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The implications of transitional behaviour for tailings

Conséquences du comportement transitionnel pour les stériles miniers

Abigail Cartwright & Matthew Richard Coop
Department of Civil, Environmental and Geomatic Engineering, University College London, England, a.cartwright.12@ucl.ac.uk

Andy Fourie
Department of Civil, Environmental and Mining Engineering, University of Western Australia, Australia

ABSTRACT: The Fundão and Brumadinho dam disasters have focussed attention on the stability of tailings dams, although in fact there have been around 250 tailings dam incidents in the last century. In recent years it has been identified that many natural soils of complex mineralogy and/or mixed grading have modes of behaviour that differ from conventional soil mechanics in that the effects of the initial void ratio at their deposition cannot be erased by loading at engineering stress and strain levels. The normal compression lines and critical state lines that they reach in terms of void ratio are therefore not unique but depend strongly on this initial state. From their origins as crushed rock, it may be expected that the "transitional" behaviour would occur in tailings, but it has often been overlooked as tests on samples of different initial void ratios required to identify this behaviour are rarely carried out. The paper describes laboratory tests on tailings designed to investigate transitional behaviour highlighting how the behaviour is dependent on specific volume at deposition. The data show how the normal compression and critical state lines move in the void ratio – stress space depending on the initial density. Implications for cyclic liquefaction are discussed along with the role of the placement method.

RÉSUMÉ : Les ruptures catastrophiques des barrages de Fundão et Brumadinho ont concentré l'attention sur la stabilité des barrages miniers, bien qu'en fait plus de 250 incidents concernant des barrages de stériles miniers ont été notés pendant le dernier siècle. Durant ces dernières années, on a identifié que nombreux sols ayant une minéralogie complexe et/ou une courbe granulométrique mélangée ont des modes de comportement qui diffèrent de ce qui est prédit en mécanique des sols, dans le sens où l'influence de l'indice des vides initial résultant de la déposition ne peut pas être effacée aux niveaux de contraintes et déformations typiques des constructions géotechniques. Les courbes de chargement isotrope et aux états critiques que ces sols atteignent en termes d'indice des vides ne sont donc pas uniques, mais dépendent de l'indice des vides initial. Les stériles miniers étant créés par broyage de roches on pourrait s'attendre à ce qu'ils aient un comportement « transitionnel », mais comme les essais nécessaires pour l'identifier, à partir d'indices des vides différents, sont rarement effectués, cet aspect a été négligé dans le passé. Cet article décrit des essais en laboratoire effectués sur stériles miniers, conçus pour investiguer leur comportement transitionnel et particulièrement comment leur comportement dépend du volume spécifique à la déposition. Les résultats montrent comment les courbes de chargement isotrope et aux états critiques changent d'emplacement dans le plan d'indice des vides contre pression selon la densité initiale. Les implications pour la liquéfaction cyclique sont discutées ainsi que le rôle de la méthode d'installation des stériles miniers.

KEYWORDS: Tailings; transitional behaviour; liquefaction; cyclic stress ratio.

1 INTRODUCTION.

There are an increasing number of soils that are found to have a mode of behaviour that is often referred to as "transitional". While most soils may have well defined normal compression lines (NCLs) and critical state lines (CSLs) in the void ratio (e) or specific volume ($v = 1 + e$): log stress plane, for these materials the locations of these lines are strongly a function of the initial void ratio at the point they are deposited or created (Martins et al. 2001; Ferreira & Bica 2006). While such effects must be a function of the soil fabric, identifying where is the seat of that fabric and at what scale has proven elusive, although it is often unrelated to the means of sample preparation in laboratory prepared reconstituted samples (Shipton & Coop 2015). The types of soils it can be found in are wide ranging, but typically it does not occur in poorly graded sands or the more plastic soils, but in soils that are well and perhaps finer graded and often with complex mineralogy (Shipton & Coop 2012). Particle breakage may or may not occur in soils with this behaviour. All soils must eventually reach a critical state with unique stresses, volumes and fabric if they are sheared far enough, so the absence of such unique states in these soils merely indicates that the strains applied by our laboratory tests (and around our engineering structures) are far too small to reach them (Todisco & Coop 2019).

