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Hard rock rockflour platinum tailings geotechnical characterization: case study

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ABSTRACT: As part of the Global Industry Standard on Tailings Management (GISTM) requirements of best practice, a platinum tailings storage facility's (TSF) tailings material was geotechnically characterized. Platinum tailings mined using underground mining techniques, exhibit hard rock rockflour sandy soil behaviour, which is notoriously difficult to sample and test in an undisturbed manner, and even more so at depth within the TSF body. Three different methods were used to provide a robust solution in terms of characterisation. These included in-situ Cone Penetration Tests with pore pressure measurements (CPTu), Flat Dilatometer tests (DMT) probing and electronic Vane Shear test (eVST); laboratory testing on bulk sampled remoulded tailings material and in-situ sampled (non-remoulded) tailings material taken at depth using a Dames and Moore sampler. The triaxial compression results from non-remoulded tailings material had a predominantly contractive behaviour with a phase transfer to dilation whereas the remoulded tailings material was contractive. The triaxial tests completed on the remoulded tailings material also indicated that the material had a slightly lower drained strength than the non-remoulded tailings material even though the prepared void ratios were in the same range as the non-remoulded samples. This difference indicates that there are significant fabric and potential sample disturbance effects on the behaviour of the tailings material. The possible disturbances that could have occurred during the in-situ sampling with the Dames and Moore sampler includes using a sonic rig to advance the sampler; the actual insertion of the sampler into the tailings; the taking of the sample, the extraction of the sampling tube; transportation of the sample tubes; sample preparation in laboratory, saturation of the sample and testing of the sample, etc. The samples taken below the phreatic surface were mostly flash frozen and extracted from the sample tubes by cutting the tubes open. This paper explores the variances in material behaviour based on sampling and testing preparation methods. It also reviews the variance in void ratio, density and saturation within the same Dames and Moore sample tubes to assess possible densification.

KEYWORDS: Tailings, site characterization, field and laboratory testing, Dames and Moore sampling, GISTM, critical state soil mechanics

1 INTRODUCTION

The Global Industry Standard on Tailings Management emphasizes best practices for tailings storage facilities. The GISTM has 6 Topics to ensure that there is proper governance and understanding of the TSF. This work focused on Topic 2, which pertains to the integrated knowledge base. Platinum tailings, derived from underground mining, exhibit hard rock rockflour sandy soil behaviour, which poses significant challenges for geotechnical characterization. Sampling and testing undisturbed material at depth within a TSF body is particularly difficult due to the material's contractive behaviour and susceptibility to disturbance and is usually the traditional reason why characterization leans so heavily on CPTu in-situ testing.

This study focuses on the geotechnical characterization of a platinum TSF, using a combination of in-situ testing, laboratory testing on remoulded samples, and laboratory testing of in-situ (non-remoulded) samples. The objective is to explore variances in material behaviour throughout the profile depth looking at different sampling and testing preparation methods. The outcomes of the study will be used to motivate compliance with GISTM. The study included sampling and testing that took place over a three-year period.

2 SITE DESCRIPTION AND TAILINGS MATERIAL

The TSF is located in the Limpopo Province, South Africa, and is part of a platinum mining operation that extracts ore from the Merensky and UG2 reefs. The tailings material is classified as silt with low plasticity (ML) or silty sand (SM) under the Unified Soil Classification System (USCS) and exhibits a particle size distribution ranging from silty fine sand at the outer crest to fine silt and clay at the penstock, which is the consequence of the tailings deposition beaching process.

Key geotechnical properties include:

- Specific Gravity (SG): ranges from 3.06 at the penstock to 3.52 at the outer crest, with an average of 3.44 for the structural zone.
- Void Ratio: varies significantly from the outer crest to the inner basin ranging from 0.7 to 1.3, respectively.
- Plasticity: the material is predominantly non plastic, with slight plasticity observed in isolated samples.

The TSF's structural integrity is influenced by the tailings material's expected contractive behaviour, making accurate characterization essential for stability assessments. It is important to note that the TSF was constructed in an upstream manner using cycloning. It hence comprises an underflow tailings outer shell followed upstream by overflow tailings.

3 METHODOLOGY

3.1 *Field sampling*

Sampling of the tailings material was undertaken near surface and at depth. Near surface sampling included high quality block samples as well as bulk samples taken at three locations along Monitoring Line F. on the eastern flank of the TSF The sampling locations included the outer crest, 10 m from crest and penstock area. The in-situ sampling at depth comprised Dames and Moore sampling as well as MOSTAP sampling. The MOSTAP samples were taken below the phreatic surface by the CPTu Contractor. A PVC pipe and sock encased the sample, which was pre-punched and pushed through the undisturbed tailings material. Samples were capped, labelled, and transported upright to the laboratory.

