A practical seismic liquefaction zoning system for risk management of urban development

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ABSTRACT

Following the Canterbury earthquakes, affected land was zoned to indicate the potential of future land damage due to liquefaction or lateral spreading under earthquake loading. In order to apply a corresponding zoning for unaffected land, as well as land in other provinces, a zoning system has been adopted for mapping purposes. In this way a guide to the appropriate level of site investigations that would be warranted for any particular development could be indicated on hazard maps for any district. In view of the implications of the events in Canterbury, Queenstown Lakes District Council commissioned a revision of liquefaction hazard maps covering their urban regions. This article addresses the developed zoning system, as well as its application within council. The zoning system is pragmatic and allows owners and developers to tailor investigations to the level of hazard presented. It could be readily applied to other areas of New Zealand, particularly those situated on recent normally consolidated sediments where subsurface information from liquefaction investigations is sparse. To facilitate liquefaction assessment in such cases, a heavy duty dynamic probe (in common use in the UK) has been adopted that allows testing in remote areas or where access is poor, to depths of up to 25m, at somewhat lower mobilisation cost than the more traditional testing rigs (CPT or SPT).

1 INTRODUCTION

Following the Canterbury earthquakes, affected land in the Christchurch area was zoned TC1-TC3 to indicate the potential of future land damage due to liquefaction or lateral spreading. This paper describes a parallel liquefaction hazard zoning system developed for land not affected by the current liquefaction problems present in Canterbury. Hazard zoning was commissioned by the Queenstown Lakes District Council (QLDC) to cover the major urban areas of the Queenstown Lakes District region. The QLDC deemed the assessment necessary as it would provide a structured and clear method with which to address planning, development and consenting issues in the region. The assessment was completed in 2012.

The hazard zoning system is based on the local site investigation database, Otago Regional Council groundwater data, and existing geological mapping. The system was developed for use in the Queenstown –Lakes district, but may well be applicable in other areas of New Zealand, where subsurface information from ground investigations is sparse.

2 GEOLOGICAL SETTING OF THE QUEENSTOWN -LAKES DISTRICT

Basement rock in the district is Otago Schist that has been tectonically uplifted over the past 10 million years along regional faults and the Alpine Fault to the west. Successive Pleistocene glacial advances have eroded the rising Southern Alps, depositing glacial till and outwash gravels in the Queenstown and Wanaka areas. During interglacial periods, and the post-glacial era, lake sediments of silt and sand have been deposited in lakes behind the terminal moraines. In the early post glacial period lake levels were different to those present today. Lake Wakatipu, for example, was approximately 50m higher than its current level. Lake sediments can therefore be found in elevated locations around the edges of the lakes, often in locations attractive for development. Alluvial sediments have also accumulated in post glacial times, often in fans and deltas deposited in low lying areas and lake margins. These young, normally consolidated materials, particularly the lake sediments, are considered most at risk of liquefaction during a major earthquake.

3 SEISMIC HAZARDAND LIQUEFACTION EFFECTS

Historically, most earthquakes affecting Queenstown and Wanaka have originated in Fiordland, with felt intensities typically up to MM6.

The strongest shaking reported in the district in historic times appears to be as a result of the 1943 Lake Hawea earthquake, which subjected Wanaka to MM7 and Queenstown to MM6 (Reyners, 2005). In Wanaka "Practically no shop or house... escaped damage. Many articles were shaken from shelves, and bricks and mortar fell from chimneys " Southland Daily News , 10 May, 1943.

There are no known reports of liquefaction effects or lateral spreading in the Queenstown Lakes District during this or any other historic earthquake. However, sand boils and lateral spreading were reported on the shoreline of Lake Te Anau to the west of the district during the 2003 Fiordland earthquake, with a local felt intensity of MM7 (Hancox et al.,2003). This occurred in an area where fine grained lake sediments, similar to those around the shoreline of Lakes Wakatipu and Wanaka, are believed to be present beneath beach gravels.

Queenstown and Wanaka lie about 80 km from the Alpine Fault that forms the Pacific-Australian plate boundary. Paleoseismic data indicate an average return period of about 300 years for earthquakes on the fault, with the last event in 1717. A recent review of previous Alpine Fault studies has indicated a 30% probability of a major quake in the next 50 years, likely to be up to Mw 8.1 (Berryman et al., 2012). Felt intensities ranging from MM7 in the east to MM9 in the extreme west (Figure 1) would be expected. The main population centres of Queenstown and Wanaka lie between the MM7 and MM8 isoseismals.

