Undrained Cyclic Shear Behaviour of Pumice Sand

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ABSTRACT

Because of their lightweight, highly crushable and compressible nature, pumiceous sands are problematic from engineering and construction viewpoints. There has been very little information on their liquefaction characteristics and most empirical procedures available in evaluating the liquefaction potential of sands are derived primarily from hard-grained sands. To understand the undrained cyclic behaviour of pumice sands, several series of undrained cyclic triaxial tests were performed on two sets of pumice samples. One set of samples consisted of undisturbed pumiceous deposits taken from a site in Waikato, while the other set involved reconstituted pumice sands in both loose and dense states. The results obtained were compared with those observed in Toyoura sand, a typical (hard-grained) sand. The degree of particle breakage in pumice during cyclic shearing was examined, highlighting the effect of the crushable nature of the grains on the cyclic response of the soil.

Keywords: pumice, crushable sand, liquefaction, undrained cyclic tests, undisturbed samples, reconstituted samples

1 INTRODUCTION

Because of New Zealand's tectonic location, the seismic-resistant design of soil structures requires a clear understanding of the soil properties and behaviour under earthquake loading. The 1987 Edgecumbe earthquake, for example, showed widespread liquefaction of sands of volcanic origin. Liquefaction and the associated ground deformations are considered as major geotechnical hazards and significant research efforts have focused on understanding the mechanism and evaluation of these phenomena.

Pumice materials are frequently encountered in many engineering projects in the North Island of New Zealand. Because of their lightweight, highly crushable and compressible nature, they are problematic from engineering and construction viewpoints. Most existing engineering correlations originally developed for ordinary sands are not applicable to this material (Wesley et al., 1999; Wesley, 2001). In terms of evaluating liquefaction potential, empirical procedures currently available for sands were derived primarily from hard-grained (quartz) sands. No information is available whether these procedures are applicable to pumice deposits because there has been very little research done to examine the liquefaction characteristics of pumice.

Thus, a research programme was undertaken to understand the cyclic/dynamic properties of pumice. In this paper, the results of several series of undrained cyclic triaxial tests performed on two sets of pumice samples are presented. One set of samples consisted of undisturbed deposits taken from a pumiceous site, while the other set involved reconstituted specimens of commercially-available pumice sands in both loose and dense states. The results obtained were compared with those observed in typical (hard-grained) sand, like Toyoura sand. The findings can have serious implications on the use of conventional in-situ liquefaction potential methods to pumiceous deposits.

2 MATERIALS USED

Two sets of materials were used in the tests. The first set of specimens was obtained through push tube sampling at a pumiceous site in Waikato in central North Island. The upper 20m of the site consisted of current-bedded fluviatile pumice, rhyolite and ignimbrite sands and gravels interbedded with organic silts. The materials used in the tests were taken between 6.0-6.6m from the ground surface, described in the boring log as light grey gravelly fine to coarse “loose” pumice sand. The closest standard penetration test (SPT) N-value was 13 (at depth 6.7-7.0m). Although the samples thus taken may have been “disturbed” one way or the other, the degree of disturbance may be considered insignificant, as the samples maintained their soil structure and fabric; thus they are referred to as ‘undisturbed” in this paper. The properties of the soils, obtained using methods based on NZ Standards (1986), are shown in Table 1. The other set of materials used was commercially-available pumice sand. 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. This material has been used extensively in the Geomechanics Laboratory of the University of Auckland (e.g., Pender, 2006; Pender et al. 2006; Kikkawa, 2008; Kikkawa et al., 2009) and the properties indicated in the table are those reported by Kikkawa et al. (2011). The grain size distribution curves of the materials used are shown in Figure 1. It is noted that the undisturbed samples contain smaller particles than the commercially available pumice sand. For comparison purposes, the properties of Toyoura sand, a sub-angular hard-grained sand commonly used in experimental tests in Japan, are also indicated, and the values are those as reported by Yoshimoto et al. (2006).

Table 1: Properties of the soils used.