Tailings are the residual materials after extracting valuable minerals from the ores. The characteristics of tailings are highly variable depending on the composition of the ores and the extraction processes used. From their gradings and mineralogies, it might be expected that some or even many tailings would have transitional behaviour. Unfortunately, researchers and engineers rarely look for this behaviour since it requires tests to be carried out from samples with a range of different starting void ratios at the point of setting the sample up, which is laborious, and researchers generally follow set procedures with a fixed initial void ratio. Li & Coop (2019) and Li et al. (2018) did look for transitional behaviour in tailings and while they did not find it in iron ore tailings of various gradings, they did find a weak transitional behaviour in a gold tailings. The purpose of this research was to identify the behaviour of more strongly transitional tailings, examining how this would influence its behaviour under both monotonic and undrained cyclic loading in a seismic event.

2 MATERIALS AND METHOD

2.1 *Material tested*

The tailings chosen is one from a mineral sand surface excavated mine from about 100km South of Perth, Australia. This was chosen because the separation process for the heavy minerals (generally rutile and zircon) is a gravimetric one, so obviating the need for excessive laboratory safety measures, because no chemicals have been used in the process. To accentuate the transitional behaviour, the sand part of the fraction was removed by sieving; such grading separation often occurs when tailings are deposited hydraulically. The resulting grading curve is given in Fig. 1, which has been determined with a Malvern Morphologi particle analyser, using the mean of nine analyses because of the small sample size. The tailings is quite well graded, and compared with many gradings of tailings from Li et al. (2018), this tailings is finer-grained. The mean particle size (d_{50}) is 0.087 mm and the coefficient of uniformity (C_u) is 4.09. This tailings is slightly less well graded than the pond or middle beach tailings found in the research by Li & Coop (2019) from an iron ore tailings in Panzihua City, China. The C_u value for the pond material was 6.7 and was 10 for the middle beach material (Li & Coop 2019). The characteristics of the mineral sand tailings are therefore quite similar to many hydraulically placed tailings.

Li & Coop (2019) used the empirical chart proposed by Krumbein and Sloss (1963) to identify a sphericity of 0.66 for the pond tailings and 0.58 for the middle beach tailings, and the same roundness of 0.34. These relatively low values indicate angular to sub-angular shapes. The same method was used to identify a sphericity of 0.76 for the mineral sand tailings and a roundness (R) of 0.79. The sphericity (S) is also calculated using equation 1, which is equivalent to the circularity defined by Wadell (1933):

$$S = \frac{2\sqrt{\pi A}}{P_{real}} \quad (1)$$

where P_{real} is the particle perimeter and A is the particle area. Using this equation, the sphericity from the Malvern Morphologi apparatus was 0.73. In comparison with Li & Coop (2019), this higher value indicates sub-angular to sub-rounded shaped particles. The grading is therefore similar, but the particle shapes are different and this is because the mineral sand tailings is not a crushed rock. The particles are more rounded as they have not been crushed.

The specific gravity (Gs) of the grains was found to be 2.529. This was measured following the procedures recommended in the ASTM D 854 (ASTM 2002). Many tailings tend to have relatively high Gs values due to the presence of metal minerals, but in fact these tailings do not. The plastic limit of the tailings is 30.1% and the liquid limit is 59.6%. The mineralogy of the tailings is predominantly quartz.

The Malvern Morphologi apparatus was also used to construct a cumulative frequency graph for aspect ratio, which is given in Fig. 2. Aspect ratio is used to describe shape and is defined as the particle width, measured along the minor axis, divided by particle length, measured along the major axis. The minor axis runs perpendicular to the major axis. The graph displays quite a range of aspect ratios arising from the nature of the material. This particular tailings underwent no crushing but there may have been some abrasion during the separation process, which involves washing the material through a sequence of spiral separators. Abrasion would also have occurred during the wind-blown transportation process from which the parent material originated.

