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Liquefaction in tailings dams: critical assessment of susceptibility in underflow tailings

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Abstract

Liquefaction in tailings storage structures represents one of the most critical instability mechanisms in geotechnical works. In such systems, the presence of fine-grained, unconsolidated, and saturated materials promotes a sudden loss of shear strength under undrained loading, particularly in contexts where contractive behaviour predominates. The assessment of liquefaction susceptibility requires an integrated approach, grounded in detailed geotechnical investigations, representative laboratory testing, and interpretive models based on critical state soil mechanics.

In this context, the present study investigates the liquefaction susceptibility of a cyclone-deposited tailings dam with underflow material, constructed using the centreline method. The analysis is based on the reinterpretation of geotechnical data obtained from field and laboratory campaigns. Seismic piezocone tests (SCPTu) were employed and interpreted according to the methodologies proposed by Robertson (2009), Jefferies & Been (2016), and Plewes et al. (2017), enabling the identification of zones with predominantly dilative behaviour, as well as the detection of localised layers exhibiting contractive tendencies.

This interpretation was complemented by undrained triaxial tests and the evaluation of state parameters, allowing for the vertical discretisation of the tailings based on their mechanical response. Saturated zones exhibiting contractive behaviour were incorporated into stability analyses through limit equilibrium methods, considering critical piezometric conditions. Despite compliance with regulatory criteria, the presence of liquefiable materials highlights the importance of real-time monitoring, continuous geotechnical characterisation, and the adoption of robust preventive strategies in the risk management of tailings dam stability.

Keywords: *liquefaction, tailings dams, SCPTu tests, contractive behaviour, critical state*

1 Introduction

Liquefaction in tailings dams constitutes one of the most critical instability mechanisms in geotechnical engineering, being responsible for high-impact socio-environmental failures in various mining regions (Seed & Idriss 1982; Casagrande 1975). This phenomenon occurs when saturated, predominantly fine-grained, and loosely consolidated materials abruptly lose shear strength under undrained loading, particularly under contractive behaviour, in which the soil volume tends to decrease during shearing (Been & Jefferies 1985; Mesri & Castro 1987). Susceptibility to liquefaction is influenced by multiple factors, including grain size distribution, void ratio, degree of saturation, relative density, and soil state parameters, with the distinction between contractive and dilative behaviour being fundamental for risk assessment (Lancellotta 1996; Bolton 1986).

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The evaluation of liquefaction susceptibility requires an integrated approach that combines detailed geotechnical investigations, representative laboratory testing, and interpretative models based on critical state soil mechanics (Schofield & Wroth 1968; Jefferies & Been 2016). Among the employed methodologies, seismic piezocone testing (SCPTu) stands out, allowing for the identification of dilative and contractive zones and providing parameters that correlate with shear strength and relative density of the materials (Robertson 2009; Plewes et al. 2017). Complementarily, undrained triaxial tests enable the evaluation of soil behaviour under rapid loading conditions and the determination of critical parameters, such as undrained friction angle and contractancy index, which are essential for vertical discretisation and stability modelling of tailings dams (Kramer 1996).

Recent studies reinforce the importance of detailed characterisations for assessing liquefaction susceptibility. Da Costa et al. (2024) investigated iron ore tailings dams using SCPTu tests, identifying contractive behaviour in more than 90% of samples, indicating a high risk of flow liquefaction. In this context, the combination SCPTu and undrained triaxial tests provides a comprehensive understanding of the mechanical response of tailings, enabling more precise and safe stability analyses. These studies highlight the necessity of integrated methodologies capable of capturing spatial and vertical heterogeneities in tailings deposits.

The present study addresses the susceptibility to liquefaction of a tailings dam constructed using the central (centreline) method, with deposition of underflow material from cyclone separation. The analysis is based on the reinterpretation of geotechnical field and laboratory data, including SCPTu and undrained triaxial tests, complemented by the evaluation of state parameters. The identification of saturated layers exhibiting contractive behaviour and their incorporation into stability analyses using limit equilibrium methods provide a basis for technical recommendations and preventive strategies, highlighting the importance of continuous monitoring and proactive risk management in tailings dams.

