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Unsaturated Shear Strength Characteristics of Filtered Tailings through Modified Direct Simple Shear (MDSS) Apparatus

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ABSTRACT: Filtered Tailings Storage Facilities (FTSFs) are increasingly recognised as a sustainable alternative to conventional slurry tailings storage facilities within the mining industry, owing to their enhanced stability and environmental benefits. However, the geotechnical design of FTSFs presents unique challenges due to the unsaturated state of filtered tailings. A fundamental gap hampers their design by limiting understanding of unsaturated shear strength, as empirical models fail to capture the unique response of tailings. A significant knowledge gap exists in applying Critical State Soil Mechanics principles, which are mature for saturated soils, to unsaturated materials such as tailings. Consequently, this study aimed to evaluate the unsaturated shear strength of tailings and the critical-state behaviour of filtered tailings. Laboratory experiments were conducted on tailing specimens with a dry density of 1.9g/cm³ under low suction (30kPa) and saturated conditions. The tests were performed using a Modified Direct Simple Shear apparatus, specifically designed to incorporate a through-the-test suction-control feature to circumvent the time-consuming triaxial testing program. The study demonstrates that higher density (1.9g/cm³) and matric suction (30kPa) significantly enhance the shear strength of tailings. Critically, comparison of the results from the study with literature indicates that a unique critical state line (CSL) does not exist for this material; instead, a family of parallel CSLs can be observed, governed by the initial particle size distribution and compaction fabric, demonstrating transitional behaviour where the end-state retains a memory of the initial structure. A key limitation of this research is the focus on a single density and suction level. Future research must expand testing to a broader range of suction and density conditions to support the development of predictive models that integrate the effects of suction and fabric, thereby enabling reliable design standards for FTSFs.

KEYWORDS: Filtered tailings, Unsaturated shear strength, Direct simple shear, Unsaturated soil, Critical state line

1 INTRODUCTION

One of the most pressing challenges in modern mining operations is the safe and sustainable management of tailings. Conventional slurry disposal methods pose significant environmental and safety risks, as evidenced by catastrophic failures worldwide (Wilson, 2021). In response, filtered tailings have emerged as a promising alternative in most cases, aligning with the best available technique principles by reducing water content and promoting unsaturated conditions. This approach enhances tailings stability through dilatant behaviour, minimising the risk of liquefaction and failure (Oldecop & Rodari, 2021). Despite these advantages, the widespread adoption of filtered tailings is hindered by a critical lack of fundamental understanding of their unsaturated shear behaviour. Current design practices rely heavily on empirical models developed for natural soils, which often fail to capture the unique geo-mechanical response of tailings under varying suction and density conditions (Wilson, 2021). This knowledge gap complicates the stability assessment of Tailings Storage Facilities (TSFs), underscoring the need for targeted research to develop reliable predictive frameworks.

Despite decades of research, fundamental disagreements persist regarding how the net stress friction angle ($\tan\phi^a$) varies with matric suction in unsaturated soils. While foundational models (Alonso et al., 1990; Fredlund et al., 1978; Oberg & Sallfors, 1997) assume $\tan\phi^a$ equals the saturated friction angle ($\tan\phi'$) and treating the suction-related parameter $\tan\phi^b$ as constant, experimental evidence reveals more complex behaviour. Studies by Gan et al. (1988) and Vanapalli et al. (1996) demonstrate that $\tan\phi^b$ decreases with increasing suction, prompting revised theoretical frameworks. More sophisticated approaches (Gallipoli et al., 2008; Toll & Ong, 2003) explain these variations through soil fabric dynamics - where moderate suction strengthens aggregates (increasing $\tan\phi^a$), but excessive suction causes aggregate breakdown and strength reduction. This reveals a critical limitation of conventional models: their inability to capture the nonlinear, microstructure-dependent nature of unsaturated shear strength.

