A Framework for Interpreting Variable Penetration Rate CPTu Tests in Mine Tailings

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Abstract

Cone penetration testing with pore pressure measurements (CPTu) is widely used in tailings engineering, but interpreting results when penetration occurs under partially drained conditions remains challenging. This study presents variable-penetration-rate CPTu tests performed at 0.2, 2, 10, and 15 cm/s in a tailings storage facility containing both conventional and thickened tailings. Complementary measurements, including shear-wave velocity, dissipation tests, vane shear tests, and laboratory triaxial tests, support the assessments. Conventional tailings exhibit greater variability than thickened tailings because segregation and layering lead to a broader range of partially drained responses. The field data also illustrate the uncertainty involved in defining drained and undrained reference conditions using feasible penetration rates. To address these challenges, a framework is presented that integrates variable-rate field testing, laboratory-calibrated critical-state modeling, and large-deformation numerical simulations of CPTu penetration. At representative depths, the framework constrains the state parameter, the operative coefficient of consolidation, and plausible backbone rate-effect curves. The resulting interpretation provides a systematic basis for evaluating variable-rate CPTu tests in mine tailings and for reducing uncertainty in parameters used in engineering assessments.

Introduction

Cone penetration testing with pore-pressure measurements (CPTu) is a central tool for characterizing mine tailings. Standard CPTu testing is commonly performed at a penetration rate of 2 cm/s. At this rate, sandy soils with high coefficients of consolidation tend to respond in a drained manner, whereas clayey soils with low coefficients of consolidation tend to respond in an undrained manner. Mine tailings frequently fall between these extremes. Their response may be partially drained and may depend on cone geometry, penetration rate, hydraulic properties, stress state, and mechanical properties (Oliveira et al., 2011; DeJong et al., 2012; Dienstmann et al., 2018; Ayala et al., 2023).

Partially drained penetration complicates CPTu interpretation because conventional correlations are often developed for drained or undrained reference conditions. Tailings also differ from many natural soils because their angular particles, compressible fabrics, depositional processes, and spatial variability may influence the strength-dilatancy response mobilized during penetration (Macedo & Vergaray, 2022; Macedo et al., 2024). Variable-rate CPTu testing offers a practical means to assess these effects by varying the CPTu penetration rate and compiling information on the associated responses.

This paper presents field observations from an active tailings storage facility (TSF) containing conventional and high-density thickened tailings, hereafter referred to as thickened tailings. The two deposits provide an opportunity to compare rate effects across different depositional methods. The paper then presents a framework that combines field data, laboratory testing, and large-deformation numerical simulations to constrain the tailings state, the operative coefficient of consolidation, and plausible backbone rate-effect curves. The paper is intentionally focused on the interpretation workflow and the engineering insights obtained from the case study. Additional details on how to interpret variable-rate CPTu data can be found in Macedo and Cornejo (2026).

Variable-Rate CPTu Interpretation

A useful basis for interpreting partially drained CPTu responses is the normalized penetration rate, V_h, and the normalized cone resistance, Q:

$$V_h = vd/c_h$$

$$Q = (q_t - \sigma_v)/\sigma'_v$$

where v is penetration rate, d is cone diameter, c_h is the horizontal coefficient of consolidation, q_t is corrected cone resistance, and σ_v and σ'_v are the total and effective vertical stresses. In loose contractive materials, Q generally approaches a maximum drained value, Q_D, at low V_h and a minimum undrained value, Q_U, at high V_h. Dilative materials show the opposite trend. The transition between these end states forms a backbone rate-effect curve. For natural soils, drained and undrained reference conditions are commonly separated by two to three orders of magnitude in V_h (DeJong & Randolph, 2012; DeJong et al., 2012).

