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Soil suction effects on CPT data interpretation

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ABSTRACT. The Cone Penetration Test (CPT) is one of the most widely used *in situ* test for site characterization and estimation of geotechnical parameters estimative. Its benefits include speed, reliability, repeatability, and the ability to provide continuous data. Although the interpretation is well-established for saturated and dry soils, it remains limited for unsaturated soils. This paper presents and discusses the influence of the unsaturated condition in CPTs performed on tropical soil site. Four CPT campaigns and gravimetric water content profiles have been determined in different periods over two years. Soil-water retention curves (SWRC) were used to estimate *in situ* soil suction. It was observed that the CPT data were influenced by soil suction up to 6.0 m depth. Two semi-empirical approaches based on bearing capacity theory and effective stress principle were used for data interpretation. These approaches allowed to assess the soil suction influence on CPT and to define the typical test profile with no suction effects. The importance of considering soil suction in the CPT interpretation on unsaturated soils is highlighted, and the effective stress approach is suggested as a starting point.

Keywords: site characterization; *In situ* testing; CPT; unsaturated soil; suction.

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Introduction

An appropriate site characterization campaign must determine the geometry of relatively homogeneous zones, groundwater conditions and define indexes, strength, and stiffness properties of the soils within these zones.

The Cone Penetration Test (CPT) has been widely used for site characterization for more than 80 years (Doan & Lehane, 2021; Duan et al., 2022; Fateh, Eslami, & Fahimifar, 2017; Hung, Nguyen, Lee, & Kim, 2016; Robertson, 1990; 2009; 2016; Zhang, Zou, Zhang, Yuan, & Wu, 2021). It has been used in geotechnical and geo-environmental projects all over the world. The CPT has several advantages compared to traditional site investigation methods, since it is fast and continuous profiling, economical and productive, repeatable, the data is reliable and operator-independent, and its interpretation has a strong theoretical basis (Lunne, Robertson, & Powell, 1997; Robertson, 2009). Soils can be classified according to their geomechanical behavior using classification charts (Robertson, 2009). The cone - CPT (q_c and f_s) and the piezocone - CPTu (q_c, f_s, and u) data are also useful to define the strength and stiffness parameters from well-established correlations (Lunne et al., 1997; Salgado, Mitchell, & Jamiolkowski, 1997; Vésic, 1975).

Most of the experiences acquired with the CPT and CPTu are based on tests performed on saturated and well-behaved soils, such as isotropically consolidated reconstituted clays and reconstituted clean silica-sands (young and uncemented). Therefore, interpretation methods are effective in classifying and predicting the behavior of "*ideal soils*" (Leroueil & Hight, 2003; Robertson, 2016). However, it can be less effective for unusual soils, such as unsaturated and aged and/or cemented geomaterials, intermediate soils (partial drainage), and calcareous sand (Dienstmann, Schnaid, Maghous, & DeJong, 2018; Robertson, 2016; Schnaid, Dienstmann, Odebrecht, Maghous, 2020; Lehane, & Fahey, 2004). Ideally, soil suction must be incorporated in CPT interpretation. However, there are few studies on the effect of soil suction on CPT data (Fioravante, Giretti, Dodaro, Gragnamo, & Gottardi, 2022; Giacheti, Bezerra, Rocha, & Rodrigues, 2019; Hryciw & Dowding, 1987; Lehane, Ismail, & Fahey, 2004; Lo Presti, Stacul, Meisina, Bordoni, & Bittelli, 2018; Marchi et al., 2022; Miller, Tan, Collins, & Muraleetharan, 2018; Pournaghiazar, Russell, & Khalili, 2013; Russell et al., 2022; Yang & Russell, 2016).

The properties of unsaturated soil are influenced not only by the geological history and formation environment, but also by the soil-water energy state resulting from soil suction (Blight, 2003). Suction is a

negative pore water pressure between the soil grains, generating capillary and adsorption forces, which bring the grains together and increase the strength and stiffness of the soil. The unsaturated soil mass should be studied as a continuum medium with spatial and seasonal variations, since the magnitude of soil suction is directly related to the weather and atmospheric phenomena of the environment (precipitation, evaporation, heat, and radiation exchange between soil and atmosphere) (Blight, 2003).

Four CPT campaigns were performed on an unsaturated tropical sandy soil research site in different seasons of two subsequent years. The test data were interpreted considering the principles of unsaturated soil mechanics, using both gravimetric water content profiles and soil-water retention curves (SWRC) to evaluate the effect of soil suction on data variability, based on two different approaches. The typical test profile with no suction effects was presented for the site to define soil behavior to estimate geotechnical parameters in the most critical condition.

Study site

Site location and geology

In situ tests campaigns were carried out at the experimental research site of the University of São Paulo - USP (Lat.: 22º0'38.44"S; Long.: W 47º53'45.69" W) in the city of São Carlos, State of São Paulo, Brazil (Figure 1).

