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Liquefaction Resistance of Hamilton Pumiceous Sands

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ABSTRACT

Conventional empirical methods used to assess the liquefaction resistance of soils from in situ tests, such as CPT and SPT, have been developed for hard-grained sands, and may not accurately characterise the liquefaction resistance of sedimentary pumiceous sands. The NZ Transport Agency commissioned a programme of cyclic triaxial laboratory testing, to better understand the liquefaction resistance of pumiceous sands local to the Hamilton Basin. The results of this testing confirm that the pumiceous sands in the Hamilton area are susceptible to liquefaction, and that the risk of liquefaction cannot be ruled out by the observation that the sand is pumiceous. When compared to similar testing on relatively hard-grained sands found in geotechnical literature, the results show that Hamilton pumiceous sands are generally more resistant to liquefaction than hard-grained sands of the same relative density. Current empirical methods for estimating liquefaction resistance from common field tests (SPT, CPT, Shear wave velocity) are mainly based on data from hard-grained sands, so these may underestimate the resistance of pumiceous sands to liquefaction.

Keywords: liquefaction, pumice, volcanic soils, cyclic triaxial testing, Waikato Expressway

1 INTRODUCTION

Alluvial soils within the Waikato basin contain a significant proportion of sedimentary pumiceous soils derived and transported from the Taupo Volcanic Zone. These pumiceous sands are a mixture of pumice sand and quartz sand particles. Pumice sand particles are characterised by highly porous grains with high crushability. These properties give pumice sand high void ratios, high compressibility, and low density. As a result, their behaviour may be very different to that of hard-grained soils when subject to cyclic loading (Orense and Pender 2013).

Researchers at the University of Auckland (Wesley, et al. 1998) carried out CPT testing on pure pumice sand and regular quartz sand at different relative densities (RD), and an effective overburden pressure equal to 200 kPa. Cone penetration resistance of both the loose and dense pumice sands are very similar, showing that the CPT does not distinguish very well between dense and loose states of pumice sand. Both pumice sand traces are also similar to results for loose hard-grained sand. This implies that a liquefaction assessment using the Cyclic Resistance Ratio (CRR) based on empirical correlations developed for CPT results in hard-grained sands (Boulanger and Idriss 2014) may underestimate the liquefaction resistance of dense pumice sands.

This paper describes the results of a cyclic triaxial laboratory testing programme, commissioned by the NZ Transport Agency, aimed at better understanding the liquefaction resistance of alluvial pumiceous sands. This assessment was done by the comparing the results of cyclic triaxial testing of pumiceous soils from the Hamilton Section of the Waikato Expressway to those of relatively hard-grained sand soils found in geotechnical literature.

2 TESTING METHODOLOGY

2.1 Scope

In order to better understand the liquefaction resistance of the alluvial pumiceous sands found within the Waikato Basin, we have carried out a series of consolidated undrained cyclic triaxial tests on re-constituted samples. The samples were prepared with a range of gradings and densities as follows:

- Loose, coarse pumiceous sand
- Loose, fine pumiceous sand
- Dense, coarse pumiceous sand
- Dense, fine pumiceous sand

The test specimens are re-constituted in order to isolate the effect of pumiceous particles on liquefaction resistance. As a result, the effects of in-situ soil structure, cementation, and aging are nullified. These factors would tend to increase the resistance of the soil (CRR) to liquefaction.

2.2 Sample Soils

Pumiceous sands in the Hamilton area are re-deposited sedimentary soils, with a mixture of hard-grained (quartz) and pumice particles. The coarse and fine samples were obtained as bulk samples from test pits located along the designation of the Hamilton Section of the Waikato Expressway, and are representative of the pumiceous sands typically found in the Hamilton Basin. Properties of the sample soils are summarised in Table 1.

Table 1. Pumiceous sand samples soil properties

Sample	Grading					Solid Particle Density (t/m³)	D_{50} (mm)	ρ_{max} (t/m³)	ρ_{min} (t/m³)
	Gravel (%)	Coarse Sand (%)	Med. Sand (%)	Fine Sand (%)	Fines (%)				
Coarse	5	46	36	10	3	2.54	0.6	1.58	1.3
Fine	0	1	24	56	19	2.48	0.15	1.38	1.12

Scanning Electron Microscope (SEM) imaging was performed on two of the test specimens to assess pumice content. The term “pumiceous” covers a large range of pumice content, and liquefaction resistance may be affected by the relative abundance of pumice particles and hard-grain particles within the soil. Figure 1 shows two of the produced images.

