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BAUXITE RESIDUE: A DATA-DRIVEN APPROACH TO STRENGTH CHARACTERISATION

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Cone penetration, pore pressure dissipation, and vane shear tests are commonly employed to gauge the state and potential response of saturated tailings. This paper illustrates cone penetration-derivedstate and strength characterization for bauxite residue deposited in a Tailings Storage Facilities. It presents the application of a model to predict normalized peak undrained shear strength based onthe net cone factor which was evaluated on mean absolute errorand correlation coefficient.Cone penetration, pore pressure dissipation and vane shear tests were conducted in near embankment residue.The state parameter was estimated based on a single set of presumed critical state parameters, as proposed by Plewes et al. (1992). The drainage boundary conditions were evaluated following the methodology proposed by Schneider et al. (2008). The general behavior of the residue was assessed in terms of the SBT indices proposed by Robertson (2016) and Jefferies and Been (2016).Using calibrated net cone factor, peak undrained strengthwas predicted from the empirical correlation between corrected cone resistance and total vertical stress whilenormalized peak undrained shear strength wasassessed in terms of state parameter. Peak undrained strength was measured by triaxial testing and estimated considering the theoretical formulation proposed by Wroth (1984).Characteristic strength was derived by statistical analysis of the state observed within the near embankment residue.

Keywords: peak undrained shear strength ratio; machine learning; data-driven; red mud, bauxite residue; cone penetration test; tailings behaviour; NorSand

1. Introduction

Red mud residue is a waste product of the bauxite refining process to extract aluminawhich is traditionally stored within Tailings Storage Facilities due to the large volume of waste produced during refinement. Characterization of undrained shearstrength -as influencedby in situ state and imposed boundary and loading conditions -is essential for evaluating the stability of residue containing Tailings Storage Facilitiesembankments.

One methodfor assessing the in-situ state, behavior, and strength of the residue is through field testing, which provides valuable data for understanding in-situ conditions.Commonly employed are cone penetration (CPT) associated with pore pressure dissipation (PPD), and vane shear (VST) tests.Another method relies on the derivation of representative properties based on laboratory data and theoretical formulations.

This paper presentsresiduestrength characterizationexpressed in terms of in-situ state parametersobtained from CPTand VST probing of near embankment residueand CIU testing of the residue compared to the theoretical variation of strength across a range of state parameters.In this case study, the residue deposition varied between predominately sub-aqueous to sub-aerial.

2. Residue classification and CPT drainage response

Theresidue herein presented is a silt-clay-sized (40% clay, 60% silt) material with significant variation in specific gravity (2.66-3.58). Its plasticity index ranges from 9% to 21%, which characterizes the material as low to medium plasticity. The utilized dataset derives from CPTand associated VST probing.The unit weight adopted for stress calculation was calibrated against the bulk density obtained from undisturbed samples at depth. Determination of equilibrium pore water pressure was based on PPD tests.

In terms of the methodology proposed by Schneider et al. (2008), the probing profiles presented predominantly undrained responsesduring penetration. In terms of Robertson's (2016) classification, the residue responds asclay-like contractive,sensitive.

3. Strength characterization

3.1. Critical state

At the critical state, soil continues todistort at constant shear stress, normal stress and void ratio (Atkinson, 2007). The projection of the critical state locus (CSL) onto void ratio(e) – mean effective stress (p') space is given by Eq. 1 which relates void ratio (e_c)to mean effective stress (p'_c) at the critical state. • , the void ratio at reference p'_c of 1 kPa and slope $»_e$ (referenced to natural log base) are intrinsic properties and were determined through triaxial testing of the residue as 2.133 and 0.172 respectively.

