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Liquefaction Susceptibility of Pleistocene Aged Wellington Alluvium Silt

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ABSTRACT

The Arras Tunnel on Buckle Street, Wellington, New Zealand, passes through Pleistocene aged alluvium and colluvium deposits, simply termed Wellington Alluvium. A significant portion of the deposit is silt, with a soil behaviour index I_c between 2.1 and 2.6. CPT procedures for sand-like behaviour indicate the likelihood of significant liquefaction in the 1855 Wairarapa earthquake but for which there is no evidence on site. Sampling and laboratory plasticity testing indicates that soil layers with fines contents as low as 35 % meet the criteria for clay-like procedures. These indicate significantly less susceptible layers closer to the historic performance in 1855 and distinguish a decrease in susceptibility with depth that CPT did not show. This case study highlights the need to support CPT with an appropriate sampling and laboratory testing regime for moisture content, liquid limit and plasticity index, particularly in the Wellington alluvium when the fines content is greater than 35 % and at lower fines content if plasticity is likely.

Introduction

The Arras Tunnel on Buckle Street, Wellington, New Zealand, passes through Pleistocene aged alluvium and colluvium deposits, simply termed Wellington Alluvium. The alluvium deposit consists of interbedded gravel, sand and predominantly silt layers ranging from a few hundred millimeters to multiple meters thick. It is the assessment of the liquefaction susceptibility of these silt layers that is the focus of this paper. Design and construction of the tunnel, which is a cut and cover underpass structure, and investigation around the neighboring Basin Reserve enabled characterisation of the silt and historic performance of the site in the 1855 Wairarapa earthquake.

Figure 1 is a map of the general area of the site, showing geological and topographical features discussed. Across the site the Pleistocene alluvium deposit sits directly on the basement rock. Between Taranaki Street and the historic Buckle Street slope (approximately Sussex Street) the Pleistocene alluvium extends to the surface, except in the center of the Tunnel where the end of the rock ridge splits the deposit. At the Basin Reserve the same Pleistocene alluvium deposit has been cut down by stream and sea ingress and a thickness of Holocene marginal marine deposits sit over top. By 1855 the combination of regional uplift and this cut down process had formed a slope of 10 to 15 degrees, 7 to 8 m high, the toe of which is adjacent to what is now Cambridge Terrace. The stability of this slope in the 1855 earthquake provides a historical basis for the assessment of liquefaction susceptibility of the silt material, which makes up the majority of the deposit.

In 1855 the Wairarapa Earthquake shook Wellington. It was felt with a Modified Mercalli Intensity of 9 (Grapes & Downes, 1997). The epicenter of this earthquake was 35 km from the

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site. It had an estimated magnitude of 8.2 or greater (Little & Rodgers, 2005) and the duration of shaking is reported at 50 seconds (Grapes & Downes, 1997). Wellington was in the early stages of European settlement with widespread liquefaction around the region noted (Grapes & Downes, 1997), however, not at the site.