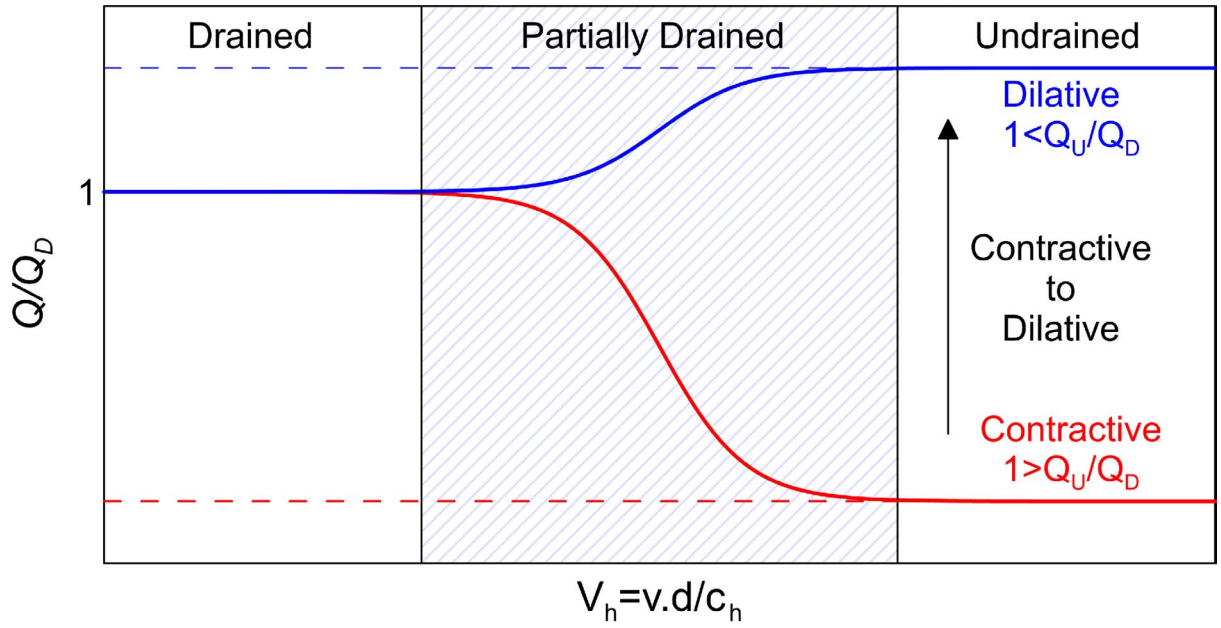


Figure 1: Schematic illustration of drainage effects on normalized CPTu resistance in contractive and dilative materials

Field-scale studies of variable-rate CPTu testing in tailings remain limited. Oliveira et al. (2011) examined silty tailings using a miniature cone in centrifuge tests. Dienstmann et al. (2018) evaluated field data from a gold-tailings facility and highlighted the influence of stiffness and strength on the drained-to-undrained resistance ratio. Schnaid et al. (2020) proposed an alternative velocity normalization that reduces reliance on a directly estimated coefficient of consolidation, and Dienstmann et al. (2024) further examined inherited variability. These studies establish a foundation but also show that the field response can remain difficult to interpret when the available rates do not clearly reach both drainage end states.

Site Investigations

Tailings Deposits and Testing Program

The investigated TSF is associated with a gold mine that has produced and deposited tailings since the 1990s. Conventional tailings were deposited from 1990 to 2010 at a solids content of approximately 35%. Thickened tailings have been deposited subsequently at a solids content of approximately 65%. Both deposits are low-plasticity silts with fines contents generally exceeding 70% and plasticity indices between 0% and 2%. The thickened tailings exhibit a narrower particle-size distribution range, consistent with their lower tendency to segregate.

Table 1: Average Particle-Size Distribution Properties and Atterberg Limits for Conventional and Thickened Tailings

Property	Conventional Tailings	Thickened Tailings
Sand fraction (%)	28.70	24.70
Silt fraction (%)	67.70	70.90
Clay fraction (%)	3.60	4.40
Specific gravity (Gs)	3.31	3.38
Limit limit (LL)	22	22
Plasticity index (PI)	2	2

The field investigation included CPTu tests with shear-wave velocity (V_s) and compression-wave velocity (V_p) measurements, dissipation tests, vane shear tests, and borehole sampling for laboratory triaxial tests. CPTu tests were performed at the standard rate of 2 cm/s and at non-standard rates of 0.2, 10, and 15 cm/s. The variable-rate soundings were located within 1.5 m of the central standard-rate sounding. This spacing is less than half the previously estimated average horizontal correlation length of approximately 3.2 m for the deposited tailings (Macedo et al., 2024).