2 Methodology

The dam under study was constructed using the centreline method, characterised by progressive, centrally aligned raising with simultaneous deposition of underflow and overflow tailings. These tailings exhibit distinct geotechnical properties, with the underflow tailings being particularly relevant associated with their fine grain size, high bulk density, and contractive behaviour when saturated (Jefferies & Been 2016; Jewell & Fourie 2015).

Underflow tailings correspond to the denser and more concentrated fraction obtained from cyclone effluent in hydraulic classification processes. Their tendency to undergo volumetric reduction under loading and to lose strength in saturated conditions makes them critical for the structural stability assessment. In contrast, overflow tailings exhibit a coarser grain size, lower bulk density, and predominantly dilative behaviour, making them less susceptible to liquefaction (Fourie et al. 2021).

In this study, emphasis is placed on underflow tailings, aiming to characterise their essential geotechnical parameters and assess their susceptibility to liquefaction through an integrated approach of laboratory testing and in situ piezocone penetration testing (CPTu). Laboratory tests, including triaxial and direct shear tests, allow determination of shear strength under drained and undrained conditions, void ratio, relative density, and contractive/dilative behaviour (Jefferies & Been 2016).

Additionally, CPTu tests provide in situ profiles of cone resistance, sleeve friction, and pore pressure, enabling estimation of relative density, microstructural behaviour, and liquefaction susceptibility (Robertson 2009; Plewes & Robertson 2010). Integrating these datasets provides a robust basis for evaluating the stability of underflow tailings and supports mitigation strategies and continuous dam monitoring.

2.1 Laboratory characterisation of underflow tailings

The laboratory characterisation of underflow tailings constitutes a fundamental step to understand the geotechnical properties of the material and assess its susceptibility to liquefaction. For this study, representative samples of underflow tailings were collected at various depths using techniques designed to minimise structural alterations and preserve the material's integrity. Samples were stored and transported under controlled conditions to ensure that the natural characteristics of the tailings were maintained for laboratory analysis.

The laboratory tests performed included:

- Proctor compaction test: used to determine the relationship between void ratio and dry density of the tailings, providing reference parameters for compaction state and relative density (ASTM International 2012).
- Consolidated-drained (CD) and consolidated-undrained triaxial tests: allowed determination of shear strength under drained and undrained conditions, essential for evaluating the stability and liquefaction susceptibility of the tailings (Jefferies & Been 2016).
- Determination of void ratio and Atterberg limits: provide information on the natural compactness of the tailings and their volumetric deformation properties.

The focus on laboratory characterisation of underflow tailings is due to their higher susceptibility to liquefaction compared to overflow tailings, owing to lower void ratios and predominance of contractive behaviour under loading (Olson 2001; Sadrekarimi 2014). Laboratory analysis provides the fundamental parameters for subsequent interpretation of field tests (CPTu/SCPTu) and application of liquefaction assessment methodologies, enabling an integrated understanding of the tailings' in situ behaviour.

The dataset obtained from laboratory tests allows the definition of geotechnical parameters necessary for numerical modelling and stability analysis, in addition to providing support for designing interventions and monitoring underflow tailings safety.

2.2 Susceptibility to flow liquefaction

The in situ geotechnical characterisation of the underflow tailings was carried out through CPTu and seismic piezocone testing (SCPTu), techniques widely recognised for their ability to provide continuous and accurate subsurface data essential for assessing liquefaction susceptibility. These tests allow for the development of detailed profiles of cone resistance (q_c), sleeve friction (f_s), and pore pressure (u_2), which are fundamental parameters for analysing the mechanical behaviour of tailings under saturated conditions and cyclic loading.

To evaluate the liquefaction susceptibility of the underflow tailings, well-established methodologies from the geotechnical literature were adopted, including Plewes et al. (1992), Olson (2001), Sadrekarimi (2014), Robertson (2016), and Jefferies & Been (2016). The integrated application of these approaches enables the determination of shear strength, the identification of contractive or dilative behaviour, and the estimation of liquefaction potential, combining field test data with interpretations supported by laboratory results and established theories of soil mechanics.

