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Comparison of assessments of liquefaction potential in selected New Zealand pumiceous soils

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ABSTRACT: The computed liquefaction potential of volcanic soils in the Waikato region of New Zealand can vary significantly depending on which evaluation method is used. CPT-based procedures often indicate liquefaction potential extending to considerable depth, while Vs-based methods generally predict a lower liquefaction potential. This difference has been attributed to ageing effects not recognised by the CPT and/or to crushing of the pumice and volcanic glass grains present in these soils by the CPT cone. Utilising the extensive database of co-located CPT and Vs tests from the Hamilton Section of the Waikato Expressway, we compare liquefaction potential assessed using two CPT-based procedures (a new procedure and the commonly used procedure), a Vs-based procedure, and the results of a paleoliquefaction study. For the low-moderate seismicity cases and relatively deep alluvial soils in the region, the new CPT-based procedure more closely aligns with the Vs-based approach and the results of the paleoliquefaction study.

1 INTRODUCTION

The Waikato region of New Zealand, and in particular a geomorphic region known as the Hamilton Lowlands, is characterised by late Pleistocene alluvial sandy deposits high in pumiceous content and a relatively high water table. Conventional Cone Penetration Test (CPT) based liquefaction assessment using the procedure proposed by Boulanger & Idriss (2014) [BI14] predicts the potential for liquefaction to extend to considerable depths in these soils (Clayton et al., 2017a). Recent research into the effect of aging and crushing of pumice/glass suggests that the liquefaction potential may be overestimated by such methods (Orense & Pender, 2013). Additionally, local paleoliquefaction assessments (Clayton et al., 2017b) indicate that the area has experienced less liquefaction than is suggested by the CPT-based liquefaction assessment methods.

This paper compares the assessed liquefaction potential using the BI14 CPT-based procedure with that resulting from using the CPT-based procedure proposed by Green et a. (2018) [Gea18]. Further comparisons of the assessed liquefaction potential are made using the results from the small-strain shear wave velocity (Vs) based approached proposed by Kayen et al. (2013) [Kea13] and observations from a paleoliquefaction study performed in the region. To better understand the differences in the assessed liquefaction potential resulting from the different procedures, key factors, such as r_d (stress reduction coefficient), Magnitude Scaling Factor (MSF), Cyclic Stress Ratio (CSR), Factor of Safety against liquefaction (FS_{liq}), Liquefaction Potential Index (LPI, Iwasaki et al., 1978), and Liquefaction Potential Index (Ishihara) (LPI_{ish}, Maurer et al., 2015), are compared and discussed.

2 BACKGROUND

2.1 *CPT-based liquefaction assessment methods*

Several researchers have noted that conventional penetrometer-based liquefaction assessment methods (e.g., CPT-based methods) can over-predict liquefaction triggering potential in some soils (Orense & Pender, 2013). The over-prediction has been attributed to the effects of particle crushing and/or ageing but may also be due to relationships inherent to a given CPT-based procedure.

Particle crushing has been reported during CPT testing in pumiceous soils (Wesley et al., 1998). Where significant crushing occurs during penetrometer testing the relative density may be underestimated and, hence, liquefaction potential overestimated.

Over time granular soils tend to gain strength through a number of mechanisms. Creep between particles may lead to more stable contacts among grains and/or cementation may develop. Several researchers (e.g., Andrus et al., 2009) have noted that the cementation that develops may arise from a number of mechanisms, some of which are relatively weak. It is thought that the more stable contacts among grains and the comparatively weaker bonds may contribute to liquefaction resistance not fully recognised by large strain penetrometer based methods, leading to an underestimation of the liquefaction potential of older soils by these methods.