Material	Specific Gravity	Maximum density (kg/m^3)	Minimum density (kg/m^3)
Undisturbed sample	2.49	1450	1150
Pumice sand	1.77	709	576
Toyoura sand*	2.64	1615	1338

[a] Values as reported by Yoshimoto et al. (2006).

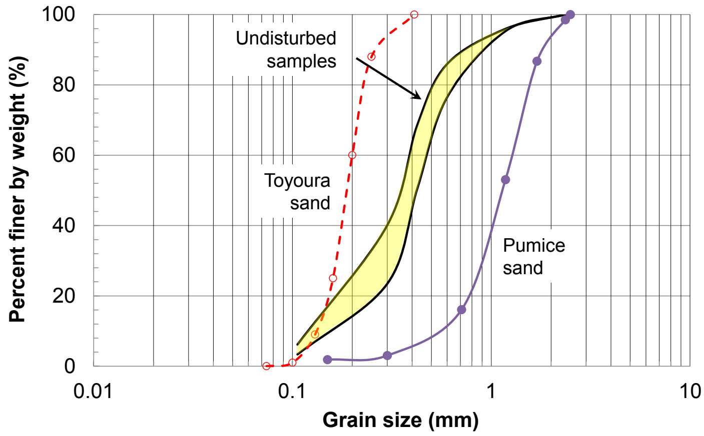


Figure 1. Grain size distribution curves of sands used in the tests.

3 SAMPLE PREPARATION AND EXPERIMENTAL METHOD

After obtaining the soil samples from the site using 60mm push tubes, they were carefully transported to the laboratory and placed in a freezer. The boring logs indicated that the soil deposits at the target depths were loose and, in order to maintain the soil structure, it was necessary to freeze the specimens prior to extrusion. The frozen specimen was extruded from the sampling tube using a laboratory hydraulic jack. Trimming was carried out at the two ends of the specimens for the preparation of square ends. The height of the specimen used was 100mm. Filter papers were placed at the ends to prevent clogging of the porous discs. The specimen was placed inside a rubber membrane and then allowed to thaw. Saturation of the specimen was ensured by allowing water to enter the specimen by increasing the back pressure to 700 kPa. B-value check was carried out to confirm that fully saturated condition had been achieved. Specimens were then isotropically consolidated at effective confining pressure of σ_c'=75 kPa.

For the reconstituted specimens, it was not easy to completely saturate pumice sand because of the presence of voids from the surface to the particle interior. For this purpose, saturated specimens were made using de-aired pumice sands, i.e., sands were first boiled in water to remove the entrapped air. To prepare the test specimens, the sand was water-pluviated into a mould which was then gently tapped until a target relative density of 25% or 70% was achieved. The actual densities for the loose samples thus formed ranged from 20-31%, while the range for dense samples was 68-70%. Next, the specimens were saturated with appropriate back pressure and then isotropically consolidated at σ_c'=100 kPa. B-values > 0.95 were obtained for all specimens. The test specimens were 75mm in diameter and 150mm high.

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 0.1Hz under undrained condition. In addition to the axial load, the cell pressure, pore pressure, volume change and axial displacement were all monitored electronically and these data were recorded via a data acquisition system onto a computer for later analysis.

4 UNDRAINED CYCLIC TEST RESULTS

4.1 Cyclic shear behaviour

Figures 2 show the plots of double amplitude axial strain ε_{DA} and excess pore water pressure ratio, $r_u=u/\sigma_c'$ against normalized number of cycles N/N(at ε_{DA}=5%) obtained from undrained cyclic shear tests on reconstituted loose pumice specimens (D_r=25%) corresponding to different cyclic shear stress ratio, $\sigma_d/2\sigma_c'$ where σ_d is the cyclic deviator stress. The curves for each double amplitude axial strain ε_{DA} are dispersed, with the variation dependent on the level of applied cyclic shear stress while the corresponding excess pore water pressure ratio, u/σ_c', show practically similar behaviour. Comparison of the two plots indicate that while the development of excess pore water pressure with cyclic loading is more or less linear, the development of ε_{DA} starts only after significant number of cycles of load application.