The interpretation of the underflow tailings data was conducted in two stages:

- Saturated tailings: base on the groundwater level determined during SCPTu testing, the geomechanical parameters of the saturated layer were analysed.
- Saturated tailings with contractive behaviour: within the saturated layer, only the portion of the material exhibiting contractive behaviour was considered, as this condition is associated with a higher susceptibility to liquefaction.

Accordingly, the analysed sections were discretised based on this evaluation, allowing for the definition of geomechanical parameters specific to each condition observed within the underflow tailings.

2.2.1 Plewes et al. (1992)

Plewes et al. (1992) suggested a relationship between the slope of the critical state line (λ_{10}) and the normalised friction ratio (F or F_r) as shown by Equation 1 and Equation 2.

$$\lambda_{10} = \frac{F}{10} \tag{1}$$

$$F \text{ or } F_r = \frac{f_s}{(q_t - \sigma_{v0})} \times 100\% \tag{2}$$

where:

f_s = sleeve friction resistance

q_t = corrected cone resistance

σ_{v0} = total vertical stress.

2.2.2 Olson (2001)

Olson (2001) conducted an extensive analysis of 33 historical cases of flow failures associated with static liquefaction, developing a systematic and comprehensive procedure for evaluating the behaviour of materials susceptible to liquefaction. The method proposed by the author addresses 3 fundamental aspects:

- the assessment of liquefaction susceptibility
- the triggering or initiation of the liquefaction process
- the post-triggering stability and flow failure behaviour.

To estimate the susceptibility to flow liquefaction, Olson (2001) recommended the use of the contours proposed by Robertson & Fear (1995), originally developed from empirical correlations based on data obtained through the standard penetration test. These contours were later adapted for application with the cone penetration test (CPTu), allowing for a more continuous and precise assessment of in situ soil resistance conditions.

The correlations between peak shear strength and residual (liquefied) shear strength derived from CPT data are expressed by Equations 3 and 4, as proposed by Olson (2001), which are applicable to materials with a normalised cone resistance (q_{c1}) lower than 6.5 MPa. This threshold reflects the typical behaviour range of sandy-silty and silty-sand tailings with varying degrees of saturation and relative density, representing realistic conditions commonly encountered in underflow tailings.

$$\frac{Su_{(pico)}}{\sigma'_{v0}} = 0{,}205 + 0{,}0143(q_{c1}) \pm 0{,}04 \tag{3}$$

$$\frac{Su_{(liq)}}{\sigma'_{v0}} = 0{,}03 + 0{,}0143(q_{c1}) \pm 0{,}03 \tag{4}$$

where:

$Su_{(pico)}$ = represents the peak undrained shear strength

$Su_{(liq)}$ = represents the undrained shear strength at the liquefaction state (residual strength)

σ'_{v0} = is the initial effective vertical stress in the soil.

The methodology developed by Olson (2001) has become widely adopted in the stability assessment of tailings storage facilities as it integrates field test results with empirical parameters and interpretations grounded in observed failure mechanisms. This approach provides a robust framework for estimating liquefaction susceptibility and evaluating the structural stability of tailings deposits under critical static loading conditions.

2.2.3 Sadrekarimi (2014)

Sadrekarimi (2014) refined the approach originally proposed by Olson (2001) by incorporating the effect of the shear mode during the flow liquefaction failure process. While Olson's model primarily considers a simple and uniform shear condition, Sadrekarimi methodology recognises that segments of a potential failure plane are subjected to different principal stress directions, corresponding to distinct shear modes that vary along the failure surface.

This approach represents a significant advancement in the understanding of static liquefaction as it integrates observations from triaxial compression and simple shear (DSS) laboratory tests with analyses based on complex failure mechanisms, thereby reflecting more accurately the anisotropic and heterogeneous conditions typically found in mining tailings. The method is particularly applicable to materials with normalised cone resistance (q_{c1}) lower than 8.0 MPa, encompassing the typical behavioural range of dense fine-sand and silty-sand tailings.