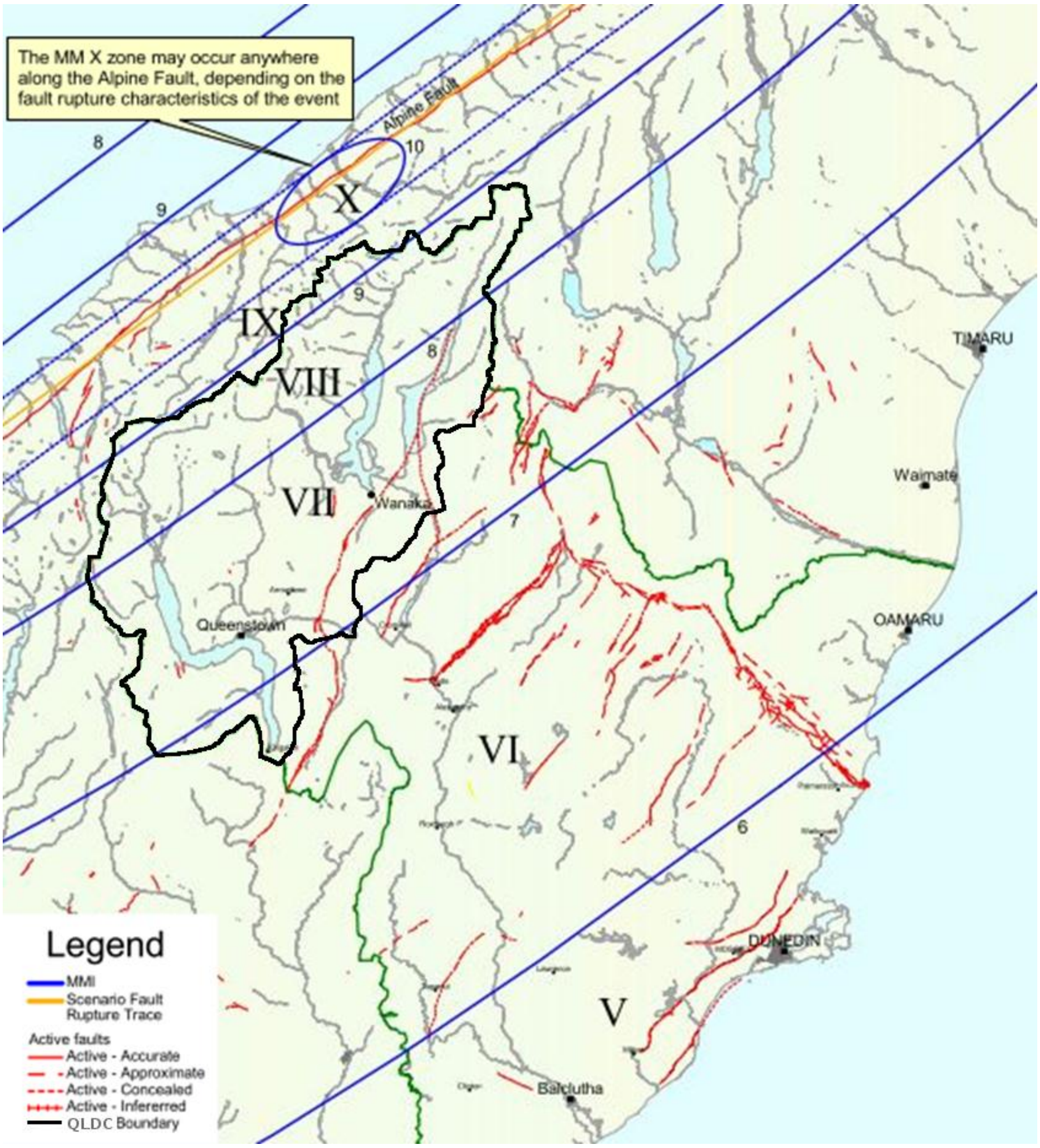

Figure 1: Isoseismals, Magnitude Mw 8.0 on the Alpine Fault (from ORC report, 2004)

Earthquakes on local regional faults, such as the Nevis-Cardrona and Pisa Faults are considered capable of generating more intense shaking. However, they present a much lower seismic risk because of their long average assessed return periods, typically ranging from 5,000-20,000 years.