The unique behaviour of tailings further complicates the prediction of unsaturated strength. Although the modified Mohr-Coulomb framework (Fredlund, 2006; Fredlund et al., 2012) provides a theoretical basis, empirical validations show alarming inconsistencies. Garven and Vanapalli (2006) found that most of the models perform poorly for tailings, with even the best by Vanapalli et al. (1996) achieving only 70% accuracy. Gold tailings studies by Rassam and Williams (1999a, 1999b) reveal particularly complex behaviour: strength increases linearly with suction up to the air-entry value, then transitions to nonlinear plateaus near residual saturation. These findings underscore a critical research gap - current models fail to universally predict tailings behaviour because they don't adequately account for material-specific responses to suction changes. This limitation poses significant challenges for the design of filtered tailings facilities, where precise strength estimation is crucial for stability.

The extension of critical state soil mechanics (CSSM) to unsaturated conditions remains a contentious topic, with researchers divided over fundamental aspects of soil behaviour under suction. While some studies (Bolton, 1986; Wheeler & Sivakumar, 1995) argue for a unique critical state line (CSL) in the mean effective stress(p')–deviatoric stress (q) plane, others (Cai et al., 2024; Sivakumar et al., 2010) report non-parallel CSLs in the ln p'-specific volume (υ) plane, suggesting that suction alters the soil's intrinsic compression behaviour. This discrepancy raises critical questions: Does suction merely shift the CSL, or does it fundamentally alter the soil's critical-state response? Proponents of the unique CSL hypothesis contend that suction acts as an independent stress variable, preserving the CSSM framework's simplicity (Alonso et al., 1990). However, critics highlight that fabric changes and partial saturation disrupt particle interactions, leading to suction-dependent critical states, a phenomenon that is particularly evident in high-plasticity clays

(Estabragh & Javadi, 2008). The lack of consensus undermines the reliability of predictive models for slope stability and earth structures, where accurate strength estimation is paramount.

Further debate centres on material-specific responses, particularly in transitional soils like silty sands. Research by Rampino et al. (2000) and Cai et al. (2024) demonstrate that low-density silty sands exhibit shear shrinkage, whereas dense specimens dilate, implying that density and suction jointly govern critical-state behaviour. Yet, the validity of a unified M* parameter (e.g., M* = 1.4 for silty sand) across suction levels remains contested. If suction-induced particle aggregation (Toll, 1990) enhances dilatancy, should M* be suction-dependent? Opposing views emerge from studies on kaolin (Sivakumar et al., 2010), where non-parallel CSLs suggest that M* varies with hydration. This inconsistency challenges the universality of CSSM for unsaturated soils and calls for a microstructure-informed approach. Until these uncertainties are clarified, practitioners must critically evaluate whether existing critical-state frameworks can adequately address practical challenges in unsaturated soil, or whether fundamentally new theoretical approaches may be required.

Critical gaps in understanding the unsaturated shear strength characteristics of tailings underscore the urgent need for additional experimental research to advance both theoretical frameworks and practical applications. While filtered tailings offer a promising approach to sustainable mine waste management, the current inability of empirical models to reliably predict their mechanical behaviour under varying suction and density conditions poses significant challenges for TSF design and stability assessment. Therefore, this study employs Modified Direct Simple Shear (MDSS) testing as a pragmatic and efficient method to evaluate unsaturated tailings behaviour, compared with triaxial testing, which requires a sophisticated setup and time-consuming procedures that often limit its practicality for extensive parametric studies.

2 TEST MATERIAL AND BASIC SOIL PROPERTIES

Gold mine tailings procured from a gold ore mining site in Australia are used in this study. The tailings from the same mine site have previously been the subject of investigation in related research by Nayanthara et al. (2024); Nayanthara et al. (2023); Pahalage (2024) and Pahalage Nishadi et al. (2024). The Particle Size Distributions (PSDs) of the gold tailings obtained by previous studies and this study are shown in Figure 1, which indicates a clear difference among the PSDs. Table 1 compares the previously reported basic index properties of gold tailings with those obtained in the present study, highlighting several key differences. Fine content decreased from 67.2% and 64.0% in earlier studies to 56.3% in this study, and the mean particle size (D50) increased substantially from 25µm and 40µm to 65µm, suggesting that the current sample is considerably coarser, likely due to differences in ore mineralogy. All the gold tailings exhibit low plasticity indices, classifying them as low-plasticity materials. According to the Unified Soil Classification System (USCS), these tailings can be identified as Silty Clay (CL-ML).