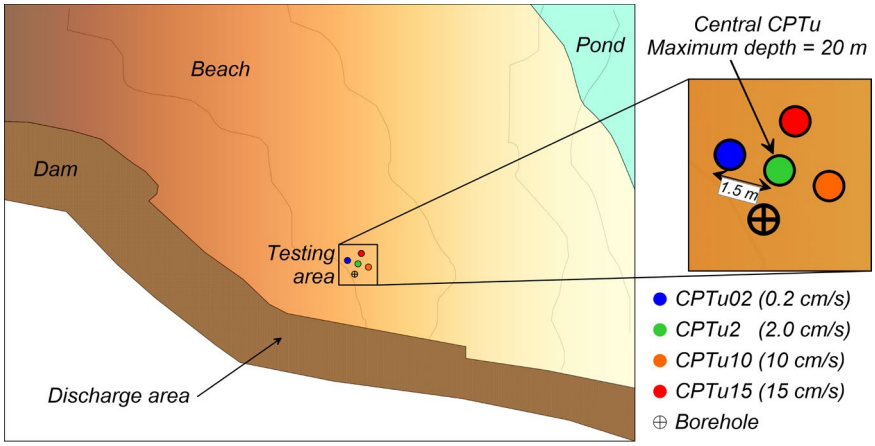


Figure 2: Layout of the variable-penetration-rate CPTu tests at the investigated TSF

General CPTu Response

The standard-rate sounding extended to a depth of 20 m. The first 2 m correspond to an access pad. Thickened tailings overlie conventional tailings, with a boundary at approximately 8.8 m. Dissipation tests indicate a groundwater level near 6 m, while V_p values become indicative of full saturation at approximately 7.5 m. The intermediate interval is likely nearly saturated. V_s values are typically around 200 m/s, reflecting the relatively soft nature of the deposited materials.

The thickened tailings are comparatively uniform, with q_t generally below 5 MPa and sleeve friction typically below 50 kPa. The conventional tailings exhibit larger and more frequent fluctuations. Their q_t values generally range from 5 to 10 MPa, and sleeve friction values typically range from 50 to 100 kPa. These contrasts are consistent with the greater susceptibility of conventional tailings to segregation and layering during deposition.

Variable-Rate Field Responses

Cone Resistance and Pore Pressure Trends

Figure 3 compares the variable-rate CPTu measurements. Within the thickened tailings, q_t for the slowest sounding, pushed at 0.2 cm/s, is approximately 4 MPa and exceeds the values recorded at faster rates. The q_t profiles at 10 and 15 cm/s are similar and are generally around 2.5 MPa, suggesting that the response approaches undrained conditions at rates exceeding 10 cm/s. However, the u_2 values from the 0.2 cm/s sounding do not fully converge to the hydrostatic profile. Thus, the thickened tailings have not clearly reached drained conditions even at the slowest field rate.

