Case study in the use of shear wave velocity 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 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 saturated Pleistocene sandy alluvial soils. Conventional CPT/SPT penetration resistance based methods generally indicate a liquefaction potential for these soils that extends to considerable depth. Some researchers have however suggested that conventional penetrometer based methods may overestimate the liquefaction potential in these soils due to their age and pumice content. In recognition of this effect liquefaction assessment on this project has been undertaken utilising shear wave velocity as the primary indicator of liquefaction triggering and for the derivation of liquefied shear strength. Recognising the less well developed state of both the acquisition of shear wave data and the associated liquefaction assessment methodology the design team undertook a number of measures to validate data and approaches. Side by side downhole/crosshole tests provide the opportunity to consider the repeatability of Vs testing as well as side by side CPT, DMT and shear wave measurements (crosshole and downhole) as well as paleoliquefaction investigation (discussed in companion paper – Clayton et al,, (2017)) provide the opportunity to compare and contrast the liquefaction potential indicated by these various methods in these specific soils.

1 INTRODUCTION

The City Edge Alliance (The Alliance) has been commissioned to undertake detailed design for the 21.8 kilometre long Hamilton Section of the Waikato Expressway in 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 geomorphic region known as the Hamilton Lowlands which is characterised by late Pleistocene alluvial sandy deposits and a relatively high water table. Conventional penetrometer based liquefaction assessment within these soils indicate a liquefaction potential that extends to considerable depth, however recent research into the effect of aging and particle crushing suggest that the liquefaction risk may be overestimated by such methods. This paper compares the assessed liquefaction potential based on CPT, downhole and crosshole shear wave velocity methods. Measured to estimated velocity ratio (MEVR) is used to discuss possible reasons for the differences between liquefaction resistance indicated by penetrometer and Vs based methods in these soils.

2 BACKGROUND

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

2.1 Particle Crushing

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.

2.2 Age Effects

Over time granular soils tend to gain strength through a number of mechanisms. Creep between particles may lead to a denser state of packing and/or cementation may develop. A number of researchers (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 these comparatively weaker bonds may contribute to liquefaction resistance but may not be fully recognised by large strain penetrometer based methods leading to an underestimation of the liquefaction potential of older soils by penetrometer based methods.

2.3 Role of Shear Wave Based Liquefaction Assessment

Methods based on shear wave velocity have been suggested as being more appropriate for liquefaction assessment in the aged and/or pumiceous soils of the Waikato as 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, shear wave velocity based methods are not as well developed as penetrometer based methods and the project team had concerns about the reliability of shear wave velocity (Vs) measurement methods. To address concerns about the reliability of Vs measurement paired tests were undertaken at 10 locations along the route in a range of ground conditions including stiff silts/dense sands of the Piako Group and relatively loose sands of the Hinuera Formation utilising a number of different methods including crosshole, downhole true interval and (a lesser number of) downhole pseudo interval. Results were also compared to those of a paleoliquefaction study, which is the subject of a companion paper (Clayton et al., 2017)

3 GEOLOGY, GROUNDWATER AND SEISMICITY

Refer to companion paper (Clayton et al., 2017) for details of geology/soil conditions, ground water and seismicity within the study area.

4 METHODS OF ASSESSMENT

4.1 CPT Testing

Cone Penetrometer Tests (CPT) were regularly undertaken along the route with multiple tests at each bridge abutment. CPT were utilised to refine stratigraphy, inform saturation and groundwater level in highly permeable soils, and to provide correlation to fines content and soil behaviour index (Ic). The latter utilised specific correlations for some units (Wong & Clayton, 2017). Where paired testing was undertaken, using a combination of co-located CPT, seismic dilatometer (sDMT), Crosshole Seismic Tests (CST), these tests were undertaken around 2m apart in a triangular formation to avoid disturbance related effects.