According to Sadrekarimi (2014), empirical correlations derived from in situ tests, such as the CPTu, are advantageous tools for estimating the ratios of peak and residual shear strength in potentially liquefiable materials, provided they are calibrated against representative laboratory results. The method thus introduces the influence of the predominant failure mode (direct shear, triaxial, or combined) in the estimation of undrained shear strength ratio and liquefied strength, extending and refining the correlations proposed by Olson.

2.2.4 Robertson (2016)

Robertson (2016, 2022) developed one of the most widely adopted approaches for the interpretation of CPTu, aiming to characterise soil behaviour and infer the liquefaction potential from normalised resistance and friction parameters. The methodology is based on the concept of the soil behaviour type (SBT) classification, which relates the cone resistance, sleeve friction, and pore pressure responses to the material's density, plasticity, and structure.

The approach begins with the normalisation of cone resistance and friction values to account for effective stress conditions and depth effects. The normalised cone resistance (Q_{tn}) and friction ratio (F_r) are defined as follows:

$$Q_{tn} = \frac{(q_t - \sigma_{v0})}{p_a} \left(\frac{p_a}{\sigma'_{v0}} \right)^n \tag{5}$$

$$F_r = \frac{f_s}{(q_t - \sigma_{v0})} \times 100 \tag{6}$$

where:

- q_t = corrected cone tip resistance
- σ_{v0} = total vertical stress
- σ'_{v0} = effective vertical stress
- f_s = sleeve friction
- p_a = reference atmospheric pressure (≈ 100 kPa)
- n = stress normalisation exponent (typically ranging from 0.5 to 1.0).

Using these normalised parameters, Robertson (2016) introduced the SBT Index (Ic), which allows a continuous classification of soil materials according to:

$$I_c = \sqrt{(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2} \quad (7)$$

For liquefaction susceptibility assessment, Robertson (2016) proposed that the contractive or dilative behaviour of soils can be inferred from the SBTn classification. Materials with $I_c > 2.6$ tend to exhibit contractive behaviour and are thus considered potentially liquefiable, whereas materials with $I_c < 2.6$ are predominantly dilative and less susceptible to liquefaction.

In his 2022 revision, Robertson refined the methodology by incorporating correlations between the behaviour type index and the reference stress state, allowing better distinction between structured natural soils and remoulded or disturbed materials. The updated framework also introduced the ΔI_c parameter, which represents the variation of the behaviour type index with depth and microstructural changes, improving the prediction of liquefaction susceptibility in fine-grained mining tailings.

Overall, the Robertson (2016, 2022) approach provides a robust and empirically validated framework for interpreting CPTu data in mining tailings, enabling the identification of contractive and dilative zones and the delineation of potentially liquefiable layers within the underflow tailings deposit.

3 Results and discussion

The particle size distribution curves of the collected samples are presented in Figure 1. On average, the tailings exhibit a granulometric composition ranging from silty sand to sandy silt, consistent with the observations from in situ field tests. The samples are predominantly silty sand, with clay content reaching up to 9%. Furthermore, the data indicate a spatial variability in the composition of the deposited material along the tailings storage area, highlighting heterogeneity inherent to the deposition process.

