The Flat Dilatometer Test in an Unsaturated Tropical Soil Site

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TECHNICAL NOTE

The Flat Dilatometer Test in an Unsaturated Tropical Soil Site

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Abstract The site characterization of unsaturated soils is well stablished based on laboratory tests, which are expensive and time-consuming. In-situ testing methods, such as the flat dilatometer test (DMT), are an alternative to the traditional approach of drilling, sampling, and laboratory testing. The literature on DMT interpretation is well established on saturated and well-behaved soils. Only few studies deal with DMT interpretation in unusual soils, and little is known about the influence of soil suction on this test. This paper presents and discusses the influence of soil suction on four DMT campaigns carried out in an unsaturated tropical soil site, also incorporating the soil suction influence on the DMT interpretation. Soil suction was estimated by the soil–water characteristic curve (SWCC) and water content profiles. The water content profiles range from 11.3 to 19.7% which corresponds to a suction range estimated by SWCCs mostly between 6 and 200 kPa. Soil suction significantly influenced DMT data up to 5 m depth at the studied site (the unsaturated active zone) increasing the intermediate DMT parameters. The average horizontal stress index (K_D) was equal to about 1.7 and the average dilatometer modulus (E_D) was about 4.7 MPa in the active zone and practically doubled their values due to in situ soil suction. The estimated peak friction angle (ϕ) was 20–30% higher due to soil suction influence on DMT assuming the soil behaves as a sand like material. Soil suction must be considered to assess the behavior of the investigated soil by the DMT. The suction influence should be incorporated in the effective stress and this approach considerably improved the site characterization of the studied site.

Keywords Flat dilatometer test · Water content profile · Soil–water characteristic curve · Suction

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1 Introduction

Unsaturated soils are widely found worldwide in several geotechnical engineering applications such as foundations, embankments, dams, and slopes. Suction increases the shear strength and stiffness of soils (Alonso et al. 1990; Russell and Khalili 2006). Unsaturated soils can only be properly characterized by special laboratory tests, which are expensive and time-consuming since this process involves undisturbed soil sampling. In-situ testing methods such as the flat dilatometer test (DMT) can be used as an alternative to the traditional approach of drilling, sampling, and laboratory tests, mainly in cohesionless soils, from which reliable undisturbed soil samples cannot be retrieved.

The flat dilatometer test is simple, operator-independent, rapid, and increasingly used in geotechnical engineering practice (Marchetti 1980; Campanella and Robertson 1991; Marchetti and Monaco 2018; Ricceri et al. 2002; Viana da Fonseca et al. 2006). The used approach to interpret DMT was developed based on saturated and dry, young and uncemented sandy, silty, and clayey soils (Marchetti 1980; Lunne et al. 1989; Marchetti et al. 2001).

Studies on the suction influence on in-situ tests have increased from CPT data (Hryciw and Dowding 1987; Lehane et al. 2004; Pournaghiazar et al. 2013; Collins and Miller 2014; Yang and Russell 2016; Lo Presti et al. 2016, 2018; Miller et al. 2018; Giacheti et al. 2019) and little has been done on DMT in unsaturated soils. Berisavljević and Berisavljević (2019) present an approach for investigating the presence of microstructure in soils based on seismic dilatometer (SDMT) data. The authors state that the influence of soil suction on DMTs carried out above the groundwater level is unknown, but they believe it can be significant. Cruz et al. (2014) suggested an approach to characterize granitic residual soil from DMT data, which considers the influence of cementation and suction.

This paper presents and discusses the influence of soil suction on DMT carried out in an unsaturated tropical soil site. DMTs and water content profiles were determined in four different campaigns during 2016 and 2017. The test data are presented and interpreted considering the soil–water characteristic curves (SWCC). Soil suction influence was incorporated to the effective stress following Bishop's (1959) equation to interpret the DMT data.

2 Material and Methods

2.1 DMT

The flat dilatometer test consists of pushing a 94 mm wide and 14 mm thick steel plate with an approximate 16° cutting edge into the soil and expanding a 60 mm diameter thin metal membrane, mounted flush on one side of the plate, horizontally against the soil by gas pressure. Two pressure readings are taken: the A-pressure is required to just begin to move the membrane into the soil and the B-pressure is required to move its center 1.1 mm against the soil. Then, these two pressures are corrected for membrane stiffness and converted into p_0 and p_1.

The interpretation of DMT data begins by determining three intermediate DMT parameters (Marchetti et al. 2001):

$$\text{Material index, } I_D = \frac{p_1 - p_0}{p_0 - u_0} \tag{1}$$

$$\text{Horizontal stress index, } K_D = \frac{p_0 - u_0}{\sigma'_v} \tag{2}$$

$$\text{Dilatometer modulus, } E_D = 34.7(p_1 - p_0) \tag{3}$$

where u_0 represents the pre-insertion in-situ equilibrium pore pressure and σ'_v is the in-situ vertical effective stress.

2.2 Effective Stress Approach

Suction causes contact forces on particles in the unsaturated soil, increasing the strength and stiffness of the soil compared to saturated and dry soil states. The macroscopic effects are increase in the stiffness of the soil skeleton and in the effective stress (Leroueil and Hight 2003; Pournaghiazar et al. 2013).

Following the study of Bishop (1959), effective stress σ'_v is defined as:

$$\sigma'_v = \sigma_v + \chi(u_a - u_w) \tag{4}$$

where σ_v is the in-situ total vertical stress; χ is the effective stress parameter (1 for saturated soils and 0 for dry soils); $(u_a - u_w)$ is the suction, being the difference between pore air (u_a) and pore water pressure (u_w). The χ parameter is usually assumed to be equal to the degree of saturation, S_r varying from 0 to 1 for practical applications. (Fredlund et al. 1995; Öberg and Sällfors 1997; Leroueil and Hight 2003; Robertson et al. 2017; Giacheti et al. 2019).

2.3 Study Site

The in-situ tests were conducted in a tropical soil research site at the University of São Paulo in São Carlos, Brazil. Tropical soils are formed predominantly by chemical alteration of the rock and includes both lateritic and saprolitic soils. Saprolitic soils are necessarily residual and retain the macro fabric of the parent rock. Lateritic soils can be either residual or transported and are distinguished by the occurrence of laterization process. Following laterization, high concentration of oxides and hydroxides of iron and aluminium bonds support a highly porous structure. The weathering process of the lateritic soil is responsible for the complete lack of texture and structure of the bedrock caused by intense pedogenetic and morphogenetic processes during the soil formation, which shows isotropic, mineralogical, and grain size homogeneity not only vertically but also horizontally (Vaz 1996).

The site profile is a saprolitic sandstone residual soil layer covered by a lateritic clayey sand layer (6 m thick colluvial soil—Cenozoic sediment) that exhibits collapsible behavior upon wetting (Machado and Vilar 1998). A 0.2–0.5 m thick layer of pebbles separates the Cenozoic sediment layer from the residual soil. The groundwater table varies seasonally between 9 and 12 m below the ground surface.

