Effect of saturation procedures on direct simple shear testing of silt tailings

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Words: 2038 (Main body text)

Figure: 5

Tables: 3

Manuscript submitted to Géotechnique Letters October 2024

Abstract

The direct simple shear (DSS) test carried out under constant volume (CV) conditions forms one of the primary laboratory devices to characterise soils and tailings. The use of CV conditions to simulate undrained shearing is supported by historical evidence on the testing of a saturated clay and dry sands, with this evidence being incorporated into current guidelines and state of practice procedures. However, some recent comparisons of the results of undrained hollow cylinder simple shear (HCSS) and CV DSS tests on predominately silt gold tailings adopting state of practice test procedures (i.e., inundation of the sample after loose moist tamping) showed much less post-peak strength loss in the gold tailings than the undrained HCSS tests. The current study investigated this discrepancy further by carrying out DSS tests under high back pressures, undrained confined simple shear (CSS) tests and DSS tests after flushing with carbon dioxide and with use of a small back pressure. In all cases, the undrained tests or DSS tests with greater effort put towards saturation exhibited more pronounced post-peak strength loss more consistent with the HCSS and the critical state line. The importance of these results on the estimation of tailings brittleness in engineering practice was outlined.

Introduction

The direct simple shear (DSS) forms one of the key laboratory tests for the monotonic and cyclic characterisation of soils. An important aspect of common DSS testing is the use of the constant volume (CV) approach to reproduce undrained shearing conditions. There is strong evidence that for saturated clays CV tests produce results indistinguishable from undrained shearing (Dyvik et al. 1987). Further, for sands, it has been found that the CV technique allows tests on dry sands to give the same results as saturated sands (Finn and Vaid 1977), with the approach of testing near-dry specimens being advocated more generally for non-plastic soils (Chen et al. 2022) and adopted in determination of the critical state line (CSL) by means of CV DSS tests (Chen and Olson 2021). However, it is noted that for cyclic testing of clayey sands this similitude between dry and saturated samples has been questioned (Monkul et al. 2015). Further, Fanni et al. (2022) showed that simple shear tests carried out in a hollow cylinder torsional shear system (HCSS tests) showed far more brittle behaviour than CV DSS tests of the same gold tailings at similar states, raising questions about the efficacy of conventional saturation procedures.

Mine tailings, which comprise a wide range of material types and gradation from sands to clays, often consisting predominantly of low plasticity silts, are increasingly being characterised using CV DSS (e.g. Jefferies et al. 2019). Such tests are often prepared initially unsaturated using loose moist tamping (LMT) and saturated through flushing, followed by keeping samples in contact with water at atmospheric pressure. Current standards for CV DSS testing, and specifically their requirements around sample saturation (or not) are as follows:

- Cyclic DSS testing (ASTM 2019): testing of dry or saturated samples are permitted, with saturated samples to be “inundat[ed] with water”.

- Monotonic testing of fine grained soils (ASTM 2017), which does not include mention of testing dry samples and also requires saturated samples to be “inundat[ed] with water”.

As noted, the current standards either permit testing dry samples or mandate inundation. However, as emphasised by the results of Monkul et al. (2015) and Fanni et al. (2022) there remains uncertainty as to whether testing tailings silts dry, or even saturated through flushing and then keeping the sample in contact with water at atmospheric pressure (i.e. “inundation”), will ensure reliable results. The purpose of the current study is to expand on the work of Fanni et al. to further investigate this issue and provide preliminary recommendations on means to improve the monotonic response of LMT-prepared tailings silts in CV DSS tests.

Materials and methods

Materials

The study was carried out on a low plasticity gold tailings previously used by Fanni et al. (2022), having been characterised in a number of parallel studies (Reid et al. 2022; Ayala et al. 2022; Fanni et al. 2024) and a low plasticity platinum tailings batch previously used for cyclic and limited monotonic testing (Reid, Fanni, and Fourie 2024; Reid and Fanni 2024) with the critical state line (CSL) obtained by Reid (2022). The index properties and CSL of the two materials are summarised in Table 1.

