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Layering – the missing factor in fabric studies?

La stratification – le facteur manquant dans les études de structure?

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ABSTRACT: The debate over which form of sample reconstitution best reproduces in situ fabric of primarily silty tailings has been ongoing for over two decades and is still no closer to resolution. The debate has two related, but distinct aspects: (i) which reconstitution technique best reproduces in situ fabric, such that small and medium strain behavior can best be simulated, and (ii) do different reconstitution techniques result in samples tending to a different critical state line (CSL) - which, if the case, would raise significant questions as to the applicability of the laboratory-measured CSL when assessing in situ state and behavior. The limited data available from fabric studies on primarily silty tailings suggest that samples reconstituted using either moist tamping or slurry deposition - the leading options available in the laboratory - do not tend towards the same CSL as intact specimens. One aspect of the available fabric studies worth noting is their lack of detailed consideration of layering, i.e. significant gradation changes that occur on a very small vertical scale during hydraulic placement. This paper outlines observations of such layering, with significant gradation changes over as little as 20mm vertically, by examining block samples taken from four different tailings deposits. This scale of layering is well within the scale of a typical laboratory element test. Finally, an additional site where minimal layering was observed, and where the resulting comparison between reconstituted and intact samples was much more favorable, is outlined. Triaxial tests for one layered and one unlayered site are compared, the results of which suggest that layering is the likely cause of many of the differences seen between intact and reconstituted specimens.

RÉSUMÉ : Le débat sur la forme de reconstitution d'échantillon qui reproduit le mieux la structure in situ de résidus principalement limoneux se poursuit depuis plus de deux décennies et n'est toujours pas près d'être résolu. Le débat a deux aspects liés, mais distincts: (i) quelle technique de reconstitution reproduit le mieux la structure in situ, de sorte que le comportement de petite et moyenne déformation puisse être simulé au mieux, et (ii) est-ce différentes techniques de reconstitution aboutissent-elles à des échantillons ayant ligne d'état (CSL) - qui, le cas échéant, soulèverait des questions importantes quant à l'applicabilité de la CSL mesurée en laboratoire lors de l'évaluation de l'état et du comportement in situ. Les données limitées disponibles à partir d'études de structure sur des résidus principalement limoneux suggèrent que les échantillons reconstitués à l'aide d'un tassement humide ou d'un dépôt de boue - les principales options disponibles en laboratoire - ne tendent pas vers le même CSL que les spécimens intacts. Un aspect des études de structure disponibles à noter est leur manque de considération détaillée de la stratification, c'est-à-dire des changements de gradation importants qui se produisent à très petite échelle verticale pendant le placement hydraulique. Cet article décrit les observations d'une telle stratification, avec des changements de gradation significatifs sur aussi peu que 20 mm verticalement, en examinant des échantillons de blocs prélevés dans quatre dépôts de résidus différents. Cette échelle de stratification est bien dans l'échelle d'un test d'élément de laboratoire typique. Enfin, un site supplémentaire où une stratification minimale a été observée, et où la comparaison résultante entre les échantillons reconstitués et intacts était beaucoup plus favorable, est décrit. Les tests triaxiaux pour un site stratifié et un site non stratifié sont comparés, dont les résultats suggèrent que la stratification est la cause probable de nombreuses différences observées entre les échantillons intacts et reconstitués.

KEYWORDS: tailings, laboratory testing, fabric, critical state line

1 INTRODUCTION

Debate over which form of laboratory reconstitution method for sands, silty sands, and sandy silts best reproduces in situ fabric and accessible density ranges has been ongoing for decades (Vaid and Sivathayalan 1999, 2000, 2001 , Høeg et al. 2000, Chang et al. 2011). Support for the benefits of water pluviation (WP) in reproducing alluvially-deposited sands has been provided by reference to in situ frozen specimens (e.g. Vaid and Sivathayalan 1999). Alternatively, for soils made up predominately of silts – which includes most mine tailings – many studies have shown that no available reconstitution method provides a reasonable reproduction of in situ fabric and undrained shearing behavior (Høeg et al. 2000, Chang et al. 2011). This is of great importance in the characterization of tailings storage facilities (TSFs) as it is generally impossible to obtain high quality undisturbed samples of saturated low plasticity tailings from significant depths.

