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Liquefaction potential of the micaceous lake sediments in the Queenstown area

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ABSTRACT

Queenstown is a known seismically-active area. Following the September 2010 Canterbury earthquake, the local authorities in Queenstown have taken more initiative to improve their knowledge of the regional subsoils in order to better determine the liquefaction risk and the potential impact posed to the functionality of buildings and infrastructure should liquefaction-induced ground deformation occur. The authors carried out in-situ and laboratory testing and evaluated the liquefaction risk of the inter-bedded silt/ sandy silt laminated lake sediment layers overlying the schist bedrock. Despite a comprehensive list of assessment methods used, the data retrieved from conventional liquefaction analysis did not neatly consolidate towards a definitive conclusion and engineering judgement was needed to better interpret the body of evidence. In this paper, the authors present their liquefaction assessment and outline their findings. This paper is intended to provide readers an introduction to the topic and recommendations are given for further research to better understand the cyclic behaviour of these soils.

Keywords: Liquefaction, Queenstown, micaceous soils, lake sediments

1 INTRODUCTION

Located in the southern part of South Island, Queenstown is important to the New Zealand tourism industry and its local population also continues to grow. The nearby mapped active faults – the Alpine Fault, Nevis Fault and Cardrona Fault – are all capable of producing earthquakes greater than M_w 7. According to the recent seismic hazard study undertaken by the Otago Regional Council for the Queenstown Lakes District, the primary seismic hazard facing the region is an Alpine Fault earthquake; which is predicted to have a 30% probability of rupturing in the next 50 years. However, the modern buildings and infrastructure in the area are yet to be tested by such an event.

Given the seismological setting, we sought to evaluate the liquefaction potential of the horizontally inter-bedded silt/ sandy silt laminated lake sediment soils (lake sediments). In order to provide a measureable benchmark we carried out our liquefaction assessment in accordance with the simplified procedure set out in Modules 1 and 3 of the New Zealand Geotechnical Society (NZGS) Modules for Earthquake Geotechnical Engineering Practice (2016). Additional methods to assess liquefaction triggering were also utilised.

Conventional industry-approved procedures of determining liquefaction potential have been mostly derived from earthquake case histories of sites where the soils comprise Holocene uncemented alluvial soil deposits, and quartz is likely a dominant mineral in the soil composition. However, the microstructure of the Queenstown lake sediments, which is dominated by platy minerals, does not meet this criterion and engineering judgement was required to interpret the findings.

This paper presents our liquefaction evaluation of the lake sediments and provides recommendations for further research.

2 GEOLOGICAL SETTING

Queenstown and the surrounding Wakatipu Valley are underlain by schist of the Caples and Rakaia Terranes. The schist is actively being folded, faulted and eroded in response to regional compression and strain distributed across the mid to lower South Island. Much of the fault activity and uplift in the

area has occurred over the past five million years, which is reflected in the ruggedness of the local mountain ranges.
Repeated glaciations have carved deep troughs into the landscape, with Lake Wakatipu occupying the largest trough in the area. Lake Wakatipu covers an area of approximately 290 km^2 and is over 370 m deep. Furthermore, during the last glacial (Otira) period, the glacial lake covered a much larger area and was significantly deeper.

The surficial materials are likely to have been deposited at the end of the most recent (Otira) glaciation (i.e. late Pleistocene / early Holocene deposits).The Otira glacial period ended about 15,000 to 18,000 years ago; late and post-glacial events were marked by widespread erosion along the tributaries of Lake Wakatipu (particularly the Shotover River). The resulting sediment was deposited in Lake Wakatipu, forming deep deposits of inter-laminated silt and sandy silt.

3 GEOTECHNICAL PROPERTIES OF LAKE SEDIMENT SOILS

We carried out geotechnical investigations at four locations adjacent to Lake Wakatipu. The geotechnical investigations comprised piezocone penetration testing (CPTu), sonic-cored boreholes with Standard Penetration Tests (SPTs) and down-hole shear-wave velocity (V_s) testing. We note that the lake sediments were a minimum of 25 m thick at the investigation locations and the sites were classified as Class D - deep or soft soil sites - in accordance with NZS1170.5.

