

Geotechnical properties of liquefied pumiceous layers in lakes

Propriétés géotechniques de couches ponceuses liquéfiées dans des lacs

Jordanka Chaneva, Max O. Kluger, Vicki G. Moon, David J. Lowe

School of Science, University of Waikato, New Zealand, jc409@students.waikato.ac.nz

Rolando P. Orense

Department of Civil and Environmental Engineering, University of Auckland, New Zealand

ABSTRACT: Earthquake failures in volcanic-ash soils are relatively common, considering their physical nature and the fact that such deposits tend to occur in areas with high seismicity, where, the volcanism responsible for their emplacement shares some tectonic-related origin. However, experimental and empirical data related to geotechnical properties and their mechanical behavior are still quite limited compared to those for hard-grained soils. Moreover, the limited data largely focus on pumiceous sands, whereas pumiceous silts have not been significantly investigated to date. We summarize relevant geotechnical properties of volcanic-ash layers preserved in lake sediments in the Hamilton lowlands in North Island, New Zealand. These highly pumiceous layers are hypothesized to have liquefied within the past 20,000 years, based on paleo-liquefaction features observed in some of the lakes. In the geotechnical characterization of the samples in this study, we identified the ones that are liquefaction susceptible and we described the specific gravity vs. fines content and pumice content trends. Additionally, the characteristic void ratios of five samples were discussed as they generally tested with higher values compared to those documented for hard-grained soils.

RÉSUMÉ : Les glissements de terrains dans les sols de cendres volcaniques sont des phénomènes communs, étant donné leur nature et le fait que ces dépôts ont tendance à apparaître dans des zones hautement sismiques, puisque le volcanisme à l'origine de leur formation repose sur les mêmes procédés tectoniques que ceux qui causent les tremblements de terre. À ce jour, les données expérimentales et empiriques liées aux propriétés géotechniques et leur comportement mécanique sont limitées par rapport à celles des sols à grains durs. De plus, les données disponibles sont spécifiques aux sables ponceux, tandis que les silts ponceux n'ont pas encore été étudiés. Cet article résume les propriétés géotechniques pour certaines couches de cendres volcaniques présentes dans les sédiments lacustres autour d'Hamilton (Nouvelle-Zélande). Ces couches ponceuses sont supposées avoir été liquéfiées par le passé, basé sur des observations caractéristiques de la paléo-liquéfaction observés à certains endroits. Leur caractérisation géotechnique est une étape cruciale pour estimer leur potentiel de liquéfaction et ainsi évaluer les anciens tremblements de terre qui ont pu engendrer ces formations. En outre, les propriétés géotechniques de ces limons ponceux vont contribuer à la base de données mondiale de résistance à la liquéfaction de ces sols.

KEYWORDS: geotechnical properties, pumice, liquefaction, lacustrine volcanic-ash deposits

1 INTRODUCTION

Earthquake failure (e.g., liquefaction, landslides) of volcanic-ash soils has been observed in the recent past, including in Japan, South and North America, and New Zealand (Ishihara et al., 1986; Pender et al., 1987; Bommer and Rodríguez, 2002; Orense et al., 2002; Uzuoka et al., 2005). Yet, experimental and empirical data related to relevant geotechnical properties and their mechanical behavior are still quite limited compared to those obtained on hard-grained quartzitic soils. Moreover, the limited data are largely focused on pumiceous sands (Hyodo et al., 1998; Wesley et al., 1999; Pender et al., 2006; Orense et al., 2012), whereas pumiceous silts have not been significantly investigated to date (Rolo et al., 2004). Existing studies often label these vesicular sands as 'problematic' because of their crushability, compression characteristics, liquefaction resistance, etc., that are highly dependent on the grain size and pumice content (Hyodo et al., 1998; Miura et al., 2003; Orense et al., 2012). Related research also shows that the geotechnical properties (e.g., particle density) of these soils are strongly dependent on the laboratory method adopted, mainly because of their vesicularity (Wesley 2001, Pender et al., 2006). This means that, unlike quartzitic soils, where, e.g., the specific gravity is considered constant ($G_s=2.65-2.67$) and independent of the method used, the determination of geotechnical properties of pumiceous soil mixtures is challenging. Their problematic nature makes these soils challenging in conventional engineering liquefaction studies where, the purpose is to assess liquefaction as a geotechnical hazard, as both laboratory and in-situ methods can induce particle crushing (Orense et al., 2012; Asadi et al.,

2018; Orense et al., 2020). Thus, it has been hypothesized that pumice content is the key property that needs to be evaluated prior to a relevant geotechnical study sensitive to the issues mentioned above (Orense, 2020; Stringer, 2019). The dependence of specific gravity on the pumice content and on the grain size, could be exploited for this purpose. Possible relations with other relevant geotechnical properties, such as the characteristic void ratios (e_{min}, e_{max}), could also guide researchers and engineers to the most optimal solution for determining the pumice content in a soil mixture.

