In-situ state parameter assessment of non-plastic silty soils using the seismic cone

Helena Paula Nierwinski
Federal University of Santa Catarina, Joinville, Brazil, helnier@gmail.com

Fernando Schnaid
Federal University of Rio Grande do Sul, Porto Alegre, Brazil, fschnaid@gmail.com

Edgar Odebrecht
University of State of Santa Catarina, Joinville, Brazil, edgar@geoforma.com.br

ABSTRACT: The state parameter allows the evaluation of the *in-situ* state of soils which can be particularly useful in tailings impoundments where flow liquefaction is the most common model of failure. Positive values of state parameter characterize a contractive response during shearing and for non-plastic soils can be an indicator of flow liquefaction susceptibility. This paper presents a methodology developed for state parameter (ψ) estimation for non-plastic silty soils based on seismic cone penetration measurements. The method relies on formulations developed for sands that use the ratio of the small strain shear modulus and the cone tip resistance G_0/q_t for ψ assessment. For non-plastic silty soils, drainage conditions taking place during cone penetration have to be accounted for and are used to correct the cone tip resistance. An empirical formulation is proposed to correct q_t for partial drainage measurements producing good comparisons between laboratory and in-situ test results.

Keywords: cone penetration test; state parameter; non-plastic silty soils

1. Introduction

The term liquefaction can be used to describe different phenomena in soils. However, it is historically associated with excess of pore pressure generated in saturated granular soils by rapid loading (monotonic or cyclic) under undrained conditions.

According to Robertson and Fear [1], liquefaction of granular soils splits into two main groups: cyclic softening and flow liquefaction. The distinction is given to loading type and soil behavior during undrained loading. In the case of cyclic softening, the soil must present strain hardening behavior on undrained conditions and must be submitted to cyclic loading. On the other hand, the flow liquefaction can occur if the soil present a strain-softening behavior on undrained conditions, and both static and cyclic loadings can trigger the phenomenon.

Considerable experience has been gathered in the evaluation of liquefaction associated with cyclic loading provided by large earthquakes [2, 3, 4]. In this case, for example, the susceptibility evaluation can be made using a CPT-based approach, relating the measured cone resistance to the cyclic shear stress ratio [5, 6].

Flow liquefaction, however, received much less attention, despite the recognition of risks in activities such as reclaimed land and mining storage facilities. In the mining industry, there is an increasing demand for sustainable and adapted infrastructures, setting new challenges for geotechnical engineering concerning the need to store large volumes of waste disposal in more extensive and higher storage facilities. Within the entire range of failure modes that have occurred at tailings impoundments, flow liquefaction is likely to be the most common and has already taken hundreds of lives [7, 8]. One recent example is the 100m height Fundão tailings dam failure in 2015 in Brazil, in a liquefaction flow slide that resulted in a complete loss of the material in the storage pit [9].

Saturated or near-saturated metastable loose cohesionless sands and silts can be susceptible to flow liquefaction [10] with various mechanisms to trigger the collapse, comprising both static and cyclic loading. In the former, slope instability, incremental impoundment raise construction, transient saturation of the downstream shell and lateral movements of soft slurries in the dam can induce static loads. In the latter, equipment vibration, mine blasting, and even a seismic event can characterize cyclic loads.

As a requirement to the occurrence of flow liquefaction, the soil must exhibit a contractive behavior on undrained shear. The state parameter ψ can be used to identify this condition. In the void ratio (e) and mean effective stress ($p'=(\sigma'1+2\sigma'3)/3$) space, the state parameter ψ is defined as the difference between current void ratio (e) and critical state void ratio (e_c), at the same mean stress [11]. The degree of contractiveness or dilatancy of soils characterize by positive or negative ψ values, respectively. In practice, a state parameter equal to -0.05 is considered as a limit of minimum state to ensure satisfactory engineering performance against flow liquefaction [12].

For sands, the state parameter ψ can be assessed directly from cone tests [13] or, in a more robust approach, using the combination of measurements from independent tests. For instance, it is possible to use the ratio of the elastic stiffness to cone resistance, G_0/q_t [14]; or cone resistance to pressuremeter limit pressure, q_c/p_L [15].

The present paper focuses on the seismic cone and the use of the G_0/q_t ratio to derive ψ. Both the stiffness (G_0) and the shear resistance (q_t) are controlled (although differently) by void ratio, mean stresses, compressibility, and soil structure and are therefore different functions of the same variables [16]. As a ratio, these two measurements can be useful in predicting the soil state [16, 14, 17, 18].

The G_0 value can be determined from *in situ* shear wave velocity measurements (V_s), as in Eq. (1).

$$G_0 = \rho \cdot (V_s)^2 \quad (1)$$

where, ρ is the measured mass density (equal to total unit weight divided by the acceleration of gravity) of the soil.