3 MODIFIED DIRECT SIMPLE SHEAR TESTER AND PROCEDURE

The Conventional Direct Simple Shear test setup has been modified to control matric suction by continuously applying a negative pore-water pressure to the sample via vacuum throughout the test. The porous disk in the base pedestal was replaced with a 100 kPa Air-Entry-Value (AEV) ceramic disc (Figure 2) to perform shear tests on the sample under direct matric suction up to 80 kPa.

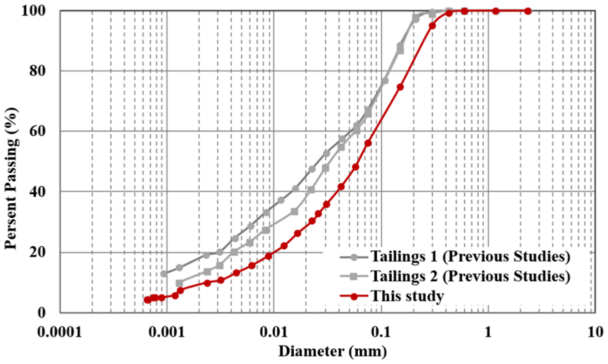

Figure 1. Particle size distribution of the gold tailings

Table 1. Basic index properties of the gold tailings

Property	Previous Studies		This Study#
	Tailings 1+	Tailings 2*	
Liquid Limit	26.6%	24.0%	25.6%
Plastic Limit	19.4%	18.0%	17.7%
Plasticity Index	7.2%	6.0%	7.2%
Fines Content (<75µm)	67.2%	64.0%	56.3%
Mean particle size (D50)	25µm	40µm	65µm
Specific Gravity (GS)	2.78	2.76	2.72
OMC (Standard Proctor)	-	-	14.5%
MDD (Standard Proctor)	-	-	1.87g/cm^3

+ Tailings 1 by Nayanthara et al. (2024 & 2023) & Pahalage (2024)
* Tailings 2 by Pahalage Nishadi et al. (2024) & Pahalage (2024)
# Basic index properties were obtained in accordance with the Australian Standards

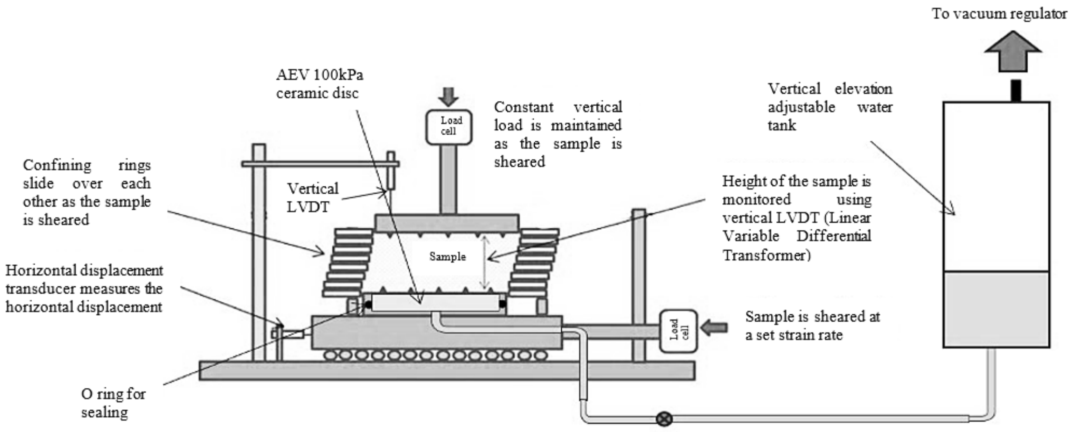

Figure 2. Schematic diagram of the Modified Direct Simple Shear Test setup.

