Liquefaction resistance and possible aging effects in selected Pleistocene soils of the Upper North Island

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ABSTRACT

The assessment of a soil’s liquefaction potential can often have major financial implication for infrastructure projects. An overly conservative assessment can lead to unnecessary expenditure on foundations or ground improvement.

The assessment of liquefaction potential in recent deposits of alluvial soils with grains of lithic origin is becoming increasingly well defined, however where older soils or soils of volcanic origin are analysed, the level of uncertainty is higher. It has been suggested that comparison of liquefaction analysis based on the most commonly applied investigation methods e.g. Standard Penetrometer and Cone Penetrometer Tests against smaller strain methods e.g. Shear Wave Velocity might provide useful evidence of aging, cementation or particle crushing effects in some soils.

We have sought evidence of such effects by comparing liquefaction potential of soils of Recent and Pleistocene age and/or volcanic origin at sites in the Waikato Region using large and small strain methods. Our analyses, utilising a small strain method, indicated a higher liquefaction resistance than large strain tests in a selection of the Early Holocene and Late Pleistocene soils.

1 INTRODUCTION

A number of significant infrastructure projects are in progress or have recently been completed within the Waikato region of the upper North Island of New Zealand. This area is characterised by a comparatively low seismicity, and significant deposits of Early Holocene and Late Pleistocene deposits of tephra and volcanogenic alluvium. Despite an age of >10,000 years, insitu testing of these materials often indicates a relatively loose state. Consequently, where saturated, conventional liquefaction assessment methods typically indicate a significant liquefaction potential. This appears inconsistent with the liquefaction risk indicated by screening tools such as that proposed by researchers Youd and Perkins (1978).

A number of authors have suggested that the application of conventional investigation and liquefaction assessment tools may be inappropriate in such soils for the following reasons:

- Such volcanogenic soils may contain a high proportion of crushable particles e.g. Pumice, such that large strain test methods may underestimate their resistance to cyclic stress Marks (1998) and Wesley (1998) Orense et.al (2012).
Soils in a low seismicity area may, over long periods of time may develop a degree of cementation that improves their resistance to cyclic stress but is not fully recognised by a large strain test, Hayati and Andrus (2009).

In order to investigate these potential effects within commonly encountered soils in the Waikato region we have compared data gathered on two recent infrastructure projects in the Waikato region utilising large strain conventional penetrometer (CPT) and small strain Seismic Cone Penetrometer (SCPT) methods. Initially we carried out liquefaction analysis on the data and compared the derived liquefaction risk. From these analyses we noted a trend of lesser liquefaction risk predicted by small strain methods compared to large strain methods, suggestive of aging or particle crushing effects. In order to evaluate these effects we have first carried out a visual assessment of crushable grain (pumice) content and then compared the age implied by this trend through the use of age to Measured to Estimated (shear wave) Velcity Ratio (MEVR) correlations proposed by Hayati and Andrus (2009). The resulting conclusions regarding liquefaction risk are compared against that indicated by the screening tool proposed by Youd and Perkins (1978).

2 GEOLOGY AND SEISMICITY OF THE STUDY AREA

2.1 Geologic Setting

The Waikato area encompasses a wide variety of Geologic Terranes including Palaeozoic and Mesozoic bedrock, Tertiary volcanics and sedimentary units and Quaternary volcanics, tephra and alluvial deposits. The study area is within the Hamilton Lowlands, a part of the Waikato area which consist of a large depression formed in between uplifted basement hills to the west (Western Uplands) and east (the Central Hills – separating the Hamilton and Hauraki Basins). The Basin records a history of infilling and subsequent erosion/reworking of many volcanic airfall and pyroclastic deposits from the Taupo / Coromandel Volcanic Zone by the Waikato / Waipa river system McCraw (2011).

The geological units represented in investigations considered in this study can be described as follows, Edbrooke (2005), Lowe (2008):

- Post Oruanui Ash and Alluvial Deposits including Taupo Pumice Formation and Recent alluvium/colluvium (17ka to present). Not considered in this study.
- Hinuera Formation (Late Quaternary, two phases 50 to 27ka, and 27 to 17ka) and Volcanic Airfall Deposits (61 to 21ka) The Hinuera Formation typically comprises cross bedded sands/ gravels and silty sands.
- Walton Subgroup – Within the study area comprising Puketoka Formation (Late Pliocene to middle Quaternary, 1.8 Million Ma) to 340,000 (340ka)) The Puketoka Formation comprises interfingering lenses of primary (ignimbrite – unwelded in the study area) and reworked rhyolitic sand/gravelly sand and silt.

Fig 1: Location of Study Area
2.2 Tectonic Setting

According to national seismic hazard model developed by Stirling et al. (2000) the Hamilton Lowlands are located in a Normal Faulting Seismotectonic Zone. Based on NZS1170.5:2004 the study area has a seismic Hazard Factor (Z = 0.18) approximately 140% of Auckland and 45% of Wellington ie a low to moderate ground shaking hazard.