In parallel to ongoing debates about which reconstitution method is best, engineering practice for TSFs generally utilizes the moist tamping (MT) technique, as evidenced by its ubiquitous application in recent major TSF failure investigations (Morgenstern et al. 2016, Jefferies et al. 2019, Robertson et al. 2019). This, despite lack of certainty as to the relevance of MT specimens to in situ behavior, as argued frequently with respect to MT when applied to predominately silt tailings (Vaid and Sivathayalan 2001, Daliri et al. 2015). While these criticisms have been focused on hydraulically-deposited tailings, it is noted that application of filtered tailings deposition has been steadily increasing, and that the deposition of moist tailings from conveyor or truck, followed by spreading and potential compaction, is conceptually similar to the MT reconstitution method. Finally, an important outstanding question regarding reconstituted specimens is whether, in some cases, *any* reconstitution method can reproduce the densities of tailings that are subaqueously deposited into quiescent water (Shuttle and Cunning 2007, Reid et al. 2018, Reid 2021).

A potential major limitation of most fabric studies carried out thus far has been the implicit assumption that any reconstitution method could even be expected to reproduce the behavior of in situ deposits that are almost invariably layered – often at a very small scale. This is demonstrated clearly by Baziar and Dobry (1995), who compare intact layered samples to homogenous and layered reconstituted specimens. Their testing was on hydraulically placed fill within a water retaining dam, which in many respects is similar to hydraulic deposition of tailings. With respect to major fabric studies of tailings, Høeg et al. (2000) note visual evident of layering after drying of specimens, while Chang et al (2011) indicate they attempted to avoid layering in their block sampling, while review of photographs of the block samples presented by Chang (2009) suggests that, common to most hydraulically deposited tailings, avoiding small-scale layering in their intact specimens may have been impractical.

The purpose of this work is to highlight the ubiquitous nature of layering in hydraulically-deposited tailings by means of block samples from four different TSFs. Each displayed a varying degree of layering. The implications of this layering on resulting undrained behaviour compared to reconstituted specimens – which are usually prepared with the explicit goal of gradational uniformity – are highlighted by this comparison.

2 MATERIALS, SAMPLING, AND BLOCK EXAMINATION

To enable an investigation of the potential effect of layering on fabric studies, block samples from four TSFs were examined. A summary of the material from each TSF is outlined in Table 1 – where the index properties listed are for composite samples made up by "blending" the various layers from each block, of necessity to enable sufficient material quantities for most studies. Two of these block samples have been investigated in previous publications – the gold tailings by Reid et al. (2018), and the iron ore tailings by Reid and Fanni (2020). The gold tailings blocks are from the same TSF where a large bulk sample was sourced for a critical state line (CSL) round robin program (Reid et al. 2020), calibration chamber testing (Alaya et al. 2020) and investigation of different reconstitution methods (Reid et al. 2021a, 2021b). Similarly, a large bulk sample sourced from the platinum TSF was used to supply material for calibration chamber testing (Ayala et al. 2022).

Table 1. Index properties of tailings discussed in current study

Parameter	Gold	Platinum	Copper	Iron ore
% < 75um	58	72	54	84
% < 38um	44	42	40	73
Specific Gravity	2.78	2.97	2.65	3.00
Liquid limit (%)	18	24	25	Non plastic
Plastic limit (%)	16	18	20	
Plasticity Index (%)	2	6	4	

All of the TSFs where the block samples were sourced from were in arid or semi-arid environments, with subaerial deposition and cycling of deposition around the TSF beach to promote air drying and desiccation. Block samples were obtained from areas that were sufficiently dry to access and recover blocks that were not saturated. All of the block samples were obtained from surface, or near surface, with the exception of the copper tailings which were obtained from a battered excavation approximately 4.0 m deep. All block samples were wrapped thoroughly first with plastic wrap, then aluminum foil, then a final layer of plastic wrap, before being placed in foam-lined boxes for transport.

