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Partial drainage in tailings using the cone penetration test

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Abstract

Due to the difficulty in obtaining good quality undisturbed samples, as well as the index properties and in situ state variability, the characterisation of tailings materials is often performed by in situ tests, such as the cone penetration test with pore pressure measurements (CPTu) or vane tests. CPTu is the most widely used in situ tests, for it allows for a quasi-continuous investigation reaching significant depths and encompasses a vast theoretical framework correlating with the most relevant soils' physical and geomechanical parameters. However, while this framework was established and proven as suitable for natural soils, its complete applicability to tailings materials is often questioned. One of the common pitfalls is the use of the standard piezocone penetration rate (2 cm/s). This rate is based on the presupposition that permeable soils (sands) will respond in drained conditions and impermeable ones (clays) will present undrained behaviour. However, tailings materials often have high fine contents, mainly within the silt fraction, thus they have the potential for partially drained behaviour during penetration. In such cases, higher penetration rates are recommended. This paper presents the hydraulic characterisation of different tailings from different geographical origins, based on CPTu measurements at a constant penetration rate of 2.0 cm/s. The tailings are analysed in terms of their ore type (iron, aluminium, copper and zinc), index properties (grain size distribution, specific density, plasticity), in situ state (void ratio, water content) and deposition method (slurry, paste/thickened and filtered). The hydraulic properties are estimated based on the CPTu and dissipation tests, performed in different sites, and the results are discussed within the existing theoretical framework of partial drainage. As a result, the partially drained behaviour of a range of different tailings materials – from sandy-silt iron ore to red mud – and the potential need to implement a different CPTu standard velocity for these tailings is assessed and discussed.

Keywords: *tailings, permeability, penetration rate, CPTu, partial drainage*

1 Introduction

The cone penetration test with porewater pressure measurement (CPTu) is one of the most widely used in situ tests for soil characterisation. It consists of an electronic cone probe penetrating the soil at a constant rate (usually 2 cm/s) that automatically measures the resistance of the material to penetration and the generated porewater pressure up to significant depths and in short intervals, thus allowing for a quasi-continuous geo-profile of the soil. Moreover, it is possible to correlate the results obtained during the test with important geomechanical and hydraulic parameters of the soil by means of an extensive and robust theoretical framework that allows for a reliable interpretation of soil's behaviour (e.g. Robertson & Cabal 2022; Jefferies & Been 2016).

The porewater pressures generated during the CPTu, measured by means of a transductor, usually installed immediately before the cone face (u_2), are due to the penetration of the soil by the probe, hence being closely related with the soil's compressibility and permeability. Commonly, CPTu are accompanied by dissipation tests, which consist of stopping the penetration and allowing for the excess porewater pressures to dissipate until it reaches equilibrium (usually the hydrostatic pore pressure, u_0). This type of test allows for the evaluation of the porewater pressure at the test depth, which can be used to infer the position of the water

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level and the existence of vertical gradients (upward or downward water flux). They also allow for the estimation of some the soil's hydraulic parameters, such as its hydraulic conductivity (k) and consolidation coefficient (c_{vh}). However, the CPTu framework was established for natural soils where the dichotomy fine (clay-like)– coarse (sand-like) is usually prevalent. This dichotomy assumes that fine materials will present an undrained response to penetration whereas coarse material will be sufficiently permeable for drained conditions to exist (Fourie et al. 2022).

For (sandy to clayey) silts soils, commonly called transitional soils (Schneider et al. 2008), CPTu conducted with a standard penetration rate (2 cm/s) can lead to partial drainage due to the dissipation of part of the porewater pressures around the cone (i.e. partial consolidation). The influence of the penetration rate in silty materials is well studied, showing that partial drainage increases penetration resistance while generating less porewater pressure (Garcia Martínez et al. 2016; DeJong & Green 2020; Jaeger et al. 2010; Randolph & Hope 2004; Schneider et al. 2008) and affects dissipation measurements (DeJong & Randolph 2012). Ultimately, partial drainage can overestimate undrained strengths estimated from the CPTu results, insofar as the prevalent correlations (Lunne et al. 1997; Mayne & Peuchen 2018; Schnaid 2021) are based on the cone factor (N_{kt}), which in turn is a function of the normalised porewater pressures (B_q). Thus, for transitional soils, penetration rates higher than 2 cm/s might be warranted to generate fully undrained response.

In order to understand the effects of partial drainage, Randolph & Hope (2004) proposed a parameter that consists in normalising the penetration velocity (V) by means of the consolidation coefficient (c_{vh}). Values of V ranging between 0.3 and 30, as well as t_{50} ranging between 0 and 100 s, are considered representative of partial drainage conditions (DeJong & Randolph 2012), whereas values of t_{50} less than 10 and more than 75 s define nearly drained and undrained conditions, respectively (DeJong & Green 2020). c_{vh} is related to the time for 50% consolidation (t_{50}) and is typically estimated by the Teh & Houlsby (1991) method, assuming undrained penetration. However, partial consolidation can lead to inaccurate estimations of c_{vh}, insofar as the initial excess pore pressures may be low compared to the ones when fully undrained conditions are guaranteed. Indeed, the estimated c_{vh} tends to decrease with increasing partial consolidation (DeJong & Randolph 2012).

This is particularly relevant when dealing with mine tailings, both because of their typically loose, contractive in situ state and because of their grain size composition (mostly silts), which presents permeabilities ranging from 10^{-5} to 10^{-8} m/s (Schnaid 2021), typical of transitional materials. Indeed, studies with varying penetration rates on different tailings showed high ratios between normalised tip resistances for drained penetration and undrained penetration (Q_d/Q_u), ranging from 4 in iron ore tailings and 12 in gold tailings (DeJong & Green 2020). Similar effects due to partial drainage are observed in vane tests on this type of materials depending on the rotation rate (Hogan et al. 2025; Reid 2016).

Tailings are anthropic materials derived from mining excavation for ore exploitation. Hence their physical, geomechanic and hydraulic properties depend on the extraction process, main ore element and deposition method (Lunne et al. 1997). Despite their great heterogeneity – because of the unique conditions upon which these materials are produced – mine tailings can be divided in terms of their grain size distribution and are closely related to the extraction method, with the latter associated with the ore being exploited, e.g. bauxite being often finer and more plastic tailings than copper and zinc (Vick 1990). The ore element can also influence the weight of the material, with a particular example falling upon iron ore which, due to their high content of steel minerals, may present specific gravities (G_s) as high as 5 (Carneiro et al. 2023).

Another determinant factor for tailings behaviour is the deposition method. Different methods are used – sometimes depending on cost, sometimes depending on the desired outcome, as in subaqueous deposition – to avoid or retard oxidation (Fourie et al. 2022). Typically, tailings are deposited as a slurry either through a single discharge or spigotting. Cyclones are also used to separate the coarser fraction from the finer one, in order to create more stable and permeable embankments with the former and push the latter further in into the reservoir. A conventional slurry behaves almost like a liquid due to its high water content (up to 70–80%). To reduce the amount of water lost in the process and increase storage capacity, other methods were developed, namely the thickened discharge, which reduces the water content to around 40–50% and behaves more like a fluid or a paste, and the 'dry' disposal, where even more water is filtered out reaching 70–80% solid content and the transport has to be made by trucks instead of pipelines (Fourie et al. 2022; Vick 1990).