$$e_c = \Gamma - \lambda_e \ln\left(p'_c\right) \qquad (1)$$

3.2. In-situ state

The state parameter (È) is the difference between the current void ratio (e) and e_c at the same p'. Plewes et al. (1992) proposed that in-situÈ be estimated as follows from CPT probing data:

$$\psi = \ln\left[\frac{Q'_p}{M_{tc}\left(3 + \frac{0.85}{\lambda_{10}}\right)}\right]\left(\frac{1}{13.3\lambda_{10} - 11.9}\right) \qquad (2)$$

where:

$$Q'_p = Q_p\left(1 - B_q\right) + 1 \qquad (3)$$

$$Q_p = \frac{q_t - p_0}{p'_0} \qquad (4)$$

and M_{tc} is the critical friction ratio referenced to triaxial compression taken as 1.417, Q'pis normalized effective tip resistance, B_q is normalized excess pore water pressure and q_t is corrected cone tip resistance. Torres-Cruz (2021) pointed out that the "Plewes method"is a screening tool withan uncertainty level of 0.06 (±0.03).For the probing profiles herein considered, a value of 1 for the horizontal stress ratio (K_0) was adopted to calculate p_0 and p'_0.

Figure 1 presents the variation of in-situ Èwith vertical effective stress ($Ã•_v$) and a histogram and cumulative distribution function (CDF) of È. The 5th and 95th fractilesof Èare 0.03 and 0.31 respectively with COV of 34%. The residue is predominantly contractive for$Ã•_v$>50 kPa. The similarity between $È_{mean}$ (H 0.19) and the boundary separating •over consolidated• from •normally consolidated• states at È = 0.12 (where 0.12 = 0.7 $»_e$ according to Jefferies and Been, 2016) suggests that the residue is normally consolidated at depth.

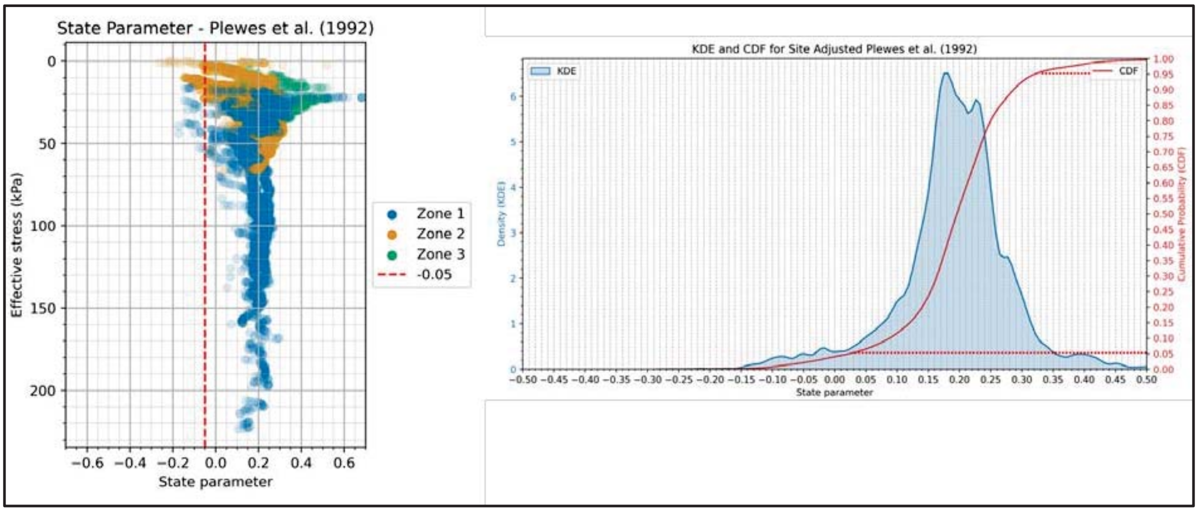

Fig. 1. Distribution of state parameter based on Plewes et al. (1992)

3.3. Peak undrained shear strength derived from CPTu test

Peak in-situ undrained shear strength (s_u) relates to q_t and total vertical stress ($Ã_v$) via the net cone factor (N_{kt}) as indicated in Eq. 5.

