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A review of CTP-based soil classification correlations applied to mine tailings

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ABSTRACT

The cone penetration test (CPT) has been widely used in Chile in the last decade, being one of the preferred tests on mining waste, highlighting its application in tailings. One of the primary uses of CPTs lies in assessing soil type and stratigraphy, however most of the existing correlations widely used in practice were not calibrated for these heterogeneous manmade soils and do not differentiate if soil is in a saturated state or not.

In this paper, the CPT-based soil classification correlations proposed by Robertson (1990), Jefferies & Davies (1991), Eslami & Fellenius (1997), Shuttle & Cunning (2008), Robertson (2010), and Robertson (2016) are evaluated using real CPT data from copper mine tailings. Each estimation is compared with the Unified Soil Classification System (USCS) results obtained in the laboratory from MOSTAP samples collected from twin boreholes associated with each CPT.

Sands are typically classified accurately by most methods, although it should be noted that there are relatively few sandy samples in analysis. The methods proposed by Robertson (2010, 2016) and Eslami & Fellenius (1997) consistently yield reliable classifications. Soils classified as low plasticity silts are not consistently grouped clearly in the classification charts, but the charts by Robertson (2010) and Eslami & Fellenius (1997) appear to distinguish these soils more effectively. Based on the results, it is observed that the degree of saturation does not have a major impact on the precision of the different methodologies in estimating soil type.

INTRODUCTION

In Chile, several mining companies are employing the Cone Penetration Test (CPT) to characterize and understand the geotechnical behavior of mine tailings for subsequent engineering design stages. The CPT offers significant advantages over traditional field methods such as the Standard Penetration Test (SPT), as it is repeatable, continuous, and easier to perform at depths below 30 meters, among other benefits.

Nonetheless, while the SPT can obtain samples through the test and compare the obtained number of blows with the type of soil, the CPT measures the response of the soil to an applied displacement without knowing the type of soil (and its properties) since no sample is obtained from the test. Hence, the interpretation of CPT (as well as almost any in-situ test) becomes an inverse boundary value problem (BVP), i.e., a mathematical problem that involves determining the properties or parameters of a system based on the boundary conditions or constraints imposed on the system.

Most guidelines therefore recommend complementing CPT tests with laboratory tests to measure index properties, ideally from samples obtained from twin boreholes. However, this is not always feasible, usually due to economic constraints, and the designer must then rely directly on the CPT correlations.

One of the first and most studied CPT-based correlations is soil classification. However, while soil is usually classified based on grain size distribution and plasticity in the laboratory, determining soil type from field tests relies on the response to penetration, presenting some challenges. Indeed, empirical correlations used to determine soil type from CPT data could exhibit significant uncertainty and scattering when compared to laboratory tests on the same soil, especially if the user does not consider the assumptions made by the author(s) who proposed these correlations.

In this paper, the CPT-based soil classification correlations proposed by Robertson (1990), Jefferies & Davies (1991), Eslami & Fellenius (1997), Shuttle & Cunning (2008), Robertson (2010), and Robertson (2016) are evaluated using real CPT data from copper mine tailings. Each estimation is compared with the Unified Soil Classification System (USCS) results obtained in the laboratory from MOSTAP samples collected from twin boreholes associated with each CPT. The results are then analyzed and discussed to evaluate prediction accuracy and the factors influencing the outcomes of the correlations.

CTP-BASED SOIL CLASSIFICATION CORRELATIONS

As identified by Robertson (2016), one of the primary applications of the CPT is to determine soil stratigraphy as well as soil type. Several correlations exist in the literature where soil is classified using parameters derived from the fundamental outcomes of the CPT, such as cone resistance (q_c), sleeve resistance (f_s), and dynamic pore water pressure (u_2). However, most modern expressions use q_t instead of q_c, since it includes the correction factor for the area of the cone (a) as well as the effect of the dynamic pore pressure, being defined as follows:

$$q_t = q_c + u_2 \cdot (1 - a) \tag{1}$$

Robertson (2016) demonstrated that for fine-grained soils, such as tailings, better results are obtained when shear wave velocity tests and pore water pressure dissipation tests are added. These tests are typically assumed to incorporate possible sources of error into the estimations. Indeed, dissipation tests are crucial for assessing the hydrostatic pore water pressure profile (u_0), which is used in many calculations. On the other hand, another relevant parameter is the soil's unit weight (γ), which is typically assumed to be constant with depth and is essential for determining the vertical in-situ stress (σ_{v0}) for subsequent calculations.

