Case study in the use of paleoliquefaction techniques to investigate liquefaction potential of Waikato soils for the Hamilton section of the Waikato expressway

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ABSTRACT

The four-lane, 21.8-km long, Hamilton Section of the Waikato Expressway is the largest road project undertaken in the Waikato region's history and one of the larger highway projects currently being undertaken in New Zealand. Many of the seventeen expressway bridges in the Hamilton Section are underlain by saturated Pleistocene silty and sandy alluvial soils that have considerable pumice and volcanic glass content. Conventional penetration based methods generally indicate that the potential for liquefaction for these soils extends to considerable depth. However, some researchers have suggested that conventional penetrometer-based methods may overestimate the liquefaction potential in these soils due to the pumice and volcanic glass fragments' tendency to crush during penetration testing and the penetration-based liquefaction evaluation procedures' lack of accounting for aging effects on liquefaction resistance.

To investigate these effects and to inform design, the liquefaction hazard was also assessed using small strain shear wave velocity (Vs) based procedure (discussed in companion paper – Clayton et.al 2017) and a paleoliquefaction study was performed. The paleoliquefaction investigation was comprised of the excavation of seven trenches at sites proximal to the expressway where liquefaction is anticipated. Detailed logging of features encountered in the trenches accompanied by C14 dating of samples was undertaken to document and determine approximate ages of paleoliquefaction features. Observations from the paleoliquefaction study were more consistent with predictions for the Vs-based liquefaction evaluation than they were with those penetration-based method and indicate that the penetration-based methods overestimate the liquefaction potential of the study sites.

1 INTRODUCTION

The City Edge Alliance (The Alliance) has been commissioned to undertake detailed design for the 21.8-km long Hamilton Section of the Waikato Expressway on the North Island of New Zealand. The Alliance is made up of the New Zealand Transport Agency, Fletcher Construction, Higgins, Beca and Coffey. The Alliance approach was adopted to maximise the potential for full integration of the traditional roles of client, designer and constructor for the benefit of the project, enabling a collective approach and risk sharing. Within the geotechnical sphere of the project, this has been further enhanced through a Geotechnical Steering Group with representatives from the designer, constructor and client. This Group enabled consideration of 'best for project' approaches and thereby the ability to look at approaches and methods that would not normally occur within more traditional contracts.

Much of the route passes through a geographic region known as the Hamilton Lowlands which is characterised by late Pleistocene alluvial silt and sand deposits with a high pumice and volcanic glass content and a relatively high water table. Liquefaction assessments performed using conventional penetrometer-based procedures (i.e., Standard Penetration Test, SPT, and Cone Penetration Test, CPT, based procedures) indicate that the potential for liquefaction extends to considerable depth at many of the seventeen expressway bridges within this section. However, the penetration-based procedures are thought to over predict the liquefaction potential of these deposits because of the tendency for the pumice and volcanic glass fragments to crush during in-situ testing, resulting in an underestimation of soil density and liquefaction resistance. Additionally, the penetration tests are inherently large strain and, thus, are not sensitive to aging effects that increase the liquefaction resistance of the deposits (e.g., Orense and Pender, 2013). Accordingly, alternative assessment procedures were used to evaluate the liquefaction potential of sites along the Hamilton Section of the expressway, to include using small strain shear wave velocity (Vs) based procedures and performing a paleoliquefaction study to look for evidence of liquefaction during previous events.

This paper documents the methodology and results of the paleoliquefaction investigation undertaken and compares the observations with the liquefaction potential assessed using both CPT- and Vs-based evaluation procedures. Reference should also be made to a companion paper (Clayton et al., 2017) that reports the results of the Vs-based liquefaction assessment undertaken for this same project.

2 BACKGROUND

2.1 Penetration-based liquefaction evaluation

A number of researchers have noted that conventional penetrometer-based (e.g., SPT- and CPT-based) liquefaction assessment methods can over predict liquefaction triggering potential in some soils (e.g., Orense and Pender, 2013). The over prediction has been attributed to the effects of particle crushing and/or aging, among other factors.