We have measured relevant geotechnical properties of a large number of volcanic-ash samples (also referred to as tephra samples) preserved in lake sediments in the Hamilton lowlands in North Island, New Zealand. Many of the layers are highly pumiceous and show paleo-liquefaction features in some lakes (Kluger et al., under review). Their characterization and liquefaction susceptibility assessment are crucial first steps in assessing their liquefaction potential from which we aim to estimate timing and occurrence of past earthquakes in the lowlands. The geotechnical properties we document for these mainly pumiceous silts will be a significant addition to the existing pumice sand database, leading to a better understanding of how these properties vary with the silty pumiceous soil mixtures.

2 STUDY AREA

The Hamilton lowlands lie within the pre-Quaternary tectonically-formed Hamilton Basin in North Island. Volcanic-

ash layers deposited from numerous eruptions from active rhyolitic (silica-rich) volcanic centers and andesitic volcanoes in central/western North Island are found in lakes in the Hamilton lowlands (Figure 1) (Lowe, 1988). Around 30 lakes in total, each ~20,000 years old and underlain partly by volcanogenic alluvium (Green and Lowe, 1985), lie scattered amidst the faults in the lowlands. Designated as having a low to moderate seismic risk (Stirling et al., 2012), the Hamilton lowlands, until recently, also lacked any known active faults (Edbrooke, 2005; Langridge et al., 2016). The recently identified faults, as well as the evidence of past seismic activity from paleo-liquefaction studies, supported the hypothesis of potential liquefaction features found in the lacustrine volcanic-ash layers in the area (Kleyburg, 2015; Moon and Lange, 2017; Van Dissen et al., 2021).

This study focuses on volcanic-ash samples retrieved from seven lakes: Areare, Kainui, Rotokauri, Waiwhakareke, Rotokaeo, Rotorua and Ngaroto (Figure 1).

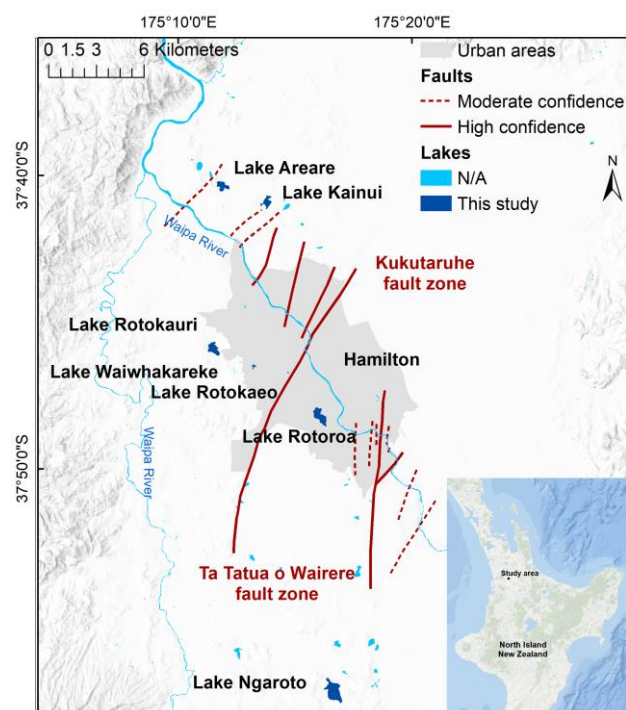


Figure 1. Study area: Hamilton Basin with locations of lakes considered in this study (dark blue) and faults

3 MATERIALS AND METHODS

The focus of this paper is four rhyolitic pumiceous tephra (volcanic ash) layers: Tuhua (Tu), Mamaku (Ma), Waiohau (Wh) and Rotorua (Rr). The tephra layers, each between ~2 and ~8 cm thick (Kluger et al., under review), were sampled from a number of ~1.5 m-long piston cores collected at six lakes (Figure 1). They occur at different depths in the lake sediments ranging from 0.5 m to 2.0 m (Kluger et al., under review; Lowe, 1988). The tephra layers mainly comprise volcanic glass (in the form of glass shards and glassy pumice fragments) and minor crystals, (Figure 2) (Lowe, 1988). They show differences in compositions in terms of grain size and pumice content in the different lakes (Lowe, 1988).

Because the layers are relatively thin (2–8 cm), it was not possible to analyze all the relevant physical and geotechnical properties from the small volumes provided by the cored samples. Therefore, additional onshore block sampling was made at Lake Areare (Figure 1), where lowered lake levels facilitated easy access to shallow (near-surface) deposits of Tu and Ma. This sampling provided sufficient material to

characterize these pumiceous soils more comprehensively by, e.g., Atterberg limit tests.

In total, 45 individual samples were taken from cores and block samples, comprising 17 samples of Tu, 11 samples of Ma, 17 samples of Rr and four samples of Wh. For each of the 45 samples, particle density (thus specific gravity, G_s) and grain-size distribution analyses were performed. The particle density of the samples was obtained following ASTM-D5550-14 (ASTM, 2014) using a Quantachrome Ultrapyc 1000 nitrogen-filled gas pycnometer. The particle-size distribution of the samples was determined by means of laser diffraction analysis (LDA) in a Malvern Mastersizer 3000, using small-volume samples retrieved from the cores and the onshore blocks.

Scanning electron microscope (SEM) analysis, using a Hitachi S-4700 FE SEM and X-ray diffraction (XRD), using a Panalytical Empyrean Series 2 XRD, were undertaken for a number of representative samples from each tephra in order to further examine their pumice content and clay mineralogy.

