LIQUEFACTION HAZARD MAP OF RICHMOND, BRITISH COLUMBIA

parts of NTS 092G/02 and 092G/03.

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Metres

0   500   1000   2000   3000

Projection: Universal Transverse Mercator, Zone 10 North.
Datum: North American Datum 1983

Scale: 1:20 000 (when printed on 36x60 inch paper)

The City of Richmond, British Columbia, is located in one of the most seismically active regions in Canada (Rogers, 1998). The effects of earthquakes are not only dependent upon the magnitude of the earthquake and the distance from the source, but can vary considerably due to local geological conditions. These conditions can be mapped using existing geological and geotechnical data. This map shows the variation in the earthquake-induced liquefaction hazard in City of Richmond, British Columbia. The city is located entirely within the modern Fraser River delta, and the deltaic sediments on which the city is built are particularly susceptible to earthquake induced liquefaction (e.g. Byrne, 1978; Finn et al., 1989; Byrne and Anderson, 1991; Clague et al., 1992, 1997, 1998b; Watts et al., 1992). This map has been prepared as part of an earthquake hazard mapping project in the city. An accompanying map shows the Quaternary geology of the Richmond area.

This map is intended for regional purposes only, such as land use and emergency response planning, and should not be used for site-specific evaluations. This map can be used with other criteria to help planners select potential areas for development, avoid geologically vulnerable areas, and prioritize seismic upgrading programs. *However, this map does not replace the need for site-specific geotechnical evaluations* prior to new construction or upgrading of buildings and other facilities. The qualifications and limitations of this map are discussed in more detail below.

Liquefaction Hazard Mapping

Liquefaction is the transformation that occurs when earthquake shaking (or other disturbance) causes a saturated granular soil (e.g. sand) to lose its strength and behave like a liquid. Liquefaction can be one of the major causes of damage during an earthquake. The susceptibility of a site to liquefaction is dependent upon the depth to the water table and the density, grain size and age of the underlying deposits (e.g. Youd and Perkins, 1978).

The initial step in the regional assessment of the liquefaction hazard of Richmond was the preparation of a geological map that reflects subsurface variation in the Quaternary stratigraphy, not just the surficial geological materials, which are either organic silt or peat throughout Richmond. Because the variation in earthquake hazards is most affected by geological conditions in the upper 20 to 30 metres, the geological map primarily reflects the variation within the Fraser delta topset, which forms the upper 20 to 35 meters of the deltaic succession. The topset forms an overall fining-upward sequence that grades up from a lower sand facies, through an interbedded sand and silt facies, to an upper organic silt facies, which is locally overlain by peat (Clague et al., 1983, 1998a; Williams and Roberts, 1989; Monahan et al., 1993, 1997; Monahan, 1999). The sand facies dominates the topset and is 8-30 metres thick. Geological map units were defined to show areas where thick silts occur above the sand facies, where thick silts include interbedded sands, where Pleistocene deposits occur at shallow depth, and to reflect age differences in the sand facies. The map units were defined on the basis of the geological materials at surface only where they provide information about the sediments below. The amplification of earthquake ground motion hazard is potentially greater where thick silts occur, and may in some circumstances be reduced where Pleistocene deposits occur at shallow depth (e.g. Monahan and Levson, 2001). The liquefaction hazard decreases with increasing depth and increasing age of the potentially liquefiable sand layer (Youd and Perkins, 1978; Monahan et al., 2000b). Within the topset, the liquefaction hazard decreases with the thickness of the overlying organic silt facies, the presence or absence of peat at surface, and proximity to historic sloughs. Older sands occur beneath thicker accumulations of organic silt, where peat occurs at the surface, on the outer (i.e. convex) side of arcuate sloughs, which represent abandoned distributary channels, and on the landward side of sloughs bordering present day river channels. In addition, where the shell-bearing subfacies of the sand facies occurs adjacent to the shell-free subfacies, the shell-bearing subfacies is older.

The geological map is based on a combination of surface and subsurface data. The subsurface data consists primarily of geotechnical testhole data from 2193 locations, including 19 scientific testholes drilled by the Geological Survey of Canada, 601 locations with cone penetration tests (CPTs), and 723 locations with boreholes deeper than 10 metres. Each location where testhole data was used is shown on the map, and each location may have one or more closely spaced testholes. Surficial geological data that were used to define the boundaries of the geological map units include the surficial geological mapping by Armstrong and Hicock (1980a, b), soils mapping by Luttmerding (1980, 1981) and a map of the historical sloughs prepared by the City of Richmond (Township of Richmond, undated).