Table 2. Summary of experimental results of the MDSS tests (Constant Load tests only)

	Test No.	Initial Conditions			Consolidation Stage		Peak (UF)	Critical State (CS)		
		Υ_d (g/cm3)	S (kPa)	e_i	e_{pc}	σ'_{v0} (kPa)	τ_{peak} (kPa)	σ'_{vCS} (kPa)	p'_{CS} (kPa)	e_{CS}
This Study	MDSS (1.9)_S0_σ_{v50}	1.88	0	0.474	0.281	44.8	31.5	46.3	30.9	0.263
	MDSS (1.9)_S0_σ_{v100}	1.86		0.482	0.274	101.0	70.4	106.2	70.8	0.269
	MDSS (1.9)_S0_σ_{v200}	1.88		0.482	0.267	192.1	98.9	211.1	140.7	0.193
	MDSS (1.9)_S30_σ_{v50}	1.89	30	0.466	0.399	50.0	41.0	49.9	33.3	0.377
	MDSS (1.9)_S30_σ_{v100}	1.81		0.531	0.347	104.5	77.3	95.8	63.8	0.318
	MDSS (1.9)_S30_σ_{v200}	1.91		0.451	0.318	210.1	139.7	211.5	141.0	0.278
Pahalage (2024)	DSS (1.3)_S0_σ_{v50}	1.37	0	1.03	0.656	50.0	15.8	49.0	32.6	0.609
	DSS (1.3)_S0_σ_{v100}	1.31		1.12	0.630	100.0	30.5	106.3	70.8	0.407
	DSS (1.3)_S0_σ_{v200}	1.31		1.11	0.985	199.9	58.3	208.0	138.7	0.401

The MDSS apparatus was used to test tailings under controlled suction. Specimens were prepared by placing a latex membrane-lined sample between filter papers within a steel ring stack to maintain a constant cross-section. After applying a 10N seating load, specimens were saturated. The negative pore water pressure was then applied to achieve the desired suction by adjusting the vacuum in the water tank, maintaining system airtightness for more than 27hours to reach equilibrium. This step was omitted for the saturated (0kPa suction) test series, in which consolidation began immediately after saturation. The consolidation stage proceeded under target normal stress until primary consolidation was complete, indicated by stabilised vertical displacement. Shear testing employed a controlled displacement rate of 0.0002mm/s, selected based on the findings of Gan et al. (1988) which established that rates ≤0.00022mm/s are necessary to maintain pore-air pressure equilibrium in clayey soils (Gallage & Uchimura, 2016). This low strain rate prevents the development of non-uniform suction conditions that may arise from particle rearrangement and shear band formation during testing. During shearing, a constant normal stress was maintained, allowing volume changes only through specimen height adjustment, facilitated by the steel rings. Horizontal and vertical loads and displacements were recorded throughout the test. Post-shearing, the specimen's final moisture content was determined.

4 RESULTS AND DISCUSSION

4.1 *Experimental Results*

This study examined the shear behaviour of tailings specimens with a dry density of 1.9g/cm³ under various stress conditions using the MDSS System. The testing program included both saturated (S0) and unsaturated (S30, with 30 kPa matric suction) conditions, conducted under constant axial loads representing three axial stress levels: 50 kPa, 100 kPa, and 200 kPa. Figure 3 presents the shear stress versus shear strain relationships for specimens under both S0 and S30 conditions. Shear strain was calculated as the ratio of lateral displacement to the specimen height at the end of the consolidation stage. Identified 'Ultimate Failure' points and 'Critical State' points for each test are represented with a rectangle and circle, denoted as UF and CS in the legend of Figure 3 and 4, respectively. Key experimental observations, including initial dry density (Υ_d), applied suction (S), initial and post-consolidation void ratios (e_i and e_{pc}), normal/axial stress at the end of consolidation (σ'_{v0}), peak shear strength (τ_{peak}), normal/axial stress at the critical state (σ'_{vCS}), mean effective normal/axial stress at the critical-state (p'_{CS}) and void ratio at the critical-state (e_{CS}), are summarised in Table 2 and will be discussed in Section 4.2 and 4.3. Figure 4 illustrates the variation of volumetric strain (equivalent to axial strain in this test series) with shear strain for the 1.9g/cm³ specimen. Despite being compacted to maximum dry density in accordance with the standard Proctor compaction test, the specimens exhibited contractive volumetric strain behaviour under these testing conditions.

