Geotechnical characterisation of iron tailings using SCPTu and laboratory testing

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ABSTRACT: Numerous tailings storage facilities (TSFs), initially deemed safe, no longer meet the updated safety requirements set by the Global Industry Standard on Tailings Management (GISTM) published in August 2020. This necessitates remedial work on many TSFs in South Africa, including adding stability buttresses, cutting back slopes, or remining parts of the facilities to comply with the current international standards. Continuous monitoring and stability evaluation are essential in this process and understanding the engineering properties of tailings is critical to inform design and safety analyses. This study characterises iron tailings using in-situ cone penetration tests with pore water pressure and seismic measurements (SCPTu), along with geotechnical borehole sampling and laboratory testing. The SCPTu, combined with geotechnical laboratory analysis, provides sufficient information to understand and characterise iron tailings for design and safety evaluations. The characterisation reported in this paper adds to the current body of knowledge and can be used as a further reference for iron ore tailings, facilitating comparisons and recommendations in the literature, for future projects.

1 INTRODUCTION

Numerous tailings storage facilities (TSFs), initially deemed safe, no longer meet the updated safety requirements set by the Global Industry Standard on Tailings Management (GISTM) published in August 2020. This necessitates remedial work on many TSFs, including adding stability buttresses or cutting back of slopes to comply with the current international Factor of Safety (FoS) standards. With recent advances in technology and the depletion of high-grade iron ore reserves in South Africa, remining of waste dumps are also becoming a more viable option (Singh & Maistry 2025). Before during and after these processes the stability and the safety of the facilities are vital.

The physical and geotechnical properties of tailings play a crucial role in the performance and structural integrity of a tailings dam. Consequently, ICOLD bulletin 194, which outlines recommended technical practices for the planning, design, construction, operation, and closure of tailings dams, emphasizes the importance of tailings characterisation (ICOLD 2019).

This study aims to characterise iron tailings from a TSF in Limpopo, South Africa, using in-situ cone penetration tests with pore water pressure and seismic measurements (SCPTu), along with rotary core borehole sampling and laboratory testing. This characterisation can be used as a reference for fine iron ore tailings from ore bodies in the Penge formation in South Africa, facilitating comparisons and recommendations in the literature, for future projects.

The iron tailings from this study were also compared to the iron tailings from the Corrego do Feijão Dam 1 near Brumadinho, Brazil, as a reference.

2 BACKGROUND

Geotechnical properties of tailings material are influenced by several factors, including the geology and mineralogy of the mined materials, the ore extraction and processing methods as well as the type and operational parameters of the TSF. Therefore, a brief background of the study material is presented below.

2.1 *Geology and mineralogy of mined materials*

The study area encompasses an iron mine characterised by stratabound orebodies occurring in the Penge Iron Formation, Transvaal Supergroup in South Africa. These orebodies consist of localised, hard, high-grade iron ores, primarily featuring hematite and martite mineralisation in irregular tabular formations.

These formations are interspersed with low-grade dolomite-hematite and calcite-hematite ores, embedded within carbonaceous shales, dolomites, chert, and medium-grade banded ironstones, with a dolerite hanging wall (Gutzmer et al. 2005).

After ore extraction and processing, the waste material predominantly contains minerals such as iron oxides, silicates, carbonates, and oxides, including, but not limited to Hematite (Fe_2O_3), Goethite ($FeO(OH)$), Quartz (SiO_2), Aegirine ($NaFe_3^+ Si_2O_6$), Orthoclase ($KAlSi_3O_8$) Kaolinite ($Al_2Si_2O_5(OH)_4$) Biotite ($K(Mg,Fe)_3AlSi_3O_{10}(OH,F)_2$) Dolomite ($CaMg(CO_3)_2$), Siderite ($(Fe,Mn)CO_3$), Calcite ($CaCO_3$), Cryptomelane ($KMn_8O_{16}$) and Pyrolusite ($MnO_2$) (Omaga et al. 2024).