Also plotted in the figure is the cyclic shear behaviour of loose (D_r=50%) Toyoura sand, as reported by Yoshimoto et al. (2008). It is seen that axial strain did not occur at the early stage of cyclic loading; however, it suddenly increased to almost the maximum values at N/N(at ε_{DA}=5%) of about 0.9 to 0.95. Similarly, the magnitude of excess pore water pressure ratio for Toyoura sand is lower than pumice, but the rate increases at a much faster rate just prior to liquefaction (development of ε_{DA}=5%).

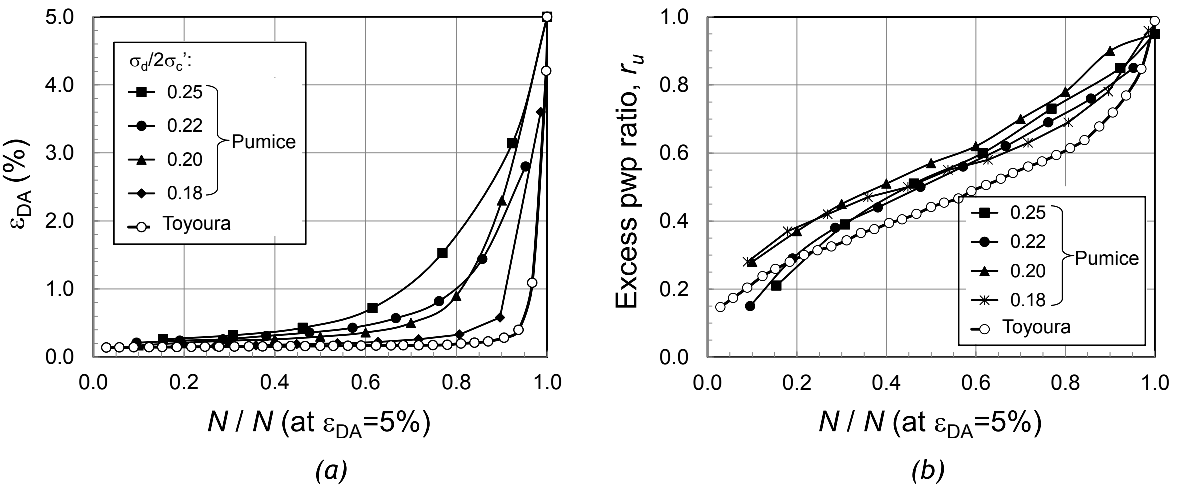
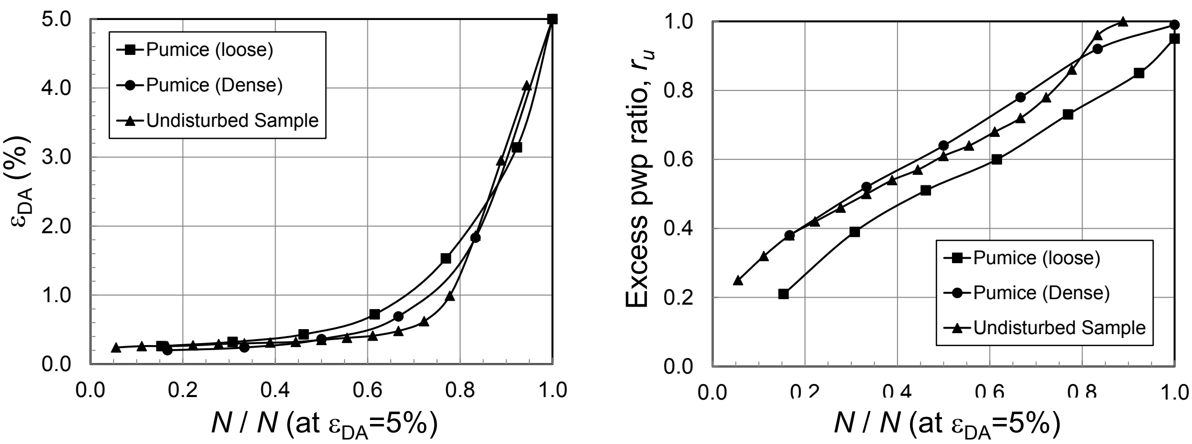


Figure 2. (a) Double amplitude axial strain ε_{DA} and (b) excess pore water pressure ratio $r_u=u/\sigma_c'$ plots against normalized number of cycles N/N(at ε_{DA}=5%) for loose pumice specimens.

