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Geotechnical site characterization by DMT and laboratory tests on an unsaturated tropical soil site for slope stability analysis

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Article

Keywords
Site characterization
Slope stability
In situ tests
DMT
Unsaturated soils
Suction

Abstract

The slope stability is an important topic because it presents risks of socio-economic losses caused by eventual ruptures. It is necessary to identify the site profile, as well as obtaining soil strength parameters for the slope stability analysis. This paper presents and discusses the use of the Flat Dilatometer Test (DMT) in the geotechnical site characterization for slope stability analysis in an unsaturated tropical soil site. Six DMTs were performed to define the stratigraphical profile and estimate geotechnical parameters. Shear strength parameters were determined in the laboratory using saturated and unsaturated triaxial compression as well as soil water retention curves (SWRC) to support DMT data interpretation. A commercial software was used to perform the slope stability analysis a cut slope with 6.6 m height and a gradient around 55° to illustrate the application of DMT and triaxial test data. The DMT allowed the representative site profile to be identified, as well as estimating the design parameters that compared well to those interpreted from unsaturated triaxial test data for the in-situ soil suction. The DMT can be used as logging test in the preliminary characterization of studied site specially to define the stratigraphical profile, site variability, select the regions to collect disturbed and undisturbed soil samples and as the first attempt to estimate the geotechnical design parameters via correlations. It is important to emphasize that laboratory tests on undisturbed soil samples are essential in the slope stability analysis of unsaturated tropical soil profiles.

1. Introduction

Slopes can be natural or man-made, and their stability is a very important issue because of the risks of socio-economic losses caused by eventual failures. Slope failures can damage buildings, road infrastructure, as well as cause injury or death to people (Rahardjo et al., 2019). One of the relevant aspects that leads to the complexity of slope stability is that it can be formed by rock, soil, or both, requiring a proper understanding of the stress state and failure mechanisms.

The need for stabilization and adequate preventive measures for slope protection has gained great relevance in the context of sustainable development of urban areas, especially in times of climate change. In the light of the effects of climate change, longer periods of drought and higher intensity and shorter duration rainfall are expected in the future, and it is necessary to prevent future rain-induced slope failures for slope protection against rainfall.

Changes in rainfall patterns, in particular, will influence the boundary condition of flow at the ground surface. Changes in groundwater hydrology associated with extreme events at the soil-atmosphere interface demonstrate the complex nature of time-dependent problems such as slope stability that can only be best analyzed in the context of Unsaturated Soil Mechanics.

The behavior of unsaturated soils depends on the soil suction (Alonso et al., 1990). Changes in the water content and suction in an unsaturated soil occurs due to climate variations (Blight, 2003; Cui et al., 2008). Climate events (i.e., extreme precipitation and droughts) are dominated by soil-atmospheric interactions in which soil water content and soil suction can change seasonally (Rahardjo et al., 2019). The changes in soil suction could reduce the shear strength of soil that may result in rainfall-induced slope failures and consequent destructions and deaths (Cho & Lee, 2002; Ng & Shi, 1998; Tohari et al., 2007). Therefore, the effects of unsaturated soils should be considered in slope stability

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analyses for geotechnical designs (Alonso et al., 2003; Fredlund & Rahardjo, 1993; Ng et al., 2001).

It is necessary to determine unsaturated soil properties for a proper unsaturated slope stability analysis, such as unsaturated shear strength, hydraulic conductivity, and soil water retention curve (SWRC). So, suction-controlled, and conventional triaxial tests as well as tests to determine the soil water characteristic curves (SWRC) (i.e., suction-plate, pressure-chamber, and filter-paper) should be carried out on undisturbed soil samples. It is important to recognize the significant progress that suction control tests have brought to the understanding of unsaturated soils, especially Hilf's (1956) axis translation technique. It is important to mention, however, that suction control techniques are complex to use and expensive, which brings the need to search for more cost-effective alternatives.

In the slope stability analysis, it is necessary to identify the geomaterials in the site profile, their thicknesses, the ground water level position, as well as the strength parameters of each of these materials. Geotechnical site characterization can be carried out by means of in situ and laboratory tests. In situ tests, such as the Flat Dilatometer (DMT) can be used as an alternative to the traditional drilling, sampling, and laboratory testing, especially in sandy soils, where sampling is complex and does not always maintain the natural characteristics of the soil. Combining the use of a in situ profiling test with a specific determination of some indexes or properties is a modern approach to better characterize the site.

This paper presents and discusses the use of the Flat Dilatometer Test (DMT) in the geotechnical site characterization of an unsaturated tropical sandy soil profile, with emphasis on its application to the slope stability analysis. The classification of the soil profile and the estimative of strength parameters were done and compared with laboratory test data. In addition, the stability analysis on a cut slope in unsaturated sandy soil profile is presented and discussed.

2. Flat dilatometer test (DMT)

The Flat Dilatometer Test (DMT) is a simple and repeatable in situ test, and its data can be used to identify the soil type and estimate design parameters such as in situ coefficient of lateral earth pressure (K_0), undrained shear strength (S_u), friction angle (ϕ), overconsolidation ratio (OCR), and vertical drained constrained modulus (M_{DMT}) (Marchetti, 1980). The test can also be used to predict settlements of shallow foundations, monitoring densification (i.e., soil compaction), liquefaction analysis as well as in the detecting slip surfaces in overconsolidated clays slopes. Moreover, dissipation tests can be performed to estimate the in situ consolidation (coefficient of consolidation, c_h) and flow parameters (coefficient of permeability, k_h) (Marchetti et al., 2001; Marchetti & Monaco, 2018; Schmertmann, 1986).

