Geotechnical Characterization of Cyclone Underflow Tailings under High Confining Pressures

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Abstract

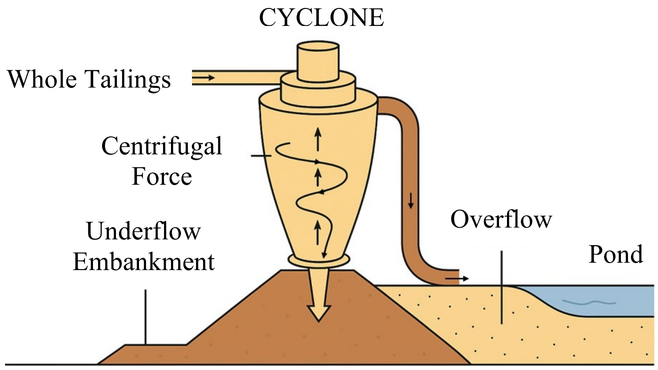
Despite the widespread use of cyclones for dam construction, limited published data exists on the geotechnical behaviour of cyclone underflow tailings, particularly under high confining pressures. This paper presents the results of a comprehensive laboratory testing program aimed at characterizing the geotechnical properties of cyclone underflow tailings to inform stability analyses of cyclone-constructed embankments subjected to high stress conditions. The program included triaxial compression, direct simple shear (DSS), bender element, and flexible wall permeability tests on specimens reconstituted both loose via moist tamping and compacted to 95% Modified Proctor density. A composite lower-bound strength envelope was developed based on DSS and triaxial tests for input into limit equilibrium stability analyses. Permeability tests revealed stress-dependent reductions in hydraulic conductivity, particularly for samples with fines content exceeding 15%. The test data suggest that the fines content for the cyclone underflow should be limited to approximately 10% to maintain drainage performance near the base of the proposed embankment.

Introduction

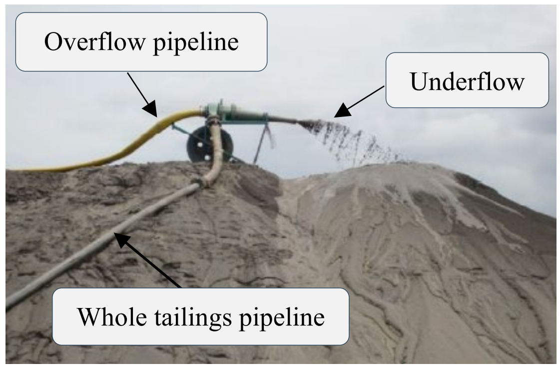
Tailings are a by-product of the mining process. Material excavated during mining operations is generally classified as either ore or waste rock (Morrison, 2024). The waste rock is typically hauled to a designated dump for storage. The ore is processed to extract a desired commodity (e.g., copper or gold), and the remaining material—often composed of finely ground rock, water, and reagents—is categorized as tailings. These tailings are usually transported to a tailings storage facility (TSF) in pressurized pipelines in the form of a slurry with a high water content.

Conventional TSFs are usually raised in stages to accommodate ongoing tailings production throughout the life of a mine. The tailings are typically contained by embankments constructed of earth fill and/or rockfill. One of the most economic approaches is to use the tailings themselves as construction material to form the embankment that impounds subsequent tailings. An increasingly common method of construction is the use of cycloning, where the tailings are hydraulically separated to produce a coarse sands fraction (underflow) and a fines fraction (overflow).

The cyclone device functions on a centrifugal separation principle, as illustrated in Figure 1a. The tailings slurry enters a cylindrical feed chamber where the coarser particles in the slurry spiral downwards through the apex at the bottom, and the finer fraction, along with most of the slurry water, rises to the outlet and is impounded in the TSF (Vick, 1990). The underflow is used to build the containment embankment, while the overflow is deposited into the TSF basin. In some cases, on-wall cycloning is used for dam construction, where the underflow is discharged directly onto the embankment, as illustrated in Figure 1b. The underflow may also be deposited into constructed cells and subsequently compacted to meet density specifications.



(a)



(b)

Figure 1: Cyclone operation in tailings management.
(a) Schematic illustration showing the principle of cyclone operation for tailings separation.
(b) Photograph of on-wall cycloning on a tailings dam (Knight et al., 2012)

Despite the widespread use of cyclones for dam construction, there is limited published data on the geotechnical behaviour of cyclone underflow tailings, particularly under high confining pressures. This paper presents the results of a comprehensive laboratory testing program aimed at characterizing the geotechnical properties of cyclone underflow tailings to inform stability analyses of cyclone-constructed embankments subjected to high stress conditions.