4.2 Shear wave velocity

Shear wave velocity testing was undertaken utilising a variety of methods including seismic cone penetrometer (sCPT), sDMT & CST methods. For this study the sDMT tests utilised a true interval approach utilising two geophones/accelerometers located 0.5m apart and a surface source (sledgehammer striking timber sleeper). Stacking was undertaken where low signal to noise (S/N) ratio occurred. Internal validation was undertaken by comparing left hand and right hand polarised tests. Tests were typically undertaken at 0.5m intervals vertically. Direct-push crosshole tests (CST) (Wotherspoon et al., 2015) were also undertaken. A source and a receiver sensor were advanced separately into the ground to the same depth using standard CPT rods and two small-scale cone penetrometer rigs. At each depth testing was performed using a hammer impact source applied to the top of the source rod, with at least three separate tests performed at each depth and stacked to increase signal-to-noise ratio.

5 INTERPRETATION METHODOLOGY

The interpretation methodology adopted for this comparison is summarised below in Table 1

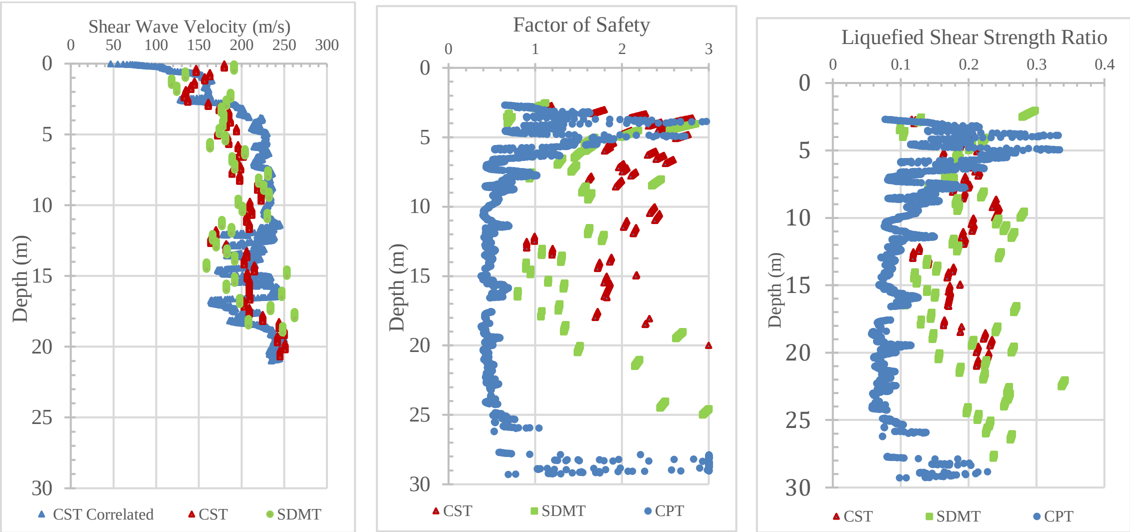
Table 1 interpretation methodology

Test Method	Methodology for susceptibility	Methodology for Triggering assessment	Methodology for Liquefied shear strength
CPT	Based on Ic with Ic cutoff calibrated to Atterburg tests on samples from paired borehole. Refer to Young and Clayton (2017).	Following approach published by Boulanger and Idriss (2014).Fines content correlated to Ic with calibration using laboratory grading tests on paired borehole samples.	Following approach published by Idriss and Boulanger (2014).
All Vs methods	Based on Ic from paired CPT with calibrated Ic Cutoff as per CPT based assessment.	Based on Kayen et al. (2013) Fines content correlated to Ic from paired CPT, calibrated as per CPT based assessment.	Based on Ozener (2012)

6 ANALYSIS RESULTS

6.1 Profile comparisons

Comparisons have been undertaken between different measured Vs profiles and Vs correlated to CPT qc. Refer example plot in Figure 1a. To illustrate the consequence of variations in Vs, liquefaction potential and liquefied shear strength have also been determined (sDMT & CST) utilising methodology published by researchers (Kayen et al. 2013) and (Ozener 2012). For comparison analysis direct from CPT (Idriss and Boulanger 2014) is also presented. Refer Figures 1b&c.