Fourteen target-soil samples were retrieved from the SPTs at depths ranging from approximately 2 m to 27 m below ground level and sent for laboratory testing to determine the soil composition and material properties. The results are presented in Table 1.

Table 1. Index properties of Queenstown lake sediments

Parameter	Value	Comment/s
USCS	ML	-
Unit weight (γ)	17.6 kN/m^3	These are averaged values, but the dataset range is not too dissimilar.
Fines content (FC) [<75 µm]	90%	
In-situ water content (w_o)	38%	
Plasticity index (PI)	8 to 15%	Few samples were simply recorded as 'non-plastic).
Liquid limit (LL)	37 to 46%	Not applicable for 'non-plastic' samples.
Overconsolidation ratio (OCR)	1.8 to 3.6	The lake sediments are in an overconsolidated stress-state as the loads of glaciers had previously been applied over them.
Compression index (C_c)	0.16 to 0.17	

Figure 1 provides the median CPT-derived profile down to 34 m below ground level and Figure 2 provides the median V_s-derived profile. It should be noted that fine to coarse grained beach gravel was encountered at the surface overlying the laminated lake sediments, and this is reflected in the upper 1.5 m of the ground profile.

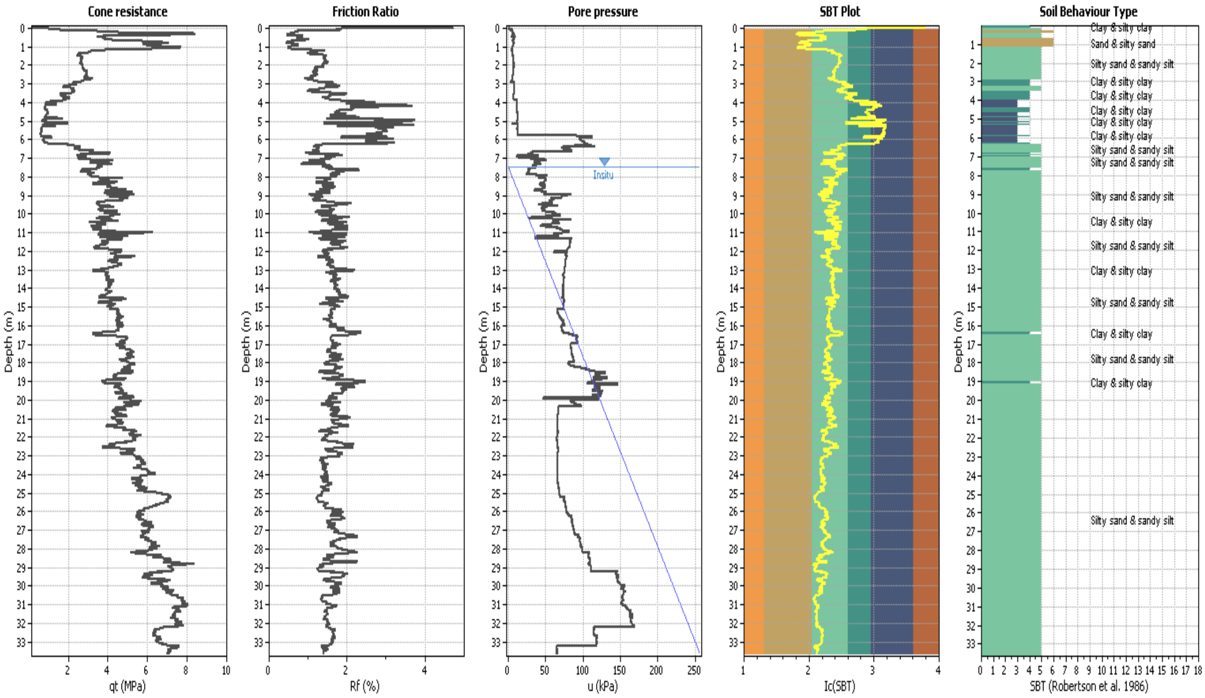

Figure 1. Median profile (design groundwater table taken at 7.5 m)