2.2 *Vs-based liquefaction assessment methods*

Liquefaction evaluation methods based on Vs have been suggested as being more appropriate for liquefaction assessment in the aged and/or pumiceous soils of the Waikato, because small strain methods do not subject the soil to stresses high enough to result in significant particle crushing or disruption of weaker bonds (Clayton & Johnson, 2013). While considered more appropriate, Vs-based methods are not as well developed as CPT-based methods. Vs correlates more directly with the void ratio (e) of a soil than its relative density (Dr), with the latter being a better metric of liquefaction potential. As a result, two soils that have the same e, but very different Dr, may have the same predicted liquefaction potential via Vs-based methods, but the soil with the higher Dr may actually have a lower liquefaction potential.

2.3 *Paleoliquefaction-based liquefaction assessment methods*

Liquefaction (paleoliquefaction) features are often preserved in the geologic record where host-sediments remain largely intact. Paleoliquefaction features are typically comprised of injection structures in the form of sand dikes or sills intruded through and cross cutting the surrounding stratigraphy. In a paleoliquefaction investigation, shallow trenches are excavated to determine whether liquefaction features can be observed in the near surface. While this technique provides information about liquefaction response in past earthquakes and an indication of the intensity of the causative shaking, investigation can be limited by depth and insights about the intensity of causative shaking can be highly uncertainty for non-siliceous and aged soils.

2.4 *Geologic methods*

Geologic age and origin of the soil has been long recognized as having a significant influence on its susceptibility to liquefaction triggering (e.g. Youd & Hoose, 1977). However, this influence has been largely expressed qualitatively (e.g. Youd & Perkins, 1978), making it difficult to incorporate quantitative metrics in engineering liquefaction hazard analyses (e.g. Semple, 2013).

3 GEOLOGY, GROUNDWATER AND SEISMICITY

3.1 *Geology*

The published Geological and Nuclear Science (GNS Science) 1:250,000 scale geology map of the Waikato area (Edbrooke, 2005) shows the lowlands within the Hamilton area as being underlain primarily by alluvial fan deposits of the Hinuera Formation, Piako Subgroup. These alluvial sediments infilled the Hamilton basin mostly in two episodes between about 17,000 to 50,000 years ago, sourced from volcanic events within the Taupo Volcanic Zone, located approximately 100 km southeast of Hamilton.

3.2 *Groundwater*

Within the case study sites groundwater levels were investigated using a range of methods. For liquefaction assessment we have assumed that the groundwater conditions at the time of investigation are representative. However, for paleoliquefaction observations, we note that groundwater is likely to have been higher in the past, with down cutting having occurred over the last 20,000 yrs. Thus, the liquefaction hazard would have been higher prehistorically, and as a result, the deposits are less susceptible to liquefaction now than they were in the past.

3.3 *Seismicity*

For the purpose of this comparison we have assumed that the case study sites are subject to an earthquake shaking hazard expressed in terms of a design acceleration for a range of return periods. These are summarised in Table 1 for structures of high importance, such as bridges.

4 SCOPE OF STUDY

In order to compare the results of various methods, in-situ testing comprised of borehole sampling, CPT, Vs, and paleoliquefaction trenching was performed in a 2-m triangular pattern to minimise ground variability while avoiding the disturbance from one test influencing subsequent tests. Refer to Clayton et al. (2017b) for further details about the four case study sites (Puketaha 1-3, and Ruakura). The sites are all within the Hinuera Formation which is inferred to post-date the Oruanui Eruption (26,500y BP). For these late Pleistocene soils, age correction factors for liquefaction resistance are relatively low. Correction factors published by Hayati & Andrus (2009) were noted to not have a material effect on the indicated liquefaction potential.

4.1 *CPT testing*

CPT were utilised to refine stratigraphy, provide information about depth to the groundwater table, and to provide estimates of fines content (FC). The latter utilised region-specific correlations relating FC to soil behaviour index (Ic) for some units (Yong & Clayton, 2017).

Table 1. Design acceleration and representative magnitudes for Ultimate Limit State (ULS) and Maximum Credible Earthquake (MCE) motions.