The Dames and Moore samples were taken to attempt to retrieve less disturbed in-situ samples throughout the tailings profile. These were taken along two lines that are actively being monitored. These are referred to as Lines C and F. These two lines have the highest embankment height and Line F has previously been subject to seepage and was subsequently buttressed. The focus was on the tailings material within the structural zone, which largely comprised tailings situated below the phreatic surface. The samples were retrieved with a sonic rig advancing the sampler to the desired depth. Ten samples were taken along Line F from three different benches at depths of 11, 11.5, 17, 15, 24, 14 and 23 m. Nine samples were taken along Line C from three different benches at depths 15, 15.5, 19, 19.5, 22, 22.5 and 29 m.

The sampler, consisting of a brass tube, was hydraulically pushed into the tailings material. After retrieval, the sample recovery was measured, and the brass tube was capped and labelled. It was tightly packed in high density foam and transported to the laboratory. The distance from the cap to sample was measured prior to transportation and upon arrival at the laboratory to ascertain sample disturbance.

Attempting to extrude the samples from the tube proved more difficult than expected with some samples either completely collapsing or clearly densifying or remaining visually intact. The samples taken along Line F were carefully extruded from the tubes whereas the samples taken along Line C were dipped in liquid nitrogen for 16 minutes to freeze the material. The frozen sample tubes were cut open longitudinally to extract the sample. The frozen samples were then placed in triaxial cells and defrosted during the flushing cycle before testing.

The sonic rig drilling contractor also extracted core of the full profile during the Dames and Moore sampling. The boreholes were logged and samples were taken for the Scanning Electron Microscope (SEM), X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) testing.

3.2 *In-situ testing*

Three in-situ testing methods were employed:

- Cone Penetration Testing with Pore Pressure Measurement (CPTu): used to determine state parameters and undrained shear strength ratios (USSR).
- Dilatometer Testing (DMT): provided K_0 values for calibrating CPTu results.
- Electronic Vane Shear Testing (eVST): measured peak and residual undrained shear strengths.

3.3 *Laboratory testing*

Laboratory tests were conducted on both remoulded and non-remoulded samples. Remoulded samples were prepared to eliminate fabric effects and tested for critical state lines (CSL) using triaxial compression tests. Non-remoulded samples were tested in their in-situ state to assess the impact of sampling disturbances.

Laboratory testing completed on remoulded samples included: CSL testing using consolidated isotropic undrained and consolidated isotropic drained triaxial testing; normal consolidated line (NCL) form triaxial testing; cyclic direct simple shear (CDSS) testing; monotonic direct simple shear (MDSS) testing; permeability from flexible wall triaxial testing; foundation indicator testing; SEM, XRD and XREF.

Laboratory testing completed on non-remoulded samples included: consolidated isotropic undrained triaxial testing and foundation indicators.

Quality control measures included daily equipment calibration and adherence to ASTM standards.

4 RESULTS AND DISCUSSIONS

4.1 *In-situ testing*

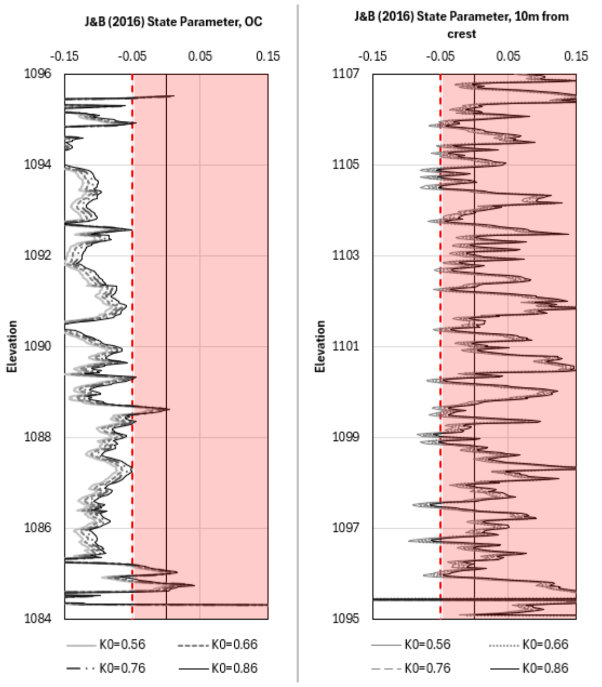
4.1.1 *Electronic Vane Shear Testing*

Undrained test conditions were not achieved during the eVST testing in the platinum tailings and therefore the desired outcome of the test, during execution, was not achieved. At best, the test indicated that the tailings material was partially drained. This finding corresponded to the results of the CPTu tests which also confirmed partially drained behaviour during the testing. All platinum TSFs tested in SRK's portfolio produced similar results.