2.3.1 Site Investigation from Laboratory Tests

Figure 1 presents the grain size distribution and some index properties (dry unit weight, void ratio, liquid—w_L and plastic—w_P limits) and the typical profile of the study site. The particle unit weight (γ_s) can be assumed constant over depth and equal to 27.2 kN/m^3. According to Unified Soil Classification System (ASTM D 2487-2011), both soil layers (the residual soil and Cenozoic sediment) are classified as clayey sand—SC group.

The soil–water characteristic curves (Fig. 2a) were determined by Machado (1998) from undisturbed samples collected at 2, 5 and 8 m depth. The soil samples were firstly saturated and then drained under increasing suction (desorption curves). Two techniques were used: suction plate for suction values lower than 13 kPa and pressure chamber (ASTM D 6836-2016a) for suction values between 13 and 350 kPa and the data were adjusted according to the van Genuchten (1980) equation. A common characteristic of the three curves is that the air entry value is very low (nearly zero). The curves are typical of sands in that most of the water is extracted by a small change in soil suction, in this case from 1 to 100 kPa. This type of curve has a steep macrostructure desaturation zone, i.e. the water content varies greatly with slight suction variation in the Region 1. The opposite trend occurs in the Region 2 where the values of suction vary significantly with little water content variation.

Triaxial compression and oedometer tests were performed on saturated and non-saturated samples,

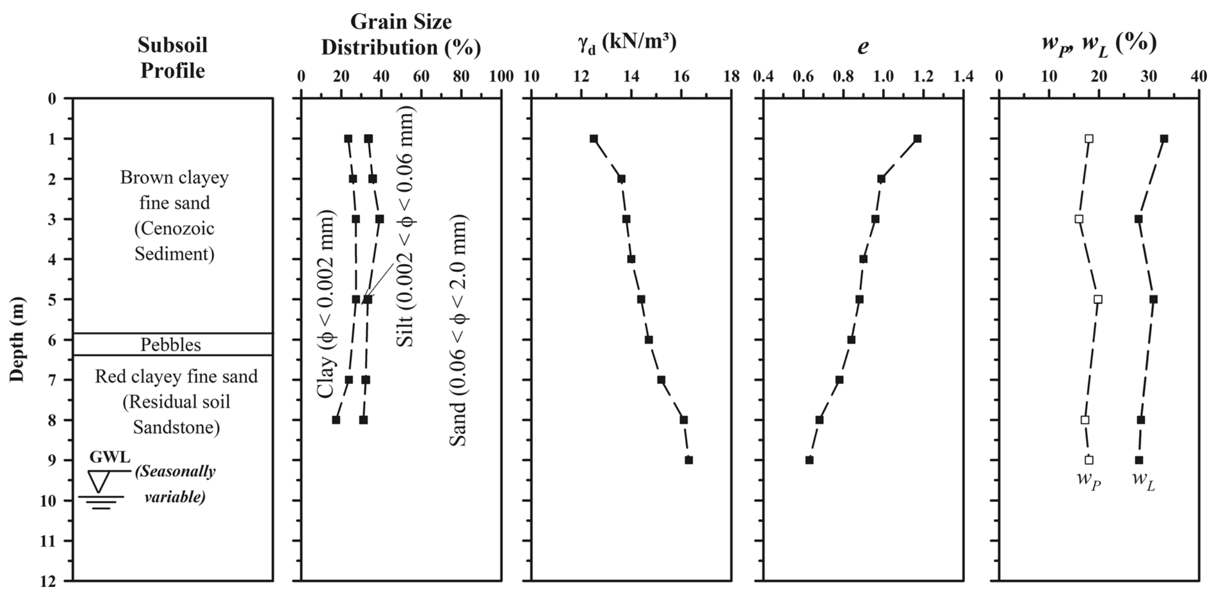

Fig. 1 Subsoil profile, grain size distribution and index properties of the soil in the study site. Adapted from Machado (1998)

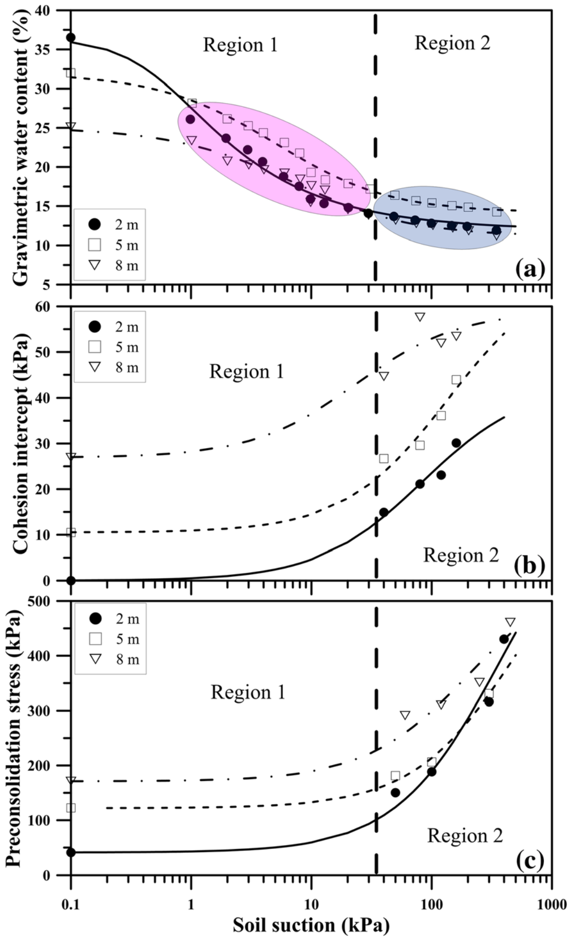

Fig. 2 **a** Soil–water characteristic curves, **b** cohesion intercept and, **c** pre-consolidation stress for the soil samples collected at 2, 5 and 8 m depth. Adapted from Machado (1998)

using hand-carved undisturbed blocks taken from 2, 5 and 8 m depth from a sampling pit (Machado 1998). Controlled suction tests were carried out by imposing the desired suction according to axial translation technique (Hilf 1956). The unsaturated triaxial tests were carried out with suction values equal to 0, 40, 80, 120 and 160 kPa and net stress values of 50, 100, 200 and 350 kPa (Fig. 2b). The unsaturated oedometer tests were carried out with suction values of 50, 100, 300, 400 and 450 kPa (Fig. 2c).

Figure 2 also shows the influence of suction on cohesion (c—Fig. 2b) and pre-consolidation stress (σ_p—Fig. 2c) for samples representative of the three tested depths. It shows that the values c and σ_p increase with soil suction. It is also observed in this figure that the values c and σ_p are slightly influenced by suction for water content higher than 15–16%, i.e., Region 1 of SWCCs. This is the desaturation zone of the curve, where the water in the soil mass is generally exposed to gravitational forces. In Region 2 of SWCCs, both c and σ_p vary markedly with suction, for water content values below 15–16%. In this region a slight variation in water content substantially modifies soil suction. Although the influence of soil suction on the geotechnical behavior of this soil has been well studied from laboratory tests, (Fig. 2), little is known about the influence of soil suction on in-situ test data.