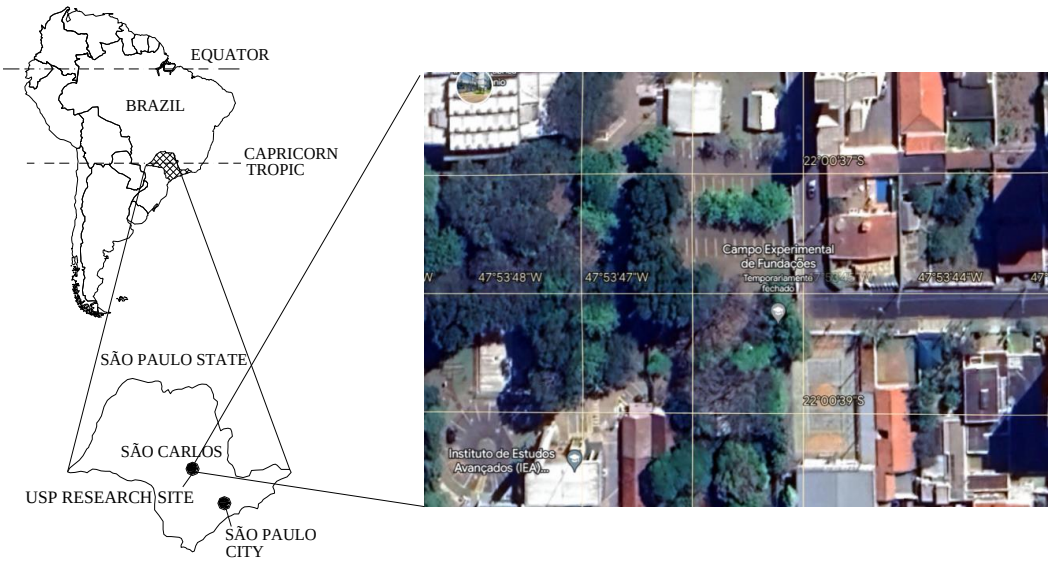

Figure 1. The location of the study site (adapted from Google Earth, 2022).

The city of São Carlos is located over the São Bento Geological Group, which is constituted of eolian sandstones from the Botucatu Formation and volcanic rocks from the Serra Geral Formation. Conglomerates and Sandstones from the Bauru Group underlay the Cenozoic Sediments in the site. The sediments were subjected to the laterization process by the action of weathering at local climate conditions typical of tropical regions characterized by high temperatures, intense rainfall, and good drainage conditions (De Mio, 2005). The sandstones belong to the Bauru Group, which is typical from fluvial-lacustrine deposition environments. There is a clayey fine to medium sand in the study site with two well-defined layers: unsaturated lateritic Cenozoic sediment (up to around 7.0 m depth) overlaying the Residual soil derived from Sandstone. The two distinct layers (Cenozoic sediment and Residual soil) are separated by a layer of pebbles about 0.3 m thick (Costa, Cintra, & Zornberg, 2003; De Mio, 2005; Giacheti, Röhm, Nogueira, & Cintra, 1993). The depth of the groundwater table varies seasonally from approximately 9.0 to 12.0 m below the ground surface (Morais, Tsuha, Neto, & Singh, 2020). The hydraulic conductivity of lateritic layer ranges from 10^{-4} to 10^{-6} m s^{-1} (Vilar, Bortolucci, & Rodrigues, 1985).

Site characterization via laboratory tests

Figure 2 shows the grain size distribution determined with and without dispersant, dry unit weight (γ_d), void ratio (e), and Atterberg limits (w_P and w_L) up to about 9.0 m depth. The particle unit weight (γ_s = 27.3 kN m^{-3}) can be considered constant along depth. The soils from both layers are classified as clayey sand (SC), according to the Unified Soil Classification System (American Society for Testing and Materials [ASTM], 2000).

The climate on the site is classified as tropical wet and dry ("Aw", according to the Köppen climate classification), with a rainy summer season from December to March (wet season) and a low precipitation winter from June to September (dry season). This type of climate is appropriate to seasonally modify the *in situ* soil suction since it presents high annual temperatures during the wet summers and the dry winters.

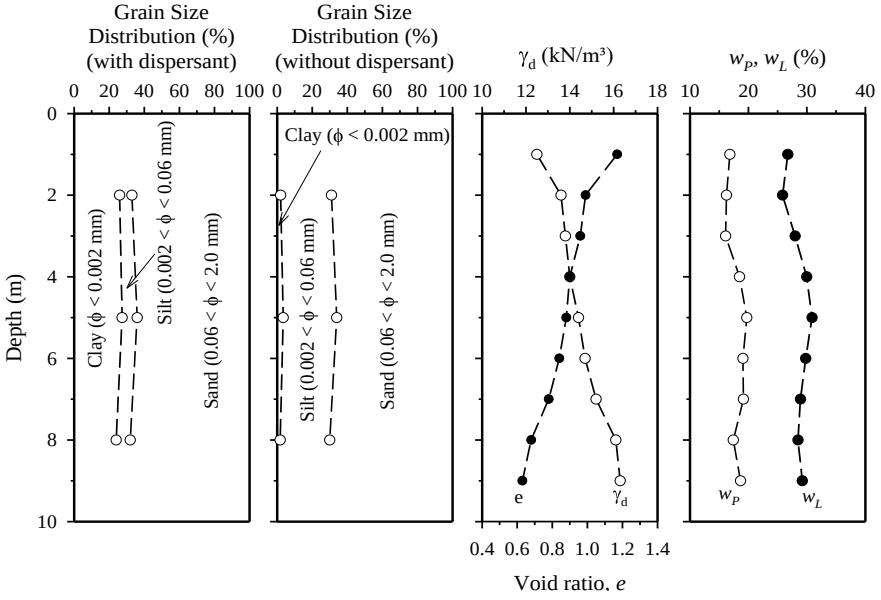

Figure 2. Grain size distribution with and without dispersant and index properties of the studied site (adapted from Machado 1998 and Rocha 2018).

Morais et al. (2020) conducted a study at this research site to investigate the potential use of energy piles in tropical soils. Due to the alternation of dry and rainy periods in tropical climatic regions, the authors monitored the water table, precipitation, gravimetric moisture content and soil suction, since these variables affect the efficiency of energy piles. Figure 3 shows monthly precipitation, soil suction and groundwater variation over a three-year period (2016 to 2018). The precipitation data were obtained by the São Paulo Department of Water and Electricity (DAEE) and the soil suction was determined by using four tensiometers installed at 1.0 and 1.3 m depth close to the energy pile. Figure 3 illustrates that soil suction decreases as rainfall increases, indicating a significant climatic influence on the topsoil. The upper layer (active zone) is more prone to the effects of rain on soil suction, as can be observed in September and October 2016, for example.