2.2 *Methods used for extraction and processing*

Throughout the operational lifespan of the mine, iron ores were predominantly extracted via open-pit mining and underground sub-level caving techniques. Post-extraction, the ore was transported to a primary gyratory crusher, followed by conveyance to a stockpile and finally to the beneficiation plant. Here, the ore underwent further crushing, milling and separation. Followed by the dewatering and thickening of the waste to produce tails. These methods resulted in the production of relatively fine iron tailings material. This material is pumped as a slurry to be deposited and stored on a TSF.

2.3 *Type and operation of TSF*

The TSF at the mine comprises multiple ring dyke dams, constructed using an upstream raising method. A hybrid paddock and spigot delivery system are employed for deposition. During deposition, the paddocks, formed from dry tailings to elevate the walls upstream, are filled to capacity with tailings. By raising the outer paddocks, it ensures that the required freeboard is achieved. By following a rotational deposition method, it allows the coarser tailings material to settle and consolidate, on the outer perimeter of the TSF creating a stronger outer zone. The finer tailings which is still in suspension, will flow to the middle of the dam away from the outer zone, forming a low strength fine material in the basin. Excess water is being directed to the Return Water Dam (RWD) through a penstock decant system.

3 METHODOLOOGY

Rotary core boreholes with disturbed and undisturbed sampling, as well as SCPTu tests, were done as part of a geotechnical investigation at the TSF. The tests were positioned in such a way as to represent sections through the main embankments and enable characterisation of different tailings material encountered. Detailed cross sections were determined for stability analyses.

3.1 *SCPTu testing*

The CPTus were done according to international industry standards (ASTM D5778-12 & ISO 22476-1). The CPTu probe comprises a solid cone with a 60° point and 10 cm^2 probe area (3.6 cm diameter) that is thrust at a constant rate of 2 cm/s into the ground using hydraulic pressure of 20 tons. The tip resistance (q_c), sleeve friction (f_s) and dynamic pore-water pressure, with the filter position just behind the solid tip, (u_2) were measured every centimetre as the CPTu instrumented probe advanced into the tailings. The total force acting on the cone, Q_c, divided by the projected area of the cone, A_c, produces the cone resistance, q_c. The total force acting on the friction sleeve, Q_s, divided by the surface area of the friction sleeve A_s, produces the sleeve friction, f_s (Robertson & Cabal 2022).

Dissipation tests were performed at different depths to measure the equilibrium pore pressures (u_0) within the TSF. The CPTu probe is halted, and the pore pressure dissipation over time is measured. The dissipation rate depends upon the consolidation coefficient, which, in turn, depends on the compressibility and permeability of the soil. The rate of dissipation also depends on the diameter of the probe (Robertson & Cabal 2022).

After the CPTu testing, seismic soundings were carried out at 2.0 m depth increments following the ASTM D7400 standard test method for downhole seismic testing. The seismic soundings enabled the determination of the shear wave velocities at selected test positions, from which the small strain shear modulus (G_0) can be calculated using:

$$G_0 = \rho V_s^2 \quad (1)$$

where ρ = mass density of soil in kg/m^3 and V_s = shear wave velocity (m/s).

The data was analysed with the software CPeT-IT by GeoLogismiki.

3.2 *Rotary core boreholes*

Eleven vertical rotary core boreholes were drilled with an NQ size drill bit (47.6 mm core size). Boreholes were drilled through the tailings and terminated in the residual material. The boreholes were logged on-site according to the South African guideline for soil and rock logging (Brink & Bruin 2001).

3.3 *Laboratory testing*

A selection of disturbed and undisturbed material samples retrieved from drilled core and Shelby tubes were submitted to an accredited laboratory for geotechnical material testing. The following tests were conducted on the collected samples according to acceptable standards (SANS 3001 GR1, GR3, GR10, GR12 & BS 1377), namely (a) Grading with Atterberg Limits; (b) Constant Head Permeability Tests; (c) Consolidated Undrained Triaxial Tests; (d) Moisture Content; and Specific Gravity.

