Liquefaction potential of Rotorua soils

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ABSTRACT

The soils underlying much of central Rotorua include several metres of diatomaceous silts and pumiceous sands. The properties of these complex soils are often outside the ranges used to establish the current liquefaction criteria, and the assumptions and simplifications made in establishing these criteria may therefore be invalid for the Rotorua area. Cone penetration tests give low results for both cone resistance and sleeve friction which may affect the accuracy of the resulting parameters. These factors make it difficult for the local geotechnical community to reliably predict the liquefaction potential of these soils. This paper provides an introduction into the topic. A review of the existing research on the properties of similar soils is presented and recommendations are given for further research to increase our understanding of the seismic behaviour of these soils.

1 INTRODUCTION

The city of Rotorua in the central North Island of New Zealand is underlain by up to tens of metres of soft diatomaceous silts and pumiceous sands. Little research has been undertaken to establish the detailed geotechnical properties of these deposits, however index tests indicate that their behaviour is likely to be different from the soils used to establish the empirical relationships for determining liquefaction triggering criteria and ensuing ground deformation. The soils also have low values of cone resistance and sleeve friction, so the potential inaccuracy of the CPT field data obtained at the lower end of the instruments' measurement capabilities is likely to result in errors when calculating liquefaction susceptibility. Further research is required to establish whether the established empirical relationships are applicable to the Rotorua soils, and whether the current practice for establishing liquefaction susceptibility in Rotorua needs to be adjusted.

In this paper, the predominant soils in the Rotorua area are described, including basic geotechnical parameters from limited soil test data. This is followed by a review of the existing state of knowledge on the liquefaction potential of fine grained and pumiceous soils. From this, recommendations are given for further research that is needed to gain a better understanding of the cyclic behaviour of these types of soils.

2 ROTORUA SOILS

2.1 Geology

The city of Rotorua is located on the shores of Lake Rotorua, which has formed in a large caldera that is part of the Taupo Volcanic Zone. Some volcanic domes are present within the caldera basin, however the current lake margins are predominantly underlain by a mixture of alluvial, volcanic airfall and lacustrine deposits that are over 100 metres thick in places (Nairn, 2002). These deposits are generally of Holocene age and are a result of the complex interaction between volcanic activity, lake level changes, erosion and deposition.

Parts of central Rotorua are located on an active geothermal field, and hydrothermal alteration (e.g. by chemical alteration or cementation by deposition of silica) of the soils can therefore be expected.

The groundwater level is generally within 5 metres of the ground surface. There are some streams into the lake and the lake edge itself which could allow lateral spreading to occur in case of liquefaction.

Limited soil data was obtained from Gammon and Nelson (1988) and unpublished local geotechnical investigation data, as presented in the following sections. It is reiterated that these parameters are based on a limited amount of data, and a comprehensive set of in-situ and laboratory testing is recommended to better characterise the behaviour and variability of these soils.

2.2 Diatomaceous Silts

Of particular interest to the local geotechnical community are the lacustrine (lake) deposits, which include diatomaceous silts formed from the accumulation of the microscopic silica shells of diatoms (an algae). These deposits can be up to tens of metres thick, and are generally overlain by several metres of more recent volcanic ash, lacustrine beach deposits or uncontrolled filling. Some of these surficial deposits are potentially liquefiable.

The geotechnical properties of the diatomaceous silts are summarised as follows:

- High natural moisture content (160% to 230%);
- Medium to very high plasticity (plasticity index 13 to 97);
- High to very high liquid limit (64 to 158);
- Percentage of clay sized particles varies (10% to 50%);
- High void ratio (3.4 to 5.2);
- Low dry density (approx. 500 kg/m^3);
- Low bulk density (1,270 to 1,300 kg/m^3);
- High coefficient of consolidation c_v (13 to greater than 30 m^2/year);
- Compression index C_c of 0.56 to 1.2;
- Low undrained shear strength (20 to 50 kPa, typically 30 kPa);
- Typical SPT result N=0;
- Typical CPT cone resistance q_c: 0.4 to 1.5 MPa (accuracy +/- 0.1 to 0.2 MPa, depending on cone used);
- Typical CPT sleeve friction f_s: 0.01 MPa (accuracy +/- 0.001 MPa);
- Typical Soil Behaviour Type Index I_c: 2.8 to 3.4 (silty clay to clay).

Under static loading (one dimensional compression) the silt behaves like a saturated normally consolidated clay and shows a time-dependent response to loading due to consolidation. The void ratio after testing is still relatively high due to the internal voids within the structure of the particles.

Although no shear strength measurements are available for the diatomaceous silts, the field description of borehole samples suggests low shear strengths, high sensitivity and dilatant behaviour. Although the sensitivity can be estimated from the CPT test results, the low cone resistance and sleeve friction values compared to the accuracy of the measurements mean that the values for sensitivity may not be accurate. This also applies to the calculation of the soil behaviour type index that is used in the assessment of susceptibility to liquefaction, which is mostly affected by inaccuracies in the cone resistance (Robertson, 2009).