$$s_u = \frac{q_t - \sigma_v}{N_{kt}} \qquad (5)$$

N_{kt} was estimated as 12 by calibration of VST results in accordance with Lunne et al. (1997). The linear regressionmodel was calibrated considering an 80% train and 20% test split ratio.The train and test components were evaluated through the coefficient of determination (R^2) and mean absolute error (MAE) according to Eq. 6 and Eq. 7 respectively. R^2 is commonly used to evaluate how well the adopted fit represents the data variability, ranging from 0 to 1. MAE is used to assess the average error by comparing the predicted values with the real values.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_{i,observed} - y_{i,predicted})^2}{\sum_{i=1}^{n}(y_{i,observed} - y_{i,mean})^2} \qquad (6)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_{i,observed} - y_{i,predicte\ d}\right| \qquad (7)$$

Based on the values of R^2 and MAE, the bestfitsresult for N_{kt}= 12 with R^2values of 0.73 and 0.80 and MAEvalues of 3.57 and 3.27 kPa respectively for the train and test sets (see Figure 2).The relative convergence of R^2 and MAE between the train and test datasetsindicatesthat the fits are of relatively high quality. The corresponding MAE value of 3.27 kPa is low in relation to the observed distribution of in situ s_u.

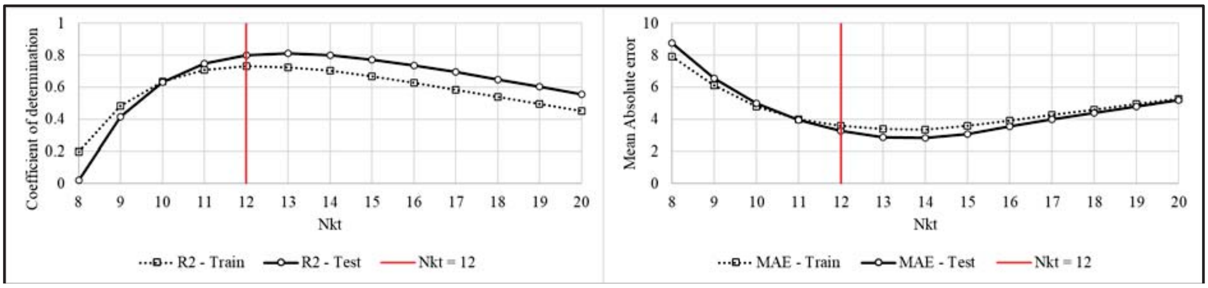

Fig. 2. Nkt model calibration

3.4. Peak undrained shear strength

Wroth (1984), derived a relationship forpeak undrained shear strength ratio (s_u/p'_0)as provided by Eq. 8:

$$\frac{s_u}{p'_0} = \frac{M_{tc}}{2}\left(\frac{R}{r}\right)^{\Lambda} \qquad (8)$$

where › = (1 – º/»$_e$). For the residue, º (average slope of the unload-reloadrelationships) was found equal to zero, thereby reducing › to 1. Settingr = 2as suggested byWroth (1984), R = 1 for a normallyconsolidationstate andM_{tc} = 1.417, s_u/p'_0 = 0.35which approximately equals to the average for three CIU tests.The residual undrained shear strength ratio (s_r/p'_0) is given by Eq. 9(Jefferies and Been, 2016):

$$\frac{s_r}{p'_0} = \frac{M_{tc}}{2}\exp\left(\frac{\psi_0}{\lambda_e}\right) \qquad (9)$$

By setting equation 8 equal to equation 9and rearranging, it follows that

$$r = \exp\left(\frac{\psi_0}{\lambda_e}\right) \qquad (10)$$

r was evaluated by Monte Carlo simulation for normal distributions of »$_e$ and È$_0$ (mean and COV values respectively 0.172, 0.1 and 0.19, 0.1).Theresulting distribution of rwas used to calculates$_u$/p'$_0$and È$_0$from equations 8 and 10 respectively.The average r was found to be approximately 3.1.

4. Discussion

Figure 3 shows s_u/p'_0 = 0.35, È$_0$ = 0.12, and the standard width zones for $s_u/p'_0$and È$_0$based on the distributions of r obtained from the Monte Carlo simulation, and s_r/p'_0 as provided by Eq. 9. Figure 3 also shows coordinate pairs from a contour plot of (s_u/Ã•$_v$; È$_0$),from CPT (N_{kt})and VST field investigations and CIU tests. The highest concentration of (s_u/Ã•$_v$; È$_0$) coordinate pairsis indicated in red.