Particle crushing has been reported during CPT testing in carbonate and pumiceous soils. Where significant crushing occurs during penetration testing, the relative density and, hence, liquefaction potential are underestimated. Additionally, over time granular soils tend to gain strength through a number of mechanisms, referred to as 'aging'. Creep between particles may lead to a more stable packing and/or cementation may develop. These effects increase the liquefaction resistance of soils, but may not be fully recognised by large strain penetration-based liquefaction evaluation methods. Methods based on Vs have been suggested as being more appropriate for liquefaction assessment of crushable soils and older deposits. This is because the small strain nature of Vs testing does not result in particle crushing and is capable of directly recognising age related effects. While considered more appropriate in these soils, Vs-based liquefaction evaluation procedures are not as 'mature' as penetration-based methods, and therefore, it was decided to validate Vs-based assessments by also undertaking paleoliquefaction investigations.

2.2 Paleoliquefaction study

Liquefaction features are often preserved in the geologic record where host-sediments are remain largely intact. These features, termed paleoliquefaction features, are commonly comprised of subvertical dikes and/or injection structures, in which sand dikes or sills intrude through subsequent layers and cross-cut the surrounding stratigraphy.

By examining the presence and/or absence of paleoliquefaction features against liquefaction potential based on in-situ test results, we have sought to demonstrate the reliability of our proposed approach to liquefaction assessment and the inherent conservatism of penetration-based liquefaction assessment methods in the Waikato soils of rhyolitic volcanic origin. Towards this end, paleoliquefaction investigations have been undertaken at seven locations along the alignment of the Hamilton Section of the Waikato Expressway.

3 GEOLOGY AND SOIL COMPOSITION

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. Holocene (~12,000 years ago to present) volcanic ashfall, peat bogs, and lake deposits locally overlie the Hinuera Formation. Refer to Fig 1.

The selected sites for the paleoliquefaction investigations are all situated within the younger soils of the Hinuera Formation inferred to post-date the Oruanui Eruption (26,500y BP).

3.2 Soil Composition

Most of the primary soils underlying this section of the Expressway are comprised of fluvially deposited rhyolitic soils sourced from volcanic events within the Taupo Volcanic Zone, located approximately 100 km southeast of Hamilton. The soils are comprised of significant amounts of volcanic glass, pumice, and other rhyolitic gravels, as well as crystalline minerals of quartz, feldspar (plagioclase), oxides (magnetite), pyroxenes (hypersthene, augite), amphibole (hornblende), and mica (biotite) (Hume et al., 1975). The grains are typically angular with a limited amount of rounding.

4 SEISMICITY

The seismicity of the Expressway alignment has been investigated by GNS Science as part of the preparation of the Site Specific Seismic Study (SSHA) for the wider Waikato Expressway Project (Buxton et al., 2010). Table 1 summarises the characteristics of the known faults near the project area. The SSHA presents interpretation of the seismic hazard along the route combining the contribution of known faults and unknown fault potential to derive a probabilistic earthquake shaking hazard expressed in terms of a design acceleration for a range of return periods. These are summarised in Table 2 for structures of high importance (IL3).

Table 1: Known faults contributing to the project area seismic hazard (Buxton et al., 2010)

Fault Segment	Approx. Dist. to Hamilton Section (km)	Maximum Estimated Magnitude (M_w)	Inferred Recurrence Interval (yrs)
Kerepehi South	22	6.6	3,400
Kerepehi Central	27	6.9	5,400
Kerepehi North	48	6.8	8,900
Kerepehi Offshore	75	7.2	20,000
Wairoa North	85	6.7	13,000

Table 2: Design acceleration and representative magnitudes for Ultimate Limit State (ULS) and Maximum Credible Earthquake (MCE) motions (Stirling et al., 2010)

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)				