4 TAILINGS CHARACTERISATION

4.1 *Grading with Atterberg limits*

Table 1 presents the physical properties of the tailings material, based on the results of three samples taken at varying depths from a single borehole, which is representative of other boreholes in the study. The iron ore tailings have an average specific gravity, G_S, of 3.94, which aligns with the upper range of metal tailings (Hu et al. 2017). This high G_S value is attributed to the iron oxide mineral content and fines content. Omaga et al. (2023) observed that hematite and goethite concentrations increase in finer fractions of the material leading to a higher G_S.

The iron tailings are of intermediate plasticity (Knappett & Craig, 2012).

Table 1. Physical properties of iron tailings

Properties	Iron tailings – sample depth (m)		
	0.5-1.5 (Outer)	9.0-10.0 (Basin)	21.0-22.5 (Basin)
Liquid Limit (%)	31	30	37
Plastic Limit (%)	18	17	20
Plasticity Index (%)	13	13	17
Linear Shrinkage (%)	6.5	6.5	9.0
% Gravel	0	0	0
% Sand	9	7	8
%Silt	65	67	63
% Clay	26	26	29
Activity	0.5	0.5	0.6
Grading Modulus	0.02	0.02	0.01
Moisture Content (%)	25.1	16.4	N/T*
Specific Gravity (G_S)	4.006	4.036	3.779

* N/T: Not Tested

Based on the results of grading and Atterberg Limits, all the tailings material, from different locations and depths, are classified as CL, a lean clay with silt and sand, according to the unified soil classification system (ASTM D2487).

These tailings are comparable, in terms of their grading, Atterberg Limits and G_S, to the fine iron tailings and slimes, rather than the coarse tailings, from the Feijão Dam I (Robertson et al. 2019).

4.2 *Stratigraphy and behaviour type (SBTn)*

SCPTu measurements respond to the in-situ mechanical behaviour of soils and can be used for reasonably accurate soil profiling and classification. The method suggested by Robertson (Robertson, 2010) was used to determine and describe the in-situ stratigraphy and is referred to as the soil behaviour type (SBT) distribution. The CPT data requires normalisation for overburden stress to remove the influence of depth for both q_c and f_s and therefore the updated normalised SBT_n charts suggested by Robertson (2016) were used to classify the soil types.

Figure 1 shows a borehole log of a rotary core borehole, positioned in the basin tailings, alongside an adjacent CPTu result. The figure shows q_c in MPa alongside the normalised soil behaviour type (SBT_n) with depth. It is evident that the stratigraphy shows approximately 2 m of clayey sandy silt outer tailings followed by approximately 20 m of fine sandy clayey silt tailings on top of the residual hillwash material. This is consistent with the soil classification from the laboratory results.

The CPTu results show a more detailed stratigraphy chart than the adjacent borehole log.