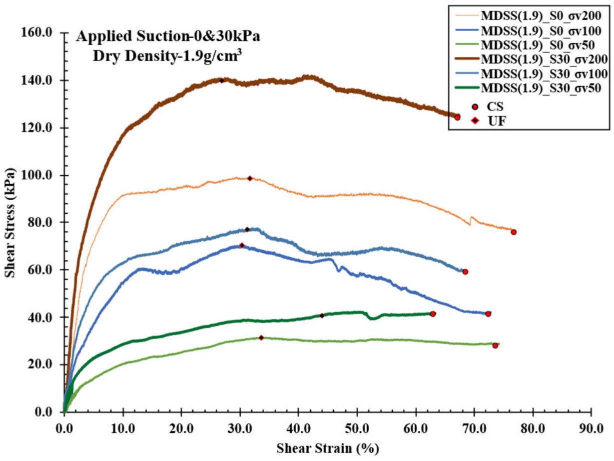

Figure 3. Shear stress variation over shear strain of specimens of dry density 1.9g/cm^3 when saturated and under constant suction of 30kPa

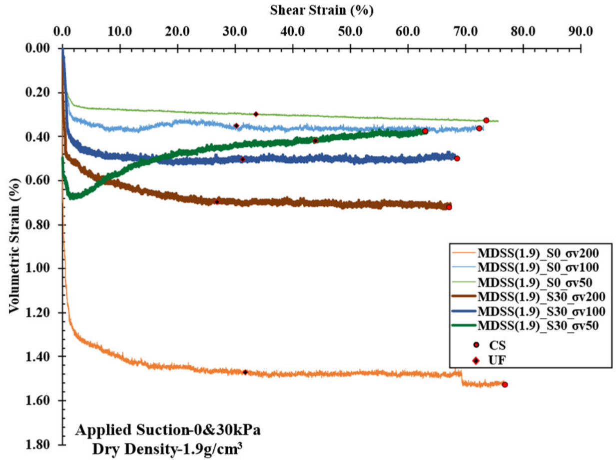

Figure 4. Volumetric strain variation over shear strain of specimens of dry density 1.9g/cm^3 when saturated and under constant suction of 30kPa

4.2 *Peak shear strength and Ultimate Failure (UF) envelope*

Figure 5 illustrates the relationship between peak shear strength and applied axial stress (50, 100, and 200kPa) for tailings specimens compacted to an initial dry density of 1.9g/cm³ under both saturated (S0) and unsaturated (S30) conditions in this study. For comparative density analysis, experimental data from

Pahalage (2024) were included, in which specimens prepared by slurry deposition (initial density = 1.3g/cm³) were examined under similar loading conditions. The derived geotechnical parameters, including the axial stress-dependent friction angle (ϕ^a) and apparent cohesion, are systematically presented in Table 3.

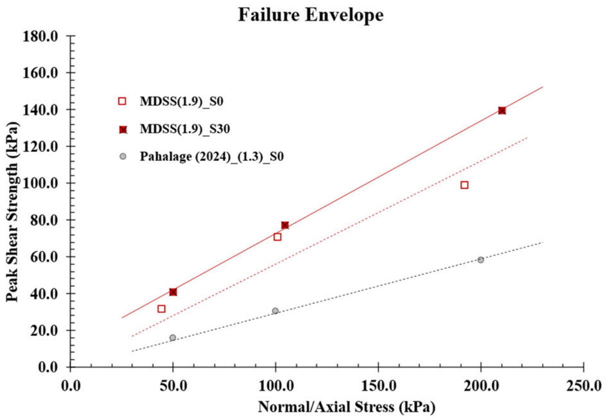

Figure 5. Comparison of peak shear strength of tailings specimens for S0 & S30 under axial stresses of 50 kPa, 100 kPa, and 200 kPa