SEM image based particle counting for quantifying pumice content has been used before (Asadi et al., 2019). The SEM approach has been referred to as time consuming and not fully representative of large soil volumes as a small number of particles are examined and converted into percentages (Stringer, 2019). This study however, deals with thin layers on which most of the laboratory tests (i.e., particle density, grain-size distribution) are already made using small quantities, so we considered this approach as the most efficacious. Therefore, we quantified pumice content using a point-counting approach (Frolov and Maling, 1969). In this method, five SEM images of representative pumice clusters were chosen for each sample and were counted systematically on crossing points (> 200 points per sample) of rectangular grids. The pumice content (PC) was defined as the ratio of the number of grid points that define the area that covers pumice looking particles (based on visual features i.e., vesicular) ($N_{A,pumice}$) to the number of grid points that define the area of all particles ($N_{A,total}$):

$$PC = \frac{N_{A,pumice}}{N_{A,total}} * 100\% \quad (1)$$

Dominant clay minerals in selected silty samples were determined qualitatively by XRD. Samples were prepared following standard methods based on Lowe and Nelson (1983) and

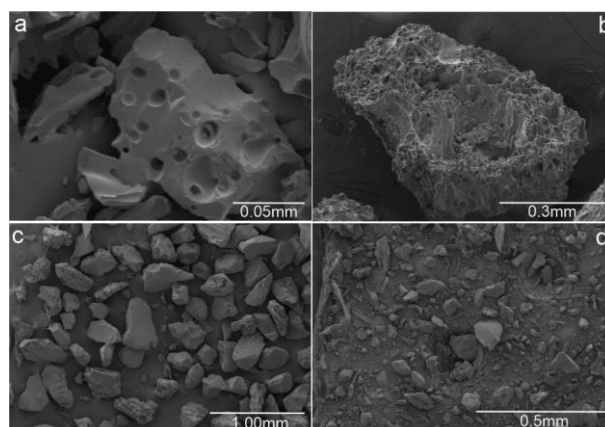


Figure 2 (a) and (b): SEM images of particles in Rr tephra, Lake Kainui (c) and (d) SEM images of mainly glass shards and pumice particles in Ma tephra, lake Areare

Whitton and Churchman (1987). Mineral identifications were based mainly on clay mineral identification diagrams formulated by USGS (2001).

The minimum and maximum dry densities (thus maximum and minimum void ratios, respectively), as well as the Atterberg limits, were determined on samples retrieved from the onshore location at Lake Areare. The minimum and maximum densities of five samples (three Mamaku and two Tuhua) were determined following the Japanese standard method (JGS0161-2009) modified by Mijic et al., (2021). The JGS procedure has been proven to cause negligible particle crushing in natural pumiceous soils found in the North Island of New Zealand (Asadi et al., 2019). The silty samples from the onshore blocks from lake Areare (Table 1) were tested for their liquid and plastic limits following the ASTM-D4318-17e1 (ASTM, 2017) procedure.

4 GEOTECHNICAL PROPERTIES

4.1 Grain-size analyses and Atterberg limits

The grain-size distribution curves of all samples retrieved from the seven lakes are presented in Figure 3. The highlighted curves show samples of the Rr tephra (blue solid lines) from different lakes, as well as the Ma tephra (orange dashed lines) composed of three different layers by means of grain-size distributions in the onshore samples from Lake Areare. The fines content (% < 0.075 mm) for all the samples ranges from ~10% to 99%. The silty samples from the lakes can contain up to ~10% clay-sized particles (< 0.002 mm). According to the Unified Soil Classification System-USCS (ASTM-D-2487), the samples can be classified as silts, sandy silts (37 samples) or silty sands (eight samples).

Each tephra (Tu, Ma, Wh, Rr) can have a different grain-size composition in different lakes (e.g., silty Rr in lakes Waiwhakareke and Ngaroto, versus sandy Rr in lakes Kainui and Rotorua: Figure 3). Their thickness and interlayering (within each tephra deposit) also vary in between lakes, meaning they can be found as thin single layered pure silts, or comprising more than two different layers by means of grain-size in the same tephra layer (e.g., Ma tephra from Lake Areare: Figure 3). Additional information about thicknesses of the different tephras in the lakes are reported in Kluger et al. (under review).

The geological conditions (such as age and origin) and the grain-size composition are an important preliminary check for the liquefaction susceptibility of soils. In this regard, there is a general agreement that young Holocene sands, non-plastic silts and gravels, and their mixtures, are susceptible to liquefaction.

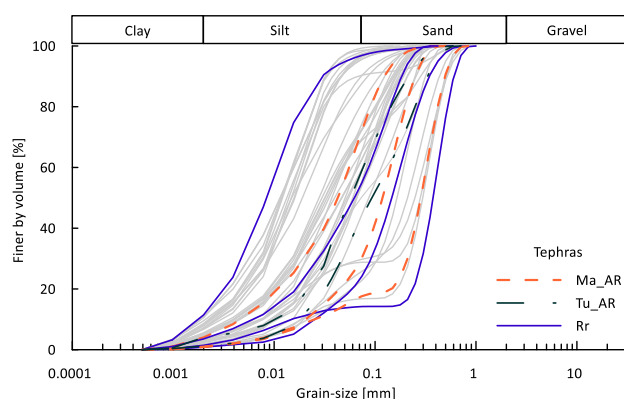


Figure 3. Grain-size distribution curves of all samples (grey curves). Highlighted blue (solid) curves show the Rotorua (Rr) tephras from different lakes: Waiwhakareke, Ngaroto, Kainui, and Rotorua (from top to bottom: silt to silty sand). Highlighted dark green (dash-dotted) and orange (dashed) curves represent Tuhua (Tu) and Mamaku (Ma) tephras, respectively, sampled onshore at Lake Areare (denoted using the suffix AR).