4.1.2 *Flat Dilatometer Testing*

DMT testing allows you to determine the coefficient of earth pressure at rest (K_0). This assists in understanding what the in-situ stress condition is in the TSF. K_0 can be affected by the material's consolidation state as well as material type. The DMT probe is advanced down the profile and a reading is taken at 0.2 m intervals.

The DMT results show the in-situ K_0 is 0.56 on buttressed Line F and 0.50 on unbuttressed Line C. This was used as input parameters for the CPTu interpretation to calculate the Jefferies and Been state parameter. These results proved to be significant since a conservative approach (i.e. selection of conservatively high values for K_0) was adopted prior to this confirmation. To illustrate the point, the state parameter for a CPTu probe location on Line F in both the outer crest and 10 m from crest tailings material is plotted using 0.1 intervals for K_0. The results are presented in Figure 1, with the results for the underflow and the overflow materials presented in 1(a) and 1(b), respectively. Only the lower 12 m of the 10 m from crest probes are shown for clarity. For the coarser, underflow tailings material, graph shown in 1(a) the change in dilative to contractive behaviour is not as pronounced as for the finer overflow tailings material, graph shown in 1(b). If a high K_0 is used for the CPTu interpretation of the fine tailings, nearly the entire lower 12 m appears contractive; however, with the field-determined K_0 of 0.56, dilative layers are present within this depth.



(a) (b)

Figure 1. Sensitivity of state parameter to K_0 for underflow (a) and overflow (b) tailings material

4.1.3 *Cone Penetration Testing with Pore Pressure Measurements*

The CPTu results were analyzed conventionally and used to identify weaker layers along Line C and F based on residual undrained shear strength ratio values. This was possible as probes were conducted at every bench, the crest, inner crest, basin, and pool area. The method described by Visagie and du Plessis, 2024, was used to discern the weaker layers. For Line C, residual USSR values were 0.07 for weaker layers and 0.15 for matrix material. For Line F, residual USSR values were 0.06 for weaker layers and 0.15 for matrix material. Peak USSR values were determined as 0.38 for Line C and 0.31 for Line F.

The phreatic surface was estimated using pore pressure measurements from RSCPTu probing and validated with vibrating wire piezometers (VWPs). Flow gradients were calculated from pore pressure dissipation data. The results showed a significant increase in drawdown towards the toe:

- Line F: hydraulic gradient increased from 3.14 kPa/m at the toe to 7.47 kPa/m in the basin.
- Line C: hydraulic gradient increased from 1.89 kPa/m to 7.13 kPa/m on the inner crest.

These results are expected because of the functioning toe drain.

4.2 *Remoulded testing*

4.2.1 *Critical state testing*

The critical state testing was completed at a range of predetermined void ratios and confining pressures to ascertain the effect of these on the tailings material behaviour. The effective pressures selected for the tests included 100, 200, 400 and 1000 kPa. 48 tests were completed in total across all three sampling locations on Line F.

The remoulded tailings material exhibited a contractive behaviour during triaxial testing. This behaviour was consistent across all tested locations (outer crest, 10 m from crest, and penstock). Each location showed a zone of CSL behaviour rather than a single line, with upper and lower bounds. The key CSL parameters as defined by Jefferies and Been, 2016, include the y-axis intercept at an effective pressure of 1 kPa, Γ, and the slope of the CSL, λ_{10}. The CSL parameters for each location are as follows:

- Outer crest: $\Gamma = 0.89$, $\lambda_{10} = 0.025$
- 10 m from crest: $\Gamma = 0.98$, $\lambda_{10} = 0.045$
- Penstock: $\Gamma = 1.01$, $\lambda_{10} = 0.055$

The critical state zone and NCL (blue line) for the 10 m from crest sampling location is shown in Figure 2. The CSL and NCL for all three sampling locations are shown in Figure 3. It is worth mentioning that the NCL, obtained through triaxial isotropic compression testing, is parallel to the CSL.

