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Improving the sustainability of tailings disposal through better practices in filtered tailings stacks

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Abstract

Filtered tailings stacks are increasingly considered as a preferable option for tailings storage facilities, as they can enhance stability and structural integrity, thereby reducing the risk of catastrophic failures. This technique involves compacting unsaturated tailings, requiring less disposal area, reducing the risk of groundwater contamination, and allows water recovery from the processing cycle, making it a more sustainable solution with lower environmental impact. This is particularly important in countries with a humid climate (like Brazil) and high tailings production volumes, which distinguish them from international cases. Topics related to particle breakage, transitional behaviour, and the effects of under-compacted materials on static liquefaction vulnerability in iron ore and rare earth tailings are addressed. Mechanical and morphological characterisation of iron ore tailings originating from the Iron Quadrangle region in Minas Gerais, Brazil, are discussed. The mechanical behaviour has been assessed through consolidated undrained (CIU) and consolidated drained (CID) triaxial tests, performed on specimens moulded under varying compaction conditions, including moisture content, compaction degree, and energy application method. The results interpreted under the framework of critical state soil mechanics, when compared with particle morphology data, allowed the evaluation of how grain size distribution and particle shape influence mechanical behaviour. Additionally, the effects of moisture content and compaction energy application method on strength parameters and the determination of the critical state line have been studied. An evaluation of how the grading can affect the compaction characteristics, particle arrangements and overall strength and stiffness of anthropic mixtures of diverse ore tailings, and the importance of the changing of morphological and mineralogical with the increasing of fines content is addressed. A comprehensive characterisation of the mechanical behaviour of these tailings indicates a relevant influence of these factors on their overall performance.

Keywords: *mine tailings disposal, compacted filtered tailings stacks, particles size distribution, mineralogy and morphology analysis, fabric, compaction methods, critical state line, instability and softening*

1 Introduction

Recent tailings dam failures (Mt. Polley, Cadia, Fundão, Dam 1 in Brumadinho, Derna Dam in Libya, and Arbat Dam in Sudan) have motivated the pursuit of alternative and safer methods for tailings disposal worldwide. Some studies (Carvalho et al. 2024; Delgado et al. 2025; Rios et al. 2025) indicate that the characteristics of this type of material are strongly influenced by its anthropogenic origin, with little to no chemical weathering. As a result, tailings typically consist of predominantly non-plastic silty or silty sand artificial soils, which, by their nature, exhibit a particular sensitivity to instability induced by liquefaction triggering.

Considering the degree of saturation of the deposited material resulting from conventional hydraulic disposal methods, tailings are highly susceptible to flow liquefaction. In this context, filtered tailings stacking – where tailings are compacted following a prior filtration process to achieve an unsaturated condition close to the optimum moisture content defined by Proctor compaction standards – emerges as an alternative disposal

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method capable of optimising landform use as it requires less storage area. However, the proper design of such stacks demands a comprehensive understanding of the geotechnical behaviour of compacted filtered tailings under atypical climatic conditions, particularly in tropical environments, and across a range of stress states. This is especially important given the high stress levels to which these materials may be subjected, potentially inducing significant changes in their mechanical behaviour as stress increases.

Thus, filtered tailings stacks, in addition to requiring less area for tailings disposal, offer the additional advantage of a shorter run-out distance in the event of a potential failure when compared with tailings dam arrangements. Nevertheless, it remains essential to understand the mechanical and hydraulic behaviour of the tailings to enable a rigorous assessment of the associated disposal structures.

On this basis, this paper presents and discusses recent advances from the authors' experience and research into the mechanical behaviour of mining tailings when compacted and subjected to high stress levels for stacking purposes, with emphasis primarily on iron ore tailings from the Iron Quadrangle region in Minas Gerais, Brazil, but also including rare earth tailings from other Brazilian deposits.

2 Background

2.1 Some recent case-histories

Two recent failures in Brazil represent the concerns associated to misleading stability analyses.

The first one occurred in the Pau Branco iron mine, Nova Lima (Minas Gerais, Brazil) on 5 January 2022 and was triggered by exceptionally heavy and persistent rain in the region, which saturated the waste materials (Figure 1a). A slope failure involving 3 banks of the Cachoeirinha mine waste pile resulted in a release of mine waste into the Lisa water retention dam (dyke). It overflowed along its entire length, resulting in the closure of the BR-040 highway (an important road connecting Belo Horizonte to Rio de Janeiro) which runs below the structure. There were no fatalities, the company's operations were suspended by the National Mining Agency (ANM), and the state fined the company BRL 288 million for the environmental damage caused by the overflow of the Lisa dyke. Inherent operational risks were linked to rapid expansion of mining complexes and challenges of managing large volumes of waste rocks in close proximity to sensitive infrastructure. The Pau Branco mine was a pioneer in using filter presses to dewater mineral waste, allowing for 'drained piling' rather than a wet rock pile. The sliding mass fell into the nearby Lisa sediment pond (a water retention structure), which caused the water and mud to overflow.

The second case was in Turmalina Gold mine, operated by Jaguar Mining in Conceição do Pará (Minas Gerais, Brazil). On 7 December 2024, a landslide occurred in the north wall of the Satinoco tailings pile, which consisted of an estimated 600,000 m³ of dry-stacked filtered gold ore tailings and waste rock 'slumped' (Figure 1b). The tailing travelled 500 m, covering an area of approximately 10 ha and impacted some of the infrastructure at the mine. It also damaged 7 residential houses in the village of Casquilho de Cima, with 255 residents evacuated from 162 buildings (no injuries) and 889 animals rescued. The incident likely involved a pre-existing plane of weakness or a 2-phase failure where a lower slope/buttress failed first. The ultimate cause points to a failure in design, engineering, or management of the tailings stack.

On 4 December 2025 a new standard for the elaboration and definition of the terms of design and safety evaluation of disposal structures of dewatered tailings stacks (NBR 13028-3) was published (Associação Brasileira de Normas Técnica [ABNT] 2025). Its principals are herein reproduced:

> *"These facilities or industrial waste structures from ore processing aimed to meet safety, operability, cost-effectiveness, and decommissioning requirements, minimising environmental impacts. Furthermore, the applicability of this standard to structures formed by co-disposal or shared disposal of tailings and waste dump will depend on the relative influence of each material fraction on the geotechnical stability of the structure. In cases where waste dump predominates, the criteria established in the most recent version of ABNT NBR 13029 must be observe."*

It is emphasise that:

> *"is the responsibility of the user of this Standard, in the event of potential conflicts in normative procedures, to establish the appropriate practices for each case, in accordance with current legislation and good engineering practice."* (ABNT 2025).

An important recommendation is now included in the new standard:

> *"considering good engineering practices and based on the experimental data obtained (field and laboratory tests), analyses based on Limit Equilibrium Methods (LEM) can, when necessary, be complemented by analyses that consider the non-linearity between stress and strain through methods based on constitutive stress-strain (T-D) relationships, and their use and application should be carried out with appropriate engineering judgment."* (ABNT 2025).

This means that for safety assessment, the LEM may not identify the several plausible failure modes associated with mechanisms induced by triggering factors that induce changes in states of stress and/or strains in distinct draining conditions.

(a) (b)

Figure 1 Recent failures of dry-stacked filtered tailings piles in Minas Gerais, Brazil. (a) Pau Branco iron mine (5 January 2022); (b) Turmalina Gold mine (7 December 2024)

2.2 Critical State approach on high stress levels

As it is now generally recognised, and clearly stated in ABNT (2025), that one of the critical issues in the mechanical behaviour of filtered tailings stacks is the response of the material under high stress levels, particularly for stacks reaching heights of around 200 m or more. The role of compaction in establishing depositional arrangements that determine distinct behavioural patterns is equally critical. Phenomena such as particle breakage and the potential for transitional behaviour become central concerns for tailings storage facility (TSF) design and are subsequently examined.

Within the framework of critical state soil mechanics (CSSM), the void ratio (e) is recognised as a fundamental parameter – together with the stress state, expressed by the mean effective stress (p') and deviator stress (q) – that governs the mechanical behaviour of soils through the state parameter (ψ) (Jefferies & Been 2016):

$$\psi = e_0 - e_{cv} \tag{1}$$

where e_0 and e_{cv} represent, respectively, the current (or initial) void ratio and the critical state void ratio (corresponding to constant volume shearing) at the same stress level. The latter is considered an intrinsic property of each soil type and stress condition, independent of the stress path and initial state (Schofield & Wroth 1968).

The conventional CSSM framework defines a unique and linear critical state line (CSL) in both the Cambridge $p' - q$ and $e - p'$ planes, which are respectively expressed as:

$$q = Mp' \quad (2)$$

and

$$e = \Gamma - \lambda \ln p' \quad (3)$$

where:

M = critical state friction ratio

Γ = void ratio at the reference pressure of 1 kPa

λ = slope of the CSL.

The constants M, $\Gamma$and λ are fundamental material parameters (Schofield & Wroth 1968).

Several researchers (Verdugo & Ishihara 1996; Li & Wang 1998) have reported that, for cohesionless granular materials, a single but curved CSL provides a more accurate representation in the $e - p'$ plane, which can be expressed by a power law:

$$e = A - B(p'/100)^C \quad (4)$$

where:

A, B, and C = empirical fitting parameters derived from laboratory data

100 = the reference pressure equivalent to 1 atm (≈100 kPa).

The shape of the CSL, combined with the initial state of the material, governs its potential for static liquefaction. Based on undrained triaxial tests under axisymmetric stress conditions, it is theoretically possible to identify the state of instability at which the onset of flow liquefaction induces a rapid increase in both strain and porewater pressure. The shearing ratio at the instability line (η_{IL}) in the $p' - q$ plane can be compared with in situ conditions (η_0) in the same plane (Figure 2a) to ensure that:

$$\eta_0 < \eta_{IL} \quad (5)$$

where $\eta = q/p'$ is the stress ratio, with $q = \sigma'_1 - \sigma'_3$ and $p' = (\sigma'_1 + 2\sigma'_3)/3)$, in which σ'_1 is the major effective principal stress and σ'_3 is the minor effective principal stress.