The Malvern Mophologi image analysis captures a 2D image of a 3D particle and calculates various size and shape parameters from this 2D image. The particle lies in its lowest energy position on the plate and so the largest area of the particle is presented to the camera. One of the principal diameters calculated, and the calculated diameter used in this study, is the circular equivalent (CE) diameter, which is the diameter of a circle with the same area as the 2D image of the particle. Because the particles are at rest, the minor diameter is omitted from all calculations, including aspect ratio and CE diameter. Greyscale images of a selection of individual particles taken using the Malvern Morphologi particle analyser are given in Fig. 3.

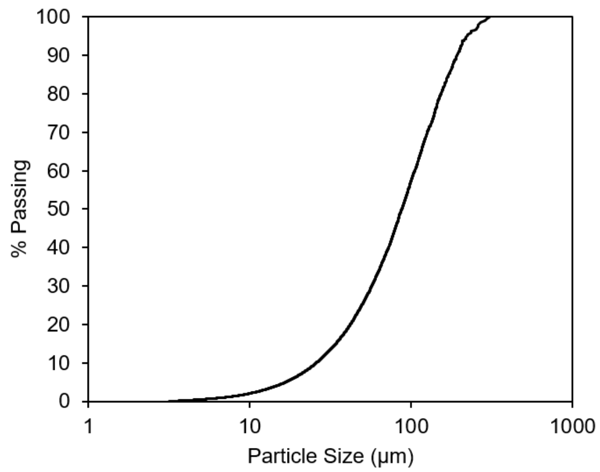

Figure 1. Grading curve of mineral sand tailings from Perth, Australia.

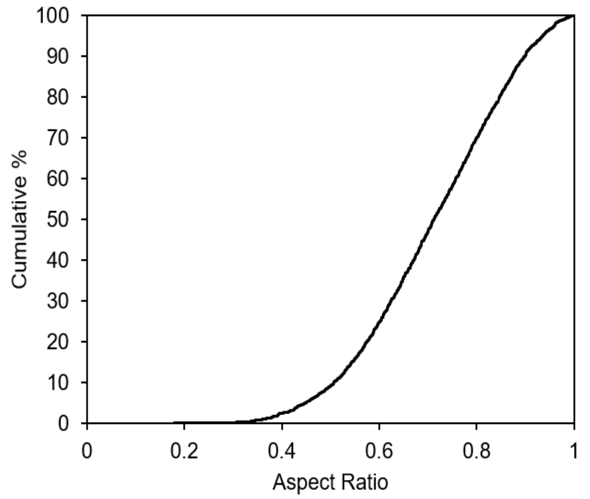

Figure 2. Cumulative frequency graph for aspect ratio.

Sampling of undisturbed tailings is often impractical and as a result the laboratory tests in this study have been carried out on reconstituted samples. The investigation presented here was also a fundamental investigation of the effects of transitional behaviour. This requires samples of different initial densities which could not be achieved with intact samples. The oedometer and triaxial samples were reconstituted in pastes or slurries, depending on the water content used at the time of mixing. Distilled water was gradually added into the dry tailings until the desired water content was reached. For the lower water contents this created a paste, and a slurry was created when higher water contents were used. Research by Shipton and Coop (2012) has suggested that for transitional soils different sample preparation methods seemed to have no significant effect other than the different initial densities they created, but here the only difference in preparation was the water content of the mix.