The liquefaction hazard map was prepared by assigning a hazard rating or range of hazard ratings to each geological map unit based on quantitative analyses of geotechnical testhole data. Quantitative analyses were conducted on 278 testholes, comprising 222 cone penetration tests (CPTs), 21 dynamic cone penetration tests (DCPTs) and 35 standard penetration tests (SPTs). Because of the greater repeatability of CPT data, these were used preferentially, and analyses were conducted using the other forms of data where CPT data were not available.

The CPT, DCPT, and SPT data were analyzed according to the procedures recommended by Youd et al. (2001). This method compares the cyclic resistance ratio (CRR), which is a measure of the resistance of the soil to liquefaction, to the cyclic stress ratio (CSR), which is a measure of the earthquake shaking. Where the CSR is greater than the CRR, liquefaction can be triggered.

The liquefaction susceptibility at the various sites has been quantified here by calculation of the Probability of Liquefaction Severity (PLS; Levson et al., 1996a, 1998; Monahan et al., 1998, 2000a). PLS is defined by:

$$PLS = \frac{\Sigma (W_i P_i)}{\Sigma (W_i)}$$

where P_i is the probability of liquefaction at depth i (calculated from 0 to 20 metres), which is calculated from CRR and the probabilistic National Building Code of Canada seismic model (J. Cassidy, Geological Survey of Canada, 2002 personal communication); W_i is the layer thickness; and W_i is a depth weighting function that decreases linearly from 0.1 at the surface to 0 at 20 metres.

Calculation of PLS provides not only a relative index of liquefaction susceptibility within an area, but also permits comparison of the liquefaction hazard between areas of different seismicity because it takes into account both seismicity and in situ liquefaction susceptibility. Hazard ratings have been assigned to specific PLS ranges (Table 1).

Table 1. Liquefaction Hazard Ratings (modified from (Levson et al., 1996b, Monahan et al., 1998, 2000a)

PLS (in 50 years)	Hazard Rating
>35%	extremely high
25-35%	very high
15-25%	high
5-15%	moderate
2-5%	low
0-2%	very low

The objective of this map is to show the relative natural hazard without anthropogenic influences. However, a few metres of anthropogenic fill can have a significant effect on the PLS, which is strongly influenced by small changes in the depth to the water table. Consequently, the PLS was calculated for each site with the effects of fill removed. To do this, the data were normalized using the conditions at the site when the test was conducted, that is with the fill in place and using the observed water table, according to the procedures recommended by Youd et al. (2001). The PLS was then calculated from the normalized data using the depth from the inferred natural ground level. Furthermore, the PLS was calculated assuming a water table that is one metre below the natural surface, based on the assumption that the delta surface is at approximately the same elevation throughout Richmond. This method was used in order to remove the effects of seasonal variations and to be able to compare the relative hazard at each site.

Calculation of the PLS was simplified by assuming a Magnitude 7 earthquake, rather than a range of earthquake magnitudes, based on the assumption that most of the earthquake hazard is derived from a Magnitude 7 earthquake. A conservative magnitude scaling factor of 1.19 was applied to the analyses (Youd et al., 2001). Although this simplification does remove the real effects of variability of earthquake magnitude, it enabled the processing of a large volume of data. Because all data were analyzed in the same way, the relative differences in liquefaction hazard are valid.

A uniform amplification of acceleration resulting from the thickness of deltaic soils was used in the PLS calculation and was based on the ratio of the design acceleration on firm ground to the acceleration recommended by Byrne and Anderson (1991) for use in the Fraser River delta. This simplification is more questionable, because amplification varies with the thickness of the deltaic section (e.g. Uthayakumar and Naesgaard, 2004). However, the thickness of the deltaic section is not well constrained beyond the northern margin of the delta in northern Richmond, so that the effect of the variation in deltaic thickness could not be consistently applied.