This paper assesses the criteria, within which partial drainage may occur, namely the normalised velocity (V), the dissipation time (t_{50}) and the soil's permeability (k), for a set of different mine tailings, from several origins, with diverse main ore element (bauxite, copper and zinc, and iron) and different deposition methods (beach below water [BBW], slurry, thickened, filtered). The hydraulic properties (k and c_{vh}) – from which the different tailings are analysed and grouped based on their main characteristics – are estimated based on CPTu dissipation tests and the conditions for partial drainage are evaluated. This may, on one hand, inform the need for performing CPTu with different penetration rates and, on the other, allow understanding of if and which of the criteria presented in the literature is well suited for these materials.

2 Assessing potential partial drainage from cone penetration tests

The hydraulic characteristics of soil materials can be estimated through CPTu tests. This estimation is based on a semi-empirical framework established for this test that encompass a set of correlations between the resistances and porewater pressures measured during the test and some relevant soil's property. The 3 main parameters measured during the penetration are the cone tip resistance (q_c), sleeve friction (f_s) and the porewater pressure measured behind the probe's shoulder (u_2). These 3 parameters can be corrected and normalised to take into consideration the confining conditions (Q_t, F_r and B_Q, respectively), allowing for a comparison of the soil's behaviour in depth (Mayne et al. 2023; Robertson & Cabal 2022), which in turn allows for the classification of the different materials in terms of their typical behaviour, namely through a soil behaviour type (SBT) index (I_c) (Jefferies & Been 2016; Robertson 2009).

The excess porewater pressures (Δu) generated during the CPTu are the consequence of the probe penetration in the soil. In the moment the penetration ceases, the porewater pressures start dissipating, taking a longer or shorter time to reach equilibrium (u_0) depending on the material's permeability. Hence, during CPTu the penetration is halted in order to measure the porewater dissipation, called a dissipation test, with the purpose of evaluating the hydraulic properties of soils in depth. Two main parameters can be estimated by the dissipation rate measured during these tests: the soil's consolidation coefficient (c_{vh}) and permeability (k). These parameters are typically considered horizontal, but since the dissipation occurs in every direction around the probe's tip, they will be considered general parameters (i.e. independent of the direction of flow).

c_{vh} is a parameter that represents the rate of porewater dissipation and can usually be estimated by the Teh & Houlsby (1991) solution, based on CPTu dissipation tests results, assuming an undrained response during penetration, as follows (in cm^2/s):

$$c_{vh} = \frac{T'_{50} \times (a_c)^2 \times \sqrt{I_R}}{t_{50}} \tag{1}$$

where:

- T'_{50} = theoretical modified time factor for 50% consolidation
- a_c = piezocone radius (cm)
- I_R = undrained rigidity index for small strains
- t_{50} = time for 50% consolidation (s).

However, for soils that present potential for partial consolidation during penetration, the Teh & Houlsby (1991) solution cannot be directly applied, underestimating c_{vh} for a given t_{50} (DeJong & Randolph 2012). For that reason, DeJong & Randolph (2012) proposed the estimation of partially drained c_{vh} as follows (in mm^2/s):

$$t_{50} = \frac{\sqrt{I_R}}{c_{vh}}(78 + 0.25 \times c_{vh}{}^{1.2}) \tag{2}$$

The above formula diverges from Teh & Houlsby's (1991) one, showing a non-linearity for t_{50} values below 100 s (Figure 1). Based on the work of DeJong & Randolph (2012), Ayala et al. (2023) proposed a simplified linear relation between the 2 variables, which leads to higher values of c_{vh} (in cm^2/s) than DeJong & Randolph's (2012) solution above the apparent asymptote of the latter formulation:

$$c_{vh} = \frac{T'_{50} \times d^2}{t_{50}} = \frac{3.327 \times 0.061 \times \sqrt{I_R} \times (a_c \times 2)^2}{t_{50}} \quad (3)$$

The intersection between Equations 2 and 3 is, approximately, the asymptote ($t_{50,asym}$) of Equation 2. This intersection point can then be used to combine both equations, so that t_{50} can be estimated by Equation 2 for $t_{50} > t_{50,asym}$ and by Equation 3 for $t_{50} \le t_{50,asym}$, therefore avoiding overestimating c_{vh} above $t_{50,asym}$.

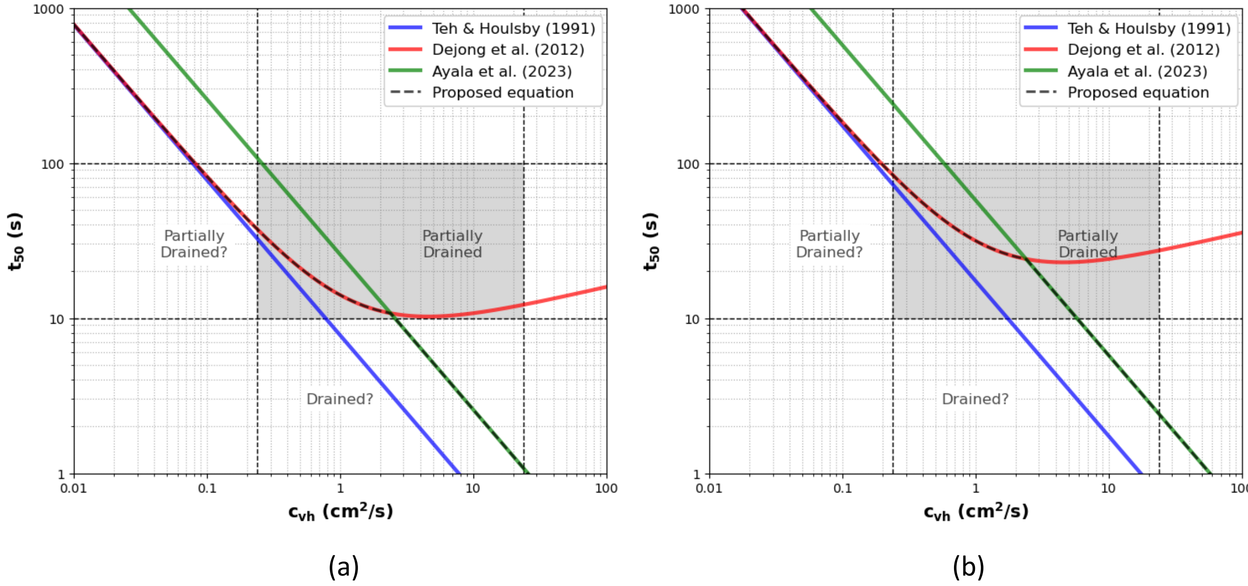


Figure 1 Comparison of c_{vh} estimation following Equations 1, 2 and 3. (a) I_R = 100; (b) I_R = 500

The estimation of t_{50} from CPTu dissipation tests depends on the type of porewater dissipation responses: monotonic or dilatory. A monotonic dissipation corresponds to a response where the porewater pressure always decay from the initial porewater pressure (u_2) until the equilibrium one (u_0), whereas a dilatory dissipation presents an increase of porewater pressure in the initial part of the response. The initial dilatory response is due to negative porewater pressures generated in a thin layer around the probe. For the monotonic response, the initial porewater pressure (u_i) corresponds to the one measured at the start of the test, thus t_{50} can simply be considered equal to the time passed for $(u_2\text{-}u_0)/2$, as in Figure 2a. However, in the case of dilatory responses, one must discard the negative porewater pressures around the probe. This can be done by projecting a line from a post-peak u_2 point back to t = 0 to estimate the initial porewater pressure (u_i), using the square root of time, so as to obtain an equivalent monotonic response. In this case, t_{50} can be considered equal to the time passed for $(u_i\text{-}u_0)/2$ as in Figure 2b.