A comparison of the cyclic shear behaviour of loose and dense reconstituted pumice sands, as well as that of undisturbed samples is performed next. Similar behaviour as in loose samples was noted in dense and undisturbed samples, i.e., while the curves for double amplitude axial strain ε_{DA} are dependent on the level of applied cyclic shear stress, the corresponding excess pore water pressure ratios, u/σ_c', show practically similar trend. Thus, for comparison purposes, the results for the three specimens subjected to cyclic shear stress ratio $\sigma_d/2\sigma_c'$=0.25 are compared and these are shown in Figure 3. It is observed that as far as the development of axial strain is concerned, the response of undisturbed pumice appears to be delayed when compared to the reconstituted specimens; however, the development of excess pore water pressure is similar for undisturbed sample and loose reconstituted sample while the dense reconstituted specimen shows slower response. Note that as discussed below, the three types of materials have different liquefaction resistance, and this may have affected the trends shown in the figure.



(a) (b)

Figure 3. (a) Double amplitude axial strain ε_{DA} and (b) excess pore water pressure ratio $r_u=u/\sigma_c'$ plots against normalized number of cycles N/N(at ε_{DA}=5%) for loose and dense reconstituted pumice sands and undisturbed specimens for $\sigma_d/2\sigma_c'$=0.25.

4.2 Cyclic Shear Resistance

The cyclic resistance curves of the three pumice materials corresponding to double amplitude axial strain ε_{DA}=5% are shown in Figure 4. The curve for loose samples is gentle when compared to that of dense sand, with the later having higher cyclic resistance. On the other hand, the curve for undisturbed sample is as gentle as the loose reconstituted samples, but the cyclic deviator stress ratio is about three times higher.

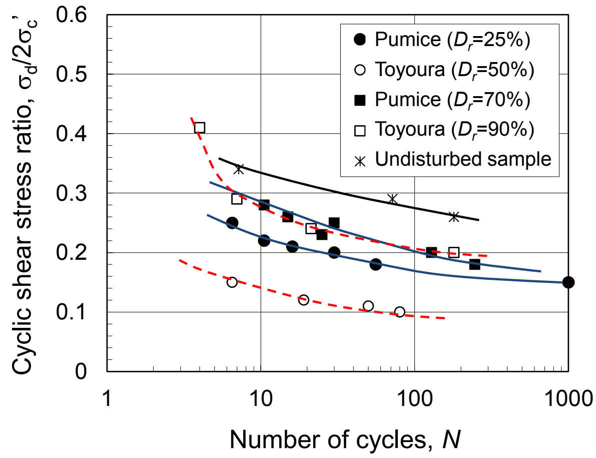


Figure 4. Cyclic resistance curves for the samples used.

Also plotted in the figure are the cyclic resistance curves for loose (D_r=50%) and dense (D_r=90%) Toyoura sand, as reported by Yamamoto et al. (2009). Comparing the curves for Toyoura sand and for reconstituted pumice sands, two things are clear: (1) loose specimens have gentle cyclic resistance curves, while dense specimens have resistance curves rising sharply as the number of cycles decreases; and (2) while the effect of relative density is very pronounced for Toyoura sand, the difference between loose and dense pumice specimens appear to be not as remarkable.

If the liquefaction resistance is defined in terms of the cyclic deviator stress ratio corresponding to 15 cycles, then dense Toyoura sand (with D_r =90%) and dense pumice sand (D_r =70%) practically have the same resistance. On the other hand, the cyclic resistance of loose pumice sand (D_r =25%) is about twice of that of loose Toyoura sand (D_r =50%). The undisturbed pumice sand has cyclic resistance of about three times that of loose pumice. Aside from its finer particles, the undisturbed samples maintained its soil structure and fabric, accounting for its higher strength.