After arrival in the laboratory, a block sample from each TSF was unwrapped and examined for visual signs of layering. After initial inspection, small sub-samples of sufficient mass to enable wet sieving to be carried out were taken at different heights from the face of the blocks. Where visual evidence of layering was apparent, efforts were made to discretize these layers with the sub-sampling procedure. However, it is noted that in most cases, particularly the gold and platinum tailings blocks, layering was at such a small scale that some "smearing" of the very thin layers present was unavoidable.

The results of the sub-sample wet sieving are overlayed on the block sample photographs in Figures 1 to 4. The iron ore block sample, which appeared visually homogenous, is excluded from Figure 4 to improve clarity of the presentation of gradation results. Sieving of the copper tailings (Figure 1) used both 38 and 75 µm sieve sizes, while for the remaining tailings only one sieve was used that best suited the general range of gradation for that particular material.

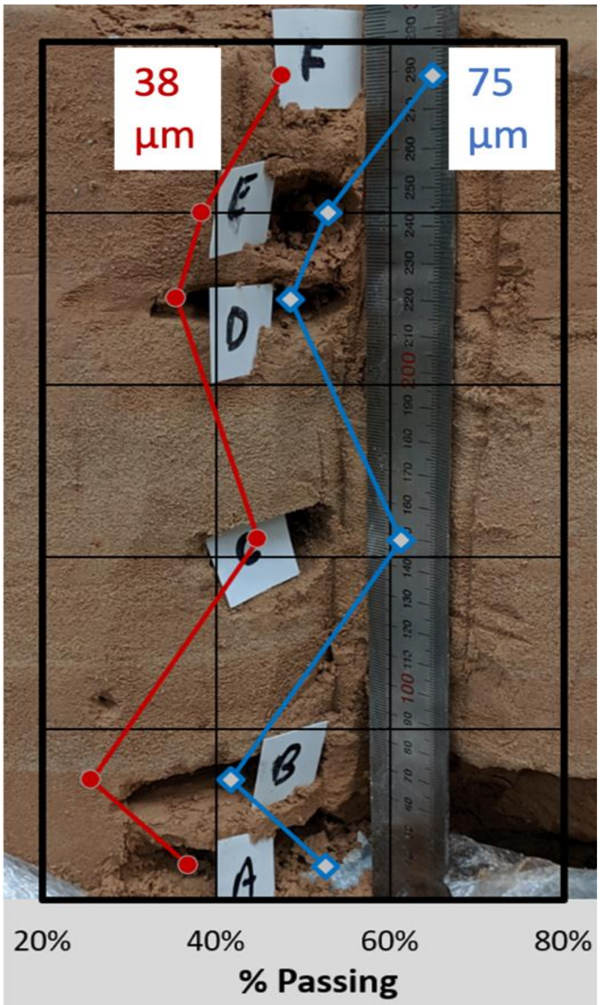

Figure 1. Copper tailings block sample and gradation result (mm units on ruler shown in photograph)