Given the considerable heights – reaching hundreds of metres – anticipated for filtered tailings stacks, numerous studies have investigated the mechanical behaviour of tailings under very high stress levels (Delgado et al. 2023; Silva et al. 2023; Consoli et al. 2024). At such stress levels an increase in the non-linearity of the CSL in the $e - p'$ plane has been observed, which may be attributed to particle breakage or to significant morphological evolution of the tailings' particles (Figure 2b) (Schnaid et al. 2013; Soares & Viana da Fonseca 2016).

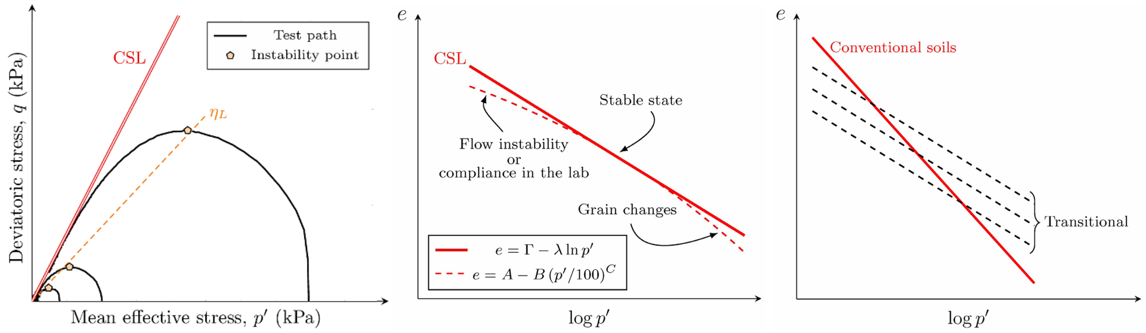


Figure 2 Schematic representation of (a) the instability line, (b) the non-linearity of the critical state line (CSL), and (c) the transitional soil behaviour (after Viana da Fonseca et al. 2021)

Other researchers have also reported transitional behaviour, characterised by non-unique (either straight or curved) CSL (Figure 2c), whose positions are strongly dependent on the initial void ratio (e_0) (Coop 2015). This behaviour is more frequently observed in mixed-grading or structured soils and less commonly in mining tailings. A more detailed investigation at the microstructural level (at particles level) may therefore provide valuable insights into both the observed non-linearity of the CSL and the potential occurrence of transitional behaviour.

Viana da Fonseca et al. (2022) and Delgado et al. (2025) reported a marked non-linearity of the CSL in the $e - p'$ plane at higher stress levels for iron ore tailings of the Brumadinho reservoir. Viana da Fonseca et al. (2022) attributed this non-linearity to grading modifications resulting from the morphological evolution of the particles. This evolutionary behaviour was observed for initial mean effective stresses exceeding 800 kPa.

Changes in the CSL slope at higher stress levels, associated with increased grain angularity, have also been reported by Soares & Viana da Fonseca (2016). Studies aimed at quantifying particle morphology changes through laboratory testing and discrete element method (DEM) simulations could contribute to validating this stress-strain behaviour at the macroscale.

3 Geomechanical behaviour

3.1 Macro-behaviour from triaxial testing

One of the critical issues in the mechanical behaviour of filtered tailings stacks is the response of the material under high stress levels, particularly for stacks reaching heights of around 200 m or more. The role of compaction in establishing depositional arrangements that determine distinct behavioural patterns is equally determinant. Phenomena such as particle breakage and the potential for transitional behaviour become central concerns for TSF design and are subsequently examined.

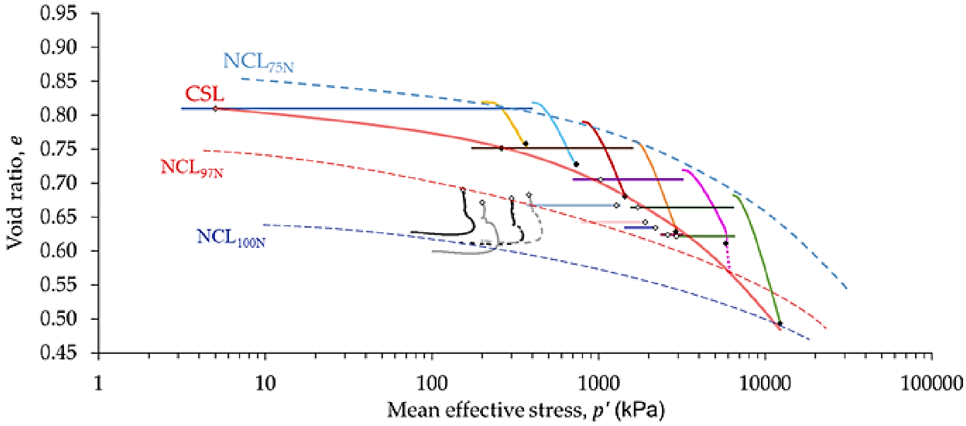
3.1.1 High stress levels and particle breakage

Delgado et al. (2023) carried out triaxial tests on silty sand iron ore tailings from the Brazilian Iron Quadrangle region, with specific arrangements, such as the use of a neoprene membrane and copper pipe drainage, to withstand high pressures. They highlighted that from about 3,200 kPa of mean effective stress onwards, distinctive behaviours emerge. As shown in Figure 3a, although the resulting non-linear CSL did not exhibit transitional behaviour, different compaction energies led to distinct normal consolidation lines (NCL), which nevertheless showed a clear tendency towards convergence at high stress levels, significantly higher than those commonly expected for most tailings' stacks. The parameters fitted for the CSL using a power-law relationship were A = 0.8291, B = 0.0494 and C = 0.4012.

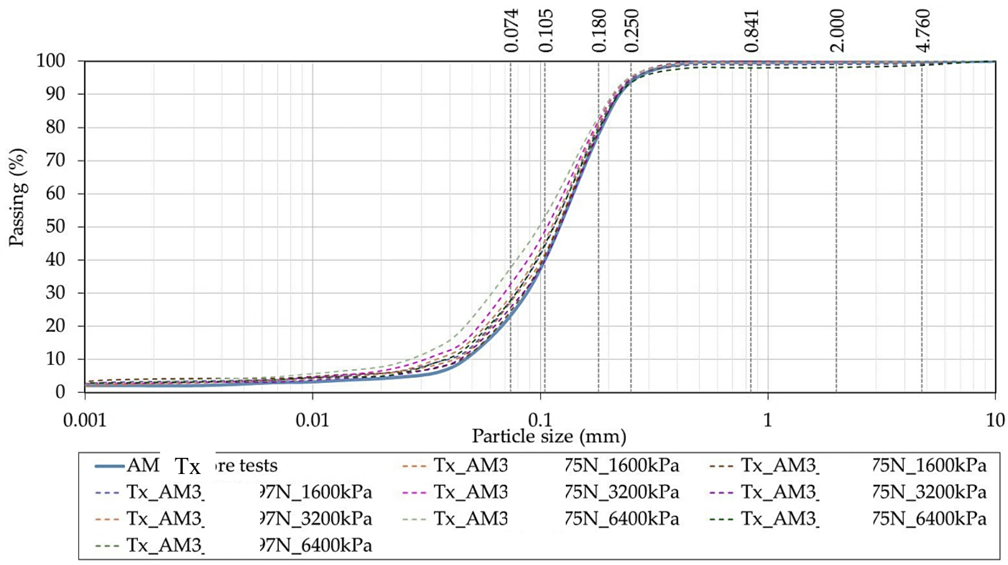
Evidence of particle size distribution (PSD) evolution was also observed at the end of shearing (Figure 3b), particularly for specimens subjected to higher stress levels with lower degrees of compaction under drained shearing (Tx _CID_75N_3200kPa and Tx _CID_75N_6400kPa). In the long-term this may compromise the performance of the structure if it were to experience such stress levels, since changes in the state parameter – from dilative to contractive behaviour under drained shearing – can increase susceptibility to liquefaction (in the event of loading that induces strain-stress response under undrained conditions). This potential for liquefaction induced by state changes of the material at high stress levels should be rigorously investigated during design and re-analysis stages throughout construction, using appropriate stress-strain constitutive models and numerical simulations.

The results reinforce the need to establish sufficient compaction efforts to induce dilative states and avoid under-compaction. From Figure 3a, a slight increase in compaction energy from 97 to 100 N was already enough to promote a more conservative response. In practice, quality control must also prevent significant variations in PSD curves, as such changes may alter the CSL and compromise density-based in situ control procedures. Accordingly, continuous field monitoring is recommended, combining periodic sampling of the PSD curve with in situ void ratio determinations and, where possible, complemented by state parameter estimation through in situ testing.

In another study on silty sand iron ore tailings from the Brazilian Iron Quadrangle region under the high pressures, Corrêa de Oliveira et al. (2025) observed that the introduction of fines resulted in a downward translation of the CSL in the $e - p'$ plane.



(a)



(b)

Figure 3 Triaxial compression tests results (after Delgado et al. 2023). (a) Critical state line (CSL) and normal consolidation lines (NCL) in the $e - p'$ plane; (b) Particle size distribution curves before and after some triaxial tests

Consoli et al. (2023) carried out drained triaxial tests, under mean effective stresses up to 120 MPa, of silty sand iron ore tailings from the Brazilian Iron Quadrangle region from low to high pressures, highlighting that particle breakage induced by high pressures exerts a significant influence on the mechanical and hypothetical convergence trend of the NCL at high stress levels and proposed a 5-parameter equation, which describes an 'inverted S' shape curve, as an alternative to representing the CSL in the $v - \ln p'$plane.