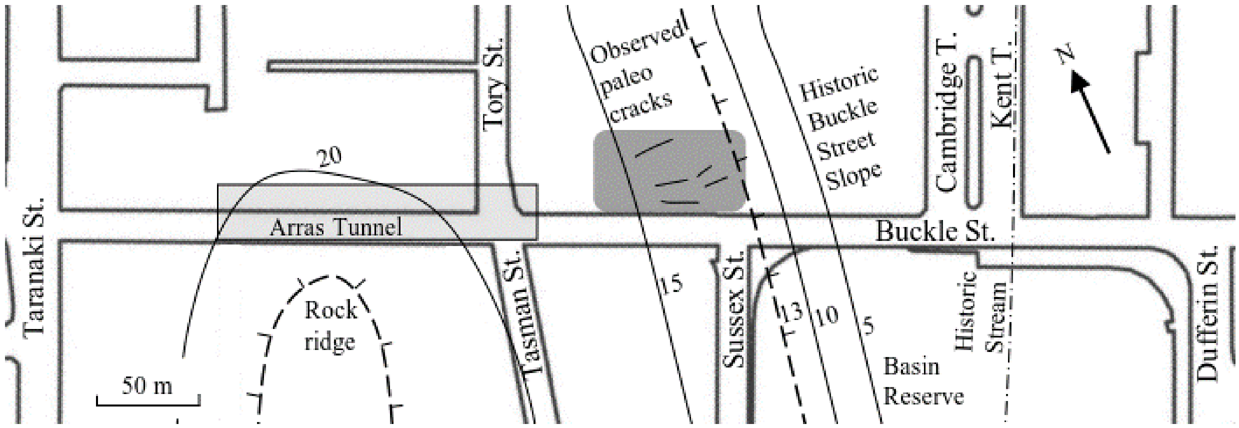

Figure 1. Map of site showing key features discussed

1855 Wairarapa Earthquake

Historic Evidence of Liquefaction

The ground at the site was extensively exposed through surface clearing, investigation test pits, bulk excavation and cuts. Laterally extensive cracks indicative of a paleo lateral displacement were exposed at the east end of the Arras Tunnel. These extend to 3 to 4 m depth. Carbon dating indicates the cracks are 5,000 to 8,000 years old (Grose et al., 2015) and the upper soil layers, which the cracks exist in, are 10,000 years old at the surface to 46,000 years old at 3 to 4 m depth. The age of the cracks indicate they are not as a result of the 1855 Wairarapa earthquake 160 years ago.

The orientation of the cracking indicates movement on a north south axis, not towards the free face of the Buckle Street slope. Exposure of the Buckle Street slope by cut indicates no deeper instability in the 1855 earthquake. The slope and its founding layers are the silty soils typical of the Pleistocene alluvium. The groundwater generally follows the topography, approximately 3 to 4 m depth beneath the surface upslope of the crest and 1 to 2 m at the slope toe. Before the 1855 earthquake the site was 1.5 m lower, uplifted by tectonic related regional movement during the earthquake. The toe of the Buckle Street slope was low lying and swampy with a stream running through the Basin Reserve (Basting, 1936). Artesian groundwater pressures exist beneath the Basin Reserve and the Buckle Street slope. In 1855 saturation to at least the level of the slope toe was likely. Significant liquefaction is unlikely to have occurred in this material in 1855 without notable instability of the Buckle Street slope.

CPT Investigation

Extensive investigation of the site was made using cone penetration testing (CPT). Figure 2 shows a typical CPT profile (CPT 37) through the middle of the Buckle Street slope. A significant portion of the soil profile has a soil behaviour index I_c, defined by Robertson and Wride (1998), between 2.1 and 2.6. Assessment of liquefaction using the CPT procedure Boulanger & Idriss (2014) indicates a significant portion of the silt layers liquefied in the 1855 earthquake. This is contrary to the historic observations on the site.

For the assessment a peak ground acceleration of 0.5g and magnitude 8.2 was applied to represent the 1855 earthquake. The thickness of liquefaction is sensitive to the variation of the I_c filter value for clay-like behaviour, as shown by the graphic plots of liquefaction in Figure 2 for different filter values 2.6, 2.4 and 2.2. Figure 3a indicates this sensitivity plotting cumulative liquefaction thickness with variation of I_c filter value, normalised by the thickness at the filter value 2.6. Four other CPTs to a similar depth of approximately 15 m are also shown for comparison across the site. For CPT 37, at an I_c filter value of 2.35 liquefaction thickness is halved and by 2.2 it is quartered. This shows that the filter value is critical at this site when using CPT procedures for liquefaction assessment.