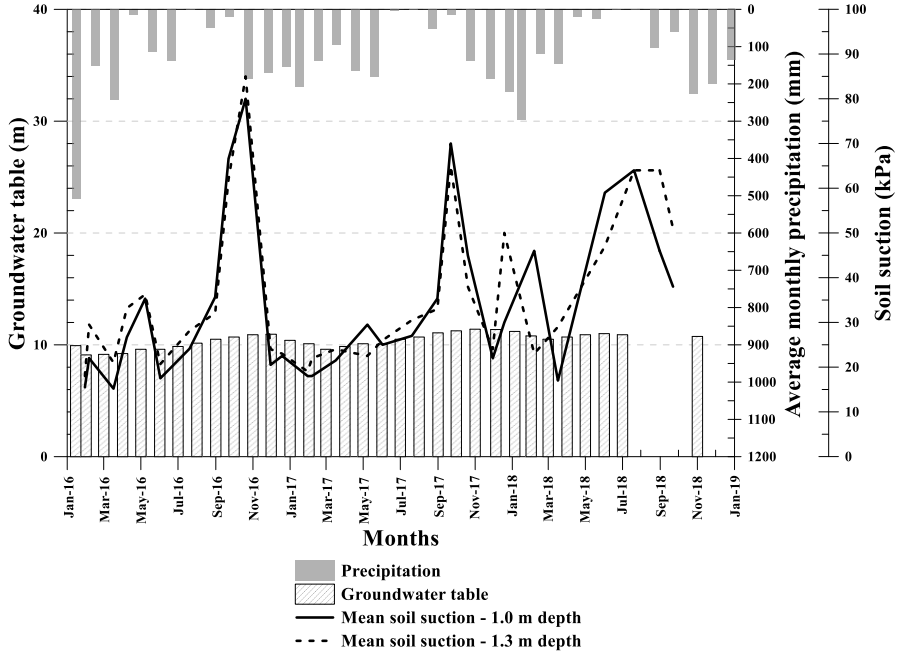

Figure 3. Precipitation, soil suction and groundwater variation over a three-year period (2016 to 2018) (modified from Morais et al. 2020).

It is worth noting that the CPT tests and soil sampling presented in this paper were performed at approximately 30 m from the installed tensiometers, and thus, the suction values used in the CPT interpretation were estimated by means of soil water retention curves (SWRC) (Figure 4) and gravimetric water content profiles (Figure 6).

The soil-water retention curve (SWRC) is a key component in the unsaturated soil characterization, since it allows linking suction to some physical index of the soil, such as the gravimetric water content. Figure 4 shows the SWRCs for the soils of the studied site, determined from undisturbed samples collected at 2.0, 5.0 and 8.0 m depth, in order to assess the influence of suction on soil behavior (Machado, 1998). Two techniques were used: suction plate and pressure chamber (American Society for Testing and Materials [ASTM], 2003). The data were adjusted according to the van Genuchten (van Genuchten, 1980)' equation. Machado (1998) also carried out unsaturated triaxial tests as well as unsaturated oedometer tests from undisturbed samples collected at 2.0, 5.0 and 8.0 m depth. In the mentioned work, for triaxial tests, suction values were equal to 0, 40, 80, 120 and 160 kPa, and net stress values were 50, 100, 200 and 350 kPa, while in the unsaturated oedometer tests, suction values of 50, 100, 300, 400 and 450 kPa were used. The axis translation technique was adopted to apply suction to the soil samples (Hilf, 1956).

The SWRCs presented in Figure 4 are typical of sandy soils with a low water retention capacity. In this type of curve, a zone of marked desaturation of the macrostructure is observed, i.e., the gravimetric water content varies greatly with slight suction variation (Region A). The opposite trend occurs in the Region B, where the values of suction vary significantly with little gravimetric water content variation.

Rocha (2018) and Rocha, Rodrigues, and Giacheti (2021) discussed the influence of suction on the pre-consolidation stress (σ_p) and cohesion intercept (c) data obtained by Machado (1998). The authors observed that c and σ_p values increased with increasing soil suction. Moreover, c and σ_p values were little affected at the low suction range (below 20 kPa), which corresponds to gravimetric water contents values higher than 16% - 17%. This region, referred to as Region A of the SWRCs (Figure 4), represents the desaturation section of the curve, where the gravimetric water content is generally exposed to gravitational forces. In Region B of the SWRCs, both c and σ_p markedly varies with soil suction for the gravimetric water contents lower than 16% - 17% (suction value greater than 20 kPa). In the Region B, it can be noted in Region B that a slight variation in gravimetric water content can substantially modify the soil suction. The laboratory test data highlight the variation of geotechnical parameters in Region B, since a slight change in gravimetric water content causes a major alteration in soil suction.

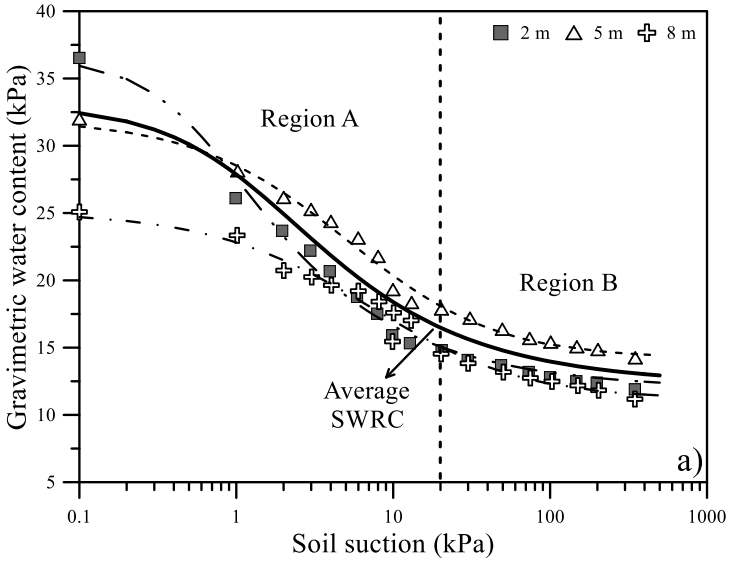

Figure 4. Soil-water retention curves for the soil samples collected at 2 m, 5 m and 8 m depths (adapted from Machado 1998).

