Crushing-induced liquefaction characteristics of pumice sand

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ABSTRACT: Pumice sands, which are crushable volcanic soils, are often referred to as problematic materials and they present difficult subsurface conditions for civil engineering due to their highly crushable and compressible nature. Consequently, there are concerns on whether empirical liquefaction potential evaluating procedures derived primarily from hard-grained (quartz) sands are applicable to pumice sands. To further investigate the effect of particle crushing on pumice sand's liquefaction characteristics, SEM image analysis and angle of repose tests were performed on original and crushed pumice particles. Next, a series of undrained monotonic triaxial tests were conducted and the results showed that all the pumice specimens, regardless of the initial relative density, displayed similar stress paths; this indicates that pumice sand's stress-strain-strength behaviour is not primarily governed by the relative density. In previous study, cyclic triaxial tests were performed on loose and dense pumice sands and the results were compared with those for Toyoura sand, a hard-grained sand. The results showed the effect of relative density on pumice sand's liquefaction resistance was not as pronounced as that for Toyoura sand, confirming that the relative density is not a good parameter to differentiate the liquefaction characteristic of crushable pumice sand. Moreover, the mixture of hard-grained sand and pumice sand displayed lower liquefaction resistance compared with pure pumice sand. Finally, the development of particle crushing during monotonic and cyclic loading was tracked and the results showed particle crushing and associated grain interlocking during shearing induce the higher liquefaction resistance of pumice compared with natural sands.

1 INTRODUCTION

The 2010-2011 Canterbury earthquakes in New Zealand have caused significant damage to many residential houses due to varying degrees of soil liquefaction over a very wide extent of urban areas unseen in past destructive earthquakes (Cubrinovski et al. 2012). As a result, the central government, regional and local councils and the engineering community in the country are now aware of the importance of understanding the seismic performance of various local soils, i.e., whether soils in certain localities will undergo the same degree of liquefaction as the Christchurch soils did.

Pumice deposits are found in several areas of the North Island, originated from a series of volcanic eruptions centred in the Taupo and Rotorua regions, called the "Taupo Volcanic Zone" (Packard 1957; Healy 1963). They exist mainly as deep sand layers in river valleys and flood plains, but are also found as coarse gravel deposits in hilly areas. Their concentration in river valleys and flood plains means they tend to coincide with areas of considerable human activity and development. Thus, they are frequently encountered in engineering projects and their evaluation is a matter of considerable geotechnical interest.

Pumice sand is characterized by a number of distinctive properties, such as it is generally lightweight, highly frictional, crushable and compressible due to their vesicular nature. Very few information is available about whether empirical liquefaction potential evaluating procedures derived for hard-grained soils are applicable to pumice because there has been very little research done to examine the liquefaction characteristics of pumice. Previous study based on laboratory tests indicated that pumice sands' liquefaction behaviour is greatly dependent on the particle crushing and also showed pumice sands do not liquefy as easily as hard-grained sands under cyclic loading (Orense et al. 2014). However, during the 1995 Great Hanshin Earthquake, widespread liquefaction occurred in Port Island and Rokko Island (Hyodo et al. 1998); both were reclaimed land areas using a crushable granite soil, Masado, which was previously regarded as a fill material with minor liquefaction risk during earthquakes. Liquefaction of a crushable volcanic soil, Shirasu, was also observed during the 1997 Kagoshimaken-Hokuseibu Earthquake (Hyodo et al. 2000). Note that these sands may not be as crushable as the pumice sands used in this study, which can be crushed under fingernail pressure.

In order to further investigate the governing mechanism of pumice sand's liquefaction behaviour, several series of undrained monotonic and cyclic triaxial tests were conducted on reconstituted specimens consisting of commercially-available pumice sands in both loose and dense states, with measurements of particle sizing to track the degree of crushing during shear and to observe the change in the granular composition of the soil, with the aim of clarifying the crushing-induced liquefaction characteristics of pumice sand.