Testing Framework and Objectives

The laboratory testing program was conducted as part of a feasibility-level design of a TSF. The Main Embankment of the TSF is a valley-fill impoundment developed in stages throughout the life of the mine. The ongoing raises of the Main Embankment will be constructed using cyclone underflow tailings, which will be spread in cells and compacted using bulldozers to achieve a target dry density of 95% Modified

Proctor compaction. The Main Embankment is designed to reach a final vertical height of approximately 290 m, resulting in foundation stresses expected to exceed 5,000 kPa. At these high stress levels, the mechanical response of the underflow tailings becomes increasingly complex.

A key concern is whether the compacted underflow, expected to exhibit a dilative response under low confining stresses, may transition to contractive behaviour under high stress levels. Saturated and contractive materials can mobilize undrained shear strengths that can range from approximately 10% to 50% of the drained shear strength (Jefferies & Been, 2016). Understanding the stress level at which this transition occurs is critical for selecting appropriate strength parameters for use in stability assessments and for determining whether drained or undrained strength parameters should govern the analysis at various depths within the embankment.

Therefore, the primary objective of the testing program was to evaluate the impact of stress level on the mechanical response and shear strength of the material by defining the critical state line (CSL) and assessing the behaviour of specimens prepared to represent field conditions across a range of stresses. A series of triaxial compression tests, comprising undrained (CIU) and drained (CID) tests, was carried out on both loosely reconstituted and densely compacted specimens. As commercial laboratories are generally limited to consolidation stress levels of approximately 2,000–2,500 kPa, drained tests on loose specimens were used to define the CSL at stress levels of approximately 4,000 kPa. The densely compacted samples were then tested at varying stress levels to observe their position relative to the CSL and assess whether they crossed from dilative to contractive behaviour, as illustrated in Figure 2.

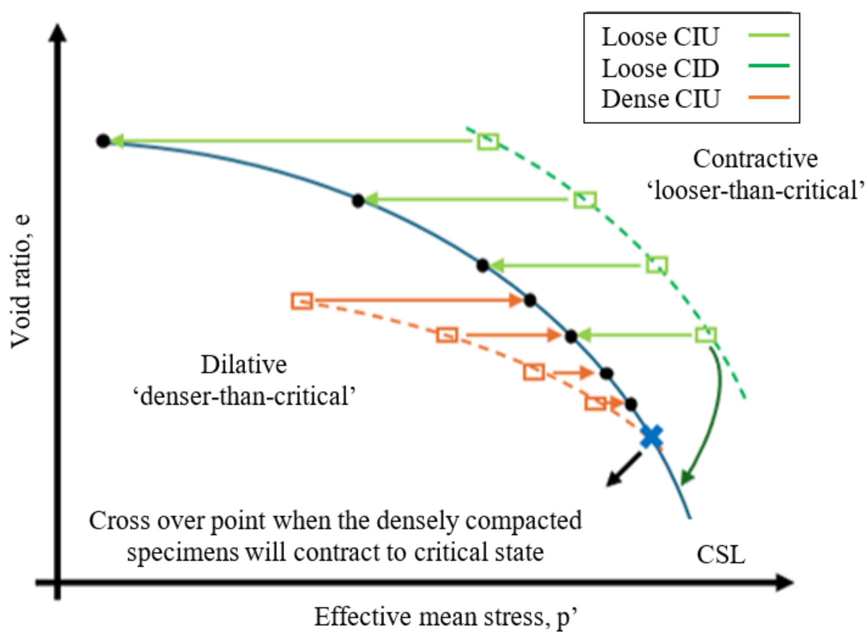


Figure 2: Void ratio versus mean effective stress plot showing the CSL, and specimen behaviour trends

The full suite of the testing program included classification tests (Particle Size Distribution (PSD), Atterberg limits, specific gravity), compaction tests (Modified Proctor), shear strength tests (direct simple shear and triaxial compression), bender element stiffness measurements, and flexible wall permeability tests. Pre- and post-test PSDs were used to evaluate the extent of particle crushing.

Material Overview

The PSD of a representative bulk sample of cyclone underflow tailings is presented in Figure 3. The sample is classified as a silty sand (SM) in accordance with the Unified Soil Classification System, with a fines content of 17.5% (i.e., the percentage passing through the #200 sieve). Atterberg Limits tests indicated that the sample is non-plastic, and the specific gravity was determined to be 2.68.