2.3 Pumiceous Sands

There are various depositional origins of the pumiceous sands. Although they are all volcanic in origin, the material could have been emplaced by direct airfall, pyroclastic flows or have been reworked by alluvial processes. The characteristics of pumiceous sands are therefore expected to be variable.

The geotechnical properties of the pumiceous sands, as obtained from the available data, are summarised as follows:

- Grain size distribution is well graded (fine to coarse);
- Percentage of gravel particles varies (2% to 65%), so some deposits are (sandy) gravels;
- Low dry density (500 to 750 kg/m^3);
- Low bulk density (980 to 1120 kg/m^3);
- Variable friction angle of 25° to 40°;
- Variable SPT results (N=5 to N=38);
- Typical CPT cone resistance q_c: 3.0 to 12.0 MPa;
- Typical CPT sleeve friction f_s: 0.02 to 0.05 MPa;
- Typical Soil Behaviour Type Index I_c: 1.6 to 2.2.

3 PREDICTION OF LIQUEFACTION POTENTIAL

3.1 Current Practice

Until recently, the assessment of the liquefaction potential of a Rotorua site was not always undertaken as part of a geotechnical investigation, or only a qualitative assessment was used in which finer grained materials were not considered to be liquefiable.

In 2012, the geotechnical requirements of the Rotorua Civil Engineering Industry Standard were updated by Rotorua District Council to include the requirement to consider liquefaction potential. For all residential and small (<110 m^2) commercial buildings the potential for liquefaction must now be considered, however investigations and analyses may not be required depending on the building type, complexity and potential for lateral spreading. CPT testing and analysis is required for all larger commercial developments.

Although CPT testing is now frequently undertaken in Rotorua, there are no requirements as to the minimum accuracy of the results or whether the susceptibility of fine grained soils should be included, nor is there currently sufficient information to determine which analysis method and input parameters provide the most accurate results in these materials.

3.2 Fine Grained Soils

The liquefaction potential of fine grained soils has been the topic of much research by various authors with notable recent contributions including Bray and Sancio (2006), Boulanger and Idriss (2007), Robertson (2009), and Prakash and Puri (2010). For a comprehensive review of the recent developments and proposed analysis methods the referenced papers should be referred to, however a brief summary of the points relevant to this paper is given here.

Traditionally, fine grained soils (i.e. clay and silt) were considered to be non-liquefiable. Once it became apparent that fine grained soils can be affected by earthquake loading, criteria were developed to establish which fine-grained soils are likely to be susceptible to liquefaction. These criteria were based on the percentage of clay particles, liquid limit and ratio between the natural water content and the liquid limit. As more case studies and laboratory testing data became available, these criteria were refined and adjusted by various researchers. It was found that liquefaction susceptibility relates well to the plasticity index of the soil and ratio between the natural water content and the liquid limit, although these properties are not always used in routine liquefaction hazard analyses. An expanded data set of case history data is used by Bray and Sancio (2006), including data with a plasticity index of up to 40, liquid limit of up to 70 and moisture content of 25 to 45. The properties of Rotorua's diatomaceous silts are well in excess of these ranges.

In "clay-like" soils the reduction of shear strength under cyclic loading can result in significant deformations, even if the pore water pressures do not increase sufficiently to result in zero effective stress. Since zero effective stress in generally not reached, the term 'cyclic softening' is used instead of 'liquefaction'. Boulanger and Idriss (2007) state that the strength loss is likely to result in relatively high settlements for sensitive soils with a high liquidity index (such as the Rotorua soils). Whereas relative density controls the settlement magnitudes in sands, sensitivity controls deformation in "clay-like" soils.

Boulanger and Idriss (2007) and Robertson (2009) made an effort to quantify the susceptibility to liquefaction in a similar manner as was developed for sands, and identified two types of soil behaviour under seismic loading: "clay-like" and "sand-like" (based on the plasticity index and soil behaviour type index (Ic) respectively). The resistance to liquefaction (expressed as the CRR) was related to the overconsolidation ratio (OCR) and shear strength profile of the soil, thus allowing a factor of safety to be established. Robertson (2009) suggested methods to correlate the CPT results to these and other parameters, including sensitivity, by relating the shear strength to the cone resistance and the remoulded shear strength to the sleeve friction.

Prakash and Puri (2010) looked at the relationship between the plasticity index (PI) and CRR. They found a critical PI of approximately 5 for which the lowest CRR was obtained. Similar results were obtained for the fines content in research by Athanasopoulos and Xenaki (2008), which identifies a critical fines content of 42% with the lowest liquefaction resistance and lowest relative density.

3.3 Pumiceous Soils

The cyclic behaviour of pumiceous sands was investigated by Orense et al. (2012). The materials tested included both fluvial sands and processed sand. The reworking of these sands by natural and man-made processes has resulted in relatively pure pumice which is more uniformly graded than the Rotorua sands.