Some discussion has been done on the position of the CSL in the $v - \ln p'$plane, where v_0 is the limiting (maximum specific volume at critical state that the material could achieve), which is similar to the concept of $e - \ln p'$plane, maximum void ratio. This is discussed in several works and is addressed in Section 3.2 of this paper, at the level of the PSD and particles morphology (shape and surface indices and their probability distribution, hereby identified as PM). The evolution of the position of CSL due to PSD changing, especially of fine content (FC) and PM, when high pressures are involved, which occurs in very high tailings stacks due to particle breakage or disaggregation of rough surface, may be responsible for the curvature of the CSL at high pressures. Concurrently, the NCL, both in isotropic and anisotropic conditions mean effective pressure increasing, is also ruled by this evolution of the particles, as well as their organisation at micro (structure) and mezzo-scale levels.

Still, the non-linearity (curvature) pattern has been clearly identified through advanced and rigorously conducted laboratory tests. Consoli et al. (2023) suggests a potential 'inverted S' shaped CSL. This hypothesis is quite unique and should be applied with caution, as it may be influenced by spurious localised rupture structures (shear bands). The conclusions supporting this inversion of the convexity of an ultimate CSL at very high stress levels are based on only a few tests. No published results exhibit such trends at comparably extreme pressures. Some data exist at higher – although not excessively high– pressures, where particle breakage plays an important role in the material response. Paradoxically, increased breakage leads to higher compressibility and therefore a steeper CSL inclination, which is the opposite of what the authors present in Figure 4.

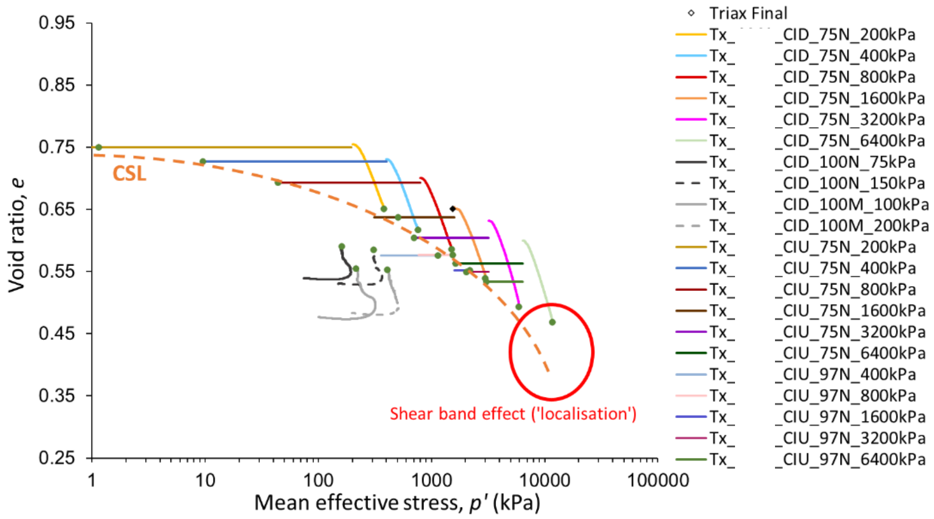
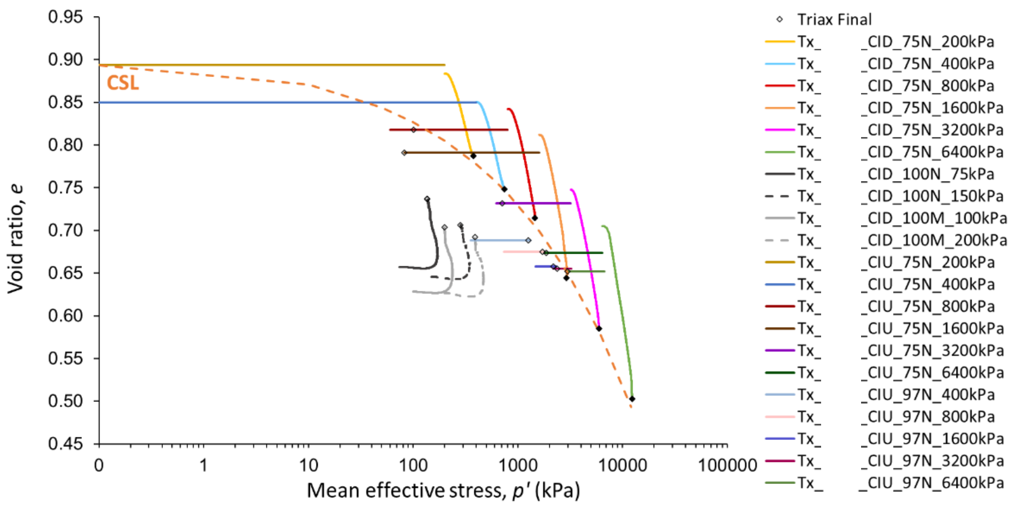


Figure 4 One iron ore tailings set of tests to a compacted stacking disposal in a project in Minas Gerais: one inconsequent test pointing out to a hypothetic 'Inverted S' shape critical state line in $e - p'$ plane

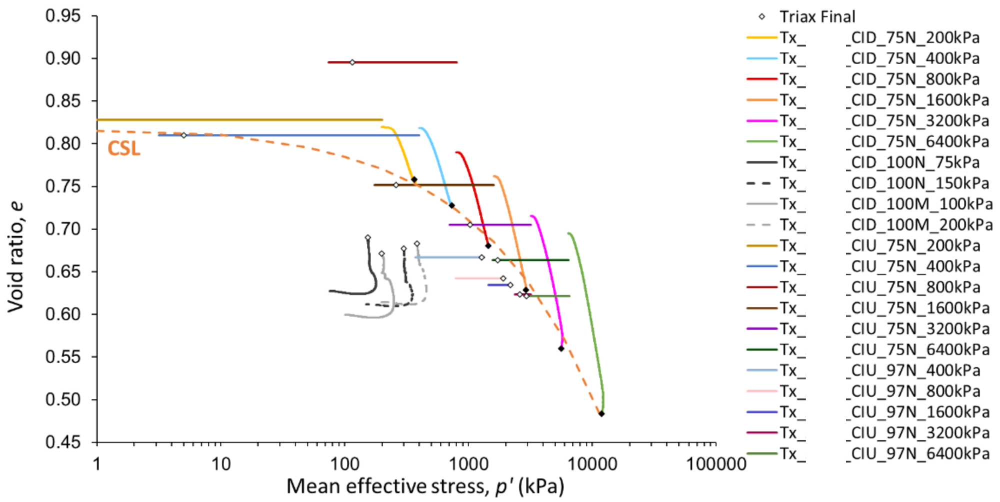
A spurious result from one test, corresponding to the highest confining effective pressure (consolidation under an isotropic mean effective pressure of p' = 6,400 kPa), indicated a failure void ratio on the CSL in the $e - ln\,p'$ plane well above the expected trend. It was later found that this test had been affected by 'localisation' due to shear band effects. A new test was carried out, and a lower void ratio value, meaning a greater volume reduction during shearing, was obtained by ensuring proper guidance of the top cap and therefore concentric vertical deformation of the specimen. This is a decisive factor for maintaining the cylindrical shape up to failure in critical state, where large strains of 20% or more are typically required (see details in Viana da Fonseca et al. 2021).

This is one of the tailings produced by 3 iron ore mines in the same mining complex for a large tailings stack project in Minas Gerais, Brazil. Two other tailings from the same site were tested using the same technical procedures in the geotechnical laboratory of the University of Porto. As shown in Figure 5, one of these 2 tailings was clearly consistent with the expected pattern. The results of the third tailing, together with the additional tests performed under high pressures, are currently under review in a journal.

The 'novel' finding of an inflection of the CSL for very high mean effective pressures would have implications in real works of tailings stacks that could reach superlative vertical stresses, which would correspond to stacks unrealistically high.



(a)



(b)

Figure 5 **$e - p'$ curved critical state line (CSL) sustained by 2 other filtered iron ore tailings for compacted stacking disposal in Minas Gerais. (a) AM2; (b) AM3 (partially published in Corrêa de Oliveira et al. 2025)**

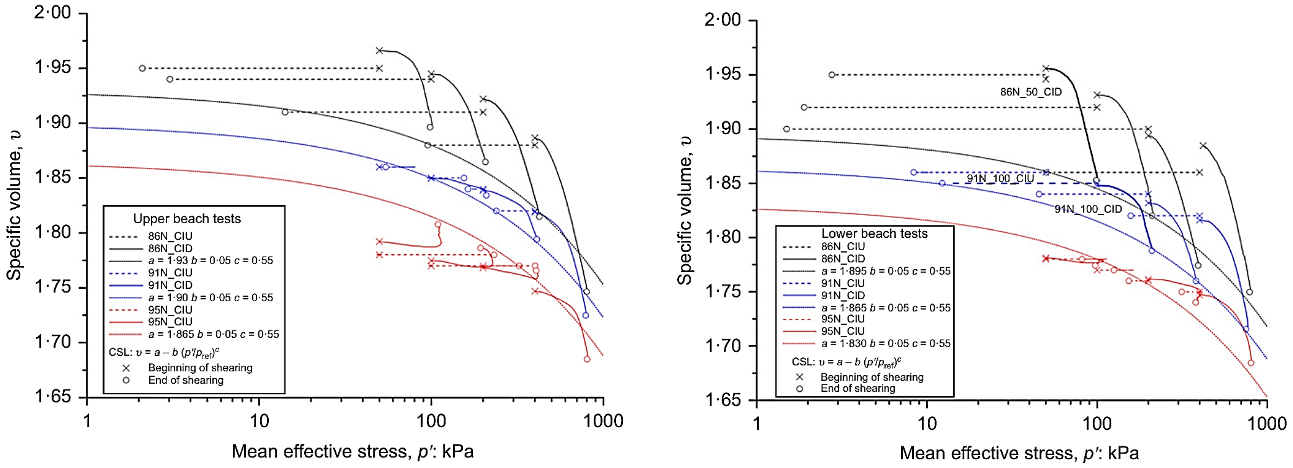
3.1.2 Transitional behaviour

A particular concern is the potential for tailings to exhibit transitional behaviour, making the prediction of mechanical response more difficult. Transitional behaviour, originally reported for natural soils (Ferreira & Bica 2006; Shipton & Coop 2015), should be carefully investigated during design studies with the aim of supporting more detailed material zoning within the stacks and improving the understanding of the micro-behaviour influence (particle morphology and fabric effects).