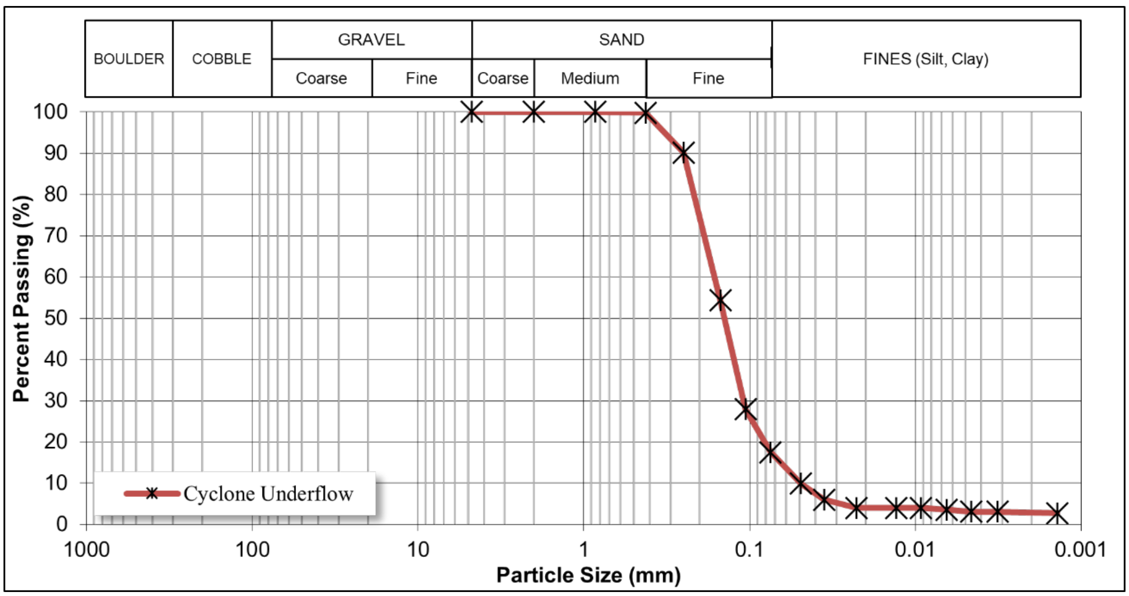


Figure 3: Particle size distribution of a representative sample of simulated cyclone underflow tailings

Shear Strength Behaviour

Thirteen triaxial compression tests were conducted to estimate shear strength properties of the tailings: nine CIU tests and four CID. Seven specimens were prepared loose via moist tamping, and six were compacted to 95% Modified Proctor compaction. DSS tests were performed on densely compacted samples to evaluate the influence of shear mode on material response.

The CIU test results on the loose specimens are presented in Figure A1 in the Appendix, in deviatoric stress (q) and mean effective stress (p') space. The stress-strain data are also presented in Figure A1, showing the response of the deviatoric stress as the axial strain increases. All five loose specimens showed contractive behaviour, as indicated by the generation of positive pore pressure during shearing, with specimen "CIU 800 loose" and "CIU 1600 loose" transitioning through a phase transformation and exhibiting dilative behaviour at large strains. The effective shear strength was interpreted based on a critical state friction angle, Phi'$_{cs}$, ranging from 36° to 39°. The minimum peak undrained strength ratio (S_u/σ'_{vo}) was estimated to be 0.22. The residual strength ratio (S_r/σ'_{vo}) varied widely but generally increased with increasing confining stress, consistent with expected critical state behaviour.

The CIU tests on the dense specimens are presented in Figure A2 in the Appendix. The plots demonstrate that each specimen initially exhibits contractive behaviour but transitions through a phase transformation to a final dilative stage (increasing effective stress) with increasing strain. The results indicate a critical state friction angle of approximately 36°, with a peak undrained shear strength ratio of 0.41 estimated for the specimen consolidated to 2,400 kPa.

The stress paths and stress-strain data for the CID tests are presented in Figure A3 in the Appendix. The two loose specimens contract up to the end of the test, but are not considered to reach a critical state. The shear stress plots for the dense samples reach a critical state between 15% to 25% axial strain. The results indicate a critical state friction angle of approximately 32° to 33°. The DSS test results, presented in Figure A4 in the Appendix, indicate a Phi'$_{cs}$ of approximately 31°. The stress-strain behaviour of each specimen exhibited an initial contraction, followed by a phase transformation and significant dilation. At large strains (>12%), the specimens tended to contract to the critical state, with no significant strength loss.

The estimated peak and residual undrained shear strength ratios from the triaxial compression and DSS tests are plotted as a function of initial vertical effective stress in Figure 4. The residual strength ratios for specimens which exhibited phase transformation followed by dilative shearing were conservatively selected at the point of phase transformation. Strength ratios were capped at 0.8 for illustration.