It must be mentioned that in the current analysis, u_0 was considered equal to the porewater pressure at the end of the test when the dissipation rate was very small (almost zero). When that was not the case, the dissipation curve was extrapolated. Furthermore, for fine soils it is not unusual that equilibrium (u_0) is not reached, due to the slow consolidation time of these soils, which could lead to very long tests. In these cases, the incomplete curve can be extrapolated up to equilibrium (the asymptote).

c_{vh} also depends on the rigidity index (I_R), the latter defined as the ratio between the soil's shear modulus (G) and its undrained strength (s_u). Krage et al. (2014) proposed the estimation of I_R based on seismic CPTu as follows:

$$I_R = 0.26 \times \left(\frac{G_0}{\sigma'_{v0}}\right) \times \left(\frac{1}{0.33 \times \left(0.33 \times \frac{(q_t - \sigma_{v0})}{\sigma'_{v0}}\right)^{0.75}}\right) \quad (4)$$

where:

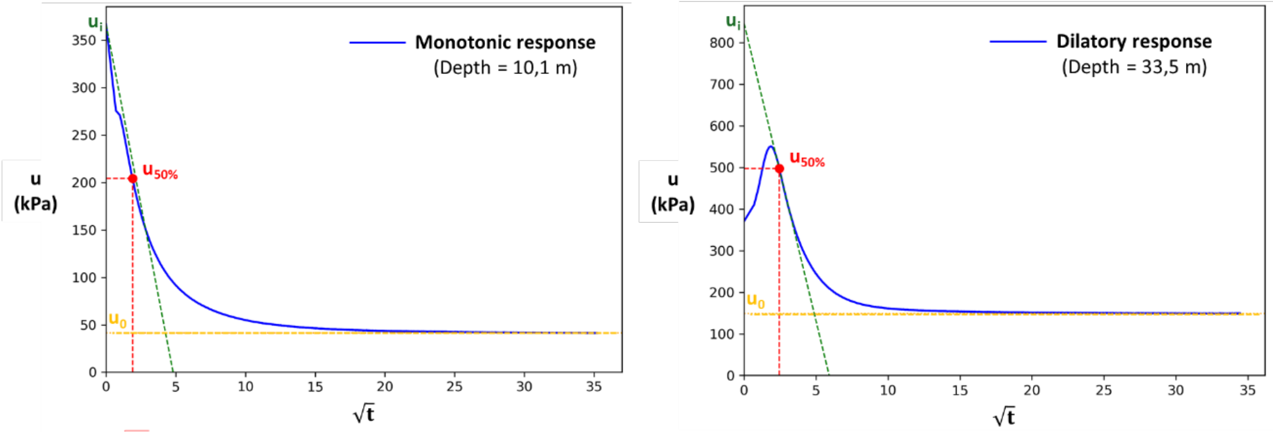
G_0 = initial shear modulus, for small strains (kPa)

σ_{v0} = total pressure (kN/m^2)

σ'_{v0} = effective pressure (kN/m^2)

q_t = cone net tip resistance (kN/m^2).

All the parameters used in Equation 4 were obtained following the well-established CPTu framework presented in Mayne et al. (2023) and Robertson & Cabal (2022). Some important points are worth noting are that the total and effective pressures were calculated based on physical indexes of the materials estimated by lab tests, the water levels for the definition of u_0 at the CPTu execution date were defined/validated by the measurements of in situ piezometers, and the shear wave velocities (V_s) – necessary for the estimation of G_0 – were estimated from the CPTu data in order to ensure the highest number of points and to take into account variation of V_s in depth, but were also validated by in situ measurements using the seismic cone.



(a) (b)

Figure 2 Examples of t_{50} estimation. (a) Monotonic dissipation response; (b) Dilatory dissipation response

k, also known as the soil's hydraulic conductivity, represents a flow water rate for the particular in situ hydraulic regime. Using bands of permeabilities for different soils, based on different t_{50} estimated from CPTu dissipation tests in normally consolidated deposits (after Parez & Fauriel 1988), Mayne et al. (2023) proposed the following correlation between k and t_{50} (in cm/s):

$$k_h = \left(\frac{1}{251 \times t_{50}}\right)^{1.25} \tag{5}$$

Finally, the potential for partial drainage in the tailings can be assessed by the normalised velocity (V), proposed by Randolph & Hope (2004) and extensively used in the case of tailings (DeJong& Randolph 2012; Schnaid 2021; Ayala et al. 2023), as follows:

$$V = \frac{v \cdot d}{c_{vh}} \tag{6}$$

where:

v = CPTu penetration rate (cm/s)

d = piezocone diameter (cm)

c_{vh} = soil's consolidation coefficient (cm^2/s).

Assuming a constant value of V, Equation 6 can be solved in order of c_{vh}. If one sets the V boundaries for partial drainage (0.3 and 30), the standard penetration rate (2 cm/s) and d equal to 3.56 cm (a standard 10 cm^2 piezocone), one obtains the values 0.24 and 23.7 cm^2/s for the partial drainage interval of c_{vh}.

Similarly, assuming a constant value for the t_{50} boundaries for partial drainage (10 and 100 s), using Equation 5 one obtains the values 3.2×10^{-8} and 5.6×10^{-7} m/s for the partial drainage interval of k_h.

As already mentioned, the CPTu classifies the soil in terms of its behaviour during penetration. Using the soil behaviour index (I_c) it is possible to differentiate between coarse, transitional and fine soil. It must be said that this classification is somehow qualitative to the extent that the behaviour translates a like-type behaviour (e.g. clay-like behaviour for fines and sand-like behaviour for coarse soils). Nonetheless, it is reasonable to adopt this classification to understand if the like-type behaviour correlates well with hydraulic and compressibility properties of the materials. Hence, the subsequent analysis will also take into consideration the I_c proposed by Jefferies & Been (2016), estimated by Equation 7. The $I_{c,JB}$ was adopted as it takes into consideration the normalised porewater pressures (B_q), contrary to the Robertson and Wride (Robertson 2009) index that considers only Q_t and F_R, allowing for a finer differentiation between fine materials with significant porewater pressure generation.

$$I_{c,JB} = \sqrt{3 - \log(Q \cdot (1 - B_1) + 1)^2 + (1.5 + 1.3 \cdot \log(F_R))^2} \quad (7)$$

where:

Q_t = normalised tip resistance

F_R = normalised sleeve friction.