In the calculation of the CRR using CPT data, points with $I_c > 2.6$ were considered too clay-rich to liquefy, as suggested by Youd et al. (2001). From other investigations by the authors in Richmond, this cutoff generally approximates the limits of potentially liquefiable soils as determined by the Chinese criteria, with some specific exceptions. In map unit sF^t, in which the sand facies is shell-bearing, the overlying interbedded sand and silt facies, 10 to 20 metres thick, has similar ranges of PLS values and hazard ratings to high to very high in western Richmond, where sands occur within a few metres of the surface. That hazard is extremely high in southwestern Richmond, where the youngest sands occur. Consequently, most silt beds have less than 15% clay, and so are potentially liquefiable, in contrast to non-bioturbated silts in this facies. However, the I_c usually exceeds 2.6 in the silts as well as some of the sands, so that the procedures used here underestimate the PLS somewhat in map unit sF^t. In map unit sF^t, the interbedded sand and silt facies consists of laminated sandy to clayey silts. Although I_c generally exceeds 2.6 in these sediments, 4 of 10 samples analyzed have less than 15% clay, and so are potentially liquefiable according to the Chinese criteria. Consequently, the PLS may be somewhat underestimated in this map unit as well.

The range of PLS values and the assigned hazard rating for each map unit are shown on the legend. The liquefaction hazard varies from very low in parts of eastern Richmond, where thick silts and peats occur, where the sand facies is greater than 10 meters below the surface, to high to very high in western Richmond, where sands occur within a few metres of the surface. The hazard is extremely high in southwestern Richmond, look wherever the youngest sands occur. Areas where the interbedded sands and silts and thick have significantly different hazard ratings from adjoining areas of shallow topset sand only where the interbedded sands and silts consist primarily of silt (unit sF^t and have a moderate to low hazard rating, and where the topset sands are very young (unit sF^{vy}) and have an extremely high hazard rating. PLS calculations based on CPT data are often higher than those based on DCPT and SPT data. In map units where the PLS values for CPT data were significantly higher, the assigned hazard ratings were based primarily on these data, because of their greater repeatability.

QUALIFICATIONS AND LIMITATIONS OF THIS MAP

1. **This map is intended for regional purposes only, such as land use and emergency response planning, and should not be used for site specific evaluations.**
2. The map is based on interpretations of borehole records, the *approximate* locations of which are shown on the map. Where borehole data are scarce, subsurface conditions had to be *inferred* from the deposits at the surface and geomorphic evidence.
3. The boundaries of most map units are gradational. Consequently, map unit boundaries are *approximate*, may enclose smaller occurrences of other map units, and are subject to revision as more borehole data become available. Furthermore, geological materials are variable, and deposits of a map unit may locally have unusual properties. **Consequently, the hazard at a specific site may be higher or lower than shown on the map.**
4. This map only addresses the relative hazard due to earthquake-induced liquefaction. It does not address the relative effects of liquefaction adjacent to river banks, where slope failures could occur, or beneath major buildings.
5. This map does not address man-made alterations to ground conditions, whether the changes decrease or increase the hazard at a site. High hazard sites may have been improved during construction by densification or other factors, which will change the hazard from that shown on the map.
6. Areas of fill are not shown on this map. The addition of fill may in some cases reduce the hazard, by effectively increasing the depth to the water table. However, adjacent to a river bank, the addition of fill could increase the hazard by increasing the weight above the liquefiable layer. Furthermore, the hazard may increase if the fill extends below the water table. The properties of fills vary from dense engineered fills with a very low liquefaction hazard to loose fills with a very high liquefaction hazard. Non engineered fills historically perform very poorly in earthquakes.
7. This map shows areas where the earthquake hazard is potentially increased due to liquefaction only. However, a low hazard on these maps does not mean freedom from earthquake hazards, because all areas could be subjected to *significant ground shaking during an earthquake*. Furthermore, other earthquake hazards, such as tsunamis, land subsidence and ground rupture are not addressed on this map.
8. This map cannot be used to directly predict the amount of damage that will occur at any one site because many other factors, such as building design and construction details, must be considered. The map in no way shows how different types of buildings or other man-made structures will perform during earthquakes. This map can be used to estimate the relative natural hazard due to liquefaction susceptibility alone.

Legend

Probability of Liquefaction Severity

	Very Low
	Very Low - Low
	Low - Moderate
	Moderate
	Moderate - High
	High - Very High
	Very High
	Very High to Extremely High

Geologic Contacts:
Defined
Approximate
Inferred

Road Types:
Highway
Major Road
Secondary Road

Test Hole Types:
Cone Penetration Test
Oil & Gas Well
Standard Cone Penetration Test
Borehole
Borehole < 10 m
Borehole > 10 m
Borehole > 5 m
Shearwave

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