4 PREVIOUS LIQUEFACTION HAZARD MAPPING

The first QLDC Natural Hazard Register maps to include liquefaction risk were printed in 2002. These A3 map books were an update of the original map series created in 1999. As part II of the Hazards Register project, Opus was commissioned to collect and provide additional hazard information. Woodward-Clyde (1998) provided the information on seismic hazards. It was noted in the report that "The ground shaking hazard area has been mapped as merely the areas underlain by Quaternary sediments, without consideration of earthquake sources and amplification likely." It further stated that "In the present form, the existing ground shaking hazard information in the Hazards Register is of limited use, without further study of the seismicity and ground shaking hazard." Areas were categorised as 'susceptible' and 'possibly susceptible' to liquefaction.

More recently the Otago Regional Council report on seismic risk in Otago (Opus, 2004) categorised the liquefaction and settlement hazards as either 'Possibly Susceptible', 'Low Susceptibility' or 'Not Susceptible'. The latter maps were based essentially on geology, and appear conservative in the assessment of liquefaction hazard.

5 NEW MAPPING PROGRAMME

In 2012 QLDC commissioned a revision of liquefaction hazard information covering the urban areas of the Queenstown area, Wanaka, Glenorchy and Kingston, in view of the implications of events in Canterbury.

QLDC now stores hazard related information in a Geographic Information System (GIS) and no longer produces hardcopy hazards maps. Hazards information is layered in a GIS viewing package available to QLDC staff and to the public via bespoke maps. This allows the users to view information at any scale and to combine different layers of data together. Below we can see the liquefaction risk layer which is a composite of Tonkin & Taylor Ltd (2012) data and Opus (2002) data. Presenting this information in a GIS environment also allows council to attribute each risk polygon and store full metadata in the database. This application is currently only available internally but is ultimately intended to be disseminated via QLDC's public webmaps application.