Jefferies & Been (2016), similarly to the Robertson (2009) SBT classification, defines $I_{c,JB}$ ranges for different materials. Transitional materials are commonly within the range of 1.8 to 2.76, with the value of 2.4 dividing silty sands to sandy silts from clayey silts to silty clays. Despite being dependent on soil conditions, therefore not necessarily fixed boundaries, the values of 2.2 and 2.58 have been also adopted as limits before which and after which drained and undrained conditions occur, respectively. Hence, between this interval, soils can present partial drainage response. It is important to note that partial drainage conditions may influence the tip resistance and the porewater pressures measured during the test, which in turn affects the normalised parameters from which the soil is characterised and classified in terms of its response to penetration. Therefore, the $I_{c,JB}$ estimated in this study might be impacted by this condition.

3 Piezocone test data and tailings properties

In this study, data from 5 different origins was gathered, some of them with more than one tailings storage facility (TSF) in a total of 7 TSFs, in which a total of 970 CPTu dissipation tests were performed. All the CPTu tests were performed with a standard penetration rate of 2 cm/s. Four of the TSFs (from 2 different origins) stored so-called red mud – a waste industrial product from aluminium industries which is produced during the extraction of alumina from the bauxite ore – 2 TSFs stored waste by-products of iron ore mineral extraction, and another copper-based and zinc-based tailings.

Besides the different ore elements, different deposition methods were used, in some cases also in the same TSF. In order to assess the possible contribution of the deposition method in the hydraulic characteristics of the different tailings, the tailings were differentiated based on the classifications used in each TSF. When that was not possible (e.g. due to the lack of characterisation of the deposited tailings or missing information), the deposition method was qualitatively classified based on the information available (historical photos and observational descriptions). Table 1 presents a summary of these main descriptors.

The analysis herewith is based on the CPTu framework. However, the CPTu, per se, does not provide a lithological and physical description of the materials tested, only a mechanical behaviour during penetration from which, through a set of correlations, one can estimate other soil's properties. Indeed, in TSF, samples are rarely collected in depth close to CPTu that can be tested and from which one can estimate the in situ properties to (re)calibrate the CPTu correlations – a particular relevant aspect for tailings due to their high heterogeneity. That is the case with the present data for most of the origins presented.

Table 1 Number of piezocone (CPTu) dissipation tests per origin, ore element and deposition method

Origin	Structure	Ore element	Deposition method	Number of dissipation tests (CPTu)	
A	S1.1	bauxite (red mud)	Beach below water	14	198 (bauxite)
			Slurry	21	
	S1.2		Beach below water	16	
			Slurry	29	
			Filtered	5	
B	S2.1		Filtered	62	
	S2.2		Filtered	51	
C	S3	Copper and zinc	Slurry	416	603 (copper and zinc)
			Thickened	187	
D	S4	Iron	Slurry	140	169 (iron)
E	S5		Slurry	29	

Most of the sites, though, have a more or less extensive investigation based on superficial sampling, which can give an overall idea of the type of materials. The main characteristics of the tailings, by origin and deposition method, are the following:

- Origin A (red mud):
  - Slurry: clayey-silt (up to 40% clay) to sandy-silt bauxite ore tailings, disposed with 20–30% of solid content by weight, low plasticity, medium to high water content, high specific gravity (average 3.4) and in situ loose state.
  - Filtered: sandy-silt bauxite ore tailings disposed by the dry stacking method (filtration), with 65–70% solid content by weight and <20% clay content, low plasticity and low to medium water content.
  - BBW: sandy-silt to silt bauxite ore tailings disposed by the dry stacking method (filtration), with 65–70% solid content by weight, with up to 30% clay content, low plasticity and relatively high water content.
- Origin B: (red mud, filtered): bauxite ore tailings disposed by the dry disposal method (filtration) with approximately 70% solid content by weight. Predominantly silt, with clay content up to 30%, low plasticity and in situ loose state. Despite the dry stacking deposition, these tailings present high water content.
- Origin C (copper and zinc):
  - Sandy-silt to silty sand slurry, disposed with 20–25% of solid content by weight, medium to very high water content, high specific gravity (>3.3) and in situ loose state.
  - Sandy-silt thickened tailings, disposed with 60–70% of solid content by weight, high specific gravity (>3.2) and in situ loose state.
- Origin D: none to low plasticity iron ore tailings, predominantly silt, with high fine content (FC) content (average 84%) and up to 12% clay material. In terms of in situ state, the tailings are loose and present high specific gravity (>3.4). Although no information about the deposition method exists, based on the observed consistency and old photos showing deposition through spigots, it was classified as slurry.

- Origin E: low plasticity iron ore tailings, predominantly sandy-silt, with high FC content and up to 10% clay material. In terms of in situ state, the tailings are loose and present high specific gravity (>3.1). Although no information about the deposition method exists, based on the observed consistency and old photos showing deposition through spigots, it was classified as slurry.

The tailings characteristics are summarised in Table 2 by means of main physical parameters, namely clay (<2 µm) and FC content, average particle size (D_{50}), specific gravity (G_s), void ratio (e) and water content (w), as well as by their classification following the Unified Soil Classification System (ASTM 2006).

Table 2 Index properties of the tailings (based on in situ investigations)

Site	Ore	Deposition method	<2 µm (%)	FC (%)	D_{50} (mm)	IP (%) [(1)]	G_s [(1)]	e [(1)]	w (%) [(1)(2)]	USCS[(5)]
A	Bauxite (RM)	BBW [(3)]	12–30	66–97	0.005–0.04	9 (7–12)	–	–	39 (27–44)	ML
		Slurry	9–42	52–99	0.003–0.07	12 (8–20)	3.4 (2.5–4.3)	1.3 (0.9–1.8)	40 (30–47)	ML
		Filtered	5–23	51–79	0.02–0.07	12 (11–14)	–	–	28 (15–42)	ML
B		Filtered	4–31	68–92	0.008–0.05	10 (8–15)	3 (2.8–3.2)	1.3 (0.8–1.6)	43 (27–52)	ML
C	Copper and zinc (C&Z)	Slurry	<15	20–100	0.006–0.16	–	3.6 (3.3–4.1)	1.2 (0.4–2.5)	32 (11–71)	CL-ML
		Thickened	<14	45–96	0.007–0.09	–	3.5 (3.2–3.7)	1.1 (0.8–1.4)	31 (24–43)	CL-ML
D	Iron (IR)	Slurry	<12	35–95	0.02–0.1	NP [(4)] (4–16)	4.0 (3.4–5.0)	1.1 (0.6–2.7)	20	CL[(4)]
E		Slurry	<10	45–95	0.01–0.06	9 (4–23)	4.3 (3.1–4.7)	1.1 (0.6–2.1)	22 (9–38)	CL