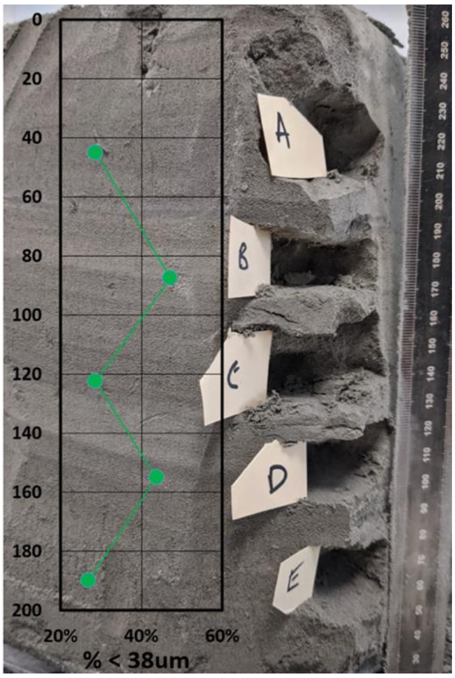

Figure 2. Platinum tailings block sample and gradation results (mm units on ruler shown in photograph)

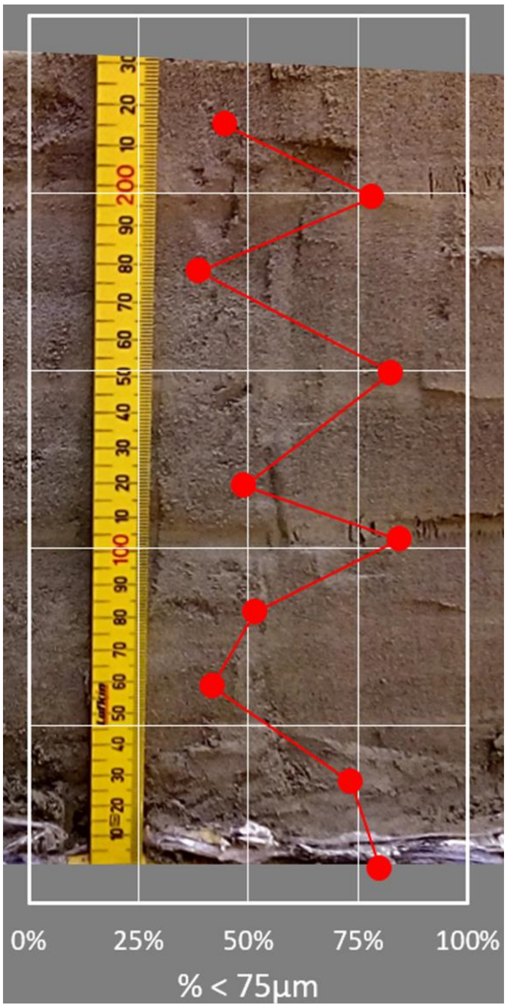

Figure 3. Gold tailings block sample and gradation results (mm units on ruler shown in photograph)

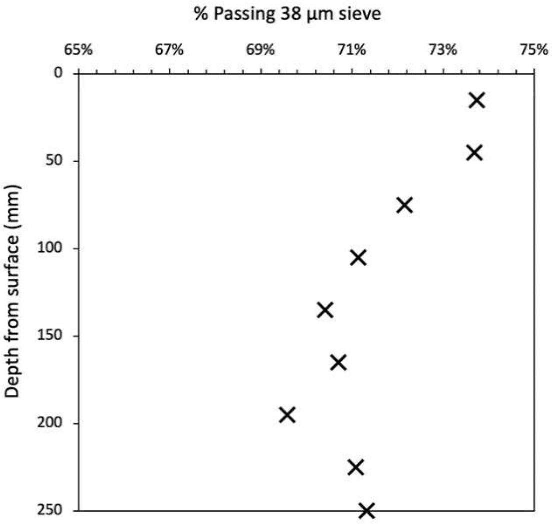

Figure 4. Iron ore tailings gradation result (after Reid and Fanni 2020)

The wet sieving process indicates that the copper, gold, and platinum tailings each consist of layers with a wide range of gradations. This indicates that it would be completely impractical to obtain a gradationally homogenous specimen from any of these blocks. Such observations are common to hydraulically placed fills (Baziar and Dobry 1995, Jamiolkowski 2014) and appear consistent with photographs (Chang 2009) of block samples used in previous fabric studies (Chang et al. 2011). Alternatively, the iron ore tailings are comparatively quite homogenous, ranging from 69 to 74% for particles less than 38 µm. The implications of the observed layering were then investigated further through triaxial compression tests of the copper and iron ore tailings. As the testing of the iron ore tailings was previously outlined by Reid and Fanni (2020), the primary focus of this paper is on the testing of the copper tailings.