Design Case	Design Acceleration (g)	Representative Magnitude (M_w)	Return Period (yrs)	Equivalent number of events*
ULS	0.29	5.9	2,500	~10
MCE	0.39	6.9	~20,000	~1

* Design return period compared to the time since deposition of the soils investigated (Hinuera Formation, post Kawakawa/Oruanui ash 26,500y BP)

4.2 *Shear wave velocity*

Shear wave velocity testing was undertaken at the case study locations utilising three different investigation methods comprising downhole (sCPT, sDMT) and crosshole (CST) testing.

5 METHODOLOGY FOR INTERPRETATION

5.1 *Liquefaction potential assessment methods used*

Methods used for the interpretation of liquefaction potential are summarised below in Table 2.

5.2 *Method comparison*

The three simplified liquefaction evaluation procedures (BI14, Gea18, and Kea13) are semi-empirical and were developed using the same general approach using liquefaction/no-liquefaction field case histories. However, relationships inherent to these procedures do differ, and as a result, even the two CPT-based procedures can yield different results for scenarios not well represented in the case history databases on which the procedures were derived (e.g., small and large magnitude events, silty soils, and very shallow and very deep strata). The most notable differences between the BI14 and Gea18 procedures are the r_d and MSF relationships employed by the procedures. r_d, or the stress reduction factor, accounts for the non-rigid response of the soil profile during earthquake shaking, and MSF, or magnitude scaling factor, accounts for the duration of shaking on liquefaction triggering. The Kea13 procedure also employs its own r_d and MSF relationships, in addition to characterizing the soil using Vs in lieu of normalized CPT tip resistance.

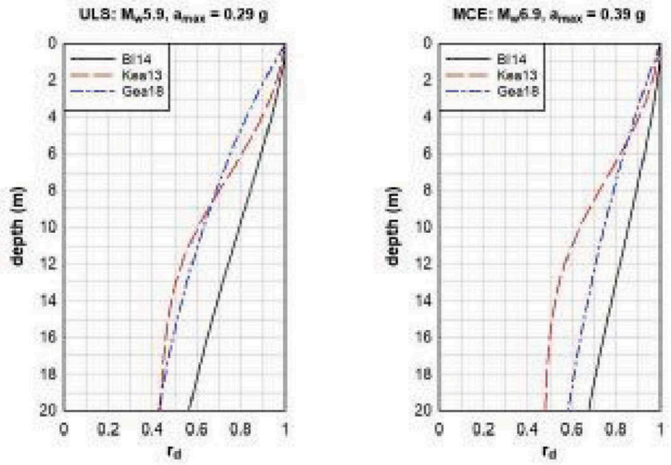
The r_d relationships adopted by the three methods considered are presented in Figure 1 for the ULS and MCE for the study area. All relationships presented indicate a clear variation with depth and magnitude, with Kea13 also being dependent on the average Vs in the upper 12 m of the profile (i.e., Vs12). As may be observed from this figure, the Kea13 and Gea18 r_d relationship yield lower values than the BI14 relationship, implying a lower seismic demand imposed on the soil.

The MSF adopted by the three methods considered are presented in Figure 2. BI14 utilizes a MSF relationship that is dependent on penetration resistance of the soil and magnitude, whereas Gea18 utilizes a MSF relationship that is dependent on peak ground acceleration (a_{max}) at the ground surface and magnitude. The Kea13 relationship is solely dependent on magnitude. The BI14 MSF relationship for dense soils and lower magnitudes yields higher values than the other relationships, implying a lower seismic demand imposed on the soil.

A more detailed comparison of the procedures for the study sites are presented in the next section.