Figures 1a, 1b&1c: Plot of measured and estimated (correlated) shear wave velocity vs depth, FOSliq vs depth and liquefied shear strength vs depth.

6.2 Soil Unit Comparisons

A convenient way of identifying if particle crushing or aging effects (or other mechanisms affecting liquefaction potential) are present is through the use of measured Vs to estimated Vs as a velocity ratio (MEVR) (Andrus et al., 2009; Clayton & Johnson, 2013). Comparison has been undertaken by calculating MEVR using a ratio of Vs(CPT) correlated from CPT - Andrus and Stokoe (1994) and measured Vs, and then compiling the results from ten sites where side by side tests were undertaken, refer Fig 2a.

$$Vs \ = sqrt\ Gmax/mass\ density$$

Gmax = 1634(qc)^0.25(sigv')^0.375

Ratio have also been prepared for liquefaction factor of safety (FOSliq) based on CPT (FOSliq(CPT)) / FOSliq(Vs), refer fig 2b).

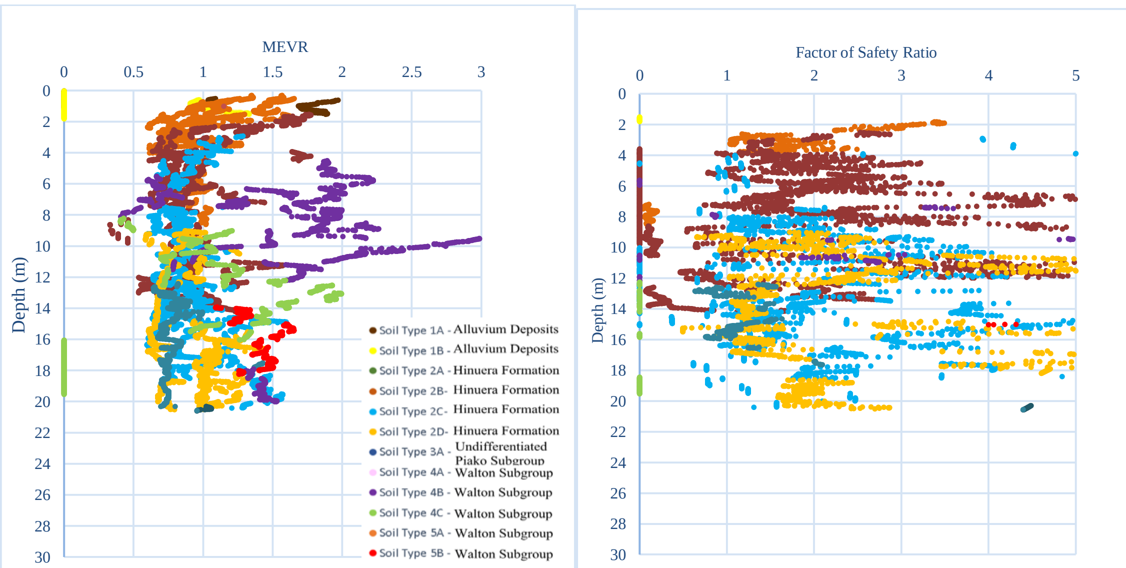


Figure 2a & 2b: Shear wave MEVR and FOSliq ratio vs Depth

In order to investigate the MEVR of soils which have different pumice contents and different age since deposition we have selected specific soil units for comparison:

- Hinuera Formation soils (Unit 2a-d) are relatively young (circa 26Ka) alluvial deposits that may contain a significant proportion of rhyolitic glass (pumice). Figure 3a presents MEVR vs depth for Hinuera Formation deposits.

- Walton Subgroup (sandy) soils (Unit 4c & 5b) are older (0.34 to 1.8Ma) alluvial and pyroclastic flow deposits. Figure 3b presents MEVR vs depth for selected (sandy) Walton Group deposits.