2.3.2 *Water Content Profiles*

Water content profiles were determined in the site by Morais et al. (2020) and during this study. Precipitation is constantly monitored in São Carlos city by the São Paulo Department of Water and Electricity (DAEE) (DAEE 2020) and was assumed representative for the site. Precipitation is higher during the summer, from December to March, and lower during the winter, from June to September. The total precipitation was higher in 2015 and 2016 than in 2017 and 2018. Figure 3 shows the differences in gravimetric

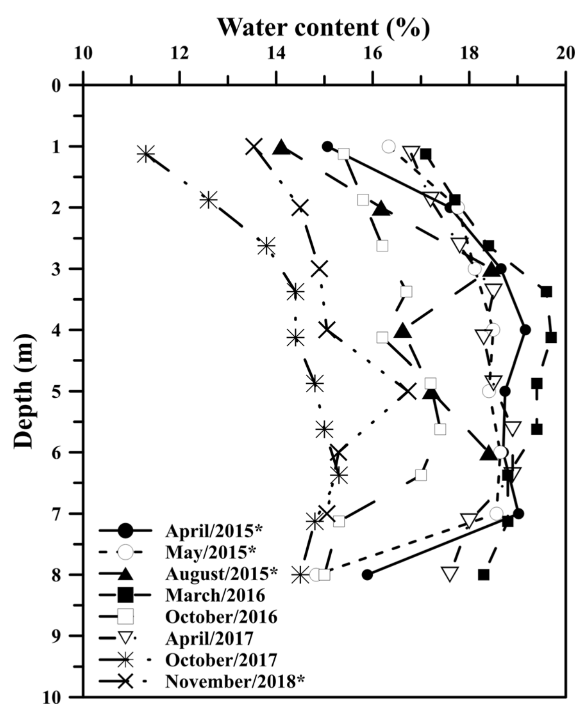

Fig. 3 Water content profiles determined in the study site (*data from Morais et al. 2020)

water content in the dry and wet seasons between 2015 and 2018. March/2016 was the period with higher moisture content and October/2017 was the lowest at the end of the dry season.

The low water content values in October/2017 can be explained by the presence of trees on the site. The extraction of water via the roots of the trees during the dry season brought the level of saturation to approximately 40% and, consequently, high values of soil suction. Lehane et al. (2004) and Giacheti et al. (2019) reported the influence of soil suction on CPT data caused by tree roots. Lehane et al. (2004) estimated soil suction values equal to 125 kPa and 220 kPa at 3.5 m depth and lower values at 6.5 m depth.

2.3.3 In Situ Experimental Program

Four in-situ tests campaigns were performed in the study site. Three DMTs and one soil sampling were conducted in each campaign. Figure 4 shows the position of DMTs and soil samplings. These campaigns were performed in March and October/2016 and, April and October/2017. DMTs were performed down to 10.0 m depth. Soil sampling was performed by using a helical auger, collecting samples every 0.75 m intervals down to 8.0 m depth to determine the water content profile and its variation over depth for each campaign. The soil samples were weighed and oven-dried to determine the gravimetric water content, according to ASTM D 4959 (2016b). The DMTs were performed according to ASTM D 6635 (2015).

3 Test Data

3.1 Water Content and Intermediate DMT Parameters

Figure 5 shows the water content profiles determined in March/2016, October/2016, April/2017 and October/2017. The water content values determined in October/2017 campaign are lower than 15.3%, ranging from 11.3 to 15.3%, basically in the Region 2 of the SWCC (Fig. 2a). The water content values from all the other campaigns (March/2016, October/2016 and April/2017) are higher than 15.6% in the colluvium soil layer (up to around 6.5 m depth) and they are mainly in the Region 1 of the SWCC (Fig. 2a).

Region 1 is the part of the curve where the macrostructure desaturation zone occurs, i.e., the water content varies greatly with slight suction variation. The opposite trend occurs in Region 2, where the suction values vary significantly with little water content variation.

Figures 6, 7, 8, and 9 show the DMT data and the intermediate DMT parameters respectively for March/2016, October/2016, April/2017 and October/2017 campaigns. The I_D, K_D and E_D profiles were determined using the current DMT correlations (Marchetti 1980).

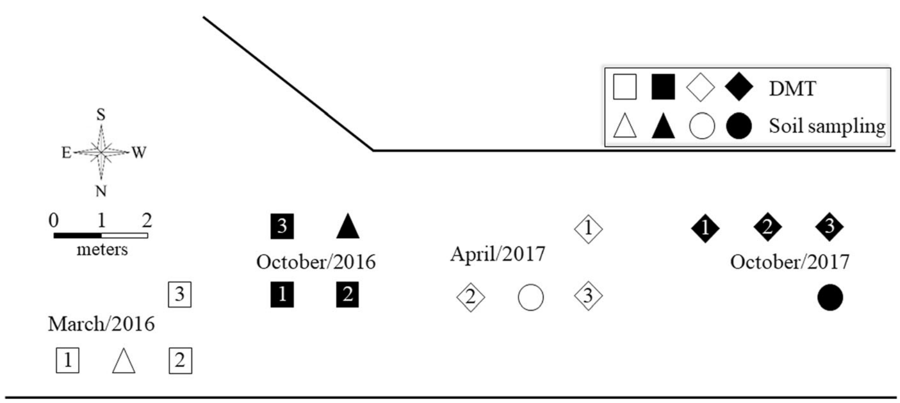

Fig. 4 DMTs and soil sampling carried out at the site

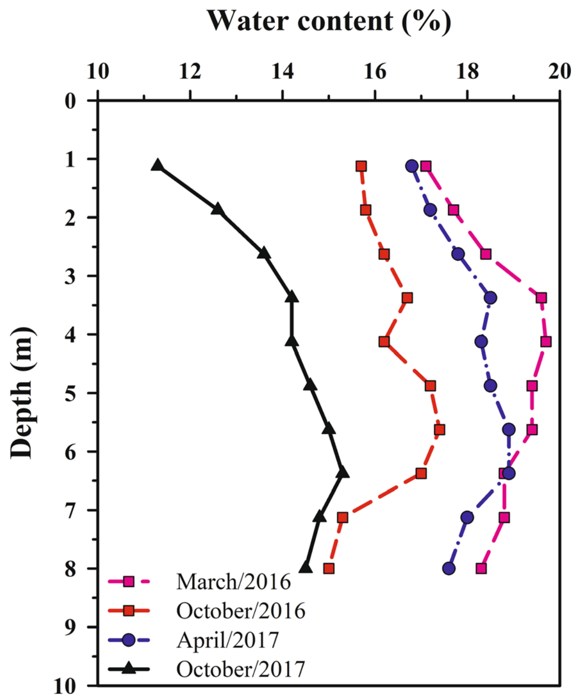

Fig. 5 Water content profiles determined during the DMT campaigns

4 Suction Influence on DMT Data

4.1 DMT Parameters and Water Content Profile

Figure 10 was designed to emphasize the difference between two DMTs carried out in quite different water content conditions and presents p_0, p_1, I_D, K_D and E_D for each test. One test was performed in the lowest water content (October/2017) and the other in highest water content (March/2016). These tests sought to present the soil suction influence in DMT. The variation in DMT is significant until approximately 5 m depth, the unsaturated active zone, mainly on the horizontal stress index (K_D) and on the dilatometer modulus (E_D). Such differences can be explained by the SWCCs presented in Fig. 2a. DMT carried out in March/2016 tend to be in Region 1, and the DMT from October/2017 in Region 2. The estimated soil suction values are lower for March/2016 and higher for October/2017. The observed variation in soil suction can significantly affect the behavior of engineering works constructed on the upper layer of the study profile, as discussed by Costa et al. (2003), Lim et al.