4.2.2 *Cyclic direct simple shear*

The CDSS test as defined by the ASTM D8296-19, 2019, is used to determine the liquefaction characteristics of a material. This was achieved by testing the tailings material at a predetermined void ratio, vertical stress and cyclic stress ratio (CSR). The test result is the number of cycles to material failure (N_f). The tests were completed on remoulded MOSTAP samples taken from Line F in the structural zone where the failure plane is likely to traverse. The CSR versus N_f results are included in Figure 4 for two samples, remoulded to void ratios of 0.7 and 0.82; these are depicted in the figure by the green and blue lines, respectively.

These results show that the void ratio has a large impact on the material's resistance to liquefaction. The more dense (lower void ratio) the tailings material is the greater the number of cycles required to fail the tailings material for similar cyclic loading conditions.

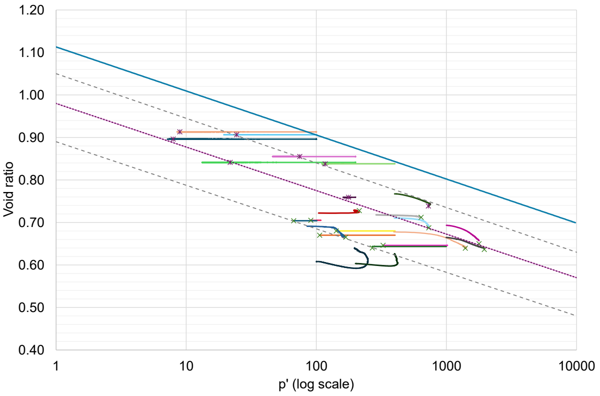


Figure 2. Critical state zone for Line F 10 m from crest

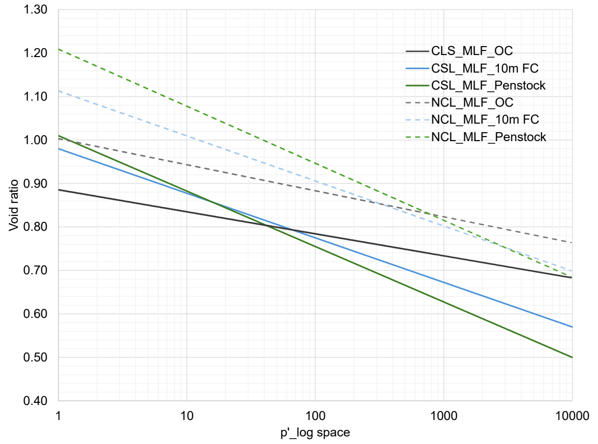


Figure 3. Line F CSL and NCL for all three sampling locations

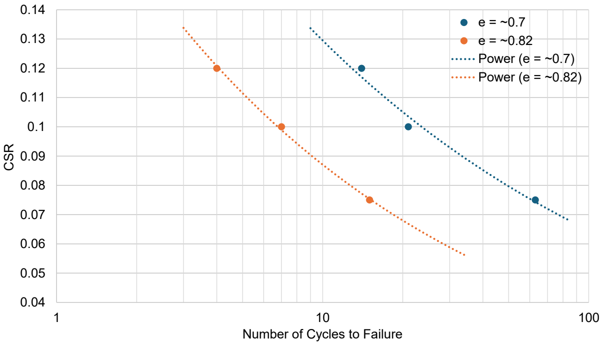


Figure 4. Cyclic stress ratio vs Number of cycles to failure

4.2.3 *Permeability*

Triaxial permeability tests were performed on the block samples taken from all three sampling locations for Line F. The results are included in Table 1. The permeability was tested to ensure that the underflow tailings material of the outer structural zone of the TSF can drain as per the design. The permeability test results are also usually a good indicator if the material is clay-like. From the permeability results obtained it can be confirmed that the design assumptions are met.

Table 1. Triaxial permeability results

Location	Permeability (m/s)	Void ratio of sample
Outer crest	8.88E-06	0.76
10 m from crest	2.87E-06	0.73
Penstock	4.07E-07	0.91

4.2.4 *SEM, XRF and XRD*

SEM, XRF and XRD are all non-destructive testing. The aim of these tests is to confirm if there are clay sized particles or clay chemical compositions contained within the tailings material. It is also important to determine if the particles contain any flocks bridging larger particles or filling voids between larger particles. Chang et al. (2011) found that flocks tended to have a lower stiffness than bulky particles and they also tended to deform under undrained shear conditions, resulting in a lower effective strength. Flocks can be defined as masses of short fibers. This is similar to fabric of naturally occurring silty clays where clay particles bridge the larger sized silt particles.