The theoretical correlation between ψ and the G_0/q_t ratio is presented in Eq. (2) [14]:

$$\psi = \alpha \left(\frac{p'}{p_a}\right)^{\beta} + \chi \left(\frac{G_0}{q_t}\right) \quad (2)$$

where, α=0.520, β=0.07, and χ=0.180 are average coefficients obtained from calibration chamber data for clean sands. The parameters p' and p_a are the mean effective stress, and the reference mean effective stress, respectively, and for sands, with fully drainage, q_c=q_t.

Considering the high susceptibility of mining tailings dams to flow liquefaction failures and knowing that most of the mining tailings are silty grain-sized, this paper aims to present an adaptation of an early method introduced by Schnaid *et al*. [19]. The methodology includes an empirical correction of q_t to consider the partial drainage conditions during cone penetration in tailings. The adoption of corrected q_t values leads to ψ estimates that generally fall in the range of values obtained through laboratory tests.

2. Drainage conditions on CPTu tests

Geotechnical designs require the definition of drained or undrained conditions in respect to the soil response to a given imposed load. For transient soils in the intermediate permeability range (10^{-5} m/s < k < 10^{-8} m/s), such as silty soils and mining tailings, there are no consensual guidelines for correct testing and data interpretation [20, 21]. The results of a standard cone penetration test (CPTu) (v=20 mm/s) are affected by partial drainage during the penetration [22], and may induce errors in the prediction of soil parameters.

Several studies aim to analyze the CPTu test results varying the penetration velocity, achieving thus full drainage conditions at low penetration velocities and completely undrained conditions at high penetration velocities [23, 24, 25, 26]. This assessment is usually performed based on the normalized penetration velocity, as presented in Eq. (3).

$$V = \frac{v \cdot d}{c_h} \quad (3)$$

where v in the cone penetration rate; d is the penetrometer diameter; and, c_h is the coefficient of horizontal consolidation. According to Randolph and Hope [23], the fully undrained penetration occurs when V values are higher than a value around 30–100, and fully drained penetration occurs when V values are less than a value around 0.03–0.01.

Schnaid [27] emphasizes that each soil will have a unique drainage characteristic curve, and the transition between drained to totally undrained conditions has to be defined locally. Such a behavior justified by the influence of OCR and soil rigidity index. Dienstmann *et al*. [21] presented a set of theoretical and experimental drainage characteristic-curves for different geomaterials, including gold mining tailing. The authors highlighted that the variation between drained and undrained resistance is lower in clays than in sands. In the study, drained to undrained resistance ratios around 2 for clays, 8 to 10 for granular soils, and around 10 for gold mining tailings has been reported

In addition the evaluation of drainage conditions from the piezocone pore pressure parameter B_q can be helpful; B_q greater than 0.5 is enough to characterize undrained conditions and lower values may be indicating partial drainage.

3. State parameter and flow liquefaction evaluation for non-plastic silty soils

This section aims to present the developed methodology to estimate the state parameter for non-plastic silty soils, using seismic cone test data.

3.1. Developed methodology

A methodology developed for the classification of granular soils based on seismic cone penetration measurements has been proposed by Schnaid *et al*. [19]. The method uses a two-stage soil classification system that is first applied to categorize soil groups and identify drainage conditions. The ratio of the small strain shear modulus and the cone tip resistance G_0/q_t is the basic element for soil classification that, on a subsequent stage, is combined to the state parameter ψ to identify sands that potentially exhibit strain softening response upon undrained loading.

However, application of the methodology in non-plastic silty soils requires accounting for the partial drainage conditions taking place during cone penetration to obtain drained and undrained cone tip resistances [21]. Besides that, the relation between drained cone tip resistance (q_{tD}) and undrained cone tip resistance (q_{tUD}) is a function of soil type.

One way to categorize each soil is through the effective friction angle (ϕ'). Senneset *et al.* [28] proposed a theoretical solution for determining ϕ' from CPTu test results, after comparison and calibration with laboratory test results performed on a wide range of soils. In this solution, the pore pressure measurements provided by the CPTu allow the estimation of effective resistance parameters based on concepts of the bearing capacity and plasticity theories, providing application to all soils [29]. This solution is the result of Norwegian Technology Institute (NTH) experience on correlating the cone resistance number (N_m = Q), the effective resistance parameters (c' and ϕ'), pore pressure parameter (B_q) and the angle of plastification (β) (Eq. 4):

$$N_m = Q = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \quad (4)$$

where σ_{v0} and σ'_{v0} are the total and effective vertical stresses, respectively.