Velten et al. (2022) reported this behaviour for non-plastic copper tailings collected from 2 different places (upper and lower beaches) in the reservoir of a tailings dam in northern Brazil. The tailings were compacted using 3 distinct effort levels, 86, 91, and 95 N, corresponding to 86, 91, and 95% of the standard proctor test effort, respectively. As shown in Figure 6, the authors obtained a distinct set of CSLs that varied according to the initial state of the tailings.

Delgado et al. (2025) studied the uniqueness of the CSL for iron ore tailings sampled from the fault zone of Dam 1 at Córrego do Feijão mine in Brumadinho (Brazil), after the dam failure. A series of advanced triaxial tests were carried out, varying the initial state (dense or loose), the stress paths (drained and undrained, in both compression and extension), and the consolidation type (K_0). The advanced triaxial tests were performed using triaxial cells with lubricated end platens and an embedded connection piston in the top cap, as well as a Bishop–Wesley-type stress path triaxial cell.

For comparison, Table 1 presents the main physical characteristics of the copper tailings studied by Velten et al. (2022) and the Brumadinho iron ore tailings researched by Delgado et al. (2025). This comparison is relevant because both copper and iron ore tailings studied were non-plastic and exhibited similar PSD curves. The materials are broadly similar in their physical characteristics, except the high specific gravity (G_s) of the tailings from the Brumadinho reservoir. Whilst such high values are uncommon, they have been reported in the literature (Carneiro et al. 2023) and may lead to elevated stress states.



(a) (b)

Figure 6 Critical state line (CSL) in the $v - log\ p'$ plane for copper tailings from northern Brazil (Velten et al. 2022). (a) Upper beach; (b) Lower beach

Table 1 Physical characteristics of silty sand copper tailings and iron ore tailings (after Velten et al. 2022 and Delgado et al. 2025)

Characteristic	Material		
	Copper tailings (upper beach)	Copper tailings (lower beach)	Iron ore tailings
Specific gravity, G_s	2.844	2.943	4.990
Mean particle size, D_{50} (mm)	0.275	0.095	0.093
Maximum void ratio, e_{max}	1.050	1.127	1.220
Minimum void ratio, e_{min}	0.831	0.842	0.480
Plasticity index (%)	NP	NP	NP

Figure 7 presents the main results obtained by Delgado et al. (2025) for the Brumadinho tailings, allowing the evaluation of the CSL position and the instability lines in undrained tests. No transitional behaviour was observed, with a unique CSL obtained for both compression and extension tests. However, the authors report that the instability line (IL) showed significant variation depending on whether the applied stress path was in compression (uis) or in extension (uis_e). This highlights the need for advanced approaches capable of simulating the different loading conditions imposed on the structures, such as hydromechanically coupled stress–strain analysis (Rógenes et al. 2024; Coutinho et al. 2025; Fanni et al. 2025; Viana da Fonseca 2026), continuously updated through monitoring (performance-based approach).

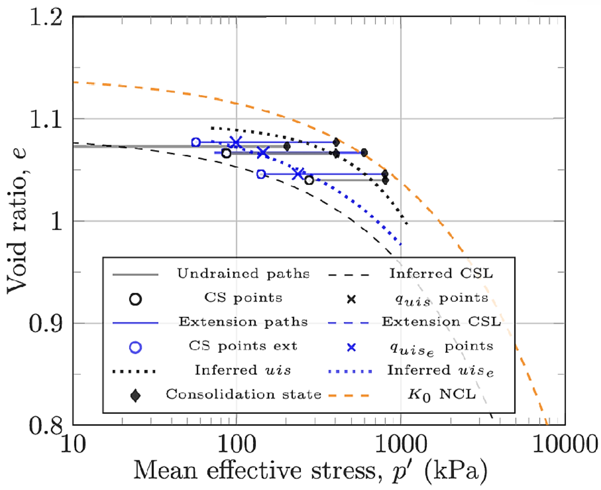


Figure 7 Onset of instability on undrained compression and extension tests on the $e - ln\,p'$ plane (Delgado et al. 2025)

3.1.3 The influence of the curvature of the critical state line in the evaluation of the state parameter in situ

The state parameter (ψ) measures how a soil's current void ratio differs from its critical value under the same stress, helping to predict soil behaviour. Traditional CPT-based methods assume a linear critical state line (CSL), which becomes inaccurate at high stresses due to particle crushing and resulting nonlinearity.

Recently Robertson (2026) proposes a new approach based on Bolton's relative dilatancy index (IR), which accounts for nonlinear CSL behaviour and stress effects. It combines CPT-derived relative density with the soil behaviour index (Ic), incorporating sleeve friction data to better distinguish soil types and, for clean sands, compressibility is also considered. At high stress levels, the IR-based method represents an advancement over traditional methods that assume a linear CSL. The accuracy of the estimated normalised cone resistance input parameter (now designated QB) becomes more sensitive to high overburden stresses. For high-risk projects, where detailed analyses are required, QB needs to be estimated for a given soil based on a laboratory measured CSL over a wide stress range. In the end the IR-based approach improves the interpretation of CPT data in high-stress environments by explicitly linking ψ to soil compressibility, FC, and stress-dependency being using Bolton's QB parameter

3.2 Micro-behaviour influence

Since the early development of soil mechanics, researchers have sought to adopt a continuum mechanics-based framework to interpret macro-scale mechanical behaviour by adopting the concept of effective stress rather than total stress (Coop 2024). This approach, long considered indispensable given the intricate interactions among particles at the microstructural level, has generally been successful, yet exhibits limitations when accounting for certain specific phenomena, such as transitional behaviour. Recent advances in imaging techniques, coupled with DEM, have enabled advances aimed at enhancing the understanding of soils and other particulate geomaterials through discrete approaches capable of calibrating the observable macro-scale behaviour of particle assemblies.

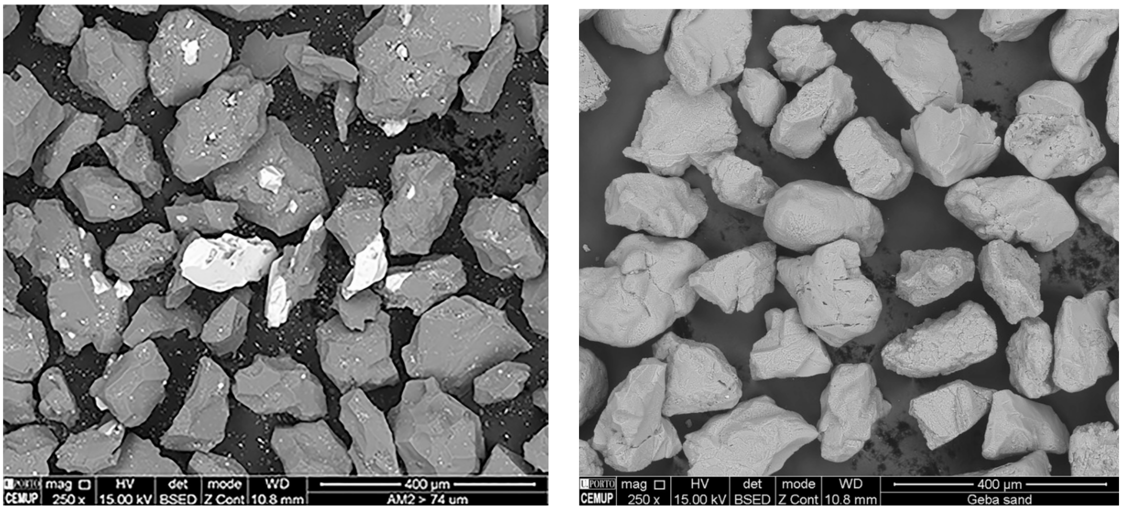
Tailings, produced as a byproduct of mineral beneficiation processes, constitute artificial soils whose microstructural characteristics differ markedly from those of natural soils formed through prolonged weathering. Consequently, mineralogical factors and variations in beneficiation techniques govern the generation of particles with distinct morphologies and differing resistance to breakage and crushing, which in turn influence macro-scale mechanical behaviour. Another critical aspect in the context of micro-behaviour is the so-called fabric, which exerts a significant effect on tailings behaviour and is shaped by the deposition techniques employed, resulting in diverse particle arrangements. These considerations are addressed in the following sections.

3.2.1 Particle morphology

Regarding particle morphology, it should be noted that although no universal consensus has yet been reached, most researchers currently accept that 3 properties are sufficient to characterise particle geometry: sphericity, angularity, and surface texture (roughness). Altuhafi et al. (2016) emphasise that whilst sphericity is a property associated with the overall shape of particles and indicates the degree to which a particle is elongated or spherical, angularity – characterised by the presence of sharp edges and protrusions (Wadell 1932) – governs roundness, which reflects the relationship between the curvature of corners and edges and that of the particle as a whole. Although the quantification of sphericity is relatively well established, several alternative methods have been proposed for measuring angularity, considering, for example, the corner angle of particle asperities (Lees 1964) or the particle perimeter (Kato et al. 2001). Despite various quantitative approaches suggested by some authors (Yoshimoto et al. 2012; Rouse et al. 2014; Tatsuoka et al. 2008), most researchers continue to describe roundness in qualitative terms.