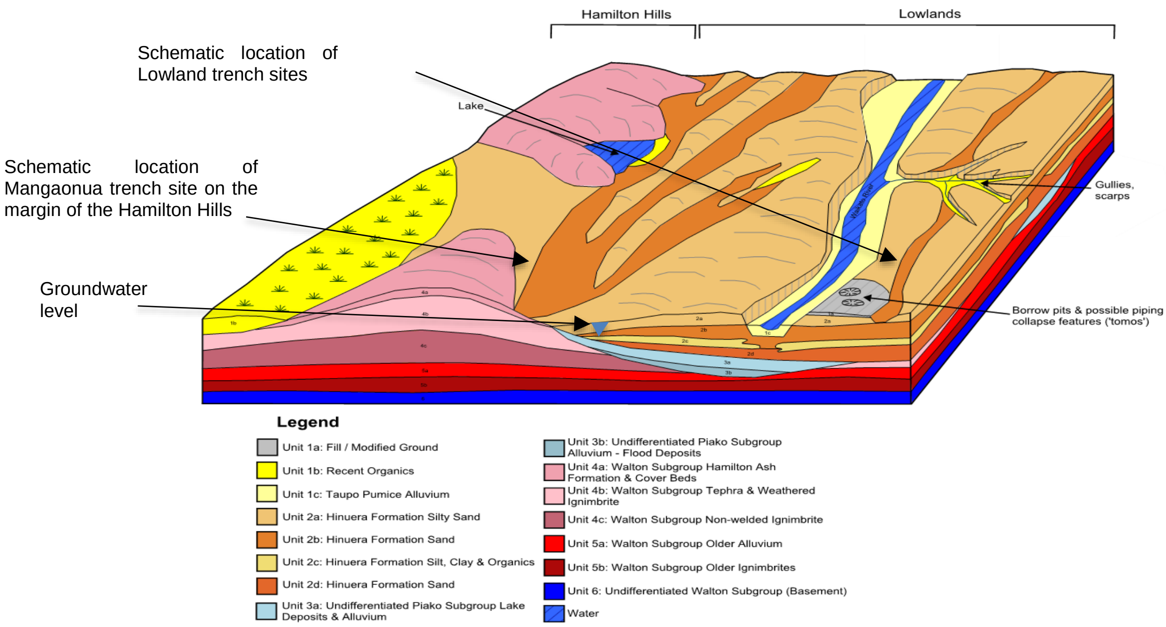


Figure 1: A Schematic block diagram showing the two geological terrains Hamilton Hills and Lowlands (modified from Lowe, 2010)

5 GROUNDWATER

Groundwater levels were investigated through a range of methods, including observations during drilling and CPT testing, monitoring of piezometers, and through seismic compression wave studies. For liquefaction assessment we have assumed that the groundwater conditions at the time of investigation are representative. However for paleoliquefaction correlations, we note that it groundwater is likely to have been higher in the past, down cutting has occurred over the last 20,000 yrs. Thus the liquefaction hazard would have been higher historically and if the soils haven't liquefied in the past, then they are unlikely to in the current groundwater conditions.

6 LIQUEFACTION POTENTIAL BY IN-SITU METHODS

Liquefaction potential was evaluated using the CPT-based and Vs-based simplified procedures proposed by Boulanger & Idriss (2014) (B&I14) and Kayen et.al (2013), respectively. In the analyses, we assumed that soils having a CPT Soil Behaviour Type Index (Ic) less than or equal to 2.6 were liquefiable and soils having Ic > 2.6 to be not susceptible (Robertson & Wride, 1998). The analyses considered Cyclic Resistance Ratios (CRR) corresponding to both 15% probability of liquefaction (in line with the standard deterministic approach to liquefaction assessment for design) and 50% probability of liquefaction (for direct comparison to observed effects). The difference between the results from using the CRR curves corresponding to the two probabilities of liquefaction was not found to be significant where liquefaction potential was low.