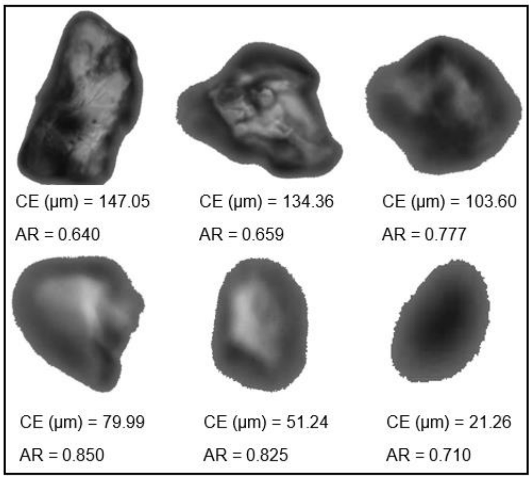

Figure 3. Greyscale images of individual particles. CE = circular equivalent diameter, and AR = aspect ratio.

A total of six triaxial tests were completed in this study. Pastes and slurries were placed directly into the oedometer ring, but for the triaxial, the higher water content slurries were first consolidated in a separate consolidometer tube until they were stiff enough to be handled, while the denser pastes could be placed directly into the membrane held on the platen inside a mould. A dense paste sample was also created using the consolidometer to see how the behaviour would compare with the other samples. Four loose samples were made using the consolidometer. A slurry or paste was spooned into the consolidometer before weights were added in stages and left for at least 24 hours. After being pushed out carefully from the consolidometer, the samples were cut to the correct length using a wire saw. Two dense samples were made directly on the platen, where a paste was placed and compacted gently in consistent layers in a split mould.

When investigating transitional soils, it is imperative to distinguish whether any differences of specific volume (or void ratio) are merely the result of errors in their measurement. Following similar procedures to Rocchi & Coop (2014) each value was therefore calculated in at least three different ways, using data from sample dimensions, wet weights, dry weights and water contents, before and after the test. This gives positive proof that each value of specific volume is accurate, and from these comparisons of methods it may be estimated that the typical error of specific volume in these tests is around ±0.03, much less than the differences recorded between tests. Others (e.g. Fourie et al. 2021) have standardised end-of-test freezing, but methods from Rocchi & Coop (2014) were preferred here as these tell us the accuracy.

2.2 *Test procedures*

The oedometer apparatus used in this research had a ring diameter of 50 mm. A total of four tests were carried out with initial specific volumes (v_i) ranging from 2.081 to 2.883. A summary of the oedometer tests is presented in Table 1.

Table 1. Summary of oedometer tests. σ'_{vmax} = maximum vertical effective stress.

Test No.	v_i	σ'_{vmax} (kPa)
1	2.081	320
2	2.883	7994
3	2.408	7994
4	2.439	7994

A Bishop and Wesley triaxial cell was used in this study that can provide a maximum of 800 kPa confining pressure. A rubber suction cap (Atkinson & Evans 1985) was used to prevent the initial tilting of the sample to improve the alignment of the sample and load cell. It is also required for cyclic loading as it allows a negative deviatoric stress to be applied. For the cyclic tests, the cycling was carried out slowly at one cycle every five minutes. The aim was not to replicate earthquake frequency, but to be able to track the pore pressure response accurately during the cycles.

All samples were approximately 76 mm in height and 38 mm in diameter. The Skempton B-value for all undrained cyclic tests was $\geq$ 0.99. After saturation, samples were isotropically compressed and undrained cyclic loading was applied or the samples were sheared monotonically. Two drained monotonic tests and four undrained cyclic tests were carried out. A summary of these tests can be found in Table 2.

Table 2. Summary of triaxial tests. Cyc = cyclic test, Mt = monotonic test and p'_i = initial mean effective stress, CSR = cyclic stress ratio

Test No.	Drained/ undrained	Preparation method	v_i	p'_i (kPa)	CSR
Cyc1	Undrained	Consolidometer	2.163	100	0.25
Cyc2	Undrained	Platen preparation	1.951	100	0.25
Cyc3	Undrained	Consolidometer	2.192	400	0.0625
Cyc4	Undrained	Platen preparation	1.918	400	0.0625
Mt1	Drained	Consolidometer	2.313	400	-
Mt2	Drained	Consolidometer	1.962	400	-

3 TEST RESULTS

3.1 *Compression behaviour*

Oedometer tests were carried out to identify whether non-convergent compression behaviour existed. The oedometer compression data are shown in Fig. 4. There is a clear non-convergence of compression paths from different initial states.