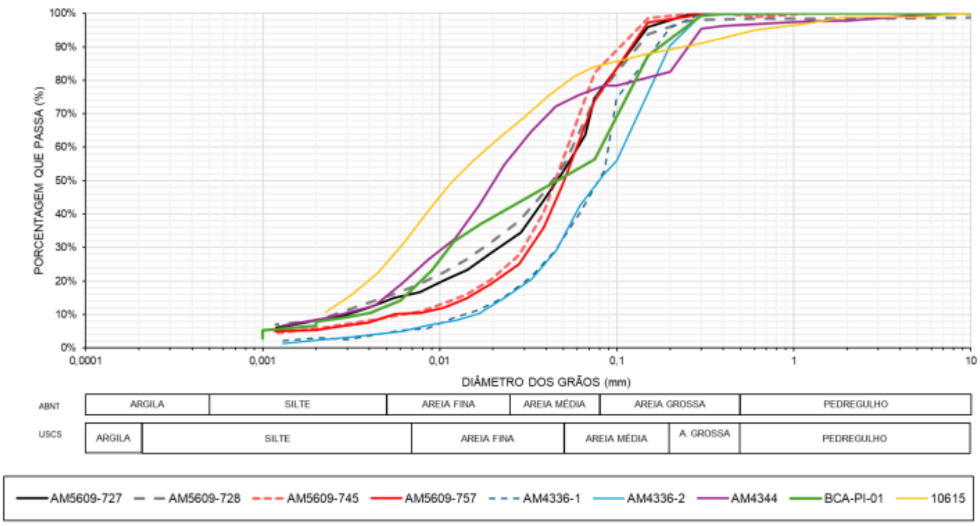

Figure 1 Grain size distribution of the underflow tailings

For the underflow tailings, Denison-type samples were collected, subsequently remoulded at void ratios of 0.5/0.6 and 0.8/0.9, and tested in the laboratory to determine the shear strength parameters based on the critical state soil mechanics theory. The tailings behaviour was modelled using the Norsand constitutive model, and the interpretation of the triaxial and direct shear tests was conducted following the methodology described by Jefferies & Been (2016), allowing the derivation of the parameters required for the geotechnical characterisation of the material.

Regarding the shear strength parameters, such as cohesion and friction angle, these were determined from the results of triaxial compression tests, DSS tests, and SCPTu tests. In the drained and undrained triaxial tests (CIUsat and CIDsat), the critical friction angle was initially established for each condition. Figures 2 and 3 present the effective stress paths and the critical envelope obtained for the different underflow tailings mixtures.

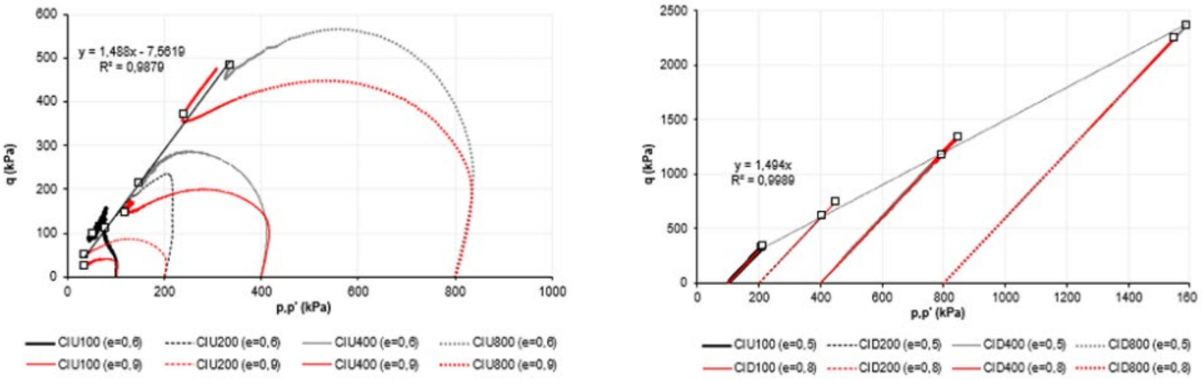

Figure 2 **Effective stress paths. (a) AM5609-727 – CIUsat; (b) AM5609-727 – CIDsat**