The SEM images confirmed that no flocks are present in the tailings material. This can be seen in Figure 5. The squares on the images provide a scale ranging from 62 to 1000 micrometers. The images show a clear variation in particle sizing throughout the profile and the heterogeneous nature of tailings deposition. The vertical variability suggests non-uniform permeability (Cho, 2006) in the deposited layers and supports the finding of weaker layers in the profile as identified with the CPTu probing.

The XRD testing indicates that enstatite is the predominant mineral composition of all samples that were tested. Enstatite is a magnesium rich silicate mineral commonly found in igneous rocks.

XRF testing indicated that the primary components of the tailings are Al_2O_3, Cr_2O_3, and Fe_2O_3. These results confirm that the tailings material lacks clay. The permeability testing results also confirm that the material is not clay or clay-like.

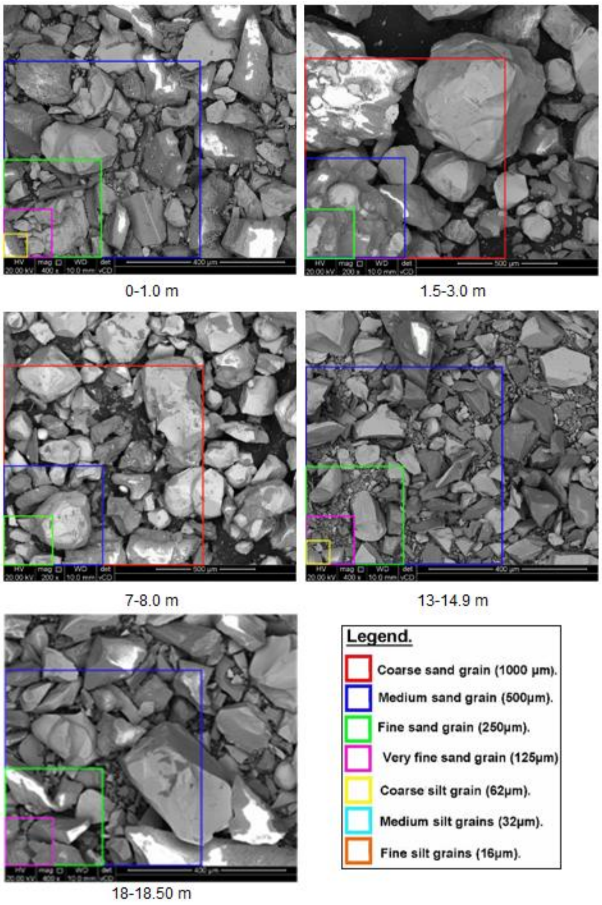


Figure 5. SEM image of sample taken on Line F

4.3 *Non-remoulded testing*

4.3.1 *Near surface non-remoulded sample testing*

Particle size distribution testing indicated that the outer crest material comprised 54% sand, 42% silt and 4% clay size particles. The triaxial tests completed on the high-quality near-surface block samples for Line F indicated the following behaviour:

- Outer crest: tailings material exhibited a contractive behaviour;
- 10 m from crest: tailings material exhibited phase transfer behaviour, and;
- Penstock: tailings material tested at 100 kPa effective pressure exhibited contractive behaviour and the samples tested at 200 and 400 kPa exhibited phase transfer behaviour.

The stress paths are shown in Figure 6. From this testing the average friction angle is 34.6° with a 20th percentile of 32.3°.