Table 3. Summarised friction angle to the normal/axial stress and the apparent cohesion of the 1.9g/cm³ & 1.3-1.4g/cm³ dense tailings specimens

	Controlled Suction (kPa)	Friction angle ϕ^a (°)	Apparent Cohesion (kPa)	R2
This Study (1.9g/cm³)	0	28.5	0	0.980
	30	31.5	11.47	0.999
Pahalage (2024) (1.3-1.4g/cm³)	0	16.45	0	0.999

Analysis of the experimental results reveals that specimens compacted to a higher density (1.9g/cm³) exhibit superior peak shear strength characteristics. Notably, these specimens exhibit a significant increase in shear resistance under increased matric suction (S30 condition), highlighting the combined influence of density and unsaturated conditions on mechanical behaviour. Dense specimens exhibit higher friction angles than loose samples due to enhanced particle interlocking and dilatancy during shearing (Bolton, 1986; Yang & Luo, 2015). The tighter packing in dense soils forces particles to override each other, requiring greater energy expenditure that manifests as increased shear resistance. This mechanical interlocking is complemented by pronounced dilatancy, where upward particle movement generates additional normal stresses at contacts, effectively amplifying the mobilised friction angle (Been & Jefferies, 1985). Furthermore, dense specimens develop more uniform force chains and stable particle orientations during shear, delaying the formation of failure planes and maintaining higher shear resistance until larger strains are reached (Guo & Su, 2007). These particle-scale mechanisms collectively explain why compacted tailings with lower void ratios exhibit higher shear strength than looser deposits.

Although the data are limited for comparison, the determined apparent cohesion values were again compared with the matric suction levels, as shown in Figure 6. The friction angle with respect to matric suction (ϕ^b) was found to be 20.9 °. The models proposed by many researchers (Alonso et al., 1990; Fredlund et al., 1978; Oberg & Sallfors, 1997), consider $\tan\phi^b$, the friction angle associated with matric suction, as a constant independent of other factors. This simplification aids in modelling but has been challenged by the experimental data. However, experimental results from researchers like Gan et al. (1988) and Vanapalli et al. (1996) indicate that $\tan\phi^b$ decreases with increasing suction, contradicting the assumption of its constancy. Further testing is expected to be conducted in future to investigate these points under this study.

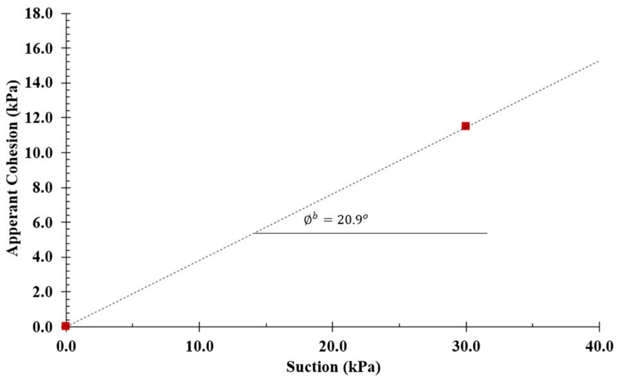

Figure 6. Apparent cohesion with S0 and S30 suction levels for 1.9g/cm³ dense specimen.

4.3 *Critical State Line (CSL)*

Critical state conditions from Table 2 were graphically interpreted in Figure 7. Two different equations (Equation 1 and 2) could be distinguished for S0 and S30 conditions of the 1.9 g/cm³ specimen. Equation 3 was developed for the gold tailings (tailings 2 in Figure 1 & Table 1), by Pahalage Nishadi et al. (2024). The tailings specimen was prepared adopting both the moist-tamped and slurry-deposited methods. Dry density of those specimens varied between 1.3-1.45g/cm³, representing a relatively very loose state of tailings compared to the specimen used in this study.

