Field characterisation and mapping of pumiceous deposits in central North Island, NZ

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ABSTRACT

Pumice materials are frequently encountered in many engineering projects in the central part of the North Island, New Zealand. Because of their lightweight, highly crushable and compressible nature, existing empirical correlations developed for hard-grained (quartz) sands are not applicable, and therefore they are problematic from an engineering and construction viewpoint. With engineering developments currently on-going in the region, a better understanding of the characteristics and locations of these pumiceous layers has become necessary. This paper attempts to identify the field characteristics of pumice deposits based on conventional geotechnical methods for the purpose of mapping the locations of pumiceous layers across the Bay of Plenty and Waikato regions. For this purpose, existing geotechnical data within the target regions, including standard penetration tests (SPT), cone penetration tests (CPT), seismic dilatometers (sDMT), machine boreholes and associated laboratory testing, are compiled. In addition, pumice deposits are identified within the existing data as well as the extent of the stratigraphic unit(s) and typical trends within the data set and correlations across various test types are analysed. It is envisioned that the outputs presented in the paper will be beneficial to researchers, practising geotechnical engineers, roading authorities and council planners in terms of providing better engineering understanding of these problematic soils.

Keywords: volcanic soil, pumice, mapping, geotechnical database, field characterisation

1 INTRODUCTION

Pumice is a type of volcanic soil that originates within pyroclastic deposits of explosive volcanic events and can be found in numerous locations around the world. Across some portions of the central part of North Island, New Zealand, pumice-rich soils are frequently encountered, in particular, within the Bay of Plenty and Waikato Regions; these are areas where rapid development have been occurring recently. These pumice deposits originated from a series of volcanic eruptions centred in the Taupo and Rotorua regions, called the Taupo Volcanic Zone (TVZ) (see Figure 1). The pumice material has been distributed initially as air fall due to the explosive power of the eruptions and associated airborne transport; over time, they have been reworked and redeposited alluvially due to erosion and river transport. Presently, pumice-rich deposits exist mainly as deep sand layers in river valleys and flood plains, but are also found as coarse gravel deposits in hilly areas. They are frequently encountered in engineering projects and their evaluation is a matter of considerable geotechnical interest.

Pumiceous sand particles are often described in terms of their vesicularity, which results in the particles having special features, such as being light weight, highly crushable and compressible, with very rough and angular surfaces. As a result, soils containing pumice are problematic in terms of their characterisation. Questions are being asked whether current empirical

Fig. 1. The Taupo Volcanic Zone (TVZ) in the North Island of New Zealand (from www.explorevolcanoes.com).
methods for sands, derived primarily from hard-grained (quartz) sands, are also applicable to pumice-rich sands. While extensive laboratory tests have been performed on the dynamic response and engineering properties of pumice sands, in-situ analysis of the behaviour of pumice-rich deposits is not as well documented or researched; as a result, the lack of in-situ characterisation provides challenges for practising geotechnical engineers when determining the most appropriate testing methods for identification of pumiceous soils.

In this paper, attempts were made to identify the field characteristics of pumiceous deposits based on conventional geotechnical investigation methods used in New Zealand, and to map the extent of the pumiceous layers across the Bay of Plenty and Waikato regions. For this purpose, geotechnical data including borehole logs, standard penetration tests (SPT), cone penetration tests (CPT), seismic dilatometer tests (sDMT) and laboratory sampling, were collated and analysed. The summary of the collated information was then interpreted and its usefulness as a means for in-situ characterisation was discussed.

2 PREVIOUS LABORATORY STUDIES

Previous researches at the University of Auckland have examined the engineering properties of pumice sands in the laboratory (e.g. Marks et al., 1998; Wesley et al., 1999; Wesley, 2001; Pender, 2006; Pender et al., 2006; Kikkawa et al., 2009; 2011; 2013; Orense et al. 2012; 2013; 2014; Asadi et al. 2018). Some of the results obtained are discussed below.

2.1 Particle characterisation

In order to observe the grain structure of pumice in detailed but qualitative way, Kikkawa et al. (2013) scanned many particles of pumice using Skyscan 1172 high-resolution micro-CT scanning machine. They noted that the distinction between surface and internal voids was important, as once particle crushing occurs more internal voids are exposed to the surface, creating a greater number of voids between particles. Due to the vesicular nature of pumice, and in particular the isolated voids present in the particles, the true density of pumice sand is different to that of the apparent density. They detected the surface and internal voids using CT scanning and subsequently calculated the true density and void ratio of the pumice sand particles sampled. CT images obtained on various grain samples of different sizes are shown in Figure 2.