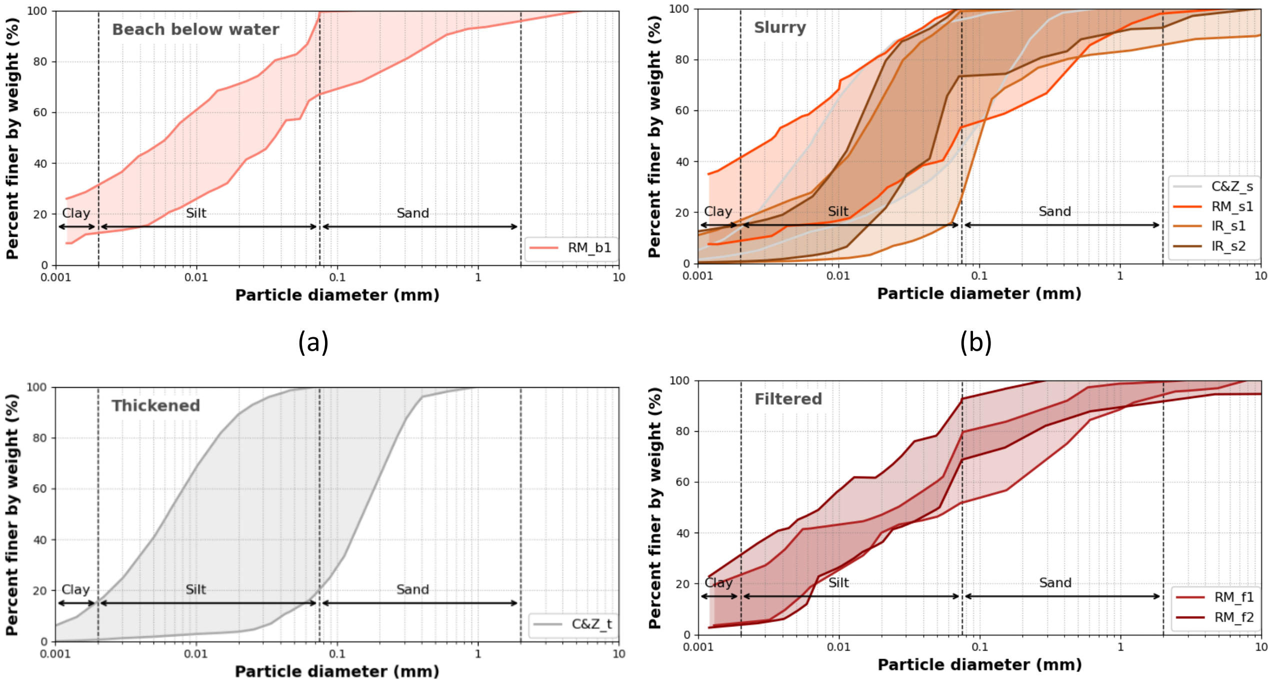
[(1)] Average / (min.-max.); [(2)] Samples collected (sometimes years) after deposition; [(3)] Beach below water; [(4)] 58% of cases are NP; [(5)] Unified Soil Classification System

In general, all tailings have a large portion of silt materials, with the red mud tailings presenting a higher clay content and the copper and zinc tailings a higher sand content. The difference in grain size distribution band is presented in Figure 3. Based on their physical properties, all the studied tailings are predominantly transitional materials (silts), thus having the potential for partial drainage during penetration, although the differences in grain size distribution, as well as the method of deposition, might play a role on the extent of that potentiality.

On the other hand, iron ore tailings are heavier than all the others, due to the weight of the iron mineral and its high content in the soil (Carneiro et al. 2023). All tailings present, on average, low plasticity and a loose in situ state. Both the red mud and the copper and zinc tailings present medium to high water content, with the slurry type of the latter presenting, in some cases, high water content (~70%). The contrast is seen within the iron ore tailings, where the average water content is around 20%. It must be said that these water contents do not in all cases represent the water content immediately after deposition. In fact, in most cases the tested samples represent years-long consolidated soil, insofar as all the TSF presented in this study are operating for decades and some already ceased operations. Regarding the void ratio (e_0), it seems that the highest value obtained in filtered and thickened tailings were slightly smaller than their more liquid counterpart (slurry), the latter presenting maximum void ratios in general above 2.0, whereas the former remain below that threshold. This might be indicative of the lower water content in the moment of deposition and, consequently, a denser state when deposited.

It is also noticed that the minimum void ratios in the copper and zinc slurry tailings are lower than their thickened counterpart and that the void ratio range is larger in the former case, which may also be associated with the looser state during deposition, promoting a more significant rearrangement of the particles within the material when loaded, but also with the fact that the slurry tailings are deposited below the thickened ones, thus under a higher surcharge. In fact, it is seen that the void ratio tends to decrease in depth, as expected. The same difference between the minimum void ratio and its range is not seen in the case of the Bauxite tailings, which show similar values between the slurry and the filtered tailings. This can be justified with the thinner and more well graded grain size distribution of these tailings, corroborated by the consistency of this range in depth in the case of the filtered tailings, but also with the small amount of data in the case of the slurry.

Based on the aforementioned description, the physical properties do not show any relevant differences between the different deposition methods within the same type of tailings, apart from the natural water content (influenced, as mentioned, by the time of exposure) and the void ratio between the denser and the more liquid types of deposition. This is within expectations, insofar the material explored in each TSF is the same independently of the deposition method, the difference falling on the state of the material due to the higher or smaller amount of water during deposition.



(c) (d)

Figure 3 Tailings' grain size distributions. (a) Beach below water; (b) Slurry; (c) Thickened; (d) Filtered

4 Analysis and results

In the previous section, it was shown that all the tailings are predominantly silty, loose, with low plasticity or non-plastic. In summary, all tailings in the current study might fit within what is commonly called transitional materials. Nonetheless, the tailings origin is very diverse, a fundamental difference being associated with their ore type. It is also known that different deposition methods may lead to different behaviours. Hence, the analysis presented aims at evaluating the partial drainage potential of the different tailings, based on their main ore element (aluminium, copper and zinc, and iron) and deposition method (BBW, slurry, thickened, filtered).

The potential for partial drainage is assessed taking into account the aforementioned criteria (t_{50}, k, c_{vh}, $I_{c,JB}$). Equation 2 was used for $t_{50} > t_{50,asym}$ (Figure 3) and Equation 3 for $t_{50} < t_{50,asym}$. Figure 4 presents the boxplots of the main indicators, with each indicator interval of interest. It can be seen in Figure 4(a) and (b) that, independently of the ore element and deposition method, all the data within the interquartile range (IQR) – i.e. the 50% most frequent (or central) values – is classified as a very thin soil ($I_{c,JB} > 3$), thus outside of the interval proposed by Ayala et al. (2024) for partially drained soils. It must be mentioned, though, that this interval is probably soil dependent and that the SBT classification was not yet validated for non-natural soils (Wiklund 2024). Furthermore, the $I_{c,JB}$ in this study may be affected by the partial drainage itself. At the very least, these results warrant questions about the use of this index to assess the drainage behaviour of soils.