Table 1: Index properties of soils tested in this study

Property	**Gold tailings**	**Platinum tailings**
% < 75 µm	59	72
% < 38 µm	43	60
Liquid limit (%)	18	18
Plastic limit (%)	16	12
Plasticity Index	2	6
Specific Gravity (-)	2.78	3.04

Conventional CV DSS approach

The first set of tests were carried out on gold tailings using “conventional” CV DSS testing to confirm and expand the results of Fanni et al (2022). The tests carried out are summarised in Table 1. Samples of 100mm diameter were prepared in an SGI DSS manufactured by GDS Instruments. Active CV control was applied by means of a linear variable displacement transducer mounted directly to the top cap, recording displacement on a smooth stainless steel “track” mounted to the base of the bottom platen.

Samples were prepared using LMT, then placed within the DSS and a bedding load ranging from 25 - 500 kPa applied, with saturation bedding load used to target different loose densities as per Reid et al. (2023). The samples were flushed from bottom to top with deionised water until bubbles ceased exiting the top of the specimen and saturation collapse as tracked through vertical displacement of the sample ceased. Both ends of the sample were then connected to the deionised water reservoir placed at the same height as the sample - i.e., an approach to saturation that is consistent with typical industry practice for the testing of moist tamped tailings silts (Jefferies et al. 2019) and aligns with the requirement for “inundation” of samples as per ASTM (2017). Samples were then consolidated to the target vertical effective stress, prior to CV shearing at 5%/hour.

Table 2: Summary of tests carried out on gold tailings in current study and Fanni et al. (2022)

Test no.	**Test type**	**Test source**	**Consolidated state**				**Shearing response**			
			Vertical effective stress, σ'_{vc} (kPa)	**Drained static shear stress, τ_{vh-c} (kPa)**	**Consol. void ratio, e_c**	**Ψ_0**	**Peak τ_{vh} (kPa)**	**σ'_v at end of shear (kPa)**	**τ_{vh} at end of shear**	**I_B**
G-DSS1	Inundate only	Fanni et al. (2022)	300	0	0.70	0.09	46	63	37	0.20
G-DSS2		Fanni et al. (2022)	300	0	0.70	0.09	47	61	37	0.20
G-DSS3		Fanni et al. (2022)	200	0	0.72	0.10	30	37	23	0.23
G-DSS4		Fanni et al. (2022)	496	0	0.69	0.11	76	117	59	0.22
G-DSS5		This study	200	0	0.72	0.10	28	45	22	0.23
G-CSS1	CSS	This study	202	0	0.71	0.09	29	3	5	0.81
G-DSS-500BP-1	500 kPa BP	This study	199	0	0.69	0.07	29	9	10	0.66

Confined simple shear

A second set of tests on the gold tailings were carried out in a confined simple shear (CSS) system, also manufactured by GDS, where lateral confinement is applied through a cell pressure. This form of testing was outlined by Boulanger et al. (1993) and is commonly referred to as "Berkeley-type" simple shear.

Samples were prepared using LMT within a membrane-lined split mould. Initial flushing was carried out under an 50 kPa vertical bedding load with the split mould still in place. After saturation collapse ceased, a suction of 20 kPa was applied to the sample using a pressure/volume controller and the split mould was removed. This process allowed the sample diameter to be accurately measured after saturation collapse, removing the most significant uncertainty in calculating sample volume. The samples were then back pressure (BP) saturated to 500 kPa, achieving a minimum B value of 0.95.

Consolidation was carried out to a vertical effective stress of 200 kPa while maintaining a K_0 of 0.5, then the drainage valves closed, and the sample sheared undrained at 5%/hour. During shearing, the cell pressure was held constant.

CV DSS within CSS

Another test on the gold tailings was carried out using the CV DSS approach with lateral confinement provided by Teflon rings, but with the entire sample within the CSS system enabling a BP of 500 kPa to be applied, resulting in a B value of 0.95.