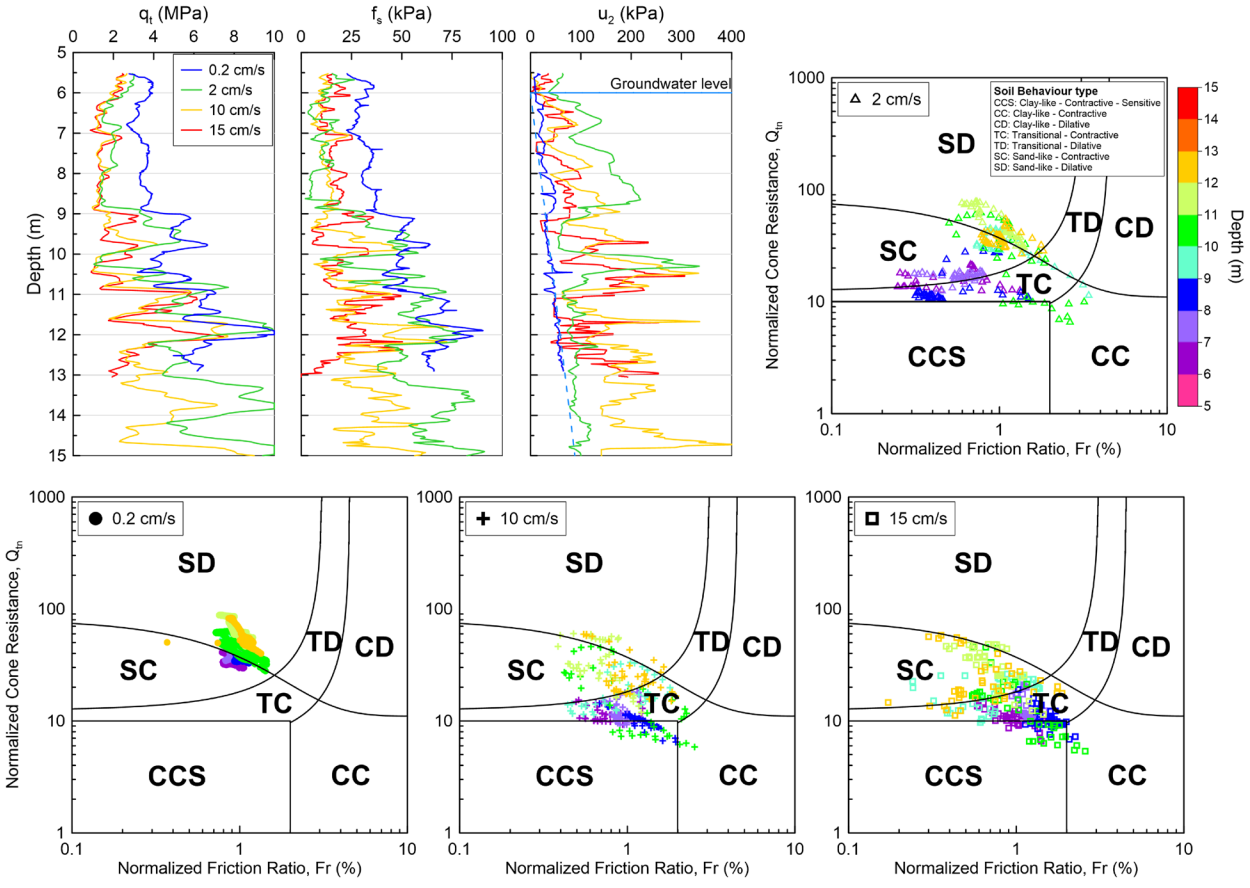


Figure 3: Variation of q_t, f_s, and u_2 for CPTu tests pushed at 0.2, 2, 10, and 15 cm/s

The conventional tailings exhibit a more complex response due to their greater layering and spatial variability. A general reduction in q_t with increasing penetration rate remains evident, but local variations complicate the definition of undrained resistance. In contrast to the thickened tailings, the u_2 measurements from the slow sounding commonly approach the hydrostatic profile, indicating that drained behavior is more plausibly reached at 0.2 cm/s. At high penetration rates, pore pressure measurements may also be affected by viscous effects, dilatancy, or limitations in the response of the pore pressure measurement system (Chow et al., 2018; Peuchen & Terwindt, 2014).

Dissipation Tests and Consolidation Estimates

Dissipation tests were conducted at selected depths in the different CPTu soundings. The higher-rate tests generally produce faster subsequent dissipation. This observation is consistent with partial consolidation during slower penetration, which can modify the initial pore pressure field and lead to a larger interpreted t_{50} than when a test is initiated under conditions closer to undrained penetration (DeJong & Randolph, 2012). The fastest soundings, therefore, provide the primary basis for interpreting t_{50}. The resulting values range from approximately 3 to 7 s in the thickened tailings and from approximately 1 to 8 s in the conventional tailings, with the lower values associated with sandier units.

Vane shear tests and laboratory triaxial tests were used to constrain operative undrained strengths. The vane shear tests suggest S_u values of approximately 50 to 70 kPa in the thickened tailings and 40 to 110 kPa in the conventional tailings. The triaxial tests indicate an S_u/σ'_v ratio close to 0.2 for both materials. Shear-wave velocity measurements were used to estimate G_{max}, with average values of approximately 65 MPa for the thickened tailings and 100 MPa for the conventional tailings.

The coefficient of consolidation was evaluated from dissipation data using approaches based on Teh and Houlsby (1991) and Mayne et al. (2023). The calculations require an operative rigidity index, $I_r = G/S_u$, and therefore depend on the modulus level adopted for the interpretation. The resulting c_h estimates span approximately one to two orders of magnitude, illustrating a key uncertainty in the direct construction of field backbone rate-effect curves.

