The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.

Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)
© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2

Cyclic behavior of undisturbed samples from pumice-rich soils

M.E. Stringer
University of Canterbury, Christchurch, New Zealand

M.B. Asadi, R.P. Orense, M.S. Asadi & M.J. Pender
University of Auckland, Auckland, New Zealand

ABSTRACT: Pumiceous soils are present across large areas of the North Island of New Zealand, and have been encountered on a number of projects of engineering significance. These soils are considered problematic owing to the difficulties in characterisation, and the differences in behaviour relative to hard-grained material. In this paper, the results from a series of cyclic triaxial tests on undisturbed soil samples from a site on the North Island are presented. It is shown that despite a wide range in the pumice content, the majority of samples have cyclic resistances which lie in a reasonably tight band. This similarity may arise from the competing effects of pumice content and differences in the particle size distributions, as well as the possibility for interaction between different layers within the specimens.

1 INTRODUCTION

Pumice-rich soils are encountered across large portions of the central to upper North Island of New Zealand, and in particular, across the Hamilton basin which is an area of rapid development. These soils were generated by a series of volcanic eruptions in the Tāupo Volcanic Zone, initially being deposited over wide areas as airfall deposits and over time can be reworked and redeposited alluvially. Pumiceous soil grains are often described in terms of their vesicularity, which results in the grains having an exceptionally low unit weight (large grains can float), their outer surfaces being very rough and angular, and the grains having a very low crushing strength. As a result of these properties, soils containing pumice are problematic in terms of their characteristation. In particular, calibration chamber tests on purely pumiceous material have shown that the CPT can be completely insensitive to relative density (Wesley et al. 1999). This result implies that the simplified liquefaction analyses based on the CPT may not provide a good estimate of liquefaction resistance in pumice-rich soils.

Triaxial testing on reconstituted specimens of pumiceous material have shown that the accumulation of strain in these materials in dense states tends to be heavily biased towards the extensional side of loading, and that the soil specimens tend not to collapse even at low effective stresses (Hyodo et al. 1998, Asadi et al. 2018). Additionally, Orense & Pender (2015) highlighted that relative density played a lesser role in the cyclic resistance of “pure” pumice materials (i.e. commercially separated pumice). The differences in the behaviour of reconstituted laboratory specimens of pumiceous and hard-grained soils and the difficulties in the characterisation of pumiceous soils clearly highlight the need for experimental research into the behaviour of natural pumiceous materials, which contain varying amounts of pumiceous and hard-grained soils. This paper presents preliminary results from a series of triaxial experiments on undisturbed samples of pumice-rich soils, and in particular the cyclic resistance of these materials.

2 SAMPLING IN WHĀKATANE

Undisturbed sampling was performed at a site in the town of Whākatane, which lies at the north end of the Rangitāiki plains. As shown in Figure 1, the site lies approximately 250 m south of the present-day Whākatane River. Pumice-rich soils were confirmed at this location (from logged boreholes), and the presence of pumiceous fine sand ejecta as well as extensive damage to the neighbouring sewage pumping station following the M_W 6.5 1987 Edgecumbe earthquake (Pender & Robertson 1987) indicate that these deposits are liquefiable. As shown in Figure 1, a number of oxbow lakes are present within the current town and indicates the movement of the river channel in relatively recent times and while airfall deposits are likely to have been deposited across the area, it is assumed that the pumice at the location of sampling are alluvial deposits.

The sampling targeted soils between 1 and 6m below the ground surface (water table was approximately 1.2m below the ground surface). The logged borehole had identified these soils to be composed of interlayered pumice and quartzitic sands/gravelly sands. Sampling was carried out with a total of four different downhole soil samplers to determine the most appropriate sampling technique for these pumice rich soils; these were two hydraulically activated fixed piston samplers (Dames & Moore, DM, and Gel-Push ``static“, GP-S), a triple-tube sampler (Gel-push ``triple tube“, GPTR) and conventional push tubes (PT). During operation, the DM sampler hydraulic pressure advances a thin-walled brass tube directly into the ground, obtaining specimens approximately 63mm in diameter, and 45cm in length. The two gel-push sampling techniques are described fully by Mori & Sakai (2016), with the key feature being the use of a lubricating polymer gel which coats the soil specimens as they enter the samplers to significantly reduce the effects of sidewall friction. The GP-S sampler advances a metal cutting shoe and barrel into the ground, while the soil sample (≈ 70mm diameter, 92cm long) is captured in a plastic liner barrel inside the tool and a core catcher prevents the soil sample from dropping when the tool is retrieved. The GP-TR sampler is similar to a Mazier core barrel, featuring a rotating outer shell and reaming shoe, and an inner assembly which does not rotate. The inner assembly is spring loaded and comprises a metal barrel with a cutting shoe that normally protrudes past the reaming shoe, and an inner plastic liner to capture the soil sample (≈ 83mm diameter, 100cm long). The sampler is gradually advanced by the driller while using a combination of rotation (≈ 60RPM) and a modest mud flow rate. The conventional push tubes were fixed to a cruciform and directly pushed into the ground using pressure from the drilling rig.

