Characterisation of a subaqueously deposited silt iron ore tailings

D. REID*, R. FANNI†, K. KOH† and I. OREA†

A geotechnical investigation was carried out to characterise a subaqueously deposited, primarily silt, iron ore tailings. Piezocene penetration tests (CPTu) were carried out followed by piston tube sampling at a selected target depth. Piston samples provided measures of in situ density (by means of gravimetric water content), and supplied material for reconstituted and intact laboratory testing. Reconstituted samples prepared using moist tamping (MT) for determination of the critical state locus (CSL), along with intact specimens, were both tested. The potential existence of layering within the recovered specimens was also assessed, indicating near-homogenous samples. The laboratory testing of intact specimens suggested that they appeared to tend towards the same CSL as that obtained from reconstituted loose MT specimens. This tentative result differs from some previous comparisons – with the agreement seen in this case being suggested to primarily result from a lack of layering. In situ state as inferred from both CPTu data and comparison of tube densities to the CSL suggested a loose state.

KEYWORDS: in situ testing; laboratory tests; silts

ICE Publishing: all rights reserved

INTRODUCTION

Silts present unique geotechnical characterisation challenges (Shuttle & Jefferies, 2016), as (a) they may suffer significant disturbance when sampled, (b) methods developed for clays to correct for sample disturbance may be inapplicable, (c) there is a paucity of calibration chamber to assist in piezocene penetration test (CPTu) interpretation and (d) reconstituted samples may not provide a reasonable proxy for in situ material fabric and shear behaviour (Hoeg et al., 2000; Chang et al., 2011). Further, many tailings deposits – which are likely the largest structures currently created by humans (Robertson, 2011), and suffer from a poor safety record (Davies, 2002) – comprise primarily silt-sized particles.

Of the challenges previously listed, perhaps the most fundamental is the difference frequently seen between reconstituted and intact specimens of silt tailings (Hoeg et al., 2000; Chang et al., 2011). While differences in in situ and reconstituted fabric would be expected to have an effect at low strains (Shuttle, 2006), the work of Hoeg et al. and Chang et al. show fabric effects extending to high strains – of such a magnitude that a unique critical state locus (CSL) appears implausible. The reasons for these observations are currently unclear. They may include layering – which was noted by Hoeg et al. for their samples, and appears to be visually evident in the block samples used by Chang et al. (Chang, 2009). The potential significant differences exhibited by layered and reconstituted samples were outlined by Baziar & Dobry (1995). More recently, differences in pore fluid chemistry has been speculated as another potential cause for the differences seen in intact and reconstituted specimens (Jamiolkowski, 2014).

This study presents the results of the geotechnical investigation and laboratory testing of a subaqueously deposited silty iron ore tailings, where the results enable assessment of a number of the previously discussed challenges related to silt characterisation. Initial assessment was based on CPTu-based screening techniques, with four tube samples then obtained from a selected target depth adjacent to a CPTu, followed by reconstituted and intact testing. This work includes efforts to assess the uniqueness of the CSL between reconstituted and intact samples, and assessing the existence of layering in situ.

GEOTECHNICAL INVESTIGATION

Site description

The site is an iron ore tailings deposit located in Australia. The tailings are non-plastic, predominantly silt-sized, and are deposited at a slurry density that minimises segregation. While deposition is subaerial within the majority of the tailings storage facility (TSF), in an isolated zone near the perimeter embankment deposition occurred subaquously due to difficulties managing the supernatant pond. The tailings depth in this area was approximately 9 m at the time of the investigation. A thin surface crust of dried tailings was sufficient to enable access by a tracked CPTu rig. As there is evidence that subaquously deposited silts may result in a looser in situ state compared with subaerially deposited materials (e.g. Reid & Jefferies, 2017), emphasis was placed on the area of historic subaqueous deposition.

