

Application of soil specific correction factors for liquefaction assessment: case study in Waikato soils for the Hamilton section of the Waikato expressway

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ABSTRACT

The four-lane, 21.8 kilometre long, Hamilton Section of the Waikato Expressway is the largest roading project undertaken in this region's history and one of the larger projects currently being undertaken in New Zealand. Many of the seventeen expressway bridges in the Hamilton Section are underlain by Pleistocene soils assessed as having a high liquefaction potential. Typically the soils encountered are volcanic in origin either as primary tephra deposits or reworked volcanically derived material. A number of researchers have noted the potential for misclassification of such soils by the CPT, therefore it was decided to undertake co-located borehole/SCPT/SDMT and laboratory classification testing for use in conjunction with a site wide geologic model to develop soil specific correction factors for use in liquefaction assessment. Soil specific correction factors were investigated for the Ic sand like/clay like cut-off (B&I 2014) and the fines content (Cfc). The specific correction factors derived are presented along with examples from the project showing the consequence, some of which are significant, of adopting soil specific correlations. Given the widespread occurrence of some of the soils considered e.g. Hamilton Ash, within the Waikato and Bay of Plenty region, the authors suggest that the database of testing presented in this study could be readily supplemented by results from other sites and the proposed soil specific correction/correlations extended.

1 INTRODUCTION

This paper presents a case study of the development of site specific CPT derived soil behaviour/composition correlations within volcanogenic sediments of the Waikato Region of the north island of New Zealand. Two correlations are considered:

- a) Soil Behaviour Index (Ic) to fines content (FC) and;
- b) Soil behaviour Index (Ic) to Plasticity Index (Ip) as a proxy of liquefaction susceptibility

These two correlations are key to the assessment of liquefaction susceptibility and so the authors have chosen to investigate how they may vary from the norm in volcanogenic sediments, in particular those containing pumice (NZ Geotechnical Society, 2010).

This study uses data sourced from the extensive investigation undertaken for the Hamilton Section of the Waikato Expressway, a recently designed 21.8km long highway project including 17

bridges. The project area lies in the centre of the Hamilton Basin, a large alluvial plain approximately 40km wide by 90km long.

Many of the soil types encountered in this study are widespread across the region. In the future the authors would like to extend the database by incorporating suitable investigation data from elsewhere within the Waikato and Bay of Plenty region, where similar soils are known to exist.

2 GEOLOGY & SEISMICITY OF AREA

The Hamilton Basin can generally be divided into two geological terranes, the Hamilton Hills and the Lowlands. The Hamilton basin was infilled with sediments derived from volcanic activity within the Taupo Volcanic Zone, located approximately 100 km southeast of Hamilton, during the Quaternary period (last 2 Million years). Most of the basin is a broad alluvial floodplain (lowland) with widely spaced rounded hills (Hamilton Hills) that protrude some 20 m to 70 m above the plain surface. Most of the primary (airfall and pyroclastic deposits) and reworked (alluvial fans and lacustrine) soils in this region are rhyolitic in composition sourced from volcanic events within the Taupo Volcanic Zone, located approximately 100 km southeast of Hamilton. The soils contain significant amounts of volcanic glass, pumice, other rhyolitic lithic gravels, as well as crystalline minerals.

2.1 Hamilton Hills

The Hamilton Hills comprise older volcanic ignimbrites mantled by volcanic airfall deposits whose upper surface forms a characteristic stiff to very stiff orange-brown weathered silt-clay crust (Hamilton Ash Formation). These hills comprise a sequence of at least three distal ignimbrites (pyroclastic density currents) deposited approximately 1 to 1.2 Million years ago interfingering with alluvium. The hills have since been eroded by the ancestral Waikato River into a series of rounded hills and valleys, which in turn deposited reworked volcanic sediments. Subsequently the hills were mantled by ash fall beds known as the Kauroa and Hamilton Ash Formations and undifferentiated younger tephra beds (cover beds). The surfaces of the Hamilton Hills have been deeply weathered with the highly reactive volcanic glass fragments altering to sensitive clay minerals such as allophane and halloysite (Moon et al, 2015).

2.2 Lowlands

The Lowlands are the valleys between the Hamilton Hills that have been infilled with younger (late Quaternary, last 25,000 yrs) alluvial sediments of the Piako Subgroup. The Lowlands typically have a very gently tilting (south to north) topographic surface, known as the Hinuera Surface. Deposits underlying the surface are known as Hinuera Formation. Interfingering with the thick and often pumice rich sand beds are silt layers comprising silicic fragments (volcanic glass with limited weathering) as well as silty/sandy and occasionally organic alluvium.