Robertson (1990)

This classification is primarily based on the normalized tip resistance (Q_t) and the normalized excess pore pressure $\left(B_q\right)$. Among the assumptions, the soil's unit weight and hydrostatic pore water pressure must be considered to ensure a reliable estimation. Robertson (1990) proposed the use of normalized and dimensionless parameters for the classification charts, including:

$$Q = \frac{q_t - \sigma_{v0}}{p_a} \tag{2}$$

$$\mathrm{R_f} = \left(\frac{f_s}{q_t}\right) \cdot 100\% \tag{3}$$

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} = \frac{\Delta u}{q_t - \sigma_{v0}} \tag{4}$$

However, for the soil classification charts Robertson (1990) used the q_c/P_a vs R_f relationship. Based on this, seven types of soils were defined, ranging from sands to fine soils. However, when applied to real data, many of the estimations lie outside the domain of the defined polygons.

Jefferies & Davies (1991)

Jefferies and Davies (1991) identified that the reason for the poor performance of the $Q_t - B_q$ estimation is based on the cavitation effect and a tendency of the graph to classify soils towards wet, shallow clays:

$$Q \cdot \left(1 - B_q\right) = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \left(1 - \frac{u_2 - u_0}{q_t - \sigma_{v0}}\right) \tag{5}$$

$$F_r = \left(\frac{f_s}{q_t - \sigma_v}\right) \cdot 100\% \tag{6}$$

In this classification, an extension to the fines zone is introduced, differentiating between silts and clays. The authors acknowledge the challenge of correctly handling negative values of B_q, primarily caused by cavitation. Additionally, an area of normally consolidated soils is proposed within the expanded fine soils section of the chart.

Eslami & Fellenius (1997)

Eslami & Fellenius (1997) assert that Robertson's (1990) method of soil classification involves plotting a variable against its inverse value on graphs, which violates the fundamental rule that dependent and independent variables must be rigorously separated, thus distorting the data. An "effective" cone resistance, $q_E = q_t - u_2$, is utilized in this graph instead of the cone resistance, q_c. The diagram employs a logarithmic scale for q_E and f_s to elucidate relationships in soft, loose soils. Five types of soils are described, including collapsible-sensitive soils, soft and stiff clays or silts, silty sands, and gravelly sands. Notably, no distinction is made between silts and clays.

Shuttle & Cunning (2008)

Shuttle and Cunning (2008) uses a normalized penetration resistance parameter, $Q \cdot \left(1 - B_q\right) + 1$, which accounts for excess pore water pressure. Additionally, they incorporate soil behavior by incorporation the state parameter (Ψ) into the $Q \cdot \left(1 - B_q\right) + 1$ vs F_r plot, illustrating that the upper part of the graph corresponds to dilative soils, while the lower part could be labeled as contractive soils. Finally, the classification includes five soil types: gravelly sands, sands with some silt, silty sands, sandy silts, clayey silts, and clays, including other sensitive soils.