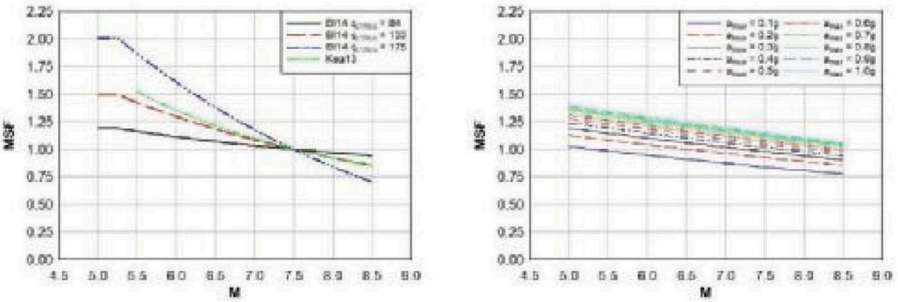
Table 2. Interpretation Methodology.

Test Method	Methodology for susceptibility	Methodology for triggering assessment	Methodology for Fines Correction
All CPT methods	Based on Ic with Ic cutoff calibrated to Atterberg limits of samples from paired borehole. (Yong & Clayton 2017)	Following BI14 (50%ile) Following Gea18 (50%ile)	Fines content correlated to Ic with calibration using laboratory grading tests on paired borehole samples.
All Vs methods	Based on Ic from paired CPT with calibrated Ic cutoff, per CPT based assessment	Following Kea13 (50%ile)	Fines content estimated based on correlation to Ic from paired CPT, calibrated as per CPT based assessment. Fines correction of Vs1 following Kea13.
Paleo-liquefaction	A qualitative assessment undertaken in shallow trenches at chosen sites. Evidence of dykes in these shallow trenches is taken as indication of a large event where liquefaction effects are expected to have manifested at the surface.		
Geological	A qualitative assessment undertaken based on the age and depositional environment indicated by published mapped geology.		



(a) (b)

Figure 1. r_d relationships inherent to BI14, Kea13, and Gea18 simplified liquefaction evaluation procedures for: (a) ULS: M_w5.9 & a_{max} = 0.29 g; and (b) MCE: M_w6.9 & a_{max} = 0.39 g, where a_{max} is the peak ground acceleration at the surface of the profile. For the Kea13 r_d relationship, V_{S12} = 160 m/s was assumed.



(a) (b)

Figure 2. MSF for: (a) BI14 and Kea13; and (b) Gea18.

6 ANALYSIS RESULTS

6.1 *Direct comparison of empirical methods*

The BI14 procedure is generally considered to be the standard-of-practice for evaluating liquefaction potential in New Zealand. We have compared r_d, MSF, CSR and the resulting FS_{liq} parameters for Gea18 and Kea13 with those for BI14 as a ratio in Figure 3. For the comparison we have used ULS and MCE seismic events for the case study as detailed above (Table 1).

For the case study ground conditions and seismic loading, the r_d factors calculated utilising Gea18 and Kea13 are significantly lower than BI14, especially at depth. MSF are similar for BI14 and Kea13 and significantly lower for Gea18. In simple terms, this means that for the case study Gea18 and Kea13 indicate lower seismic demand than BI14. The CPT-based BI14 and Gea18 methods generate almost identical CRR. The CRR calculated from Vs by Kea13 varies relative to BI14/Gea18 for the case study site. The CRR from Kea13 is higher near the surface, then relatively consistent with BI14/Gea18 at depth.