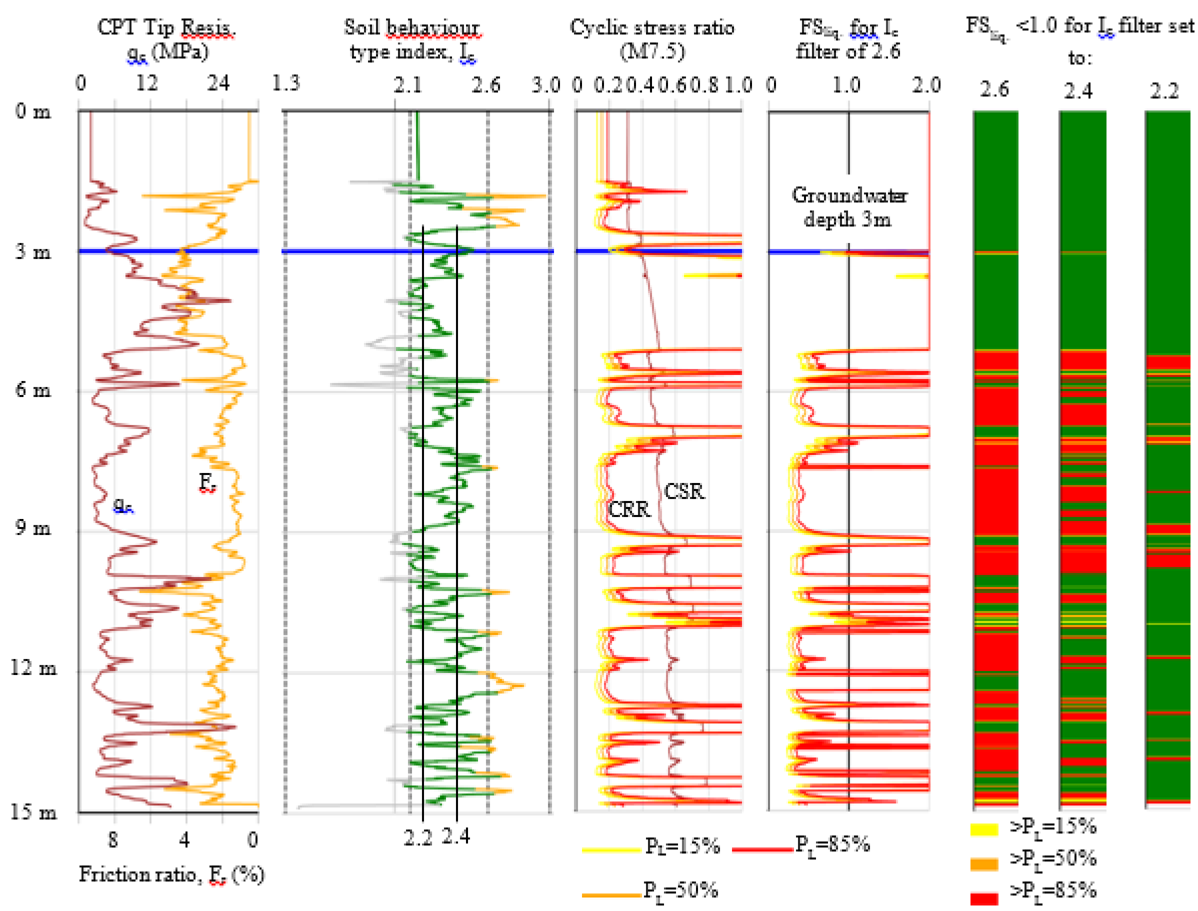

Figure 2. CPT 37 assessed using the Boulanger & Idriss (2014) procedure, run for M8.2 and PGA = 0.5g, C_{FC} = 0.29