Samples were retrieved from a total of four boreholes, to allow soils from similar depths to be collected using the different techniques. Specimens are referred to with a three part name convention, indicating the borehole, the sampler type and sample number within the borehole, and finally a letter referring to the specimen itself. Using this convention, the label 3-GPS1 A implies that the specimen was from the first sample in borehole 3, used the GP-S sampler, and was specimen A from that sample. Basic CPT data, a simplified profile and the sample depths are shown in Figure 2.

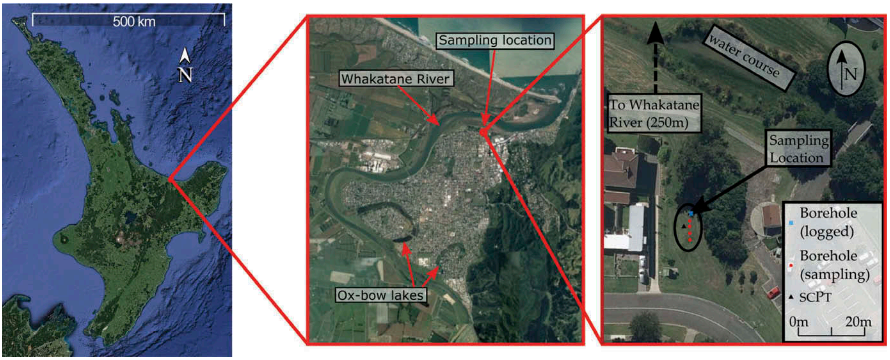

Figure 1. Location of sampling activities, modified from Stringer et al. (2018)

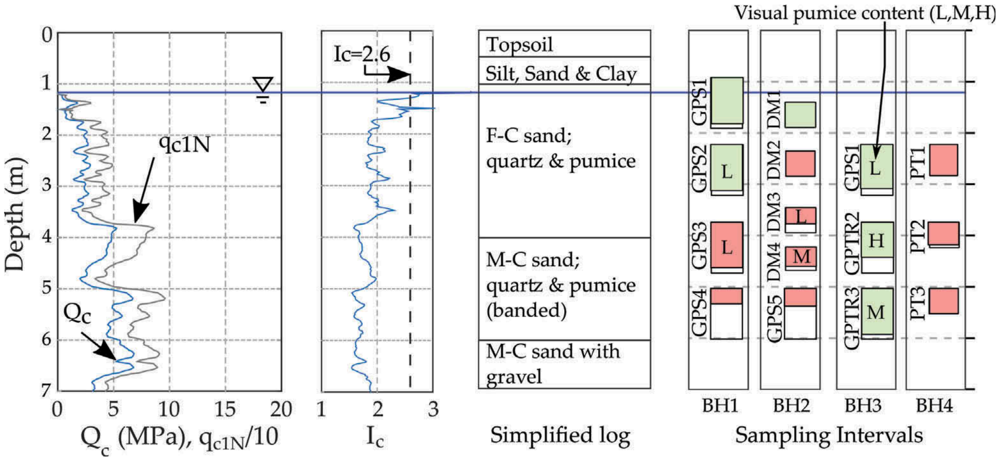

Figure 2. Soil profile and sampling targets at Whākatane site, modified from Stringer et al. (2018)

After recovery, the soil samples were drained on site and then uniaxially frozen using dry ice before transportation to the laboratories at the Universities of Canterbury and Auckland. Stringer et al. (2018) discuss the details of sampling and in particular noting that the cutting edge of the Dames & Moore sample tubes were observed to have been dented by the pumiceous gravels, and that some of the deeper GP-S specimens appeared to slump on site, suggesting poor quality of some specimens.