In recent years, there has been a marked advancement in quantitative approaches, largely driven by improvements in high-resolution image digitisation techniques applied to streams of randomly oriented moving particles. A notable example, increasingly adopted in geotechnical research, is the QicPic device (Sympatec GmbH n.d.), which can analyse particles with nominal diameters ranging from 1 µm to 20 mm whilst capturing images at rates of up to 500 frames per second across multiple focal planes. For further information on this equipment see Altuhafi et al. (2013).

Due to the anthropogenic nature of tailings, understanding the influence of particle morphology on macro-scale behaviour, particularly its susceptibility to instability, is critical. Nevertheless, few studies have addressed this issue. Rios et al. (2025) compared the behaviour of a silty sand iron ore tailings sample from the Brazilian Iron Quadrangle with that of a natural siliceous silty sand exhibiting similar PSD curves. Morphological properties of both materials were quantified using the QicPic device. Scanning electron microscope (SEM) images providing an overall view of the coarse particles are presented in Figure 8, whilst the principal physical characteristics are summarised in Table 2.



(a) (b)

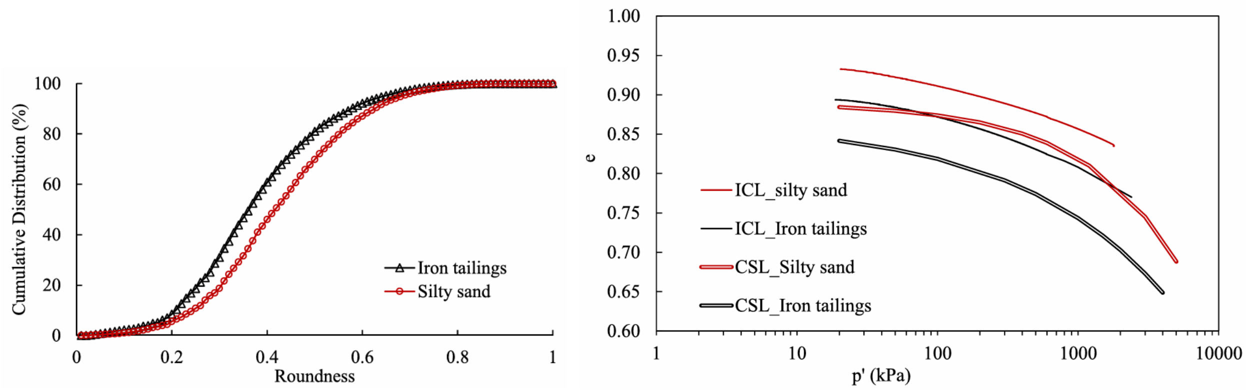
Figure 8 Scanning electron microscope micrographs of coarse fraction (>0.074 mm) (Rios et al. 2025). (a) Iron tailings; (b) Natural silty sand

Table 2 Physical characteristics of iron ore tailings and natural siliceous silty sand (after Rios et al. 2025)

Characteristic	Material	
	Natural silty sand	Iron ore tailings
Specific gravity, G_s	2.69	3.01
Mean particle size, D_{50} (mm)	0.086	0.086
Maximum void ratio, e_{max}	1.034	1.035
Minimum void ratio, e_{min}	0.626	0.526
Fines content (%) (<0.074 mm) – non-plastic	47.0	41.0
Curvature coefficient, C_c	0.74	1.01
Uniformity coefficient, C_u	2.94	2.70
Proctor optimum water content, W_{opt} (%)	19.4	14.0
Proctor maximum dry density, γ_d^{opt} (kN/m³)	15.1	18.1

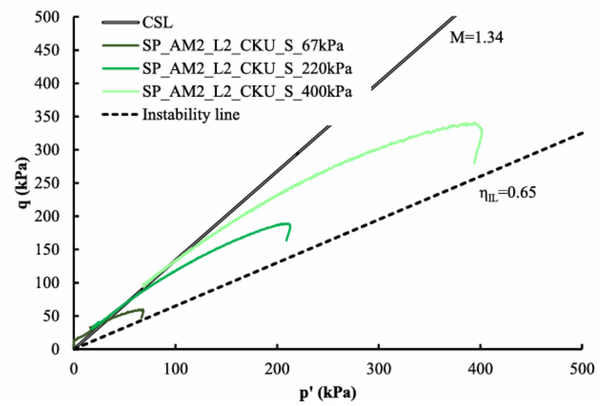
Microstructural analyses reveal that the particles of both materials are broadly similar. However, examination of particle shape indicates that the iron tailings, particularly in the finer fraction, tend to be slightly more angular and elongated than the silty sand particles. Figure 9a presents the cumulative distribution of roundness values for both materials. Since the silty sand curve lies to the right of the iron tailings curve, this indicates that the silty sand exhibits higher roundness values, thereby confirming the observations from the SEM images (Figure 8).

In terms of mechanical behaviour, the results did not reveal a significant difference in the CSL (Figure 9b), confirming that PSD curve is a key factor. However, marked differences were observed in volumetric instability, compressibility, stiffness, and compaction density, which appear to be more dependent on particle density and were higher in iron ore tailings due to the presence of iron minerals. Furthermore, the iron tailings exhibited higher brittleness and slightly higher critical state friction angles and instability stress ratios under K_0-consolidated and undrained (CK_0U) compression triaxial tests (Figure 10), which may be associated with their less rounded particles. This is important as it may influence the stability of TSFs, particularly during undrained loading. Some differences were also observed in the minimum void ratio, and hydraulic conductivity, which may be associated with small particle size differences between the materials. A very small fraction of fine particles (smaller than 0.02 mm) observed in SEM images fill in the void spaces, leading to a more continuous fabric and lower void ratios, which explains the observed differences.

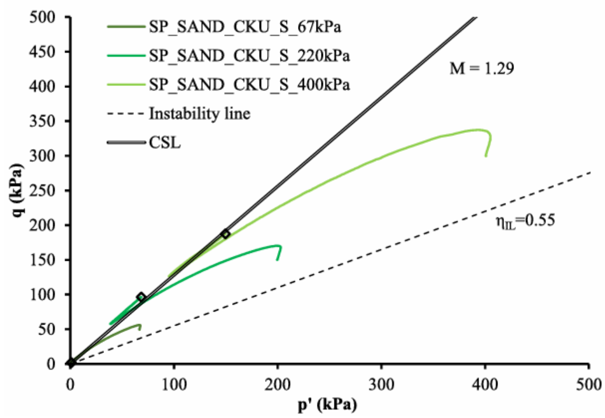


(a) (b)

Figure 9 Comparison results for both materials (Rios et al. 2025). (a) Roundness; (b) Isotropic compression (ICL) and critical state line (CSL) in the $e - p'$ plane



(a)



(b)

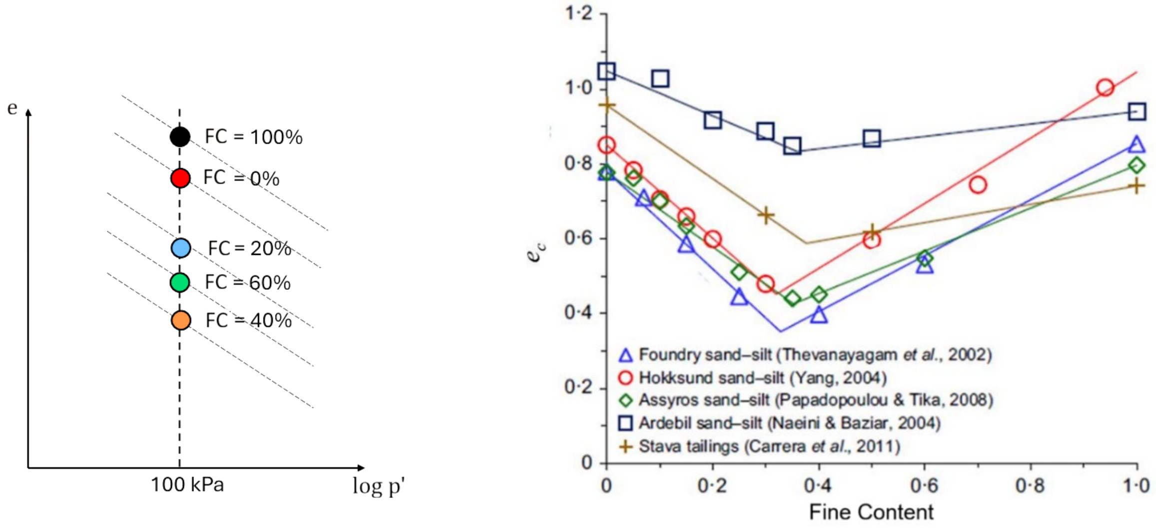
Figure 10 CK_0U tests, unique critical state line (CSL) and isotropic instability lines (IL) (Rios et al. 2025). (a) Iron tailings; (b) Silty sand soil

Rios et al. (2025) reported that the value of K_0 does not appear to influence the CSL in the $q - p'$ plane, as the same M values were obtained for both isotropic and K_0-consolidated specimens. This finding confirms the uniqueness of the CSL and its independence from the K_0 value, consistent with observations by Sivathayalan & Vaid (2002), Fourie & Tshabalala (2005), Jefferies & Been (2016), Delgado et al. (2025), among others.

3.2.2 Particle size distribution and fabric (particle arrangement)

One of the issues that should be taken into account is the optimisation of grading of tailings coming from the process. Most of the challenges that mine operations have whilst, at the ore beneficiation streams, looking for the best compromise between the disposal of total tailings or more or less FC (a very demanding decision in climates where rainy seasons are prolonged, like in Brazil), may be dependent of specific factors like grading and mineralogy to increase compressibility during stacking, enabling tailings to achieve denser conditions.