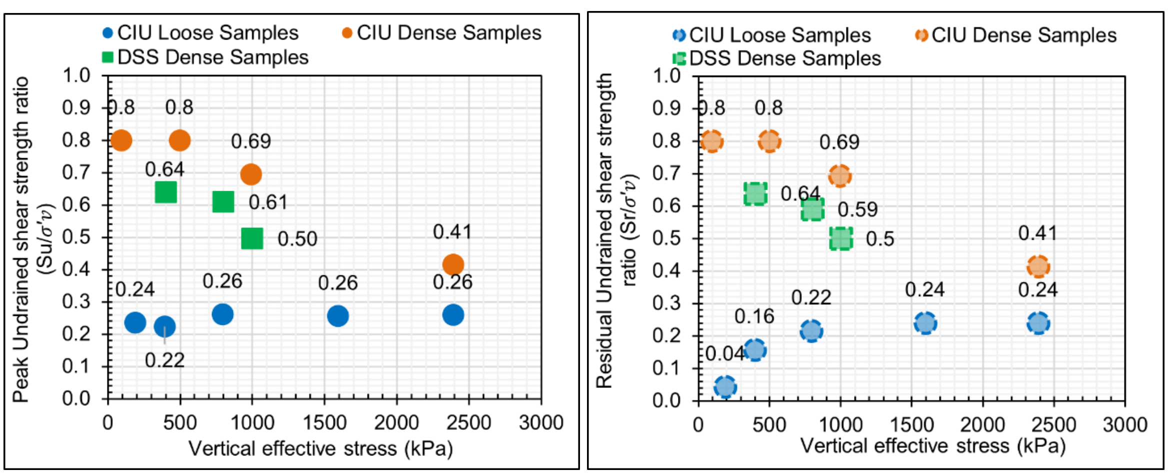


Figure 4: Undrained peak and residual strength ratios from triaxial and DSS tests on cyclone underflow tailings. Loose specimens prepared by moist tamping; dense specimens compacted to 95% Modified Proctor. Ratios capped at 0.8 for illustration

Although the dataset is limited, the results on the dense specimens confirm the findings by Ladd (1991), which show that triaxial compression tests tend to yield higher strengths compared to the DSS tests.

Stiffness and Compressibility

Bender element measurements were conducted to develop the relationship between void ratio, effective stress, and shear wave velocity for the cyclone underflow sands. These tests were intended to support potential future numerical analyses requiring small-strain stiffness inputs. Measurements were recorded in 200 kPa increments to a final mean effective stress of 2,400 kPa. The void ratio-effective stress relationship and shear wave velocity-mean effective stress relationship are presented in Figure 5.

The results indicate that the dense sample exhibits lower void ratios and higher stiffness compared to the loose sample, particularly at stress levels below 1,000 kPa. However, as the confining pressures increase and approach 2,400 kPa, the curves converge. This suggests that, at high stress levels, the initial compaction state of the samples has a reduced impact on their mechanical behaviour.

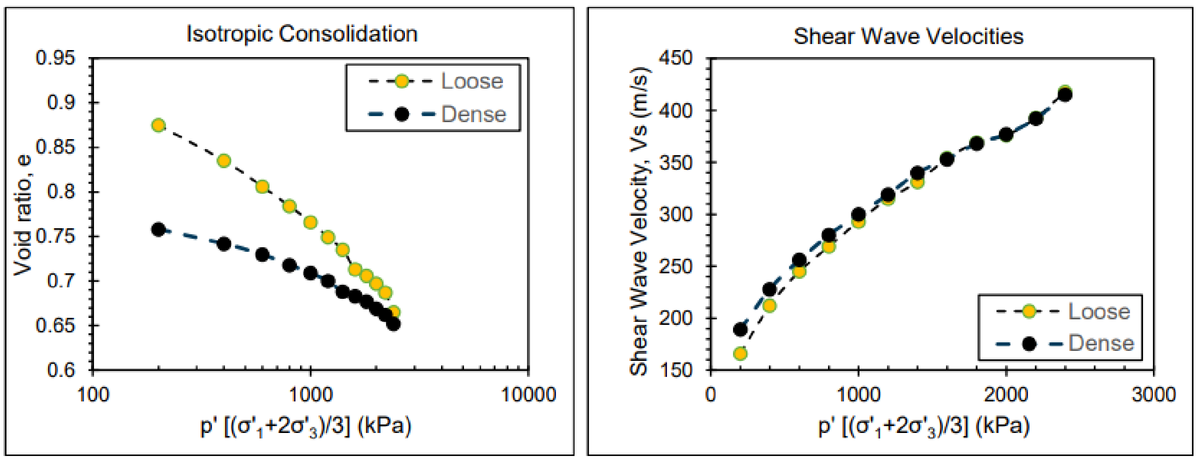


Figure 5: Bender element test results on cyclone underflow tailings specimens reconstituted loose via moist tamping and dense specimens reconstituted to 95% Modified Proctor dry density

Critical State Line Determination

The CSL for the cyclone underflow material was estimated from the results of the triaxial compression tests using a best-fit power function in the e-log(p') plane adopted from Li and Wang (1998). The CSL is presented graphically in e-log(p') space in Figure 6. The filled red squares indicate the test specimens which were considered to have reached critical state, while the empty red squares represent the points at the end of the tests for the specimens not considered to have reached critical state. The limiting compression curve (LCC) was interpreted from the loosest moist tamped samples and is presented in the dashed blue line in Figure 6.