To quantify the degree of convergence, Fig. 5 illustrates how the initial specific volume may be plotted against that at 225 kPa (v_{225}) and 5650 kPa (v_{5650}) for the oedometer tests. v_{225} and v_{5650} correspond to specific loading stages. For consistency the initial specific volume was taken in each test at 20 kPa vertical stress (v_{20}). For soils with fully convergent paths the gradient of the data on this graph, defined here as m, would be zero and for soils with perfectly parallel compression paths m would equal one (Ponzoni et al. 2014). The m values for the oedometer tests are 0.79 and 0.71 for the two stress levels, so the graph displays a clear lack of convergence. Ponzoni et al. (2014) found m values of 0.40 and 0.38 from tests on silts and silty clays from the lagoon of Venice. The tests on the mineral sands tailings seem to give quite high m values in comparison and the tailings are therefore highly transitional.

Li and Coop (2018) investigated a silt-sized gold tailings and found an m value of 0.13 at 7MPa from oedometer tests indicating slight transitional behaviour. The tailings had a d_{50} of 0.011 mm and C_u of 7.3 so was fine and quite poorly graded. The oedometer curves only converged at very high stress levels, and convergence was slow, so their tailings was not fully transitional, however, a unique NCL was not reached, even at high stresses. A comparison with the mineral sand tailings would again indicate that the mineral sand tailings is highly transitional.

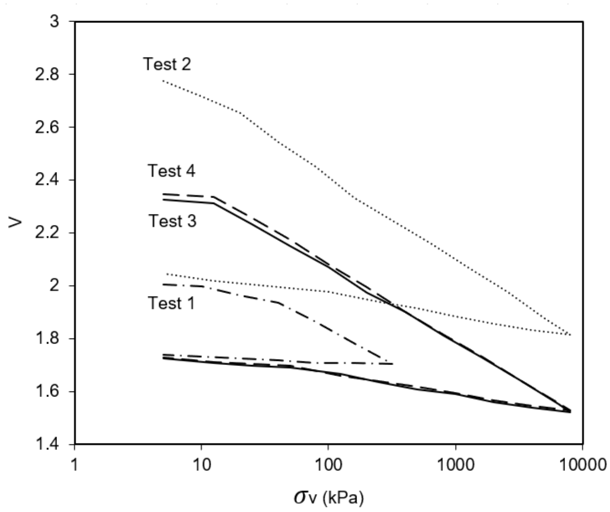

Figure 4. Oedometer compression data.

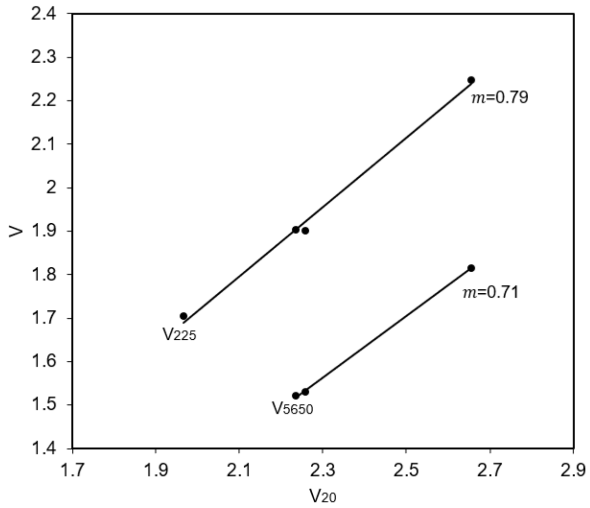

Figure 5. Quantification of convergence of one-dimensional compression curves for oedometer tests.