3 TRIAXIAL TESTING INVESTIGATION OF LAYERING EFFECTS

After sampling and gradation analysis testing, the block samples from the iron ore and copper TSFs were further investigated by means of triaxial compression (TX-C) testing. Intact specimens were produced from the blocks by advancing a sharp-edged stainless-steel tube into the block, with a scalpel was used to trim the block in advance. The tubes were 67mm in diameter and 145mm long. Five intact specimens were obtained in this manner.

During the trimming process of the copper tailings, as there was clear visual evidence of the presence of coarse and fine layers, attempts were made to segregate the material being trimmed into different bags. As such, a small batch of fine (silty) and coarse (sandy) gradation batches were produced for reconstituted testing, with enough material for one test on each. It is noted that when attempting to isolate particular lenses, it was clear that some contamination was likely – in other words, what was obtained is unlikely to represent the absolute coarsest and finest-grained layers that were present within the blocks. The remaining trimmings that made up most of the block formed the primary (composite) batch used for reconstituted testing. It is noted that this type of composite batch is what is typically used in fabric studies for comparison to intact specimens. A comparison of the gradation of the "fine", "coarse", and "composite" bulk samples of copper tailings (all obtained from the same block) is presented in Figure 5, showing the significant differences between the two material gradations.

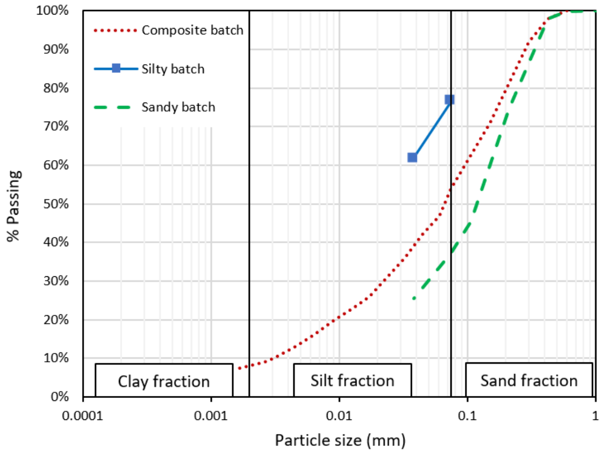

Figure 5. Gradation of composite and silty / sandy samples trimmed from copper tailings block

MT specimens were prepared in eight layers using the undercompaction method proposed by Ladd (1978) with a 5% undercompaction ratio. Subsequent testing procedures for both intact and MT specimens followed the same general procedures: (a) flushing of the sample to remove as much air as practicable (both block and MT specimens were initially unsaturated), (b) back pressure saturating to obtain a minimum Skempton's *B* value of 0.97, (c) consolidating isotropically or anisotropically to target stresses, (d) shearing drained or undrained to a minimum of 20% axial strain, ideally to inferred critical state conditions where possible, and finally (e) end-of-test soil freezing, to enable the most accurate measurement of void ratio possible (Sladen and Handforth, Reid et al. 2020). All tests were carried out with oversized lubricated end platens to promote more uniform sample deformation.

The tests carried out on copper tailings are summarized in Table 2, along with information as to which layer (i.e. coarse or fine) they represent, where relevant. Owing to the small quantities of the silty and sandy batches, only one test on each could be carried out. Undrained tests were selected as the undrained shearing response of different layers within the same block is arguably the most relevant to the focus of the current study.