The results of the triaxial compression tests indicate that all loose specimens contracted to the critical state as expected. The dense specimens, compacted to 95% Modified Proctor, exhibited dilation to critical state under confining pressures up to approximately 800 kPa, supporting the use of drained strength parameters for compacted underflow tailings in stability analyses. However, at confining pressures exceeding 800 kPa, the compacted specimens contracted to the critical state, suggesting a transition in behaviour as presented in Figure 6 (the point at which the initial void ratio of dense samples intersects the CSL). This crossover indicates that the compacted underflow can mobilize undrained strengths at high confining pressures if it is saturated (or nearly fully saturated).

The void ratio-effective stress relationship developed from the bender element tests is also plotted in Figure 6. Bender measurements on the loose sample indicate that the specimens were in a denser state compared to those moist tamped for the triaxial compression tests. However, measurements on the dense bender element tests show close alignment with the compacted triaxial compression specimens.

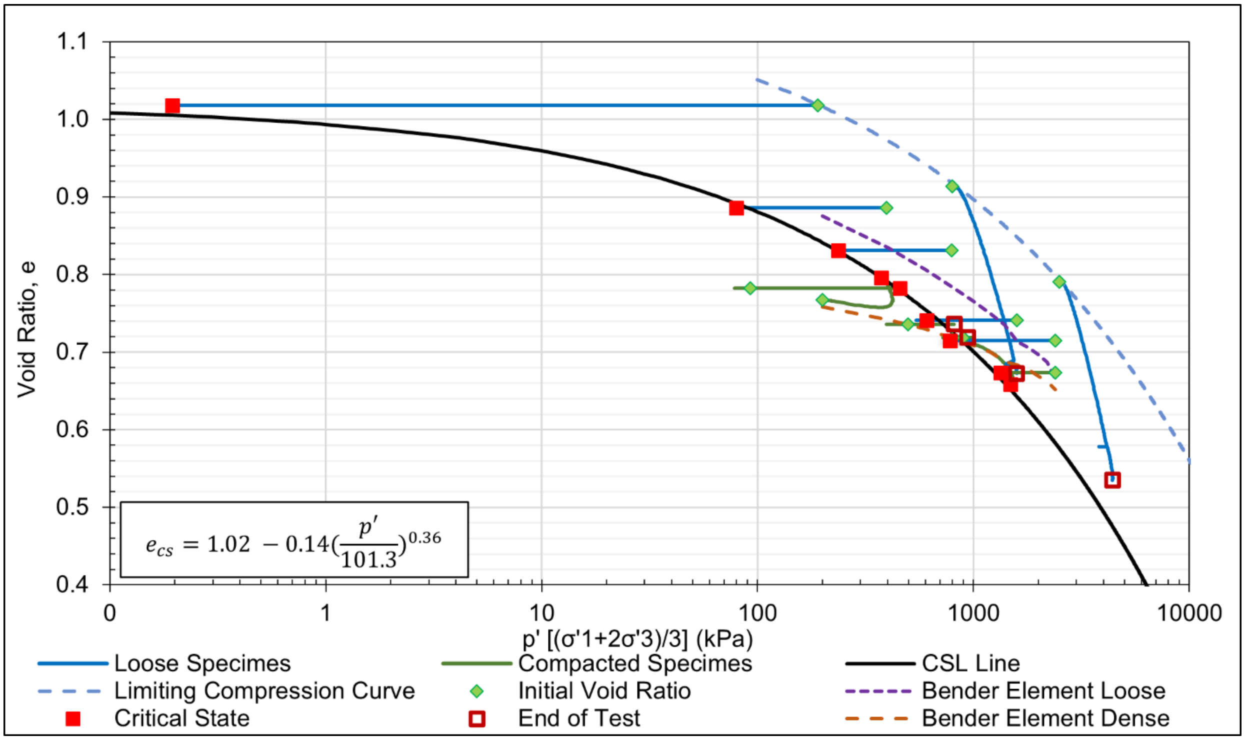


Figure 6: Mean effective stress (p′) versus void ratio (e) for cyclone underflow tailings from triaxial compression test results. Data include loose and compacted specimens reconstituted loose via moist tamping and to 95% Modified Proctor compaction

Strength Envelope

Based on the findings from the triaxial compression and DSS tests, a composite lower-bound strength envelop was developed for the saturated cyclone underflow tailings. The envelope was derived from the results of the specimens compacted to 95% Modified Proctor compaction, representing the estimated in-situ conditions, and is intended for use in stability assessments.