It is difficult to quantitatively determine the pumice ratio from the photos alone, however these images confirm that the sample contains a substantial percentage of pumice, of the order of 20%-30%. This is illustrated in Figure 1 below.

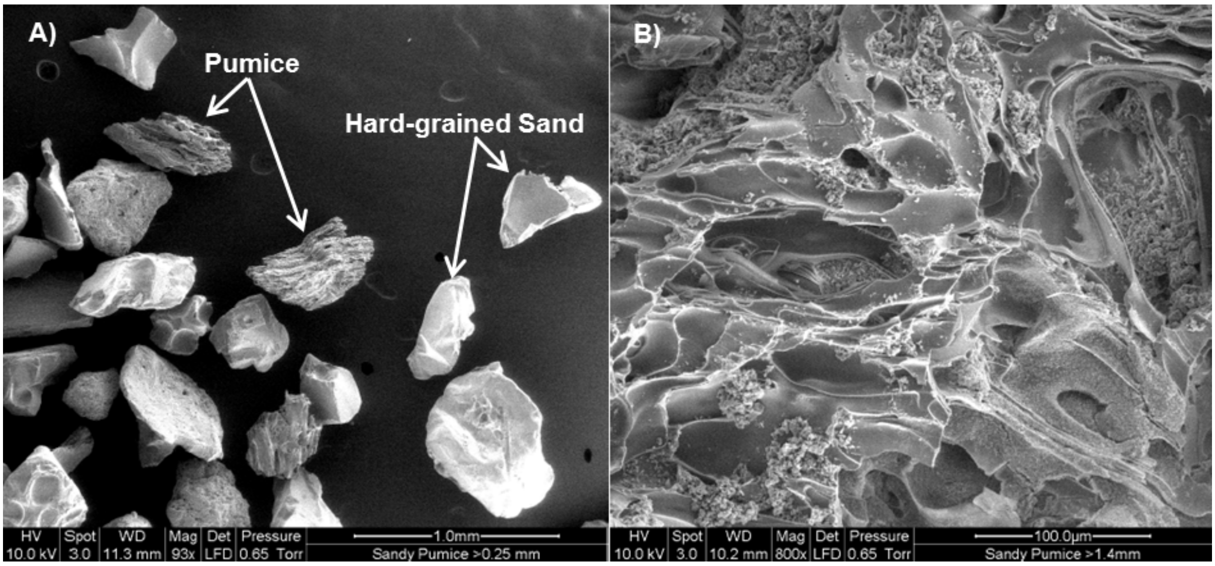

Figure 1. Example of SEM imaging used to identify quartz and pumice sand particles

Analysis of the apparent solid particle density of the pumiceous sample, relative to that of hard-grained silica sands (2.65 t/m³) and pure pumice (~ 2.10 t/m³), also indicates a pumice grain to hard-grained sand ratio of around 20%-30%.

2.3 Cyclic Triaxial Testing

Triaxial specimens were prepared within a cylindrical split mould, with a height to diameter ratio of 2:1 (63 mm diameter, 126 mm height). Before the placement of any soil, the split mould was lined with an impermeable membrane, which contained the test specimen during the triaxial test.

Each specimen was prepared using the technique of moist tamping. Moist tamping consists of placing 5 equal soil lifts of known mass in the mould, and compacting using a small weight to achieve the required lift thickness.

For the loose specimens, only slight re-arranging using the spoon (no tamping) was required to remove gaps in each lift and to smooth the surface.

The dense samples were compacted by tamping with a small weight. Because pumice particles are more susceptible to crushing during tamping, only a moderate level of tamping using the weight was carried out, to avoid undesirable levels of particle crushing. The maximum relative density of the coarse sample achieved using this method was 70-75%, and a relative density of 80-85% was achieved in the fine sample.

Undrained cyclic triaxial testing involves the initial consolidation of the specimen under an isotropic confining pressure (σ'_c) of 100 kPa. This consolidation pressure was selected to be consistent with a large body of similar testing in the literature.

The cyclic loading was applied in a stress-controlled manner using a pressurised load cell. Axial loads were applied alternately in compression and extension according to the specified Cyclic Stress Ratio (CSR), $\pm\Delta\sigma_1/2\sigma'_c$.