7 PALEOLIQUEFACTION INVESTIGATION

As part of the paleoliquefaction investigation, seven trenches were excavated to depths varying between 1.0 to 1.5 m and detailed logging undertaken (Fig. 2). Some adjacent deeper pits were excavated to assess groundwater levels. Six of the selected trench sites were predicted to have a high liquefaction potential based on investigated material properties and elevated groundwater levels. An additional site, at Mangaonua, was selected where geomorphic evidence suggested possible paleo-lateral spreading. Detailed trench logs of soil, groundwater, and soil structures have been prepared, however due to space limitations observations are summarised in Table 3.

Table 3: Summary of observations from the paleoliquefaction trenching study

Investigation Point	**Summary of findings**	**Paleo-liquefaction Features**
Trench 1 – Resolution	Interbedded sands and silts of the Hinuera Formation encountered. Groundwater at 1.75 m in adjacent test pit. Near the southern end of the trench a possible paleoliquefaction feature comprising a steep to subvertical dyke like intrusion was encountered. It is unclear whether this is a paleoliquefaction feature or a synsedimentary structure. No extensional features, consistent with lateral spreading or large cyclic ground movements were observed.	Feature assessed as having a low probability of being related to paleo-liquefaction.
Trench 2 – Puketaha 1	Interbedded sands and silts and organic soils of the late Hinuera Formation, overlain by swampy deposits. Groundwater at 2.0m	None observed.
Trench 3 - Puketaha 2	The western section is comprised of clay rich Hamilton Ash Formation dipping down slope to the south-east with on-lapping Hinuera Formation from the east. The Hinuera Formation comprises silt overlying clean sand with discontinuous moderately thin lenses of clayey silt and organic rich silt. No groundwater noted.	None observed.
Trench 4 - Puketaha 3	Hinuera Formation comprises interbedded silt and well graded clean sand in thick beds, with very thin basal lenses of coarse pumice sand/fine gravel. Groundwater seepage from perched horizons approximately 1.5m below ground level (bgl). Groundwater at 2.1m bgl in adjacent test pit. Two sand filled dykes encountered were interpreted as paleoliquefaction features arising from the liquefaction of the immediately underlying sandy bed. Homogenous infill suggests a single event. Features do not penetrate into the base of the thick organic rich topsoil. No extensional features, consistent with lateral spreading or large cyclic ground movements were observed. Features observed appeared to be locally sourced, no significant thoroughgoing dykes were identified indicative of ejecta arising from significant depth. Refer Figure 2.	Multiple small features observed.
Trench 5 – Ruakura	This trench extends from a small terrace and to lower lying ground. Hinuera Formation soils comprised of a moderately thick topsoil overlying interbedded thick silty sand /silt and clean pumiceous sand/gravel encountered. No groundwater noted.	None observed.
Trench 6 – Mangaonua	Hinuera Formation soils comprising very thin to moderately thinly interbedded sand and silt encountered. Further excavation adjacent to trench confirmed evidence of previous sand mining, which is likely to have formed observed “terracing” of the river bank, rather than extensional movement. No groundwater noted.	None observed.
Trench 7 – Matangi Rd	Hinuera Formation soils comprising interbedded silt, sandy silt and well graded clean sands encountered. No groundwater noted.	None observed.