The results indicate that at effective stresses below 800 kPa, the compacted underflow tends to dilate during undrained shearing, generating negative excess pore pressures, which would be expected to result in undrained shear strengths that are greater than drained shear strengths (prior to dissipation of excess pore pressures). However, at effective stresses above 800 kPa, the material exhibits contractive behaviour, with undrained shear strengths which are lower than the drained strengths.

The composite envelope, therefore, is defined by the drained strength at low effective stresses (up to 800 kPa), and undrained strengths at higher stresses. To account for the DSS mode of shear, a 30% reduction was applied to the triaxial compression values, following guidance from Ladd (1991), who noted that triaxial compression tests generally provide less conservative peak strengths under plane strain conditions.

The composite strength envelope is presented in Figure 7. The strength is defined by DSS data up to 1,000 kPa, as they produced more conservative results. Beyond 1,000 kPa, the envelope is extrapolated from the CIU test results at 2,400 kPa, reduced by 30% to account for the DSS failure mode, yielding an undrained strength ratio of 0.29. The strength tests conducted on the dense specimens exhibited little to no strength loss, therefore, this failure envelope is recommended to be adopted for both peak and post-seismic stability analyses.

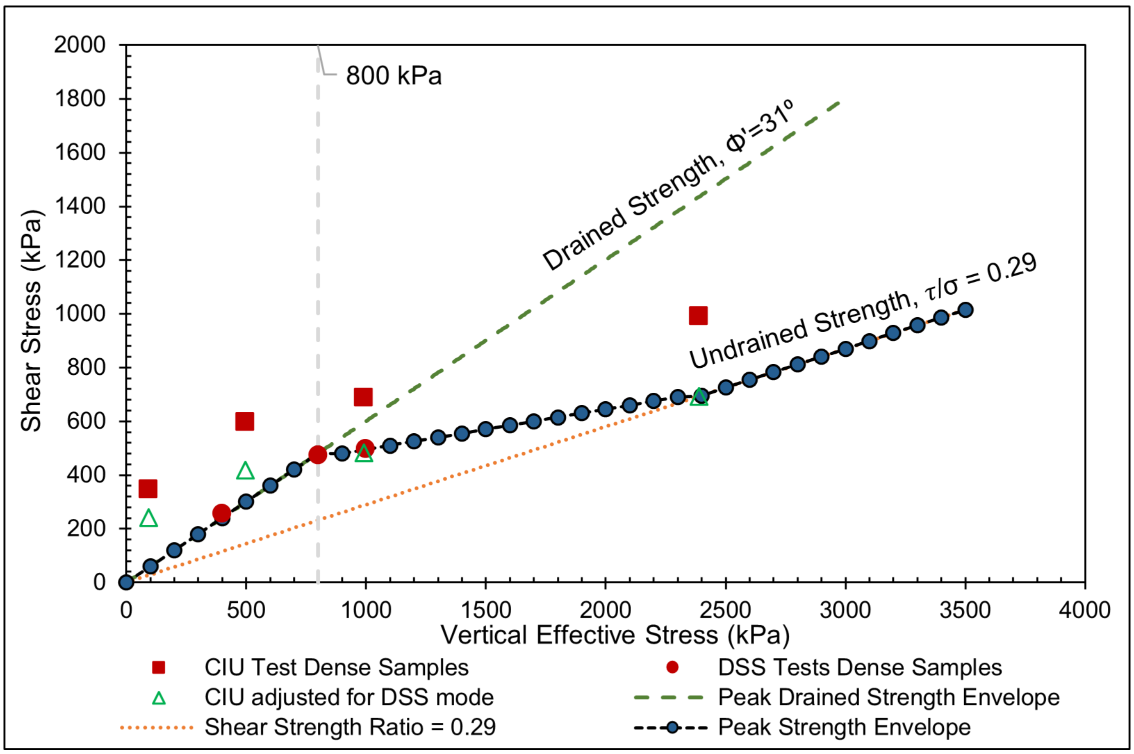


Figure 7: Proposed composite lower-bound strength envelope for saturated cyclone underflow tailings. The envelope is based on the results of triaxial compression and DSS tests. Strength values from the triaxial tests were reduced by 30% to account for the DSS shear mode

Permeability and Particle Crushing

The PSD of cyclone underflow tailings is a key design consideration for dam construction. Underflow with sufficiently low fines content is required for placement to facilitate rapid drainage and subsequent compaction. Industry guidance suggests that cyclone underflow tailings used in dam construction should achieve an in-situ permeability of at least 2×10^{-6} m/s (Barrera et al., 2011).

Flexible wall permeability tests were conducted on specimens reconstituted to 95% Modified Proctor at confining stresses of 500 kPa and 3,000 kPa. The measured permeability values were approximately 1.2×10^{-6} m/s and 7.3×10^{-7} m/s, respectively—a 40% reduction in permeability with increasing stress, falling below the suggested threshold. However, pre-test PSDs indicated that the specimens had a fines content of approximately 27%, suggesting variability in the bulk sample or unconscious sampling bias. Post-test PSDs showed only minor increases in fines content (1–3%), indicating that the observed reduction in hydraulic conductivity was largely stress-dependent rather than the result of significant particle crushing.