2 MATERIALS AND TEST METHODS

The tests were performed on commercially-available pumice sand, which has been used extensively in the Geomechanics Laboratory, University of Auckland. This is not a natural deposit but was derived by processing sand from the Waikato River. The particles were centrifugally separated from the other river sand particles so that the samples consist essentially of pumice grains. The grain size distribution curve of the pumice sand (0.075-2.36 mm) used in this research is shown in Figure 1. Also shown in the figure are those for Mercer River sand and Toyoura sand, both hard-grained sands, for comparison purpose. The index properties for the tested soils, obtained using methods specified in NZ Standards 4402:1986, are listed in Table 1.

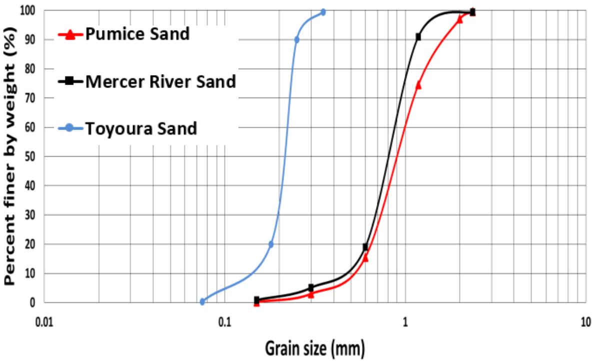


Figure 1. Particle size distribution of soils used.

Material	Specific Gravity	Max void ratio	Min void ratio
Pumice Sand	2.00	2.60	1.40
Mercer River Sand	2.65	1.80	0.70
Toyoura Sand	2.64	1.00	0.60
PS&MRS Mixture*	2.33	2.00	1.10

*Mixture of pumice and Mercer River sand, volume 1:1.

Because of the presence of voids on the surface and on the particle interior, it was not easy to completely saturate the pumice sand for the undrained tests. For this purpose, saturated specimens were made using de-aired pumice, i.e., sands were first boiled in water to remove the entrapped air. Next, the specimens were saturated with appropriate back pressure and then isotropically consolidated at the target effective confining pressure, $\sigma_c' = 200$ kPa. B-values > 0.95 were ensured for all specimens before shearing. The test specimens were 50 mm in diameter and 100 mm high. The target shear strain for the monotonic tests was above 30% to observe the specimen under the steady state of deformation, with shearing rate set at 5 mm/min.

The cyclic loading in the tests were applied by a hydraulic-powered loading frame from Material Testing Systems (MTS). A sinusoidal cyclic axial load was applied in the tests at a frequency of 0.1 Hz under undrained conditions. In addition to the axial load, the cell pressure, pore pressure, and axial displacement were all monitored electronically and these data were recorded via a data acquisition system on to a computer for later analysis.

3 RESULTS AND DISCUSSION

3.1 Angle of repost test

The angle of repose of a granular material is an effective indication of the material's shear strength in loose state. First, in order to provide a quantitative estimate on the role of crushed particles on the strength of the specimen, angle of repose tests were conducted on pumice sands with different particle size range, as well as the crushed particles collected from the ring mill and sieving after triaxial tests. Figure 2 presents the angle of repose test set-up, while the results are summarised in Table 2.

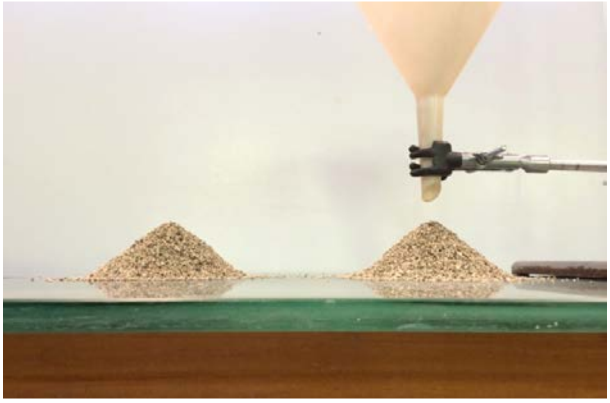


Table 2. Angles of repose for pumice

Particle size range (mm)	Angle of repose (°)
Original (0.075 – 2.36)	36.50
Original (2.00 – 2.36)	36.75
Original (1.18 – 2.00)	37.75
Original (0.60 – 1.18)	36.68
Original (0.30 – 0.60)	35.13
Original (0.15 – 0.30)	35.80
Original (0.075 – 0.15)	36.00
Original (< 0.075)	41.50
Crushed (< 0.075)	42.12