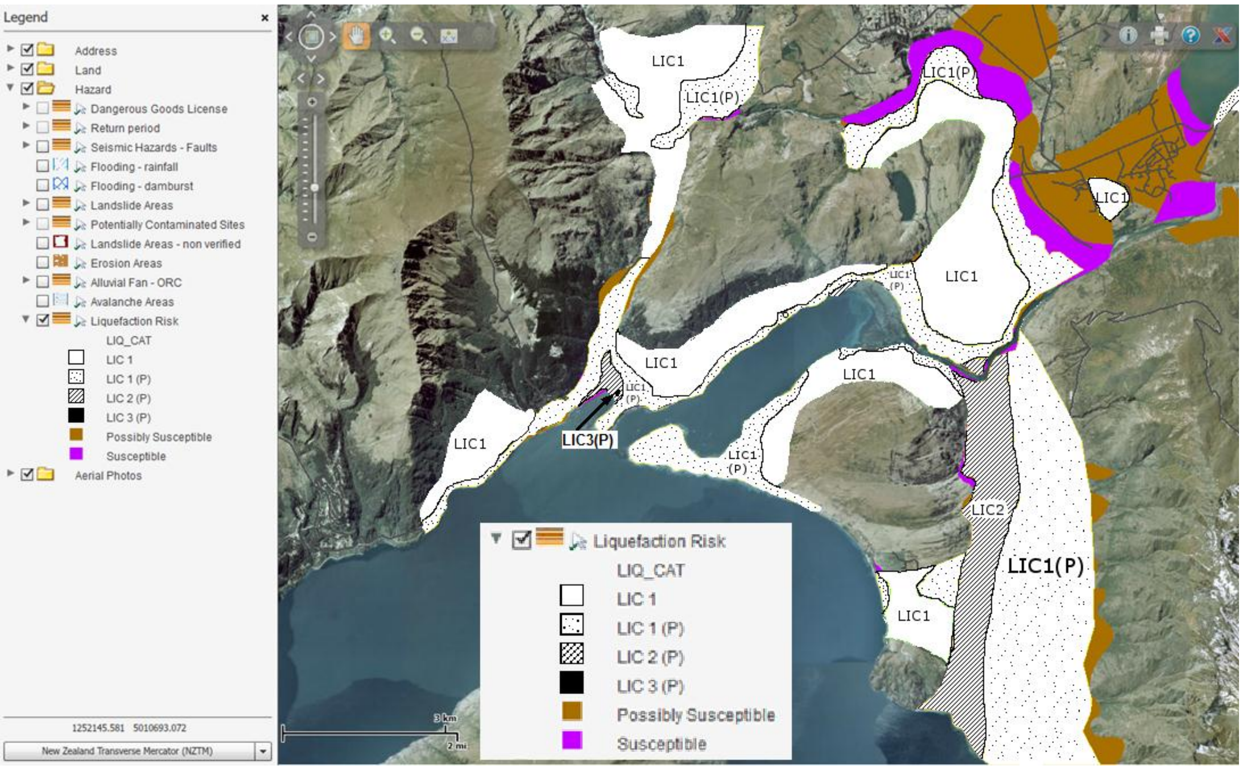

Figure 2: Liquefaction risk map of the Queenstown area

The chief difficulty for liquefaction hazard mapping in the district is the low density of cone penetrometer test (CPT) and standard penetrometer test (SPT) data in most of the QLDC region. Whilst extensive ground investigations have been completed in recent years, this information is often confined to isolated pockets, e.g. central Queenstown. It was thus not possible to produce accurate hazard maps based purely on quantitative data, as has been possible in Christchurch where intensive CPT testing has been carried out to define zones TC1, TC2 & TC3.
To deal with this issue, a parallel system for risk zoning in terms of Liquefaction Investigation Categories (LIC) as given below was devised based on geology and groundwater data. For the key geological units of the district, liquefaction risk was assessed using grain size, material

properties and geological history, coupled with available CPT and SPT results and groundwater data. Shaking intensities were based on those expected from an Alpine Fault earthquake. The liquefaction risk map of the Queenstown area is shown in Figure 2.

The maps are intended to provide QLDC engineering and planning staff with a broad scale assessment of liquefaction risk, and a guide for both Council and developers in regard to appropriate requirements for liquefaction investigations depending on the respective LIC. The level of geotechnical professional input considered appropriate is specified for each category, and recommendations for probable foundation solutions are provided. Four Liquefaction Investigation Categories (LIC) were established, as shown in Table 1.

LIC 1 covers areas where the liquefaction risk is considered nil to low based on reliable geological and groundwater data obtained in nearby ground investigations. This category typically covers areas in which schist bedrock, and soils such as glacial till are present, or groundwater can reliably be proven to be at depth.

LIC 1(P) covers areas where the liquefaction risk is probably low, however further investigations should be completed to provide confirmation. The level of investigations will vary depending on the site. In lake foreshore areas this will require subsurface investigations to a depth below surficial beach gravels or alluvium to determine the presence or absence of potentially liquefiable lake deposits. In other areas it may be possible to analyse liquefaction risk without subsurface investigation from surface geology and existing groundwater data. The level of investigation will be determined by the individual consultant who will need to be confident the geological model has been sufficiently defined.

LIC 2(P) covers areas assessed to have a possibly moderate liquefaction risk (i.e. minor to moderate land damage). LIC 2 (P) areas typically occur where there are young normally consolidated sediments (silts and sands), and the watertable is close to the ground surface. The limited CPT and SPT data from similar sites and geological materials suggest a possible moderate liquefaction risk is present. Deep subsurface investigations are required in accordance with the guidelines provided by the Department of Building and Housing (DBH).

LIC 3(P) covers areas of young normally consolidated silts and sands with a high water table and a high liquefaction risk (i.e. moderate to significant land damage is expected) indicated for adjacent sites by CPT and SPT data. This category is limited to a small area in central Queenstown.

For each category there was a provision that if initial site investigations find evidence of potentially more adverse liquefaction conditions, investigation requirements are to be raised to the next category up, e.g. if saturated silts and sands are found in a LIC 1(P) zone, it will then need to be investigated as for LIC 2(P).

6 COUNCIL PERSPECTIVE

The QLDC has developed 'guidelines for investigation and reporting of liquefaction hazard' based on the recommendations of Tonkin & Taylor Ltd. Table 4specifies the workflow required when the site (or part thereof) is shown as being in any category other than LIC 1. Workflows exist for Subdivisions and Boundary adjustments, and land use consents activities. Information is also provided and mapped as part of the LIM process as is required in the Local Government and Official Information and Meetings Act 1987.