To further evaluate the impact of particle crushing, pre-and post-test PSDs were compared after both Modified Proctor compaction and one-dimensional consolidation (constant rate of strain) tests. The consolidation test was conducted on a specimen reconstituted to loose via moist tamping and loaded to a vertical stress of 4,000 kPa. The PSD results showed modest increases in fines content (less than 4%), suggesting that high confining stress (corresponding to an increase in embankment height) was unlikely to influence mechanical performance significantly. In contrast, compaction increased the fines content by approximately 6%, indicating that the compaction process itself may contribute to the generation of meaningful fines.

Permeability tests on a separate bulk sample of cyclone underflow with an initial fines content of 15% yielded permeability values above 2×10^{-6} m/s at confining pressures up to 3,000 kPa. These results demonstrate that underflow materials with fines contents exceeding 15% may fall below the design permeability threshold even under moderate confining stress (500 kPa). To mitigate this risk, the data suggest that the fines content for the cyclone underflow should be limited to approximately 10% to maintain drainage performance near the base of the proposed embankment, ensuring that both compaction- and stress-induced crushing do not result in excessive fines accumulation and reduced permeability in the field.

Conclusion

A comprehensive laboratory testing program was carried out to characterize cyclone underflow tailings. The program included triaxial compression, DSS, bender element, and flexible wall permeability tests on specimens reconstituted both loose via moist tamping and to 95% Modified Proctor dry density.

A composite lower-bound strength envelope was developed for saturated cyclone underflow tailings based on triaxial compression and direct simple shear tests. Triaxial peak strength values were conservatively reduced by 30% to account for shear mode differences. The envelope defines drained strengths at low stresses (<800 kPa) and undrained strengths at high stresses and is recommended for both static and post-seismic stability analyses.

Flexible wall permeability tests showed a stress-dependent reduction in hydraulic conductivity. Post-test gradations indicated minimal particle crushing (1–3% increase in fines), suggesting that the permeability was primarily stress-dependent rather than influenced by particle crushing.

To maintain adequate drainage performance, the data suggests that the cyclone underflow tailings used for embankment construction be limited to a fines content of approximately 10%. This target accounts for the effects of compaction and stress-induced fines generation, supporting long-term permeability performance.

Acknowledgements

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Appendix

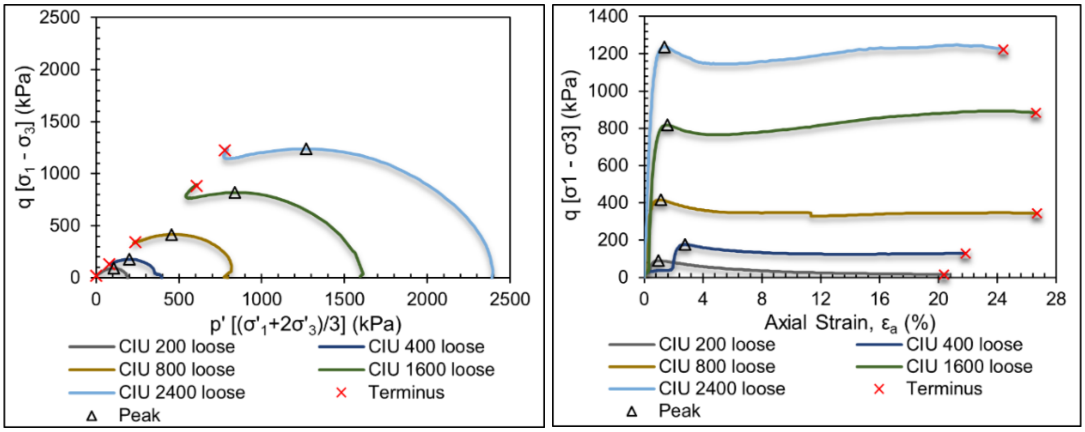

Figure A1: CIU test results on cyclone underflow tailings specimens reconstituted loose via moist tamping