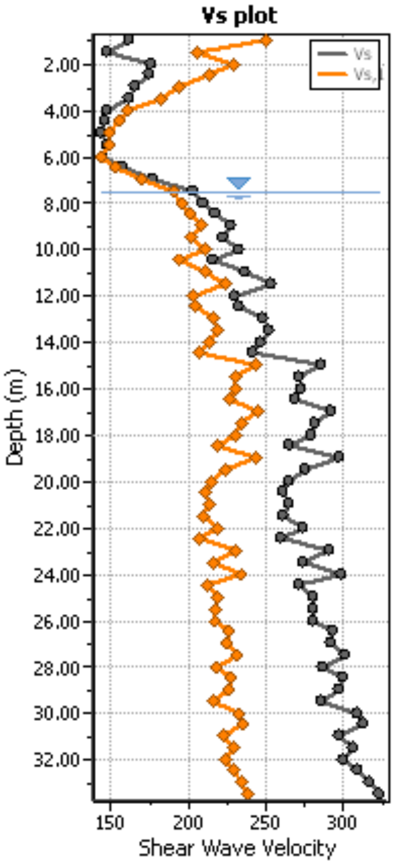

Figure 2. Median V_s and V_{s1} profile (design groundwater table taken at 7.5 m)

The laminated lake sediments in the Queenstown area are primarily derived from the schist bedrock, which contains platy mica minerals and other clay-size (i.e. finer than 75 µm) minerals. Samples were tested for mineralogy using the X-Ray Diffraction (XRD) method. It was found that the laminated lake sediments are rich in mica and chlorite (~ 84% by weight; mica and chlorite are approximately in equal amounts). Quartz makes up only 10% of the mineralogical composition and feldspars make up the remainder. Figure 3 shows the XRD patterns and their interpretations retrieved from two tests.