Robertson (2010)

Robertson (2010) is very similar to Robertson (1990); however, it incorporates the reference stress approach, normalizing the measured qt to q_{t1} as an index of soil state. Based on this, the stress-normalized CPT resistance, Q_{tn}, is given by Equations (7), (8), and (9).

$$Q_{tn} = \frac{q_t - \sigma_{v0}}{p_a} \left(\frac{p_a}{\sigma'_{v0}}\right)^n \tag{7}$$

Where,

$$n = 0{,}381 \cdot (I_c) + 0{,}05 \cdot \left(\frac{\sigma'_v}{P_a}\right) - 0{,}15 \tag{8}$$

And,

$$I_c = \sqrt{(3{,}47 - \log(Q_t))^2 + (\log(F_r) + 1{,}22)^2} \tag{9}$$

Robertson (2016)

The main difference generated in this Robertson (2016) update is based on a better understanding the soil behavior, as well as introduce a method to determine if soils have a significant microstructure, differentiating the contractive soils from the dilatant soils by the CD line. Robertson (2016) also stated that most of the exiting correlations do not fit well to soils with significant microstructure.

RESULTS

Ten CPTs were conducted on a conventional tailings impoundment with a variable depth of the water table. All these CPTs were complemented with twin boreholes, and soil samples were collected using a MOSTAP sampler, resulting in a total of 66 samples for soil classification. The Unified Soil Classification System (USCS) results indicated that 47 samples were classified as ML, 12 as SM, 5 as CL, and 2 as CL-ML. Figures 1, 2, and 3 display the results obtained for CPT1, CPT3, and CPT9, respectively.