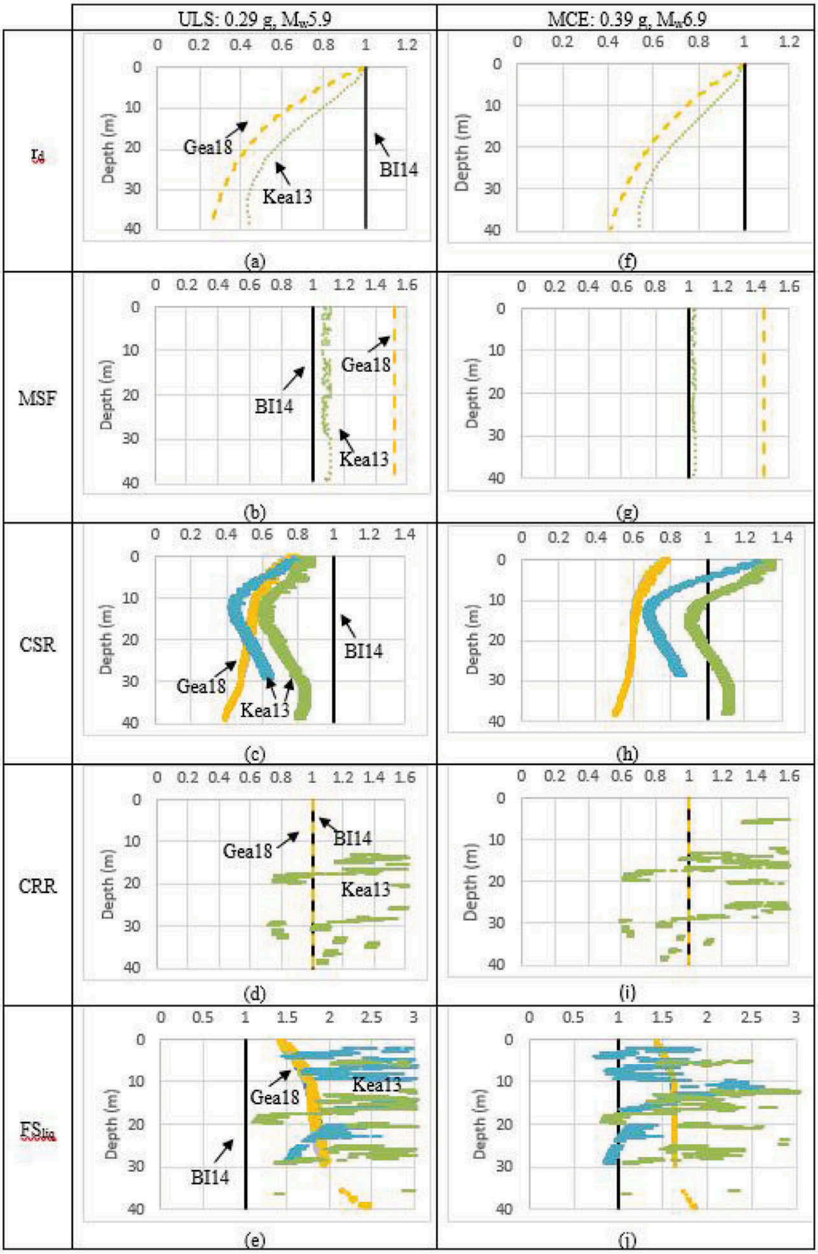


Figure 3. Ratios of r_d (a, f), MSF (b, g), CSR (c, h),, CRR (d, i) and FS_{liq} (e, j) for Gea18 and Kea13 with those for BI14 (BI14 is denominator) across data from the four sites for the ULS (left) and MCE (right) earthquake events.

The calculated FS_{liq} using Gea18 and Kea13 are consistently higher than BI14 by a ratio of around 1.5 for the range of seismic events considered. This reflects the lower CSR values from the Gea18 and Kea13 methods (and the lower CRR of the shallow Vs data).

6.2 *Comparison of empirical methods with paleoliquefaction results*

Having identified a difference between the results of the three quantitative methods we have sought to identify options for validation of the liquefaction computed hazard. A

Table 3. Summary of results from paleoliquefaction for the sites considered herein (Clayton et al. 2017b).