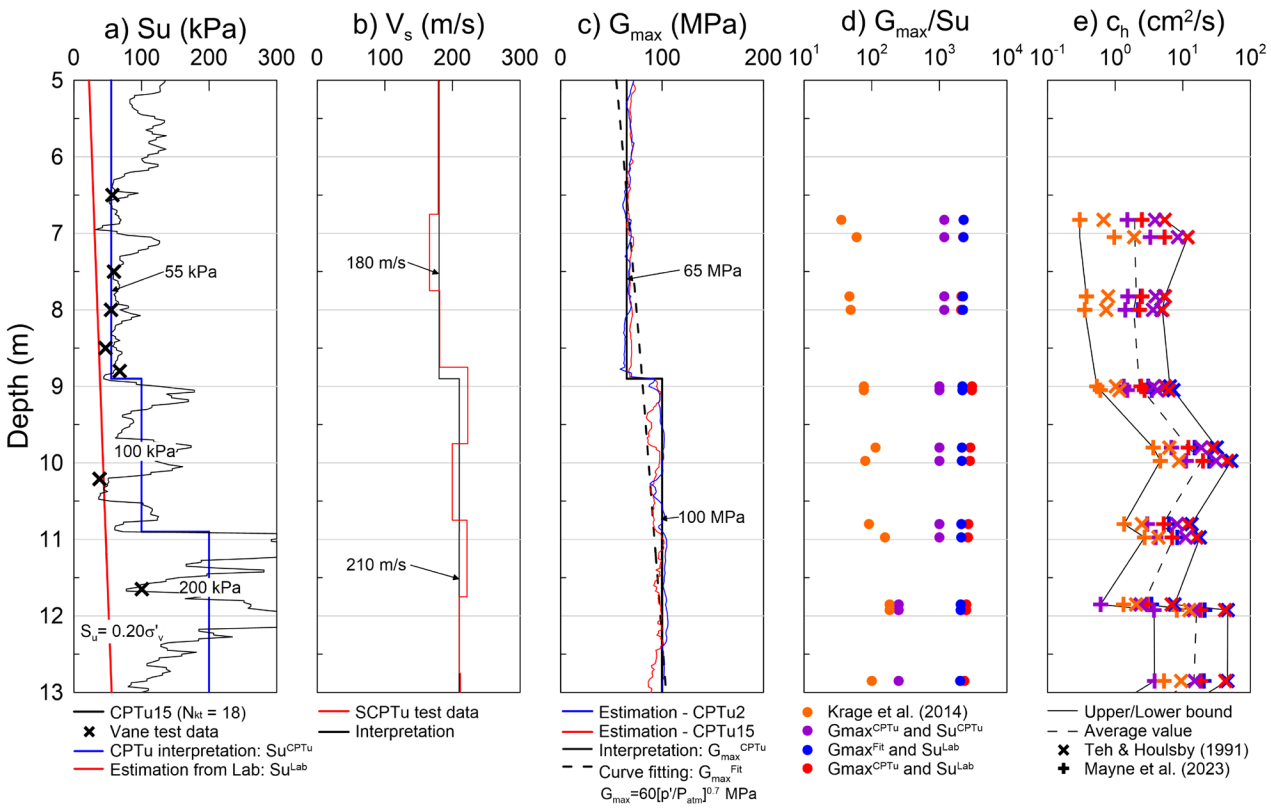


Figure 4: Variation of S_u, V_s, G_{max}, G_{max}/S_u, and c_h with depth

Field-Derived Backbone Rate-Effect Curves

Backbone rate-effect curves were constructed using the field Q values and the estimated c_h ranges. The thickened tailings are comparatively uniform, allowing the interpretation to focus on a depth interval below the groundwater table. Conventional tailings require a layer-by-layer evaluation due to their stratigraphic variability. In both deposits, Q generally decreases with increasing V_h, consistent with contractive behavior.

The curves also reveal different sources of uncertainty. For the conventional tailings, the slowest sounding reaches a drained response near $V_h = 0.1$, but fully undrained behavior may require V_h values beyond those achieved by the fastest field sounding. For the thickened tailings, undrained conditions are more clearly approached at high rates, while drained conditions would require V_h values below those reached by the slowest sounding. Consequently, field testing alone does not uniquely define the full backbone curve in either material.