The geological and compositional characteristics are not enough when it comes to characterizing fine soils that also

contain clay-sized particles because of the many significant differences in the undrained behavior of sandy and clayey soils. Plasticity characterization is considered the conclusive method when it comes to liquefaction susceptibility of fine-grained soils (Boulanger and Idriss, 2006; Bray and Sancio, 2006).

The silty samples from the onshore blocks from Lake Areare (Table 1) were tested as non-plastic (ASTM-D4318-17e1, 2017), which confirms their liquefaction susceptibility.

Table 1. Grain-size characteristics for silty onshore samples from Lake Areare

Sample	Lake	D_{50} [mm]	FC [%]	CC [%]
Tu	Areare	0.06	59	4
Ma	Areare	0.04	72	6

For the purpose of extending the non-plastic classification to the layers in the lakes, XRD analysis on the clay-sized portion of some selected samples (containing 8–10% clay-sized particles, referred to as CC) was performed.

Table 2. Minerals in clay-sized fraction of selected samples

Sample	Lake	FC [%]	CC [%]	Minerals
Tu	Rotokao	97	8	Glass >> mica
Tu	Rotokauri	99	9	Glass
Ma	Kainui	87	7	Glass >> 1.0 nm halloysite
Rr	Kainui	87	10	Glass >> 1.0 nm halloysite
Rr	Rotokauri	98	10	Glass
Rr	Ngaroto	95	10	Glass >> 0.7 nm halloysite

The results showed that the non-plastic classification can be extended to a limited number of samples, as three of the six samples were cleared from having clay minerals in the XRD analysis (Table 2). The remaining three samples showed evidence of low-activity clay minerals. Without quantification of the plasticity of these samples, the liquefaction susceptibility cannot be confirmed for all the silty samples in the six lakes without further tests.

4.2 Specific gravity (G_s)

The specific gravity values of all samples from Tuhua (dark green diamond symbol), Mamaku (orange triangle), Rotorua (blue circle), and Waihou (yellow square) tephras with varying fines contents are presented in Figure 4. The specific gravity values range from 2.10 to 2.68, for soils with fines content from ~14 to 99%. For comparison purposes, data for Toyoura sand (quartzitic hard-grained sand), Shirasu sand (pumiceous sand), pure pumice sand (commercially available) and the Tierra Bianca Silt (volcanic-ash silt) were plotted as well.

Specific representative samples were selected in order to investigate the relationship between the pumice content and the specific gravity. Figure 5 plots the specific gravity vs. pumice content of ten samples, including four of the onshore block samples from Lake Areare.

Specific gravity in soil mechanics is defined as the ratio of the unit weight of solid particles to the density of an equal volume of water at 4°C (Terzaghi and Peck, 1996). For hard-grained soils (without internal voids), this value can accurately represent the particle density and can be used to calculate related parameters, e.g., void ratios. In soils containing pumiceous particles, this becomes an issue as there is a difference between what can be defined as solid particle density, where the volume of the solid part of the particle without the voids is taken into account and the apparent particle density, where the volume of the whole particle (voids included) is taken into account (Orense et al., 2012).

Because of their nature and the nature of the tests used to analyze this physical property, the values can vary significantly according to the method used (Biolders et al., 1990; Wesley, 2001). Moreover, it has been found that the particle density of pumice is usually dependent on the particle size (Warkentin and Maeda, 1980). The pumice content in natural mixtures is also a significant parameter that affects the value of the specific gravity, as pure pumice soils have lighter weight compared to hard-grained soils (Asadi et al., 2019; Stringer, 2019).

In using gas pycnometer analysis to determine the particle density of the tephra samples, only the internal (trapped) voids are not filled with gas (whereas the surface voids, as well as the voids between particles, are filled), meaning the volume taken into account represents neither the actual mineral density, nor the bulk density of the grains in their entirety (Biolders et al., 1990).

In general, the first observation from the results (Figure 4) is that the specific gravity of pumiceous soils is dependent on the fines content. As the content of fine particles increases, the specific gravity values increase as well. All data points lie in the range between the pure pumice sand value (Asadi et al., 2019) and the representative hard-grained Toyoura sand.