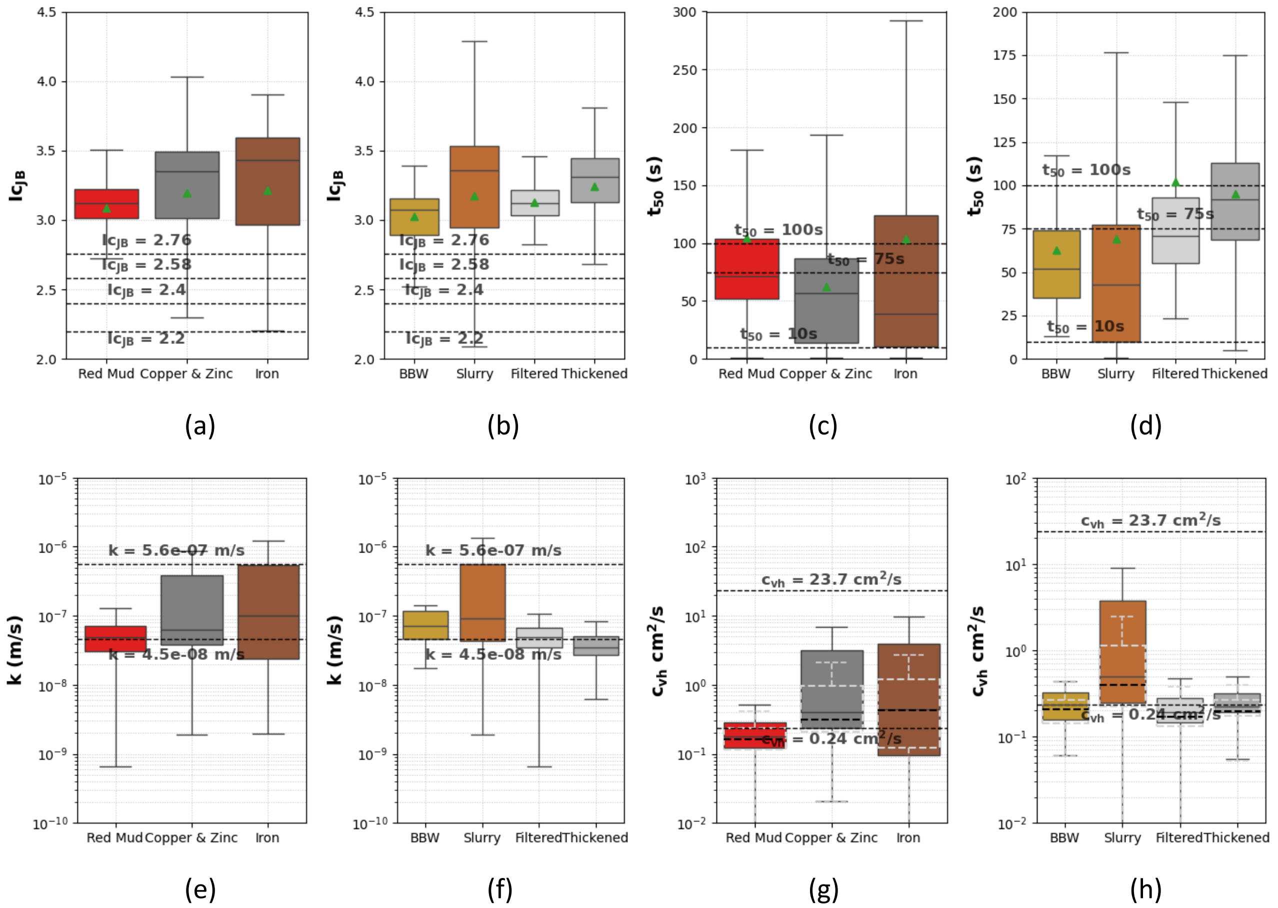


Figure 4 Main statistics of the tailings' hydraulic properties, divided by ore element and deposition method. (a) $I_{c,JB}$ ore; (b) $I_{c,JB}$ deposition; (c) t_{50} ore; (d) t_{50} deposition; (e) k ore; (f) k deposition; (g) $c_{vh,D\&R}$ ore ($c_{vh,T\&H}$ in light grey); (h) $c_{vh,D\&R}$ deposition ($c_{vh,T\&H}$ in light grey)

Figure 4cf describe all tailings within the range of soils with potential for partial drainage during penetration, whatever the ore type or the disposal method, by means of their distribution (percentiles, P). Some of the observed differences between the tailings seem to depend on their characteristics. Red mud (bauxite) present higher values of t_{50} (c) – with P50 ≈ 75 s compared to values ≤ 50 s for the remaining tailings – and lower values of k (e) – with almost 100% of the data < 10^{-7} m/s whereas the other tailings have more than 50% of the data above that threshold, which might be associated with the higher content of clay presented in these materials, as well as their higher plasticity.

Filtered and thickened tailings also present higher values of t_{50} (d) and lower of k (f) when compared with BBW and slurry. This can be explained by the fact that the filtered tailings are red mud (Figure 3d) and the thickened ones are the copper and zinc ore which, despite the wide grain size distribution band, present a big percentage of fine-like (silt) tailings, in some cases up to 100%, as shown in Figure 3c. On the other hand, the lower values of t_{50} (b) and the higher permeability (d) of the slurries might be explained by the greater coarser fraction presented in these tailings, with up to 70% of sand as seen in Figure 3b. The BBW present lower k values, similar to the filtered tailings (f), which agrees with the fact that they are both red mud and present similar physical properties.

The coefficient of consolidation values, (g) and (h), follow similar trends to the permeability ones, (e) and (f), and this is explained by the close relation between these 2 parameters, namely their dependence on t_{50}. It is worth mentioning that the c_{vh} values presented in Figure 4 are estimated following Equations 2 and 3. The boxplots obtained by using Equation 1 are presented in dashed light grey lines, showing that the adoption of Teh & Houlsby (1991) classical formula would lead to most of the tailings falling out of the partially drained range. It must be also said, though, that Ayala et al. (2023) Equation 3 leads to higher values than DeJong & Randolph (2012) recommended Equation 2 for t_{50} values above the $t_{50,asym}$ (Figure 1). This conclusion suggests that while for transitional materials with t_{50} below $t_{50,asym}$ Equation 3 seems the most suitable to take into account partial drainage, above the asymptote this equation might overestimate c_{vh}.

Figure 5 aggregates some of the discussed findings, by relating the different abovementioned parameters. It is shown that the tailings permeability reduces when $I_{c,JB}$ increases, i.e. towards a fine-like behaviour, as shown in (a) and (b). Furthermore, for tailings with $I_{c,JB}$ < 2.76 (coarser than clay-like soils), k values tend to be higher than 5.6×10^{-7} m/s (drained behaviour), whereas for clay-like and organic-like soils ($I_{c,JB}$ > 2.76), the tailings fall into the partially drained interval.

Once again, it is clear that the red mud and thickened copper and zinc tailings are concentrated in the fine-like range with lower permeability, while the slurry presents a wider behaviour. This contrast is also revealed in (c) and (d), where the linear (t_{50} dependency) relationship between k and c_{vh} is presented.

Although the parameters discussed above may help identifying partially drained conditions, the most common parameter to assess this type of response to penetration is the normalised penetration rate (V). Figures 5e and f display the relationship between t_{50} and V, as well as the different drainage behaviour boundaries. Although predominantly within the partially drained zone, there is a clear skewedness towards the undrained area in the red mud, due to its finer nature. Furthermore, despite the significant dispersion, the iron ore tailings fall mostly within the partially drained borders, due to the greater sand content. Finally, there seems to be a slightly different behaviour between the thickened copper and zinc tailings, where a portion of it presents a normalised penetration rate between 0.3 and 30, but a t_{50} below 10 s and thus a rapid consolidation. These results do not show any clear distinction between different deposition methods.