CV DSS with small BP

Given the promising results seen in the CSS and BP CV DSS tests on the gold tailings, another form of CV DSS was carried out that could be performed in a conventional apparatus. This was to produce a method of improved saturation and more realistic monotonic behaviour in a system far more common in industry than the CSS. This set of tests was carried out on the platinum tailings, with the test on this material summarised in Table 3.

Table 3: Summary of Platinum tailings CV DSS tests carried out in this study and Reid and Fanni (2024)

Test no.	Test type	Test source	Consolidated state				Shearing response			
			Vertical effective stress, σ'_{vc} (kPa)	Drained static shear stress, $\tau_{vh\text{-}c}$ (kPa)	Consol. void ratio, e_c	Ψ_0	Peak τ_{vh} (kPa)	σ'_v at end of shear (kPa)	τ_{vh} at end of shear	I_B
P-IU-1	Inundate only	This study	200	0	0.72	0.10	29	32	16	0.44
P-IU-2		This study	200	0	0.75	0.13	27	32	16	0.39
P-IU-3		This study	200	0	0.79	0.17	25	24	11	0.56
P-IU-4		Reid and Fanni (2024)	250	25	0.73	0.12	45	52	26	0.43
P-IU-5		Reid and Fanni (2024)	250	25	0.73	0.11	46	50	26	0.43
P-IU-6		This study	250	25	0.70	0.09	45	47	25	0.44
P-IU-7		This study	500	0	0.66	0.09	76	97	54	0.29
P-SAT-1	CO2 flush and 10kPa BP	This study	250	25	0.67	0.05	45	25	13	0.72
P-SAT-2		This study	250	25	0.71	0.10	40	16	7	0.83
P-SAT-3		This study	500	0	0.66	0.08	71	29	16	0.77

The modified procedure involved LMT preparation and application of a bedding load of 50 kPa, followed by flushing with CO2 and then deaired water. After bubbles had ceased exiting the sample and saturation collapse was complete (same criteria as standard CV DSS tests previously outlined), the reservoir of deaired water was placed 1m above the sample and connected to both ends of the specimen to provide a 10 kPa BP. It was found that with use of four o-rings to secure the membrane to the top platen, this magnitude of BP could be applied without leakage.

Results

Gold tailings

A summary of the gold tailings shearing behaviour as shear stress-strain and vertical effective stress - shear stress plots are provided in Figure 1. The response of the CSS tests and CV DSS test with BP is seen to be qualitatively different to those using standard saturation procedures despite similar consolidated void ratios (e_c) - a far greater post-peak reduction in strength is evident, consistent with the differences seen between CV DSS and HCSS in the previous comparison presented by Fanni et al. (2022). All the conventional CV DSS tests appear to achieve a steady state condition at high strain that would typically be assumed to represent a critical state condition in such testing (e.g. Chen and Olson 2021). The CV DSS with back pressure and CSS are still slightly softening at high strain yet may be approaching a critical state condition.