CPTu data

The results of CPTu 1, located within the subaqueously deposited tailings, are presented in Fig. 1 as normalised tip resistance (Q), friction ratio (Fr), pore-pressure response (μu) and equilibrium pore pressure (μ0). In addition, a screening-level estimate of state parameter (ψ) (Been & Jefferies, 1985) based on the method outlined by Plewes et al. (1992) – likely the most commonly applied ψ screening method used currently in silt tailings is shown (Shelbourn, 2010; Jefferies & Been, 2015; Morgenstern et al., 2016). Below a dense crust, the CPTu results through the subaquously deposited tailings are contractive, with ψ ranging from 0.05 to 0.15.
Sampling
On the basis of the CPTu 1 results, a target sampling depth of 7.6–8.0 m was selected. A CPTu piston tube sampler was then used to collect four 60 mm diameter stainless-steel tube samples from within approximately 3 m of CPTu 1. These samples form the basis of subsequent laboratory testing. Owing to the lack of plasticity of the tailings, and significant driving distance to the laboratory (>1000 km), the samples were expected to be of low quality. Care was taken to ensure that the tubes were well sealed such that they would not leak during transport.

LABORATORY TESTING
Sample management and preparation
After arrival of the tube samples in the laboratory, two tubes (tubes 1 and 2) were extruded in their entirety into drying trays. As an appreciable quantity of free water was evident above the sample within the tubes (consistent with a disturbed sample), care was taken to ensure all solids and water from the tubes were captured in the drying trays. Gravimetric water content (GWC) of tubes 1 and 2 was then measured by first drying the entire sample in a cool oven (~50°C), then thoroughly mixing the near-dry sample and taking a small sub-sample for further drying in a hot oven (~105°C). Recording mass losses from both initial cool oven drying and the sub-sample in the hot oven throughout this process enabled GWC of the original tubes to be obtained without drying the majority of the specimen in a hot oven – which could result in changes to mechanical behaviour, including potentially the CSL (Riemer & Seed, 1997). The material from the two tubes was then combined to create a single composite sample for preparing reconstituted specimens. The index properties for this composite sample are presented in Table 1. The remaining two tubes (tubes 3 and 4) were stored such that their subsequent usage could be informed by results of the initial reconstituted testing.

Testing methods
Strength testing on the sampled tailings consisted of triaxial and direct simple shear (DSS) tests. All reconstituted tests utilised the moist tamping (MT) preparation method. Triaxial tests were prepared in eight layers using the under-compaction method (Ladd, 1978). Triaxial tests included oversized, lubricated end platens, with soil freezing used at end of test to improve void ratio measurement. Samples had approximate initial dimensions of 126 mm high and 63 mm diameter. Drained tests were consolidated isotropically, while undrained tests were consolidated either under \( K_0 \) conditions (based on average sample area and volume change) or under anisotropic conditions to a specific \( K_0 \) value. Anisotropic conditions were used to improve estimates on in situ undrained strengths and brittleness, although use of such initial conditions was not required for the particular scope of this paper. All MT triaxial tests were prepared loose, except for one dense test carried out to provide state – dilatancy data. Triaxial tests carried out are summarised in Table 2.

DSS tests were carried out under constant-volume conditions, with lateral restraint provided by a membrane surrounded by Teflon-coated rings. DSS samples were 60 mm in diameter and approximately 20 mm high. DSS tests carried out are summarised in Table 3. All reconstituted DSS tests were prepared loose using the MT technique in a single layer.

After completion of reconstituted testing, intact specimens from tubes 3 and 4 were extruded directly into membrane-lined split moulds, and trimmed to the appropriate height – a sample preparation method referred to herein as ‘intact’. Although these intact samples were of poor quality, they can still provide an indication as to whether they tend towards the same CSL as that obtained from MT specimens. Indeed, one of the most prominent studies comparing intact and reconstituted samples was based on low plasticity silt materials likely to be disturbed.