The angle of plastification (β) is associated to an idealized geometry from the failure zone around the cone. It is not easy to define experimentally or theoretically the β value, however, it is known that it depends of soil properties as compressibility, aging, plasticity and, sensitivity [29]. A simplified evaluation, based on NTH theory, is presented on Figure 1, where the friction angle variation was provided as a function of Q and B_q, with c'=0 and β=0.

Considering that total and effective stresses on Eq. 4 are constant at a given depth, it can be stated that Q is directly proportional to q_t. Therefore, Figure 1 allows to estimate the drained (q_{tD}) and undrained (q_{tUD}) cone tip resistance for a specific friction angle value, which can be correlate to soil type. Drained conditions are associated with B_q=0 and undrained conditions characterized by B_q in the 0.6 to 1 interval [27, 30].

The interpretation of Figure 1 provides a direct correlation between drained and undrained cone tip resistance ratio (q_{tD}/q_{tUD}) and effective friction angle (ϕ'). This correlation is shown on Figure 2, where the variation range of q_{tD}/q_{tUD} has been established by two curves obtained from Senesset *et al.* [28]. Besides, results from the literature plotted in Figure 2 demonstrate that the method can reasonably describe experimental measurements. Figure 2 demonstrates that the q_{tD}/q_{tUD} ratio varies from 3 (for effective friction angles around 20°) to about 10 (for effective friction angles around 38° and 40°).

Two boundary conditions can be set to correlate the drained cone tip resistance (q_{tD}) and standard cone tip resistance (q_{t20}) (Eq. 5):

$$\frac{q_{tD}}{q_{t20}} = \begin{cases} 1, if\ B_q = 0 \\ \frac{q_{tD}}{q_{tUD}}, if\ B_q = 1 \end{cases} \tag{5}$$

Knowing the boundary conditions, an empirical equation was proposed to describe the variation of the q_{tD}/q_{t20} ratio for partial drainage conditions. The proposed empirical equation is dependent on the q_{tD}/q_{tUD} ratio (provide by Figure 2) and B_q (Eq. 6):

$$\frac{q_{tD}}{q_{t20}} = 1 + \left(1 + \frac{q_{tD}}{q_{tUD}}\right) \cdot \left(B_q\right)^{\alpha} \tag{6}$$

where, q_{tD}/q_{tUD} assumes a fixed value, depending on the estimated soil friction angle (Figure 2), and α is a parameter dependent on the material stiffness, ranging from 0 to 1. For an initial simplified evaluation an average value of α = 0.5 will be adopted, although this parameter depends on soil type and should be calibrated.

Figure 3 is a graphical representation of the different values of q_{tD}/q_{tUD} ratios calculated from eq. 8. Once q_{tD} values are estimated from the proposed correction, Eq. 2 can be used to determine the ψ values for non-plastic silty soils, which allows the flow liquefaction susceptibility evaluation.

An example of this empirical correction is shown in Figure 4, in which q_{t20} and q_{tD} are plotted against depth. The empirical equation provide a quick and simplified solution to obtain estimative of q_{tD} from which constitutive parameters can be assessed.

3.2. Validation and calibration

Calibration of the proposed correction for standard cone tip resistance (q_{t20}) into an equivalent drained (q_{tD}) is provided by results in gold, iron and bauxite mining tailings (non-plastic silts). Values of ψ measured in triaxial tests, using bender elements, are used for comparisons.

Predictions are shown in Figure 4, in which ψ values estimated from G_0/q_t ratio are compared to laboratory measurements.