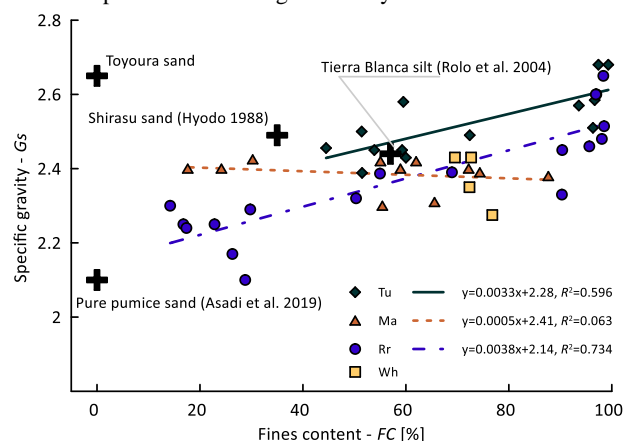


Figure 4. Specific gravity (G_s) vs. fines content (FC) graph for the four volcanic-ash samples from different lakes compared to values of relevant sands/silt in published literature.

The increase of specific gravity with increasing fines content is especially evident in the Tu and Rr trendlines (blue dash-dotted and dark green solid line, respectively). A second observation is that of the offset in between the trendlines - the specific gravities of Tu being higher in general. This is most probably a result of small differences in glass shard major elemental compositions, with Tu notably enriched in Fe ($FeO_t \sim 6wt\%$) compared to Rr with $FeO_t \sim 1wt\%$ (Lowe, 1988; Lowe et al., 2008). Note that subscript t denotes all oxidation stages of iron oxide.

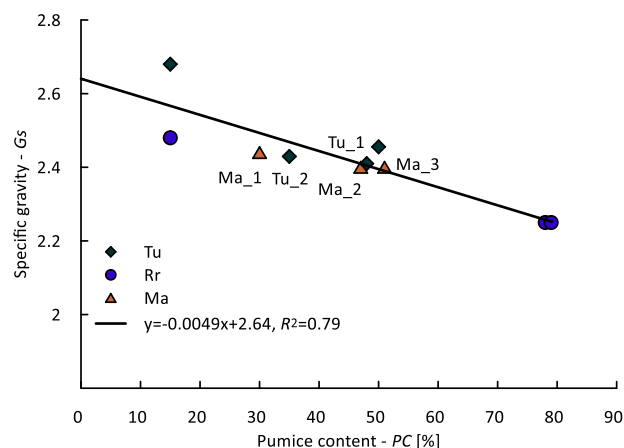


Figure 5. Specific gravity (G_s) vs. pumice content (PC) for ten selected tephra samples from the lakes

An interesting exception in the relationship between specific gravity and fines content is the trendline of the Ma tephra, where specific gravity is seemingly independent of the fines content. All specific gravity values are close to 2.4 (ranging from 2.30 to 2.43), resulting in an almost flat trendline. We infer that this could be a result of a potential lesser (if not completely lacking) content of internal voids within the pumiceous particles, as the values gravitate towards a specific gravity of 2.4, which is the specific gravity typical of volcanic glass shards. Moreover, in the case of this specific tephra (Ma), the specific gravity seems to be less sensitive to the pumice content as well, compared to the other two tephtras (Tu and Rr) (Figure 5). This indicates that an isolated tephra with these characteristics, will still probably be crushable (having pumiceous particles varying from 30 to 50%), yet it would not contribute to a trendline that would assist in deriving pumice content from G_s values. This observation may support pumice content estimation methods that are based on the crushability characteristics of pumiceous soil mixtures instead of those based on weight properties. However, the fitted line in Figure 5. (which corresponds to a value of 2.64 for 0% pumice content), supports possible G_s - PC correlations which with a large enough database (soil mixtures containing pumiceous particles with different sorts of pumice), could be used as an indicator for the pumice content of a soil mixture based on the specific gravity value (determined in an identical way – i.e., via gas pycnometer).

4.3 Characteristic (minimum and maximum) void ratios

The results for the characteristic void ratios of the samples collected from the block samples at Lake Areare for Tuhua (dark green diamond) and Mamaku (orange triangle) tephtras, as well as the trendlines and data point zone from Cubrinovski and Ishihara (2002), are presented in Figures 6 and 7.

Cubrinovski and Ishihara (2002) found that the void ratio range ($e_{max}-e_{min}$) embodies the combined effects of mean grain size, grain-size distribution, fines content and grain shape. Their large database of more than 300 soil samples tested using the JGS procedure (JGS0161-2009) resulted in correlations between the characteristic void ratios and these material properties (Figures 6 and 7).

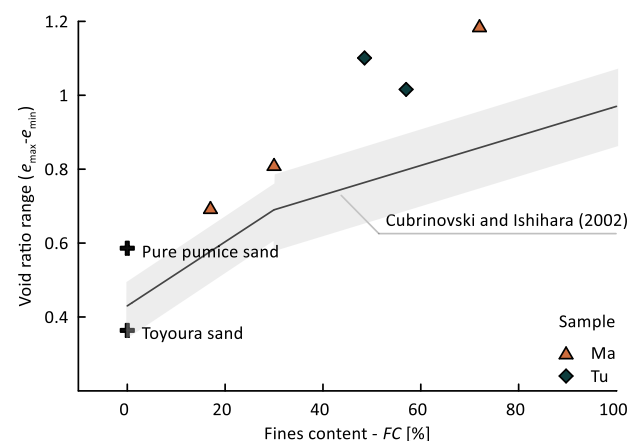


Figure 6. Void ratio range ($e_{max}-e_{min}$) vs. fines content (FC) graph for the two volcanic ash sampled onshore at Lake Areare compared to trendlines and values found in published literature

These correlations are widely recognized when it comes to hard-grained soils, yet as their database did not include pumiceous soils, it is of particular interest to examine whether this trend extends to volcanic-ash materials as well.