### Table 1. Index properties of bulk sample

<table>
<thead>
<tr>
<th>Property</th>
<th>Test type</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_s )</td>
<td>Helium pycnometry</td>
<td>Dimensionless</td>
<td>2.78</td>
</tr>
<tr>
<td>%&lt;75 ( \mu )m</td>
<td>Wet sieving</td>
<td>%</td>
<td>88</td>
</tr>
<tr>
<td>%&lt;38 ( \mu )m</td>
<td>Wet sieving</td>
<td>%</td>
<td>77</td>
</tr>
<tr>
<td>Sedigraph</td>
<td>Sedigraph</td>
<td>( \mu )m</td>
<td>78</td>
</tr>
<tr>
<td>( D_{10} )</td>
<td>Sedigraph</td>
<td>( \mu )m</td>
<td>1</td>
</tr>
</tbody>
</table>

### Fig. 1. CPTu results: (a) normalised tip resistance (\( Q \)); (b) friction ratio (\( F_r \)); (c) pore-pressure response (\( u_2 \) or \( u_\psi \)); (d) state parameter (\( \psi \))
due to sampling procedures and transport (Høeg et al., 2000).

Tube 3 was used for monotonic and cyclic DSS samples—of which only the two monotonic tests are discussed in detail herein. Tube 4 was used to obtain sample for two triaxial tests. Monotonic DSS tests were carried out at vertical effective stresses of 500 and 1000 kPa to assess the potential for higher stresses to affect undrained strength ratios and contractive or dilative response. The intact triaxial tests were consolidated higher stresses than in situ conditions in an attempt to produce less-dilative specimens that might have measurable critical state conditions.

After testing, the oven-dried intact specimens were all wet sieved through 75 and 38 μm sieves, to provide an indication on in situ layering. DSS tests were sieved as a single sample, while triaxials were split into three specimens of approximate equal length (top, middle, bottom).

**Triaxial test results**

Triaxial test results are presented in Fig. 2, and as a state diagram in Fig. 3. MT samples prepared loose exhibited contractive behaviour, with the tests reaching constant (or minimally changing) mean effective stress, deviator stress and volume change or shear-induced pore pressure with continuing strain and without visually apparent localisation. These tests allowed identification of a consistent CSL as outlined in Fig. 3. Intact specimens and the single dense MT sample exhibited dilative conditions—which were at looser states than the intact specimens, transformation to dilation at higher strains. MT samples, specimens were initially contractive, with subsequent phase

---

**Table 2. Triaxial test summary**

<table>
<thead>
<tr>
<th>Test</th>
<th>Preparation method</th>
<th>Test type</th>
<th>$p'_c$, kPa</th>
<th>$q'_c$, kPa</th>
<th>$K_c$, dimensionless</th>
<th>$e_c$, dimensionless</th>
<th>$p'_{cc}$, kPa</th>
<th>$q'_{cc}$, kPa</th>
<th>$e_{cc}$, dimensionless</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX-01 MT</td>
<td>CK</td>
<td>U</td>
<td>699</td>
<td>596</td>
<td>0-46</td>
<td>0-643</td>
<td>514</td>
<td>691</td>
<td>0-643</td>
</tr>
<tr>
<td>TX-02 MT</td>
<td>CID</td>
<td>501</td>
<td>3</td>
<td>0-99</td>
<td>0-692</td>
<td>1027</td>
<td>1577</td>
<td>0-611</td>
<td></td>
</tr>
<tr>
<td>TX-03 MT</td>
<td>CK, U</td>
<td>94</td>
<td>57</td>
<td>0-57</td>
<td>0-747</td>
<td>47</td>
<td>66</td>
<td>0-747</td>
<td></td>
</tr>
<tr>
<td>TX-04 MT</td>
<td>CAU</td>
<td>224</td>
<td>161</td>
<td>0-51</td>
<td>0-709</td>
<td>136</td>
<td>218</td>
<td>0-709</td>
<td></td>
</tr>
<tr>
<td>TX-05 MT</td>
<td>CID</td>
<td>300</td>
<td>4</td>
<td>0-99</td>
<td>0-538</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>TX-06 Intact</td>
<td>CID</td>
<td>701</td>
<td>3</td>
<td>1-00</td>
<td>0-525</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>TX-07 Intact</td>
<td>CK, U</td>
<td>436</td>
<td>452</td>
<td>0-39</td>
<td>0-597</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