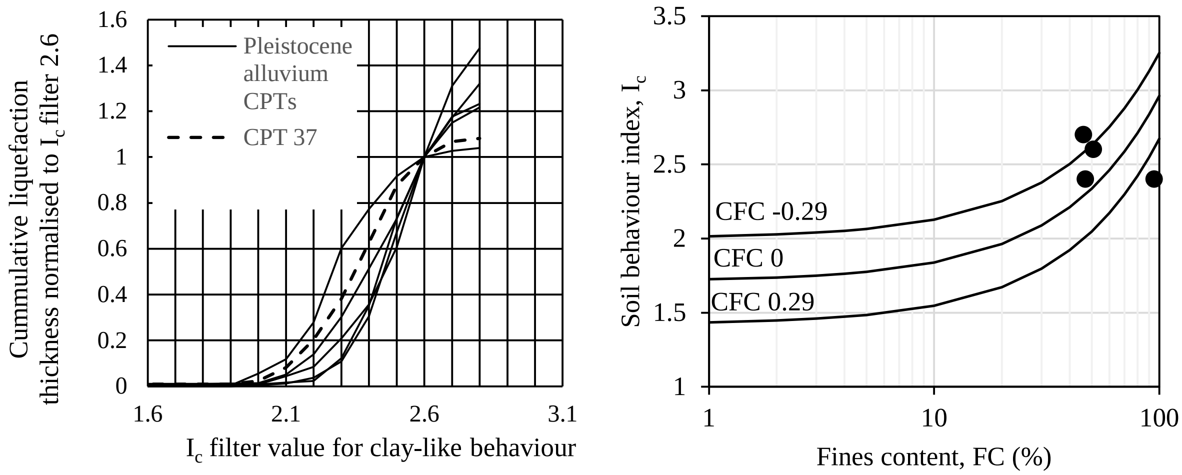

Figure 3. a) Normalised cumulative thickness of liquefaction with I_c filter for clay-like behaviour, b) I_c to fines content relationships with C_{FC} curve fitting parameter showing borehole samples adjacent to CPT

The curve fitting parameter C_{FC} for the relationship of I_c to fines content is defined by Boulanger and Idriss (2014). A C_{FC} of 0.29 was used in this case study to apply a higher fines content and therefore higher correction to clean sand cyclic resistance ratio (CRR_{cs}). While this was used there was no discernable C_{FC} value for the deposit when compared to laboratory samples as shown in Figure 3b, where adjacent borehole samples and CPT existed.

Plasticity Testing for the Screening of Clay-like Behaviour

Instead of using I_c, screening criteria for sand-like and clay-like behaviour using Plasticity Index (PI) are provided by Boulanger & Idriss (2006) for soils with fines content greater than 50 %, and in certain cases slightly lower fines content. They indicate "For many soils, it is likely that the fines fraction forms the load carrying matrix when the fines fraction exceeds roughly 35 %..."

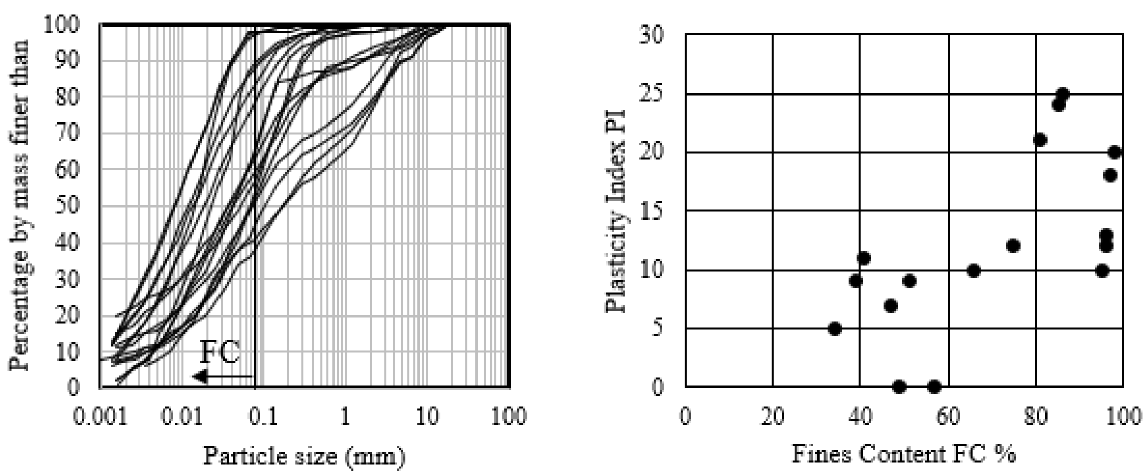

Figure 4. a) Particle size distribution of samples, b) Plasticity index samples with fines content

Particle size distribution of the samples from across the site, in Figure 4a, indicate that the fines content (FC) as the percentage particles passing 0.075 mm, is typically between 35 and 100 %. The fine fraction is such that it is likely to control the liquefaction behaviour.