Materials and methods

In situ tests campaigns were carried out in March and October of 2016 and in April and October of 2017 at the study site. Three CPTs and one soil sampling were performed in each campaign.

The CPT is an electric probe with a 10 cm^2 cross-sectional area, and it was pushed into the ground at a constant rate of 20 mm/s recording cone resistance (q_c) and sleeve friction (f_s) at 20 mm depth intervals. The test procedure was conducted in accordance with (American Society for Testing and Materials [ASTM], 2014).

Soil sampling was performed from the ground surface to 8 m depth by using a helical auger to collect samples every 0.75 m depth intervals. The gravimetric water content of the samples was determined by the oven-dry method (American Society for Testing and Materials [ASTM], 2016), assuming the reference depth to the center of the auger.

The CPTs were performed side by side, approximately 1 m apart from each other, and the soil sampling was carried out nearby the CPTs. Figure 5 shows the location of the *in situ* tests conducted at the site.

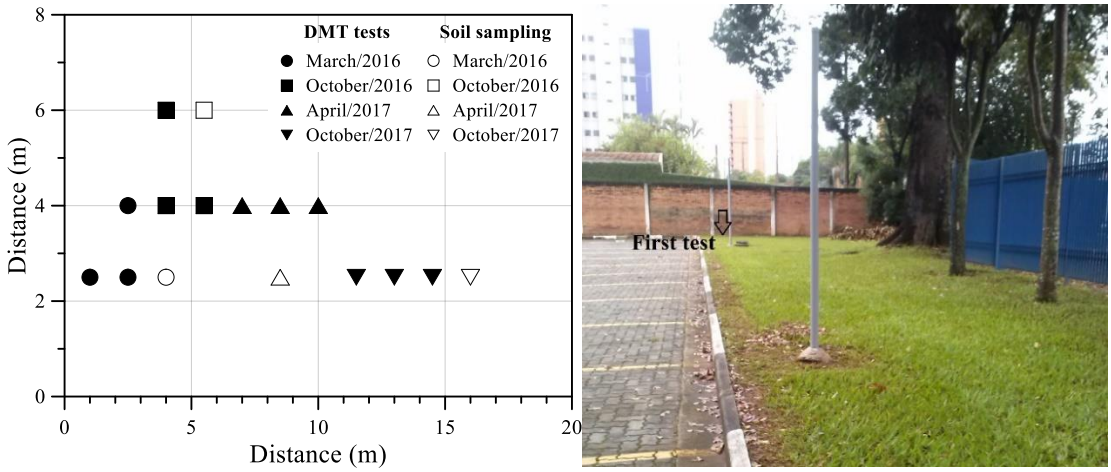

Figure 5. Representation of the spatial location of the in-situ tests at the study site.

Results and discussion

Gravimetric water content profiles

Figure 6 presents the gravimetric water content profiles determined together with each CPT campaign. A great variability is observed for the study site, which tends to decrease with increasing depth. The gravimetric water content profile for the October/2017 campaign consistently showed values lower than 15.1%. Such values are higher than 16.8% for the test campaign from March/2016 and April/2017, and range between 15.1 to 16.8% for the test campaign from October/2016. These profiles show the differences in gravimetric water content in the dry and wet seasons. March/2016 was the period with higher moisture content, and October/2017 was the lowest, being at the end of the dry season.

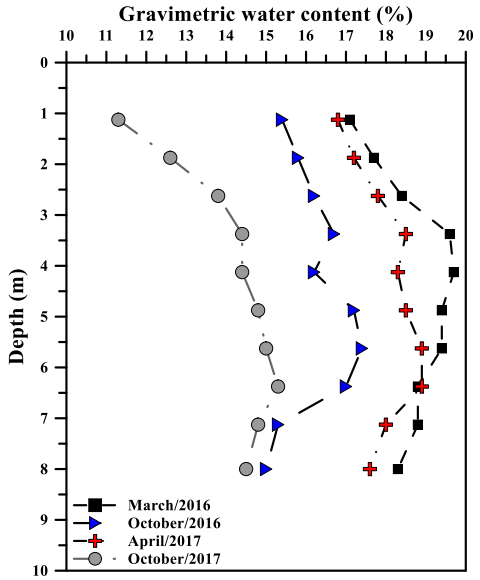

Figure 6. Gravimetric water content profiles determined during the CPT campaigns (adapted from Rocha 2018).

The variation in the gravimetric water content among the campaigns is more significant up to approximately 6 m depth (Figure 6). The gravimetric water content values tend to locate in Region A of the SWRC during March/2016 and April/2017 campaigns, in the Region B during the October/2017 campaign, and between these two regions for the October/2016 campaign (Figure 4). Such variation can affect the behavior of engineering structures settled on shallower horizons of the site, such as for shallow foundation design and for slope stability analysis (Costa et al., 2003; Krahn, Fredlund, & Klassen, 1989; Lim, Rahardjo, Chang, & Fredlund, 1996).

Considering the data in Figure 6 and based on the SWRC (Figure 4), it is possible to assess the soils suction variation along the depth for the different test campaigns. The soil suction is below 10 kPa (Region A, Figure 4) in March/2016 and April/2017, while it can exceed 100 kPa (Region B, Figure 4) in October/2017. On the other hand, the suction value may vary between 15 and 42 kPa in October/2016. The high variation in soil suction in October/2017 can be attributed to slight variations in the water content, which can cause large variations in soil suction (Region B, Figure 3).

Suction influence on CPT

The CPT campaigns conducted at the study site were interpreted to assess the influence of the unsaturated condition on the cone resistance (q_c) and sleeve friction (f_s) profiles, based on soil sampling and SWRC. Figure 7 presents the typical soil profile obtained by SPTs together with the cone resistance (q_c) and the sleeve friction (f_s) profiles for all the CPTs. Figure 7 also shows the high variation on q_c profiles in the Cenozoic Sediment horizon (up to 6 m depth) and a lower variation on the f_s profiles. The high variability of q_c up to 1 m depth can be associated with the presence of a landfill. Significant variation on q_c was also observed between 8 to 10 m, and below 16 m depth. Such variation can be associated with suction in the upper layer (up to 6 m depth) due to water infiltration, and to groundwater level fluctuation between 8 to 10 m depth. The variation below 16 m depth is due to the presence of a young residual soil. The q_c variation was studied up to 8 m, since soil samples were collected up to that depth.