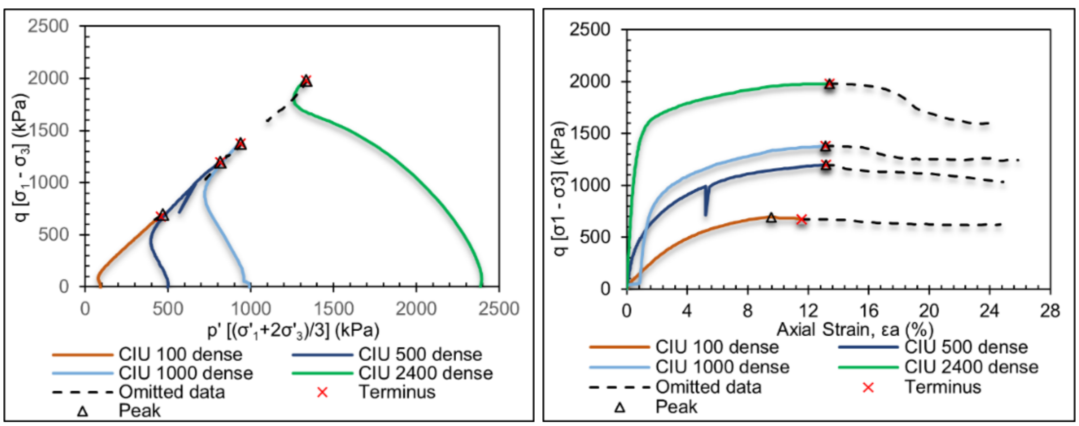

Figure A2: CIU test results on cyclone underflow tailings specimens reconstituted to 95% Modified Proctor compaction. Dashed black lines denote a portion of test data omitted due to potential shear banding, localized failure, or testing artifacts causing a sudden drop in stress

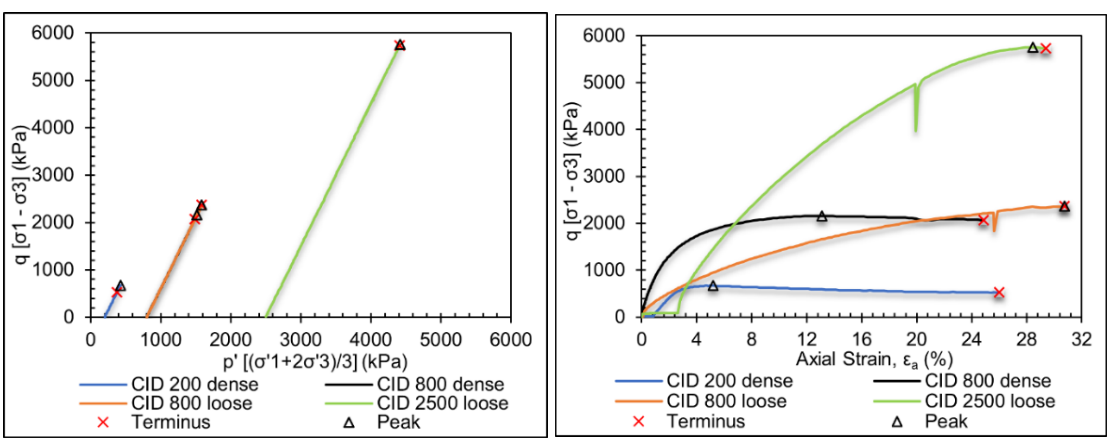

Figure A3: CID test results on cyclone underflow tailings specimens reconstituted loose via moist tamping and dense specimens reconstituted to 95% Modified Proctor compaction

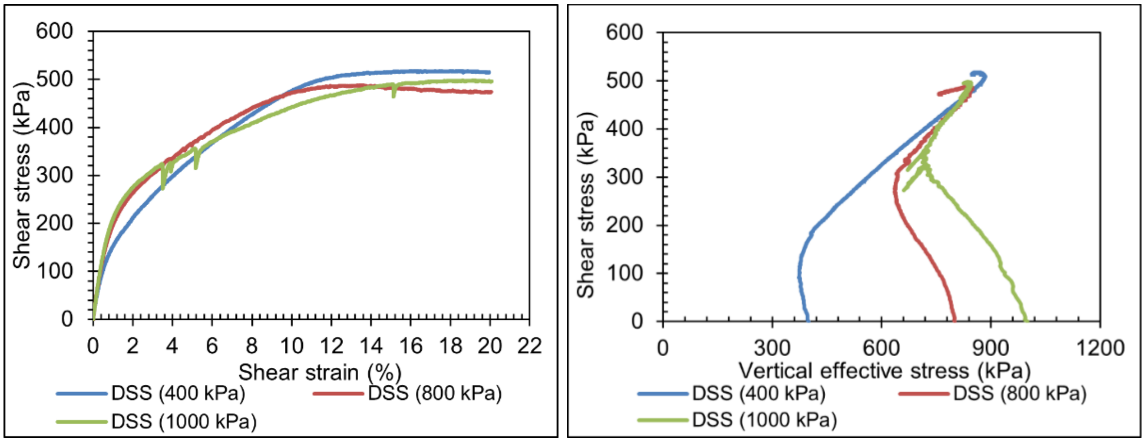

Figure A4: DSS test results on cyclone underflow tailings specimens reconstituted to 95% Modified Proctor compaction