Figure 5 also presents the difference between considering Equation 3, Equation 1 and the intersection between Equations 2 and 3 (the latter in different colours and the other 2 in different shades of light blue). Once more, one can observe a better agreement between Equation 3 results and the criteria within which soils present the potential for partial consolidation.

The exposed analysis relies mainly on CPTu data, which is indirect and based on correlation developed for natural soils. Nonetheless, it suggests that different penetration rates should be tested in these materials to understand the potential effects of partial consolidation. In particular, a higher penetration rate than the standard one (2 cm/s) could generate higher excess porewater pressures.

From the data studied, iron and copper and zinc ore-based tailings are particularly prone to partial drainage when standard penetration rates are used. In terms of deposition method, slurries are the ones that better fit the criteria (even though, the 2 characteristics, ore and deposition method, correlate with each other, insofar the slurries are iron and copper and zinc based).

5 Conclusion

This paper presents an exploratory analysis of the potential for partial drainage in different mine tailings. The different materials were divided into their main ore element (aluminium, copper and zinc, iron) and deposition method (BBW, slurry, thickened, filtered) and, supported by their overall physical properties, as well as by the CPTu SBT index (I_c), compared with well-known boundary criteria in terms of drainage and consolidation behaviour, namely the time for 50% consolidation (t_{50}) and the soil's permeability (k) and coefficient of consolidation (c_{vh}).

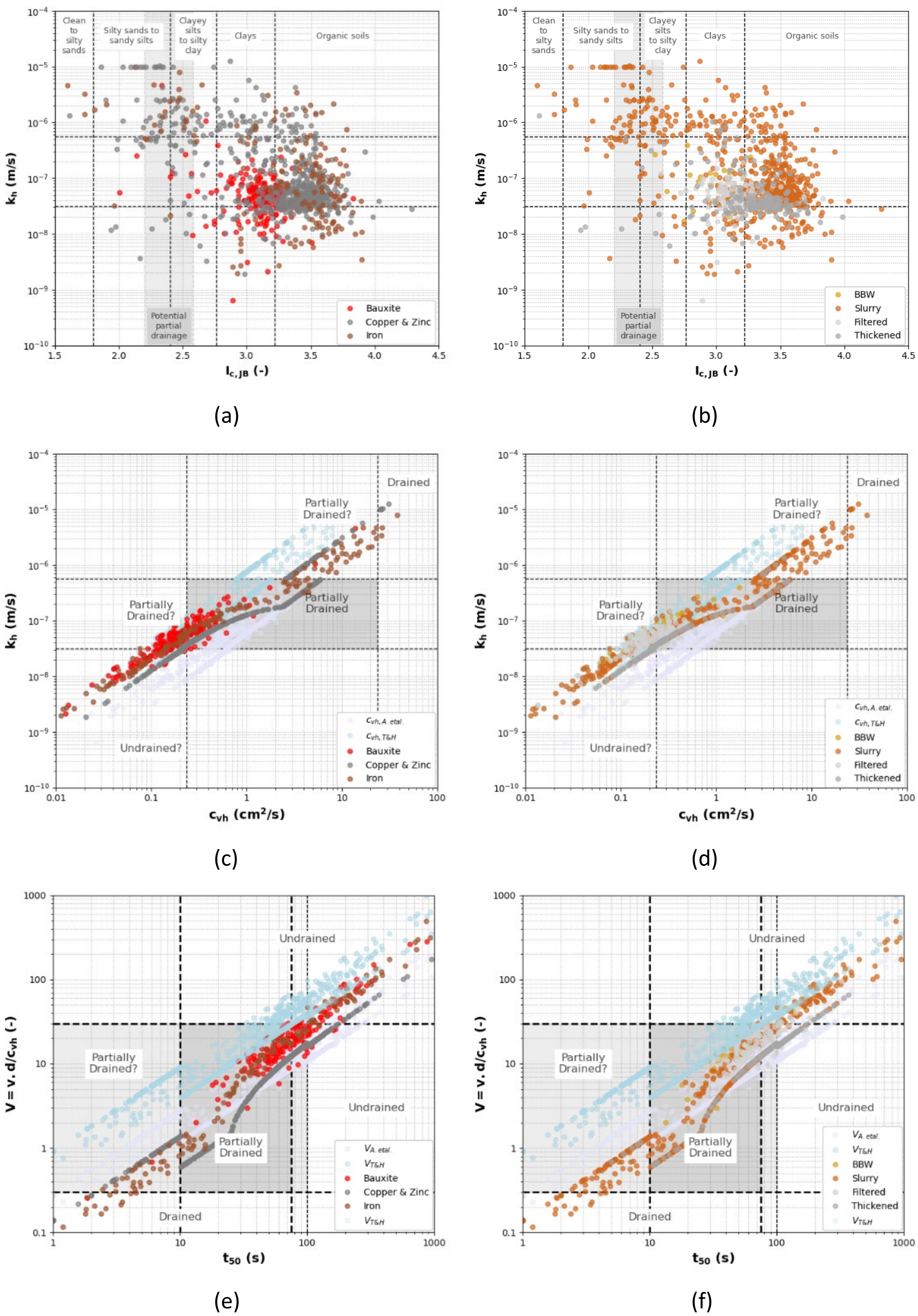


Figure 5 Tailings' hydraulic properties and partial drainage assessment, divided by ore element and deposition method ($c_{vh,T\&H}$ in blue and $c_{vh,A}$ in light blue). (a) $k – I_{c,JB}$ ore; (b) $k – I_{c,JB}$ deposition; (c) $k – c_{vh,D\&R}$ ore; (d) $k – c_{vh,D\&R}$ deposition; (e) $V – t_{50}$ ore; (f) $V – t_{50}$ deposition

The study found that, in general, all the analysed tailings could be classified as transitional materials due to the predominancy of their silty fraction, although the SBT disagreement (almost all tailings were classified as organic material), which can be related with the fact that this classification was developed for natural soils, which is soil dependent and can be affected precisely by partially drained conditions during penetration.

It was shown that most of the tailings herewith studied fall within the criteria for partial drainage when a standard penetration rate (2 cm/s) is used, although with a skewedness towards undrained behaviour in the case of red mud because of its higher clay contents and plasticity). Iron and copper and zinc slurry tailings were the ones that showed a greater potential for partial consolidation during penetration. The results did not show any clear distinction between different deposition methods, insofar all of them presented a portion of tailings with potential for partial drainage.

The study outcomes also support the use of a different correlation between c_{vh} and t_{50} than the classical one proposed by Teh & Houlsby (1991) for undrained soils, namely one that considers the increased c_{vh} in transitional materials (e.g. Ayala et al. 2023). However, it is also shown that caution must be taken when using another linear relationship, insofar the latter could overestimate c_{vh} values for t_{50} above the asymptote found by DeJong & Randolph (2012) for partially drained soils.

Finally, in accordance with the existing research (DeJong & Randolph 2012; DeJong & Green, 2020), the results suggest that different penetration rates should be tested in these materials, namely higher rates than the standard 2 cm/s. Only this test would confirm the actual existence of partial consolidation during penetration and the adequacy of the criteria used to assess it. Based on the data presented, because no distinction was observed between different deposition methods, the above suggestion is also valid for thickened and filtered tailings.