From Figure 7, it is evident that, at a constant dry density, the CSLs in the σ'_v-e plane remain parallel across different matric suctions; however, they shift leftward as suction increases. The parallel shift of CSLs under varying matric suctions at constant dry density has been robustly verified through multiple experimental studies. Alonso et al. (1990) first demonstrated this phenomenon via suction-controlled triaxial tests on kaolin and sandy clay, showing that while suction systematically translated the CSL in the ln(p')-v plane, the slope (M) remained unchanged, as evidenced by identical critical state stress ratios across suction levels (shown in their Figures 5 & 12). Wheeler and Sivakumar (1995) reinforced these findings through tests on Speswhite kaolin, revealing that suction-modified hardening laws shifted the CSL intercept (Γ) while preserving its slope (λ), with all paths converging to a geometrically similar critical state hyper line (defined by the Equations 14 & 15 in their paper). Cai et al. (2024) further validated this behaviour for silty sand, confirming that CSLs under 30–200 kPa suction maintained parallel alignment at fixed density, with consistent M* values in the p'-q plane (Conclusion d of their paper). Collectively, these studies confirm that suction-induced stiffening alters the CSL's position via pre-consolidation pressure effects, but not its intrinsic slope, governed by particle arrangement. Regardless of the testing method employed, whether suction-controlled triaxial testing or suction-controlled direct simple shear testing, a parallel shift of the CSL can be observed. This methodological independence confirms that the phenomenon is inherent to unsaturated soil behaviour rather than an artifact of specific testing conditions. However, further tests are required for a quantitative comparison.

The parallel translation of the CSL with matric suction enhances shear strength and apparent pre-consolidation, offering potential for steeper, higher-density tailings storage. This strength gain is, however, metastable. It is contingent on maintaining the unsaturated hydraulic regime, as rapid saturation can cause CSL regression, leading to collapse, strength loss, and potential static liquefaction. Therefore, capitalising on this behaviour necessitates a design paradigm focused on the rigorous, long-term management of hydraulic boundary conditions through controlled drainage and infiltration barriers to prevent catastrophic suction loss.