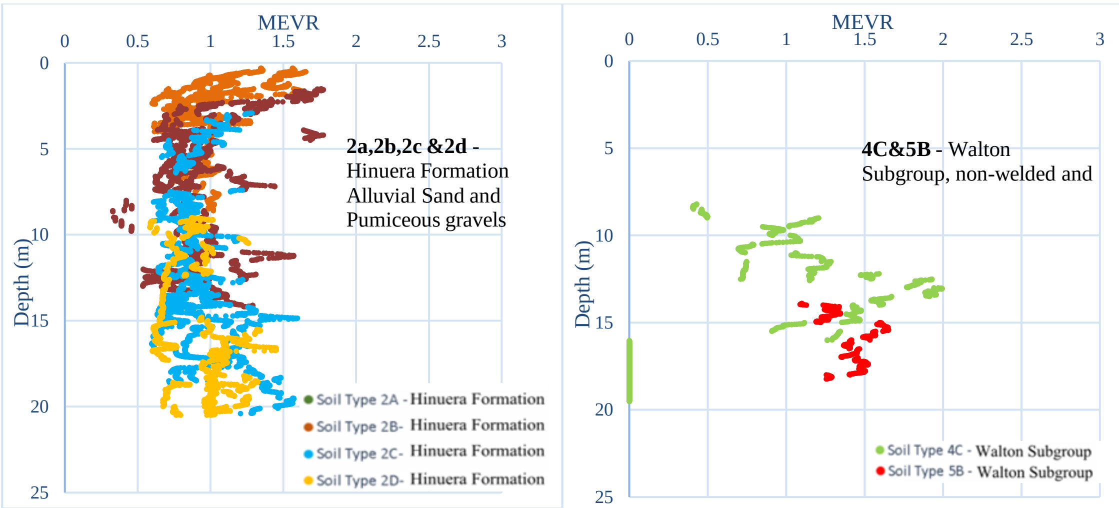


Figure 3a & 3b: Shear wave velocity MEVR vs Depth (selected soils)

7 DISCUSSION

7.1 Comparison of downhole and crosshole methods.

Comparisons have been undertaken of CST and sDMT measurements of Vs in a range of soil conditions. Test results were found to be generally consistent, with a reasonable agreement between methods. Within the majority of the soils, the ratio between Vs from CST and Vs from sDMT has a median of (0.87-0.98) indicating minimal bias and a comparatively small standard deviation (0.12-0.21). This finding supports the ongoing use of downhole methods for the determination of Vs for low-moderate risk projects on sites without complex stratigraphy, although the reliability of results should be evaluated and discrepancies further investigated or discarded in situations such as the following:

- Where paired polarised results or results of different analysis methods diverge significantly.

- Where results are benchmarked against other methods such as CPT and significant unexplainable discrepancies are identified.

Refer to further discussion on this subject in the paper by Wahab and Clayton (2017).

7.2 Comparison of FOSliq and SUliq

Comparisons have been undertaken between CST, sDMT and CPT for FOSliq and Suliq for each of the paired test locations.

7.2.1 Comparisons between CST, sDMT and CPT for FOSliq

The following general observations can be made:

- The variation between FOSliq between CST, sDMT & CPT is greater than the variation in Vs noted in 6.1. This can be attributed to the nonlinearity of CRR with respect to Vs, particularly at higher Vs.

- There appears to be a mismatch between the correlated Vs from CPT and the calculated FOSliq. Where MEVR =1, FOSliq from Vs is > FOSliq from CPT.

7.2.2 Comparisons between CST, sDMT and CPT for Suliq.

The following general observations can be made:

- The variation in Suliq between CST, sDMT & CPT is relatively small in comparison to for FOSliq, although in the case presented many of the data points derived from Vs would be irrelevant form an engineering point of view as FOSliq>1.0

7.3 Comparison between Vs and CPT

Comparisons have also been undertaken to investigate how variations between measured and correlated Vs (MEVR) vary between soil types, possible explanations for this variance are provided.