In the CT images the white areas indicate the solid portion whilst the black areas indicate the void spaces containing either water or air. The particle, shown in Figure 2(a), indicates that there are more internal voids than surface voids present in the particle, whilst the particle shown in Figure 2(b) shows the opposite. Overall, the study found that the CT scanning could measure the solid density of pumice particles more accurately than other standard laboratory procedures as it was able to distinguish between the internal and surface voids. The study also found that there was a greater volume of surface voids in a particle than there were internal voids or solid material. Due to the surface voids present in a pumice particle, the exterior surface is very rough resulting in an angular shape. This angular shape is an important distinction to other hard-grained sands and contributes to the fragility and crushability of pumice particles.

2.2 Laboratory testing

Due to the fragility of pumice sands, extensive studies have been conducted to investigate the effects of particle crushing. Grain crushing in geotechnical engineering is not typically encountered in sands unless at high stresses (Pender et al., 2006). Calcareous and carbonate sands are exceptions to this, along with pumice sands, with Orense et al. (2014) suggesting that pumice may be the most delicate of all the crushable soils found worldwide. A range of different tests have been completed for research purposes to investigate the effects of particle crushing.

Oedometer Testing

Standard oedometer testing was completed by Wesley et al. (1999) on dry pumice samples in both loose and dense states, with results compared to quartz, a typical hard-grained sand. Both samples were prepared in the laboratory to have similar particle size distributions. Overall, it was found that the pumice sand is significantly more compressible than the hard-grained quartz, where it was observed that pumice was about four times as compressible in both the loose and dense states.

Triaxial Testing

Triaxial testing has also been undertaken on pumice sands to try to define pumice behaviour. Wesley et al. (1999) performed drained triaxial tests on both loose and dense pumice sand samples and, again, compared the results to that of quartz.

Although the peak strength of the two materials is similar in the dense state, the strain at those peak strengths is quite different. In terms of volume change behaviour, the pumice and quartz sands varied in both loose and dense states. Pumice sand exhibited contractive behaviour in both states, whilst the quartz exhibited dilation in the dense state and marginal contraction and dilation in the loose state. The

![Fig. 2. Cross sectional images of pumice particles with different sizes (from Kikkawa et al. 2013).](image-url)
contractive behaviour indicates that the soil grains in both states are experiencing particle crushing.

The effective friction angle of quartz sand at failure in the loose and dense states was approximately 36.5 and 41 degrees, respectively, whilst that of pumice sand at failure in both the loose and dense states was approximately 41.5 degrees. The high frictional resistance of the pumice sand is directly related to the microstructure of the grains, as described earlier.

**Calibration chamber testing**

Penetrometer testing was undertaken on pumice sands by Wesley et al. (1999) using a calibration chamber, with results compared to hard-grained quartz sands. Results of the cone penetration tests for both sands are shown in Figure 3, where the quartz behaves as expected of a sand, with large differences in the cone resistance between the loose and dense states under the same vertical effective stress. However, the pumice sand shows unusual behaviour, with very little change in cone resistance between the loose and dense states and is only marginally greater than that of the loose quartz specimen.

![Fig. 3. Comparison of cone resistance results for: (a) pumice sand; and (b) quartz sand (after Wesley et al. 1999).](image)

2.3 Natural pumiceous soils

Pumice is not always encountered as a clean sand in engineering practice; more often than not, pumice sands exist in-situ mixed with other materials, and the deposit is referred to as natural pumiceous sands. Asadi et al. (2018) performed cyclic triaxial tests on reconstituted natural pumiceous sands and on hard-grained Toyoura sand. They noted that during the test, pumiceous sands start to deform from the start of the cyclic loading and the axial strain gradually increases until a double amplitude axial strain $\varepsilon_{DA}=5\%$ is reached. In contrast, Toyoura sand undergoes significant number of cycles with negligible deformation followed by a sudden increase in deformation in a few cycles to reach $\varepsilon_{DA}=5\%$ (see Figure 4). In addition, pumiceous sands initially show a very contractive behaviour under the application of cyclic loading, but after a few more cycles, it changes to a very strong dilative behaviour. Due to the formation of stable soil skeleton inside the pumiceous specimens, the liquefaction resistance of pumiceous sands is considerably higher than that of Toyoura sand under the same relative density.