3 LABORATORY TESTING

3.1 *Characterisation*

Basic properties were determined for a number of specimens following the completion of triaxial testing (additional characterisation on the remaining specimens is ongoing). Particle size distributions (by dry sieving) on specimens from borehole 3 are shown in Figure 3 and show that the specimens taken from 2.2m - 3.2 m were significantly finer than those obtained from deeper in the soil profile. Specific gravities for the specimens were determined according to ASTM D854-14, however it is noted that this method is problematic when used with soils which have internal porosity, since the internal voids are unlikely to be fully filled with water, so are neither representative of the mineral density or the combined density of the solid and internal voids (i.e. Wesley, 2001). Minimum and maximum densities for the specimens were determined according to the Japanese standard JGS 0161-2000, and it should be noted that these reference densities are very low on account of the presence of pumice in the materials.

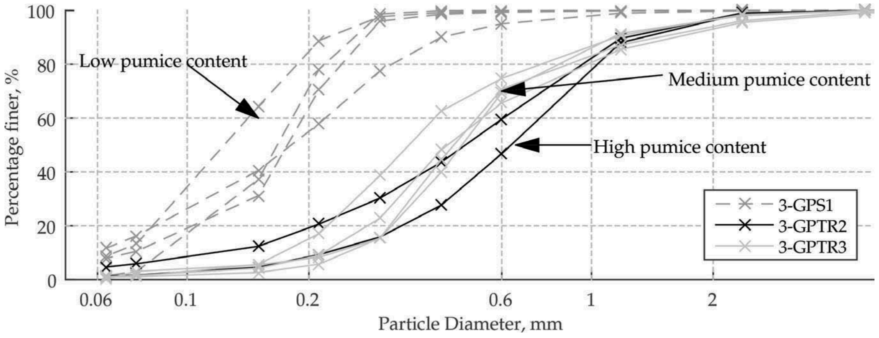

Figure 3. Representative particle size distributions of retrieved samples

Table 1. Physical characteristics of samples

Sample	Depth	D_{10}	D_{50}	FC	G_s	ρ_{min}	ρ_{max}	F_{pumice}
	(m)	(mm)	(mm)	(%)		(kg/m^3)	(kg/m^3)	(%)
3-GPS1 A	2.32	0.05	0.18	16.3	2.506	1019.9	1380.7	29
3-GPS1 D	2.68	0.09	0.17	3.0	2.595	1164.7	1472.8	
3-GPTR2 B	3.96	0.12	0.5	5.9	2.292	617.1	803.4	78
3-GPTR3 A2	5.49	0.25	0.46	1.1	2.450	951.1	1217.1	48
3-GPTR3 B	5.62	0.22	0.44	1.6	2.423	812.8	1047.6	55
3-GPTR3 C	5.74	0.17	0.36	1.2	2.477	974.8	1230.5	

In addition to these characterisation tests (summarised in Table 1), an attempt was made to quantify the pumice content of four specimens (from tubes in borehole 3) using the gravity separation method described by Stringer (2018). After separating the materials, images were obtained from a scanning electron microscope to show the differences in the floating (pumiceous) and sinking components (non-pumiceous). Representative images are shown in Figure 4, and highlight the ridged structures which are commonly present on the surface of a pumiceous particles as well as the very angular nature of the grains when compared with the non-pumiceous grains. The results from the separation tests are shown as a percentage by mass in Table 1 and allow a gross separation of the three tubes into low (L), medium (M) and high (H) pumice contents. Visual observation of the specimens allowed a qualitative determination of the pumice contents in the remaining specimens and a representative pumice content grouping (L,M,H) has been assigned to each tube as marked in Figure 2. In addition to the particle size distributions of the different test specimens, size distributions were also obtained on the gravity-separated components of 3-GPTR2 B and 3-GPS1 A and are shown in Figure 5, where “floating” refers to the pumiceous material, and “sinking” refers to the non-pumiceous materials. These additional size distributions show that the non-pumiceous