4 COPPER TAILINGS TRIAXIAL TEST RESULTS

4.1 *Intact and composite sample testing*

The results of the primary bulk sample and intact samples of copper tailings are presented as a state diagram in Figure 6. The MT specimens were all prepared sufficiently loose to exhibit contractive behavior and sheared to inferred critical state conditions characterized by negligible changes in deviator stress, mean effective stress, and shear induced pore pressure and/or volumetric strain. Similarly, the intact specimens exhibited contractive behavior. As such, a reasonably consistent CSL could be identified for both intact and reconstituted specimens, which can be adequately approximated with a linear fit in partial logarithmic space. It is noted that presumably the CSL of the intact specimens represents some sort of "smeared" outcome, where each of the various layers comprising the specimen tending to their respective CSLs as shearing occurs.

The test results show that while the intact and reconstituted CSLs are approximately parallel, they are unique. For example, the intact CSL has a consistently higher elevation of about 0.03 in void ratio terms. It seems logical that mixing of the different sandy and silty layers of the block sample into one composite mixture would result in such a lowering of the CSL and the accessible density range – both based on summaries of the effect of gradation on CSL elevation (Reid 2015, Zuo and Baudet 2015) and consistent with similar comparisons presented by Baziar and Dobry (1995).

Table 2. Triaxial test summary

Test ID	Test type	Consolidated state		Inferred critical state	
		p' (kPa)	e_c	p_{cs}' (kPa)	e_{cs}
Intact-1	CID	300	0.728	607	0.599
Intact-2	CIU	300	0.716	87	0.716
Intact-3	CIU	60	0.799	14	0.799
Intact-4	CID	61	0.788	110	0.720
Intact-5	CID	501	0.682	969	0.562
Composite-1	CID	25	0.891	51	0.684
Composite-2	Con. p'	15	0.938	14	0.770
Composite-3	CID	100	0.762	191	0.608
Composite-4	CID	501	0.640	964	0.509
Sand-1	CIU	102	0.652	n/a	
Silt-1	CIU	202	0.606	10	0.606

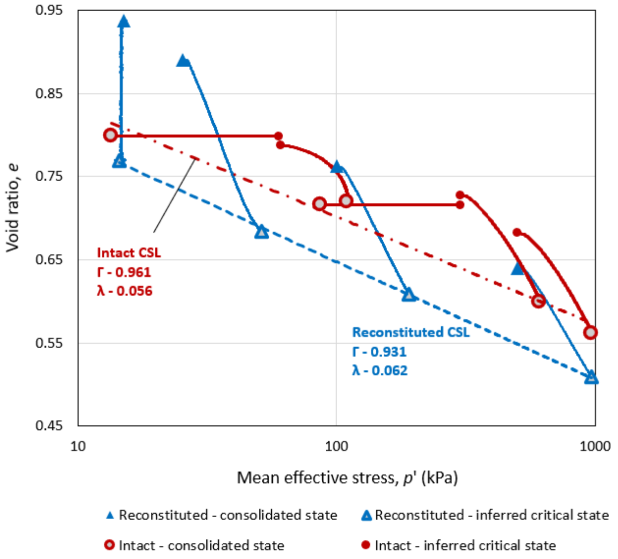

Figure 6. State diagram showing intact tests and reconstituted tests on composite batch

What is immediately clear from the CSL comparison in Figure 6 is that any attempt to prepare the reconstituted specimens to the same void ratio as that of the intact specimens, and then comparing their stress strain response, would be highly unlikely to result in similar shearing responses between the two types of specimen.

4.2 *Silty and sandy layer reconstituted testing*

The results of undrained reconstituted tests on samples prepared from the silty and sandy layers are shown in state diagram format overlaid on the intact and composite sample reconstituted CSL in Figure 7. The sandy and silty specimens were both prepared loose in a qualitative sense – that is, tamped relatively lightly to achieve as loose a state as practicable. Despite this, both achieved consolidated states close to the primary reconstituted CSL – presumably as a result of different accessible density ranges for the different gradations.