Triaxial tests were carried out to investigate the susceptibility to cyclic liquefaction and also to see whether or not there were well defined NCLs. The isotropic compression and shearing paths can be seen in Fig. 6. The stress level is represented by the mean normal effective stress p', defined as:

$$p' = (\sigma'_a + 2\sigma'_r)/3 \quad (2)$$

where σ'_a is the axial effective stress and σ'_r the radial effective stress. The triaxial isotropic compression was carried out at only 3.5 kPa/hr but nevertheless the small "tails" at the end of each compression curve represent a small amount of undissipated pore pressure. While the oedometer data appear almost parallel, there is some convergence in isotropic compression. For transitional soils, different apparatus will give different convergence rates depending on their combination of applied volumetric and shear strains (Todisco & Coop 2019). However, there is still no evidence of any unique single NCL up to 400 kPa. Test Mt2 was a paste sample (i.e. dense) that had been compressed in a consolidometer, like the loose samples, but its compression behaviour is very similar to tests Cyc2 and Cyc4 that were pastes directly placed on the platen.

The volume changes during shearing are also shown on Fig. 6. Given the significant difference in initial density and the fact that they would be expected to converge to a unique critical state specific volume, the volume changes should have been very different, which they are not. Test Mt1 was slightly incomplete and so the shearing path was completed through hyperbolic extrapolation. Mechanical constraints on the apparatus had stopped any further shearing. It is clear that both loose and dense samples compress and are not converging to a unique CSL. Shipton & Coop (2015) found that for sand-clay mixtures, no matter how dense the sample is initially, the samples always compressed on shearing. Creating a sample dense enough to dilate was not possible, which is also the case here. Shipton & Coop (2015) found parallel CSLs for different initial densities in triaxial tests, and this is likely to be the case also here.

The m value graph for isotropic compression is given in Fig. 7. The m values for the triaxial tests are 0.73, 0.51 and 0.42. For the oedometer tests, the m values show little change with larger stresses. In comparison, the triaxial tests show a greater change in m values and at lower stress levels indicating more convergence.

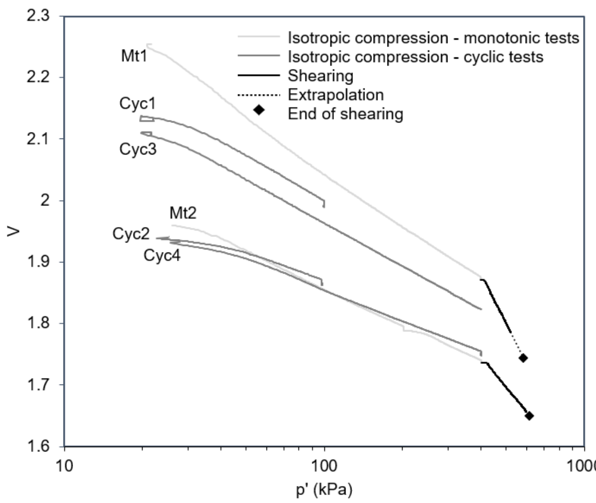

Figure 6. Isotropic compression data for four cyclic and two monotonic tests. Shearing paths included for both drained monotonic tests.

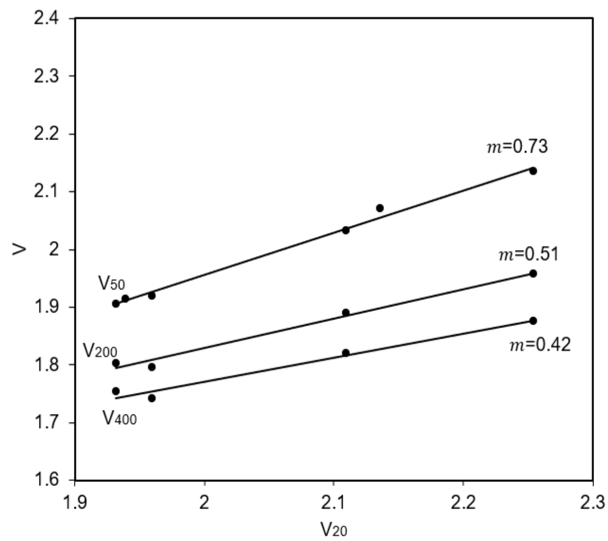

Figure 7. Quantification of convergence of isotropic compression curves for triaxial tests.