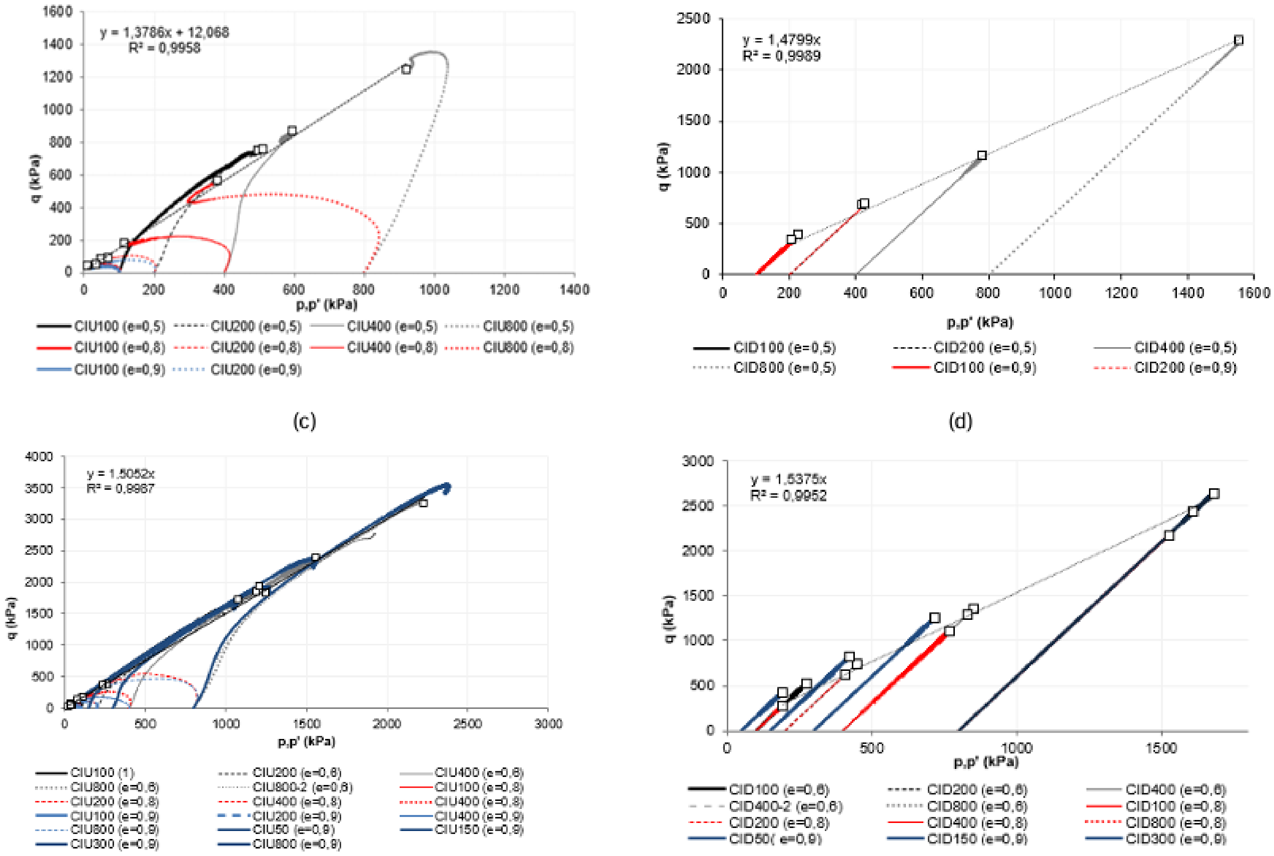

Figure 3 **Effective stress paths – (c) AM5609-728 – CIUsat; (d) AM5609-727 – CIDsat; (e) AM5609-745/757 – CIUsat; (f)AM5609- 745/757- CIDsat**

The contractive or dilative behaviour of the underflow tailings in the embankment was assessed based on the methodologies of Robertson (2016) and Jefferies & Been (2016), as detailed in Section 2. According to Jefferies & Been (2016), the underflow tailings predominantly exhibit dilative behaviour in most of the SCPTu tests conducted, with only a few points indicating contractive behaviour. Figure 4 illustrates the distribution of the state parameter plotted on the F–Q diagram, allowing the visualisation of the material's contractive or dilative tendency.