Site	Observed Paleoliquefaction Features	Inferred LPI/ LPI_{ish}
Puketaha 1	None observed.	< 4
Puketaha 2	None observed.	< 4
Puketaha 3	Two sand filled dykes encountered were interpreted as potential paleoliquefaction features arising from the liquefaction of the immediately underlying sandy bed. Features observed appeared to be locally sourced, no significant thoroughgoing dykes were identified indicative of ejecta arising from significant depth.	4 - 8
Ruakura	None observed.	< 4

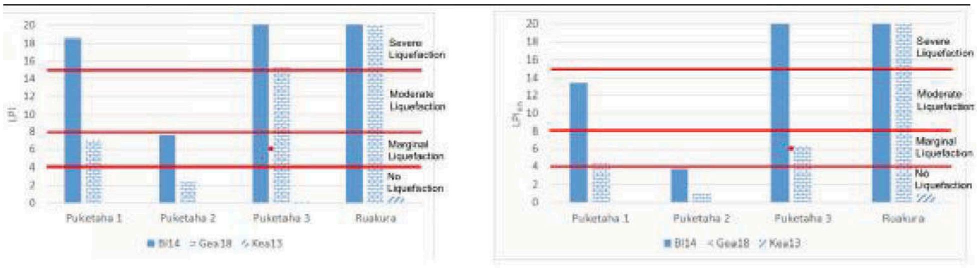


Figure 4. LPI (a) and LPI_{ish} (b) comparison across the sites considered in relation to the paleoliquefaction studies undertaken. The dot represents the potential manifestation of damage at Puketaha 3 due to liquefaction based on the paleoliquefaction study.

paleoliquefaction study undertaken alongside the paired investigation points of this case study provides this opportunity. Details about the paleoliquefaction study performed in this region are outlined in Clayton et al. (2017b). The results of the study are briefly summarized in Table 3. Features, where observed, were relatively small and as such can be considered as having resulted in marginal surficial liquefaction manifestations at the site. To allow comparison with quantitative liquefaction assessments we have estimated LPI or LPI_{ish} index values by comparison to the work by Maurer et al. (2015).

Computed (CPT and Vs) and estimated (paleoliquefaction study) LPI (a) and LPI_{ish} (b) values (ULS) are compared in Figure 4. The comparison shows that LPI_{ish} for Gea18 at the Puketaha sites is consistent with the paleoliquefaction study. The Kea13 LPI/LPI_{ish} values suggest low liquefaction potential at all sites and BI14 moderate to severe liquefaction at all sites.

The Hinuera Formation is an alluvial fan/plain deposit of late Pleistocene age. Using the relationship between liquefaction resistance, age and depositional environment published by Youd & Perkins (1978) these deposits might be expected to have a 'low' liquefaction potential.

7 DISCUSSION & CONCLUSIONS

This study was intended to compare the liquefaction potential indicated by a range of different liquefaction methods within the relatively low seismicity and deep sands of the Waikato in New Zealand. A significant difference was found in the liquefaction potential indicated by the widely adopted BI14 methodology and the more recently published Gea18 and the Vs based Kea13. A significant proportion of the differences appear to arise from the adopted r_d factor.

We have compared these methods against each other for selected sites and seismic loading. The results of the qualitative methods have also been compared with a paleoliquefaction study and published geological screening based on the depositional environment and age. This comparison indicates that at these sites the BI14 method appears to predict a higher liquefaction triggering potential than Gea18 and Kea13, with Kea13 predicting the lowest liquefaction triggering potential. The lower liquefaction potential is consistent with the paleoliquefaction study and the geological screening methods.

REFERENCES

Andrus, R.D., Hayati, H., & Mohanan, N.P. 2009. Correcting liquefaction resistance for aged sands using measured to estimated velocity ratio. *J. of Geotech. and Geoenviron. Eng*. 135(6): 735:744.

Boulanger, R.W. & Idriss, I.M. 2014. *CPT and SPT based liquefaction triggering procedures*. Report No. UCD/CGM-14/01, Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California, Davis, CA: 134 pp.

Clayton, P.J., Yong, I., & Wotherspoon, L.2017a. Case study in the use of shear wave velocity techniques to investigate the liquefaction potential of Waikato soils for the Hamilton section of the Waikato Expressway. *Proc. 29th NZGS Geotechnical Symposium*. Eds. GJ Alexander & CY Chin, Napier.