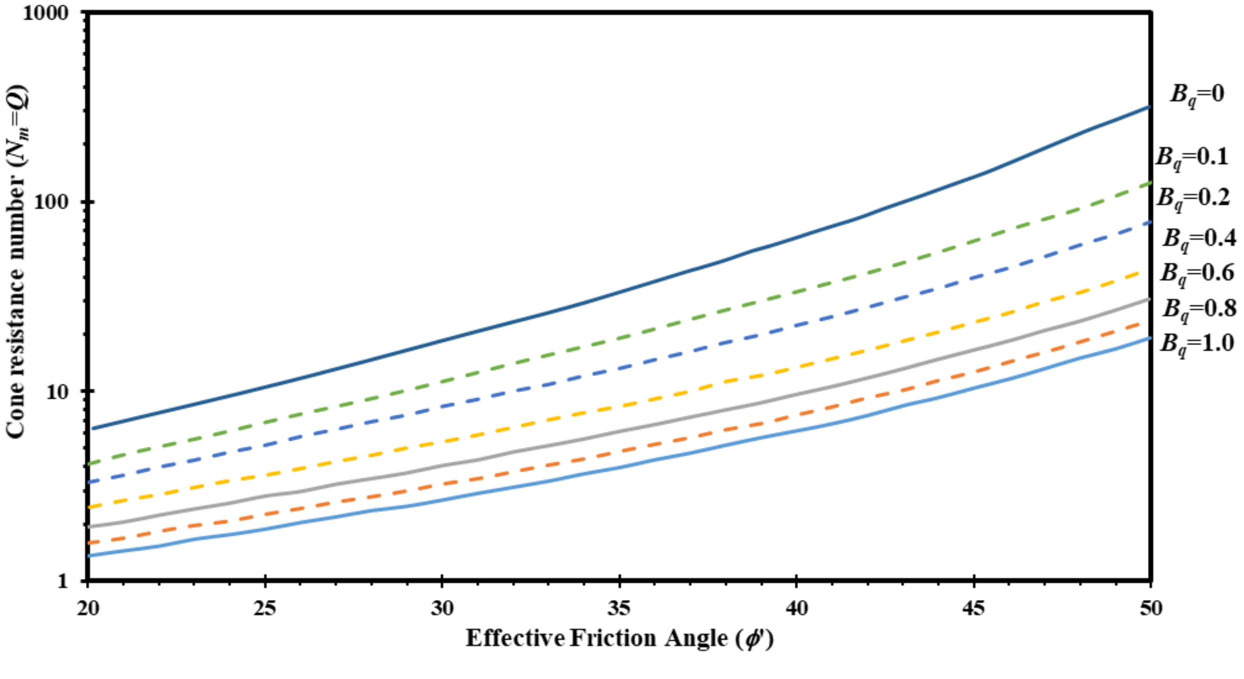


Figure 1. Theoretical solution for effective friction angle (ϕ') in terms of Q and B_q for the simplified case of c' = 0 and β = 0 (adapted from Senneset *et al.* [28])

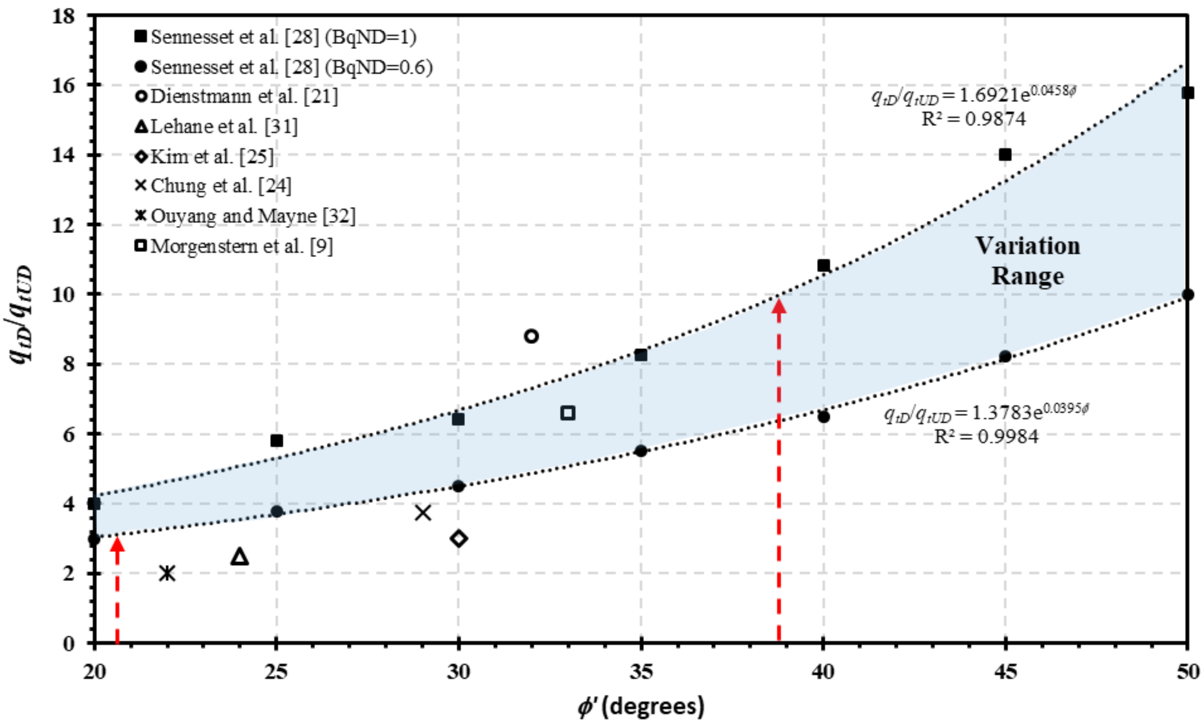


Figure 2. Variation of q_{tD}/q_{tUD} ratio obtained from Senneset *et al*. [28] solution, and test results for different materials