Although shearing commenced for both the silty and sandy specimens from about the same state (as measured against the composite sample reconstituted CSL) they have significantly different undrained shearing behavior. The sandy specimen exhibits significant contraction and strain softening, with mean effective stress reducing from 200 to about 10 kPa. This is consistent with the typical behavior of loose sandy materials prepared using MT. Alternatively, the silty sample underwent phase transformation behavior, and at the termination of the test was still dilating.

It seems clear from the results presented in Figure 7 that the sandy and silty reconstituted tests are tending to different CSLs. The sandy specimen CSL appears to be quite distinct, and at lower elevation to any of those fully defined in this study (i.e. composite reconstituted and intact), whereas the final critical state condition of the silty specimen is unclear.

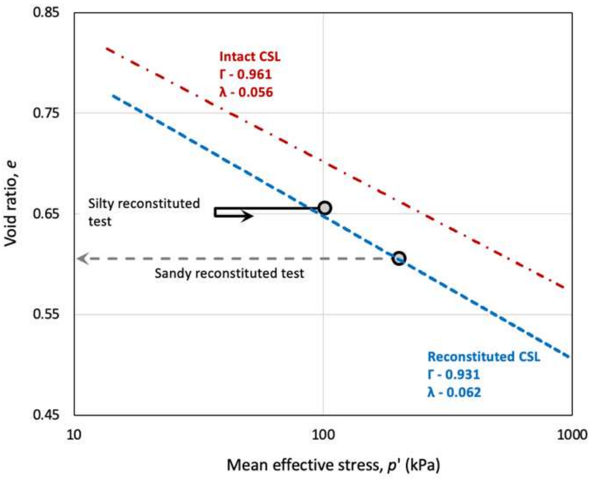

Figure 7. State diagram showing reconstituted testing on sandy and silty later material overlaid on intact and composite sample CSLs

5 COMPARISON TO IRON ORE TAILINGS BEHAVIOUR

The results of the copper tailings testing clearly show the effects of significant layering within tailings on attempts to compare reconstituted and intact specimens. Significantly different CSLs were identified for layers within ~100 mm depth range. These differences would affect any attempt to compare intact specimens to reconstituted, particularly when trying to draw conclusions as to the utility of any sample reconstitution method.

The important difference with the iron ore tailings tested by Reid and Fanni (2020) is that this block sample was free from significant layering. While not entirely homogenous, clearly the layering in this case is of a lesser magnitude (refer Figure 4).

The results of an intact – reconstituted comparison for the iron ore tailings are presented in Figure 8 as a state diagram. The CSL identified through eight MT reconstituted specimens is presented, along with the testing paths of ten intact specimens trimmed from the block. Fairly close alignment of the end point of the intact specimens is seen, with a random maximum divergence between the end-of-test intact specimens and the MT CSL of about 0.03 – a range of void ratio that is within that seen in comparisons between different laboratories all using the MT technique (e.g Reid et al. 2020). Importantly, the difference seen amongst the block samples is larger than the difference seen between any individual intact specimen and the MT CSL. This suggests that minor variations in gradation or layering profile within the intact specimens is the most likely cause of the "scatter" seen.

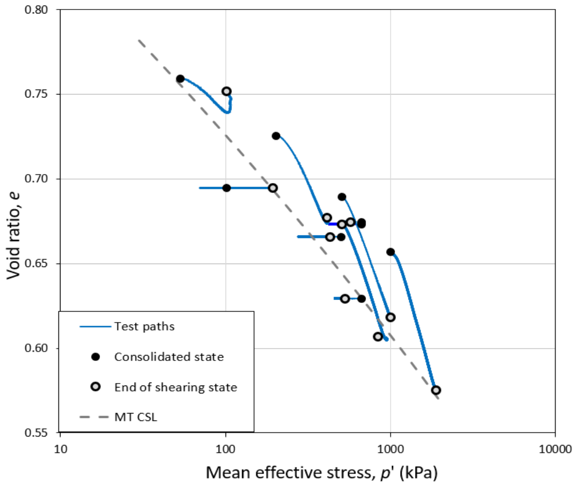

Figure 8. State diagram showing intact tests of iron ore tailings overlaid on CSL inferred from reconstituted MT tests (after Reid and Fanni 2020)