Figure 8 shows the average q_c and f_s profiles and the gravimetric water content profiles determined for each test campaign. The q_c profiles were discussed and interpreted considering the seasonal variability caused by soil suction, which may influence soil behavior and soil classification. The variability in q_c up to 1 m depth has not been interpreted, because it can be linked to the presence of a landfill.

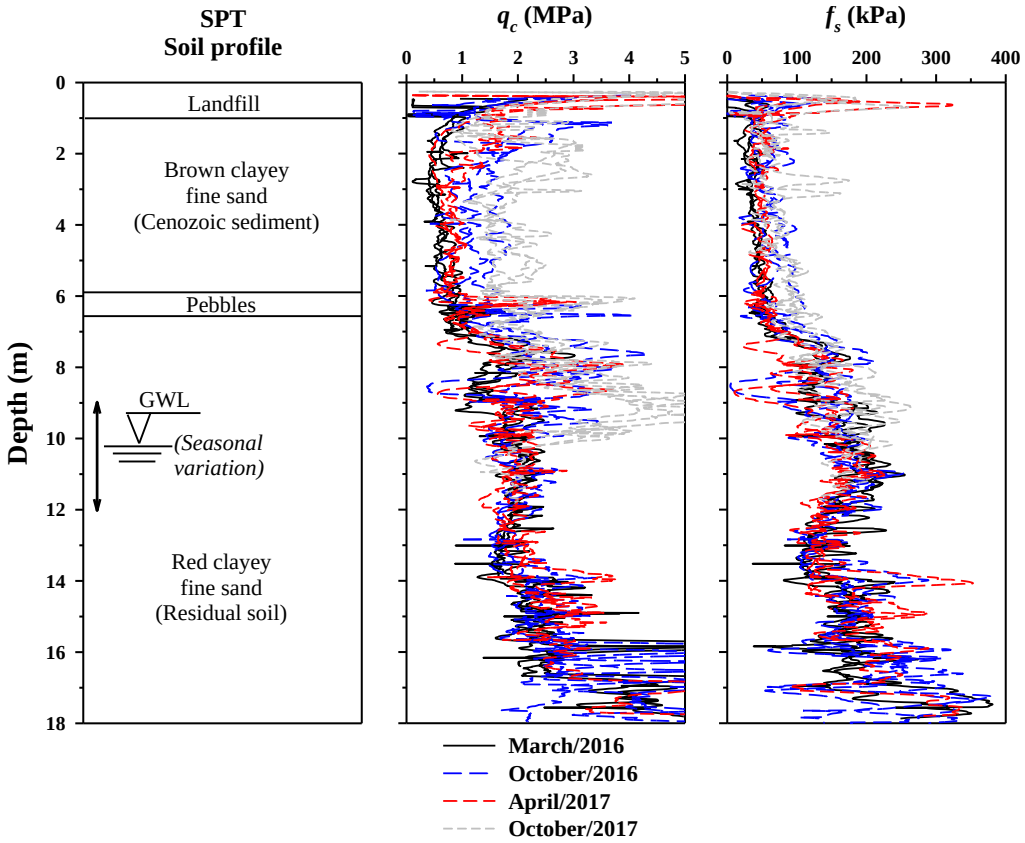

Figure 7. Typical soil profile and all the CPT data (q_c and f_s) for the study site (Rocha, 2018).

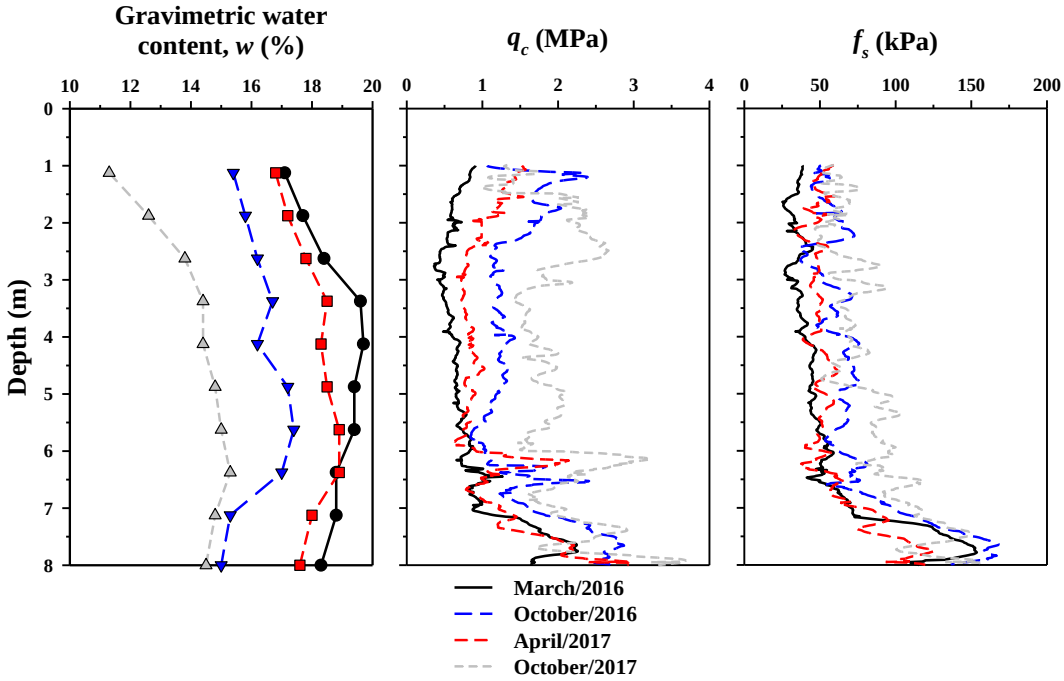

Figure 8. Average q_c and f_s profiles and gravimetric water content profiles determined for each test campaign.