As shown in Table 2, the original or uncrushed particles between 0.075 and 2.36 mm display fairly similar value of about 36.5º. For the crushed particles collected after triaxial tests which are mainly below 0.075 mm, the angle of repose is about 42º, reasonably higher than that of the original uncrushed particles. A small amount of particles with size < 0.075 mm was also collected from sieving the original "uncrushed" pumice sand, and they had an angle of repose of 41.5º, very similar to that of the deliberately crushed particles. Therefore, from angle of repose test, it is known that crushed particles have more irregular and angular shape which may lead to higher shear strength.

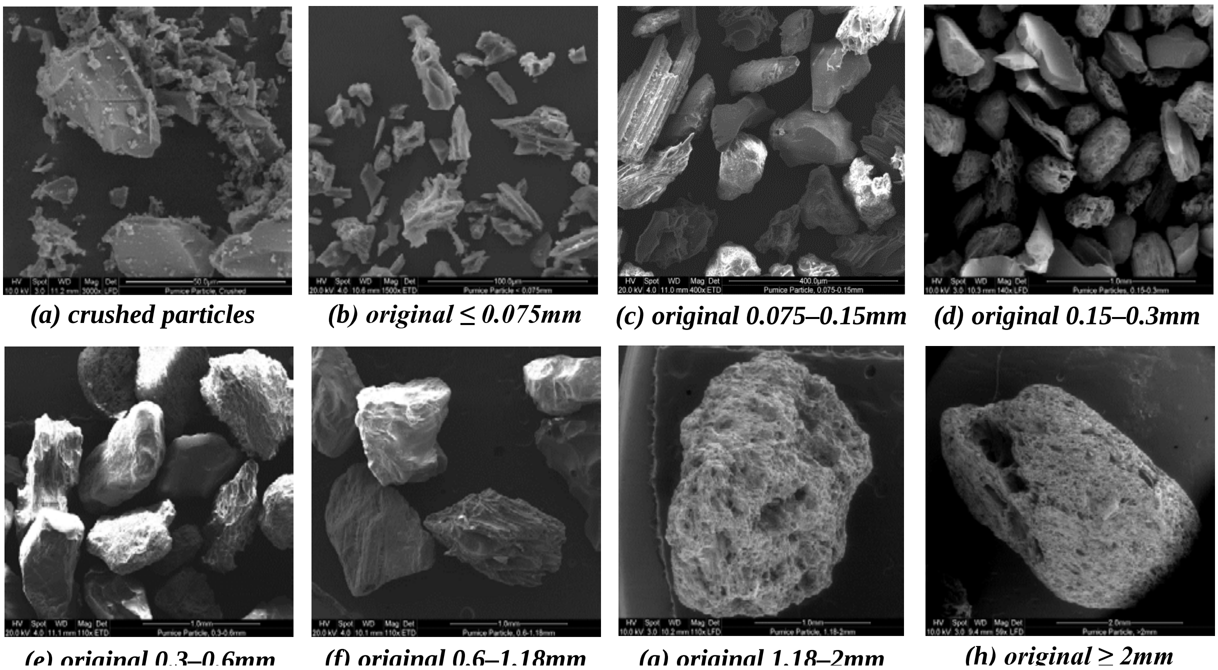
3.2 Scanning electron microscope image

Unlike hard-grained sands, the pumice sands are well-known for its vesicular nature (internal and surface voids). In order to observe the structure of pumice in detailed but qualitative way, a series of the microphotographs of pumice particles was obtained by scanning electron microscope, as shown in Figure 3. These give a clear qualitative indication that as the particle size decreases the shape and surface tend to be more irregular and angular, possibly resulting in more interlocking and potential.