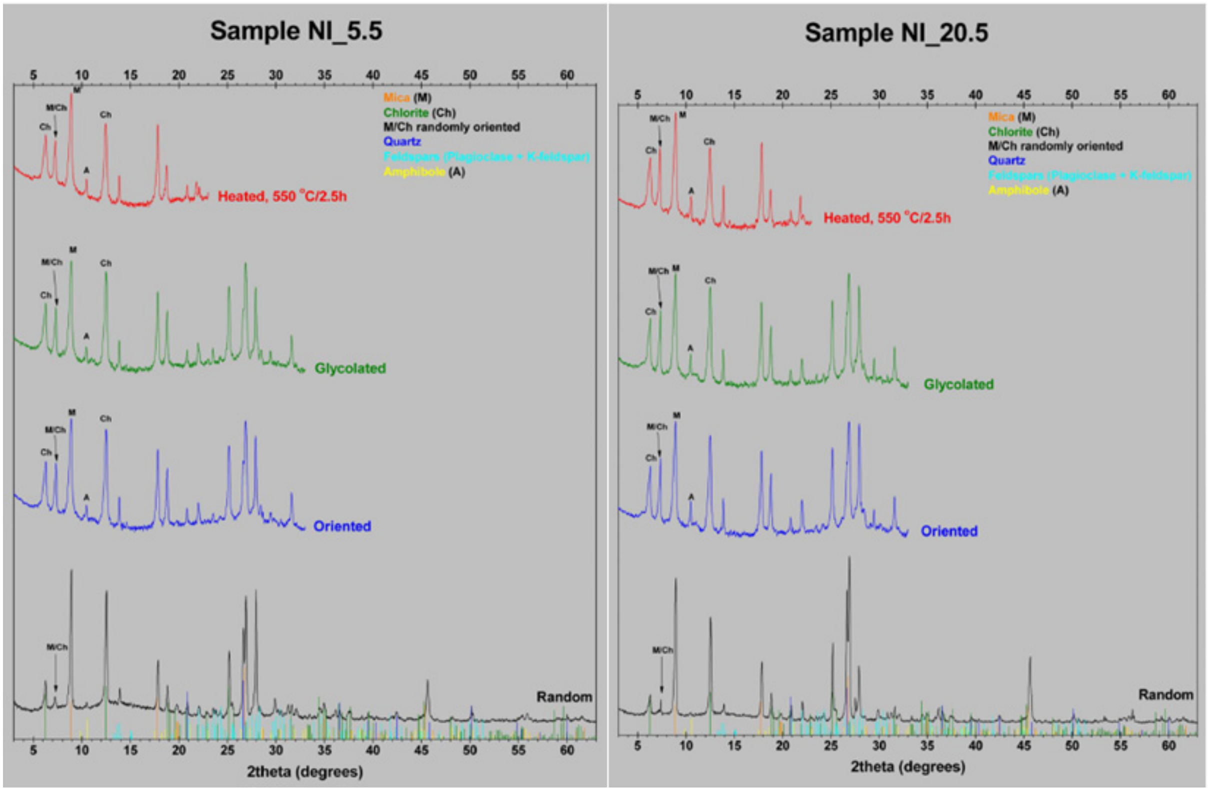

Figure 3. XRD patterns and their interpretation

4 SOIL ANISIOTROPY DUE TO MICA PARTICLES

Lee et al (2007) discusses and summarises previous research as to how the presence of platy mica particles affects the packing of soil grains and alters the mechanical behaviour of sandy soils. One of their observations is that increased mica content in sandy soils correlates with decreasing measured V_s. Even though the Queenstown lake sediments are more silty than sandy, most of the soil profile and tested samples are considered to have a 'sand-like' behaviour ($I_c < 2.6$) so the findings presented in Lee et al (2007) appear useful in providing an initial understanding. However, more research regarding the influence of mica in silty soils is needed to better understand the soil anisotropy.

5 ASSEEESSMENT OF LIQUEFACTION POTENTIAL

5.1 Previous research

The seismic hazard report by Otago Regional Council indicates that there is little geologic evidence of widespread liquefaction for sites underlain by lake sediments, despite the area having experienced multiple Alpine Fault earthquakes over its geological history. Considering the geologic timeframe, Alpine earthquakes occur frequently in the Queenstown area (every ~ 340 years).

Bowen et al (2015) carried out 13 cyclic triaxial tests on low plasticity micaceous lake sediments in Central Otago which have similar properties to the soils we assessed in Queenstown, but with a lower plasticity range – PI = 0 to 7%. The lab testing observed cyclic mobility behaviour (gradual increase of pore pressure with increasing shear strains) but not liquefaction-type behaviour (rapid increase in pore pressure leading to complete loss of shear strength).

5.2 Liquefaction susceptibility assessment

In accordance with NZGS Module 3 (2016) we utilised the liquefaction susceptibility criteria set out in Bray and Sancio (2006). Our results showed that most of the soil samples did not meet the definitive categories of 'susceptible' or 'not susceptible' to liquefaction, but mostly lie in the region that recommends more testing be undertaken to verify the liquefaction susceptibility. The results are shown in Figure 4. (We also note that the few non-plastic samples, which are not shown in Figure 4, are considered 'susceptible to liquefaction').