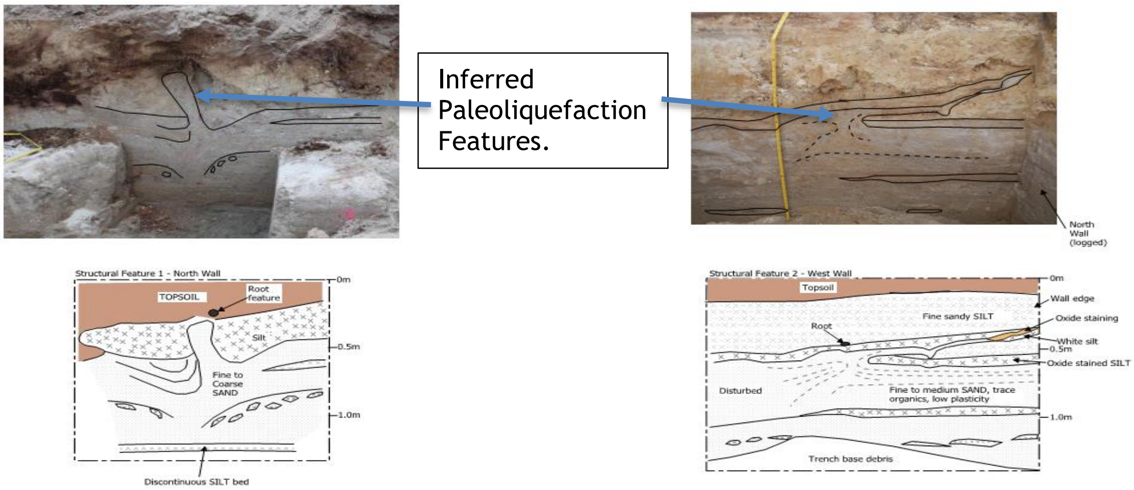


Figure 2: Sketches taken of paleoliquefaction features identified in the Puketaha trench.

Laboratory radiocarbon dating of organic samples was undertaken by Waikato University to obtain approximate age of the formation of materials overlying the paleoliquefaction feature in the north wall of Puketaha Trench 3. Two samples were successfully dated, shown in brackets below corrected for isotopic fractionation and reported in years before present (BP):

- A 2000 year (2065 +/- 20 BP) date from a charcoal deposit at 200 mm depth. The charcoal underlies a thin tephra (inferred to have originated as part of the Hatepe eruption of the Taupo Volcano around 1800 years ago). This charcoal deposit (and overlying tephra) do not appear to have been penetrated by the dyke.

- A 6000 year (5788 +/- 20 BP) date from a charcoal deposit at 700 mm depth. This charcoal deposit does not appear to have been penetrated by the dyke.

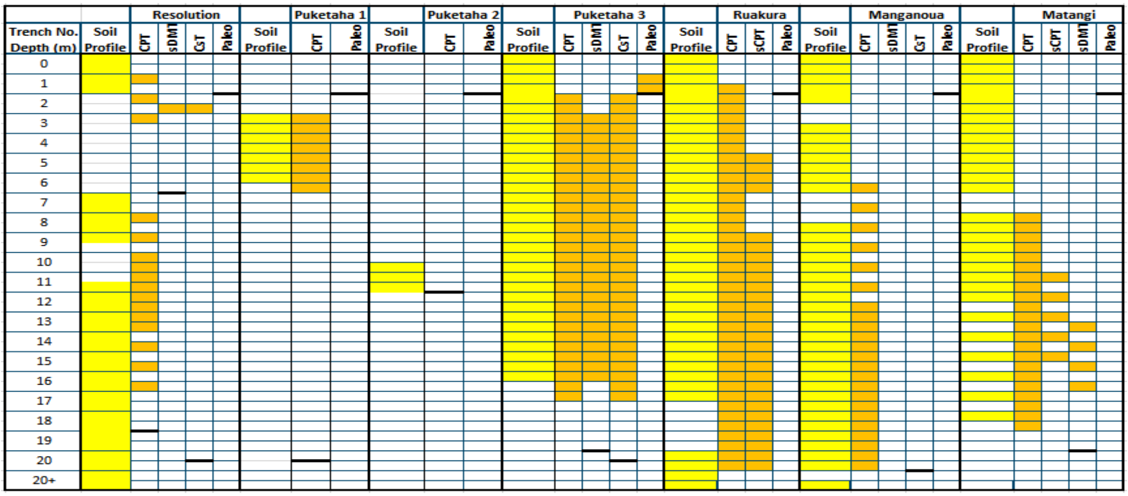
Accordingly, the liquefaction episode that resulted in the formation of the dyke is inferred to have occurred more than 6,000 years ago. In the last 6,000 years, two Ultimate Limit State (ULS) events are expected to have occurred and there is no evidence found for liquefaction in this time period.