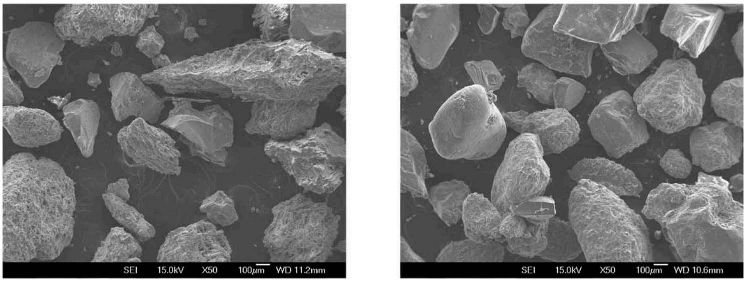

Figure 4. SEM photographs of GPTR3-3A. Pumiceous (left) and Non-pumiceous grains (right)

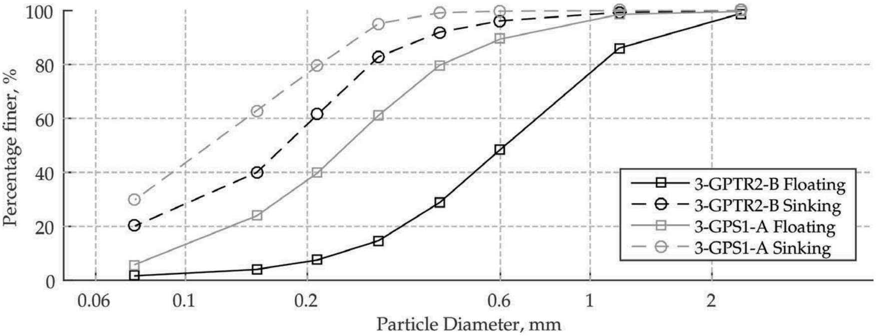

Figure 5. Particle size distributions of separated samples

fraction of the two specimens were similar, while the pumice fraction varies significantly in size, being much coarser in the highly pumiceous sample.

The sampling programme was carried out to compare soil samples from similar depths but obtained using different sampling methodologies. However, it was observed that the samples from depths of 4-5m in boreholes 1, 2 and 3 varied significantly in visual appearance (size distribution and pumice content), such that these comparisons are not thought to be reasonable. The boreholes were placed approximately 2m apart, and it is thought that the extreme variability (especially in terms of the amount of pumice in the samples) arises from the alluvial deposition.

3.2 *Layering in specimens*

A key feature of most of the samples recovered from Whākatane is the visible layering within the soil. After completing triaxial testing, many specimens were split along their longitudinal axis to reveal the internal structure which remained after testing. The photographs in Figure 6 represent specimens from each of the three pumice contents (L,M,H). In the case of the low and medium pumice content specimens there is a high degree of separation of the different materials (based on colour), such that within most of the triaxial specimens, there were typically bands of higher and lower pumice contents. This layering adds additional complexity into the behaviour of the material both in terms of the different grain sizes present in the bands, as well as significant differences in the angularity and crushability. In addition to the potential effects on the loading response, the layering of the specimens has important implications for the index testing, and in particular the minimum and maximum densities. The reference densities are measured on fully mixed material, meaning that these densities are based on a material which is much more widely graded than the bands present in the specimen. Additionally, the pumiceous grains are exceptionally angular, which is known to have a large effect on the packing of the material (Youd, 1973). This layering is therefore expected to have a significant effect on quantities such as relative density to the point that they may not represent a reasonable basis for comparing the initial state of the specimens.

3.3 *Triaxial testing*

Specimens of approximately 50 mm diameter and 100 mm height were cut from the frozen samples and allowed to defrost in the triaxial apparatus. Thawed specimens were saturated and the back-pressure increased until a B-value greater than 0.95 was achieved. Further details of the sampling and preparation of the laboratory specimens are presented in Stringer et al. (2018).

The specimens were consolidated isotropically to a stress level close to 100 kPa prior to the application of cyclic loading at 0.1 Hz until a peak-peak axial strain of 5 % was achieved, after which the specimens were either reconsolidated to their initial level of effective stress, or subjected to a displacement controlled monotonic shear test. It should be noted that the relative densities of the consolidated specimens were typically in the range of 60-70 %, but some samples were as low as 22 %. As described previously, it is assumed that the issues associated

Figure 6. View of inside of triaxial specimens. Left: 3-GPS1 A (Low pumice content). Middle: 3-GPTR3 A (Medium-high pumice content). Right: 3-GPTR2 B (High pumice content)

with these specimens (inclusion of pumice, and the segregation of the materials) means that these relative density values are not useful basis for comparison between specimens. The specimens used in this study were also noted to have been obtained using a variety of undisturbed sampling techniques and were frozen prior to transportation. It is inevitable that there will have been some variety in the quality of the specimens, even though after preparation for the triaxial testing, many appeared in good condition.