3.3 Undrained monotonic shear characteristics

It is well known that changes in relative density affect the undrained response of natural sand. The effects were therefore investigated for the pumice sand by examining the stress paths under different conditions. The pumice samples were reconstituted as triaxial specimen at two different states: dense (D_r = 80-85%) and loose (D_r = 30-35%). For each state, three tests were conducted under the same condition to confirm repeatability; this is consistent with general geotechnical engineering practice. Effective confining pressure of 200 kPa was applied for all tests.

Figure 4 presents the effective stress paths, taking deviator stress, $q = \sigma_1 - \sigma_3$, and effective mean principal stress, $p' = (\sigma_1' + 2\sigma_3')/3$. All the tests show similar overall tendency of contraction followed by dilation behaviour after the phase transformation state in which the specimen recovers its strength and restores stability. However, under the same confining pressure, there is no clear distinction in the stress paths of dense and loose specimens. Moreover, the dilative regions tend to overlap at the same failure line, indicating that the all pumice specimens, regardless of initial relative density, have approximately the same inter-particle friction angle, which also excludes the effect of relative density on strength characteristics, consistent with the study conducted earlier (Orense et al. 2012). Similar trends of excess pore water pressure development regardless of initial relative density were also observed and, as a result, it can be said that relative density is not a good parameter to differentiate the liquefaction response of pumice sand, at least not to the same level as that for hard-grained sand.



(a) crushed particles *(b) original ≤ 0.075mm* *(c) original 0.075–0.15mm* *(d) original 0.15–0.3mm*

(e) original 0.3–0.6mm *(f) original 0.6–1.18mm* *(g) original 1.18–2mm* *(h) original ≥ 2mm*

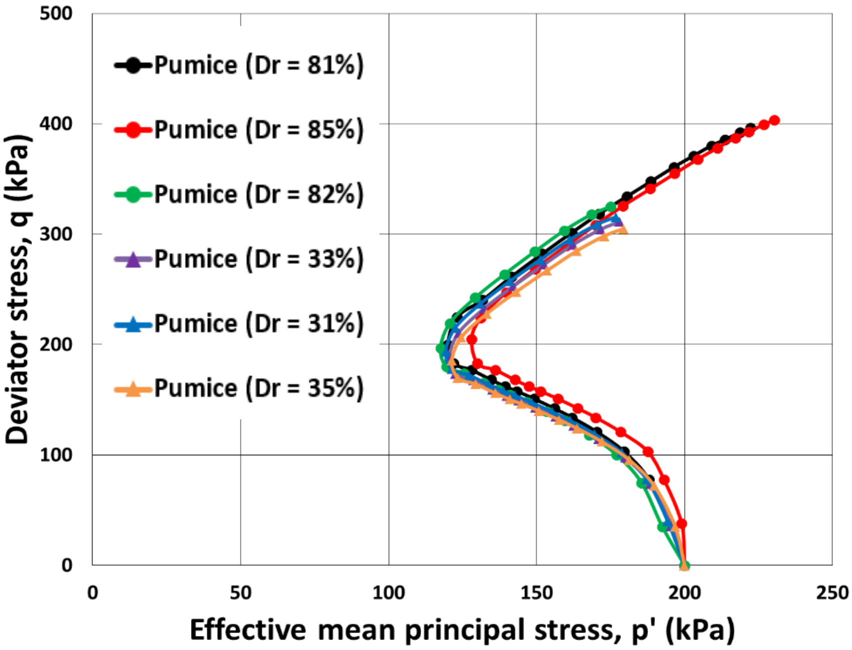
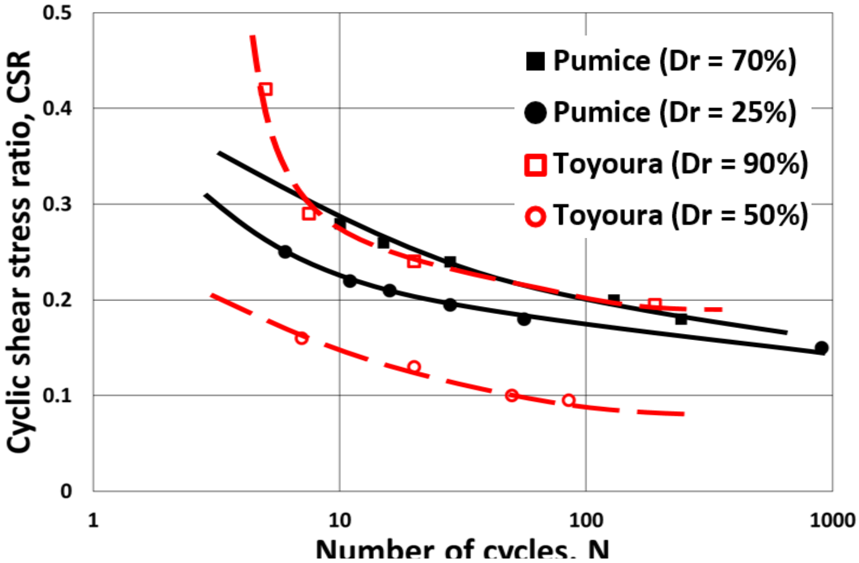