There are two alternate criteria for liquefaction in the cyclic triaxial test: when pore water pressure first reaches 95% of the initial confining pressure, or the double amplitude axial strain reaches 5%. For each cyclic triaxial test, the cyclic load was applied in compression and extension until both of these criteria were reached.

3 CYCLIC TRIAXIAL TESTING RESULTS

For the loose specimens, the two failure criteria were reached at approximately the same number of loading cycles. However, the dense specimens reached the pore pressure liquefaction criteria before reaching the strain-based liquefaction criteria.

The strain-based liquefaction criteria appears more common in the literature and will therefore be used for analysis of the current results. For each test, the number of cycles to achieve 5% double amplitude shear strain under each cyclic stress ratio are shown in Figure 2.

In the context of cyclic triaxial testing, Seed and Idriss (1982) published a curve representing the equivalent number of uniform loading cycles corresponding to various earthquake magnitudes. From this data, 15 cycles of uniform loading is taken as equivalent to shaking from a magnitude 7.5 earthquake, for comparison to standard liquefaction methods which contain magnitude weighting factors to normalise the hazard to a magnitude of 7.5.

To determine the CSR at which liquefaction would occur in 15 uniform load cycles (equivalent to a 7.5 magnitude earthquake) we fitted a power curve to the data for each grading and relative density. The resulting cyclic resistance ratios (CRR_{tx}) for a 7.5 magnitude earthquake are listed in Table 2.

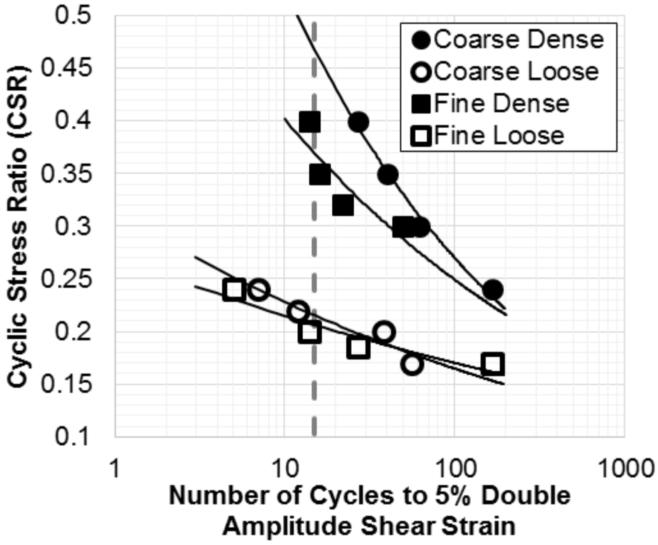

Figure 2. Cyclic triaxial testing results

Table 2. CRR_{tx} for 7.5 magnitude shaking

Sample	Relative Density (%)	CRR_{tx}
Coarse	73	0.47
	22	0.22
Fine	85	0.37
	25	0.21

4 EVALUATION OF THE CYCLIC RESISTANCE

4.1 Comparison to Published Cyclic Triaxial Results

In this study we have compared the results of the cyclic triaxial tests on Hamilton pumiceous sands to results for various hard-grained sands identified in the literature. The results from the literature (Yamamoto et al., 2009; Hosono and Yoshimine, 2004; Ishihara et al., 1980; Yoshimi et al., 1994; Thomas, 1992; Mulilis et al., 1976; and Hyodo et al., 2012) provide a benchmark for typical results to be expected for various hard grained sand materials at different densities. Each of these tests were performed on reconstituted samples at an effective confining pressure of 100 kPa.

In addition to test results on hard-grained sands, Orense and Pender (2013) performed a series of cyclic triaxial tests on commercially available pumice sand. This sand was derived from the Waikato River, and sorted into various different gradings. The sample Pumice-A is uniformly graded, and made up almost entirely of coarse sand-sized pumice particles. The Pumice-A sample is therefore coarser than both Hamilton pumiceous sand samples.

Figure 3 displays CRR_{tx} results from different published studies, for various different sands at various relative densities, along with all the cyclic triaxial testing performed in this study (labelled HamSec).