![Fig. 4. Cyclic undrained response of dense reconstituted sands showing variation with normalised number of cycles of: (a) double amplitude axial strain; and (b) excess pore water pressure ratio (from Asadi et al. 2018).](image)

3 GEOLOGY OF TARGET SITES

Before the geology of the Waikato and Bay of Plenty regions is discussed further, it is important to define the term ‘ignimbrite’ as it is increasingly used as the foundation rocks of a variety of engineering structures (Moon, 1993). Walker (1983) describes ignimbrite as pyroclastic deposit or rock body, made predominantly from pumiceous material, which shows evidence of having been emplaced as a concentrated hot and dry particulate flow. Healy (1962) describes ignimbrite as comprising of ash, lapilli and block grade which are spread as pyroclastic pumice flows and settled by compaction after coming to rest hot enough to retain plasticity.

Clearly, ignimbrites comprise pumiceous material and it is therefore very important to understand their in-situ behaviour. As both the Bay of Plenty and the Waikato regions are located adjacent to the TVZ, ignimbrites are present throughout both regions and are frequently encountered in engineering projects.

3.1 Bay of Plenty Region

Tauranga

The Tauranga region comprises six main geomorphic areas (Briggs et al., 1996) which include the Kaimai Range, Whakamarama Plateau, Tauranga Basin, Mamaku Plateau, Papamoa Range and several volcanic domes. The Tauranga Harbour is located within the Tauranga Basin, along with several north or north-east trending peninsulas underlain by a range of deposits due to various formation processes. Previous research (cited in Healy & de Lange, 1988 and Briggs et al., 1996) suggested four main origins of the terraces: 1) Volcanic constructional surfaces commonly found as un-welded pyroclastic ignimbrites;
2) Volcanic or fluvial degradation surfaces modified and/or covered by air fall tephra deposits;  
3) Fluvial terraces which have been formed by aggradation or lateral erosion; and  
4) Marine aggradation terraces, formed as a result of a higher than present sea level. These are the low-lying terraces found in the region.  

Briggs et al. (2005) also described the typical stratigraphic units present within the Tauranga Basin. These include the ignimbrites which are all pumice-rich deposits. The Matua subgroup deposits, found extensively across the region, are also known to contain fluvial pumiceous sands and air fall tephras. Finally, the more recent Holocene and Late Pleistocene tephras, deposited via air fall and originating from the TVZ, are also known to contain pumiceous sands and silts; however, the pumice content of these soils is not well quantified. Several stratigraphic units often encountered within the Tauranga region during geotechnical investigations are presented in Figure 5.  

**Rotorua**  
The Rotorua area comprises two extensive ignimbrite plateaus, the Patetere and the Kaingaroa, with the TVZ running through the middle in a north-east to south-west direction (see Figure 6). Due to the location of the region in an area of high volcanism, ignimbrites are widely distributed and encountered, with the softer and upper zones found to comprise a larger amount of pumice material (Healy, 1962).  

Ignimbrites within the area include the Te Kopia Ignimbrite, Paeroa Ignimbrite, Kaingaroa Ignimbrite, Waiotapu Ignimbrite, Matahina Ignimbrite, and the Mamaku Ignimbrite (Healy, 1962). Pumice breccias, which are more loosely compacted and younger than the ignimbrites mentioned above, are also formed by pyroclastic flows, which originated from the Maroa Volcanic Centre and the Okataina Volcanic Centre. These include the Waitahanui Breccias of Grange, and the Haparangi Rhyolite Pumice and Mihi Breccia of Grindley. Overlying the rock within the Rotorua region is a mantle of Late Quaternary volcanic ash, which originates from vents around the Okataina Volcanic Centre and comprise a series of pumice ash and lapilli beds. Healy (1962) also noted that approximately 900 years ago, an eruption from the Tarawera domes caused pumice lahars to progress down the Tarawera River and was deposited as a large fan and produced a terrace further up the river.  

3.2 Waikato Region  
The Waikato region geology has been greatly influenced by the course of the Waikato River which historically has changed its path several times. This has resulted in numerous fan deposits throughout the region, with a strong presence of alluvial pumiceous deposits that have been transported along the Waikato River following volcanic events within the TVZ. In particular, the Taupo Pumice Alluvium is generally only encountered along the banks and within the base of the Waikato River due to this fluvial deposition mode. A summary of the general stratigraphy present across the Waikato region is presented in Figures 7.  