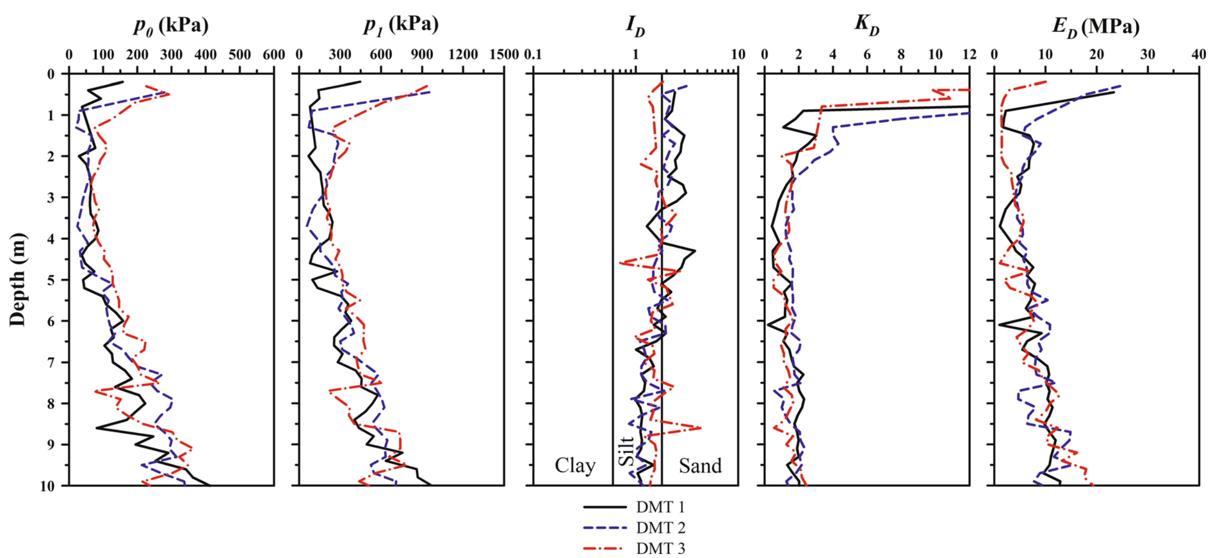

Fig. 6 DMTs carried out in March/2016 campaign

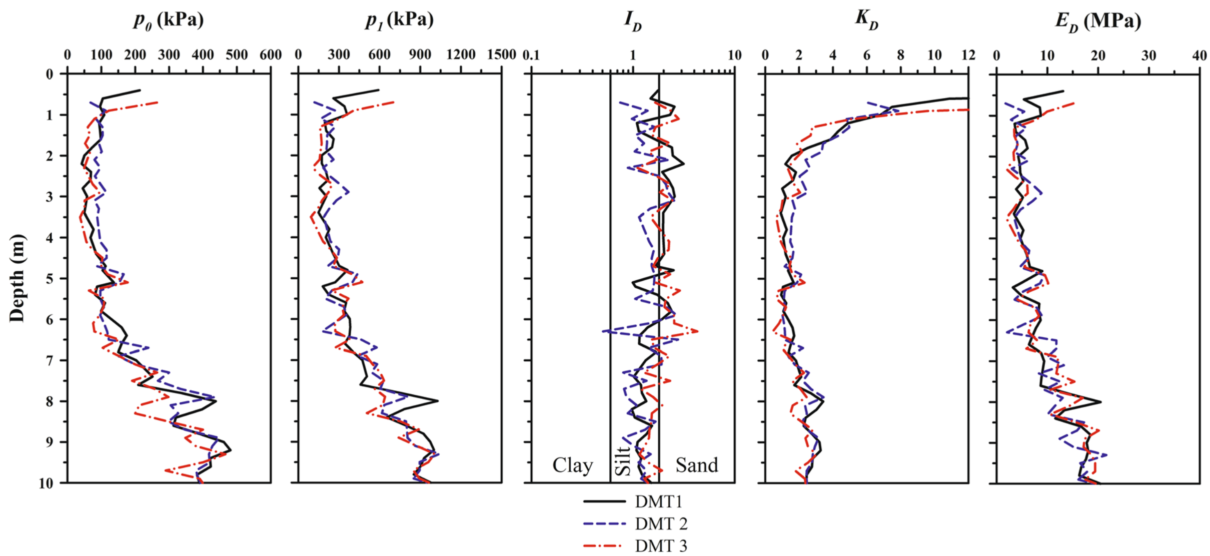

Fig. 7 DMTs carried out in October/2016 campaign

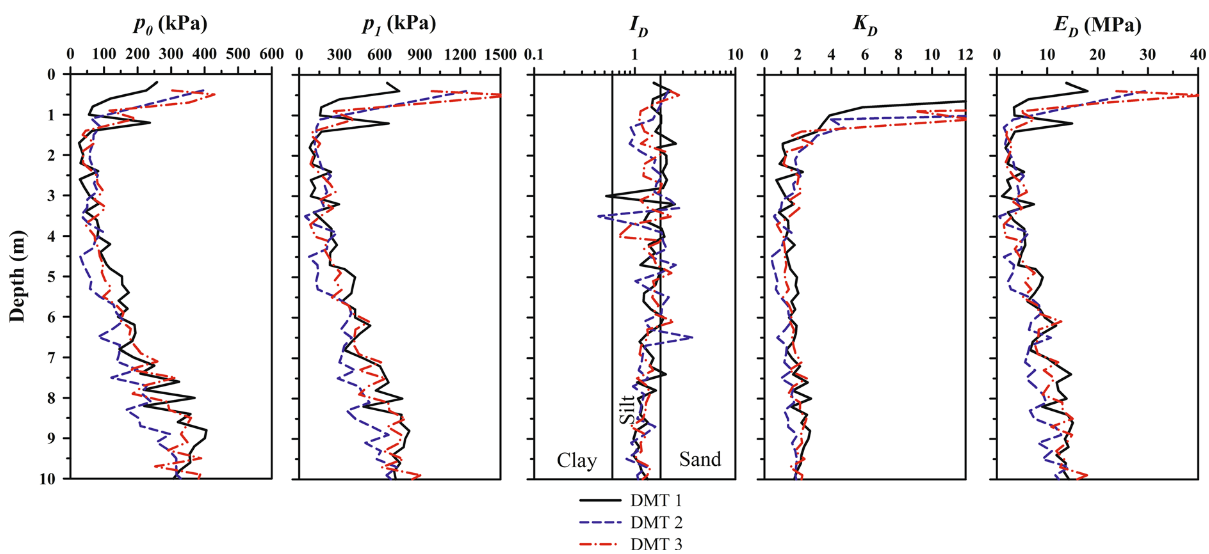

Fig. 8 DMTs carried out in April/2017 campaign

(1996) and Giacheti et al. (2019) and also affected DMTs as discussed below.