7.3.1 Hinuera Formation MEVR

Fig 2a presents MEVR from CST and CPT vs depth. The MEVR plot shows three zones:

An upper zone (surface to 3m) where the MEVR is in the range of 0.8 to 1.5. This appears to indicate the presence of a consistent ‘crust’ of high velocity material not recognised by the CPT. This zone, potentially significant for the design of lightweight structures may result from a number of possible mechanisms including negative pore pressure in the capillary zone or weak cementation e.g. ‘limonite’ in aerobic zone.

An intermediate zone where the MEVR remains relatively constant at around 0.8 to 0.9. A MEVR of 1.0 indicates an ideal Vs to CPTqc correlation, however with the correlation used in this study (reference) the MEVR of young, shallow sandy soil deposits typically yield a MEVR in the 0.8 to 0.9 range and in fact a MEVR ratio in these soils (and for the correlation used) of 0.8 to 0.9 corresponds to a FOSliq ratio of around 1.

A deeper zone (10m to 20m) where the MEVR increases from around 0.9 to 1.5. The high MEVR in this zone may result from a number of possible mechanisms including:

- Particle crushing during CPT probing. Noting that crushing is more likely under greater confinement at depth.
- Older deposits at depth. Considered less likely as the Hinuera formation deposits are relatively young and were emplaced relatively rapidly with deeper deposits not significantly older.

7.3.2 Walton Subgroup MEVR.

Fig 3b presents MEVR from CST and CPT vs depth. The MEVR plot shows a range of 0.7 to 2.0 throughout but typically between 1.2 and 1.7. This relatively high MEVR may result from a number of possible mechanisms including:

- Aging effects - The Walton Subgroup has an age of 0.34 to1.8Ma. Based on Andrus et al, (2009) this age might be expected to correlate to a MEVR of approximately 1.35 to 1.45 which is comparable to that observed.

- Particle crushing – Pumice is present within soil units 4C and 5B, but in no higher concentrations that the Hinuera Unit 2 deposits discussed in 6.3.1 above, but which show a significantly lower MEVR.

8 CONCLUSIONS

As part of the geotechnical investigation for the Hamilton section of the Waikato Expressway a number of co-located crosshole (CST) and downhole (sDMT) shear wave velocity tests were undertaken. The CST were undertaken to support the adoption of shear wave velocity based liquefaction potential and liquefied shear strength assessment in the commonly pumiceous soils present along the alignment. A paleoliquefaction study was also undertaken as part of the validation of this approach, this study is documented separately in a companion paper. Having ten co-located sets of CPT, CST & sDMT provided an opportunity to undertake a number of comparisons. Initially we compared crosshole and downhole tests and found that results were generally in good agreement which supports the ongoing use of downhole test methods for low to moderate risk projects. The study then compared the Vs data from the CST to correlated Vs from the co-located CPT, generating MEVR (measured to estimated velocity ratio) for individual soil layers. Interpretation of the MEVR within the pumiceous comparatively young (circa 26ka) Hinuera Formation has lead to the following conclusions:

- Within the Hinuera formation there appears to be a near surface zone or crust with elevated MEVR. This zone is unlikely to differ significantly in composition from underlying soils, partial crushing is therefore unlikely and the theory of superposition rules out aging effects. Postulated causes include weak cementation (e.g. limonite) related to unsaturated weathering or negative pore pressure within the partially saturated zone.

- Below the near surface zone to a depth of around 10m MEVR is low suggesting that particle crushing or aging effects are negligible in this zone. FOSliq by Vs and CPT are similar in this zone.

- Below a depth of around 10m MEVR increases. A possible explanation of this observation is particle crushing increasing with the level of confinement. The age difference between mid and lower Hinuera formation is considered unlikely to justify the observed increase in MEVR.

The apparent potential for particle crushing at greater depths supports the use of shear wave velocity based liquefaction assessment in these soils. The high MEVR within the significantly older Walton Subgroup (0.34 to 1.8Ma) supports a conclusion that aging effects may be significant for these soils and that the use of either an age correction factor with penetrometer methods or where suitable data is available, direct shear wave velocity based liquefaction assessment.

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