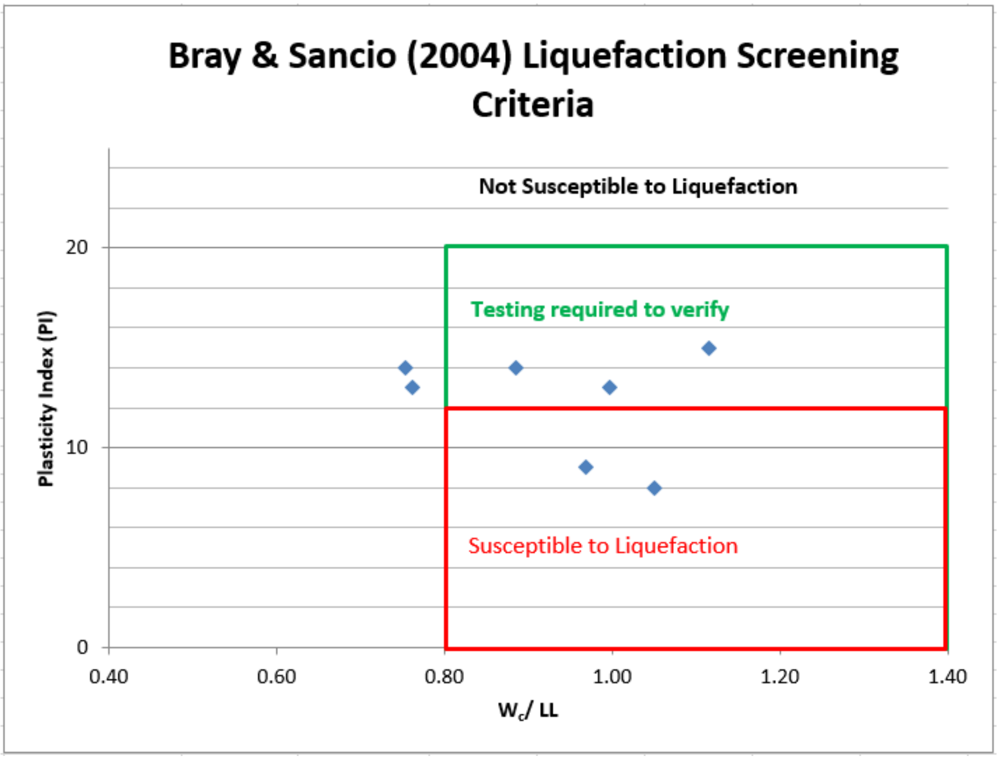

Figure 4. Liquefaction susceptibility

Overall, the results derived from the standard tests of determining liquefaction susceptibility were inconclusive.

5.3 Liquefaction triggering assessment: methodology and results

In accordance with NZGS Module 3 (2016), we adopted the procedures given by Boulanger and Idriss (2014) to assess liquefaction triggering for the CPT profiles down to 15m and applied the appropriate corrected fines content (CFC).

The ultimate limit state (ULS) ground motion parameters for a Class D sub-soil site were derived from the NZTA Bridge Manual (2014); a α_{max} of 0.4g and M_w of 6.5 (an approximate the effective value for the Queenstown area for 1000yr earthquake return period). Our investigations encountered groundwater between 3 m and 15 m, so we adopted an intermediate groundwater level at 7.5 m for the purpose of this study.

In addition, we also adopted the following methods to assess liquefaction triggering;

- Robertson and Wride (1998) analysis procedure for CPT data.
- Andrus and Stokoe (2000) analysis procedure for the small-strain V_s recorded at 0.5 m intervals.

The results of the liquefaction triggering analyses significantly varied because;

- The CPT-based methods predicted that the majority of the soil profile below the water is triggered below the water table. (It should also be noted for CPT-based methods that the Robertson and Wride [1998] procedure had slightly lower CRR profile values than the Boulanger and Idriss [2014] method).
- The Vs method considers the analysed soil profile to be non-liquefiable.

We also carried out a preliminary analysis to model an Alpine earthquake scenario. An anticipated M_w of 8.1 was adopted and in the absence of a site specific hazard assessment we adopted a large unweighted α_{max} of 1g. Our findings were the same as those outlined above.

6 DISCUSSION REGARDING RESULTS AND CURRENT INDUSTRY PRACTICE

The results from the standard tests to determine liquefaction susceptibility were inconclusive and the methods of assessing liquefaction triggering significantly varied. However, the published literature records little geologic evidence of widespread liquefaction for sites underlain by lake sediments. Based on our work, we consider that this may be due to the combination of the microstructure (i.e. the platy mineral structure), laminated layering and age of the deposits (i.e. cementation properties and overconsolidated stress state) which make the lake sediments less susceptible to liquefaction (in comparison with Holocene uncemented quartz-rich soils).