4 COLLATED GEOTECHNICAL DATA  
During the data collection process, it was found that the majority of the investigation records for pumiceous soils within the Waikato region were available in PDF format only, and therefore the raw data was not able to
be analysed. Within the Tauranga region, a much more extensive amount of raw data was available and therefore more detailed analysis and data compilation was achieved for the Bay of Plenty region.

4.1 Description of data

Borehole logs were reviewed to identify pumice deposits within the Bay of Plenty and Waikato regions (see Appendix for locations). Currently, practising geotechnical engineers and geologists only quantify pumice content of a soil unit based on visual-tactile techniques and no pumice content laboratory sampling was completed. Therefore the identification of pumice within a soil deposit was based solely on descriptions within the borehole logs.

In several instances, borehole logs varied in their description of the pumiceous material. In some cases, a borehole log would describe one unit as pumiceous whilst a borehole located within a nearby vicinity was completely missing this description at the same elevation even though all other logging details were consistent. This indicates either variability between the geologists or engineers logging the soil or variability of the material unit itself. It is more likely that there is the human error component of variability between loggers, and therefore consultancies should ensure that more training is given to field staff to ensure consistency when identifying pumiceous deposits.

4.2 Standard penetration tests

When analysing the SPT N-values within the Bay of Plenty area, consideration was given to the geological unit the test was performed in. The soils across the Tauranga region were grouped into three broad categories, being:

- Recent alluvium – sand deposits deposited recently as part of alluvial or fluvial processes;
- Matua Subgroup deposits – which consist of all tephras older than the Hamilton Ash, along with fluvial and distal ignimbrites;
- Non-welded Ignimbrite – comprising all of the various ignimbrites within the region.

The locations of the SPT sites are shown in Figure A.1 while a summary of the SPT N-values within pumiceous deposits is shown in Table 1. As can be seen from the table, there is a very wide range of N-values for each of the three geological units within the Bay of Plenty region and also for the soils in the Waikato region. Both the Matua Subgroup deposits and the non-welded ignimbrites range from zero to over 50 blows, which indicates refusal, with the Recent Alluvium – Sand deposits ranging from zero to 44. This would appear to indicate that the geological unit, and therefore the depositional mode, does not appear to have any influence on the SPT N-value.

<table>
<thead>
<tr>
<th>Geological Unit</th>
<th>No. of data</th>
<th>SPT N-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ave.</td>
<td>Std. Deviation</td>
</tr>
<tr>
<td>Bay of Plenty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alluvium – Sands</td>
<td>104</td>
<td>16.9</td>
</tr>
<tr>
<td>Matua Subgroup deposits</td>
<td>44</td>
<td>19.5</td>
</tr>
<tr>
<td>Non-welded Ignimbrite</td>
<td>123</td>
<td>23.0</td>
</tr>
<tr>
<td>Waikato</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Not Applicable</td>
<td>105</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Although SPT N-values of zero are not necessarily surprising to see in the Recent Alluvium – Sand deposits, it is more unusual to see in the Matua Subgroup and Ignimbrite deposits. It is thought that these zero readings, and the relatively low averages, are due to the effect of particle crushing within the pumice sands. A possible explanation for the wide range of N-values could be the varying pumice contents of the soil deposits, with higher pumice content resulting in more particle crushing and therefore a lower SPT N-value. However, as the pumice content of the soil deposits is not known, further research would be required to confirm this.

The influence of elevation within the Bay of Plenty and Waikato regions was also analysed with respect to the SPT N-value. The locations of the SPT sites are shown in Figure A.2 while a plot of elevation (with respect to Moturiki Datum) against SPT N-value for
each of the geological units described above is presented in Figure 8, where the wide range of scatter described above can be visually observed. It can also be concluded that there is no discernible trend relating elevation to the SPT N-value for any of the geological units.

Despite this, it can be seen that in the higher elevations, from approximately RL 40 m onwards, SPT N-values of 50+ (or refusal) are achieved within the non-welded Ignimbrite deposits. These machine boreholes were completed within the Ohauiti suburb in Tauranga, with the geological map of the area (Briggs et al., 1996) indicating that the terraces within the region are underlain by welded Waiteariki Ignimbrite. This non-welded to welded ignimbrite deposit is described as pumice rich (20%) by Briggs et al. (1996), but no samples were taken at the time of investigations, so the pumice content cannot be confirmed.