3.2 *Cyclic behaviour*

Two pairs of undrained cyclic tests were carried out and the pore pressure response curves can be seen in Fig. 8. Tests were stopped when either 5% axial strain (ε_a) was reached or 2000 cycles were completed. The change in pore pressure (Δu) has been divided by the mean initial effective stress (p'_i) so that all tests can be plotted on the same graph. Tests 1 and 2 have a cyclic stress ratio (CSR) of 0.25 and tests 3 and 4 have a CSR of 0.0625 (Table 2). The CSR is the ratio of the cycling relative to the effective confining pressure:

$$CSR = \sigma_d/2\sigma'_c \tag{3}$$

where σ_d is the difference between the maximum and minimum deviator stress, and σ'_c refers to the effective confining pressure. Tests 1 and 2 have low confining stresses and high CSRs and both tests fail after a few tens of cycles, while tests 3 and 4 have lower CSRs and higher p'_i values, but only show a small increase in pore pressure and do not fail even after 2000 cycles. For tests 1 and 2, as the pore pressure ratio moves towards unity, the strains accelerate towards failure. Despite the very large difference in initial densities for each pair, the pore pressure responses are similar with only minor differences. The dense samples tend to have slightly lower pore pressures at higher stress levels but there is no impact on the susceptibility to failure or otherwise.

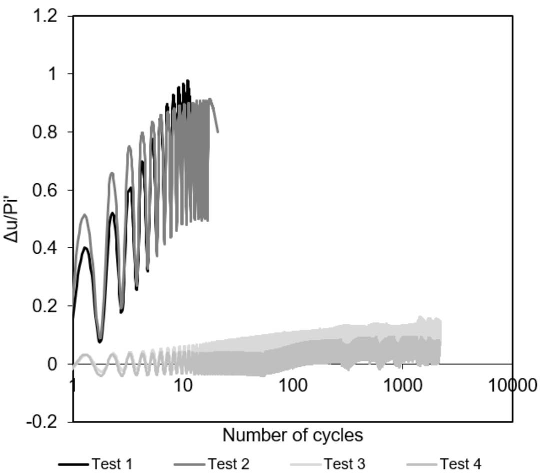

Figure 8. Pore pressure response curves for cyclic tests.

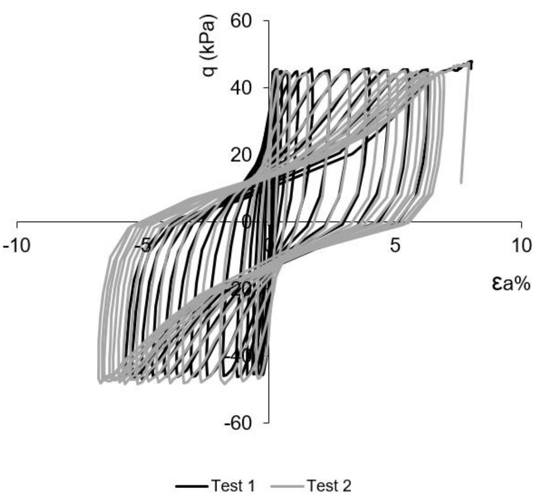

Figure 9. Stress-strain data for cyclic tests 1 and 2.