Boulanger & Idriss (2006) criteria for screening clay-like behaviour is PI ≥ 7, or PI ≥ 5 when classified as low-plasticity clay/silt (CL-ML zone on Casagrande plot, Figure 5a). There is a notable clay fraction, with between 5 and 40 % passing 0.005 mm contributing to plastic soil behaviour. Figure 4b shows PI with fines content, indicating a general increasing in plasticity with fines content. Samples with fines content as low as 35 % are shown to have a PI ≥ 5.

The sample PI values are plotted on the Casagrande plasticity chart, with their Liquid Limit (LL) in Figure 5a. Only 2 of the 29 samples plot below PI = 5, with most well above 7, indicating the silty materials in the deposit is best assessed using clay-like behaviour based procedures.

One borehole and CPT were adjacent to each other (~ 1 m apart). This allowed 3 samples with PI to be compared to CPT I_c. The results are plotted on Figure 5b. This shows an I_c = 2.4 to 2.6 measured was for a material with PI = 9 to 12. Given this and specifically that at an I_c of 2.4 the material had a PI = 10, it is possible for I_c readings less than 2.4 to have a PI greater than criteria indicating clay-like behaviour.

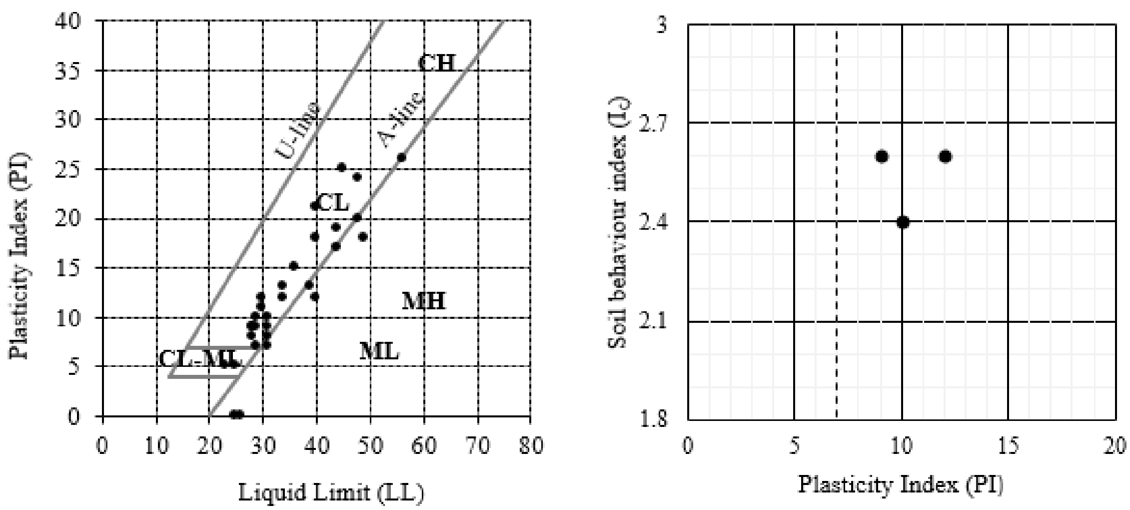

Figure 5. a) Samples located on Casagrande plasticity chart, b) I_c and PI pairs

Clay-like Susceptibility Criteria

Bray & Sancio (2006) provide liquefaction susceptibility criteria for assessment of fine grained soils as illustrated in Figure 6. This includes those soils meeting the clay-like behaviour criteria by Boulanger and Idriss (2006). Samples having PI, water content (wc) and LL are plotted against this criteria. Samples sit across all three assessments: susceptible, moderately susceptible and non-susceptible. Figure 7 shows the samples plotted with depth against the various susceptibility criteria. This indicates that with depth wc/LL limit decreases and PI increases, demonstrating a decrease in susceptibility with depth.