3 SITE INVESTIGATION

Each of the sites considered in this study have been investigated utilising both conventional large strain testing comprising Cone Penetrometer (CPT) and small strain tests comprising shear wave velocity measurements carried out downhole concurrent with CPT testing through the use of a seismic cone penetrrometer (SCPT) test methods.

4 CASE STUDY SITES

4.1 Site 1 Unnamed Near Cambridge

This site near to the town of Cambridge is underlain by a shallow ‘cap’ of alluvium/tephra around 1-2m deep (Post Oruanui), then underlain by sandy/gravelly Hinuera Fm, in turn underlain at a depth of around 22 to 30m by Walton SGp silts/sands/unwelded ignimbrite.

4.2 Site 2 Waikato Expressway

Data from this project was collated from a number of sites, in particular the Tamahere, Cambridge and Ngaruawahia sections. Varying thicknesses of Hinuera Formation, underlain by Walton Subgroup are found along the alignment that extends from north of Hamilton to South of Cambridge.

![Fig 2 – Example Insitu Testing Results](image-url)
5 LIQUEFACTION ANALYSIS

5.1 Assessment based on depositional environment and age

Youd and Perkins (1978) prepared qualitative estimates of liquefaction susceptibility of soils by age of deposit based on field observations following earthquakes. According to their assessment, deposits < 500 years old generally have high to very high susceptibility. For older deposits, the susceptibility to liquefaction is generally moderate to high for Holocene age (< 10,000 years) sediments, very low to low for Pleistocene age (10,000 to 1.8 million years) sediments. An initial assessment of liquefaction potential of the soils encountered in this study has been performed utilising inferred depositional environment and published age of the deposits. The indicated liquefaction resistance is presented in Table 1.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Inferred age of deposit</th>
<th>Depositional Environment</th>
<th>Liquefaction risk based on SCDOT method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holocene Alluvium (Post Oruanui Ash)</td>
<td>&lt;17ka</td>
<td>River channel and Floodplain</td>
<td>Very high to moderate (however unsaturated in study area)</td>
</tr>
<tr>
<td>Hinuera Fm</td>
<td>21Ka to 61Ka</td>
<td>Floodplain and Alluvial fan</td>
<td>Low</td>
</tr>
<tr>
<td>Walton SGp</td>
<td>340Ka to 1.8Ma</td>
<td>River channel and Floodplain</td>
<td>Low to very low</td>
</tr>
</tbody>
</table>

Based on the above assessment soils of the Hinuera Fm and Walton SGp could be generally expected to have a low susceptibility to liquefaction.

5.2 Comparison of Semi Empirical Liquefaction Assessments

**Assessment based on large strain testing**

Analysis of liquefaction potential utilising 9 sets of CPT data was been carried out in accordance with the recommendations of researchers Idriss and Boulanger as published in EERI MNO-12 (2008). Fig 2 presents a plot of FOS vs depth for an example test location within Walton SGp soils (Hinuera absent at this location, Recent soils (top 6m) not shown for clarity

**Assessment based on small strain testing**

Analysis of liquefaction potential based on 9 corresponding sets of SCPT data has been carried out in accordance with the recommendations of Youd and Idriss (2001) after Andrus and Stokoe (2000) who set a limiting upper value of Vs1 for cyclic liquefaction at 215 m/s for sands with fines content of up to 5%. Within this plot, and typically within other profiles analysed the normalised shear wave velocity is greater than the reference value (200-215 m/s depending on fines content) as indicated by arrowhead.

Fig 3 – Example plots of FOSliq
6 DISCUSSION

The resistance of soils to cyclic shaking as experienced during an earthquake is commonly expressed as the Cyclic Resistance Ratio, CRR. Typically in engineering practice the CRR is estimated using the simplified procedure as proposed by Seed and Idriss (1971). The simplified procedure uses semi-empirical relationships for the CRR as a function of either the standard penetration test (SPT) ‘N’ value, the cone penetration test (CPT) qc, or the shear-wave velocity (Vs). A limitation of this approach is that the relationships are largely based on observed behavior of soils deposited < 3,000 years ago, Andrus et al. (2009). A further limitation of this approach is that the strains involved in the in-situ tests do not match that of the earthquake ground shaking causing liquefaction. SPT and CPT tests involve significantly higher levels of strain than earthquake shaking and pore pressure build up. Age related effects such as particle interlocking and bonding exist in the medium strain range; Hayati and Andrus (2008) and therefore may affect liquefaction resistance and shear wave velocity but not necessarily penetration resistance. Similarly it has been suggested that while pumice soils may exhibit similar medium strain properties to quartzose soils, Marks et al. (1998), large strain tests may underestimate soil strength (and hence liquefaction resistance) in soil containing a significant proportion of particles of low crushing resistance such as pumice; Wesley et al. (1998).