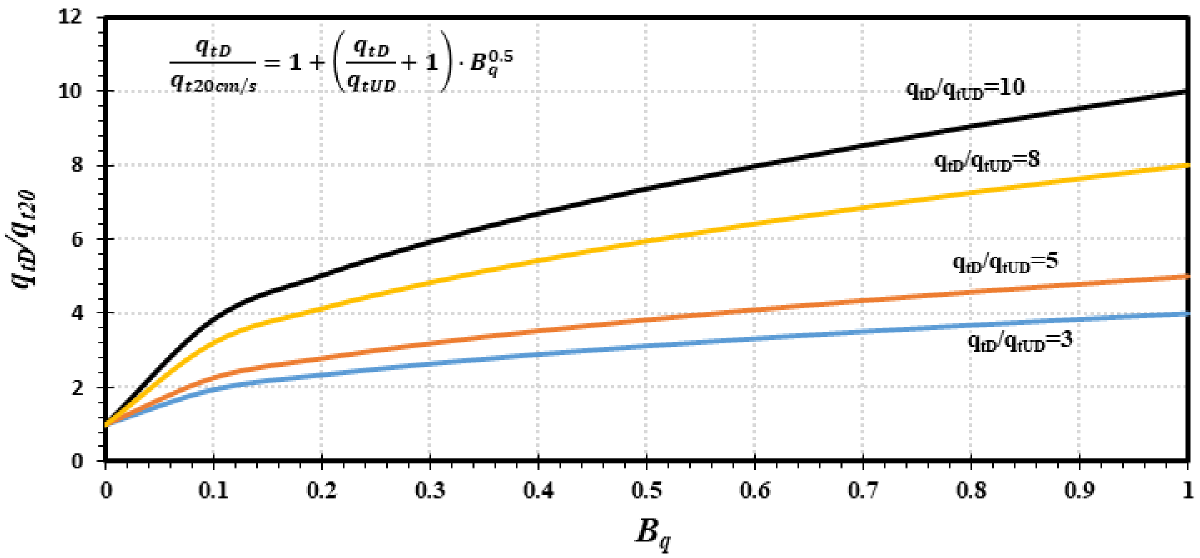


Figure 3. Proposed empirical correlation for cone tip resistance correction for standard tests performed on intermediate drainage materials (α=0.5)

The results from the iron tailings have been reported by Morgenstern *et al*. [9] and offer a good reference for predictions. In this particular case, the CPTu data yielded B_q values close to zero and the proposed correction is marginal. The ψ values calculated from the SCPTu spread across a wide range, from -0.15 to about 0.2, whereas laboratory tests fall in a much narrow range (from +0.05 to +0.08) (Figure 5). This may indicate that methods proposed originally by Schnaid and Yu [14] is not accurate or, alternatively, that field data is scattered due to the actual spatial variation of tailings. However, it is interesting to observe that both laboratory and field data indicate that these tailings show potential to flow liquefaction for the Fundão Dam.

In the case of gold mining tailings, SCPTu tests performed at standard penetration velocity generated considerable excess of pore pressure with B_q values indicating partial drainage. The friction angle of the gold mining tailings measured by laboratory tests is 32° [33]. The q_{tD}/q_{tUD} ratio was adopted as 7, considering the Senneset *et al*. [28] approach. This value is also very close to the response obtained when analyzing the results using poroelastic theory [21]. A good fitting between laboratory and field ψ values prediction is obtained for α close to unity (Figure 6).