The water content profiles and average p_0, p_1, I_D, K_D and E_D for each campaign are plotted in Fig. 11 for a better visualization and assessment of the soil suction effect in all DMTs. The top 1.0 m layer is a heterogeneous desiccated fill and was the reason of higher K_D and E_D values presented in Figs. 6, 7, 8, 9 and 10. So, these values were not considered in this analysis.

Figure 11a shows the water content profiles determined in each test campaign. The water content profile determined in October/2017 is the lowest and March/2016 is the highest up to 6.5 m depth (the colluvium soil layer). The I_D (Fig. 11b) index allows classifying the soil in the DMT classification chart manly as a silt. It is also possible to observe in this figure that soil suction had some influence on soil classification. Such classification is not in accordance with the particle size distribution of this soil (clayey fine sand) but is

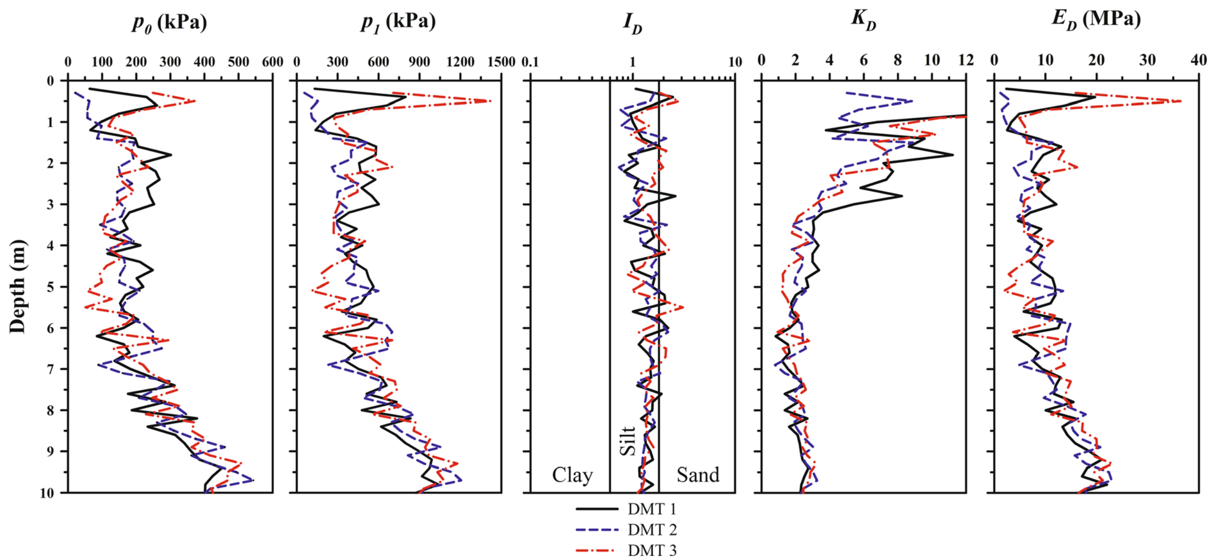

Fig. 9 DMTs carried out in October/2017 campaign

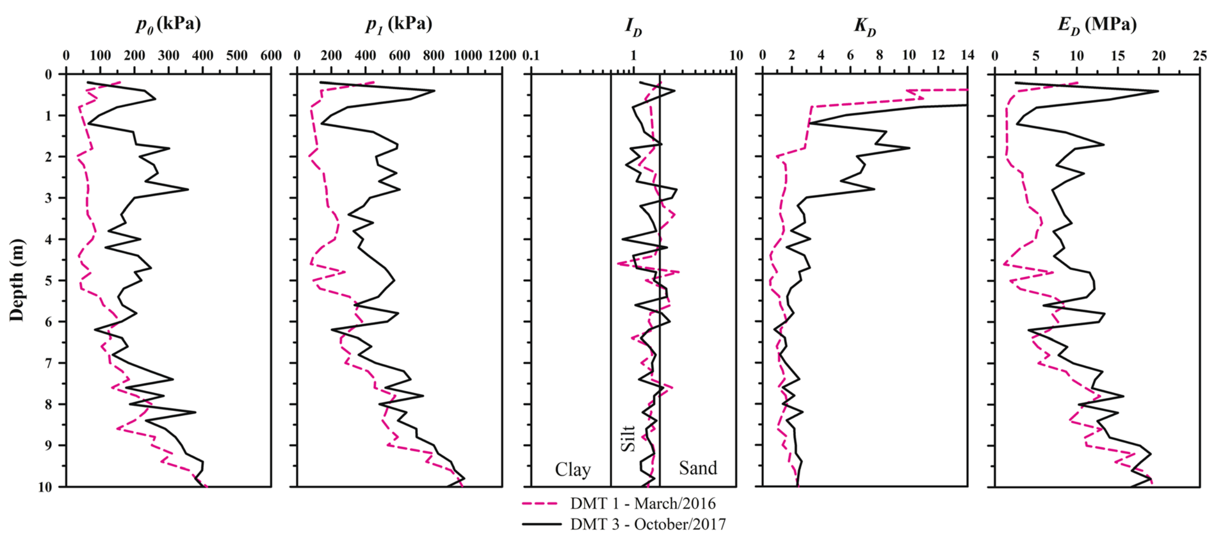

Fig. 10 DMTs carried out in different water content condition

reasonable with its behavior. It is important to point out that Marchetti et al. (2001) state the following: "In general, I_D provides an expressive profile of soil type, and, in *normal* soils, a reasonable soil description. Note that I_D sometimes misdescribes silt as clay and vice versa, and of course a mixture clay-sand would generally be described by I_D as silt."

The average K_D and E_D profiles determined in each test campaign are presented in Fig. 11c, d, respectively. The K_D and E_D profiles determined in October/2017 showed higher values than those determined in the other campaigns down to approximately 5–6 m deep. Such behavior can be explained by the influence of suction on the lower water content profile, since it is in Region 2 of the SWCC (Fig. 2a). Lutenegger (1988) reported similar behavior: a systematic decrease in K_D and E_D as the soil becomes softer (increase in water content) and little change in material index (I_D). Thus, DMTs performed on unsaturated soils should be interpreted considering variations in water content profile and the SWCC.