6.1 Pumice Effects

The studies carried out to date on the liquefaction potential of pumice soils appear to have been carried out on soils with high concentration of crushable pumice particles. Testing carried out by researchers Marks (1998) and Wesley (1998) have been carried out on refined sands with near to 100% pumice particle content (Puni Sand). Based on visual logging of recovered samples the Hinuera Fm and Walton SGp, appear to have relatively low pumice concentrations at these sites and pumice effects are considered minor for the test results considered.

6.2 Aging Effects

A number of researchers have observed that liquefaction potential tended to decrease as age increased. Based on their observations the liquefaction susceptibility of sediments placed in the last hundred years are more susceptible to liquefaction than early Holocene sediments, that Pleistocene sediments are significantly more resistant. Pre-Pleistocene sediments are considered to present a low liquefaction risk. Various relationships to account for soil aging have been suggested e.g. Leon et al., (2006), Monaco and Schmertmann (2007), Monaco and Marchetti, (2007) or Hayati and Andrus, (2009). The method proposed by Hayati and Andrus (2009) recognising that the divergence of large and small strain testing, represented as a Measured to Estimated (shear wave) Velocity Ratio (MEVR), is indicative of increasing ‘aging’ effects. This can be used to develop an age related liquefaction resistance factor (KDR) and an estimate of age in years.

Fig 4: MEVR, K_{DR} & Age (y)
Hayati and Andrus evaluated both laboratory and field correlations of with MEVR and recommended the following:

\[ K_{DR} = 1.08 \text{ MEVR} - 0.08 \quad (1) \]

They also suggested the following correlations of age \((t)\) in years with MEVR

\[ \text{MEVR} = 0.082 \log(t) + 0.935 \quad (2) \]

An example plot of MEVR, KDR and age is presented in Fig 4, Recent soils are not shown for clarity.

### 6.2 Calculation of KDR

While there is significant scatter in the MEVR between sites and within each layer a consistent pattern emerges of MEVR (and hence a \(K_{DR}\)) of greater than 1.0, potentially indicating a consistent aging effect. Analysis of the distribution of KDR values (plotted here normalized to allow comparison of Hinuera Fm and Walton SGp) indicates a \(K_{DR}\) value for both of around 1.3 to 1.4.

**Fig 5: Plot of Normalised \(K_{DR}\)**

### 6.3 Comparison of isotope and estimated age

In order to evaluate the \(K_{DR}\) estimated using the MEVR we have compared the indicated age to that established by Isotope testing as part of previous studies of the Hinuera Fm and Walton SGp Edbrooke (2005). The inferred age of the deposits are compared to isotope derived age in Fig 6.
Liquefaction resistance and possible aging effects in selected Pleistocene soils of the Upper North Island

In general the ages inferred from the MEVR correlation are generally less than that indicated from Isotope testing. The distribution of age indicated for the Hinuera Fm based on the MEVR method correlates moderately well with that determined by isotope testing, however the age indicated for the Walton SGp is generally significantly less than both the Isotope testing and that inferred from MEVR analysis for the Hinuera Fm. It is possible that the ages determined by correlation to MEVR may be less than that inferred by Isotope testing due to ‘resetting’ of the aging process in past liquefaction events.

7 CONCLUSIONS

A discrepancy was noted between liquefaction resistance determined using semi empirical methods based on large strain (CPT) testing and that determined using small strain Shear Wave Velocity (SCPT) based testing within soils of the Hinuera Fm and Walton SGp at two sites within the Waikato region.

A number of researchers have suggested that penetrometer tests i.e. large strain tests may underestimate soil strength (and hence liquefaction resistance) in soil containing high pumice content. This factor is considered unlikely to be relevant as these deposits, at the sites discussed, have relatively low pumice contents.

An alternative and in the authors opinion, more likely explanation, relates to the potential for particle interlocking and bonding to develop over time that are not discernable by large strain testing, but may be measured by small strain shear wave velocity testing. This aspect is of interest to the geotechnical designer as this effect may lead to unnecessary conservatism in the assessment of liquefaction risk.

In order to evaluate the potential for age related increased liquefaction resistance in soils at the test sites Measured to Estimated Velocity Ratios (MEVR) were used to estimate Age related liquefaction resistance factor $K_{DR}$ and infer an age since deposition.

While there is significant scatter in the data, our analyses appear to indicate age related liquefaction resistance within some Waikato soils. Based on analysis of MEVR a $K_{DR}$ value of around 1.3 to 1.4 appears potentially applicable for some Hinuera Fm and Walton SGp soils. Should this value be applied in analysis, the liquefaction potential of these soils will tend to increase to values more consistent with the liquefaction resistance suggested by the screening tools such as that proposed by Youd and Perkins (1978).
REFERENCES