Figure 4. Effective stress paths for dense and loose pumice sand.

3.4 Undrained cyclic shear characteristics

In previous study (Orense et al. 2012, 2014), the effect of relative density on the liquefaction resistance of reconstituted pumice sands were examined by performing undrained cyclic triaxial tests on dense (D_r = 70%) and loose (D_r = 25%) specimens and comparing them with those for Toyoura sand, a hard-grained sand mainly used for research purpose. The results, shown in Figure 5, indicate the effect of relative density on pumice sand's liquefaction resistance was not as remarkable as that for Toyoura sand. Under the same confining pressure of 100 kPa, the cyclic strength curve for Toyoura sand with D_r = 90% is very steep, which is a typical of a dense sand. However, this distinction is not observed for pumice sand as the slope of the curve for dense samples is almost as gentle as that for loose samples. These observations confirm that the relative density is not a good parameter, at least not as good as that for hard-grained sand, in differentiating the liquefaction characteristic of pumice sand. It is also noticeable from Figure 5 that under same test condition, pumice sand would not liquefy as easily as Toyoura sand, even when its density (D_r = 25%) only half of that for Toyoura sand (D_r = 50%).



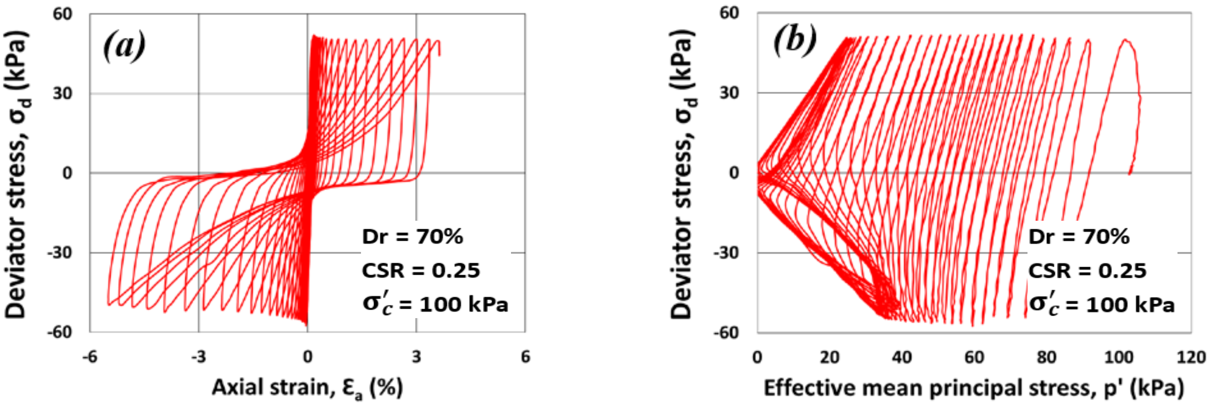


Figure 6. Pumice (D_r = 70%): (a) deviator stress-axial strain relation and (b) effective stress path.