The stress-strain data for the cyclic tests can be seen in Fig. 9. Again, despite the large difference in initial density, the stress-strain behaviours of tests 1 and 2 are similar. Tests 3 and 4 have been plotted in Fig. 10 as the strains were very small in comparison with tests 1 and 2. The data overlie each other as the strains are again very similar.

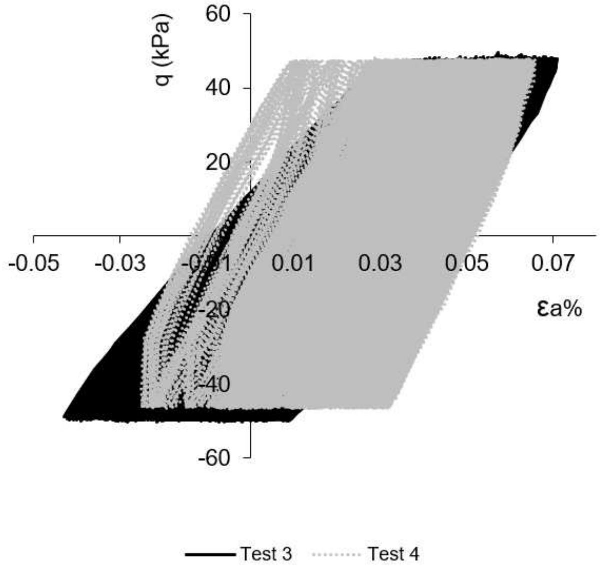

Figure 10. Stress-strain data for cycle tests 3 and 4.

4 CONCLUSIONS

The analysis of test data of mineral sands tailings from near Perth, Australia has highlighted the transitional nature of the material. In both isotropic and one-dimensional compression there is a clear non-convergence of compression paths from different initial states. More convergence can be seen in isotropic compression than in one-dimensional compression, although a unique NCL could not be reached even at 400 kPa and monotonic drained shearing did not lead to unique critical states. As for other transitional soils the volume changes seen in compression and shearing are much less different between loose and dense samples than they would be for conventional soils with unique NCLs and unique CSLs.

For this transitional soil, the tests presented in this paper show that the initial density also does not make a significant difference to the mechanical behaviour in undrained cycling and initial density was found to be much less important than CSR and p'_i.

Many tailings are hydraulically placed in loose states. If a tailings is transitional, and compression under the overburden pressure will not cause it to reach the NCL, it might have been a concern that the initial placement density would have a significant impact on subsequent behaviour. This turns out not to be the case and in compression paths converge only slowly so the amount of compression experienced will be not so different for different initial densities. In shearing and cyclic loading, the difference in behaviour for different initial densities is minor, while for a conventional soil there could be a large difference. It may therefore not be so necessary to be concerned about the placement density for transitional tailings. If the tailings had conventional behaviour the placement density could be very important.

There is nothing about the grading shape or mineralogy that allows us to distinguish why this tailings is transitional. Previous works (Ponzoni et al. 2014; Todisco & Coop 2019) have also failed to identify when and why transitional behaviour is seen in other soils. To identify whether the soil is transitional or not it must be tested and as yet there is no way to anticipate transitional behaviour.

5 ACKNOWLEDGEMENTS

Many thanks to laboratory technician Ben Boorman for his support in the laboratory.

6 NOMENCLATURE

A	particle area
AR	aspect ratio
CE	circular equivalent diameter
CSL	critical state line
CSR	cycle stress ratio
C_u	coefficient of uniformity
d_{50}	mean particle size
e	void ratio
Gs	specific gravity
m	gradient
NCL	normal compression line
p'	mean normal effective stress
p'_i	initial normal effective stress
v_i	initial specific volume
P_{real}	particle perimeter
R	roundness
S	sphericity
v	specific volume
Δu	change in pore pressure
ε_a	axial strain
σ'_a	axial effective stress
σ'_c	effective confining pressure
σ_d	maximum and minimum deviator stress difference
σ'_r	radial effective stress
σ'_{vmax}	maximum vertical effective stress

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