Particle crushing due to the material's porosity and angularity was observed by Orense et al. (2012) under (cyclic) shearing, however not from consolidation (normal stresses). A higher resistance to liquefaction was obtained after crushing. Finer grained materials were slower to build up excess porewater pressures and had a lower liquefaction resistance, comparable to the behaviour of 'normal' silica sands. The relative density of the pumiceous sands did not significantly affect the behaviour of the material in the tests undertaken, including in CPT results. Only a small increase in CPT resistance was obtained with increasing confining pressures. A relatively high friction angle was obtained for both loose and dense sands. No steady state deformations occurred at high strains, suggesting the sands maintained some stiffness. The use of shear wave velocity was proposed as a possible way to more accurately establish the cyclic resistance of pumiceous sands.

O'Sullivan and Holland (2011) presented the findings of the testing undertaken on a sensitive fine grained completely weathered pumiceous ignimbrite in the Waikato with a relatively low bulk density, high friction angle and high natural water content in excess of 100%, similar to the Rotorua soils. Seismic dilatometer testing was undertaken to obtain an in-situ strength and stiffness profile of the soil, with relatively high shear velocity values being obtained in comparison to what would be expected based on the CPT results.

3.4 Diatomaceous Soils

The geotechnical properties of diatomaceous soils with a similar origin to those found in Rotorua was investigated by Verdugo (2008). The soils tested in his research had a compression index Cc of 0.7 to 1.0 and clay-sized particle content of 37% (within the Rotorua range), while the average plasticity index of 5, liquid limit of 60, maximum dry density of 1080 kg/m^3 and void ratio between 1.5 and 2.2 were lower than those of the diatomaceous silt in Rotorua.

Verdugo found that there was no particle crushing during consolidation tests within the stress range tested (up to 3.2 MPa), suggesting high strength particles, however as observed by Orense et al. (2012) for pumiceous soils, it is possible that particle crushing would occur under shear stresses. Relatively high shear strength parameters were obtained (c' = 40kPa and φ' = 45°), however the shear wave velocity Vs was relatively low (100 to 120 m/s at 100 kPa confining pressure). The results also indicate that water within the diatom particles is isolated from the generation of pore water pressures between particles.

The review of properties of diatomaceous soils in other volcanic regions given in Verdugo (2008) indicates the soils can have a high sensitivity (up to 20) and natural water content (up to 400%), as is found in Rotorua.

4 FURTHER RESEARCH

There is clearly a lack of available data to accurately characterise the likely behaviour of the Rotorua soils under cyclic loading. It is recommended that the following research is undertaken to increase our understanding of these complex soils:

- Undrained cyclic triaxial tests on natural soils from the Rotorua area, to expand on the research undertaken by Orense et al. (2012);
- As suggested in Orense et al. (2012), establishing whether shear wave velocities in pumiceous sands are more appropriate than CPT tests for establishing liquefaction susceptibility by comparing the results to the triaxial tests. This should be expanded to include shear wave velocity measurements of the diatomaceous silts, especially since these gave relatively low results (Verdugo, 2008) while the shear wave velocities in pumiceous materials were higher than expected (O'Sullivan and Holland, 2011);
- In-situ shear strength testing in combination with CPT tests to establish appropriate Nkt values for the Rotorua soils. This would allow a more accurate use of the CPT results to establish a shear strength profile to establish the CRR in accordance with Boulanger and Idriss (2007). The research presented in the paper by Pender et al. (1998) on Tauranga and Waikato soils may be able to be expanded to include Rotorua's diatomaceous silts;
- Assessing whether the currently used CPT cones provide sufficient accuracy for the low CPT results obtained, especially considering the significance of sensitivity;
- Establishing the effect of ground temperature on the accuracy of the CPT results;
- Establishing the effects of geothermal alteration on the behaviour of soils.

5 CONCLUSIONS

The margins of Lake Rotorua, including parts of the city of Rotorua, are underlain by complex and variable soils, including thick deposits of interbedded diatomaceous silts and pumiceous sands. The geotechnical properties of these soils are often outside the range used to establish the current liquefaction (or cyclic softening) criteria, and the assumptions and simplifications made in establishing these assessment procedures are therefore likely to be invalid. Some research has been undertaken on similar materials, however it is not clear how the results of this research can be applied to the soils of Rotorua.

It is recommended that a comprehensive set of in-situ and laboratory testing is undertaken to gain a better understanding of these materials and provide recommendations for correlation parameters and the most suitable type of tests, including required accuracies. These can then be included or referred to in the Rotorua Civil Engineering Industry Standard. This would allow the local geotechnical community to more consistently and accurately assess the liquefaction susceptibility for individual low-risk projects (e.g. residential and small commercial buildings) using cost-effective site investigation methods.

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