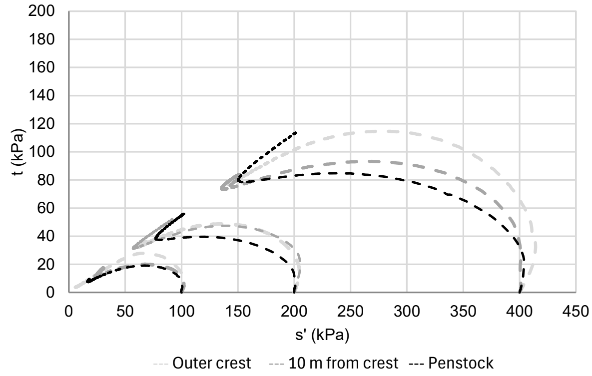


Figure 6. Stress paths for near surface non-remoulded CIU triaxial testing

4.3.2 *At depth non-remoulded sample testing*

The in-situ Dames and Moore sampled (non-remoulded) tailings material exhibited contractive behaviour initially, followed by a phase transfer to dilation. This phase transfer is either attributed to the reorientation of the material's fabric during shear or sample densification during the testing preparation stages. The phase transfer occurred at low axial strains (0.34% to 3.85%). The Line F samples that were not frozen prior to extrusion from the sampling tube had a lower strength band (31.1° to 40.7°) when compared to Line C's strength band (32.3° to 42.0°) where all the samples were frozen. The strength band and stress paths for Line F are shown in Figure 7 and Figure 8 for Line C.

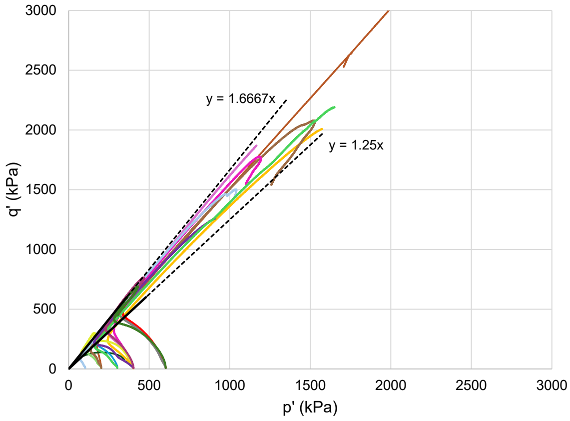


Figure 7. Strength band and stress path for Line F Dames and Moore samples

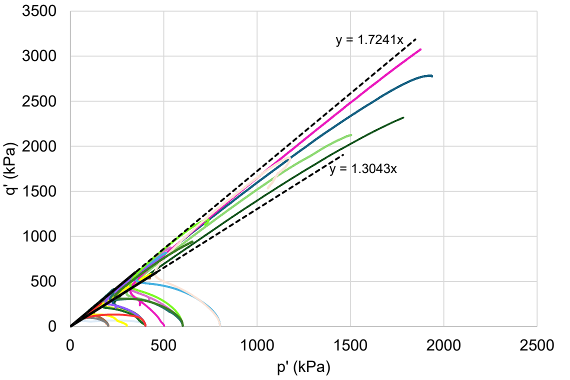


Figure 8. Strength band and stress path for Line C Dames and Moore samples

4.3.3 *Comparison of near surface and at-depth sample test results*

The results for the near surface versus at-depth testing comparison are included in Table 2. Key differences included the void ratio range and strength parameters. A void ratio of 0.53 is normally only attainable if the tailings material was densified by compaction. The possible reason for the much lower void ratio (lower bound value of 0.53) of the at-depth sampling is the densification during the sampling and extruding thereof. It is thus difficult to confirm the validity of void ratio ranges as low as 0.53.

The slightly higher friction angle observed for the at-depth tailings material could be attributed to testing a larger quantity of samples which increases the likelihood of including stronger material.

The at-depth sampled tailings exhibited phase transfer behaviour so did not have a residual strength. This strain hardening behaviour does not support the application of constitutive models that are required to perform deformation analyses. As such one cannot solely rely on these tests and would have to consider remoulded sample strength testing to aid strain softening analyses.

Table 2. Comparison between near surface and at-depth sample test results

Comparison item	Near surface	At-depth (D&M)
Specific gravity	>3.36	3.44 - 3.93
Void ratio range (outer crest)	0.80 - 0.88	0.53 - 0.80
Average friction angle	34.6°	35.4°
Peak USSR (outer crest)	0.15 - 0.28	0.16 - 0.25
Residual USSR (outer crest)	0.09 - 0.19	N/A, Phase transfer behaviour
Behaviour	Mainly contractive	Phase transfer

4.4 *Foundation indicators*

The foundation indicator tests included Atterberg limits, particle size distribution (PSD), and USCS classification. These tests were conducted on samples from both the Dames and Moore (D&M) sampling campaign and the Critical State Line (CSL) testing.

The tailings material from the CSL testing was classified as ML (silty soil) or SM (silty sand) as per the USCS classification. The material exhibited non-plastic (NP) or slight plasticity (SP) behaviour. The classification was consistent across the outer crest, 10 m from crest, and penstock locations. The results indicated that the tailings material is predominantly non-cohesive.