Wagner et al. (2025), studying the effect of FC in iron ore tailings, had previously reported that when the FC exceeds a certain limit, the fines begin to govern the mechanical behaviour, and the CSL may return to a higher position in the $e - p'$ plane (Figure 11a). This observation is consistent with findings reported by other researchers (Yang et al. 2006; Papadopoulou & Tika 2008; Carrera et al. 2011, among others), who showed that, as fines are added to a soil, the critical void ratio (e_c) gradually decreases up to a certain threshold, beyond which further fines addition leads to an increase in e_c. This trend is illustrated in Figure 11b, which presents curves of e_c variation against the FC, showing that each material exhibits an inflection point in the characteristic curve, referred to as the critical FC.



(a) (b)

Figure 11 Fine content effects (after Yilmaz et al. 2023): (a) Critical state line position; (b) Critical fines content (FC) for different soil

The recent preliminary studies presented by Wagner et al. (2025) have shown that these 2 factors influence the intergranular contacts in mixtures and explain the compression behaviour: the stronger contacts in granular media occur between coarse grains, and the contact forces become weaker as more fine particles are located between them (coarser–fine–coarser); this is also fundamental in the work of Yang et al. (2015). Those authors studied the compression behaviour as evaluated by the result of the isotropic consolidation phase of triaxial tests performed with a certain confining pressure. The specimens from 2 materials with distinct mineralogy and 5 compositions (0 to 100% of slimes) moulded at the initially dense condition corresponding to a target compaction condition of the stacks project equal to the standard effort of the Proctor test (light). As a step forward to generalise their results towards a proposition of methodology to seek for optimised solutions, the authors proposed the grading index – G_r – to optimise grinding during the ore beneficiation results in order to seek for 'better'-graded materials with a potentially continuous PSD. The plant from which the materials are collected have mixtures containing up to 20% slime tailings. The G_r is defined as the ratio of the mixture boundary (A_g) over the total mixture potential (A_t), where Ag is defined as the area between the PSD of the mixture and the PSD of the lower bound (flotation tailings, where G_r = 0, in opposition to slimes, where G_r = 1) and A_t is defined as the area between the PSDs of the upper and lower bounds (slime and flotation tailings). Still, the threshold FC, defined as the border line of FC between the condition where finer grains dominate the geotechnical material behaviour and to the one dominated by coarser grains (Thevanayagam et al. 2002; Carraro et al. 2009), which is not an intrinsic soil property (Zuo & Baudet 2015; Yilmaz et al. 2023), may be considered to define a third zone of behaviour dependent on the density of the material (Shire et al. 2016), as it is represented in Figure 12.

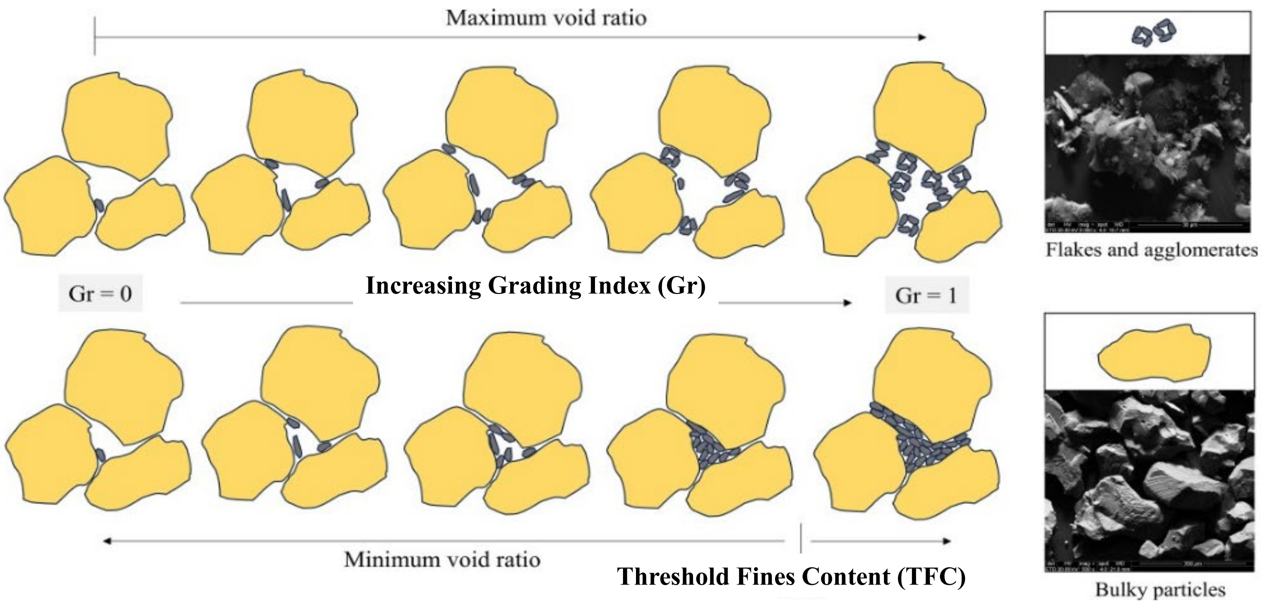


Figure 12 Schematic representation of the influence of grading on limit void ratios (adapted from Wagner et al. 2025)

The mechanical processes in flotation tailings also affect the tailings' morphology and produce very angular and rough particles (Yang et al. 2019). The tailings' mineralogy is highly dependent on the orebody and the efficiency of the ore recovery processes. G_s values vary in distinct ranges of PSD curve, it increases for higher FC (higher G_r values), as finer particles have more iron content. These mixtures of tailings can result in a more complex response than natural soils.

It is Interesting to emphasise some of the implications the higher values of G_r (finer particles) have on the increase of e_{max} meaning that the fines added to the mixtures tend to separate the larger particles. The angularity of tailings particles influences the packing condition of the mixtures: angular grains roll less efficiently into the void spaces. This suggests that not all the fines roll into the void spaces, but some are located between the coarse grains and enlarge the soil skeleton (Yang et al. 2015). Small particles of hematite may bond to each other by Van der Waals forces and form hematite aggregates with a porous structure, causing the void ratio to increase with increasing hematite content.

Figure 12 depicts the maximum and minimum void ratios obtained for tailings and mixtures as a function of the G_r, and presents a schematic representation of the contacts and particles in these different states. Different trends were observed depending on the index considered. The e_{min} follows the same 'V' shape with increasing fine particles observed in gap-graded material. Hight (2024) highlights that the void ratio alone cannot convey how soil particles are arranged (fabric). Figure 13 compares 2 hypothetical arrangements with different fabrics but in exactly the same void ratio.

Fabric-related aspects also need to be considered in dry stacking. The authors' specific experience, which relates to rare earth elements (REE), are discussed below.

In the evaluation of TSF stability in REE mining activities, the assessment of vulnerability of these very high earth structures with evolutive hypersaline materials due to spatial liquefaction triggering factors, is crucial. Therefore, it is decisive to guarantee competent responsibility in the safety assessment of these critical infrastructures by involving experts in geological and geotechnical engineering.

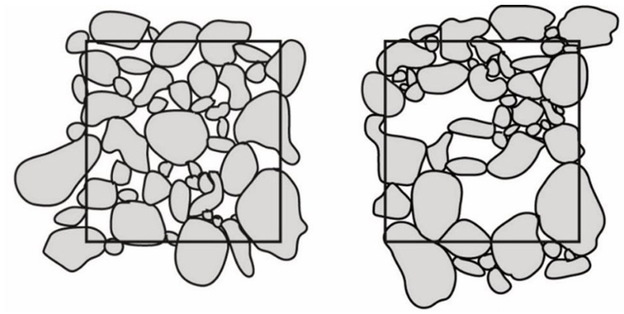


Figure 13 Illustration of possible variations in the arrangement of identical particles at an equivalent relative density (Hight 2024)

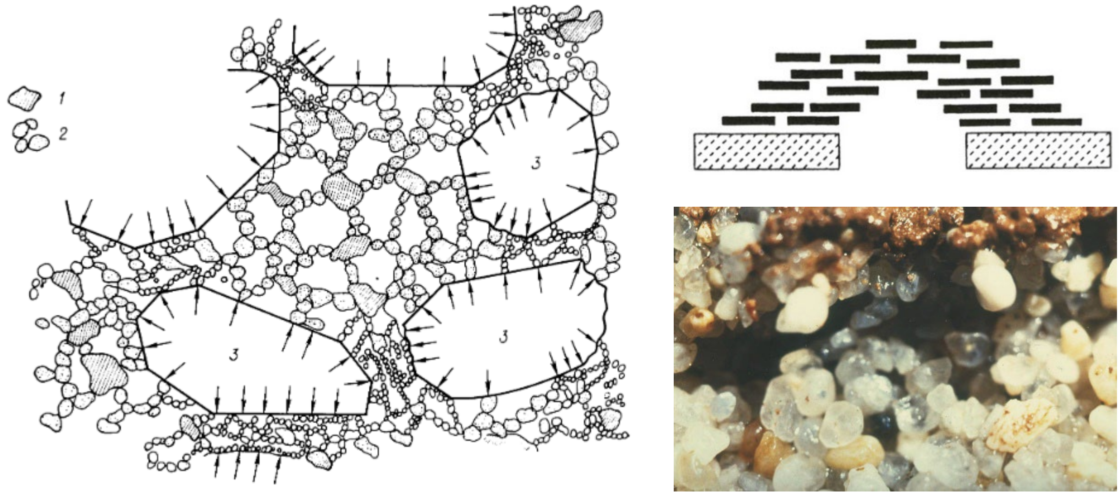
Engineering practitioners are dependent on the research and development of the best methodologies to deal with these highly sensitive materials with complex hydro and geomechanics (static and dynamic) behaviour, due to 2 main reasons.

First, because of the need to adapt our knowledge of metastable soils (Viana da Fonseca et al. 2011) – they exist in a steady state until the ephemeral interparticular crystalised structure yields and produces a collapsible behaviour.