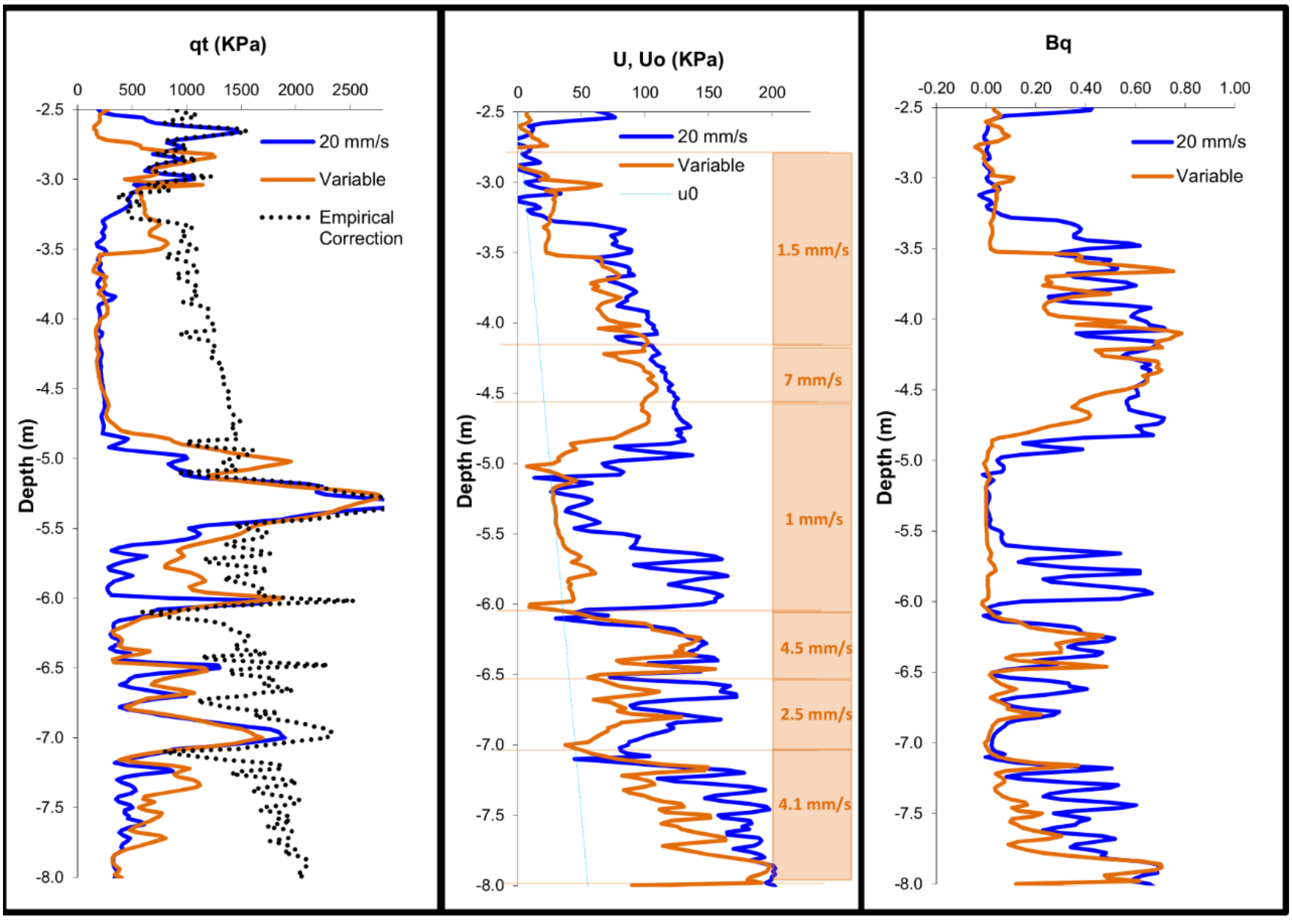


Figure 4. SCPTu profile for gold mining tailings performed on standard and variable penetration velocities and empirical estimative of q_{t20}