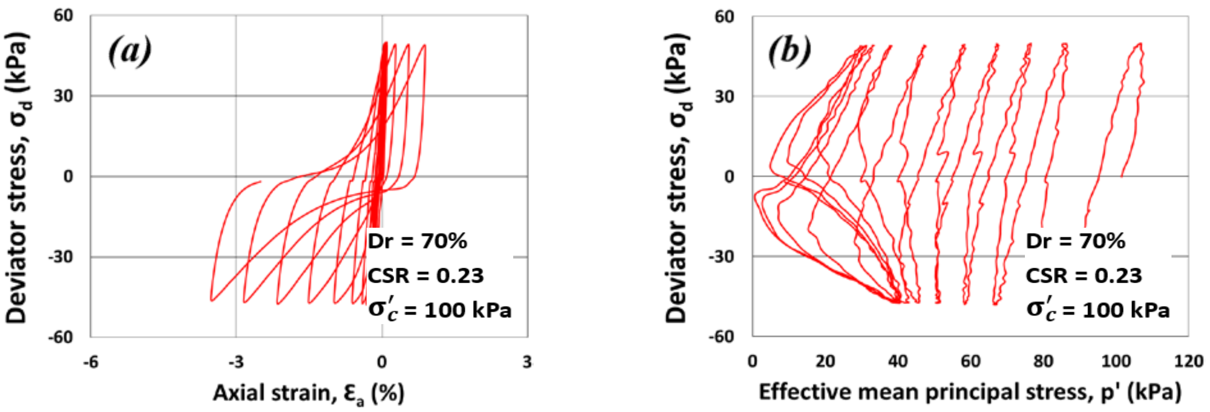
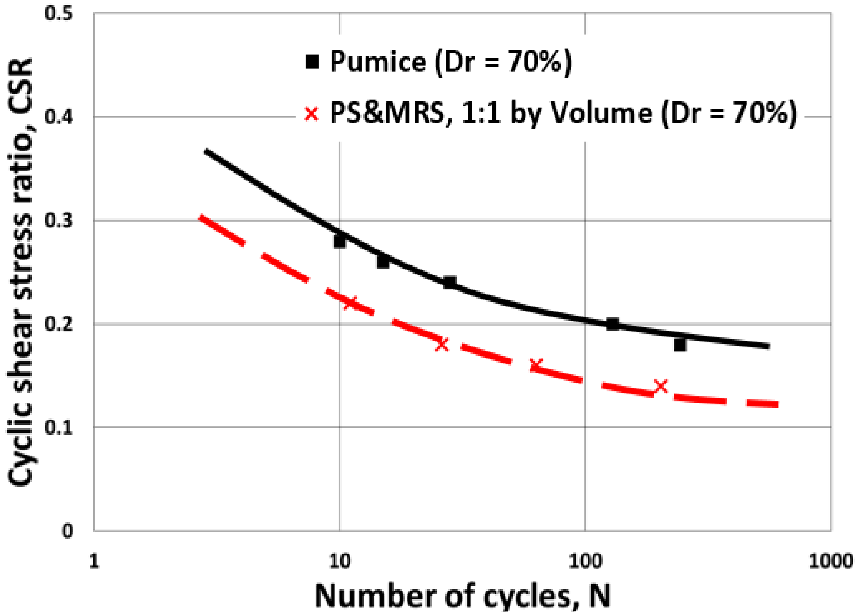


Figure 7. PS&MRS (D_r = 70%): (a) deviator stress-axial strain relation and (b) effective stress path.

Due to pumice sand's vesicular and crushable nature, when subjected to cyclic shear, particle crushing occurs, resulting in more irregularly- and angularly-shaped particles which would lead to a change in the granular composition of the soil. From conventional soil mechanics, the shearing resistance of cohesionless soil is derived from at least three different mechanisms within the soil: particle sliding effect, particle reorientation effect and dilatancy effect (Rowe 1969; Drucker & Prager 1952; Wood 1990). However, for crushable soil like pumice sand, as cyclic shearing and crushing occurs, the contact of particles will introduce an extra interlocking effect working as a new source of shearing resistance, consequently inducing a stable soil structure under cyclic shearing. In order to further investigate the crushing-interlocking interaction, undrained cyclic tests were performed on a mixture of pumice sand and Mercer River sand with a volume ratio of 1:1 under an effective confining pressure of 100 kPa. Attempts were made to form specimens with D_r similar to dense pure pumice specimens (D_r = 70%) as reported in Figure 5. Figure 6 and 7 compare the stress-strain curves and effective stress paths, respectively, of pumice subjected to CSR = 0.25 and pumice mixed with Mercer River sand subjected CSR = 0.23. The plots indicate that the development of strain and excess pore water pressure is faster for the sand mixture than for pure pumice sand at same density.