Data from two representative tests pertaining to the low and medium pumice samples are shown in Figures 7 and 8 respectively. These specimens were tested with comparable cyclic stress ratios (CSR) and failed with a very similar number of cycles. In the tests carried out, the axial strains accumulated gradually and in a ductile manner to strains which went well beyond the 5% axial strain threshold for cyclic failure. Additionally, the specimens generated high excess pore pressures in the first few cycles, such that the specimens started exhibiting phase transformation within the first 2 cycles of loading. These results are shown in Figure 9 and are consistent with the results of Asadi et al. (2018).

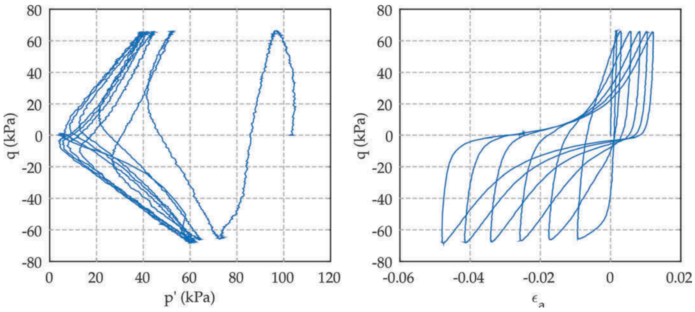

Figure 7. Cyclic testing of 3-GPS1-D (Low pumice content)

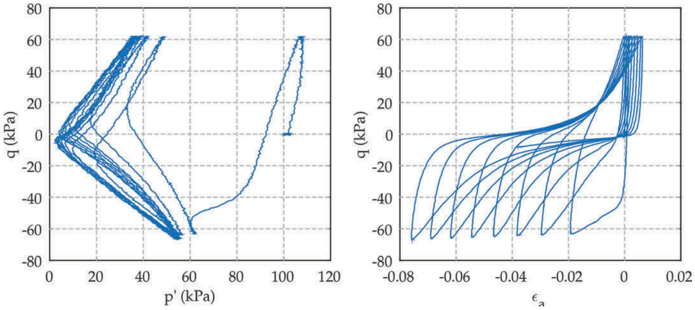

Figure 8. Cyclic testing of 3-GPTR3-B (High pumice content)

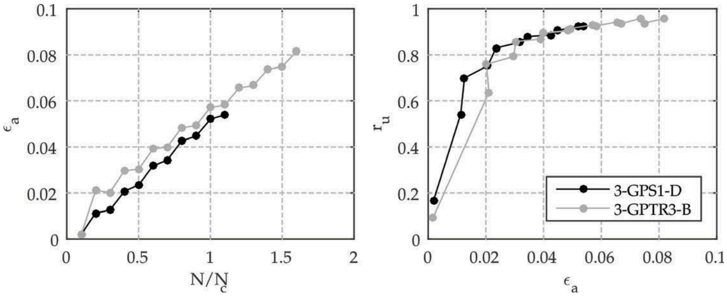

Figure 9. Development of axial strain with cycles of load (left) and generation of excess pore pressure with increasing axial strain (right)

In Figures 7 and 8, it can be observed that the initial inclination of the stress paths are quite different; in the case of the lower pumice content specimens, the stress path begins in a near vertical direction (indicating that the change in p‘ arising from the application of deviator stress is initially completely balanced by the change in pore pressure), while in the case of the medium pumice content specimen, it was observed that the stress path is more noticeably inclined (implying a less contractive response). This difference was observed in each of the tests on the low pumice content specimens and higher pumice specimens, and may indicate some greater degree of interlocking present in the high pumice content soils. While this observation separated high and low pumice contents in this study, further results are required to confirm this trend, since it is also sometimes observed in non-pumiceous materials.