In their study, Cubrinovski and Ishihara (2002) inferred that there was less scatter and better correlation between the void

ratio range and the fines content of sandy soil samples with less than 30% fines, but that in general, the void ratio range increases with the increase in fines content (Figure 6). The silty samples from our study show higher offsets from the trendline compared to the sandy ones, which is in accordance with the results of Cubrinovski and Ishihara’s study mentioned above.

The five volcanic-ash samples from our study, as well as the pure pumice sand (Asadi et al., 2019), have higher maximum void ratios compared to the hard-grained Toyoura sand (Table 3), meaning in the loosest state (minimum density), the voids to solid volume ratio is much higher for the same fines content, which is expected as the pumice particles contain voids. The minimum void ratios also follow this trend but not to the same extent in general. This results with the data points plotting above the void ratio range vs. fines content trendline, outside the standard deviation (Figure 6). This indicates that the difference between the characteristic void ratio values is generally high for pumiceous soils, which may result in higher compressibility because of the bigger range of potential void ratio values (between e_{max} and e_{min}). More research needs to be conducted in order to further analyze and interpret if that is indeed the case.

Table 3. Characteristic void ratios and pumice content for Tu and Ma samples, Lake Areare (onshore samples) and relevant void ratios from literature

Sample	Lake/Ref	D_{50} [mm]	FC [%]	PC [%]	e_{min}	e_{max}
Tu_1	Areare	0.09	44	48±14	1.047	2.148
Tu_2	Areare	0.06	59	35±11	1.152	2.168
Ma_1	Areare	0.04	72	30±10	0.881	2.069
Ma_2	Areare	0.3	18	47±10	0.817	1.513
Ma_3	Areare	0.13	30	51±11	0.705	1.518
Toyouura sand	(Zlatovic, 1994)	0.17	0	100	0.616	0.988
Pumice sand	(Asadi et al., 2019)	1.3	0	0	1.679	2.266

The mutual effects of the fines content, mean grain size and particle shape on the void ratio range are presented in Figure 7 (Cubrinovski and Ishihara, 2002). The five tephra samples from our study generally seem to fit in the trends of the grain size and the fines content, with the exception of the Ma_2 and Ma_3

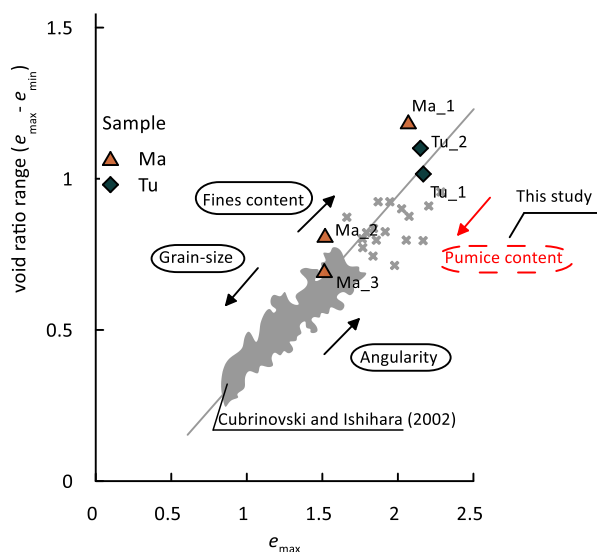


Figure 7. Void ratio range ($e_{max} - e_{min}$) vs. maximum void ratio (e_{max}) for the two volcanic-ash samples, Lake Areare compared with the values from Cubrinovski and Ishihara, (2002)

samples: Ma_2 has fewer fines and a higher D_{50} value (Table 3), so it should plot below Ma_3. In other words, it should have lower characteristic void ratios, or more voids in these two states (minimum and maximum densities achieved in laboratory conditions), so that it would be in accordance with the trendline. A possible reason for this might be the fact that Ma_3 has higher pumice content than Ma_2, thus resulting in a higher minimum void ratio on account of the voids in the pumice. Moreover, if we observe how the five tephra data points plot in the graph, a trend by means of the effect of pumice content can be observed. This would indicate the pumice content may have an effect on the void ratio range values. The observation is not based on enough data to be conclusive but it does inspire the idea for further research in defining to what extent is the pumice content relevant in the characteristic void ratio trendlines for pumiceous soil mixtures.

5 CONCLUSIONS

Geotechnical properties of up to 45 pumiceous volcanic-ash samples were presented in this paper, with the purpose of characterizing their liquefaction susceptibility as well as assess the dependence of the void ratios and specific gravity to the pumice content. The main findings can be summarized as follows:

- (1) The tephra layers found in lakes in the Hamilton lowlands can be categorized into two groups: (i) liquefaction susceptible sands, silty sands and silts with no clay minerals; and (ii) samples with a potential but unconfirmed liquefaction susceptibility: silts that contain more than 5% clay sized particles (in the form of clay minerals).
- (2) In general, the specific gravity decreases as the fines content increases. An exception to this trend was noticed in one of the tephra (Ma). We hypothesize that this could be due to a significantly lower (if not completely lacking) presence of internal voids in the pumiceous particles of this tephra, that are non-penetrable by the gas in the gas psychrometry analysis.
- (3) Soils with higher pumice content (PC) showed lower values of specific gravity (G_s), indicating that the effect of the pumice content could be exploited to derive G_s-PC correlations that could potentially be used in practice to determine the pumice content from a known value of specific gravity.
- (4) The (five) pumiceous samples from Lake Areare were found to have relatively higher characteristic void ratios compared to values for hard-grained soils. We found that they fit into relevant void ratio range trends, with a slight exception, that may be governed by the pumice content. Further research with a larger database is needed for a more conclusive result.