References

ASTM International 2006, *D 2487-06. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)*, West Conshohocken.

Ayala, J, Fourie, AB & Reid, D 2023 'A Unified Approach for the Analysis of CPT Partial Drainage Effects within a Critical State Soil Mechanics Framework in Mine Tailings', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 149, issue 6, pp. 1–14, https://doi.org/10.1061/JGGEFK.GTENG-10915

Ayala, J, Fourie, AB, Reid, D & Jefferies, M 2024, 'Inferring the state parameter from partially drained cone penetration test data using the soil behaviour-type index to adjust drained/undrained correlations', in AB Fourie & D Reid (eds), *Paste 2024: Proceedings of the 26th International Conference on Paste, Thickened and Filtered Tailings*, Australian Centre for Geomechanics, Perth, pp. 335–348, https://doi.org/10.36487/ACG_repo/2455_27

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*, no. 41, pp. 2833–2852, https://doi.org/10.1007/s10706-023-02430-8

DeJong, JT & Randolph, M 2012, 'Influence of partial consolidation during cone penetration on estimated soil behavior type and pore pressure dissipation measurements', *Journal of Geotechnical and Geoenvironmental Engineering*, no. 138, issue 7, pp. 777-788, https://doi.org/10.1061/(ASCE)GT.1943-5606.0000646

DeJong, JT & Green, KC 2020, 'Variable penetration rate CPT testing for mine tailings', *Tailings and Mine Waste 2020: Proceedings of the 24th International Conference on Tailings and Mine Waste*, University of British Columbia, Vancouver, pp. 679–694, https://tailingsandminewaste.com/2020/TMW2020_V3.pdf

Randolph, MF & Hope, S 2004, 'Effect of cone velocity on cone resistance and excess pore pressures', *Proceedings of International Symposium on Engineering Practice Performance Soft Deposits (IS Osaka 2004)*, Osaka, pp. 147–152.

Fourie, A, Verdugo, R, Bjelkevik, A, Torres-Cruz, LA & Znidarcic, D 2022, 'Geotechnics of mine tailings: a 2022 State of the Art', in Rahman and Jaksa (Eds), *Proceedings of the 20th ICSMGE-State of the Art and Invited Lectures*, Australian Geomechanics Society, Sydney, pp. 121–183, https://www.issmge.org/uploads/publications/1/120/20ICSMGE_SoA_4_Fourie_et_al.pdf

García Martínez, MF, Tonni, L, Gottardi, G & Rocchi, I 2016, 'Influence of penetration rate on CPTU measurements in saturated silty Soils', in B Lehane, HE Acosta-Martínez & R Kelly (eds), *Geotechnical and Geophysical Site Characterization 2016: 5th International Conference on Geotechnical and Geophysical Site Characterization (ISC'5)*, pp. 473–478, https://www.issmge.org/uploads/publications/25/26/ISC5_059.pdf

Hogan, AA, Kelly, SA, Sharp, JT & DeJong, JT 2025, 'A comprehensive review of field vane shear testing in mine tailings and recommendations for tailored standards', *Geotechnical Testing Journal*, no 48, issue 1, pp. 80–91, https://doi.org/10.1520/GTJ20240027

Jaeger, RA, Dejong, JT, Boulanger, RW, Low, HE & Randolph, M 2010, 'Variable penetration rate CPT in an intermediate soil', Proceedings of the *2nd International Symposium on Cone Penetrometer Testing (CPT'10)*, Huntington Beach, https://www.geoengineer.org/storage/publication/18393/publication_file/2632/50Jaevpr.pdf

Jefferies, M & Been, K 2016, *Soil Liquefaction: A Critical State Approach*, 2nd edn, CRC Press, New York.

Krage, CP, Broussard, NS & DeJong 2014, 'Estimating rigidity index (IR) based on CPT measurements', Proceedings of the *3rd International Symposium on Cone Penetration Testing (CPT'14)*, Las Vegas, pp. 727–735.

Lunne, TL, Robertson, PK & Powell, JJM 1997, *Cone Penetration Testing in Geotechnical Practice*, EF Spon/Routledge, New York.

Mayne, PW, Cargill, E & Greig, J 2023, *The Cone Penetration Test: Better information, Better Decisions. A CPT Design Parameter Manual*, ConeTec, viewed 22 October 2025, https://lankelma.com/img/ConeTec_CPT_Design_Manual-2023_First_Edition-2023-04-24_rev1.1_EN.pdf

Mayne, PW & Peuchen, J 2018, 'Evaluation of CPTU N_{kt} cone factor for undrained strength of clays', in Hicks, Pisanò & Peuchen (eds), Proceedings of the *4th International Symposium on Cone Penetration Testing (CPT'18)*, Delft, pp. 423–429, https://www.taylorfrancis.com/reader/download/1adf60b4-5643-4a64-9e20-f6477505874a/chapter/pdf?context=ubx

Parez, l & Fauriel, R 1988, 'Le piézocône. Améliorations apportées à la reconnaissance de sols', *Revue Française de Géotechnique*, no. 44, pp. 13-27, https://doi.org/10.1051/geotech/1988044013

Reid, D 2016, 'Effect of rotation rate on shear vane results in a silty tailings', in B Lehane, HE Acosta-Martínez & R Kelly (eds), *Geotechnical and Geophysical Site Characterization: Fifth International Conference on Geotechnical and Geophysical Site Characterization (ISC'5)*, pp. 369-374, https://www.issmge.org/uploads/publications/25/26/ISC5_042.pdf

Robertson, PK 2009, 'Interpretation of cone penetration tests—a unified approach', *Canadian Geotechnical Journal*, vol. 46, issue 11, pp. 1337–1355, https://doi.org/10.1139/T09-065

Robertson, PK & Cabal, K 2022, *Guide to Cone Penetration Testing*, 7th edn, Gregg Drilling LLC, Signal Hill, viewed 22 October 2025, https://www.cpt-robertson.com/PublicationsPDF/CPT-Guide-7th-Final-SMALL.pdf

Schnaid, F 2021, 'The ninth James K. Mitchell lecture: on the geomechanics and geocharacterization of tailings', *Geotechnical and Geophysical Site Characterization 2020: Proceedings of the 6th International Conference on Geotechnical and Geophysical Site Characterization (ISC'6)*, Budapest, https://doi.org/10.53243/ISC2020-501

Schneider, JA, Randolph, MF, Mayne, PW & Ramsey, NR 2008, 'Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters', *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 134, issue 11, https://doi.org/10.1061/~ASCE!1090-0241~2008!134:11~1569!

Teh, CI & Houlsby, GT 1991, 'An analytical study of the cone penetration test in clay', *Geotechnique*, vol. 41, issue 1, pp. 17–34, https://doi.org/10.1680/geot.1991.41.1.17

Vick, GS 1990, *Planning, Design, and Analysis of Tailings Dams*, BiTech publishers, Vancouver.

Wiklund, V 2024, *On Cone Penetration Tests in Tailings: The need for a calibration chamber*, PhD thesis, Luleå University of Technology, Luleå.