Table 1: The Categories for the Liquefaction Mapping, related to DBH requirements in response to Canterbury earthquakes

Liquefaction Investigation Category	Level of Data Available	Assessed Liquefaction Risk	Minimum requirements for geotechnical assessment for land development site investigations and reporting.	Comments	Probable Foundation Solution
LIC 1	Good knowledge of subsurface conditions from nearby sites in same geological terrain with no reported hazards.	Nil to Low	Additional geotechnical investigations are not mandatory (other than already prescribed in NZS 3604: Timber Framed Buildings to establish that the building platform is located entirely on ***good ground*** as defined in clause 3.1.3 of that standard). In the unlikely event that ***good ground*** is not confirmed or if saturated fine grained sediments (sands or silts) are present, then investigations shall proceed as for Zone LIC 2 (P).	Corresponds to DBH Technical Category 1 adopted for liquefaction following the Canterbury earthquakes. (LICC 1: Land damage from liquefaction is unlikely, and seismic ground deformations are expected to be within normally accepted tolerances.) Detailed investigations may still be required for non liquefaction related geotechnical aspects of the development, e.g. soft ground, deep cuts, fill placement, retaining wall design etc.	Use foundations as detailed in NZS 3604:2011 Timber Framed Buildings, as modified by B1/AS1 which requires ductile reinforcing in slabs (refer to the DBH's information sheet at http://www.dbh.govt.nz/seismicity-info)
LIC 1 Provisional LIC 1 (P)	Surrounding sites investigated with generally no reported hazards but there is limited ability to project stratigraphy because of variable geomorphology or distance from sites with subsurface investigations.	Probably Low. (Expected to be low but requires specific investigations for a definitive assessment of liquefaction).	Investigations shall be in accordance with NZS 3604: Timber Framed Buildings and with DBH Guidelines (see Note 1 below). In the event that ***good ground*** is not confirmed or if saturated fine grained sediments (sands or silts) are identified, then reporting shall proceed as for Zone LIC 2(P). Review required by an engineering Geologist or geotechnical engineer. Site investigations should extend to sufficient depth to identify potentially liquefiable formations that may lie beneath surficial deposits, such as beach gravels. If lake silts or sands, or other materials prone to liquefaction are identified then proceed to LIC2 (P).	LIC 1 is probable but uncertain. Depths of investigation may be reduced once stratigraphy is demonstrated to be consistent with surrounding sites.	If LIC 1 is confirmed, use foundations as detailed in NZS 3604:2011 Timber Framed Buildings, as modified by B1/AS1 which requires ductile reinforcing in slabs http://www.dbh.govt.nz/seismicity-info
LIC 2 (P)	Marginal to moderate liquefaction conditions identified elsewhere in the vicinity in similar terrain.	Possibly Moderate. (Nearest subsurface investigations are inadequate to establish a reliable category)	Deep geotechnical investigations and reporting in accordance with NZS 3604, DBH guidelines (see Note 1) and QLDC requirements, by a CPEng with appropriate experience in geotechnical engineering.	LIC 2 is possible. (LIC 2: Minor to moderate land damage from liquefaction is possible in future large earthquakes.) Independent peer review recommended if any report recommends a solution without a recognised solution for liquefaction.	If LIC 2 is confirmed, use light- or medium-weight cladding, light-weight roofing with suspended timber floors and foundations in accordance with NZS 3604 Or Use foundation with enhanced slab (DBH Options 1 to 4, http://www.dbh.govt.nz/seismicity-info)
LIC 3 (P)	Severe liquefaction conditions identified elsewhere in similar terrain	Possibly High. (Nearest subsurface investigations are inadequate to establish a reliable category)	Deep geotechnical investigations and reporting in accordance with NZS 3604, DBH guidelines (see Note 1) and QLDC requirements, by a CPEng with appropriate experience in geotechnical engineering.	LIC 3 is possible. (LIC 3 Moderate to significant land damage from liquefaction is possible in future large earthquakes) Independent peer review recommended.	If LIC 3 is confirmed, specific geotechnical engineering design required. Ground improvement or deep piles if suitable bearing layer <10 m. Slab support also required.