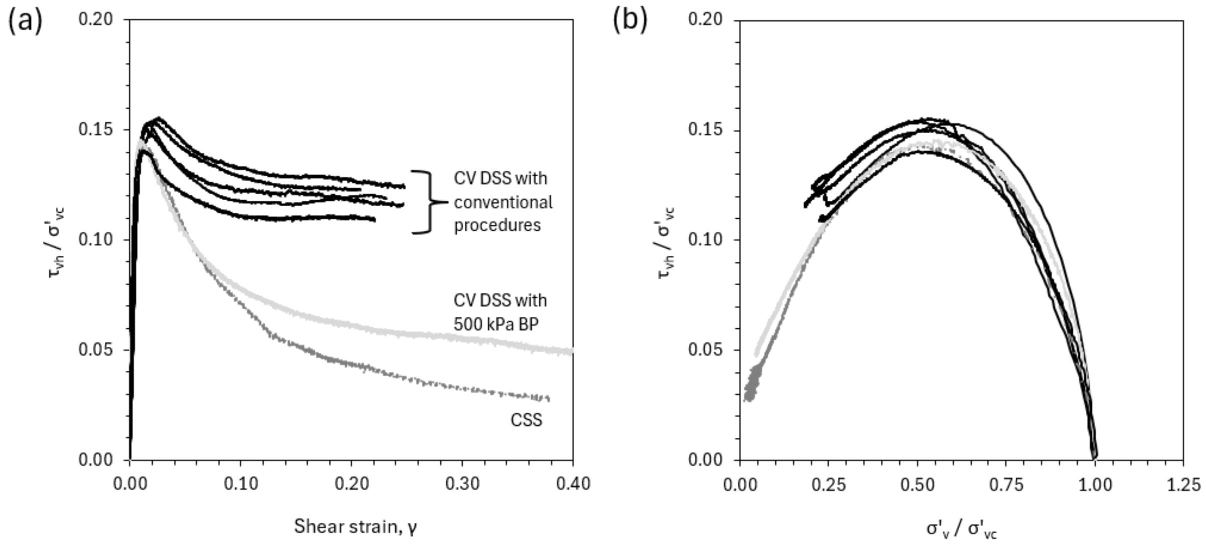

Figure 1: Summary of gold tailings CV DSS and CSS tests: (a) horizontal shear stress vs shear strain, (b) horizontal shear stress vs. vertical effective stress

The results of the gold tailings tests are summarised as a state diagram in Figure 2, with the CSL obtained by Fanni et al. (2024) included for reference. Calculation of initial mean effective stress (*p*') assumed a K_0 of 0.5. In recognition of the uncertainty in calculating *p*' in the DSS at high strain, based on Chen and Olson (2021) maximum and minimum principal effective stresses σ'_1 and σ'_3 were calculated assuming: (i) that horizontal plane was equal to maximum obliquity or (ii) that horizontal plane was the plane of maximum shear stress. Intermediate principal effective stress σ'_2 was calculated assuming that the intermediate principal stress ratio at high strain was 0.5. Based on these assumptions, at high strain CSS and CV DSS with BP appear to tend much closer towards CSL for the gold tailings obtained from triaxial tests, in contrast to the conventional CV DSS tests. It is emphasised that for this gold tailings there is no evidence for a Lode angle dependency on CSL elevation in the compression plane (Fanni et al. 2024), and thus no reason why shearing under simple shear loading should not tend towards the triaxial-determined CSL.