*Sample still dilating at 22% strain

---

**Table 3. DSS test summary**

<table>
<thead>
<tr>
<th>Test</th>
<th>Preparation method</th>
<th>$p'_c$, kPa</th>
<th>$e_c$, dimensionless</th>
<th>Peak $s_u$, kPa</th>
<th>$s_o/p'_c$, dimensionless</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSS-1 MT</td>
<td>500</td>
<td>0-674</td>
<td>79</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td>DSS-2 MT</td>
<td>250</td>
<td>0-714</td>
<td>39</td>
<td>0-16</td>
<td></td>
</tr>
<tr>
<td>DSS-3 MT</td>
<td>150</td>
<td>0-672</td>
<td>42</td>
<td>0-28</td>
<td></td>
</tr>
<tr>
<td>DSS-4 Intact</td>
<td>150</td>
<td>0-611</td>
<td>88*</td>
<td>0-59*</td>
<td></td>
</tr>
<tr>
<td>DSS-5 Intact</td>
<td>300</td>
<td>0-566</td>
<td>140</td>
<td>0-47</td>
<td></td>
</tr>
<tr>
<td>DSS-6 Intact</td>
<td>600</td>
<td>0-544</td>
<td>215</td>
<td>0-36</td>
<td></td>
</tr>
</tbody>
</table>

---

**DSS test results**

The results of DSS testing are presented in Fig. 5. Intact specimens were initially contractive, with subsequent phase transformation to dilation at higher strains. MT samples, which were at looser states than the intact specimens, were contractive giving undrained strength ratios ($s_u/p'_c$) of 0-16–0-28.

The undrained strength ratio from each DSS test is presented in Fig. 6, where test initial state ($\psi$) is plotted against $s_u/p'_c$. For the purposes of plotting the results, mean effective stress, and hence $\psi$, was calculated based on a range of likely plausible $K_o$ values from 0-4 to 0-6. The general trend of $s_u/p'_c$ to $\psi_0$ is consistent between the MT and intact DSS tests—again, potentially indicative of a single CSL relevant for both in situ and reconstituted fabrics.

---

**Gradation with depth**

The results of wet sieving on each intact specimen are outlined in Fig. 7 against depths inferred from their location within the sample tubes. Also compared is the gradation of
the bulk sample prepared from tubes 1 and 2 in their entirety. The differences seen are minimal – indeed, they are far less than those measured in many tailings, including deposits that have been tested for the purposes of comparing intact and reconstituted samples (Høeg et al., 2000; Jamiolkowski, 2014). This suggests that in situ layering was unlikely to have had a significant effect on the behaviour of intact specimens, and assists in their comparison to reconstituted samples – that is, all sample tests are relatively uniform, and have the same approximate gradation.

SYNTHESIS OF CPTU AND LABORATORY DATA

The inferred state from CPTu (Plewes et al., 1992) and void ratio calculated from tube GWC are shown in comparison with a number of the laboratory test densities in Fig. 8. Good agreement between the CPTu-inferred states and that obtained from tube sample void ratios is indicated. The significant densification of the laboratory-tested intact samples through sampling, transport and extrusion is evident. Clearly, reliance on intact samples to provide strength inputs would be unsafe regardless of the consolidation stress selected for laboratory testing with this magnitude of disturbance.

Perhaps, the most important observation from the data synthesis in Fig. 8 is the looser state in situ compared with MT samples prepared as loose as practicable in the...
It is noted that an inability to produce samples as loose in the laboratory as seen in situ for subaqueously deposited silts is not without precedent (Shuttle & Cunning, 2007).

**CONCLUSIONS**

A CPTu and laboratory characterisation programme of a subaqueously deposited silt tailings indicated (a) good agreement between CPTu and tube density-inferred state, (b) significant densification of intact specimens, such that use of their results for design would be unsafe—regardless of consolidation stress selected, (c) an inability to prepare reconstituted specimens as loose as in situ conditions and (d) reasonable agreement between the CSL obtained by testing loose MT samples and the behaviour of intact specimens. This final outcome differs from most published comparisons of reconstituted and intact testing on silty materials. A contributing factor to this outcome may be the negligible layering observed in situ.

**ACKNOWLEDGEMENTS**

We thank the anonymous reviewers for their useful review comments, which improved the clarity of the paper.

**REFERENCES**