A summary of the cyclic resistances of all the specimens tested in this study (incorporating differences in sampling methodology and pumice content) are shown in Figure 10. It can be observed that the cyclic resistances appear to fall within a reasonably narrow band, and surprisingly, without clear differences associated with the different pumice contents, with the possible exception of the specimens with “high” pumice content, which appears to lie at the top end of the band, with the single outlier, which might suggest a flatter relationship.

It is surprising that the difference in pumice content was not clearly reflected in the cyclic resistances of the soil, since the studies of Hyodo et al. (1998) and Asadi et al. (2018) have shown differences between soils which do and do not contain pumiceous material. A number of possibilities (or combinations thereof) exist for this result. The first is that the number of data points from each type of sampling methodology are relatively low such that individual trends are lost as a result of the data not being well spaced out. As discussed in Stringer et al. (2017) the quality of specimens varied significantly, and it is possible that the differences in material behaviour are being lost as a result of overall specimen disturbance. It is possible (but unlikely) that these aspects may have masked some of the differences between specimens. Despite this, it is still surprising that the vast difference in pumice content between the samples is not reflected in the data. This suggests that the material itself might be responsible for the observed behaviour.

In addition to the different pumice contents, it was shown in Figure 5 that the particle size distributions of the hard grained (sinking) material was similar between different soil units, but the pumiceous (floating) material had very different particle size distributions. This is likely to have an effect on the cyclic resistance, due to the general reduction in particle strength with increasing particle diameter noted by Orense & Pender (2015). The overall particle size distributions also show that the fines content varied between 0 and approximately 15%. It is known that the percentage of non-plastic fine grained material plays a role in reducing the liquefaction resistance of a soil. Hence, the variation in fines content likely also affected the cyclic resistance. Finally, it should be remembered that the medium and low pumice content specimens had obvious layering within the specimens. This means that the specimens might be considered to be made up of extremely high pumice content bands and very low pumice content bands (as shown in Figure 6). If one layer (i.e. pumiceous or non-pumiceous material) has a cyclic resistance which is significantly different to the other then the overall response may be dominated by the weaker material. Some interaction between the layers is also possible in

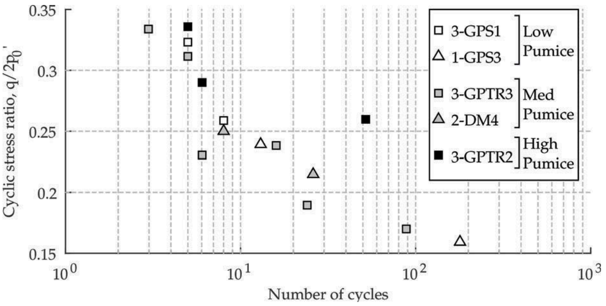

Figure 10. Cyclic resistance of samples tested during this study

particular the highly pumiceous layers may be responsible for generating large excess pore water pressures which then causes earlier straining in the hard-grained material.

The number of factors which may reasonably affect the cyclic behaviour in these undisturbed pumiceous materials is large, and at this stage it has not been possible to isolate the particular factor which is dominating the response. Additional sampling and testing in pumiceous deposits is required to shed further insight into the cyclic behaviour and resistances of these materials.

4 CONCLUSIONS

In this paper, the results of cyclic triaxial testing on "undisturbed" soil specimens have been presented. The specimens appeared to be composed of a wide range in pumice content, and were grouped into those with low, medium and high amounts of the pumice. A key feature of these soils is the layering of pumiceous and hard-grained material.

It has been shown that despite the large range in pumice content, all specimens generated very large excess pore water pressures early in the cyclic loading and apparently lay on a similar curve of cyclic resistance. Numerous factors have been identified which may be responsible for the similar cyclic resistances which include the variation in the particle size distributions of the pumiceous content, the fines content of the samples and the presence of layering.

ACKNOWLEDGEMENTS

Financial support for the sampling described in this paper was provided by the QuakeCORE (New Zealand), and financial support for B.Asadi was provided by the Natural Hazards Research Platform (NZ). We would like to acknowledge the technical assistance provided by the laboratory technicians at the University of Canterbury and the University of Auckland. The support of Whākatane District Council, AECOM and GNS Science in determining the target test sites is gratefully acknowledged. The authors also appreciate the assistance of Dr. Y Mirjafari and Miss N. Papen during the field work.

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