Figure 9 illustrates the gravimetric water content and the soil suction (u_a - u_w) influence in q_c values for São Carlos site. Soil suction was estimated from the average SWRC, and the gravimetric water content profiles (Figure 4 and 6). The average cone resistance values were plotted against the average gravimetric water content and soil suction values, considering each test campaign. The average q_c values were associated to the gravimetric water content and soil suction values over 0.3 m depth interval. Linear regression has been used to represent changes in the cone resistance for a given variation in moisture content. However, hyperbolic regression between cone strength and soil suction was used because several studies have shown that strength and stiffness tend to increase nonlinearly with soil suction (Escario & Sáez, 1986; Nyunt, Leong, & Rahardjo, 2011; Vilar, 2006). It should be mentioned that these relationships should be used with caution to evaluate changes in cone strength, due to variations in gravimetric water content or soil suction. These empirical relationships are a preliminary manner to evaluate possible variations in cone strength for a given change in water content or suction for similar soils. The presented data confirm the strong dependence of cone resistance on gravimetric water content and soil suction, even for *in situ* test data. The increase in cone resistance with soil suction is in accordance with what has been observed and reported by other researchers in calibration chambers and *in situ*, with an equivalent coefficient of determination (R^2) (Giacheti et al., 2019; Miller et al., 2018; Pournaghiazar et al., 2013; Yang & Russell, 2016).

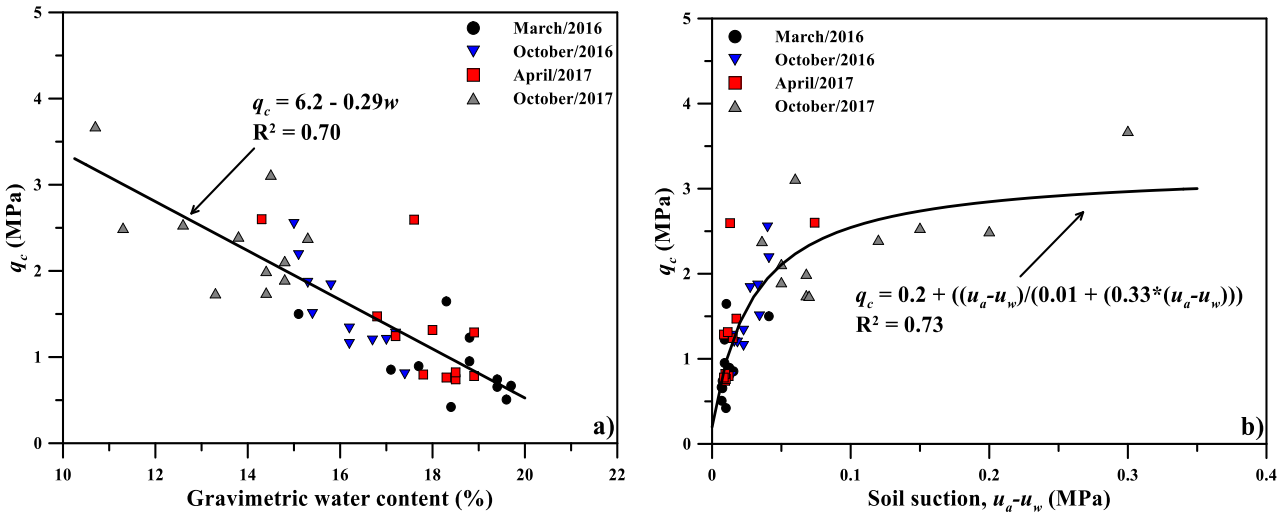

Figure 9. Average cone resistance versus gravimetric water content (a) and soil suction (b) for São Carlos site.

CPT interpretation in unsaturated soils

CPT is one of the current *in situ* tests for estimating geotechnical properties of soils. The interpretation is well established for saturated or dry soils, such as soft clays and pure sands (young and uncemented). Few approaches specifically consider the influence of soil suction on the estimative of soil properties by CPT, such as the bearing capacity theory (Miller et al., 2018, Miller, Collins, Muraleetharan, & Abuawad, 2021) and the effective stress (Bishop, 1959; Khalili, Geiser, & Blight, 2004).

Bearing capacity theory approach

Durgunoglu and Mitchell (1975) developed equations for predicting cone resistance for soils containing both stress dependent (friction angle, ϕ) and stress independent (cohesion intercept, c) components of strength. It is important to mention that there are different theoretical approaches to model penetration resistance in soil. The bearing capacity theory is a simple and practical tool. So, using this theory is a logical place to start with the analysis of penetration resistance in unsaturated soil, considering the added complexity introduced by partial saturation in soil mechanical behavior (Miller et al. 2018). Cone resistance based on bearing capacity theory is given by Equation 1:

$$q_c = cN_c\xi_c + \gamma_s B N_{\gamma q}\xi_{\gamma q} \quad (1)$$

where: c is the cohesion intercept of the Mohr-Coulomb failure envelope, γ_s is the soil unit weight, B is the cone base width, N_c and $N_{\gamma q}$ are bearing capacity factors, and ξ_c and $\xi_{\gamma q}$ are shape factors. The bearing capacity factors can be obtained by equations or charts provided by Durgunoglu and Mitchell (1975).

Miller et al. (Miller et al., 2018) extended the Durgunoglu and Mitchell's method (Durgunoglu & Mitchell, 1975) to unsaturated CPT problems by incorporating an unsaturated strength equation (Equation 2) proposed by Vanapalli, Fredlund, Pufahl, and Clifton (1996).

$$\tau = c' + (\sigma_n - u_a)(\tan\phi') + (u_a - u_w)(\tan\phi')(\theta - \theta_r)/(\theta_s - \theta_r) \quad (2)$$

where: c' = effective stress cohesion, σ_n-u_a = net normal stress on failure plane, σ_n = total normal stress on failure plane, u_a = pore air pressure, ϕ' = effective stress friction angle, u_a-u_w = soil suction, u_w = pore water pressure, θ = volumetric gravimetric water content, θ_r = residual volumetric gravimetric water content, and θ_s = saturated volumetric gravimetric water content.