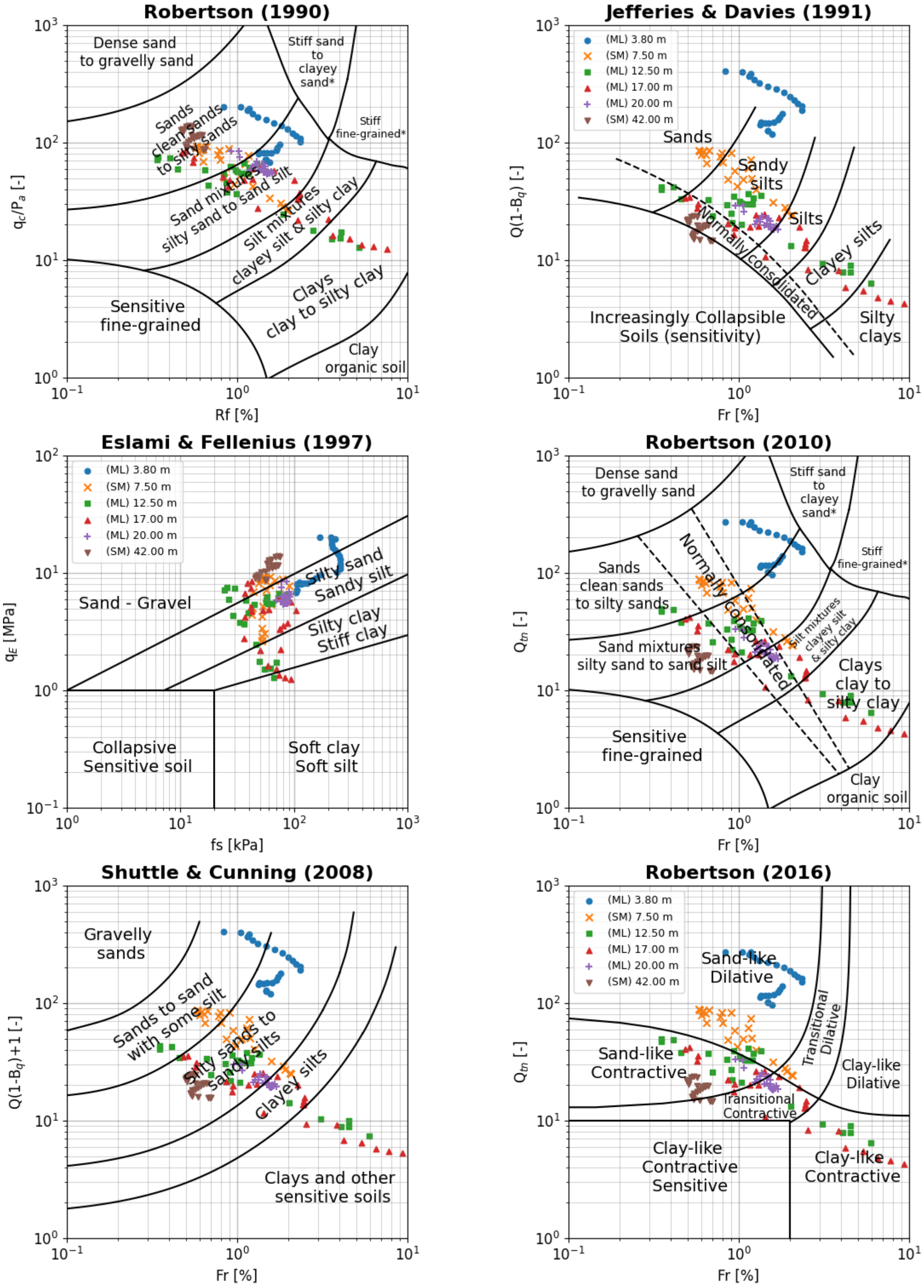


Figure 1 Soil classification results for CPT1