8 COMPARISON OF METHODS AND DISCUSSION

A comparison of the liquefaction assessment results from various in-situ test methods and the observations from the paleoliquefaction study are presented in Fig. 3. For the purpose of interpreting the findings we have grouped the test locations into two areas on the basis of inferred liquefaction hazard and current groundwater depth. The northern section (Resolution, Puketaha 1, 2 & 3, Ruakura), where the groundwater depth is typically shallow, and a southern section (Mangaonua, Matangi) where the groundwater depth is currently deep. The southern areas were still investigated because CPT data indicated the significant thickness of potentially liquefiable material at depth which could have given rise to lateral spreading and slope regression to deeply incised gullies, however such features were not evident in the investigation locations.

Paleoliquefaction features were anticipated within the five locations investigated in the northern section where relatively high groundwater levels are present, in particular where this occurs within Hinuera Formation deposits. However, evidence of liquefaction was found only in the site (Puketaha 3), which had the highest assessed liquefaction potential of all sites. At Puketaha 3 liquefiable soils are indicated to be present to a significant depth by all in-situ investigation methods. The paleoliquefaction investigation identified two features within a 25-m long, up to 2-

m deep trench (Fig 2). The features observed were relatively small in section (<100 mm across) and blind (terminating below the topsoil), did not show evidence of repeated events, and propagated in a sinuous manner suggesting that this event was unlikely to have been associated with significant lateral spreading. Evidence of widespread, deeper seated liquefaction, such as large thoroughgoing ejecta dykes, were not identified. The features are estimated to be between 6,000 and 26,500 years old.



Key: Yellow – sand in borehole samples, Orange -liquefaction potential, blank – no liquefaction potential, black line – base depth of investigation; CPT – Cone Penetration Test, sCPT – Seismic Cone Penetration Test, sDMT – Seismic Dilatometer Test, CsT –Cross Hole Seismic Test, Paleo – Paleoliquefaction trench

Figure 3: Comparison of results from CPT- and Vs-based liquefaction assessment and interpretation from the paleoliquefaction trenching study.

CPT-based liquefaction assessments indicate the potential for liquefaction throughout the majority of sand units within the northern section. Vs-based methods indicate limited shallow liquefaction throughout the northern section, with the exception of Puketaha 3. At Puketaha 3 Vs-based methods indicate liquefaction from the water table to ~10 m for the ULS (2500 y return) shaking and to ~17 m for the MCE (20,000y return). Interpretation of paleoliquefaction evidence suggests that at Puketaha 3 liquefaction occurred sometime between 6,000 y and 26,500 y ago. The observed features were likely formed during a single event, with liquefaction occurring in soils at a relatively shallow depth and did not result in significant lateral spreading. The absence of large thoroughgoing ejecta dykes is considered evidence that widespread, deeper seated liquefaction, such as that indicated by CPT and Vs-based methods has not occurred at this site.

9 CONCLUSIONS

When compared to hard grained soils, deposits containing pumice have been widely reported in the geotechnical literature to have a higher resistance to liquefaction than indicated when assessed utilising penetrometer (CPT, SPT) based methods. A number of respected sources, including NZGS (NZGS. 2010), have suggested the use of Vs-based methods for triggering assessment in these soils. However, because Vs-based methods are not as mature as penetrometer based methods, The Alliance opted to undertake a paleoliquefaction study as part of the investigation of liquefaction hazard. The goal of this effort was to provide independent and site specific validation that the use of Vs-based methods provide a reliable assessment of liquefaction potential in these soils. The results of the paleoliquefaction investigation confirms the liquefaction hazard in the Hamilton Lowlands, where expected in the alluvial sands with high groundwater. Based on the comparison undertaken as part of this study, Vs-based methods were found to be more consistent (albeit still conservative) with the findings of the paleoliquefaction investigation. More detail on the comparison between CPT and shear wave velocity testing is provided in a companion paper (Clayton et al., 2017).

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