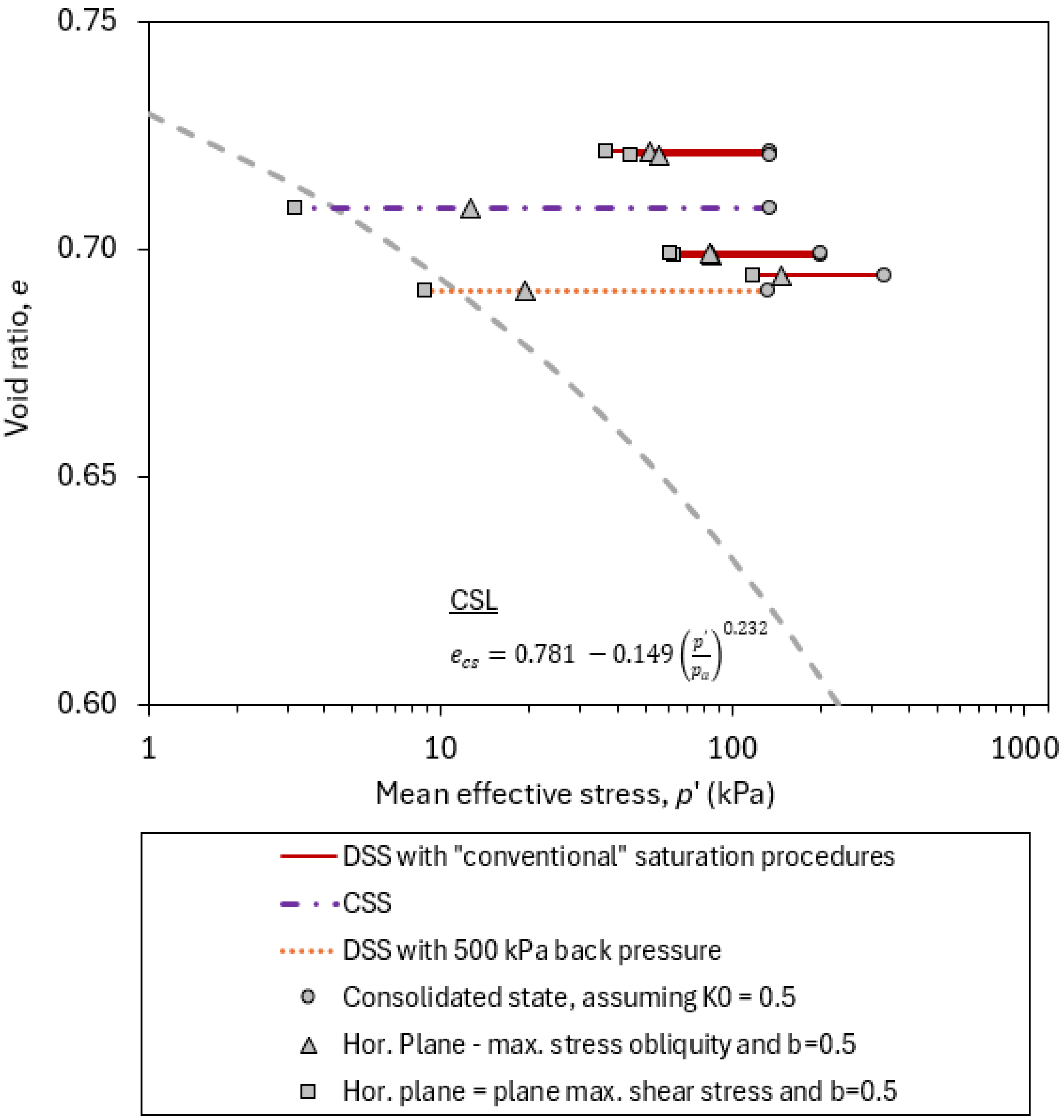

Figure 2: State diagram of gold tailings CV DSS and CSS tests, with CSL Fanni et al. (2024)

Platinum tailings

The shearing response of the platinum tailings is summarised in Figure 3. Like the gold tailings, the samples with BP exhibited a qualitatively more brittle response than conventional tests, with the end points of all tests appearing to represent a critical state condition.