3 LIQUEFACTION SUSCEPTIBILITY

3.1 Potential for Misclassification

A number of researchers have reported concerns with the use of liquefaction assessment procedures based on penetrometer testing in rhyolitic (or specifically pumiceous) soils as the structure, shape and composition of the sediment varies significantly from the more typical alluvial sediments derived from sedimentary rocks which form the basis for empirically derived liquefaction assessment tools.

Murashev et al (2014) stated in NZTA research Report 553 that conventional interpretation (i.e. penetrometer tests such as SPT and CPT) are less effective in assessing liquefaction resistance in pumice soils. Numerous researchers also have concluded that penetration tests can underestimate liquefaction resistance in pumice soils. Clayton et.al (2017), Murashev et al (2014), Clayton & Johnson (2013). Orense & Pender M. (2013)

The referenced works generally refer to the potential for underestimation of the relative densities and hence liquefaction resistance in rhyolitic soils. Should this be the case then it follows that there may be the potential for CPT tests to also misclassify such soils.

3.2 Assessment of Susceptibility

Soil response to earthquake shaking and hence liquefaction potential has been widely related to soil plasticity. Idriss and Boulanger (2006, 8, 14) suggests that all soils may be divided, based on their plasticity index into the following categories:

- Sand like* - soil that may be subject to classical cyclic liquefaction if sufficiently loose and;
- Clay like* - soil not subject to classical liquefaction, but may be subject to cyclic softening if sufficiently soft.

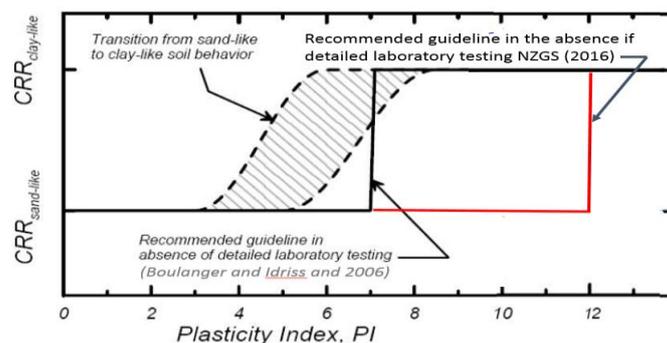


Figure 1: Sand-like & clay-like behaviour modified from Boulanger & Idriss (2006).

It is generally not viable for practitioners to directly determine the plasticity index and hence expected behaviour of every variation of soil within each profile, particularly in the complex interbedded sequences often encountered within the Hamilton Basin. Instead a correlation between the Cone Penetrometer Test (CPT) derived Soil Behaviour Index (I_c) and Plasticity Index (PI) is utilised to identify the soil susceptibility. The I_c value that corresponds to the boundary between sand like and clay like soil is termed the I_c cutoff, and typically assigned a value of 2.6, as originally proposed by Robertson and Wride (1998).

Idriss and Boulanger (2014) recommend site specific sampling and testing for major projects to evaluate the sensitivity of I_c cut-off in liquefaction assessments. The authors of this study concur, particularly within volcanically derived soils, as the correlations used have been originate primarily from testing soils derived from weathering and erosion of rocks (lithic soils).

Ideally the I_c cutoff would be established on a site and soil specific basis by undertaking side by side CPT testing (for I_c) and undisturbed sampling, with dynamic testing then undertaken on the undisturbed samples. However difficulties in obtaining truly undisturbed samples and the costs associated with undertaking the large number of tests necessary to generate a statistically valid site specific correlation are prohibitive even for substantial infrastructure projects.

An alternative is to undertake side by side CPT testing and disturbed sampling (for Atterberg testing). This approach allows the generation of a site specific I_c to PI correlation and validation (or correction) of the I_c Cutoff. In the Authors view this is particularly important in the volcanogenic soils of the Waikato and Bay of Plenty region as these soils can differ in their behaviour when subject to penetrometer tests compared to soils composed of hard lithic grains (Clayton & Johnson, 2013).

3.3 Assessment of Fines Content

Another necessary input to the liquefaction analysis is the fines content (FC). Liquefaction potential is noted to decrease with increasing fines content for a given penetration resistance, and this effect is accounted for by applying a fines correction factor. In a similar manner to the PI cut-off, correlation between fines content (FC) to CPT I_c is used to allow fines correction to be applied in analyses, without the need for closely spaced laboratory grading tests.