Clayton, P.J., Yong, I., Green, R.A., & Bastin, S.H. 2017b. Case study in the use of paleoliquefaction techniques to investigate liquefaction potential of Waikato soils for the Hamilton section of the Waikato expressway. *Proc. 29th NZGS Geotechnical Symposium*. Eds. GJ Alexander & CY Chin, Napier.

Clayton, P.J. & Johnson, J.T. 2013. Liquefaction resistance and possible aging effects in selected Pleistocene soils of the Upper North Island. *Proc. 19th NZGS Geotechnical Symposium*, Queenstown.

Edbrooke, S.W. (compiler) 2005. *Geology of the Waikato area*: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences. 1:250,000 geological map 4. 68 p. + 1 folded map.

Green, R.A., Bommer, J.J., Rodriguez-Marek, A., Maurer, B., Stafford, P., Edwards, B., Kruiver, P.P., de Lange, G. & van Elk, J. 2018. Addressing limitations in existing 'simplified' liquefaction triggering evaluation procedures: Application to induced seismicity in the Groningen gas field. *Bulletin of Earthquake Engineering* https://doi.org/10.1007/s10518-018-0489-3.

Hayati, H., & Andrus, R. D. 2009. Updated liquefaction resistance correction factors for aged sands. *J. of Geotech. and Geoenviron. Eng*. 135(11): 1682-1692.

Iwasaki, T., Tatsuoka, F., Tokida, K. & Yasuda, S. 1978. A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. *Proc. 2nd Intern. Conf. Microzonation*, Nov 26-Dec 1, San Francisco, CA, U.S., 885-896.

Kayen, R., Moss R., Thompson E., Seed R., Cetin K., Der Kiureghian A., Tanaka Y., & Tokimatsu, K. 2013. Shear wave velocity–based probabilistic and deterministic assessment of seismic soil liquefaction potential, *J. Geotech. Geoenviron. Eng*. 139(3): 407–419.

Maurer, B.W., Green, R.A. & Taylor, O.-D.S. 2015. Moving Towards an Improved Index for Assessing Liquefaction Hazard: Lessons from Historical Data, *Soils and Foundations*55(4): 778-787.

Orense, R.P. & Pender, M.J. 2013. Liquefaction characteristics of crushable pumice sand. *Proc. 18th Intern. Conf. on Soil Mechanics and Geotechnical Engineering*. 2–6 September, Paris: 1559–1562.

Semple, R. 2013. Problems with liquefaction criterian and their application to Australia. *Australian Geomechanics*. 48(3): 15-34.

Wesley L.D., Meyer V. & Pender M. J. 1998. Cone penetrometer tests in pumice sand. *NZ Geomechanics News* June 1998: 57-61.

Wotherspoon, L.M., Cox, B.R., Stokoe II, K.H., Ashfield, D.J. & Phillips, R.A. 2015. Utilizing direction-push crosshole testing to assess the effectiveness of soil stiffening caused by installation of stone columns and Rammed Aggregate Piers, *Proc. 6th Intern. Conf. on Earthquake Geotechnical Engineering*, 1-4 November 2015, Christchurch, New Zealand.

Yong, I. & Clayton, P.J. 2017. Application of soil specific correction factors for liquefaction assessment: case study in Waikato soils for the Hamilton section of the Waikato expressway. *Proc. 29th NZGS Geotechnical Symposium*. Eds. GJ Alexander & CY Chin, Napier.

Youd, T.L. & Hoose, S.N. 1977. Liquefaction susceptibility and geologic setting. *Proc. of 6th World Conf. on Earthquake Engineering*. New Delhi, pp 37-42.

Youd, T.L. & Perkins, D.M. 1978. Mapping of liquefaction induced ground failure potential. *Journal of Geotechnical Engineerig Division* 104 (4): 433–446.