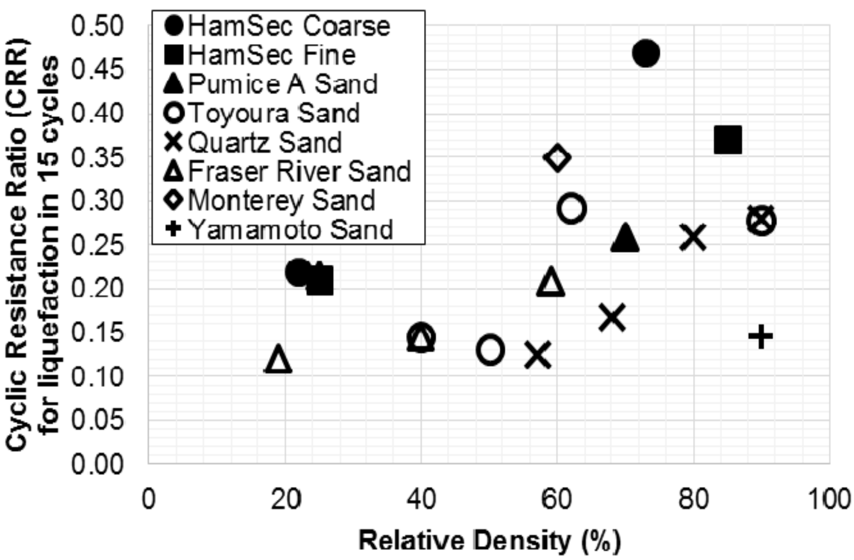

Figure 3. CRR_{tx} results compared with results from published studies for pumice and quartz sand

The cyclic triaxial results for the Hamilton pumiceous sands and the pure Pumice-A sands generally lie on the upper edge of liquefaction resistance spectrum, which suggests that the pumice and pumiceous sands are generally more resistant to liquefaction than hard-grained sands of the same relative density.

4.2 Influence of Grading

When subjected to shear forces in the cyclic triaxial test, highly crushable weak pumice grains may break down into finer particles, increasing the fines content and the liquefaction resistance (Orense, et al. 2012). Lui et al. (2015) concluded that the liquefaction response of pure pumice sand is more dependent on particle crushability during cyclic shearing than relative density.

However, unlike results of these studies on pumice sands, the pre-test and post-test particle size distributions of Hamilton pumiceous sands showed little evidence of particle crushing as a result of the cyclic triaxial testing. This is likely a result of the dominant proportion of hard-grained sands in the Hamilton pumiceous sands tested, demonstrating that the liquefaction resistance of Hamilton pumiceous soils is largely dependent on relative density.

4.3 Comparison to Inferred CPT Results

4.3.1 Conversion of Triaxial CRR to Equivalent In-Situ CRR

The stress conditions within the cyclic undrained triaxial tests are different to those experienced by soil in situ, therefore the CRR determined from cyclic triaxial testing is not equivalent to the CRR in the field. As result, conversions have been developed to relate the CRR_{tx} as determined from cyclic triaxial testing to the equivalent in-situ CRR_{field} which would be expected for a sand at a similar relative density. One such relationship is defined by Kramer (1996) as the equation below (Equation 1), with the c_r for testing in the triaxial space approximately equal to 0.69 (Kramer 1996).

$$CRR_{field}=0.9\ c_r\ (CRR_{tx}) \quad (1)$$

4.3.2 CRR from Inferred CPT Results

Robertson and Cabal (2015) published correlations to infer relative density from CPT results. This relationship was used to infer typical CPT resistances for the relative densities of the cyclic triaxial specimens, at a depth equivalent to the 100 kPa confining pressure used in the lab tests. These correlations are based on coarse hard-grained sand normalised to an overburden pressure of 100 kPa, therefore the inferred cone resistance (q_c) were converted to an equivalent $(q_{c1}N)_{cn}$ using an assumed I_c value.

Using the empirical correlations for the CRR based on CPT output published by Boulanger and Idriss (2014), the CRR_{CPT} corresponding to each relative density was calculated.

Table 3. Equivalent in situ CRRs from cyclic triaxial results compared to CRRs based on inferred CPT output

Sample	Relative Density (%)	Measured		Inferred
		CRR_{tx}	CRR_{field}	CRR_{CPT}
Coarse	73	0.47	0.29	0.13
	22	0.22	0.14	0.08
Fine	85	0.37	0.23	0.35
	25	0.21	0.13	0.08

In all but one case, the equivalent in-situ CRRs obtained from the cyclic triaxial testing of Hamilton pumiceous sand (CRR_{field}) are higher than those estimated from CPT correlations for hard-grained soils of the same relative density (CRR_{CPT}). Therefore a similar CPT response in the field, and the corresponding CRR according to conventional empirical methods, would underestimate the liquefaction resistance of pumiceous sands and therefore overestimate the liquefaction hazard. These discrepancies are further exaggerated by the tendency of the CPT test to underestimate relative density of pumice sands, as shown by Wesley, et al. (1998).