The PSD results from the D&M samples were generally consistent with the CSL testing results, showing a gradation from coarser material at the outer crest to finer material at the penstock. However, some D&M samples exhibited greater variability in PSD. Figure 9 includes all the results. Three zones are observed: the coarsest tailings are located at the embankment, finer material is present 10 meters from the crest, and the finest material is found in the pool area.

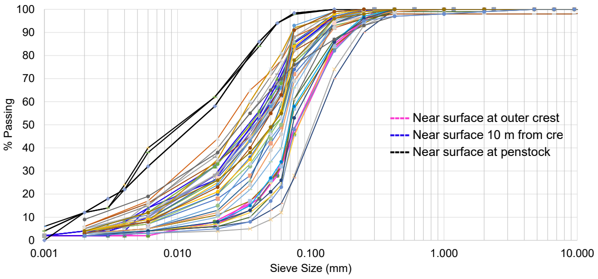


Figure 9. Particle size distribution

4.5 *Dames and Moore sample variance*

Significant variances were observed within individual Dames and Moore sample tubes. These included:

- Void ratio: variances of up to 0.294 were recorded.
- Dry density: differences of up to 333 kg/m³ were noted.
- Saturation: variations of up to 26% were observed.

These variances are attributed to factors such as densification during sampling, transportation as well as the inherent heterogeneity of the tailings material. Additional disturbances occurred during the triaxial testing sample preparation. The initial void ratio compared to the post consolidation void ratio consistently varied.

5 COMPARISON OF FIELD AND LABORATORY TESTING RESULTS

The D&M results were compared with the CPTu probing results and plotted against the CSL. The in-situ effective stresses for the D&M samples were calculated and the e_0 for the CPTu data was calculated based on the probed state parameter and outer crest (OC) CSL. It must be noted that the CPTu results were calibrated using the DMT results, with $K_0 = 0.56$. The results are shown in Figure 10. The in-situ results i.e. CPTu probing and D&M sampling with $e < 0.75$ plotted dry of critical indicating a dilative behaviour. Where the tailings had an initial void ratio above 0.75 it plotted wet of critical i.e. contractive behaviour. This is similar to what was obtained during the CSL testing.

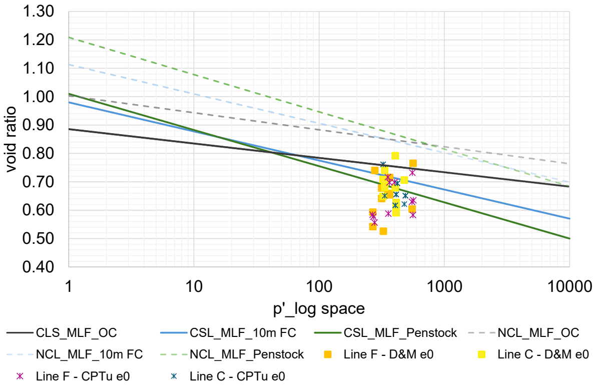
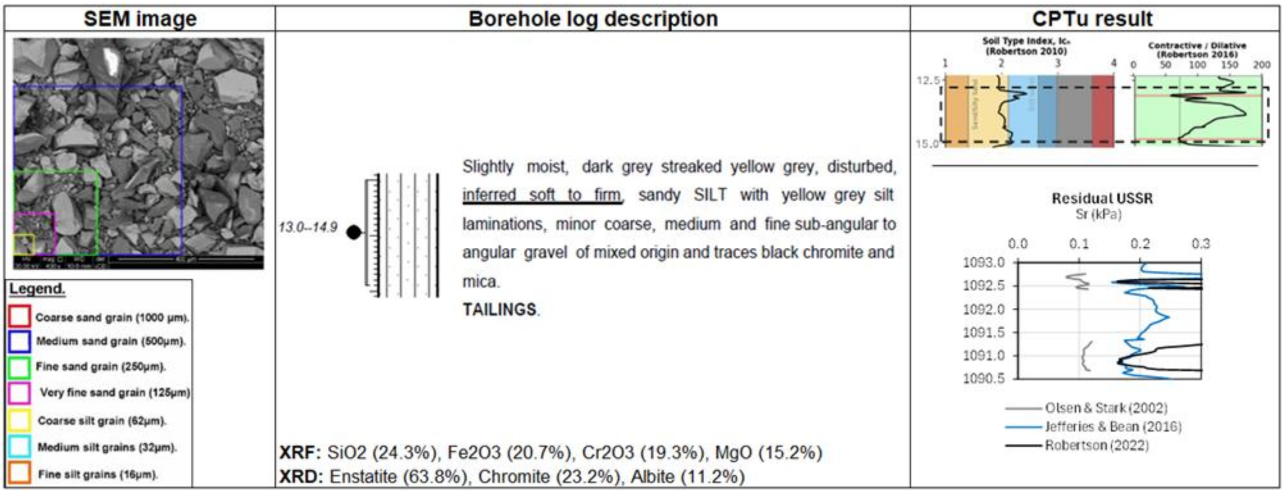