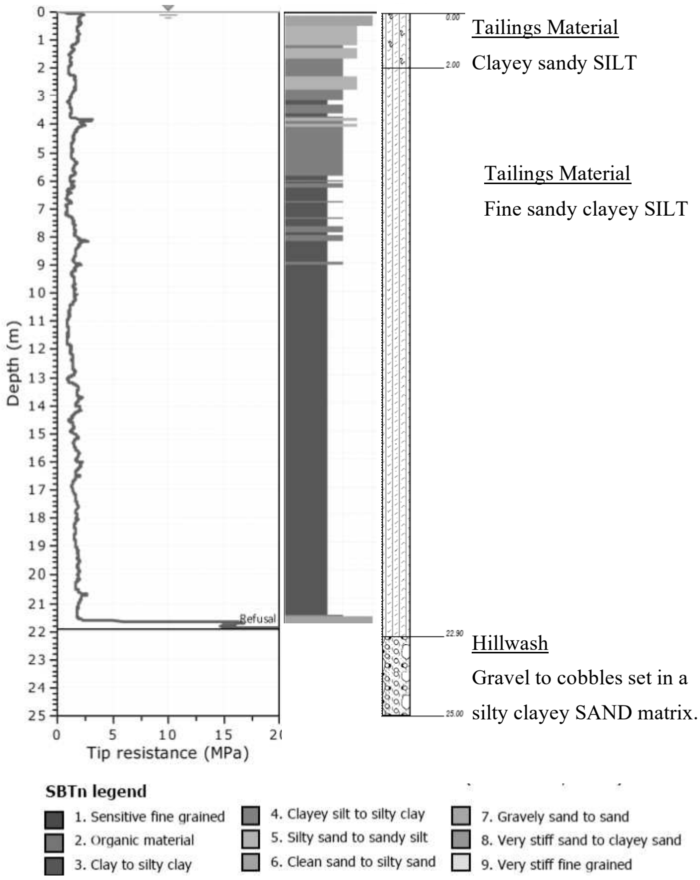

Figure 1. SCPTu and rotary borehole log comparison.

4.3 *Contractive/dilative properties*

The method described by Robertson (Robertson 2022) was used to categorise the material into two distinct categories, namely contractive (CD<70) and dilative behaviour (CD≥70). This aids in determining whether the materials are susceptibility to flow liquefaction. The contractive-dilative boundary (CD) is defined by the equation:

$$CD = (Qtn - 11)(1 + 0.06Fr)^{17} \quad (2)$$

where Q_{tn} is the normalised cone resistance; and F_r is the normalised friction ratio.

This definition however is more relevant to soils with little or no microstructure such as young soils or unbonded soils.

According to the results the outer tailings appear dilative with the basin tailings being contractive.

The seismic measurements combined with the CPTu data were used to determine whether the material has microstructure. The modified normalised rigidity index, K^*_G, suggested by Robertson (Robertson 2016) was used to estimate the magnitude of microstructure. This is a combination of the measure of large strain soil strength through the cone resistance (q_c) and small strain soil stiffness (G_0) through shear wave velocity (v_s) measures. Soils with a K^*_G value exceeding 330 often exhibit microstructure, whereas very young, uncemented soils typically have K^*_G values closer to 100.

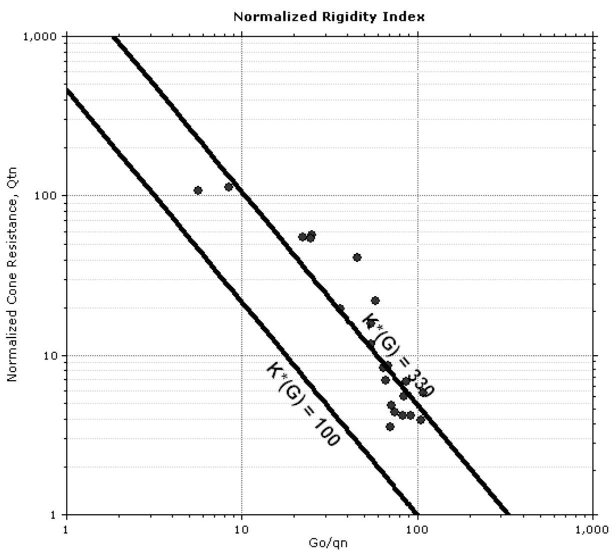

Figure 2. A plot of Q_{tn} versus I_G (G_0/q_n) displaying the K^*_G, showing microstructure for the tailings material.

The results presented in Figure 2, is from a SCPTu that was done on the embankment and shows that the tailings material has microstructure. This could be explained by the microplaty nature of the hematite ore mineral (Gutzmer et al. 2005) present in the tailings material, together with the presence of other clay minerals.

Due to this finding, the outer tailings material was considered to be dilative at small strains and contractive at large strains.

At Feijão Dam I microstructure in the form of bonding were found to be present in the iron tailings and it appeared from the Scanning Electron Microscope (SEM) images that oxidation of the iron produces bonding between particles in the form of clay-size iron oxide (Robertson et al. 2019).