Where lower SPT N-values are observed, from approximately RL 40 m and lower, the Te Ranga Ignimbrite or the Te Puna Ignimbrite are known to underlay the sites. Briggs et al. (1996) describes the Te Ranga Ignimbrite as containing “5 – 25% pumice” and states that due to its non-welded and unconsolidated characteristics, the Te Ranga Ignimbrite can often be mistaken for a “fluvially derived pumice sand”. The Te Ranga Ignimbrite can be found extensively throughout the Tauriko region of Tauranga. They also describe the Te Puna Ignimbrite as containing “white to grey fibrous pumice (15 – 25%)” and this deposit is seen throughout the Minden areas and close to the Wairoa River. As was the case for the Waiteariki Ignimbrite, no samples were obtained and so the pumice contents of the soil deposits where SPT N-values are recorded are not known.

4.3 Cone penetration tests

CPT data were analysed across the Tauranga region and, where available, within Hamilton in the Waikato region. Results of the key measurements are presented in Table 2. There was insufficient data to analyse outside the Tauranga and Hamilton city extents, and therefore results are only presented for these areas. It should also be noted that the geological units have not been taken into consideration when processing these results as these were not always known.

Table 2. Summary of CPT measurements for pumice deposits in the Bay of Plenty and Waikato regions

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Bay of Plenty</th>
<th>Waikato</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of data</td>
<td>Ave.</td>
</tr>
<tr>
<td>Cone Resistance, (q_c) (MPa)</td>
<td>25,215</td>
<td>8.34</td>
</tr>
<tr>
<td>Sleeve Friction, (f_s) (MPa)</td>
<td>25,215</td>
<td>0.08</td>
</tr>
<tr>
<td>Friction Ratio, (R_f) (%)</td>
<td>25,215</td>
<td>0.91</td>
</tr>
<tr>
<td>Soil Behaviour, (I_s)</td>
<td>25,215</td>
<td>2.37</td>
</tr>
</tbody>
</table>

The CPT data from the Tauranga region was then plotted in order to visually represent the parameters outlined in the table. The CPT parameters were plotted against the elevation in order to determine if any trends were present for the pumiceous soil units at various depths. These plots are shown in Figure 9.
The \( f_s \) values are very low, with an average sleeve friction of 0.08 MPa. In some instances, negative sleeve friction was recorded, which is typically only seen in very soft clay soils (Robertson, 2010). This very low sleeve friction could be a possible indicator of the crushing of pumice sands during the advancement of the CPT probe. The \( f_s \) value also seems to be relatively consistent with respect to elevation, and there are only a few instances of a noticeable linear increase with depth. It is possible that these instances could be occurring within sands with a lower pumice content; however further research is required to confirm this.

An interesting trend that was observed is that where the \( R_f \) value is high, so too is the \( q_c \) value, and the \( I_c \) shows that a clayey or organic soil is present. From borehole logs recorded adjacent to the CPTs, it is known that this is not the case, with the soil deposits being logged as pumiceous sands. This trend was seen in a number of the CPT plots that were collated and analysed as part of this study.

Following the identification of particle crushing tendencies within the CPT traces in the Tauranga region, the soil behaviour types, as described by Robertson (1990; 2010), were further analysed. The results are summarised in Table 3 and the overall percentage out of all the samples is given for each type.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Soil behaviour type</th>
<th>No. of data (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Organic soils – clay</td>
<td>582 2</td>
</tr>
<tr>
<td>3</td>
<td>Clays – silty clay to clay</td>
<td>2,187 9</td>
</tr>
<tr>
<td>4</td>
<td>Silt mixtures – clayey silt to silty clay</td>
<td>3,055 12</td>
</tr>
<tr>
<td>5</td>
<td>Sand mixtures – silty sand to sandy silt</td>
<td>12,471 49</td>
</tr>
<tr>
<td>6</td>
<td>Sands – clean sand to silty sand</td>
<td>6,920 27</td>
</tr>
<tr>
<td>7</td>
<td>Gravelly sand to dense sand</td>
<td>0 0</td>
</tr>
</tbody>
</table>

As can be seen in the table, the majority of the samples (76%) are classified as “sand mixtures” or “sands”. However, the remaining samples are classified as “organic clays” “clays” and “silt mixtures”. As the borehole logs recorded within the region indicated that the pumice deposits were sands or silty sands, it is unusual to see these fine-grained soil classifications within the CPT soil behaviour type traces. This misclassification is thought to be related to the particle crushing effects described earlier.