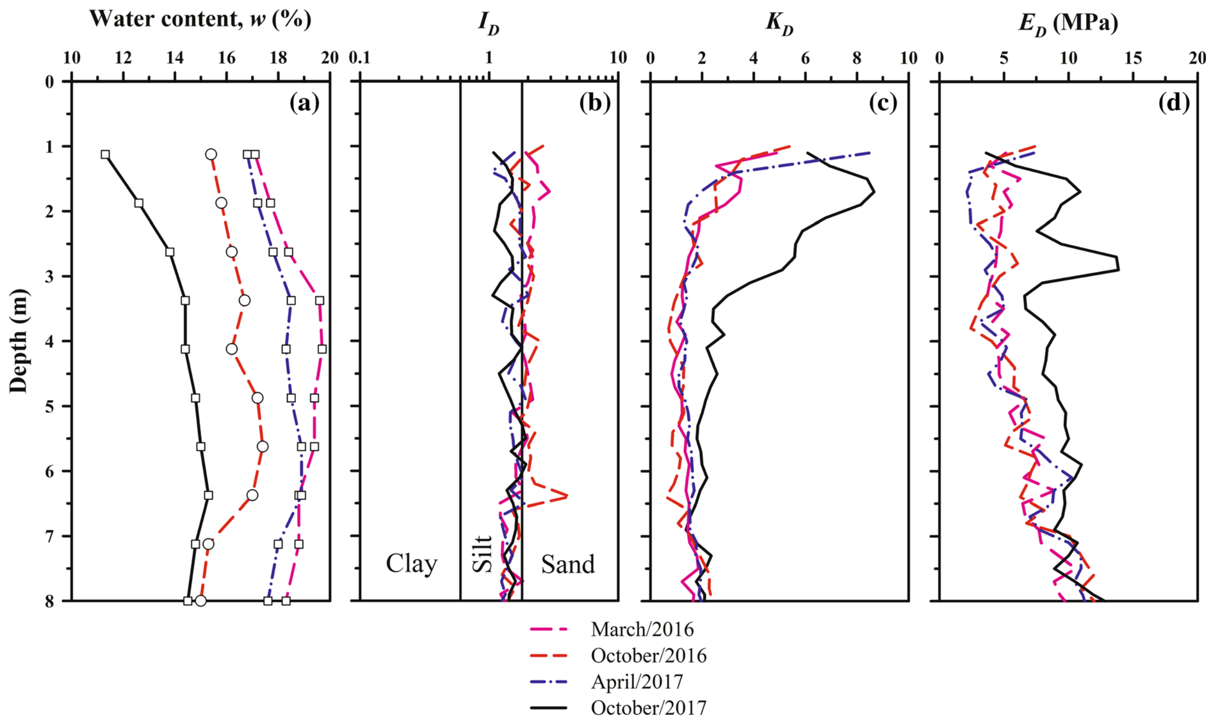

Fig. 11 Average I_D, K_D, E_D and water content profiles determined in each test campaign

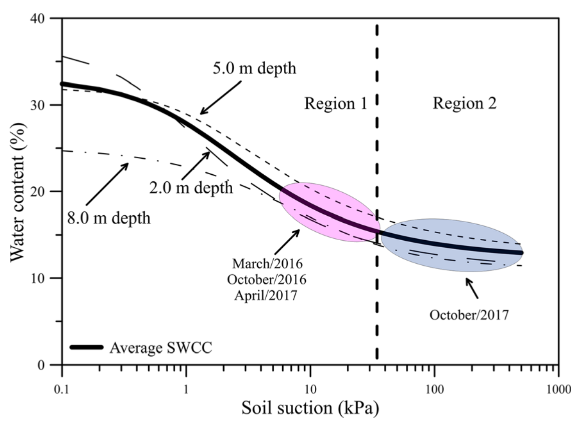

Fig. 12 Water content *versus* soil suction for each test campaign and the assumed average SWCC. Adapted from Machado and Vilar (1998)

4.2 Incorporating Soil Suction into the DMT Parameters

The estimated soil suction values were defined from the average SWCC presented in Fig. 12. The effective stress parameter (χ) was assumed to be equal to the degree of saturation (S_r) to incorporate soil suction into Bishop's (1959) effective stress equation. Fredlund et al. (1995) and Leroueil and Hight (2003) have demonstrated that χ varies linearly with S_r. It has been considered a satisfactory assumption for engineering purposes, and Robertson et al. (2017) used such approach in the site characterization of an unsaturated mine waste.

The degree of saturation (S_r) was calculated based on the water content profiles, particle unit weight (γ_s) and void ratio (e) from the data presented in Figs. 1 and 5. The in-situ water content profile ranged from 15.6 to 19.7% (Fig. 5) during the wetter campaigns (March/2016, October/2016 and April/2017), with estimated in-situ suction values varying from 6.5 to 35 kPa (Fig. 12). On the other hand, the in-situ water content profile varied between 11.3 and 15.3% in October/2017 (Fig. 5), and the estimated in-situ suction was higher than 40 kPa (Fig. 12). Hence, the parameter χ varied from 0.58 to 0.67 in March/2016, 0.51 to 0.60 in October/2016, 0.57 to 0.64 in April/2017 and 0.37 to 0.52 in October/2017. Table 1 shows the average χ parameter for each test campaign and the assumed soil suction value obtained from Fig. 12.

Figure 13a shows the measured K_D profiles without considering the soil suction influence while Fig. 13b

Table 1 χ and soil suction values assumed for each test campaign

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

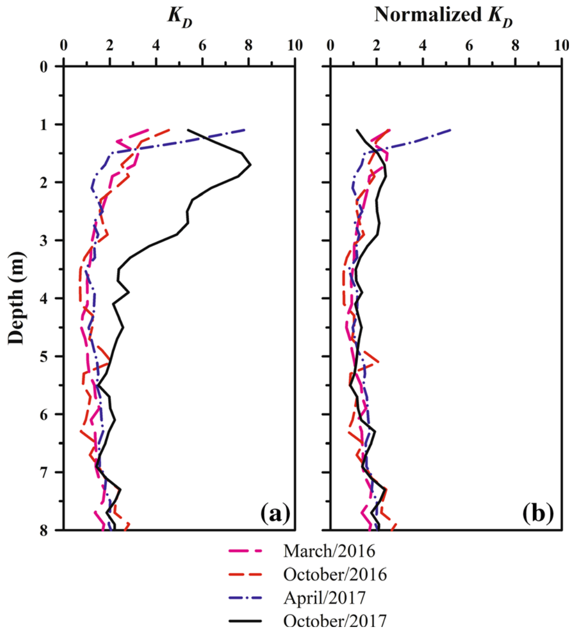

Fig. 13 **a** Determined horizontal stress index (K_D) without considering soil suction influence; **b** Normalized K_D with the soil suction incorporated in σ'_v

shows the normalized K_D profiles considering soil suction in the in-situ effective stress using Eq. (4) and χ and suction values presented in Table 1. When the suction values from each test campaign were incorporated in the effective stresses, the average K_D profiles were similar and equivalent to the no soil suction profile, with an average K_D value around to 1.7.

Soil suction influence can also be incorporated to the normalized dilatometer modulus (E_D). However, vertical effective stress is not included in Eq. (3). The Eq. (5) suggested by Janbu (1963) was used to calculate normalized E_D.

$$E_D = K_E.p_a.\left(\sigma'_v/p_a\right)^n \tag{5}$$

where n is a stress exponent (0.5 for most coarse-grained soils), K_E is the modulus number (which relates the soil stiffness to the stress state) and p_a is the atmospheric reference pressure assumed equal to 100 kPa.

Two steps were used to calculate the normalized E_D values (the modulus with no soil suction influence) based on the E_D values from DMT:

- The modulus number (K_E) was calculated by Eq. (5) considering the soil suction value (Table 1) into the σ'_v by Eq. (1).
- The normalized E_D value was calculated by Eq. (5) assuming K_E previously defined and, in this case, assigning soil suction equal to zero to calculate σ'_v.