As noted above Rhyolitic soils may respond differently compared lithic soils and existing correlations may be less reliable. Idriss and Boulanger (2014) recommend the calibration of the fines correction curve fitting parameter CFC for any CPT-based liquefaction triggering evaluation. Calibration within the project has been achieved by undertaking paired CPT testing and borehole sampling across a wide range of soils followed by regressing I_c against FC.

4 IC CUT-OFF

4.1 Soil Behaviour Index, I_c Cut-off

Paired BH and CPT were undertaken and samples selected, specifically targeting soils of relatively consistent properties within the sample depth range and generally with an I_c in the range of 2.0 to 2.6 as this was expected to be the zone where the I_c cutoff was expected to occur.

Atterburg tests were undertaken on the selected samples and the representative I_c of the sample zone assessed. The resulting PI is then plotted against I_c and compare against the Robertson & Wride (1998) cut-off value of 2.6 and the (conservatively) adopted PI cutoff line of 12. Fig 2 below presents a plot of PI against I_c based on available laboratory testing results for all soils with the exception of Units 1a, 2b, 2d, 3b and 6 which were not sampled.

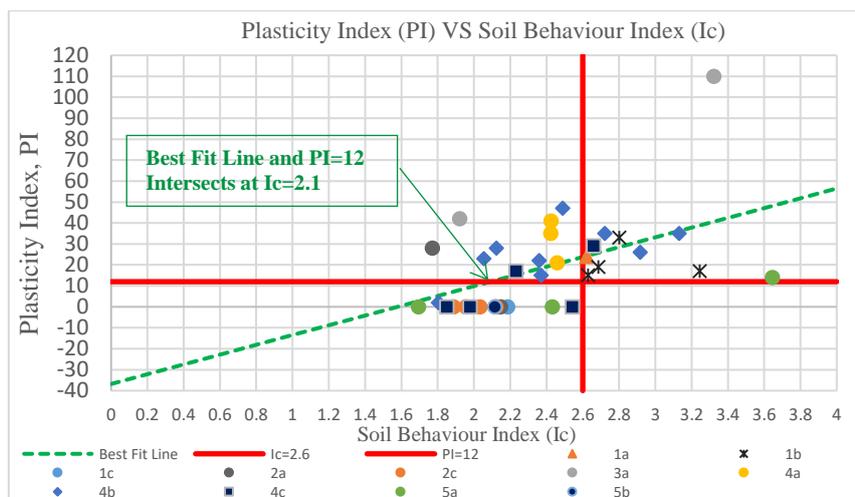


Figure 2: Plasticity Index (PI) VS Soil Behaviour Index (I_c) for all soils

In terms of design, in these soils the default I_c cutoff value of 2.6 appears conservative, compounding the already conservative adoption of an PI cutoff of 12 (refer fig 1). Considering the above results there is some justification to apply a revised I_c cutoff for all the soils encountered of 2.2, however the paucity of results for some units lead the authors to focus on deriving I_c for selected soils at this stage. During this stage of the project we chose to focus on Unit 4 which includes the Hamilton ash (a widely distributed and readily recognisable unit), associated tephra's and contemporaneous ignimbrite sands.

4.2 Individual Sub-unit Results

Figure 3 below presents the laboratory result for Hamilton Ash Formation, Tephra and Ignimbrite.

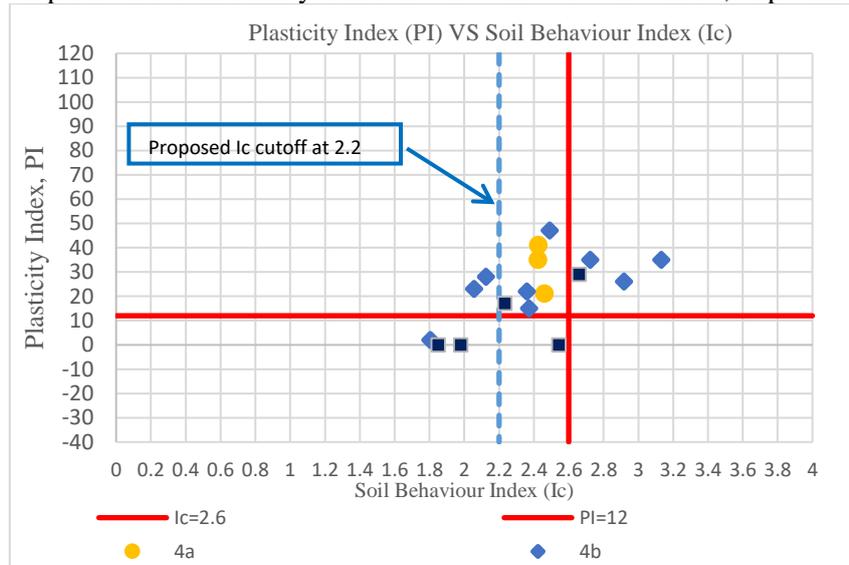


Figure 3: Plasticity Index (PI) VS Soil Behaviour Index (Ic) for Hamilton Ash (Unit 4A), Tephra (Unit 4B) & Ignimbrite (Unit 4C)