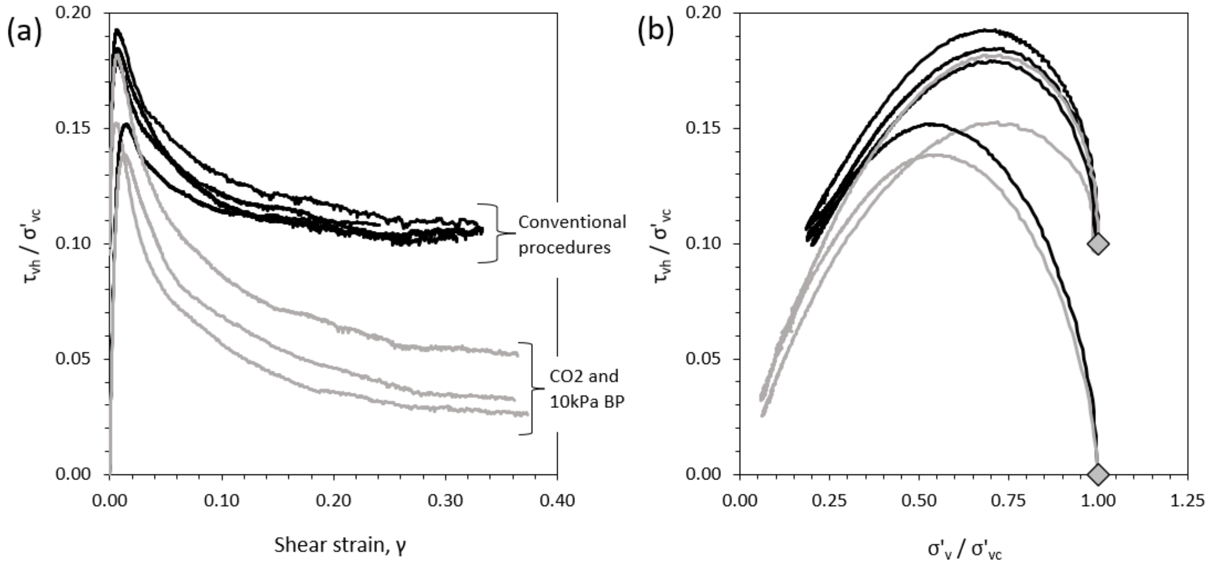

Figure 3: Summary of platinum tailings CV DSS: (a) horizontal shear stress vs shear strain, (b) horizontal shear stress vs. vertical effective stress

The platinum tailings tests are summarised as a state diagram in Figure 4 using the same assumptions as the previous gold tailings plot. The results are qualitatively similar - tests with CO2 flushing and 10 kPa BP align far better with the triaxial-inferred CSL than those using conventional saturation procedures.