Second, which is more relevant, the management of these high-volume REE-TSF is needed to guarantee the inevitable exponential demand of the modern worldwide technological industry (Ganguli & Cook 2018) respecting the principles of ALARP (as low as reasonably practicable).

This regulates the practice to assure management of safety-critical and safety-involved systems to reduce the residual risk as far as reasonably practicable. Critical State Soil Mechanics (CSSM) is considered the best theory to model the geomechanical behaviour of granular materials that develop progressive strain-softening behaviour, after the introduction of yield locus and hypo-plastic work function based on the concept of controllability developed by Nova (1994), which allowed by specific constitutive formulation the control conditions in the onset of failure, from peak strength towards a residual value.

The 17 silvery-white rare earth minerals are not uncommon in the earth's crust, but deposits that are economically viable are more difficult to find. The REE tailings are usually filtered after being processed with hypersaline pore fluid and then disposed in stacks/piles usually undried which can generate cemented crystallisation bridges in micro and mezzo particles around macrospores (Figure 14), in what is commonly described as a flocculated arrangement (fabric).



(a) (b)

Figure 14 Illustrations of metastable soils fabric determined by structural bonds between particles. (a) Tsytocich (1976); (b) Maranha das Neves (1991)

The experiments designed for this purpose must be supported by laboratory procedures that can be readily adopted in a soil-testing laboratory. These procedures will aid geotechnical studies of hydro-mechanical properties influenced by salinity variation over time and by stress confinement, which are key factors in vulnerability analyses.

This impact on the hypersaline tailings produced in REE has the same or worse impact due to the dimensions of the inbuilding TSF, like 'dry' (in reality 'less saturated' tailings) stacks or piles, which although compacted, cannot reach convenient densities to be dilatant (and consequently, safer), due to the presence of polarised salt solutions under an adsorbed liquid around the particles that make the expelling of air in the voids difficult, therefore inhibiting a good compaction. Settled with moderate relative density, ionised saline fluid will create saline bonding of the particles with high voids, creating the ideal conditions for increasing metastability and consequently the collapsibility that can potentiate liquefaction for diverse triggering actions (Viana da Fonseca et al. 2013, 2021, 2023).

The constitutive parameters that define the hydro-mechanic properties tend to change during the TSF life cycle. Consequently, extensive experimental studies have to be conducted to define this evolution. Recent advances (Ledesma et al. 2021, 2022; Sottile et al. 2022; Rógenes et al. 2024), to assess the vulnerability of tailings dams and stacks failure due to liquefaction, use a numerical model to verify if a set of actions that induce undrained shear in the tailings would result in a progressive failure and instability of the system (Figure 15).

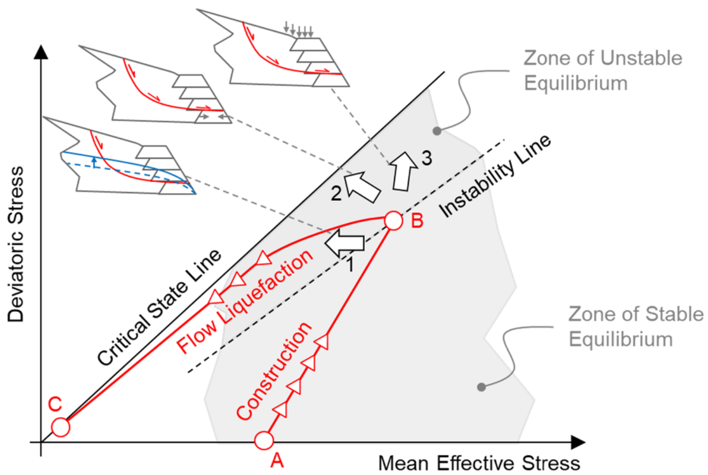


Figure 15 Conceptual stress path for a potentially liquefiable tailings element (after Ledesma at al. 2022)

4 Conclusion

Although more reliable than upstream tailings dams, filtered tailings stacks must also be designed in strict accordance with rigorous principles to ensure high safety standards. Within this context, CSSM emerges as the fundamental framework, both for design and for a performance-based approach throughout the entire life cycle of the dry stacking.

Factors such as the high stress levels imposed on these structures and the distinctive geotechnical behaviour of tailings in comparison with natural soils demand thorough preliminary studies on the mechanical behaviour of different tailings, aiming to guarantee predictability and accuracy during the design, operation, and closure phases of these TSF.

High stress levels can lead to particle breakage, potentially altering the expected behaviour of TSFs. Likewise, transitional behaviour, although rarely observed in tailings, should be investigated during the geotechnical investigation phases.

Apparent anomalous behaviours can often be explained through micro-behaviour, which should foster closer collaboration between researchers and practitioners in pursuit of higher standards for tailings management.

Particle morphology, which is influenced by mineralogy and the various mineral processing techniques, although not shown to be particularly relevant to the CSL, appears to be a key aspect of mechanical behaviour in terms of volumetric instability, compressibility, and stiffness. Similarly, the particle arrangement (fabric), although a lesser concern in filtered tailings stacking compared with upstream tailings dams, should be assessed for long-term stability due to potential material evolution driven by geochemical processes.

All these considerations, combined with stress-strain models calibrated through rigorous testing, are expected to deliver significant advances in understanding filtered tailings stacks, particularly in tropical regions where climatic conditions differ markedly from those observed in most countries with longer operational experience in this type of TSF.

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References

ABNT 2025, *NBR 13028-3: Elaboração, Apresentação de Projeto e Avaliação de Segurança de Estruturas para Disposição de Rejeitos, Contenção de Sedimentos e Reservação de água. Parte 3: disposição de rejeitos desaguados em forma de pilha (Mining — Tailings, Water and Sediment Storage Facilities — Design Development, Presentation and Safety Assessment. Part 3: Dewatered Tailings Storage Facilities)*, 1st edn; São Paulo, www.abnt.org.br

Altuhafi, F, O'Sullivan, C & Cavarretta, I 2013, 'Analysis of an image-based method to quantify the size and shape of sand particles', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 139, no. 8, pp. 1290–1307.

Altuhafi, FN, Coop, MR & Georgiannou, VN 2016, 'Effect of particle shape on the mechanical behavior of natural sands', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 142, no. 12.

Carneiro, JJV, Marques, EAG, Viana da Fonseca, AJP, Ferraz, RL & Oliveira, AHC 2023, 'Characterization of an iron ore tailing sample and the evaluation of its representativeness', *Geotechnical and Geological Engineering*, vol. 41, no. 5, pp. 2833–2852.

Carrera, A, Coop, M & Lancellotta, R 2011, 'Influence of grading on the mechanical behaviour of stava tailings', *Géotechnique*, vol. 61, no. 11, pp. 935–946.

Carraro, JAH, Prezzi, M & Salgado, R 2009, 'Shear strength and stiffness of sands containing plastic or nonplastic fines', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 135, no. 9, pp. 1167–1178.

Carvalho, JVA, Wagner, AC, Scheuermann Filho, HC & Consoli, NC 2024, 'The role of fabric, stress history, mineralogy, and particle morphology on the triaxial behavior of nontextbook geomaterials', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 150, no. 8.

Consoli, NC, Carvalho, JVA, Wagner, AC, Scheuermann Filho, HC, Carvalho, I, Cacciari, PP & Silva, JPS 2023, 'Determination of critical state line (CSL) for silty-sandy iron ore tailings subjected to low-high confining pressures', *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 16, no. 1, pp. 1684–1695.

Consoli, NC, Scheuermann Filho, HC, Wagner, AC, Carvalho, JVA, Guedes, JPC, Carvalho, I, Delgado, BG & Silva, JPS 2024, 'Insights into the mechanics of uncemented and lightly cemented compacted iron ore tailings under high confining pressures', *Soil and Foundation*, vol. 64, no. 6.

Coop, MR 2015, 'Limitations of a critical state framework applied to the behaviour of natural and 'transitional' soils'', in VA Rinaldi, ME Zeballos & JJ Clariá (eds), *Proceedings of the 6th International Symposium on Deformation Characteristics of Geomaterials*, IOS Press, Amsterdam, pp. 115–155.

Coop, MR 2024, 'The 7th Bishop Lecture: The mechanics of coarse-grained geomaterials at meso- and micro-scales', *Soils and Rocks*, vol. 47, no. 3, pp. 1–16.

Corrêa de Oliveira, SC, Delgado, BG, Paes, IT, Viana da Fonseca, AV, Pereira, EL & Paes, BST 2025, 'Influence of stress state on the expected behavior of filtered iron ore tailings for compacted stacking disposal', *Geotechnical Testing Journal*, vol. 48, no. 2, pp. 166–189.

Coutinho, RS, Silva, RSA, Almeida, MSS, Cavalcanti, MCR, Nagula, SS & Delgado, BG 2025, 'Static liquefaction susceptibility of Brazilian iron ore tailings dam: combined laboratory testing and numerical modeling approach', *International Journal of Geomechanics*, vol. 25, no. 8.

Delgado, BG, Viana da Fonseca, A, Bittar, RJ, Castilho, BM & Coelho, D 2023, 'Geomechanical behaviour of an iron ore tailings under high-stress levels for disposal by dry stacking', in F Schnaid, R Cudmani & R Verdugo (eds), *Proceedings of the 1st International Conference on Geotechnics of Tailings and Mine Waste*, International Society for Soil Mechanics and Geotechnical Engineering, London, pp. 342–351.

Delgado, BG, Viana da Fonseca, A, Bittar, RJ, Besenzon, D, Molina-Gómez, F, Cordeiro, D, Mendonça, A & Rios, S 2025, 'Critical state loci of superheavy iron ore tailings from sampling in Brumadinho reservoir', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 151, no. 10.