This effect of particle crushing on the CPT traces is interesting and highlights the inaccuracy of the CPT as a field investigation tool to characterise pumiceous deposits. Care should therefore be taken when interpreting CPT results in volcanic soils and boreholes should always be completed in conjunction with CPTs in order to visually confirm the subsurface soil profile.

### 4.4 Seismic dilatometer tests

A summary of the sDMT results obtained from within pumiceous deposits in the Bay of Plenty region is presented in Table 4. No shear wave velocity data was available for the Waikato region that had borehole locations nearby with pumice deposits identified within the dataset collated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No. of data</th>
<th>Ave.</th>
<th>Std. Dev.</th>
<th>Min. Value</th>
<th>Max. Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear wave velocity, ( V_s ) (m/s)</td>
<td>75</td>
<td>312</td>
<td>79.4</td>
<td>128</td>
<td>476</td>
</tr>
<tr>
<td>Material Index, ( I_d )</td>
<td>148</td>
<td>1.72</td>
<td>0.28</td>
<td>0.56</td>
<td>3.97</td>
</tr>
<tr>
<td>Constrained Modulus, ( M ) (MPa)</td>
<td>148</td>
<td>69.68</td>
<td>30.30</td>
<td>4.06</td>
<td>223.47</td>
</tr>
<tr>
<td>Friction angle, ( \phi ) (deg)</td>
<td>132</td>
<td>35.41</td>
<td>2.96</td>
<td>28.48</td>
<td>43.42</td>
</tr>
</tbody>
</table>

Traces of shear wave velocity and friction angle were then plotted against the elevation to determine whether any trends were observable, and these are presented in Figure 10. It can be seen that the shear wave velocity appears to be between 150 m/s and 300 m/s for pumice soil deposits in the lower elevations (i.e. from approximately RL 10 m and lower). The upper elevations show shear wave velocities between 300 m/s and 450 m/s and seem to generally increase with decreasing elevation. However, there are only a small number of samples and such trend cannot be confirmed.

![Figure 10: Graph of SDMT results within the Tauranga region showing the variation with elevation of: (a) shear wave velocity; and (b) friction angle.](image-url)
lower elevation sands may have a higher pumice content. As previously mentioned though, no pumice content quantities are known for any soils and therefore this cannot be confirmed.

5 CONCLUDING REMARKS

An attempt to characterise the field behaviour of pumiceous deposits in the central part of the North Island was made using available geotechnical data. From the results, the following conclusions are made:

- Logging of pumiceous volcanic deposits was inconsistent, with the identification of pumice grains not being included in several logs despite nearby boreholes identifying their presence.
- Pumice content was not commonly quantified in practice; thus, it was unclear how much pumice was actually present in deposits logged as pumiceous.
- It appears that geology and depositional mode has no influence on the SPT N-value of pumice sands.
- CPT traces showed relatively low \( q_c \) value and very low sleeve friction values. The majority of the \( I_1 \) values classified the soils as “sands” or “sand mixtures”, although almost a quarter of the soils were classified as “organic clays”, “clays” or “silt mixtures”. This classification as fine-grained type highlights the CPT’s unreliabilities as investigation tool for identifying pumiceous deposits.

Mapping of pumice deposits across the region has not been fully explored due to the inconsistencies with logging of the pumice deposits, the lack of pumice content data, and the lack of any discernible trend in CPT and SPT results, which made it very difficult to identify pumice deposits where borehole logs could not be fully relied upon. Thus, at this stage, reviewing the geological maps of the area and referencing the presence of pumice (e.g. ignimbrite) in the target regions is considered the most suitable method for mapping pumiceous deposits.

During site investigations, care should be taken when interpreting CPT results in volcanic soils and boreholes should always be completed in conjunction with CPTs in order to visually confirm the subsurface soil profile. Whenever possible, pumice contents should be quantified, e.g. through the method proposed by Asadi et al. (2019), and when significant pumice contents are determined, more detailed data interpretation (e.g. Orense et al. 2019), should be performed prior to design of geotechnical structures.

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APPENDIX

Fig. A.1. Locations of in-situ tests in the Tauranga Region.

Fig. A.2. Locations of in-situ tests in the Hamilton Region.