Bray and Sancio (2006) identify materials with wc/LL > 1.0 are prime candidates for liquefaction. Only one sample in the Pleistocene alluvium had a wc/LL greater than 1.0. Generally the silty material is assessed to be moderately susceptible (with albeit a few being susceptible) at shallow depths. With depth the silt soil layers are typically indicated to be non-susceptible.

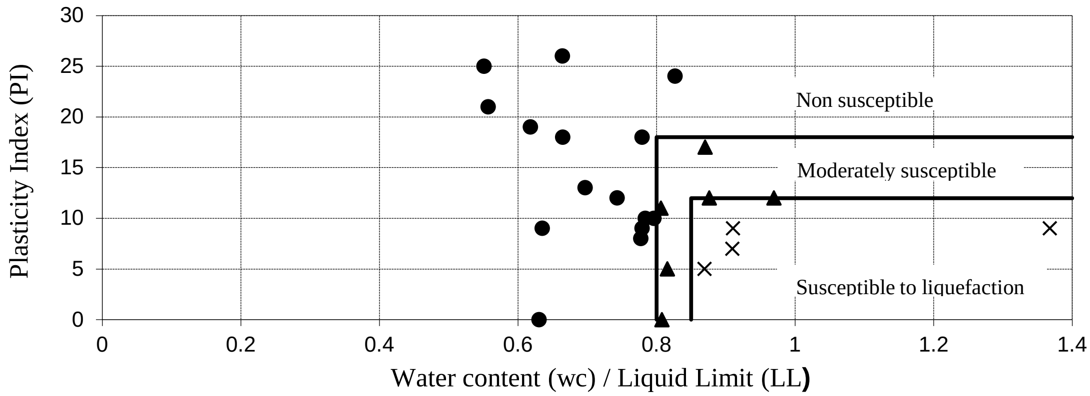

Figure 6. Plasticity index (PI) with water content (wc) to liquid limit ratio (wc/LL)

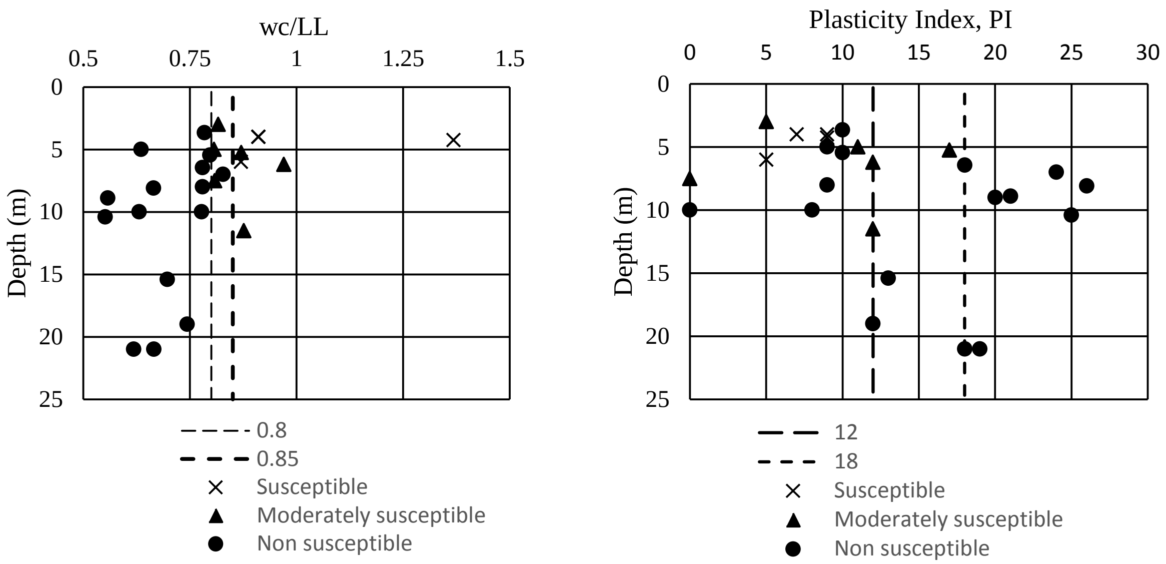

Figure 7. a) Water content to liquid limit ratio (wc/LL) with depth, b) PI with depth

