. Prior to diking of the river along the northern boundary of the study area, many of these channels were periodically occupied by flood waters. The channels are significant from an liquefaction hazard perspective, not only because they contain loose, unconsolidated sandy sediments, but also because many of them have a significant free-face toward which liquefaction-induced lateral displacements may occur. Elsewhere, Fraser River alluvium is dominated by denser gravels and sands with up to a few metres of overbank silts. Several poorly drained areas with thick surface accumulations of silt, clay and organics are also present on the Fraser Lowland. These include an area southeast of Chilliwack, interpreted as a large paleochannel fill on a relatively old part of the Fraser River floodplain and an area northwest of the Vedder fan, where a number of small, meandering stream channels have incised into the fine sediments.

Geotechnical and geological data compiled for the study area demonstrate that the Fraser River valley is underlain by about 50 metres of sand and gravel interbedded with silt and peat that is interpreted to be a Holocene prograding deltaic and overlying fluvial sequence (Figure 5; Monahan and Levson, in preparation). These deposits are underlain by early Holocene and/or earlier glaciomarine(?) silts, clays and sands that locally extend to depths of over 400 metres. The floodplain deposits pass laterally into the Holocene lacustrine sands, silts and clays that occur in the Sumas Valley (*c.f.* Cameron, 1989). Gravels deposited in the Chilliwack-Vedder River alluvial fan are over 35 metres thick at the mountain front and have prograded over older deposits in the Sumas and Fraser River valleys.

LIQUEFACTION SUSCEPTIBILITY

As the susceptibility of a soil to liquefaction is dependent on geologic parameters such as grain-size distribution, density, deposit age and water table depth, a first approximation of the liquefaction hazard for an area can be made by an analysis of the surficial geology. The first step in the production of a liquefaction susceptibility map for the Chilliwack area, was the integration of surficial geology data with geotechnical borehole data and other subsurface data such as water-well logs. Three-dimensional geologic models of the area were constructed from this information (*e.g.* Figure 5). Liquefaction susceptibility of each map unit was then estimated based on Youd and Perkins' (1978) correlations between surficial geology and liquefaction, with local modifications introduced by Watts *et al.* (1992). Table 1 is a summary of the estimated liquefaction susceptibility of the main geologic units in the area.

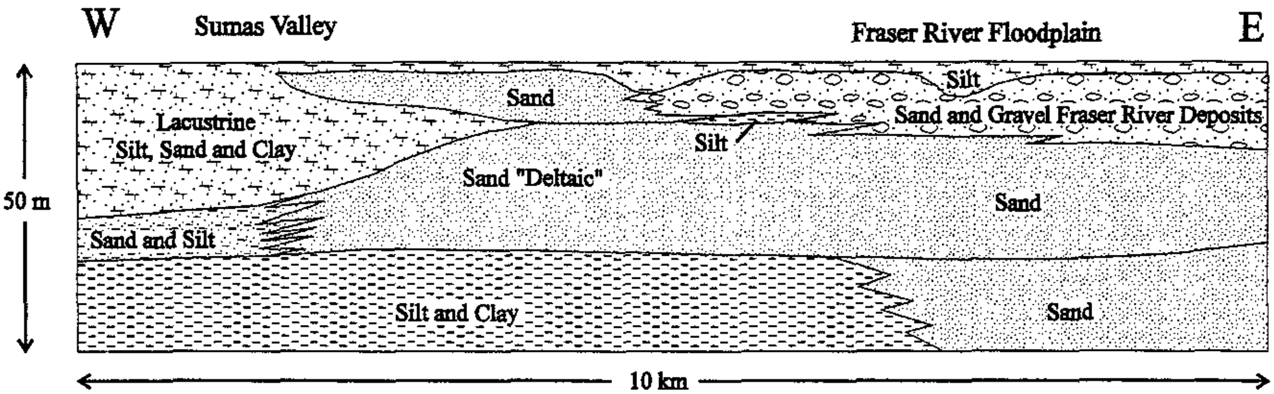

Figure 5. Schematic cross-section illustrating the main Holocene stratigraphic units in the Chilliwack area.

TABLE 1. ESTIMATED SUSCEPTIBILITY TO LIQUEFACTION OF CHILLIWACK REGION SOILS

Surficial Geology	Age	Distribution	Sediment Type	Water Table	Liquefaction Susceptibility
River channel	Very recent	Along rivers and streams	Sand & gravel	At surface	High to very high
Fraser alluvium	Holocene	Widespread on floodplain	Sand, silt & gravel	Near surface	Moderate to high
Sandy *alluvial fan*	Holocene	Lower Vedder *River fan*	Sand, silty-sand & *gravelly silty-sand*	Variable	Moderate to high
Gravelly alluvial fan	Holocene	At mouth of mountain streams	Gravel, sand & silty-sand	Variable	Low to moderate
Alluvium with surface fines	Holocene	Abandoned channels and other lows on floodplain	Silt, clay, & organics over sand & gravel	Near surface	Low to moderate
Bog	Holocene	Widespread	Peat & organic silts	At surface	Nil at surface
Lacustrine deposits	Holocene / Late Pleistocene	Sumas Valley west of Vedder Canal	Sand, silt and clay	Near surface	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	-	None