Notes

1) In view of the significance of the Alpine Fault to Queenstown, liquefaction considerations should now acknowledge procedures recently adopted in Canterbury. Engineering requirements should therefore be as in the Department of Building and Housing document "Guidelines for the investigation and assessment of subdivisions on the flat in Canterbury - minimum requirements for geotechnical assessment for land development ('flatland areas' of the Canterbury region)" http://www.dbh.govt.nz/subdivisions-assessment-guide
2) DBH requires that for each individual site, "visual assessment and reasonable enquiry does not suggest that the original classification (for liquefaction) is inappropriate and that normal geotechnical investigations are undertaken for the purposes of evaluating all other potential geotechnical issues". For areas not yet categorised for liquefaction, site specific investigations are required. Note that DBH considers: "Scala Penetrometer testing (refer NZS 4402:1998 Test 6.5.2) is often useful as a shallow investigation tool in conjunction with the methods outlined above. **However, Scala Penetrometer testing is not considered appropriate as the primary ground characterisation method for liquefaction purposes."**
3) Categories assigned in these maps assume founding within a metre of 2011 ground level or higher. For deeper excavations, site specific investigations are required.
4) Sections of the map that are not coloured have not yet been mapped for liquefaction in relation to current DBH criteria.

7 LIMITATIONS

The accuracy of the mapping is limited by the availability of actual ground investigation data. The ground investigation data that are available were often obtained in discrete locations and was not always obtained specifically for the purposes of liquefaction work. A certain level of extrapolation was therefore required when determining the extent of each category. It is therefore possible that areas at risk of liquefaction exist outside the mapped areas, and the mapped areas may be subject to change of category if future ground investigation data become available. Regular upgrading of the maps could be completed using newly acquired site investigation information. Alternatively, in key or problematic areas, specific ground investigations could be completed specifically to improve mapping accuracy.

8 DYNAMIC PENETROMETER

In the Queenstown Lakes District deep liquefaction investigations in LIC 2(P) and LIC 3(P) zones have been typically carried out using SPT and CPT equipment, however the cost is high, particularly for individual residential buildings, and rig availability is frequently an issue for Otago and Southland sites. A quicker and lower cost alternative is the use of the Dynamic Cone Penetrometer (DCP). Costs to complete an isolated investigation hole using a DCP would typically be between 10 and 20% of that expected for a traditional borehole with SPT testing. The DCP uses a falling weight to advance a rod into the ground and blow counts per 100mm advancement are recorded. The blow counts can be quickly converted to an equivalent SPT N_{300} value. The DCP is light and portable, and can be used in areas where access is difficult for larger machinery with minimum surface disturbance.

The DCP can test to maximum depths of 25m, depending on the ground conditions, and a piezometer can usually be installed in the finished hole.

Figure 3: Dynamic Penetrometer

9 DISCUSSION

In general, the liquefaction risk in the QLDC district is considered significantly lower than that of Christchurch. A small area in the Queenstown CBD underlain by very loose-loose post-glacial lake sediments with low SPT/CPT test results is the area of greatest concern. Much of the potential liquefaction risk in the district is associated with young, normally consolidated sediments comprising silts and sands.

The hazard zoning system provides an initial assessment of liquefaction risk and a guide to appropriate investigation requirements for urban development, and is thus a useful risk management and planning tool. The system may well have application to other regions of New Zealand, particularly those with recent, normally consolidated saturated sediments, where subsurface liquefaction investigation data is sparse.

10 CONCLUSIONS

Prior to 2012, QLDC's Hazards Register was based on data derived from a desktop study of the underlying geology. The result was generally an over-conservative view of the liquefaction risk in the district. With increased public awareness of natural hazards and the considerable costs being incurred during the subdivision and land use consent process, QLDC required better information about liquefaction risk and geotechnical investigation requirements for assessing liquefaction risk across the district. Liquefaction risk zoning of the Queenstown urban area has been undertaken and Guidelines have been developed for undertaking geotechnical investigations to assess liquefaction risks that are dependent on where the site is located. The Guidelines are pragmatic and provide value for money for ratepayers. The system provides much greater certainty for owners and developers who can tailor investigations to the expected level of liquefaction risk and provides clarity to council planners in their dealings with developers and owners of land potentially at risk.

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