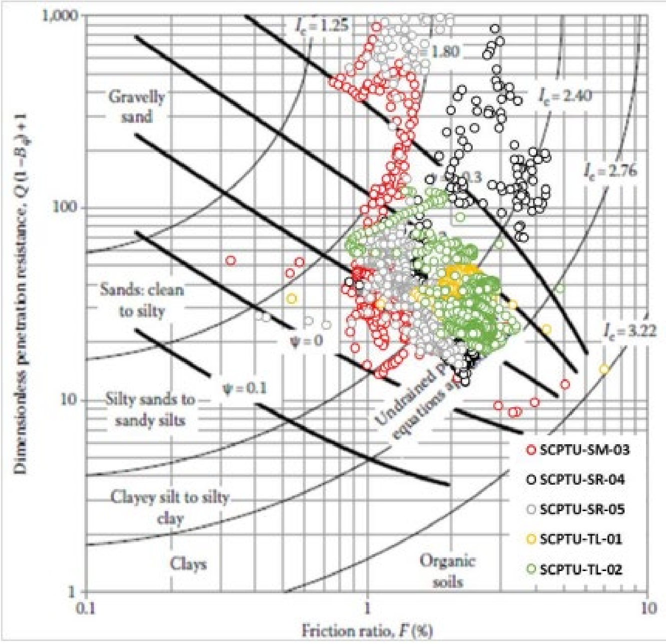

Figure 4 State parameter

Figure 5 presents the consolidated results of the SCPTu tests for the underflow tailings. According to Robertson's (2016) Q_{tn}–F_r diagram, 84.53% of the grouped points lie above the CD = 70 line, which serves as a reference to distinguish dilative from contractive behaviour, with points below the line indicating contractive material. Thus, based on the criteria defined by Robertson (2016) methodology, it is concluded that the underflow tailings are predominantly dilative and, therefore, do not meet the logical chain necessary for the occurrence of static liquefaction, which concomitantly requires:

1. the presence of contractive material
2. undrained conditions during loading
3. the existence of a credible trigger in terms of rate and/or scale of loading
4. sufficient post-peak strength loss to allow progressive instability
5. geometric continuity enabling the development of a global failure mechanism.

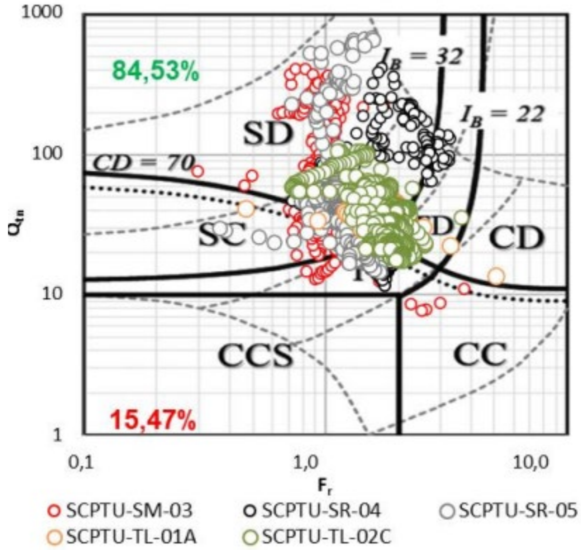

Figure 5 Seismic piezocone test (SCPTu) results

4 Conclusion

Through the integration of field tests (CPTu and SCPTu) and laboratory tests (triaxial and direct shear), it was possible to thoroughly characterise the geotechnical behaviour of the underflow tailings in the embankment. The analyses revealed that the material is predominantly silty-sandy with low clay content, and exhibits grain size variability along the deposit, highlighting the importance of comprehensive characterisation for geotechnical risk assessment.

The evaluation of contractive or dilative behaviour, conducted based on the methodologies of Robertson (2016) and Jefferies & Been (2016), demonstrated that the underflow tailings predominantly exhibit dilative behaviour. Only a small fraction of the measurements indicated localised contractive characteristics, suggesting that most of the material is not susceptible to liquefaction under cyclic loading conditions, as confirmed by the Q_{tn}–F_r

Complementary analysis methodologies, including Plewes et al. (1992), Olson (2001), and Sadrekarimi (2014), enabled the determination of both peak and liquefied shear strength parameters, integrating field and laboratory results. The application of the Norsand constitutive model, calibrated from triaxial and direct shear tests, provided appropriate parameters for numerical simulations and stability assessments of the underflow tailings.

Overall, the results indicate that the underflow tailings are predominantly dilative and, therefore, exhibit low susceptibility to liquefaction, contributing to the overall stability of the structure. These findings underscore the importance of integrating field and laboratory testing, as well as employing established methodologies, for the geotechnical characterisation of mining tailings and the assessment of associated risks.

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