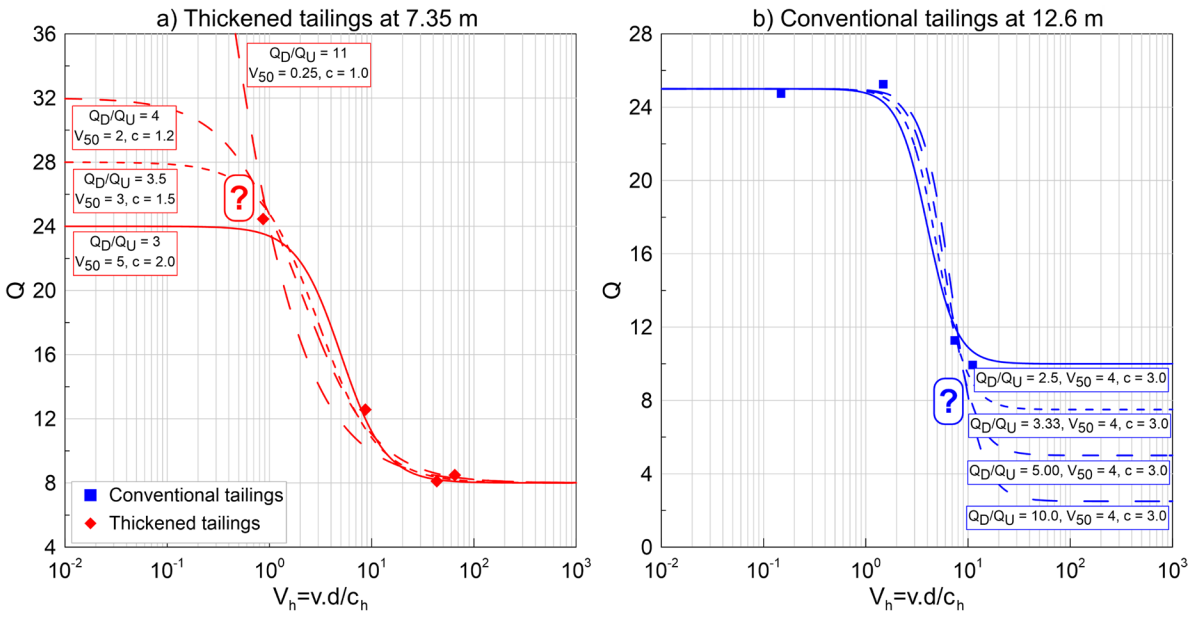


Figure 5: Plausible field-derived backbone rate-effect curves at representative depths in the thickened and conventional tailings

Framework for Interpreting Partially Drained Responses

Overview

Figure 6 summarizes the proposed framework. The procedure integrates field characterization, laboratory testing, and numerical simulations of the CPTu penetration process. Its purpose is not to eliminate uncertainty, but to identify a defensible range of tailings states and operative consolidation parameters that are consistent with the measured variable-rate response.