4.4 *Permeability*

Constant head permeability tests were conducted on samples collected from the outer and basin tailings material from two boreholes. The samples were remoulded to in-situ density. The minimum, maximum and average coefficient of permeability (k) are listed in Table 2.

Table 2. Iron tailings Coefficient of Permeability (k) from the laboratory

	Min.	Max.	Avg.
Tailings material	m/s	m/s	m/s
Outer	2.51×10^{-8}	3.64×10^{-8}	3.17×10^{-8}
Basin	1.18×10^{-9}	3.15×10^{-9}	2.15×10^{-9}

Lower permeabilities are measured with depth due to a void ratio reduction occurring through consolidation. According to the results, the tailings material exhibits very poor to non-permeable drainage character (BS 8004: 1986).

The CPTu results were also used to determine the in-situ permeabilities of the tailings material. An approximate estimate of k and variation of k with depth, can be derived from CPT soundings by using the relationship between the normalised soil behaviour type (SBT_n) and soil behaviour type Index (I_c) with soil permeability as suggested by Robertson (Robertson, 2010). Table 3 shows the recommended permeability ranges for the different SBT_n zones.

Table 3. Coefficient of Permeability (k) ranges for the different SBT_n zones (Robertson 2010).

SBT_n Zone		Range of k (m/s)
1	Sensitive fine grained	$3 \times 10^{-10} - 3 \times 10^{-8}$
2	Organic soils – clay	$1 \times 10^{-10} - 1 \times 10^{-8}$
3	Clay	$1 \times 10^{-10} - 1 \times 10^{-9}$
4	Silt mixtures	$3 \times 10^{-9} - 1 \times 10^{-7}$
5	Sand mixtures	$1 \times 10^{-7} - 1 \times 10^{-5}$
6	Sand	$1 \times 10^{-5} - 1 \times 10^{-3}$
7	Dense sand to gravelly sand	$1 \times 10^{-3} - 1$
8	*Very dense / stiff soils	$1 \times 10^{-8} - 1 \times 10^{-3}$
9	*Fine grained stiff soils	$1 \times 10^{-9} - 1 \times 10^{-7}$

* Over-consolidated and/or cemented.

Using the above method the approximate average value of k, from the CPTu results for the outer and basin tailings, are listed in Table 4.

Table 4. Tailings material Coefficient of Permeability from CPTu results

	Average k
Tailings material	m/s
Outer	2.21×10^{-7}
Basin	5.40×10^{-9}

The CPTu results for the outer tailings appear to give more permeable results when compared to the laboratory results. This can be addressed to the fact that the CPTu's were done in-situ, whereas the laboratory values are from remoulded materials. The upper tailings were logged in the field as dryer material with open structures and visible roots. The lower tailings is more consolidated and the in-situ measured permeabilities correspond well with the laboratory test results.

Much higher permeabilities were observed in the coarser iron tailings of the Feijão Dam I (Robertson et al. 2019).

4.5 *Pore water pressure and phreatic surface*

High dynamic pore pressures, compared to the expected hydrostatic pressure, were observed as the probe advanced with depth. After dissipation of the excess pore pressure, generated during probing, equilibrium pore pressures (u_0) higher than 0 were observed, but below hydrostatic pressure.

The low permeability of the iron tailings limits drainage in the tailings dam, resulting in high moisture content, but no phreatic surface was detected.

In areas where dilative soils with high moisture content and pore pressure build-up were identified in the upper tailings, a water table was incorporated in the CPeT-IT software to simulate hydrostatic conditions, ensuring a realistic approach to strength calculations.

4.6 *Shear strength properties*

Strength properties were determined in the laboratory with consolidated undrained (CU) triaxial tests. CU triaxial tests were conducted on undisturbed samples. Different depths of the tailings material were sampled to determine the material properties for the different layers observed in the CPTu test results. Table 5 gives a summary of the test results obtained. For all CU triaxial test results, the cell pressure (confinement stress) ranged between 100 kPa to 400 kPa.