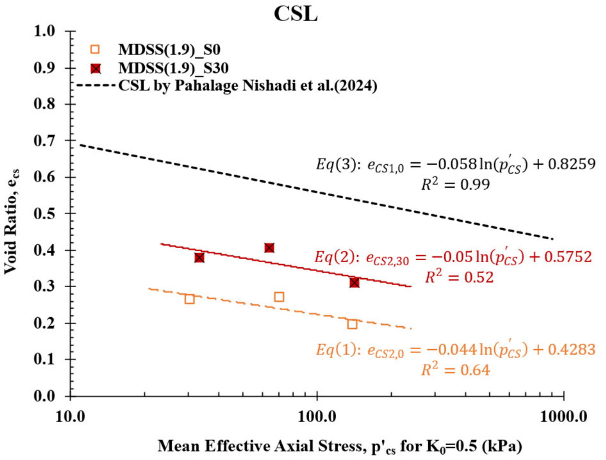

Figure 7. CSLs for gold tailings

The critical state in soils is reached after extensive shearing and represents a terminal condition characterised by invariant shear strength and void ratio under constant-volume deformation. This ultimate state is path-independent: soil with an initial void ratio lower than the critical value dilates toward it, while soil with a higher initial void ratio contracts (Jefferies & Been, 2015). Thus, irrespective of starting density or stress history, continued shear deformation converges toward this unique mechanical equilibrium. However, experimental evidence from this study challenges the assumption of a unique CSL for the tailings. As demonstrated in Figure 7, tailings samples with differing initial densities exhibit distinct CSLs. This divergence is fundamentally linked to variations in PSD, as seen in Figure 1, where Tailings 2 and the primary study material possess different gradations. Muir Wood and Maeda (2008) established that evolving gradation and particle crushing directly influence the CSL, noting that while crushing itself does not immediately alter void ratio, it modifies constitutive properties, leading to more efficient particle packing and a subsequent reduction in the critical void ratio. Contrary to a simplistic expectation that higher fines content linearly depresses the CSL, the relationship is non-monotonic. As shown by Lines and Llano-Serna (2025) CSL intercepts for soil mixtures with 5%, 40%, 50%, and 80% fines initially decreased up to 40% fines, before rising at higher fines contents. This pattern suggests that extreme gradations: either too fine or too coarse tailings can result in looser, less stable packings at the critical state, whereas well-graded tailings with moderate fines achieve lower critical void ratios due to their capability of stable particle packing.

This variability is not anomalous but systematic. Research by Rodrigues et al. (2025) and Li and Coop (2019) confirms significant CSL variations even within a single TSF, primarily driven by heterogeneity in grain size composition. Rodrigues et al. (2025) further identify sand content, rather than the dominant silt fraction, as a key determinant of geo-mechanical behaviour. Complementing this, Velten et al. (2022) demonstrate that CSLs in the ln(p')-υ plane are not unique but depend intrinsically on the initial compaction fabric. For an identical initial density, distinct PSDs yield location-specific CSLs, underscoring that grading, mineralogy, and particle shape are co-dominant factors (Li et al., 2018). The studied tailings exhibited "transitional behaviour," in which end-of-shear states failed to converge to a single CSL, retaining a dependence on the initial void ratio. This indicates the existence of a robust fabric that preserves the memory of the initial state through different compaction densities.

These findings do not invalidate CSSM but necessitate refining its constitutive frameworks by incorporating a family of parallel CSLs, each specific to a distinct initial fabric and PSD, rather than assuming a single CSL. It is conclusively established that tailings from the same deposit can exhibit substantially different geo-mechanical signatures due to compositional variability and variations in beneficiation processes and other factors. This mandates rigorous monitoring of grain-size distribution and initial compaction conditions. This adjustment is paramount for the reliable design of engineered structures like compacted dry-stack tailings dams, where spatial and temporal variations in material composition are inherent.

5 CONCLUSIONS

This study investigated the shear behaviour of tailings with a dry density of 1.9 g/cm³ under saturated (S0) and unsaturated (S30) conditions using a modified direct simple shear system equipped with a 100 kPa AEV ceramic disc for suction control via a direct negative pore water pressure application using vacuum. Testing under 50 kPa, 100 kPa, and 200 kPa vertical stresses revealed that:

- The MDSS system proved effective in characterising the shear behaviour of unsaturated tailings under various stress and suction conditions. The observed parallel shift of the CSL with matric suction aligns with findings from independent studies using different methods (e.g., suction-controlled triaxial tests).This methodological consistency confirms that the parallel CSL shift is an inherent property of unsaturated soil behaviour and not an artifact of the specific testing apparatus, thereby validating the MDSS as a suitable tool for investigating critical state frameworks in unsaturated tailings.
- Both density and matric suction significantly influence the mechanical behaviour of tailings. Specimens compacted to a higher density (1.9 g/cm³) exhibited superior peak shear strength compared to looser specimens (1.3-1.4g/cm³). The application of matric suction (S30) further increased shear resistance, highlighting the combined role of density and unsaturated conditions in governing soil strength.
- For a constant dry density, increasing matric suction causes a parallel leftward shift of the CSL in the void ratio-effective stress plane. This increases shear strength and apparent pre-consolidation but is metastable and reversible upon saturation.
- For the studied tailings, a unique CSL is not observed. Instead, two parallel CSLs exist, governed systematically by the initial PSD and compaction fabric. The end-state retains a memory of the initial structure, demonstrating transitional behaviour.

While the qualitative phenomenon of parallel CSL shift is well established, further testing is required to enable quantitative comparison and the development of predictive models that account for the combined effects of suction, PSD, and initial fabric.

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