6 IMPLICATIONS AND WAY FORWARD

This work clearly shows the widely divergent outcomes that can result in a fabric study when the intact specimens have different magnitudes of layering. This is consistent with previous studies (Baziar and Dobry 1995). However, explicit consideration of layering does not appear to be common in recent fabric studies.

It is important to draw a distinction between two different implications of the current work. The first is that comparing a layered intact specimen to a gradationally homogenous reconstituted specimen has significant limitations. Indeed, it would be a rather curious and unusual outcome if two specimens, at the same void ratio, but with different internal gradations were to behave in the same manner under shear. We would therefore argue that any attempt to carry out a fabric study requires detailed inspection of in situ layering. The authors themselves, having tried and failed to locate homogenous samples in dozens of TSFs, would argue that the "burden of proof" must be in proving homogeneity of a block sample of hydraulically placed silty sand or sandy silt.

The second implication of the current study is that given the ubiquitous nature of layered intact specimens, there is an implicit challenge to the geotechnical testing community to better develop means to incorporate layering considerations into their work. For example, fabric anisotropy of sands and silts has been frequently studied (Sivathayalan and Vaid 2002, Zdravkovic and Jardine 2001), but to our knowledge the potential implications for a gradationally heterogeneous sand or silt material when sheared with a principal stress direction rotated away from vertical stress has not received much attention -i.e., most studies of the fabric anisotropy of sands and silts have been on homogenous reconstituted specimens. The different shearing behavior of the sandy and silty copper tailings examined in this study would tentatively suggest the importance of the relative contributions of different layers to the shearing behavior of a specimen. It is also noted that much speculation around the development of post-peak strengths involves focus on partial drainage and/or the interruption of drainage by finer-grained layers within a deposit (Kulasingam et al. 2004, Kamai and Boulanger 2013, Kokusho 2003, Reid and Fourie 2014, Jefferies and Been 2015). It seems clear that expanding our understanding of such processes cannot occur without a better recognition of layering in our laboratory testing programs.

6 CONCLUSIONS

An examination of the presence of layering within block samples from four different TSFs was made by examining block samples obtained from each TSFs. This examination indicated significant layering in three of the tailings, with much less (but still measurable) layering in the iron ore tailings. To quantify the effects of the observed layering on the outcomes of fabric study, intact and reconstituted specimens of the copper tailings were tested. This showed that a different CSL would be observed for the two forms of samples, which would therefore make any comparison of the two types of sample in terms of void ratio alone unreliable. Testing of material sourced from discrete layers of the copper tailings showed significant differences, particularly for the sandier gradation.

The results from the layered copper tailings were then compared to the results of the iron ore tailings that had negligible layering. In this case, the intact specimens of the iron ore tailings generally tended to the same CSL as that identified from a composite specimen prepared using the MT technique. Indeed, larger and consistent variation was seen in the inferred end-of-test conditions between different intact specimens than between any specific intact specimen and the composite sample CSL. This suggests that minor differences between different intact specimens (overall gradation, distribution of the minor layering observed) is affecting their responses.

The primary outcome of this study is to highlight the impracticality and limitations of common fabric study methods, where intact and reconstituted behavior is compared, without direct quantification of the magnitude of layering that exists in the intact specimens. Otherwise, while different behaviors will likely be observed between the intact and reconstituted specimens, it will not be clear to what degree this is simply a result of different gradations between the specimen types, or some more fundamental limitation of a particular reconstitution technique. Finally, an increased focus on the effect and shearing response of intact layered specimens appears crucial to better quantifying the undrained behavior of tailings.

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