The liquefaction resistance curves obtained for the two samples are shown in Figure 8. Pumice sand experienced a reduction in liquefaction resistance with the addition of uncrushable hard-grained sand. Obviously, the added hard-grained particles make the soil as a whole less crushable as a consequence; compared to pure pumice sand, the cyclic shearing tends to distribute more energy from the portion which would be otherwise used to crush the overall sample to a certain limit to induce the development of excess pore water pressure. In the process, the smaller amount of crushable particles resulted in less interlocking space and potential under the cyclic shearing. It follows therefore that the liquefaction resistance of the pumice decreases by adding certain amount of hard-grained particles.

3.5 Evaluation and interpretation of particle crushing

A method of evaluating particle crushing originally proposed by Miura and Yamanouchi (1971) was used. The method involves the quantification of the surface area of the particles. The specific surface of the particles was measured by first sieving the soil using 2.36 mm, 2 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm and 0.075 mm sieve sizes. For this range of particle sizes, the specific surface area (in mm^2/mm^3) is calculated using the following equation:

$$S = \sum \frac{F}{100} \cdot \frac{4\pi (d_m/2)^2}{(4/3)\pi (d_m/2)^3 \, G_s \gamma_w} \cdot \gamma_d \tag{1}$$

where d_m is $(d_1 \cdot d_2)^{0.5}$, d_1 and d_2 are adjacent sieve sizes (e.g., 0.6 mm and 0.3 mm), F is the % by weight retained on the sieve, G_s is the specific gravity of the particles, γ_w is the unit weight of water and γ_d is the dry unit weight of the specimen.

Table 3. Surface area of pumice samples afterCU test

Specimens	S (mm^2/mm^3)
Pumice (D_r = 81%)	40.5
Pumice (D_r = 85%)	40.8
Pumice (D_r = 82%)	40.7
Pumice (D_r = 33%)	40.9
Pumice (D_r = 31%)	40.7
Pumice (D_r = 35%)	40.6

The surface areas of the specimens at the end of the tests which were presented in Figure 4 are listed in Table 3. It can be seen that there is no difference in the surface areas of dense and loose pumice specimens at the end of monotonic undrained shear application. This is evidence that pumice sands' strength characteristics are mainly governed by the particle crushing, rather than by relative density. In other words, under certain condition, similar crushability would induce similar response during undrained shearing. This supplements the similar stress paths between dense and loose pumice specimens, as shown in Figure 4. This observation, together with the trend shown in Figure 5 and 8 confirm that pumice sands' liquefaction response is significantly dependent on their potential crushability during cyclic undrained shearing, negating the dominant role of relative density.

4 CONCLUSIONS

A series of monotonic and cyclic undrained triaxial tests were performed on pumice sand to investigate the role of particle crushing on its liquefaction characteristics. The main observations are as follows:

- The original or uncrushed pumice particles display a similar angle of repose, typically, 36.5º, regardless of particle size. The crushed particles with size < 0.075 mm display a reasonably higher value, which is 42º.
- The shape and surface of pumice particles tend to be more irregular and angular as the particle size decreases.
- The fully saturated pumice specimens showed dilative behaviour when subjected to undrained shear and relative density did not seem to have significant effect on the undrained behaviour of pumice.
- Pumice sand mixed with hard-grained sand showed faster development of excess pore water pressure and lower liquefaction resistance.
- Pumice sands' liquefaction response is significantly dependent on their potential crushability during cyclic undrained shearing, negating the dominant role of relative density.

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