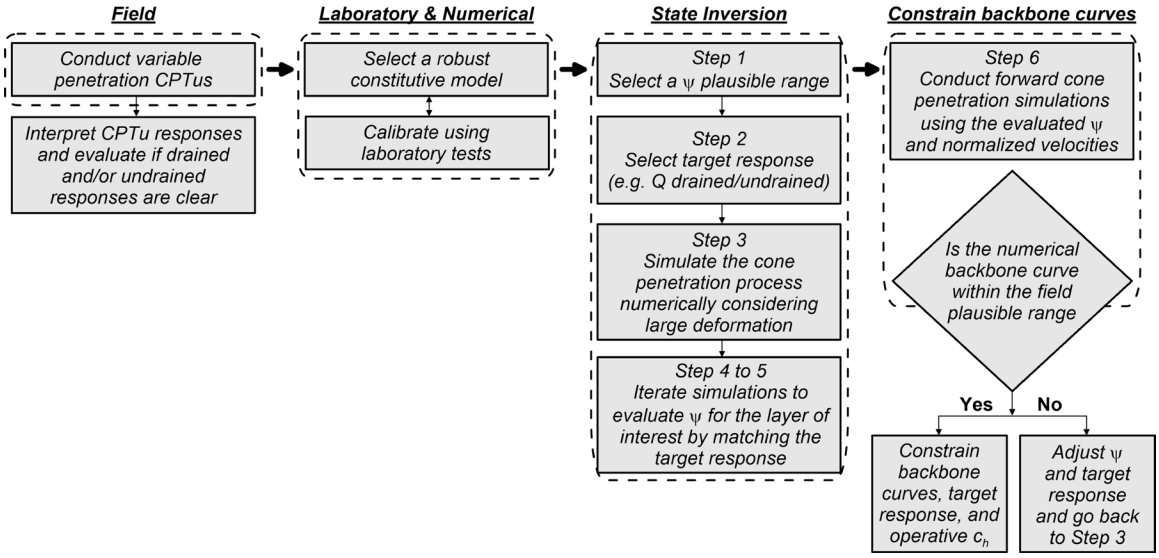


Figure 6: General framework for interpreting partially drained CPTu responses

The interpretation follows six steps: (1) define a plausible range of state parameter, ψ, and identify the drainage end state that is most reliably constrained by the field data; (2) select the corresponding target resistance, Q_D or Q_U; (3) conduct simulations at the bounds of the plausible ψ range; (4) compare the computed resistance with the field target and update ψ by interpolation; (5) repeat the process until the selected end-state resistance is matched; and (6) simulate partially drained conditions and confirm that the resulting numerical backbone curve falls within the plausible field-derived range. The simulations can also narrow the operative c_h range.

Large-Deformation Simulations and Constitutive Calibration

The numerical calculations use the particle finite element method (PFEM), which is well-suited to insertion problems involving large deformations. The simulations follow the geotechnical PFEM framework described by Monforte et al. (2018, 2021). The Clay and Sand Model (CASM) proposed by Yu (1998) is used to represent the tailings. CASM extends critical-state concepts by incorporating ψ, defined relative to the critical-state line (Been & Jefferies, 1985).

CASM parameters were calibrated using laboratory triaxial data from representative depths in the thickened and conventional deposits. The tests capture contractive, partially softening, limited-flow, and dilative patterns. The calibrated model reproduces the principal laboratory trends and provides the constitutive basis for CPTu penetration simulations.

Table 2: Calibrated CASM Parameters for Representative Thickened and Conventional Tailings

Parameter	Thickened Tailings	Conventional Tailings
Γ	2.174	2.217
λ	0.065	0.068
κ	0.032	0.034
M_{tc}	1.55	1.55
n	1.50	1.50
r	6.80	6.00
m	2.40	2.40
ψ_r	0.10	0.09
G	14 MPa	14MPa

Axisymmetric simulations were performed for representative depths of 7.35 m in the thickened tailings and 12.60 m in the conventional tailings. The cone advances at 2 cm/s, while hydraulic conductivity is varied to represent V_h values from 0.01 to 1000. The calculations, therefore, simulate conditions ranging from drained to undrained penetration while retaining the same mechanical model and stress state.

Illustrative Inversion and Constrained Interpretations

For the thickened tailings, Q_U is used as the primary target because the undrained reference condition is better constrained. For the conventional tailings, Q_D is used because the drained reference condition is more reliable. For both representative depths, an initial ψ range from 0.00 to 0.05 brackets the field target. Interpolation of the numerical results leads to $\psi = 0.025$ at both depths.

Additional simulations across the partially drained range are then compared with the field-derived curves. Figure 7 shows that the numerical curves substantially narrow the plausible field range while remaining consistent with the measurements. The simulations constrain the operative c_h to approximately 1.5 cm²/s for the thickened tailings at 7.35 m and 4.5 cm²/s for the conventional tailings at 12.60 m. The interpreted partially drained ranges are V_h = 1 to 30 for the thickened tailings and V_h = 2 to 100 for the conventional tailings. The resulting Q_D/Q_U ratios are approximately 3.2 and 3.0, respectively.