Equation 2 is included into Equation 1 to capture the influence of matric suction on the predicted cone resistance of an unsaturated soil, which gives Equation 3. Thus, having SWRC, c' and ϕ' for a given soil, the q_c value can be estimated for the complete suction range represented by the retention curve.

$$q_c = [c' + (u_a - u_w).(\tan\phi').(\theta - \theta_r)/(\theta_s - \theta_r)]N_c\xi_c + \gamma_s B N_{\gamma q}\xi_{\gamma q} \quad (3)$$

A spreadsheet was used to predict cone resistance values from bearing capacity theory (Equation 3). Figure 10 shows the predicted q_c values for unsaturated soils based on bearing capacity theory (Equation 3), SWRC (Figure 4), the assumed soil properties considering the laboratory test data (Table 1), and the estimated parameter to achieve a better match between the predicted and measured q_c values (Table 2). The N_c and $N_{\gamma q}$ were determined by Durgunoglu and Mitchell (Durgunoglu & Mitchell, 1975) charts assuming relative depth of penetration (D/B; D: depth; B: width of cone base) equal to 10 and the roughness ratio (δ/ϕ; δ: cone base to soil friction angle; ϕ: soil friction angle) equal to 0. These premises imply on deep penetration with a perfectly smooth penetrometer. ξ_c and $\xi_{\gamma q}$ values were also calculated by Durgunoglu and Mitchell (1975)' equation. This approach was exactly the same proposed by Miller et al. (2018). Volumetric gravimetric water content was calculated from gravimetric water content and dry specific mass (ρ_d).

By referring to Figure 10, it becomes evident that the trends of the predicted q_c values compare favorably to trends of the measured q_c values when c' = 13.5 kPa and ϕ' = 35.5° were obtained from Equation 3. However, the assumed shear strength parameters are quite different from those determined via triaxial tests (Machado, 1998): ϕ' = 30° and c' = 10 kPa. In addition, residual volumetric (θ_r) and saturated volumetric (θ_s) water contents are also quite different from those obtained by soil water retention curves (SWRC). The lack of agreement between the c', ϕ', θ_r, and θ_s parameters on the "best fit" model and the values obtained by the laboratory test can be explained by possible experimental errors in testing, variability, and quality of test samples, as well as in the assumptions implied by the bearing capacity theory and the application of this theory. Although all these factors can affect the predicted q_c values, the bearing capacity model has provided predicted curves of

q_c versus soil suction that correspond to trends observed *in situ* CPT data. This model can be used to generate a family of curves, corresponding to a range of strength parameters (estimated or measured), and assumed conditions based on to CPT data.

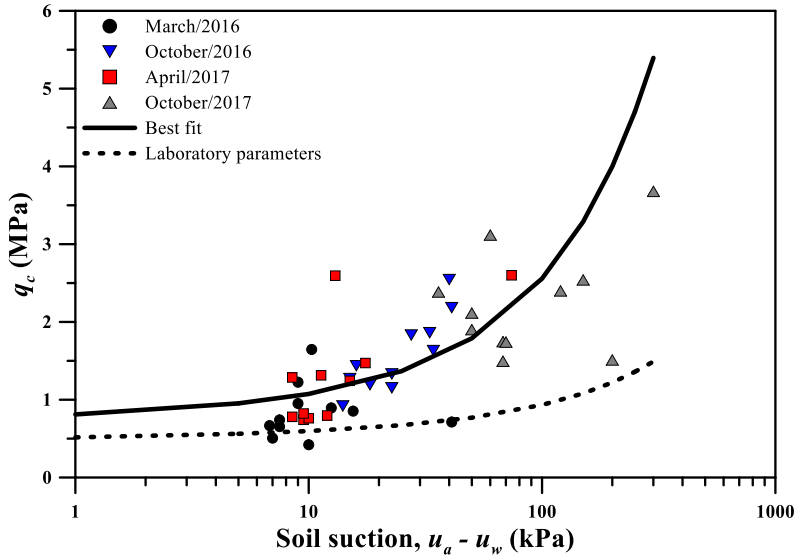

Figure 10. Measured and predicted q_c values for the study site determined by the different test campaigns.

Table 1. Adapted laboratory (triaxial tests and SWRC) and bearing capacity theory parameters.

ϕ' (°)	c'(kPa)	B (m)	N_c	$N_{\gamma q}$	ξ_c	$\xi_{\gamma q}$	θ_s	θ_r
30	10	0.0357	30.14	22.40	1.61	0.60	43.96	17.43

Table 2. Estimated parameters (triaxial tests and SWRC) and bearing capacity theory parameters.

ϕ' (°)	c'(kPa)	B (m)	N_c	$N_{\gamma q}$	ξ_c	$\xi_{\gamma q}$	θ_s	θ_r
35.5	13.5	0.0357	36.64	22.44	1.96	0.60	32.58	11.85

Effective stress approach

Another approach for CPT interpretation in unsaturated soils is to incorporate soil suction into vertical effective stress (σ'_v) (Giacheti et al., 2019; Khalili & Khabbaz, 1998; Lo Presti et al., 2018; Pournaghiazar et al., 2013; Robertson, Fonseca, Ulrich, & Coffin, 2017) following the work of Bishop (Bishop, 1959), where the *in situ* σ'_v is defined as:

$$\sigma'_v = (\sigma_v - u_a) + \chi\ (u_a - u_w) \quad (4)$$

where u_a is the pore-air pressure, u_w is the pore-water pressure, $u_a - u_w$ is the soil suction, $\sigma_v - u_a$ is the net total stress, and χ is the effective stress parameter, with a value of 1 for saturated and 0 for dry geomaterials.