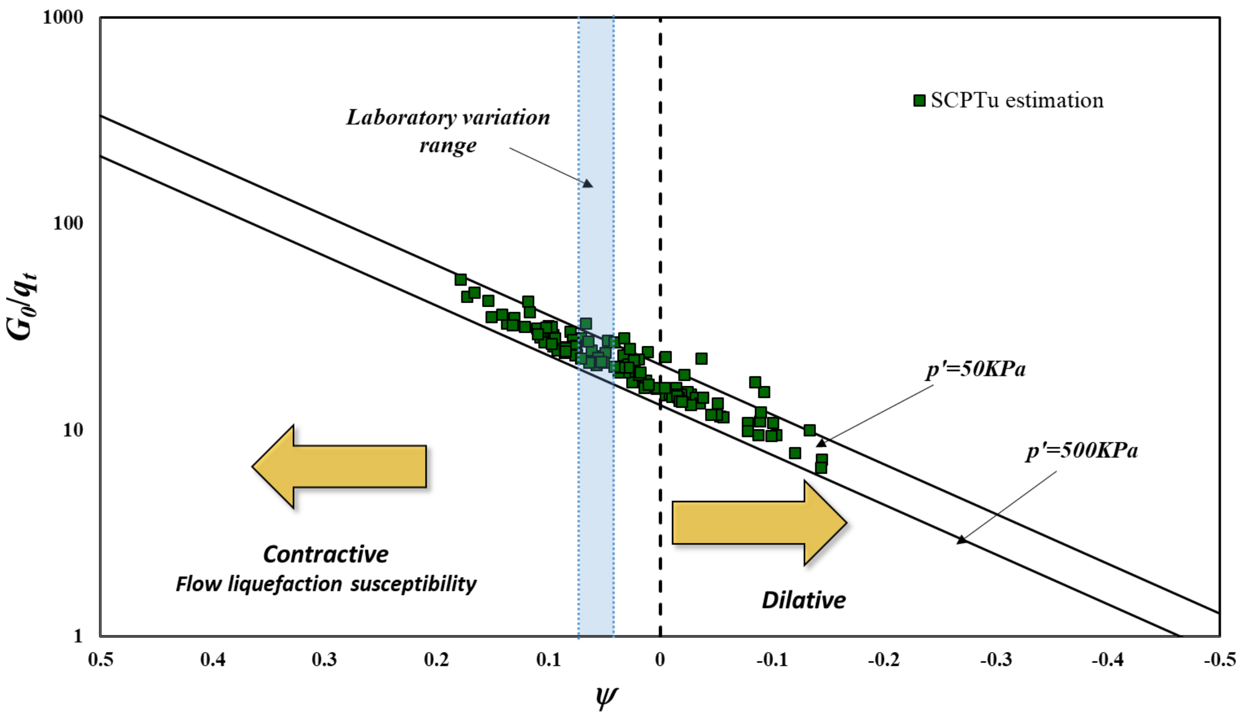


Figure 5. Estimation of ψ from SCPTu tests compared to laboratory range for iron mining tailings

To evaluate the gold mining tailings ψ values estimated from SCPTu tests, Figure 6 presents the comparison between estimation of ψ values using q_{t20} values and q_{tD} values, obtained by the proposed correction. It is verified that the estimated ψ values from q_{t20}, although has shown that the material presents contractive behavior and, consequently, susceptibility to the flow liquefaction, gives high ψ values compared to the range defined by laboratory tests results. However, with the application of the tip resistance correction for drained conditions, the estimated ψ values are much very close to the range defined by the laboratory tests results.

The bauxite mining tailings SCPTu test results also indicates a generation of excess of pore pressure, which provides typical B_q values for a partial drainage condition. In this case the correction of q_{t20} was already necessary for ψ estimation. To applicate the empirical equation to correct the q_{t20} value to drained conditions, it was adopted a q_{tD}/q_{tUD} ratio equal to 7. This value was defined through Figure 2, for a friction angle of 32.4°, which was obtained by triaxial tests. In this analysis a good fitting between laboratory and field ψ values prediction is obtained for α close to 0.5 (Figure 7).

According to ψ values evaluation, all the mining tailings evaluated in this paper may present contractive behavior during shearing and may be susceptible to flow liquefaction occurrences. However the bauxite mining tailing evaluated in this paper presented ψ values closer to zero than gold and iron tailings that presented higher ψ positive values obtained both through field and laboratory test results.