Ferreira, PMV & Bica, AVD 2006, 'Problems in identifying the effects of structure and critical state in a soil with a transitional behaviour', *Géotechnique*, vol. 56, no. 7, pp. 445–454.

Fourie, AB & Tshabalala, L 2005, 'Initiation of static liquefaction and the role of Ko consolidation', *Canadian Geotechnical Journal*, vol. 42, no. 3, pp. 892–906.

Ganguli R & Cook DR 2018, 'Rare earths: a review of the landscape', *MRS Energy & Sustainability*, vol. 5, https://doi.org/10.1557/mre.2018.7

Hight, DW 2024, 'The 9th Victor de Mello lecture: reflections and speculations', *Soils and Rocks*, vol. 47, no. 4, pp. 1–29.

Jefferies, M & Been, K 2016, *Soil liquefaction - A Critical State Approach*, 2nd edition, CRC Press, Boca Raton.

Kato, Y, Nakata, Y, Hyodo, M & Murata, H 2001, 'One-dimensional compression properties of crushable soils related to particle characteristics', in KKS, Ho, & KS, Li (eds), *Proceedings of 14th Southeast Asian Geotechnical Conference, Geotechnical Engineering Meeting Society's Meet*, A.A. Bakema, Lisse, pp. 527–532.

Ledesma, O, Manzanal, D, Sfriso, A, 2021, 'Formulation and numerical implementation of a state parameter-based generalized plasticity model for mine tailings', *Computers and Geotechnics*, vol. 135.

Ledesma, O, Sfriso, A, Manzanal, D 2022, 'Procedure for assessing the liquefaction vulnerability of tailings dams', *Computers and Geotechnics*, vol. 144, no. 5.

Maranha das Neves, E 1991,

Maranha das Neves, E 1991, *Comportamento de barragens de terra-enrocamento (Behavior of earth-rockfill dams*), PhD thesis, NOVA University, Lisbon .

Lees, G 1964, 'A new method for determining the angularity of particles', *Sedimentology*, vol. 3, no. 1, pp. 2–21.

Nova, R 199. Controllability of the incremental response of soil specimens subjected to arbitrary loading programmes, *Journal of the Mechanical Behavior of Materials* 5, 193–202.

Papadopoulou, A & Tika, T 2008, 'The effect of fines on critical state and liquefaction resistance characteristics of non-plastic silty sands', *Soil and Foundation*, vol. 48, no. 5, pp. 713–125.

Rios, S, Viana da Fonseca, A, Caetano, I, Delgado, B & Pereira, G 2025, 'Comparison of geomechanical behavior of an iron ore tailings and natural siliceous silty sand with the same particle size distribution', *Canadian Geotechnical Journal*, vol. 62, no. 1, pp. 1–19.

Rouse, PC, Fannin, RJ & Taiebat, M 2014, 'Sand strength for back analysis of pull-out tests at large displacement', *Géotechnique*, vol. 64, no. 4, pp. 320–324.

Rógenes, E, Paes, IT, Delgado, BG, Bittar, RJ, Gomes, AS, Cirone, A, Fávero Neto, AH & Rasmussen, LL 2025, 'Assessing static liquefaction triggers in tailings dams using the critical state constitutive models CASM and NorSand', *International Journal for Numerical and Analytical Methods in Geomechanics*, vol. 49, no. 4, pp. 1092–1112.

Schofield, AN & Wroth, CP 1968, *Critical State Soil Mechanics*, London, McGraw Hill.

Schnaid, F, Bedin, J, Viana da Fonseca, A & Costa Filho, LM 2013, 'Stiffness and strength governing the static liquefaction of tailings', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 139, no. 12, pp. 2136–2144.

Shipton, B & Coop, MR 2015, 'Transitional behaviour in sands with plastic and non-plastic fines', *Soils Foundations*, vol. 55, no. 1, pp. 1–16.

Silva, JPDS, Carvalho, JVDA, Wagner, AC, Cacciari, PP & Consoli, NC 2023, 'On the mechanics of filtered compacted consolidated and overconsolidated iron ore tailings at high pressures', *Canadian Geotechnical Journal*, vol. 61, no. 3, pp. 575–581.

Shire, T, O'Sullivan, C & Hanley, KJ 2016, 'The influence of fines content and size-ratio on the micro-scale properties of dense bimodal materials', Granular Matter, vol. 18, no. 3, 52.

Soares, M & Viana da Fonseca, A 2016, 'Factors affecting steady state locus in triaxial tests', *Geotechnical Testing Journal*, vol. 39, no. 6, pp. 1056–1078.

Sottile, M, Cueto, I, Sfriso, A, Ledesma, O & Lizcano, A, 2022, 'Flow liquefaction triggering analyses of a tailings storage facility by means of a simplified numerical procedure', *20th International Conference on Soil Mechanics and Geotechnical Engineering*, International Society for Soil Mechanics and Geotechnical Engineering, London.

Sympatec GmbH n.d, *Sympatec,* version 5.4.1.0, Computer software, Clausthal-Zellerfeld.

Sivathayalan, S & Vaid, YP 2002, 'Influence of generalized initial state and principal stress rotation on the undrained response of sands', *Canadian Geotechnical Journal*, vol. 39, no. 1, pp. 63–76.

Tatsuoka, F, Di Benedetto, H, Enomoto, T, Kawabe, S & Kongkitkul, W 2008 'Various viscosity types of geomaterials in shear and their mathematical expression', *Soils and Foundations*, vol. 48, no. 1, pp. 41–60.

Thevanayagam, S, Shenthan, T, Mohan, S, Liang, J 2002, 'Undrained fragility of clean sands, silty sands, and sandy silts', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 128, no. 10, pp. 849–859.

Tsytocich, N 1976, *Soil Mechanics*, Mir Publishers, Moscow.

Velten, R, Consoli, N, Scheuermann Filho, H, Wagner, A, Schnaid, F & Costa, JP 2022, 'Influence of grading and fabric arising from the initial compaction on the geomechanical characterisation of compacted copper tailings', *Géotechnique*, vol. 74, no. 5, pp. 461–472.

Verdugo, R & Ishihara, K 1996, 'The steady state of sandy soils', *Soils and Foundations*, vol. 36, no. 2, pp. 81–91.

Viana da Fonseca, A, Coop, MR, Fahey, M & Consoli, N 2011, 'The interpretation of conventional and non-conventional laboratory tests for challenging geotechnical problems', *Deformation Characteristics of Geomaterials*, vol. 1, IOS Press, Amsterdam, pp. 84–119.

Viana da Fonseca, A 2013, 'Application of in situ testing in tailing dams, emphasis on liquefaction: Case-history', in RQ Coutinho & PW Mayne (eds), *Proceedings of the Geotechnical and Geophysical Site Characterization 4*, Taylor & Francis Group, London, pp. 181–203.

Viana da Fonseca, A, Fonseca, A, Oliveira, S 2021, 'Fatores de segurança determinísticos em avaliação de estabildade de barragens de rejeitos: uma reflexão ('Deterministic safety factors in the stability assessment of tailings dams: a reflection'), *Geotecnia (Journal of the Portuguese Society of Geotechnics)*, vol. 151, no. 1, pp. 53–76.

Viana da Fonseca, A, Cordeiro, D, Molina-Gómez, F, Besenzon, D, Fonseca, A & Ferreira, C 2022, 'The mechanics of iron tailings from laboratory tests on reconstituted samples collected in post-mortem Dam I in Brumadinho', *Soils and Rocks*, vol. 45, no. 2, pp. 1–20.

Viana da Fonseca, A, Caetano, I, Meneses, B, Rios, S 2023, 'Stabilisation of tailings storage facilities for sustainable production of raw materials', in P, Long & N, Dung (eds), *Proceedings of the 5th International Conference on Geotechnics for Sustainable Infrastructure Development*, Springer, Singapore, pp. 1099–1111.

Viana da Fonseca, A 2026, 'The 10th James K. Mitchell Lecture: In situ and lab tests work together to reduce uncertainties in TSF fragility assessment: a benchmark case-history', *Soils and Rocks* (in press).

Wadell, HA 1932, 'Volume, shape, and roundness of rock particles', *Journal of Geology*, vol. 40, no. 5, pp. 443–451.

Wagner, AC, Carvalho, JVA, Scheuermann Filho, HC & Consoli, NC 2025, 'Influence of grading in compacted tailings behaviour: towards resilient design', *Géotechnique*, vol. 75, no. 13, pp. 150–163.

Yang, J, Wei, LM & Dai, BB 2015, 'State variables for silty sands: global void ratio or skeleton void ratio?' *Soils and Foundations*, vol. 55, no. 1, pp. 99–111.

Yang, S, Lacasse, S & Sandven, R 2006, 'Determination of the transitional fines content of mixtures of sand and non-plastic fines', *Geotechnical Testing Journal*, vol. 29, no. 2, pp. 102–107.

Yang, Y, Wei, Z, Fourie, A, Chen, Y, Zheng, B, Wang, W & Zhuang, S 2019, 'Particle shape analysis of tailings using digital image processing', *Environmental Science and Pollution Research,* vol. 26, no. 25, pp. 26397–26403.

Yilmaz, Y, Deng, Y, Chang, CS & Gokce, A 2023, 'Strength–dilatancy and critical state behaviours of binary mixtures of graded sands influenced by particle size ratio and fines content', *Géotechnique*, vol. 73, no. 3, pp. 202–217.

Yoshimoto, N, Hyodo, M, Nakata, M, Orense, R, Hongo, T & Ohnaka, A 2012, 'Evaluation of shear strength and mechanical properties of granulated coal ash based on single particle strength', *Soils and Foundations*, vol. 52, no. 2, pp. 321–334.

Zuo, L & Baudet, BA 2015, 'Determination of the transitional fines content of sand–non plastic fines mixtures', *Soils and Foundations*, vol. 55, no. 1, pp. 13–219.