Mean s_u/Ã•$_v$(0.26) and È$_0$(0.19) indicated by the redtriangle in Figure 3for average simulated r,suggest that the intersection of the undrained yield strength (s_u/Ã•$_v$) is somewhat lower than that estimated by equation 8 for r =2. Also, the value of È$_0$beyond which brittleness (strain softening) sets in –normal consolidated limit - is somewhat more positive than estimatedby the usual È$_0$ = 0.7 »$_e$ (Jefferies and Been, 2016).

The zone bounded by the one standard deviation limit (green square with a continuous linein Figure 3) intersects the highest concentration of (s_u/Ã•$_v$; È$_0$) coordinate pairs. This zone also straddles mean s_u/p'_0 from the VST and CIU testing.

For a cautious estimate of average r (3.1),the selection of s_u/Ã•$_v$= 0.22 as a characteristic value, is credible in relation to the CPTu and VST field- and laboratorydata depicted in Figure 3.

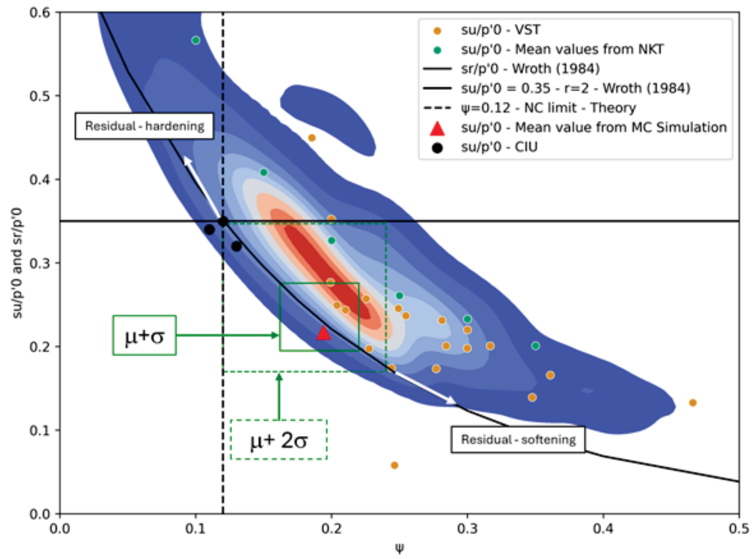

Fig. 3. Peak undrained shear strength ratio from CPT, VST, and critical state theory vs È

5. Conclusion

The residue characterized in this paper is a silt-clay-sized material of medium plasticity. It presents a predominantly undrained response to CPT probing and is characterized as clay-like contractive, and sensitive.È$_0$derived from CPT probing data ranged from 0.03 (5% fractile) to 0.31 (95%fractile) with a mean value of 0.19 and COV of 34%. The deposited, unconsolidated residue is generally normally consolidated.

For N_{kt}= 12, the train and test regression components were0.73 and 0.80 (R^2),and 3.51 kPa and 3.27 kPa(MAE) respectively. The resultings$_u$/Ã•$_v$values derived from CPTu and VST probing show significantvariation when analyzed in terms of È$_0$, which can result in non-cautious estimates of s_u/Ã•$_v$if the entire dataset is considered. The ranges of s_u/Ã•$_v$ and È$_0$up two standard deviations from the respective means, were determined by Monte Carlo simulation to obtain r based on normal distributions of »$_e$ and È$_0$. These ranges were taken as bounds to CPTu derived s_u/Ã•$_v$ for normally consolidated material states.A s_u/Ã•$_v$ value of 0.22was derived as a credible characteristic value.

A data-driven approach to the assessment of the distribution of Èwithin a bauxite residue Tailings Storage Facilitiesand commensurate selection of characteristic normalized peak undrained strength, in terms of È, was outlined.

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