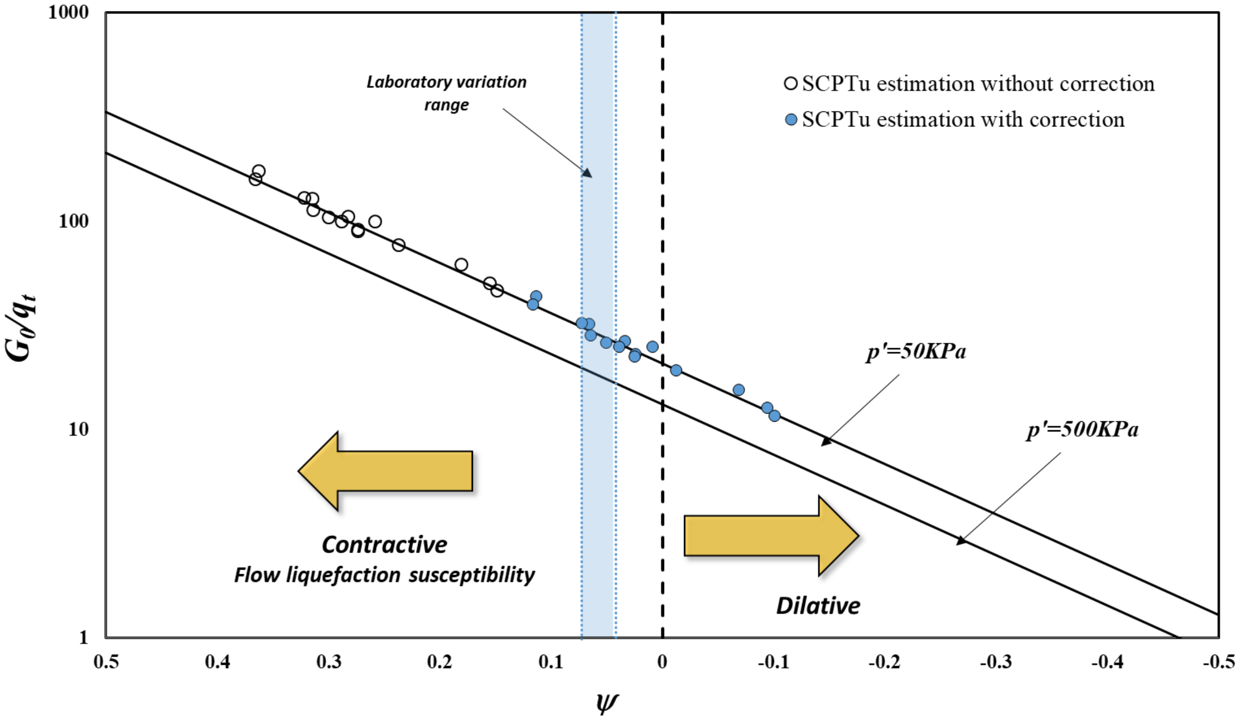
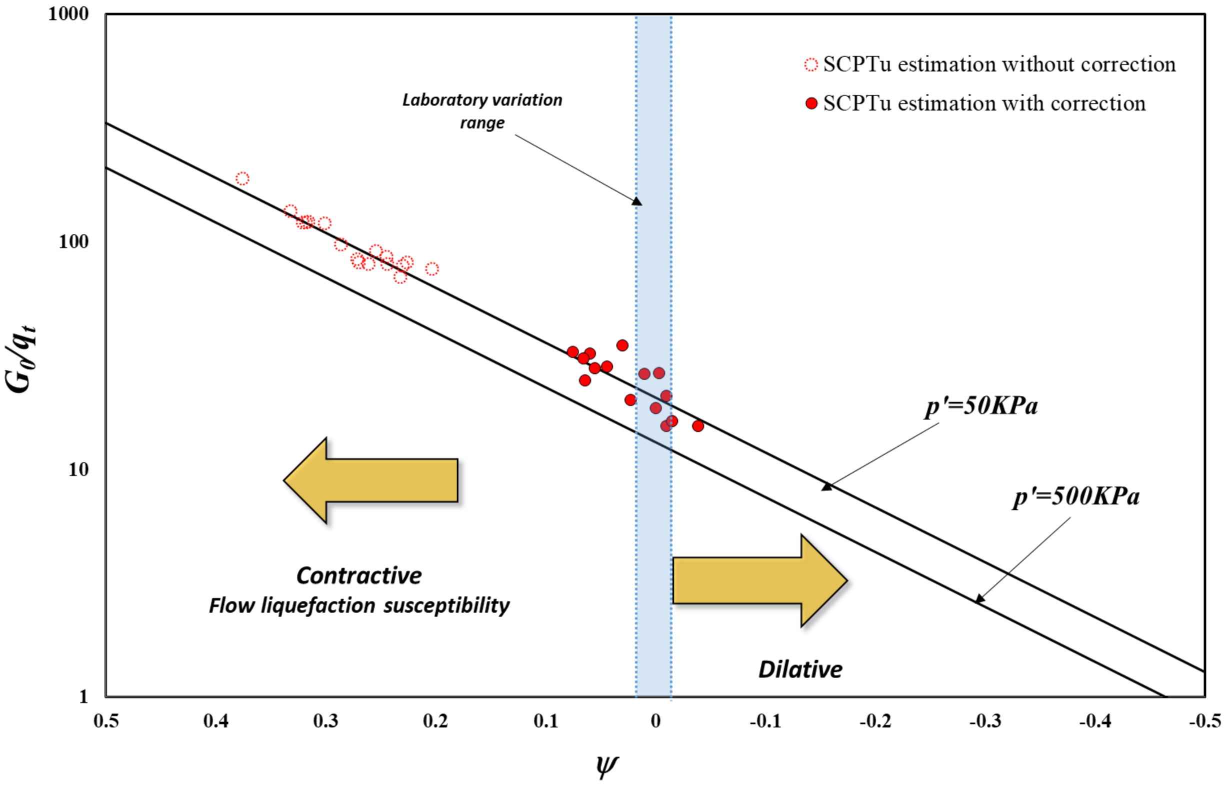


Figure 6. Estimation of ψ from SCPTu tests, considering or no the correction of q_t values, compared to laboratory range for gold mining tailings



4. Conclusions

This paper presents a method to estimate the state parameter in non-plastic silty soils based on SCPTu test results. An empirical equation was proposed to correct cone tip resistances obtained from CPTU tests performed at the standard penetration rate of 20mm/s on transient soils. Tests performed on mining tailings provided a database for calibration and validation of the proposed methodology. Values of ψ derived from field SCPTU tests are in general agreement with laboratory measurements. The method is part of a research effort that is currently under development and requires further calibration.

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