The suction values can be estimated from SWRC whereas the effective stress parameter (χ) can be assumed equal to the degree of saturation (S_r) (Giacheti et al., 1993; Öberg & Sällfors, 1997; Robertson et al., 2017; Rocha et al., 2021). The S_r profiles were calculated from the index properties presented in Figures 2 and 6. Average in-situ soil suction and average χ parameter values were determined for each test campaign (Table 3) from average SWRC (Figure 4) and S_r profiles. Based on the SWRC and physical properties of the studied soil, it can be assumed that the χ parameter can vary from 0.24 to 0.73 for S_r from 24 to 73% and the soil suction can vary from 5 kPa to 300 kPa.

Table 3. Average χ parameter and soil suction values assumed for each test campaign.

March/2016		October/2016		April/2017		October/2017	
χ	$u_a - u_w$ (kPa)	χ	$u_a - u_w$ (kPa)	χ	$u_a - u_w$ (kPa)	χ	$u_a - u_w$ (kPa)
0.65	10	0.56	28	0.62	14	0.42	150

The higher soil suctions values in October 2017 can be explained by the presence of trees on the site. During the dry season, these trees extract water from the soil through their roots, leading to a decrease in soil

saturation levels to around 40%. These values were obtained from index properties. Lehane et al. (2004) observed that water uptake by tree roots has the potential to increase large strain *in situ* test parameters (i.e., q_c) due to increase in soil suction. They estimated soil suction values between 125 and 220 kPa at 3.5 m depth, and lower values at 6.5 m depth in treed area.

The CPT interpretation starts by normalized cone resistance (Q_{tn}) determination (Equation 5), which is used for classifying soil behavior type, assessing whether the soil is contractile or dilatant, as well as estimating design parameters.

$$Q_{tn} = \frac{q_c - \sigma_v}{p_a}\left(\frac{p_a}{\sigma'_v}\right)^n \quad (5)$$

where σ_v is the total stress, σ'_v is the *in situ* vertical effective stress, p_a is the atmospheric reference pressure and $(q_c - \sigma_v)/p_a$ is the dimensionless net cone resistance, $(p_a/\sigma'_v)^n$ is the stress normalization factor, and n is the stress exponent that relates soil behavior type (SBT I_c) to σ'_v in power law relationships defined by

$$n = 0.381(I_c) + 0.05\left(\frac{\sigma'_v}{p_a}\right) - 0.15 \quad (6)$$

where $n \leqslant 1$.

When dealing with unsaturated soils, it is important to take soil suction into consideration. Failure to do so can lead to unknown misrepresentations in estimated properties and soil classification. Figure 11 shows Q_{tn} determined by Equation 5 without incorporating (Figure 11a) and considering the soil suction in the σ'_v (Figure 11b). The exponent n was calculated by an interactive method, as described by Robertson (2009). It was assumed equal to 0.97 for both saturated and unsaturated conditions for this site. When the soil suction is included in the effective stresses (Equation 4 and Table 3), the Q_{tn} profiles determined in each campaign are similar (Figure 11b).

This approach was used by Giacheti et al. (2019) to tackle the influence of soil suction in CPT carried out in Bauru site up to a depth of 4 m, and the importance of considering seasonal variability in unsaturated soil sites. The authors showed that when the soil suction was incorporated in the effective stresses, the average q_c profile determined during the dry season is like the q_c profile determined during the wet season.

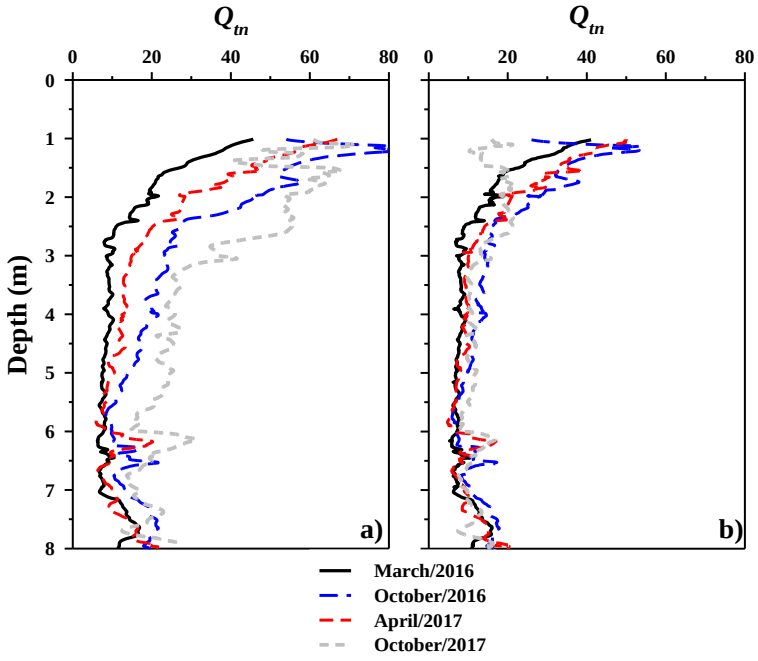

Figure 11. Normalized cone resistance (Q_{tn}) profiles, without (a) and considering (b) soil suction in effective stress for the study site.

Conclusion

An appropriate site characterization for unsaturated soil sites should consider seasonal variations in suction. The effects of soil suction are more pronounced in soils with low density and at low confining stresses. So, the influence of suction on *in situ* testing is more important to be considered for shallow depths, where a soil is more likely to be unsaturated. The presented data show the seasonal variation in gravimetric water content and soil suction, and how it significantly influences CPT data up to 6 m depth for the studied site.

The influence of soil suction on CPT was evaluated considering the bearing capacity theory and the effective stress approach. The shear strength parameters values assumed to relate the cone resistance to soil suction were quite different from the determined values in laboratory. The bearing capacity theory is a simple approach and a starting point in the CPT interpretation. Another approach was also used, where the influence of soil suction was incorporated into σ'_v by using χ and soil suction, estimated from gravimetric water content profiles and soil water retention curves, which allowed a better interpretation of CPT data.

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