PROBABILISTIC ASSESSMENT OF LIQUEFACTION POTENTIAL AND SEVERITY

Liquefaction potential was estimated for the Chilliwack area using a modified version of PROLIQ2 (Atkinson *et al.*, 1986) that combines an SPT-based method of liquefaction assessment, developed by Seed (1979), with a probabilistic method of seismic risk assessment (Cornell, 1968). The probability of liquefaction occurring in a 50-year period, at specified depths at a given site, was calculated for 65 test holes at 25 different sites. The assessment was based on the NBCC seismicity model with the mean attenuation curve of Hasegawa *et al.* (1981) and the ground amplification chart of Idriss (1991).

In a liquefaction event, the severity of surface disruption is a function of the depth and thickness of each liquefiable unit, with shallow liquefaction causing more ground disruption and potential structural damage than liquefaction at greater depths. *To account for this, the concept of* 'probability of liquefaction severity' (PLS) was introduced by Klohn-Crippen Consultants Ltd. and is given by:

$$PLS = \frac{\Sigma\,(W_i H_i Pl_i)}{\Sigma\,(W_i H_i)}$$

where Pl_i is the probability of liquefaction at depth i, H_i is the layer thickness and W_i is the value of a weighting function. The proposed weighting function has a value of 0.1 at the ground surface and decreases linearly to zero at 20 metres depth, similar to the deterministic calculation introduced by Iwasaki *et al.*, (1981). A simplified example of how PLS reflects the depth of liquefiable units is provided in Figure 6.

Figure 7 illustrates the relationship between surficial geology and liquefaction potential. Sites with similar geology are coded with the same pattern and grouped together with potential liquefaction severity (PLS) plotted on the y-axis. Sequences along semi-active channels or abandoned sloughs on the Fraser River floodplain have the highest PLS, whereas coarse alluvial fan deposits and alluvium overlain by thick sequences of fine sediments and organics have the lowest PLS in the map area. Sandy *alluvial fan deposits and sandy to gravelly alluvium* on the floodplain show intermediate PLS values.

$$PLS = \frac{\sum (Wi \times Hi \times PLi)}{\sum (Wi \times Hi)}$$

Wi = weighting function
Hi = thickness of unit
PLi = probability of liquefaction occuring within a 50 year period

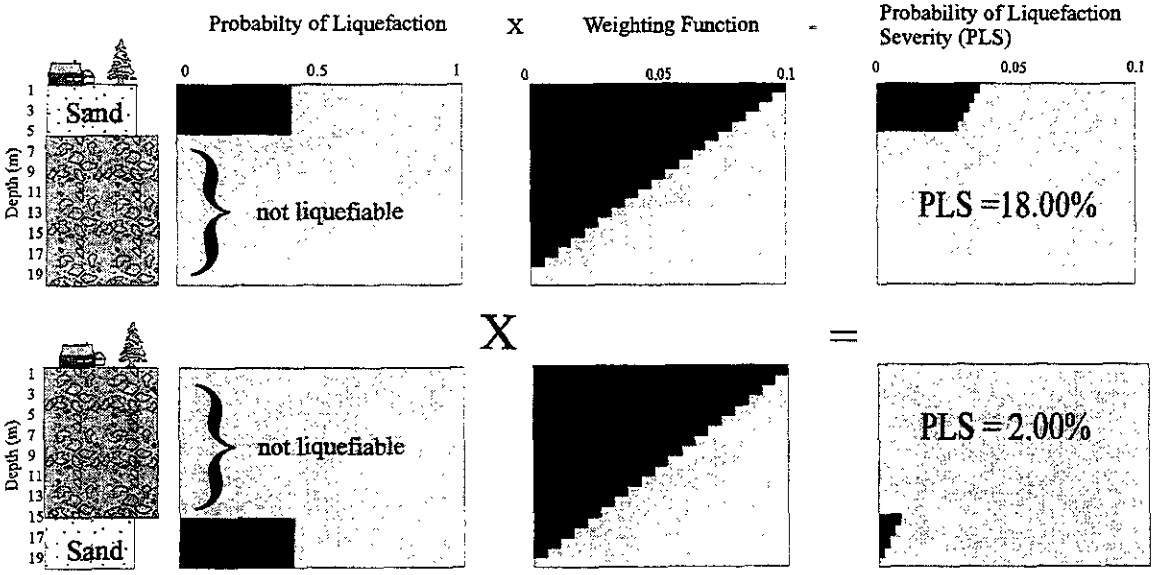

Figure 6. Method of determining probability of liquefaction severity (PLS). The thickness of the sand unit and the probability of liquefaction is the same in both cases, but the PLS is much higher in the first case, reflecting the shallower depth of the liquefiable unit.