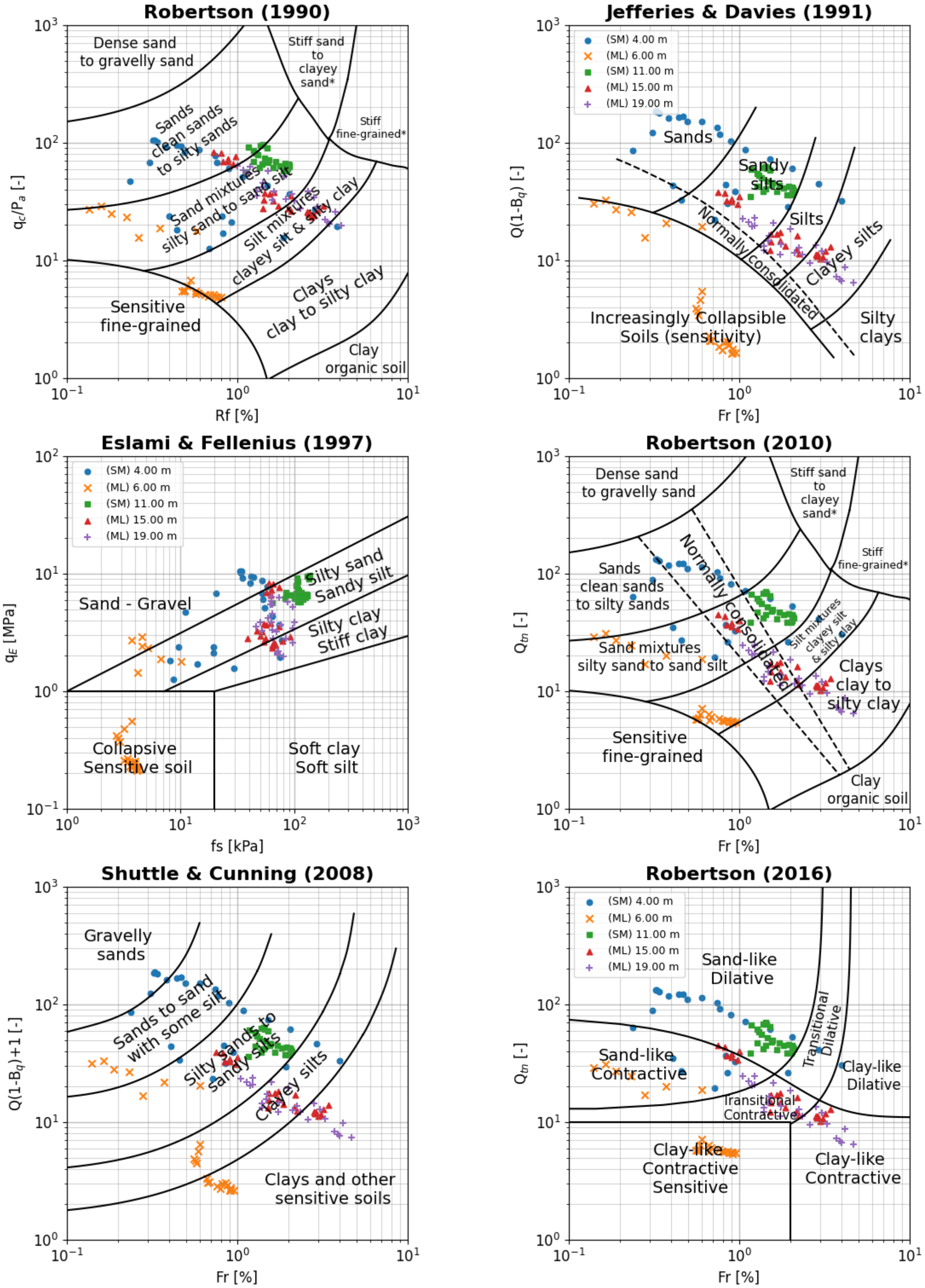
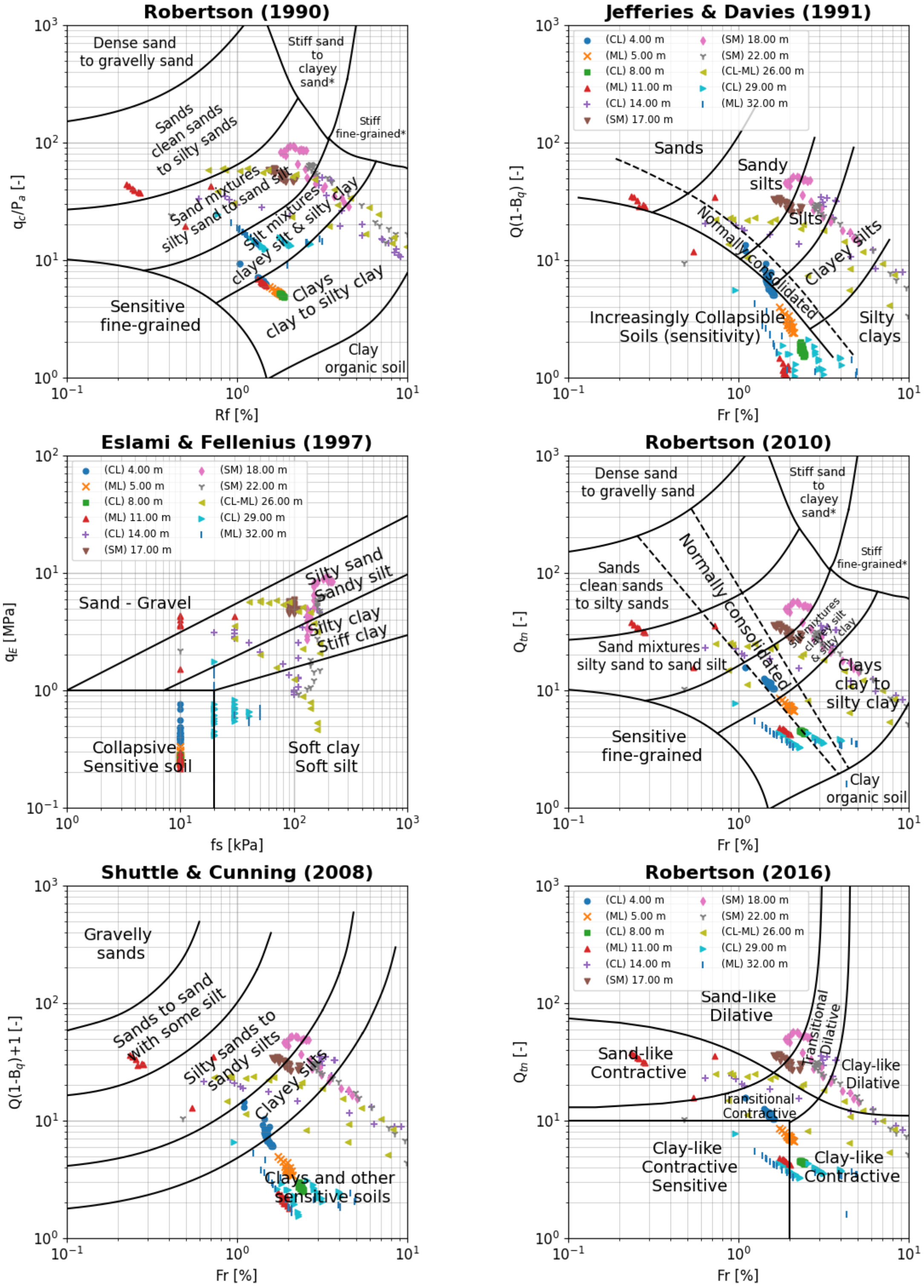