6 ACKNOWLEDGEMENTS

This research was funded mainly by MBIE Endeavour Fund (Smart Ideas) project (UOWX1903), and Marsden Fund project (UOW1902). Support was also received from the Earthquake Commission (EQC) project (15/U713), University of Waikato SIF Research Grant (to Lowe 2016), Waikato Regional Council, and QuakeCoRE. The authors thank the iwi of Ngāti Wairere and Ngā Iwi Tōpū O Waipā and the Hamilton City Council, for their support in allowing access to lakes for coring. Marcus Vandergoes, Susie Wood and Andrew Rees, representing the Lakes380 project, are thanked for sediment coring in 2019 and Nic Ross from Hamilton Radiology for CT scanning on sediment cores. Finally, we thank T. Ilanko, V. Gibbons, R. Melchert, T. Robertson, K. Vincent and H. Turner from the University of Waikato for their technical support both in the laboratory and in the field.

7 REFERENCES

- Asadi, M. B., Asadi, M. S., Orense, R. P., and Pender, M. J. (2018). Shear wave velocity-based assessment of liquefaction resistance of natural pumiceous sands. *Geotechnique Letters*, 8 (4), 262-267.
- Asadi, M. S., Orense, R. P., Asadi, M. B., and Pender, M. J. (2019). Maximum dry density test to quantify pumice content in natural soils. *Soils and Foundations*, 59 (2), 532-543.
- ASTM-D-2487 (2006). Classification of soils for engineering purposes (USCS). *American Society for Testing and Materials*.
- ASTM-D4318-17e1. (2017). Standard test methods for liquid limit, plastic limit and Plasticity index of Soils. *American Society for Testing and Materials*.
- ASTM-D5550-14. (2014). Standard test methods for specific gravity of soil solids by water pycnometer. *American Society for Testing and Material*.
- Been, K., and Jefferies, M. G. (1985). A state parameter for sands. *Geotechnique*, 35 (2), 99-112.
- Bielders, C. L., De Backer, L. W., and Delvaux, B. (1990). Particle density of volcanic soils as measured with a gas pycnometer. *Soil Science Society of America Journal*, 54 (3), 822-826.
- Bommer, J. J., and Rodríguez, C. E. (2002). Earthquake-induced landslides in Central America. *Engineering Geology*, 63 (3-4), 189-220.
- Boulanger, R. W., and Idriss, I. M. (2006). Liquefaction susceptibility criteria for silts and clays. *Journal of Geotechnical and Geoenvironmental Engineering*, 132 (11), 1413-1426.
- Bray, J. D., and Sancio, R. B. (2006). Assessment of the liquefaction susceptibility of fine-grained soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 132 (9), 1165-1177.
- Cubrinovski, M., and Ishihara, K. (2002). Maximum and minimum void ratio characteristics of sands. *Soils and Foundations*, 42 (6), 65-78.
- Edbrooke, S. (2005). *Geology of the Waikato area. Institute of Geological and Nuclear Sciences 1:250,000 Geological Map 4*.
- Frolov, Y. S., and Maling, D. H. (1969). The accuracy of area measurement by point counting techniques. *Cartographic Journal*, 6 (1), 21-35.
- Green, J. D., and Lowe, D. J. (1985). Stratigraphy and development of c. 17 000 year old Lake Maratoto, North island, New Zealand, with some inferences about postglacial climatic change. *New Zealand Journal of Geology and Geophysics*, 28 (4), 675-699.
- Hyodo, M., Hyde, A. F. L., and Aramaki, N. (1998). Liquefaction of crushable soils. *Geotechnique*, Volume 48, Issue 4, pp. 527-543.
- Ishihara, K., Kai-Lung H., Nakazumi, I., and Sato, K. (1986). Analysis of landslides during the 1984 Naganoken-Seibu earthquake. *Geologia Applicata e Idrogeologia*, 21 (2), 175-215.
- Japanese Geotechnical Society Standard, JGS0161-2009. (2009). Test method for minimum and maximum densities of sand.
- Kleyburg, M. A. (2015). Paleoliquefaction in Late Pleistocene alluvial sediments in the Hauraki and Hamilton basins, and implications for paleoseismicity *Proceedings, 12th Australia New Zealand Conference on Geomechanics (ANZ 2015)*, 22-25 Wellington 524-531.
- Kluger, M. O., Lowe, D. J., Moon, V. G., Chaneva, J., Villamor, P., Ilanko, T., Johnston, R., Loame, R. C. and Orense, R. P. (under review). First observation and implications of downward-directed lacustrine tephra-seismites. *Nature Geoscience*.
- Langridge, R. M., Ries, W. F., Litchfield, N. J., Villamor, P., Van Dissen, R. J., Barrell, D. J. A., Rattenbury, M. S., Heron, D. W., and Haubrock, S., and Townsend, D. B. (2016). The New Zealand active faults database, *New Zealand Journal of Geology and Geophysics*, 59 (1), 86-96.