The results of our assessment identified the V_s method as the most-aligned with the geologic record and cyclic traxial test results presented in Bowen et al (2015). V_s testing estimates the small-strain shear modulus (stiffness) of the soil and as noted by Andrus and Stokoe (2000); *“V_s and liquefaction resistance are similarly influenced by many of the same factors (e.g., void ratio, state of stress, stress history, and geologic age)”*. These factors are not necessarily accounted for by penetration-based methods. It should also be noted that even though the lake sediments have high mica content (which decreases measured V_s), the measured V_s values were still high enough to predict a low risk of liquefaction.

We consider that the routine penetration-based procedures used throughout New Zealand to assess liquefaction triggering may lead to overestimating the liquefaction risk for sites in the Queenstown area. Even for sites in earthquake-damaged Christchurch, the routine evaluation procedures extensively used do not always correspond with the actual observed site performance. One example of this disparity is presented in Beyzaei et al (2015) where a certain Christchurch site has a silty profile (average FC: 82.1%, average PI: 5%) and the cyclic resistance of the soil estimated by both CPT methods and cyclic triaxial testing indicate that soil liquefaction was triggered following the 22 February 2011 earthquake event; but no surface manifestation of liquefaction was observed following the earthquake. Beyzaei et al (2015) hypothesise that the stratified profile of liquefiable and non-liquefiable soils and the sub-angular particle shape may have limited the pore water pressure redistribution and the formation of sediment ejecta. They are continuing further research to better understand this phenomenon and propose to carry out nonlinear effective stress analyses. Even though it has taken decades to develop widely accepted liquefaction evaluation procedures for Holocene deposits, this example is a reminder that the while science and practice of liquefaction assessment has advanced significantly, it still has not reached perfect maturation.

7 AREAS OF FURTHER RESEARCH

This paper was prepared based on a limited number of geotechnical investigations, in-situ tests and laboratory tests. To more accurately characterise the liquefaction potential of the inter-bedded silt/ sandy silt laminated lake sediment soils, we recommend more area-wide geotechnical investigations, in-situ and laboratory testing (including more cyclic triaxial testing) be carried out throughout the Queenstown region on similar soils.

Even if further investigations and testing shows that the lake sediments do not reach a specified condition of liquefaction, the cyclic strain softening behaviour of these fine-grained soils would need to be further researched. This was not the topic of this study but we recommended more undrained shear strength testing be undertaken to better understand the sensitivity of the cohesive soils in order to adopt suitable N_{kt} values, which are needed to establish the shear strength profiles and CRR in accordance with Boulanger and Idriss (2007).

Additionally, even though there is little geological evidence of widespread liquefaction, previous earthquake events have caused landslides and river banks to collapse throughout the Queenstown Lakes District. The stability analysis undertaken by Bowen et al (2015) predicted horizontal and vertical displacements resulting from large earthquakes but demonstrated that this mechanism was unlikely the result of a sudden flow-type failure which is associated with liquefiable soils. We therefore recommend more research be undertaken to better understand how the quantity, distribution and orientation of the mica particles influence the monotonic and cyclic behaviour of the silty soil and how this might affect slope instability.

8 CONCLUDING REMARKS

Based on our investigations and assessment, it appears that the results derived from V_s testing were the most-aligned with the geologic record. However, we recommend further investigations, testing and research be carried out.

Following further research and data collection; Correlations regarding the material properties and the liquefaction potential of the Queenstown lake sediments can be established, liquefaction hazard maps can be updated, and depending on the findings the current local practices for evaluating liquefaction risk of these soils may need to be modified accordingly. We recommend the findings of this research be readily accessible on an updated searchable database, such as the New Zealand Geotechnical Database. This type of work would provide more insight to the local geotechnical community who are likely to utilise more cost-effective methods of site investigation for small-scale projects. Furthermore, this type of work would allow more informed 'day-to-day' decisions be made by the local authorities regarding the development of the typical small-scale projects in the Queenstown area.

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