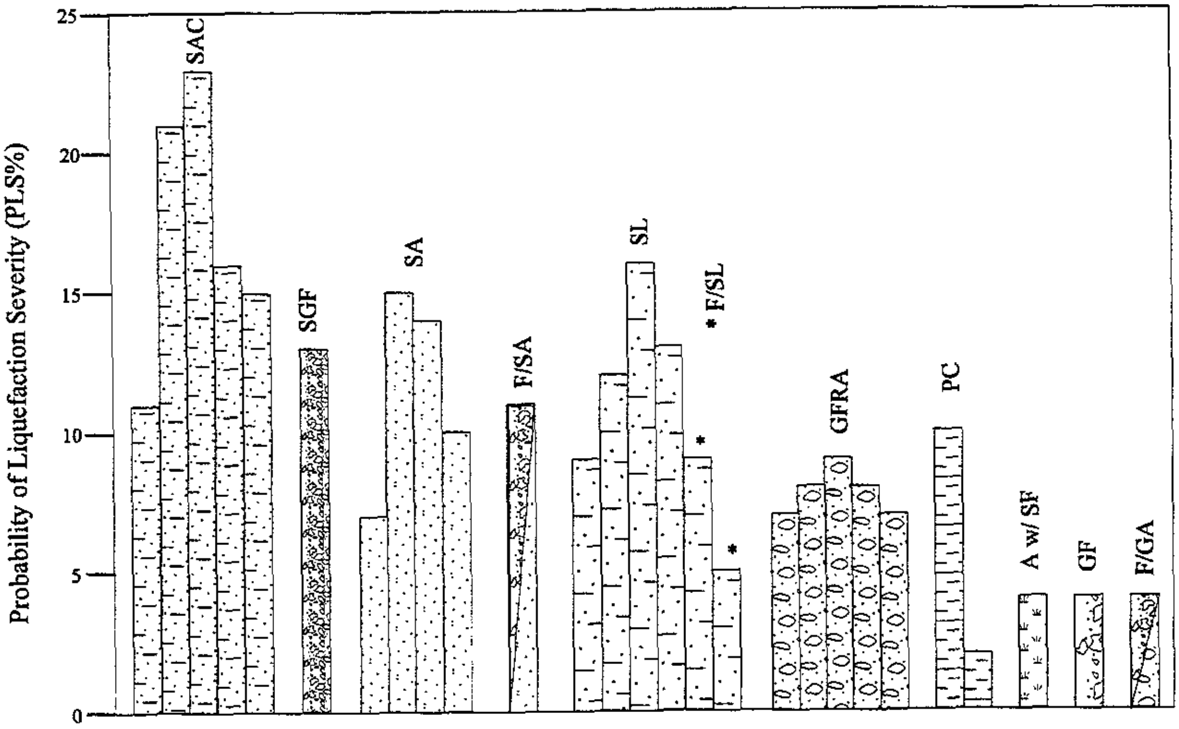

Figure 7. PLS *versus* depositional environment for eleven map units (SAC - semi-active channel, SGF - sand and gravel fan, SA - sandy alluvium, F/SA fan over sandy alluvium, SL - sandy lacustrine, F/SL fan over sandy lacustrine, GFRA - gravelly Fraser alluvium, PC - paleo-channel, A w/SF alluvium with surface fines, GF - gravelly fan and F/GA - fan over gravelly alluvium).

SUMMARY

The objective of seismic microzonation mapping is to map the relative potential for ground disturbance during an earthquake, based on local geologic, geotechnical and topographic criteria. These site conditions, in addition to earthquake source and magnitude, exert a major control on potential ground disruption. The Chilliwack pilot program has involved: collection of geotechnical data from over 1700 geotechnical test holes; 1:20 000 scale chronostratigraphic, surficial geology mapping; a field program of seismic cone penetration, spectral analysis of surface wave and Becker penetration tests; development of a geologic model; qualitative assessment of liquefaction susceptibility and quantitative assessment of liquefaction potential. This multi-disciplinary program is directed mainly towards land-use and emergency planning applications and to help prioritize funds spent by public agencies on seismic retrofitting.

Relative earthquake hazard maps can be produced from surficial geological data and from the large geotechnical database that exists for most urban areas. A first approximation of the liquefaction hazard is made by integrating surficial geology and geotechnical data to construct a geologic model of the area. Liquefaction susceptibility of each map unit is then estimated using empirical relationships between surficial geology and liquefaction occurrences that have been observed after earthquakes in other areas with similar geologic conditions. Probabilistic assessments of liquefaction that reflect the relative severity of surface ground disruption (PLS) at a number of sites in the study area, further demonstrate the relationship between geology and the liquefaction hazard and provide a more quantitative determination of the hazard in each map unit.

ACKNOWLEDGMENTS

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