- Lowe, D. J. (1988). Stratigraphy, age, composition, and correlation of late quaternary tephra interbedded with organic sediments in waikato lakes, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*, 31 (2), 125-165.
- Lowe, D. J., and Nelson, C. S. (1983). Guide to the nature and methods of analysis of the clay fraction of tephra from the South Auckland region, New Zealand. *University of Waikato, Department of Earth Sciences, Occasional Report*.
- Lowe, D. J., Shane, P. A. R., Alloway, B. V., and Newnham, R. M. (2008). Fingerprints and age models for widespread New Zealand tephra marker beds erupted since 30,000 years ago: a framework for NZ-INTIMATE. *Quaternary Science Reviews*.
- Mijic, Z., Bray, J. D., Riemer, M. F., Cubrinovski, M., and Rees, S. D. (2021). Test method for minimum and maximum densities of small quantities of soil. *Soils and Foundations*, 61 (2), 533-540.
- Miura, S., Yagi, K., and Asonuma, T. (2003). Deformation-strength evaluation of crushable volcanic soils by laboratory and in-situ testing. *Soils and Foundations*, 43 (4), 47-57.
- Moon, V., and Lange, W. De. (2017). Potential shallow seismic sources in the Hamilton Basin: final report for EQC project 16/717.
- Orense, R., Vargas-Monge, W., and Cepeda, J. (2002). Geotechnical aspects of the January 13, 2001 El Salvador earthquake. *Soils and Foundations*, 42 (4), 57-68.
- Orense, R P, Pender, M. J., and O'Sullivan, S. (2012). Liquefaction characteristics of pumice sands. *EQC Project 10/589*.
- Orense, Rolando P, Asadi, M. B., Stringer, M. E., and Pender, M. J. (2020). Evaluating liquefaction potential of pumiceous deposits through field testing: Case study of the Edgecumbe earthquake, *Bulletin of the New Zealand Society for Earthquake Engineering*, 53 (2), 101-110.
- Pender, M. J., Robertson, T. W., Gilion, D., Jennings, N., Leslie, D., and Pemberton, G. (1987). Edgecumbe earthquake: Reconnaissance report, *Bulletin of the New Zealand Society for Earthquake Engineering*, 20 (3), 201-249.
- Pender, M. J., Wesley, L. D., Larkin, T. J., and Pranjoto, S. (2006). Geotechnical properties of a pumice sand. *Soils and Foundations*, 46 (1), 69-81.
- Rolo, R., Bommer, J. J., Houghton, B. F., Vallance, J. W., Berdousis, P., Mavrommati, C., and Murphy, W. (2004). Geologic and engineering characterization of Tierra Blanca pyroclastic ash deposits. *Special Paper 375 of the Geological Society of America*, 55-67.
- Stirling, M., McVerry, G., Gerstenberger, M., Litchfield, N., Van Dissen, R., Berryman, K., Barnes, P., Wallace, L., Villamor, P., and R. L. (2012). National seismic hazard model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America*, Volume, 102 (4) 1514-1542.
- Stringer, M. E. (2019). Separation of pumice from soil mixtures. *Soils and Foundations*, 59 (4), 1073-1084.
- Terzaghi, K., and Peck, R. B. (1996). *Soil Mechanics in Engineering Practice*. John Wiley & Sons, Inc.
- USGS (2001) Clay mineral identification flow diagram, *USGS*, Open file report 01-041.
- Uzuoka, R., Sento, N., Kazama, M., and Unno, T. (2005). Landslides during the earthquakes on May 26 and July 26, 2003 in Miyagi, Japan. *Soils and Foundations*, 45 (4), 149-163.
- Van Dissen, R., Seebeck, R., N, L., Barnes, N., and Nicols, P. (2021). Development of the New Zealand community fault model – version 1.0. *Proceedings of the 2021 New Zealand Society for Earthquake Engineering Annual Technical Conference*, Christchurch.
- Warkentin, B. P., and Maeda, T. (1980). Physical and mechanical characteristics of Andisols. *Soils with Variable Change*, B.K.G. Theng Ed., 281-301.
- Wesley, L. D., Meyer, V. M., Pranyoto, S., Pender, M. J., Larkin, T. J., and Duske, G. C. (1999). Engineering properties of a pumice sand. *Proceedings of the 8th Australia New Zealand Conference on Geomechanics*, Hobart.
- Wesley, Laurence D. (2001). Determination of specific gravity and void ratio of pumice materials. *Geotechnical Testing Journal*, 24 (4), 418-422.
- Whitton, J. S., and Churchman, G. J. (1987). Standard methods for mineral analysis of soil survey samples for characterisation and classification in NZ Soil Bureau. *New Zealand Soil Bureau Scientific Report*.
- Zlatovic, S. (1994). Residual strength of silty soils. *PhD Thesis*, University of Tokyo.