In order to discuss the cyclic shear resistance of pumice, we paid attention to particle breakage during the test. For this purpose, sieve analyses were carried out after the end of cyclic shear test. A typical set of results is shown in Figure 5 for the original (virgin) sample and for two other samples (loose and dense) after the tests. It can be seen that the particle size distributions of the two samples after the cyclic tests are almost similar to each other, but when compared to that of the original sample, there is obvious increase in size of smaller particles. Thus, particle breakage is quite significant after the shearing stage, with the degree of breakage appearing to be similar for dense and loose samples.

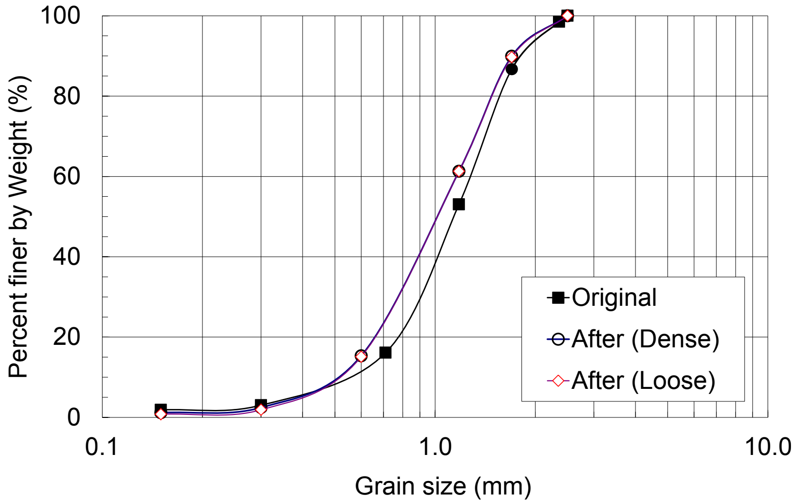


Figure 5. Grain size distribution curves before and after the cyclic tests.

Under the confining pressure considered, pumice undergoes remarkable particle crushing when subjected to cyclic shear. As cyclic shearing and particle crushing occur, the soil structure is gradually stabilized, resulting in higher cyclic shear resistance, even exceeding that of Toyoura sand. Because the degree of particle crushing appears to be similar for loose and dense reconstituted pumice specimens, cyclic shearing and the associated particle breakage resulted in stable soil structure for both cases, which may not be substantially different from each other but may be quite different when compared to the original soil sample. As a result, the effect of density is not as remarkable when compared to the cyclic behaviour of Toyoura sand.

Most conventional liquefaction potential evaluation methods are based on relative densities. However, for sands like pumice which are susceptible to particle breakage, these methods may not be applicable as the results showed no significant variation in cyclic resistance of the sand at various relative densities. Thus, other methods of evaluating liquefaction potential may be needed for pumiceous deposits.

5 CONCLUSIONS

This research was performed to investigate the undrained cyclic shear behaviour of crushable pumice sands. For this purpose, cyclic undrained triaxial tests were performed on both undisturbed and reconstituted pumice sands and the results were compared to those of Toyoura sand, a hard-grained natural sand. Based on the results presented herein, the following are the major conclusions obtained.

(1) The pore pressure and deformation response of pumice sands showed different behaviour when compared to Toyoura sand. Pumice underwent considerable particle crushing during cyclic triaxial testing.
(2) The cyclic resistance curve of loose pumice sand has gentler slope than its dense counterpart. The cyclic resistance of pumice sand is similar to that of dense Toyoura sand, while that of loose pumice sand is about twice that of loose Toyoura sand.
(3) Although the relative density has some noticeable effect on the cyclic resistance of pumice, it was not as significant when compared to that observed for Toyoura sand.

ACKNOWLEDGMENTS

The study presented in this paper was part of a research work supported by the New Zealand Earthquake Commission (EQC) under grant number 10/589. The authors would also like to thank Mr. Yi Lu of University of Auckland for the assistance in performing the experimental works presented herein and Mr Andy O'Sullivan of Hiway Geotechnical Ltd and Mr. Graham Blakeley of AECOM for the in-situ sampling and boring information at the Waikato site.

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