Figure 14 presents the E_D profiles without considering the soil suction influence in the effective stress (Fig. 14a) and the normalized ones (Fig. 14b). It can be seen in Fig. 14a that the average E_D value for March/2016, October/2016, and April/2017 campaigns in the active zone (up to 5 m depth) is about 4.7 MPa and about twice as high for the October/2017 campaign. The assumed average χ and soil suction values for each test campaign allowed eliminating the

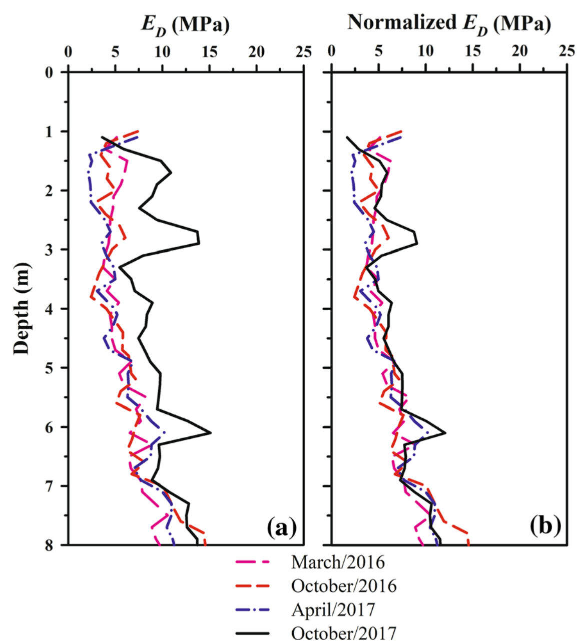

Fig. 14 **a** Determined and **b** normalized average dilatometer modulus (E_D) profiles

soil suction influence in the normalized E_D profiles (Fig. 14b).

Soil suction affects soil behavior and the estimative of peak friction angle (ϕ) by Marchetti (1997)'s equation (Eq. 6) was used to demonstrate such influence assuming the soil behaves as a sand like material.

$$\phi = 28^\circ + 14.6^\circ \log K_D - 2.1^\circ \log^2 K_D. \quad (6)$$

Figure 15a presents the estimated peak friction angle (ϕ) profile assuming the K_D values for each campaign ignoring the suction influence. Figure 15b shows the ϕ profile considering suction in σ'_v also using Eq. (4). The peak friction angle profiles were compared to ϕ values determined by triaxial tests performed by Machado and Vilar (1998) in saturated and unsaturated conditions on undisturbed soil samples collected at 2, 5, and 8 m depth. The unsaturated triaxial tests were carried out with suction values equal to 0, 40 and 160 kPa, and these suction values were selected to represent the in-situ soil conditions.

It can be observed in Fig. 15a that the estimated ϕ values by DMTs performed in March/2016, October/2016 and April/2017 are closer to the reference ones (triaxial tests) determined for 2 and 5 m depth samples. These values are 15% higher than those of the 8.0 m deep samples. In contrast, the estimated ϕ values for October/2017 campaign are 20–30% higher than the reference ones determined with the samples of 2, 5 and 8 m depth. When the soil suction influence was incorporated in σ'_v a better ϕ estimate was achieved for 2 and 5 depth (Fig. 15b).

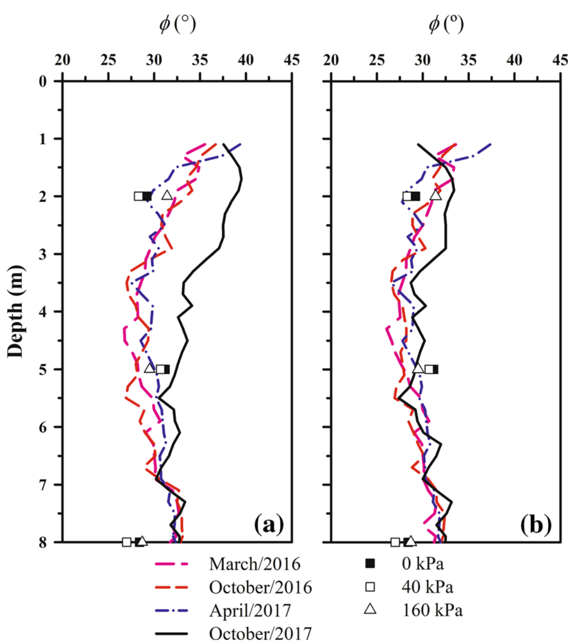

Fig. 15 Estimated peak friction angle for each campaign without (**a**) and incorporating (**b**) soil suction in σ'_v

5 Conclusions

Four DMT campaigns were performed in an unsaturated tropical research site. Significant variation on water content (from 11.3 to 19.7%) and consequently in the estimated soil suction (mostly between 6 to 200 kPa) was observed down to approximately 5 m depth, in the unsaturated active zone. Dilatometer modulus (E_D) and horizontal stress index (K_D) were affected by soil suction with minor change in material index (I_D). The average K_D value was equal to about 1.7 and the average E_D value was about 4.7 MPa in the active zone getting around two times high due to the influence of in situ soil suction. The estimated peak friction angle (ϕ) was 20–30% higher due to soil suction influence on DMT. Neglecting such influence may result in an overestimation of these parameters due to possible seasonal variability.

The effective stress approach allows soil suction to be incorporated into DMT data interpretation. This influence can be incorporated in σ'_v by using χ and soil suction based on the water content profiles and SWCC. Such approach provides a better DMT data interpretation for unsaturated soils.

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Availability of data and material The datasets used and/or analyzed during the current study are available from the corresponding author on request.

Code availability Not applicable.

Declaration

Conflict of interest The authors wish to declare that there are no known conflicts of interest associated with this publication.

References

Alonso EE, Gens A, Josa A (1990) A constitutive model for partially saturated soils. Geotechnique 40:405–430. https://doi.org/10.1680/geot.1990.40.3.405

American National Standards Institute (2011) ASTM D2487: STANDARD practice for classification of soils for engineering purposes (unified soil classification system). ASTM International, West Conshohocken

American National Standards Institute (2015) ASTM D6635 standard test method for performing the flat plate dilatometer. ASTM International, West Conshohocken. https://doi.org/10.1520/D6635-15

American National Standards Institute (2016) ASTM D6836: standard test methods for determination of the soil water characteristic curve for desorption using hanging column, pressure extractor, chilled mirror hygrometer, or centrifuge. ASTM International, West Conshohocken. https://doi.org/10.1520/D6836-16

American National Standards Institute (2016) ASTM D4959: standard test method for determination of water content of soil by direct heating. ASTM International, West Conshohocken. https://doi.org/10.1520/D4959-16

Berisavljević D, Berisavljević Z (2019) Determination of the presence of microstructure in a soil using a seismic dilatometer. Bull Eng Geol Environ 78(3):1709–1725. https://doi.org/10.1007/s10064-018-1234-5

Bishop AW (1959) The principle of effective stress. Teknisk Ukeblad 106:859–863

Campanella RG, Robertson PK (1991) Use and interpretation of a research dilatometer. Can Geotech J 28(1):113–126. https://doi.org/10.1139/t91-012