5 CONCLUSION

The conclusions resulting from this study are as follows:

- The pumiceous sands tested are susceptible to liquefaction.
- Greater cyclic liquefaction resistance was obtained in specimens of higher relative density.
- Sample grading had less effect on the liquefaction resistance than expected, however coarse sands appeared to be more resistant to liquefaction than fine sands when dense.
- Pumiceous sands of a given relative density appear more resistant to liquefaction than hard-grained sands of the same relative density.
- Empirical correlations for estimating liquefaction resistance from common field tests (SPT, CPT, V_s) are mainly based on data from hard-grained sands, and may significantly underestimate the resistance of pumiceous sands to liquefaction and therefore overestimate the liquefaction hazard.

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REFERENCES

Boulanger, R. W., and Idriss, I. M. (2014). *Report No. UCD/CGM-14/01 - CPT and SPT Based Liquefaction Triggering Procedures*. Center for Geotechnical Modeling - University of California, Davis, California, 134 pp.

Hosono, Y. and Yoshimine, M. (2004). "Liquefaction of sand in simple shear condition." *Proceedings of the International Conference on Cyclic Behaviour of Soils and Liquefaction Phenomena*, Bochum, Germany.

Hyodo, M., Orense, R.P., Noda, S., Furukawa, S., and Furui, T. (2012). "Slope failures in residential land on valley fills in Yamamoto town." *Soils and Foundation*, 52(5), 975-986.

Ishihara, K., Troncoso, J., Kawase, Y., and Takahashi, Y. (1980). "Cyclic Strength Characteristics of Tailings Materials." *Japanese Society of Soil Mechanics and Foundation Engineering*, 20(4), 127-142.

Kramer, S. L., (1996). *Geotechnical Earthquke Engineering*. Prentice Hall, Upper Saddle River, New Jersey, 653 pp.

Mulilis, J. P., Horz, R. C., and Townsend, F. C. (1976). *The effects of cyclic triaxial testing techniques on the liquefaction behaviour of Monterey No. 0 sand.* U.S. Army Engineer Waterways Experiment Station, Soils and Pavements Laboratory, Vicksburg, Mississippi.

Lui, L., Orense, R.P., and Pender, M.J. (2015). "Crushing-induced liquefaction characteristics of pumice sand." *Proceedings of the New Zealand Society for Earthquake Engineering Technical Conference, NZSEE*, Rotorua, New Zealand, Paper Number O-57.

Orense, R. P., and Pender, M. J. (2013). "Liquefaction characteristics of crushable pumice sand." *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, 1559 - 1562.

Orense, R. P., Pender, M. J., and Tai, A. (2012). "Undrained Cyclic Shear Behaviour of Pumice Sand", *11th Australia-New Zealand Conference on Geomechanics – Ground Engineering in a Changing World*, Melbourne, Australia, pp. 858-863.

Robertson, P. K., and Cabal, K. L. (2015). *Guide to Cone Penetration Testing for Geotechnical Engineering*, 6th ed. Signal Hill, California, Gregg Drilling & Testing Inc, 133 pp.

Seed, H. B., and Idriss, I. M. (1982). *Ground Motions and Soil Liquefaction during Earthquakes.* Earthquake Engineering Research Institute, Oakland, California, 134pp.

Thomas, J. (1992). *Static, Cyclic and Post Liquefaction Undrained Behaviour of Fraser River Sand*, The University of British Columbia, Vancouver, 117 pp.

Wesley, L. D., Meyer, V., and Pender, M. J. (1998). "Cone Penetrometer Tests in Pumice Sand." *N.Z. Geomechanics News*, June, 57-61.

Yamamoto, Y., Hyodo, M., and Orense, R. P. (2009). "Liquefaction Resistance of Sandy Soils under Partially Drained Condition." *Journal of Geotechnical and Geoenvironmental Engineering*, 135(8), 1032-1043.

Yoshimi, Y., Tokimatsu, K., and Ohara, J. (1994). "In situ liquefaction resistance of clean sands over a wide density range." *Geotechnique*, 44(3), 479-494.