- Hamilton Ash (Unit 4A), based on PI result is clay-like and that it is not susceptible to liquefaction. However, CPT based assessment showed I_c less than 2.6.
- Tephra (Unit 4B), referring to Figure 3, most of the laboratory results for unit 4B typically have PI more than 12, while I_c is typically less than 2.6.
- Ignimbrite (Unit 4C), shows a mix of plasticity index and I_c .

4.3 Proposed I_c Cutoff

The combined results of tests undertaken in Unit 4 supported the adoption of an I_c cutoff of 2.2 for Hamilton Ash and associated tephra deposits within the project (refer fig 3). Following additional tests elsewhere in the Waikato/Bay of Plenty area it may be possible to apply this revised cutoff wherever these units occur.

5 FINES CORRECTION

The second correlation highlighted in this paper relates to the fines content assumed in liquefaction analyses based on correlation to I_c . Idriss and Boulanger (2014) recommend the calibration of the correlation by adjusting the fines correction curve fitting parameter CFC . CFC is calibrated to site specific data by regressing I_c against FC using the following equation: $I_c = [(FC+137) / 80] - CFC$.

5.1 Fines Correction, C_{FC}

Grading tests were undertaken to determine a Fines Content (FC) on the same samples as discussed in 2.1. The FC is then converted to an equivalent I_c value using the equation: $I_c = [(FC+137) / 80] - C_{FC}$. Initially I_c as determined from the CPT is compared against the equivalent I_c determined from FC. Where a mismatch is found, the curve fitting parameter C_{FC} is varied until a match is achieved. With the scatter of the results (I_c to FC has significant inherent scatter as noted below) and the general applicability of FC correction across all soils it was decided to derive a CFC for all soils, rather than attempting to define a CFC for individual units.

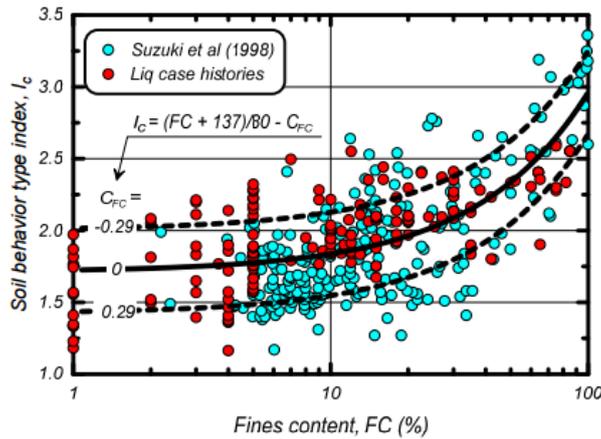


Figure 4: Recommended correlation between I_c and FC (Idris and Boulanger 2014)

5.2 Determination of Site Specific C_{FC}

Figure 6 shows a comparison between fines content (FC) from lab testing versus the estimated FC from CPT. Fig 7 utilises a CFC of zero (the nominal value) and the underestimation of fines content is clearly apparent.