Collins R, Miller GA (2014) Cone penetration testing in unsaturated soils at two instrumented test sites. In: Khalili N, Russel AR, Khoshghalb A (eds) Proceedings of the unsaturated soils: research & applications, vol 2. CRC Press, Sydney, pp 1489–1494

Costa YD, Cintra JC, Zornberg JG (2003) Influence of matric suction on plate load tests results performed on lateritic soils. Geotech Test J 26(2):219–227. https://doi.org/10.1520/GTJ11326J

Cruz N, Rodrigues C, Viana da Fonseca A (2014) An approach to derive strength parameters of residual soils from DMT results. Soils Rocks 37(3):195–209

DAEE São Paulo Department of Water and Electricity (2020) Hydrology hydrological database. Publishing DAEE. http://www.hidrologia.daee.sp.gov.br/. Accessed 20 Aug 2020

Fredlund DG, Vanapalli SK, Xing A, Pufahl DE (1995) Predicting the shear strength function for unsaturated soils using the soil-water characteristic curve. In: Alonso EE, Delage P (eds) Proceedings of UNSAT-95, the first international conference on unsaturated soils, vol 1. Balkema, Rotterdam, pp 63–70

Giacheti HL, Bezerra RC, Rocha BP, Rodrigues RA (2019) Seasonal influence in CPT: an unsaturated soil site example. J Rock Mech Geotech Eng 11(2):361–368. https://doi.org/10.1016/j.jrmge.2018.10.005

Hilf JW (1956) An investigation of pore-water pressure in compacted cohesive soils. Ph.D. thesis, Faculty of the Graduate, School of the University of Colorado

Hryciw RD, Dowding CH (1987) Cone penetration of partially saturated sands. Geotech Test J 10(3):135–141. https://doi.org/10.1520/GTJ10945J

Janbu N (1963) Soil compressibility as determined by oedometer and triaxial tests. In: Proceedings of Europen conference on soil mechanics and foundation engineering, vol 1. Deutsche Gesellschaft für Erd-und Grundbau, Wiesbaden, Germany, pp 19–25

Lehane BM, Ismail MA, Fahey M (2004) Seasonal dependence of in situ test parameters in sand above the water table. Geotechnique 54(3):215–218. https://doi.org/10.1680/geot.2004.54.3.215

Leroueil S, Hight DW (2003) Behaviour and properties of natural and soft rocks. In: Tan TS et al (eds) Characterization and engineering properties of natural soils, vol 1. Swets & Zeitlinger, Lisse, pp 29–254

Lim TT, Rahardjo H, Chang MF, Fredlund DG (1996) Effect of rainfall on matric suctions in a residual soil slope. Can Geotech J 33(4):618–628. https://doi.org/10.1139/t96-087

Lo Presti D, Giusti I, Cosanti B, Squeglia N, Pagani E (2016) Interpretation of CPTu in "unusual" soils. Riv Ital Geotecn 4:25–44

Lo Presti D, Stacul S, Meisina C, Bordoni M, Bittelli M (2018) Preliminary validation of a novel method for the assessment of effective stress state in partially saturated soils by cone penetration tests. Geosciences 8(1):1–13. https://doi.org/10.3390/geosciences8010030

Lunne T, Lacasse S, Rad NS (1989) SPT, CPT, pressuremeter testing and recent developments on in-situ testing of soils. In: Proceedings of the 12th international conference of soil mechanics and foundation engineering. Taylor & Francis, Rio de Janeiro, pp 2339–2403

Lutenegger AJ (1988) Current status of the Marchetti dilatometer test. In: De Rulter (ed) Proceedings ISOPT-1 penetration testing: special lecture, vol 1, Balkema, Rotherdam, pp 137–155

Machado SL, Vilar OM (1998) Unsaturated soils shear strength: laboratory tests and expedite determination. Solos e Rochas 21(2):65–78 **(in Portuguese)**

Machado SL (1998) [Application of elasto-plasticity concepts to unsaturated soils]. Ph.D. thesis, São Carlos School of Engineering, University of São Paulo (**in Portuguese**)

Marchetti S (1980) In situ tests by flat dilatometer. J Geotech Eng 106:299–321

Marchetti S (1997) The flat dilatometer: design applications. In: Proceedings of the 3rd geotechnical engineering conference, keynote lecture, Cairo University, Cairo, Egypt, pp 421–448

Marchetti S, Monaco P (2018) Recent improvements in the use, interpretation, and applications of DMT and SDMT in practice. Geotech Test J 41(5):837–850. https://doi.org/10.1007/s00421-008-0955-8

Marchetti S, Monaco P, Totani G, Calabrese M (2001) The Flat Dilatometer Test (DMT) in soil investigations: a report by the ISSMGE TC Committee 16. In: Proceedings of the international conference on in situ measurement of soil properties and case histories. Parahyangan Catholic University, Bandung, Indonesia, pp 95–132

Miller GA, Tanb NK, Collins RW, Muraleetharana KK (2018) Cone penetration tests in unsaturated soils. Transp Geotech 17(Part B):85–99. https://doi.org/10.1016/j.trgeo.2018.09.008

Morais TSO, Tsuha CHC, Bandeira No LA, Singh RM (2020) Effects of seasonal variations on the thermal response of energy piles in an unsaturated Brazilian tropical soil. Energy Build 216:109971. https://doi.org/10.1016/j.enbuild.2020.109971

Öberg AL, Sällfors G (1997) Determination of shear strength parameters of unsaturated silts and sands based on the water retention curve. Geotech Test J 20(1):40–48. https://doi.org/10.1520/GTJ11419J

Pournaghiazar M, Russell AR, Khalili N (2013) The cone penetration test in unsaturated sands. Geotechnique 63(14):1209–1220. https://doi.org/10.1680/geot.12.P.083

Ricceri G, Simonini P, Cola S (2002) Applicability of piezocone and dilatometer to characterize the soils of the Venice Lagoon. Geotech Geol Eng 20(2):89–121. https://doi.org/10.1023/A:1015043911091

Robertson PK, Fonseca AV, Ulrich B, Coffin J (2017) Characterization of unsaturated mine waste: a case history. Can Geotech J 54(12):1752–1761. https://doi.org/10.1139/cgj-2017-0129

Russell AR, Khalili N (2006) A unified bounding surface plasticity model for unsaturated soils. Int J Numer Anal Meth Geomech 30(3):181–212. https://doi.org/10.1002/nag.475

van Genuchten MT (1980) A closed form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44(5):892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Vaz LF (1996) Genetic classification of soils and rock weathering layers in tropical regions. Solos e Rochas 19(2):117–136 (**in Portuguese**)

Viana da Fonseca A, Carvalho J, Ferreira C, Santos JA, Almeida F, Pereira E, Feliciano J, Grade J, Oliveira A (2006) Characterization of a profile of residual soil from granite combining geological, geophysical and mechanical testing techniques. Geotech Geol Eng 24(5):1307–1348. https://doi.org/10.1007/s10706-005-2023-z

Yang H, Russell AR (2016) Cone penetration tests in unsaturated silty sands. Can Geotech J 53(3):431–444. https://doi.org/10.1139/cgj-2015-0142