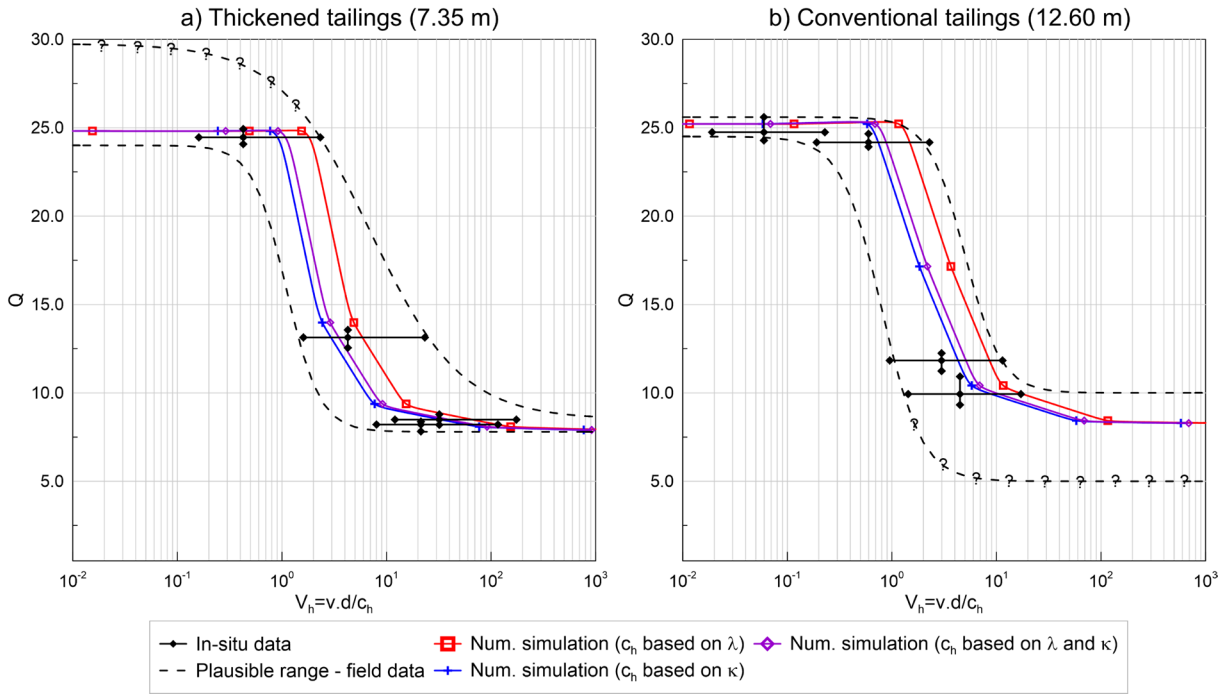


Figure 7: Numerical Constraints on Field-Derived Backbone Rate-Effect Curves at Representative Depths

Discussion

The case study demonstrates that variable-rate CPTu interpretation in tailings is controlled by both drainage effects and the material's depositional fabric. Conventional tailings are more difficult to interpret because segregation and layering increase the variability of q_t and u_2, thereby broadening the plausible backbone curves. Thickened tailings are more uniform but may require penetration rates below 0.2 cm/s to reach a confidently drained reference condition.

The results also illustrate why a single penetration rate is not sufficient for robust interpretation of intermediate tailings. A testing program should select rates that are expected to bracket drained and undrained behavior based on preliminary estimates of c_h and should include dissipation tests at multiple rates. Care is required when interpreting pore pressure measurements at the fastest rates because measurement-system response and rate-dependent material effects may influence u_2.

The numerical component provides an additional constraint when the field rates do not capture both drainage limits. The framework is not restricted to CASM or PFEM. Other critical-state models and large-deformation schemes may be used, provided that laboratory data and the numerical method support the constitutive parameters that can represent the CPTu penetration process without relying on uncertain mapping factors. Spatial variability should also be considered when extending the interpretation beyond representative layers.

Conclusion

Variable-penetration-rate CPTu tests at 0.2, 2, 10, and 15 cm/s were used to investigate partially drained behavior in conventional and thickened mine tailings. The field response differs between the two deposits because their depositional methods produce contrasting degrees of segregation and layering.

Conventional tailings show greater variability and a broader range of plausible backbone rate-effect curves. Their drained reference response is more readily identified at the slowest penetration rate, but their undrained resistance remains uncertain. Thickened tailings are more uniform and approach undrained conditions at the fastest rates, but their drained response is not fully reached at 0.2 cm/s.

The proposed framework integrates variable-rate field testing, complementary laboratory testing, and large-deformation numerical simulations. In the illustrative applications, the framework constrains ψ, c_h, the partially drained V_h range, and Q_D/Q_U. The approach provides a systematic basis for interpreting variable-rate CPTu data when feasible field penetration rates do not uniquely define drained and undrained reference conditions.

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