Table 5. Consolidated Undrained (CU) triaxial tests

	Saturated Unit weight	Friction angle	Cohesion c'
Tailings material	kN/m^3	°	kPa
Outer	24	37	10
Basin	23	38	0

The results show that the high specific gravity in the tailings produces a relatively high soil unit weight for the tailings material of around 24 kN/m^3 compared to an even higher, 26 kN/m^3, for the Feijão Dam I (Robertson et al. 2019).

The SCPTu results were used to determine the undrained strength properties of the tailings material. Since the material is mainly fine grained and cohesive, the following relationship was used:

$$S_u = \frac{q_t - \sigma_v}{N_{kt}} \quad (3)$$

where σ_v = total overburden stress, q_t = cone resistance and N_{kt} is the cone factor and typically varies between 10 to 18 with 14 as an average.

The reference database for assessing the N_{kt} cone factor, as proposed by Mayne and Peuchen in 2018 (Mayne & Peuchen 2018), was used to determine a suitable N_{kt} value. The N_{kt} cone factor deemed suitable and used in the calculations is 14.

The remoulded shear strength from the CPTu results was used as the large strain (also known as "residual") undrained shear strength. During probing, soil close to the friction sleeve experiences large strains and soil structure tends to be fully destructed or remoulded (Robertson 2022). Therefore, the remoulded s_u is approximately equal to the measured CPT sleeve friction (f_s), since both occur in undrained condition and at large strains. This relationship can be represented by the equation:

$$\frac{S_{u(liq)}}{\sigma'_{vo}} = \frac{f_s}{\sigma'_{vo}} = \frac{F_r Q_{tn}}{100} \quad (4)$$

where f_s = sleeve friction; Fr = normalised friction ratio (%); Q_{tn} = normalised cone resistance; and σ'_{vo} = effective overburden stress (kPa).

Finally, the 30th percentile peak and residual undrained shear strength ratios were calculated for the different layers of contractive material. According to Robertson case histories have shown that weaker zones tend to control stability and that representative CPT values are close to the 30th percentile value (approximately the mean minus one standard deviation, assuming a normal distribution) for most CPT data sets in contractive soils, ranging from clean sands, through clay-like fine tailings, to sensitive clays (Robertson 2022).

Table 6 lists the undrained peak and residual shear strength ratios for the outer and basin layers of the iron ore tailings material.

Table 6. Undrained shear strength properties of iron tailings

	Undrained peak shear strength ratio	Undrained residual shear strength ratio
Tailings material		
Outer	1.57	0.58
Basin	0.49	0.22

The outer tailings demonstrate high peak and residual shear strength ratios, which are noted solely for comprehensiveness. As a drained and dilative material layer, Mohr-Coulomb properties will be used for safety evaluation purposes instead.

5 CONCLUSIONS

The iron tailings were characterised as a lean clay with silt and sand with an average G_S of 3.94, intermediate plasticity and very low permeability. Considering the influence of depositional processes, the CPTu and laboratory data revealed that the TSF consists of an outer sandy silt layer with a stiff consistency and low permeability, and an inner clayey silt basin with soft to very soft consistency and very low permeability. The upper tailings appear more dilative with high undrained shear strength, while the lower tailings behave more contractive. Since the seismic analysis revealed that the tailings have microstructure, all the tailings is considered contractive at large strains.

The CPTu results are comparable to the borehole logs with even more detailed stratigraphy given, making it a reliable and acceptable tool for a geotechnical campaign. The geotechnical properties determined with the CPTu results using empirical correlations from literature compared well with the laboratory results. It is therefore derived that the CPTu can be used as a reliable tool to determine the properties of fine iron ore tailings material.

The iron tailings from this study compares only to the fine iron tailings of the Feijão Dam 1, since the Feijão Dam 1 consisted of interlayered coarse and fine tailings.

The characteristics reported in this paper contribute to the body of knowledge of iron ore tailings in South Africa.

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