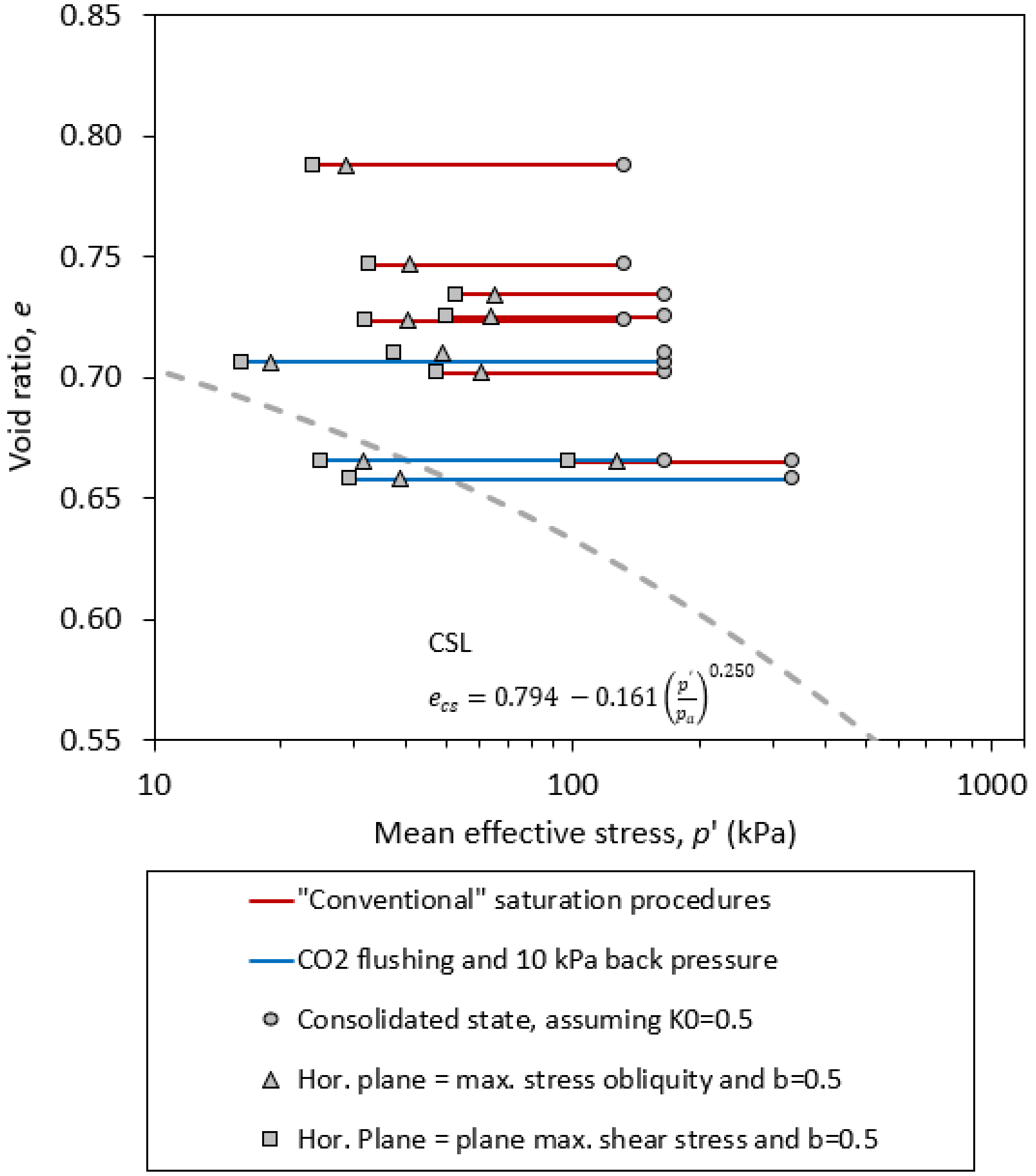

Figure 4: State diagram of platinum tailings CV DSS tests, with CSL from Reid (2022)

As to the likely cause of the response seen, insufficient saturation of conventional tests may mean some matric suction remains, and thus the samples are tending to a CSL at a higher elevation (e.g. Wheeler and Sivakumar 1995). It is noted that predominantly silt tailings prepared using LMT there is a greater potential for matric suction to exist and thus for suction-hardening of the CSL than sands. Therefore, historic testing of dry sands, and the approaches developed largely from the conclusions drawn therein, may not be useful guides as to the importance of saturation in the CV DSS testing of tailings silts.

Brittleness index synthesis

To examine the practical implications of use of conventional-saturation CV DSS on engineering practice, Figure 5 presents a synthesis of all the results from the study as Brittleness Index I_B (Bishop 1967) against consolidated state parameter, with Ψ_0 calculated adopting the same K_0 = 0.5 assumption as previous. For reference, I_B is calculated as:

$$I_B = \frac{\tau_p - \tau_r}{\tau_p}$$

Where τ_p and τ_r are peak and residual shear strength, respectively. An I_B value of 0.4 is also highlighted based on the work of Robertson (2017) showing that historic examples of flow liquefaction are generally of greater I_B. It can be seen from this synthesis that conventional CV DSS tests exhibit far greater brittleness at a particular value of Ψ_0, with these agreeing well with the results of previous HCSS testing. Further, the lesser brittleness of loose samples in conventional CV DSS could lead to potentially erroneous conclusions regarding the risk associated with a particular deposit of tailings (e.g. ICOLD 2023).