Figure 10. e_0 vs p' for laboratory and in-situ testing



Slightly moist, dark grey streaked yellow grey, disturbed, inferred soft to firm, sandy SILT with yellow grey silt laminations, minor coarse, medium and fine sub-angular to angular gravel of mixed origin and traces black chromite and mica.

TAILINGS.

XRF: SiO2 (24.3%), Fe2O3 (20.7%), Cr2O3 (19.3%), MgO (15.2%)

XRD: Enstatite (63.8%), Chromite (23.2%), Albite (11.2%)

Figure 11. Characterization at depth 13 to 14.9 m below surface

6 COMPLETE PROFILE CHARACTERISATION

The material at each profile point could be fully described using the analyses described above. A profile point is a section of the profile that has the same borehole log description. Figure 11 shows an example of a profile point for depth 13 to 14.9 m. This summary incorporates the SEM image, XRD and XRF results, borehole logging description, CPTu soil classification, behaviour in terms of the state parameter and residual USSR also from the CPTu. This further illustrates the importance of incorporating various types of characterization methods to fully understand the tailings material throughout the profile.

Using the CPTu results to determine the layering of the tailings and USSR values prior to sampling at depth is valuable so that any weaker layers can be targeted for confirmation laboratory testing.

Based on the possible sampling and preparation disturbances from the D&M sampling the CPTu results were used to delineate the tailings layering and analyse the slope stability for undrained conditions. This was done in accordance with Visagie and du Plessis, 2024, method.

7 CONCLUSIONS

This study provides valuable insights into the geotechnical characterization of hard rock rockflour platinum tailings. For the remoulded testing the following can be concluded:

- Outside of CSL testing CPTu probing is still considered one of the most valuable tailings characterization methods due to the continuous profiling of the tailings material in terms of material type, USSR and phreatic surface.
- Remoulded samples have lower drained strength and exhibit purely contractive behaviour, while non-remoulded samples show a phase transfer to dilation.
- Sampling disturbances, including densification and void expansion, significantly affect test results.
- Samples taken at-depth exhibited phase transfer behaviour which cannot be used for strain softening analyses. Thus, remoulded strength testing should be included in testing campaigns should contractive behaviour not be achieved from non-remoulded samples.
- The material exhibits a wide range of void ratios, densities, and saturations, influenced by both sampling and testing methods.
- It is essential that both field and laboratory testing be conducted to provide sufficient supplementary characterization information to allow more detailed targeted interpretations to be made.
- Behavioural insights: the contractive behaviour of remoulded samples contrasts with the phase transfer to dilation observed in non-remoulded samples, underscoring the importance of possible fabric effects and or sample densification.
- Practical implications: the findings emphasize the need for robust sampling and testing protocols to minimize disturbance and accurately characterize tailings material.
- Recommendations for future work: comparative testing of frozen vs. non frozen samples and field calibration of laboratory results are recommended to enhance understanding of tailings behaviour.
- The findings contribute to meeting GISTM requirements and improving stability assessments for TSFs.

8 REFERENCES

American Society for Testing and Materials (ASTM) International Standard test method for consolidated undrained cyclic direct simple shear test (D8296 – 19).

Chang, N. Heymann, G and Clayton, C. 2011. The effect of fabric on the behaviour of gold tailings, Geotechnique 61, No.3, 187-197.

Cho, G-C, Dodds, J. and Santamarina, J.C. 2006. Particle shape effects on packing density, stiffness and strength: natural and crushed sands. J. of Geotechnical and Geoenv. Eng, 132(5), 591-602

Jefferies, M. and Been, K., 2016. Soil Liquefaction: A Critical State Approach. CRC Press.

Soga, K., Mitchell, J.K., 2005. Fundamentals of Soil Behavior, Third Edition. John Wiley and Sons Inc.

Visagie, J., du Plessis, E., 2024. Restrictions of CPTu based interpretation methods and impact thereof on limit equilibrium modelling, Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization, Barcelona.