Figure 2 Soil classification results for CPT3



Robertson (1990)

Jefferies & Davies (1991)

Eslami & Fellenius (1997)

Robertson (2010)

Shuttle & Cunning (2008)

Robertson (2016)

Figure 3 Soil classification results for CPT9

CONCLUSIONS

Based on the analyzed data and methods, the following conclusions can be drawn:

- Sands are typically classified accurately by most methods, although it should be noted that there are relatively few sandy samples. The methods proposed by Robertson (2010, 2016) and Eslami & Fellenius (1997) consistently yield reliable classifications.
- The clayey samples shown in Figure 3, as well as in the other CPTs not shown in the article, appear to classify well in the charts proposed by Robertson (1990, 2010, 2016) and Shuttle & Cunning (2008). This is consistent with the recommendations provided by Robertson (1990, 2010), where his charts are suggested for soils with fine and saturated grain characteristics. (Note that the classification proposal by Shuttle & Cunning is based on Robertson's previous proposals, indicating that their charts should exhibit similar characteristics).
- On the other hand, CL-ML samples tend to present significant variations in most methodologies, with no author consistently predicting soil type.
- Sensitive or collapsible soils classified using the graphs proposed by Eslami & Fellenius (1997) are generally classified as collapsible in the classifications by Jefferies & Davies (1991) and Robertson (2016). As indicated by Naghibi, Eslami & Golafzani (2022), the graphs by Eslami & Fellenius (1997) correctly identify sensitive soils approximately 90% of the time in another study conducted on deltaic soil. The alignment between Eslami & Fellenius (1997) and Robertson (2016) may be attributed to the fact that the latest graph by Robertson expands (modifies) the area of sensitive soils, potentially improving the precision in identifying these soils—a phenomenon not previously observed with the graphs from 1990 and 2010.
- Soils classified as low plasticity silts are not consistently grouped clearly in the classification charts, but Robertson (2010) and Eslami & Fellenius (1997) appear to distinguish these soils with a lower error. It should be noted that Eslami & Fellenius (1997) have 5 classification groups, so soils with effective cone resistances greater than 1 to 3 MPa are generally classified as silts, provided they exceed the mentioned effective resistance. Robertson (2010) utilizes 9 classification groups and generally demonstrates good accuracy in classifying mixed soils, as observed in Naghibi, Eslami & Golafzani (2022)
- Eslami & Fellenius (1997) directly employ data measured by the cone without seeking normalization based on confinements and in-situ pore pressures, thereby tending to exhibit fewer errors in displaying the obtained results—provided the equipment is properly calibrated. Robertson's charts (1990, 2010) typically classify soils correctly, particularly clayey soils with a low water table, as mentioned in his articles. However, it should be noted that Robertson's chart (2016) tends to classify soils based on their behavior, which may lead to improved identification of sensitive soils if compared to Robertson (1990) and Robertson (2010).

- Based on the results, it is observed that the degree of saturation does not have a major impact on the precision of the different methodologies in estimating soil type.

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