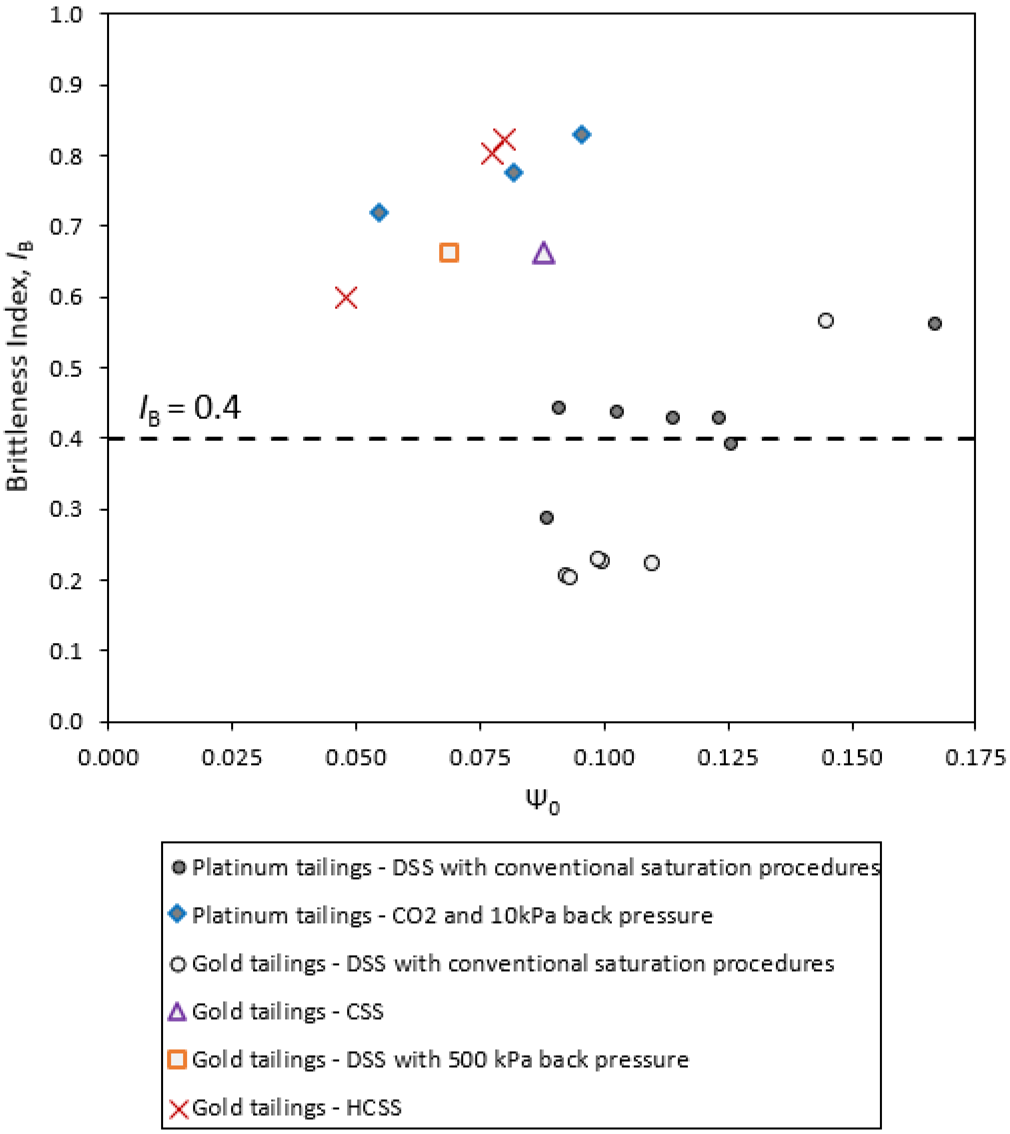

Figure 5: State diagram of platinum tailings CV DSS tests, with CSL from Reid (2022)

Conclusions

The current study involved a more detailed investigation of previously-documented issues with the large strain monotonic CV DSS shearing response of LMT-prepared silt tailings. This was carried out by further conventional and back-pressure saturated CV DSS tests and CSS tests on a gold and platinum tailings. The results of the study can be summarised as follows:

- CV DSS tests saturated using methods that represent current standard/conventional approaches (i.e. “inundation”) show less post-peak loss of strength and contractive tendency than implied by their initial state.
- CSS and CV DSS tests with varying levels of BP saturation show a behaviour more consistent with the sample initial states, tending much closer to the CSL.
- The results strongly suggest that a more accurate monotonic large-strain characterisation of silt tailings is achieved in the CV DSS if greater efforts are made to improve saturation compared to that specified in current testing standards and common industry methods.
- The reduced I_B seen from conventional CV DSS tests could lead to erroneous conclusions regarding the risk of flow liquefaction of loose tailings deposits.

Data availability statement

Data generated or analysed during this study are available in the OSF repository at DOI 10.17605/OSF.IO/EU8PG, direct link: https://osf.io/eu8pg/?view_only=aae417a84eba40a6879ace035120980a

Material availability statement

Material used for testing in this study are available from the corresponding author upon reasonable request.

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