Discussion

While excavation of the site indicates historic performance in the 1855 earthquake did not result in significant liquefaction of the typically silty main deposit, some liquefaction may have still occurred. It is possible that an earthquake causing more intense shaking could cause instability of the Buckle Street slope. The best way to assess the cyclic performance of the silt material is cyclic laboratory testing, which would be feasible given the plastic nature the material making it possible to sample and prepare.

The CPT procedure appears to struggle with the liquefaction assessment of the Wellington alluvium at this site and sampling for fines content, moisture content, plasticity index and liquid limit is best carried out. Plasticity criteria for clay-like behaviour and liquefaction susceptibility criteria for fine grained soils better fits the historic performance in 1855 and the significant increase in age of the deposit with depth.

There are inherent difficulties associated with the interbedded nature of the Wellington alluvium deposit, for representative sampling using boreholes and transition and thin layer effects for CPTs and SPTs. CPTs adjacent to boreholes are necessary to assess the many relationships in a liquefaction assessment where fine grained soils are present, as well as deal with the interbedded nature of the deposit. Continuous coring and detailed comparison with an immediately adjacent CPT is suggested. It makes sense to undertake the CPT first as it has a lesser area of disturbance and the borehole be placed 0.5 to 1.0 m from the CPT to minimise soil layer variation with distance.

Sampling and testing for clay-like criteria is appropriate at fines contents above 35 %. Sampling and testing is also appropriate at fines content lower than 35 % if plasticity is likely, however, careful understanding of the applicability of the results against clay-like criteria is necessary. It is the authors understanding that samples can easily be assessed as non-plastic in the field when a laboratory test may indicate plasticity, possibly due to observation of the sample at natural water content not within the plastic range or low fines content linked with the inexperience of the personnel logging with plasticity and liquefaction. This is an important consideration when scoping an investigation and selecting samples.

Sampling needs to be representative. For uniform layering this may be easy. For interbedded deposits like the Wellington Alluvium, sampling should consider coverage across the range of the material encountered as it may not be possible to define the same layer between investigation points.

High quality sampling practice is best to ensure the true water content of the material is captured. As well as being representative, samples should be sealed or tested quickly so not to get a falsely low water content for wc/LL ratio. A jar fully packed with soil and sealed is suggested rather than plastic bags which may contain excessive air and could be punched.

The New Zealand standard for plastic index PI, in NZS4402 (Standards New Zealand, 1988), is different than the American standard (ASTM) used in most liquefaction studies. It is understood by the author that the New Zealand method slightly underestimates PI compared to ASTM. The ASTM method should be used to be consistent with the liquefaction studies. The samples in this paper were tested using the New Zealand standard.

Not discussed in this paper, but worth consideration is compression (primary) and shear (secondary) wave velocity testing.

Conclusions

Excavation of the site at and around the Buckle Street slope down to Cambridge Terrace uncovered no features indicative of significant liquefaction in the Pleistocene aged Wellington alluvium in the 1855 Wairarapa earthquake.

CPT procedures for the assessment of liquefaction significantly over predict the liquefaction of silty materials in the Pleistocene aged Wellington alluvium for the 1855 earthquake. Plasticity criteria for clay-like behaviour and liquefaction susceptibility criteria for fine grained soils better fit the historic performance in 1855 and the significant increase in age of the deposit with depth.

In the Wellington alluvium, sampling and laboratory testing for moisture content, plasticity index and liquid limit is appropriate at fines contents greater than 35 %. Sampling and testing is appropriate at fines content lower than 35 % if plasticity is likely.

Acknowledgments

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