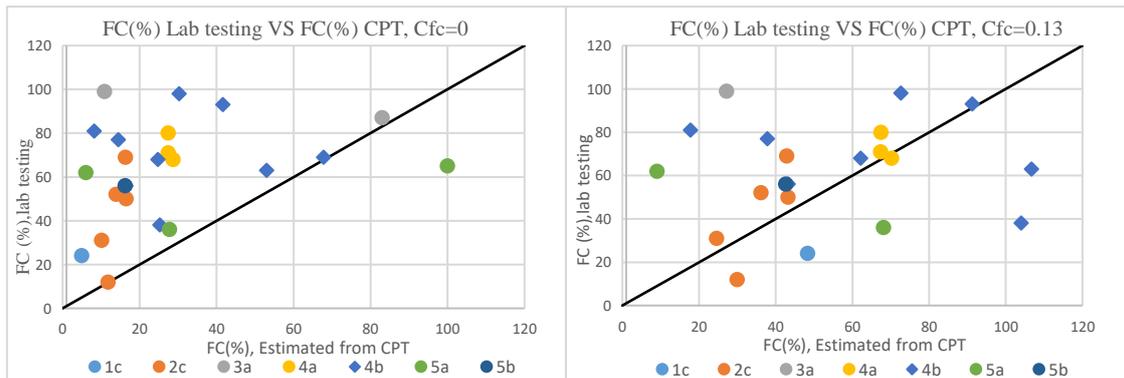


Figure 5 & Figure 6: Fines Content (Laboratory data) VS Fines Content Estimated Fines Content from CPT, $C_{FC}=0$, $C_{FC}=0.13$

Fig 6 Utilises a CFC of 0.13 for a much improved correlation. A site wide fines content correction factor (CFC) of 0.13 was therefore adopted for the project. The skew from the nominal correlation (of around half a standard deviation) is within the range suggested for sensitivity analysis by Idriss and Boulanger (2014). The application of the $C_{FC} = 0.13$ increases the fines content considered in liquefaction analysis resulting in a modest increase in FOS liq.

6 DISCUSSIONS

Liquefaction assessment using the Simplified Method requires the consideration of both susceptibility and triggering potential. There are significant unknowns relating to these two aspects for soils of rhyolitic origin. This aspect is discussed further in Clayton et al. (2017). Two aspects of the CPT based simplified method I_c/I_p and I_c/FC correlations are considered in detail.

Based on the I_c to PI plot in Fig 2, the use of an I_c cutoff of 2.6 appears (overly) conservative in many of the soils encountered in this investigation and that this leads to incorrect assumptions about the liquefaction potential of low plasticity weathered tephra/ash deposits. Sufficient testing was undertaken on the Hamilton section of the Waikato Expressway that the authors (and project designers) considered justified in reducing the I_c cutoff of selected soils. This led to a significant reduction in the inferred extent of liquefaction on the project.

The author's hypothesis is that the structure and grain composition of Rhyolitic volcanic soil common in this area of New Zealand result in a correlation between I_c and PI that differ from what might be found in soils composed of hard lithic grains. Ideally the refinement in the use of CPT testing for liquefaction assessment undertaken on this project could be extended in a number of other ways to avoid overly conservative assessment of liquefaction potential in such soils:

- Additional test data could be compiled from other paired investigation test points and laboratory testing within these units - which are present and readily recognised across much of the Waikato and Bay of Plenty. This data could be used to investigate if the lower I_c cutoff is applicable to these soils on other sites.
- Additional test data could be compiled and analysed for other soils of rhyolitic origin, for example in pumiceous alluvium and ignimbrites.
- Dynamic testing could be undertaken on undisturbed samples to examine the validity of the assumed PI cutoff in these soils to complete the connection between I_c and soil susceptibility.

In conjunction with testing and a revision of the I_c cutoff for liquefaction susceptibility the I_c to fines content correlation was reviewed. Adjustment of the curve fitting parameter C_{fc} to achieve a better match between measured and correlated fines content across the site has led to a site wide increase in fines correction and removal of unnecessary conservatism in the FOSliq. In a similar manner as for the I_c cutoff additional test data could be compiled from other paired investigation test points and laboratory testing within these soils that occur across much of the Waikato and Bay of Plenty. This data could be used to investigate if the site specific C_{fc} is applicable to these soils on other sites.

7 CONCLUSIONS

A number of paired CPT/BH investigations have been undertaken through a range of rhyolitic soils on the Hamilton Section of the Waikato Expressway, as part of the NZ Transport Agency's Waikato Expressway Project. Investigation points were paired to allow (among other things) the investigation of default CPT (I_c) to Fines Content (FC) and Plasticity Index (PI) correlations. Clear trends were identified which justified adopting a revised I_c cutoff of 2.2 for soil units related to the Hamilton Ash within the Hamilton Expressway project.

Further research is required to extend results among similar soils that commonly occur in the Waikato and Bay of Plenty. Further research is also suggested in reviewing the plasticity index (PI) cutoff used in liquefaction analysis to differentiate between sand like and clay like soil for rhyolitic soils.

A site specific fines content (FC) to soil behaviour index (I_c) curve fitting parameter (C_{fc}) was also derived for the project. A C_{fc} of 0.13 was derived by matching measured and correlated FC. The use of this site specific correction factor results in the removal of a source of unnecessary conservatism in liquefaction assessment on the project through a generally increased fines correction.

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