The DMT has a flat stainless-steel blade with a 60 mm diameter steel membrane mounted flush on one side (Marchetti, 1980). The nominal dimensions of the blade are 95 mm width and 15 mm thickness, having a cutting edge angled between 24° and 32° to penetrate the soil (Marchetti et al., 2001). The blade is designed to safely withstand up to 250 kN pushing force. The other components are the control unit, pneumatic-electrical cable, and gas tank (Figure 1).

The blade is advanced quasi statically or dynamically into the ground. The penetration rate is usually equal to 20 mm/s as in the cone penetration tests. The calibration procedure to obtain ΔA and ΔB pressures, necessary to overcome membrane stiffness, must be done before each profile. A-Pressure (just begin to move the membrane into the soil) and B-Pressure (move the membrane center 1.1 mm against the soil) are typically recorded every 200 mm during the test and p_0 and p_1 pressures were calculated. C-Pressure can also be recorded. The DMT interpretation starts with the intermediate parameters (I_D, K_D and E_D) determination (Marchetti et al., 2001):

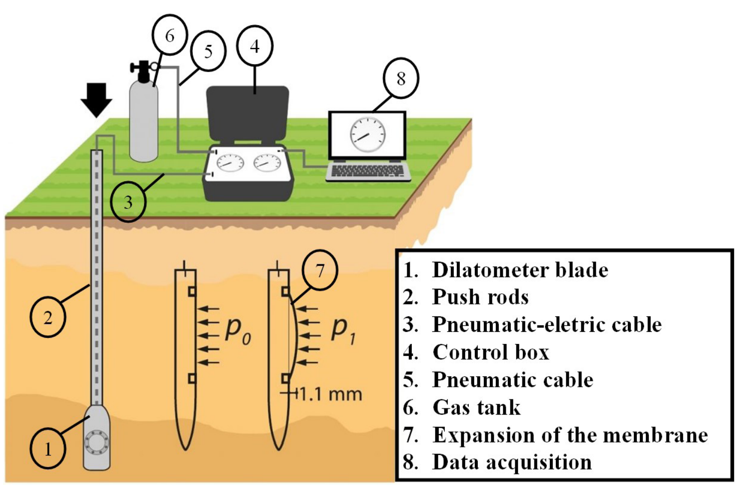

Figure 1. Schematic representation of DMT [adapted from Marchetti et al. (2001)].

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \quad (1)$$

$$K_D = \frac{p_0 - u_0}{\sigma'_v} \quad (2)$$

$$E_D = 34.7.\left(p_1 - p_0\right) \quad (3)$$

where u_0 is the hydrostatic pressure, and the σ'_v is the effective vertical stress.

I_D is calculated to identify soil type. In general, I_D provides an expressive profile of soil type and, in "normal" soils a reasonable soil description (Marchetti et al., 2001). The K_D provides the basis for several soil parameters correlations and is the key result of the dilatometer test (Marchetti et al., 2001). E_D in general should not be used as such, especially because it lacks information on stress history (Marchetti et al., 2001).

3. Study site

The study site is the experimental research area at the São Paulo State University (Unesp) - Bauru Campus and a typical cut slope (the case study) that occurs in this region. The schematic representation of the study site in the city of Bauru, state of São Paulo, Brazil, is shown in Figure 2, as well as the location of the cut slope (case study).

Several site characterization programs including SPT, SPT-T, S-SPT, DMT, PMT, SCPT, CH and DH tests were carried out at the study site. Sample pits were also excavated to retrieve undisturbed and disturbed soil blocks at 1.5, 3.0, 5.0, 7.0, and 9.0 m depth. Soil specimens from these blocks were tested in laboratory for soil characterization and determination of mechanical properties and parameters.

The site profile is a red clayey fine to medium sand identified based on SPT. MCT Classification System (Nogami & Villibor, 1981) classified the top 13 m as lateritic soil behavior (LA') followed by a non-lateritic soil behavior (NA'), as discussed Giacheti et al. (1998). The soil is classified in the Unified Soil Classification System as a SM Group soil. Some relevant geotechnical characteristics are summarized in Figure 3.

Figure 3a shows the typical site profile defined by SPT tests. Figure 3b shows that SPT *N* values increase almost linearly with depth. From CPT tests, the corrected cone resistance (q_t) and the sleeve friction (f_s) shows higher values at the top 1 m and tends to increase with depth leading to a friction ratio ($R_f = (f_s/q_t)$*100%) between 1.0 and 3.0%. Moreover, Figure 3 presents the variation of shear wave velocity (Vs) with depth (Figure 3e) measured by cross-hole (CH), SCPT and down-hole tests (DH 1 and DH2). The void ratio (e) at 1.0 m depth is equal to 0.72 and drops to about 0.60 at 16 m depth. The dry unit weight (γ_d) at 1.0 m depth is equal to 15.64 kN/m^3 and increase with depth (Figure 3f). The groundwater level was deeper than 30 m depth at this location.

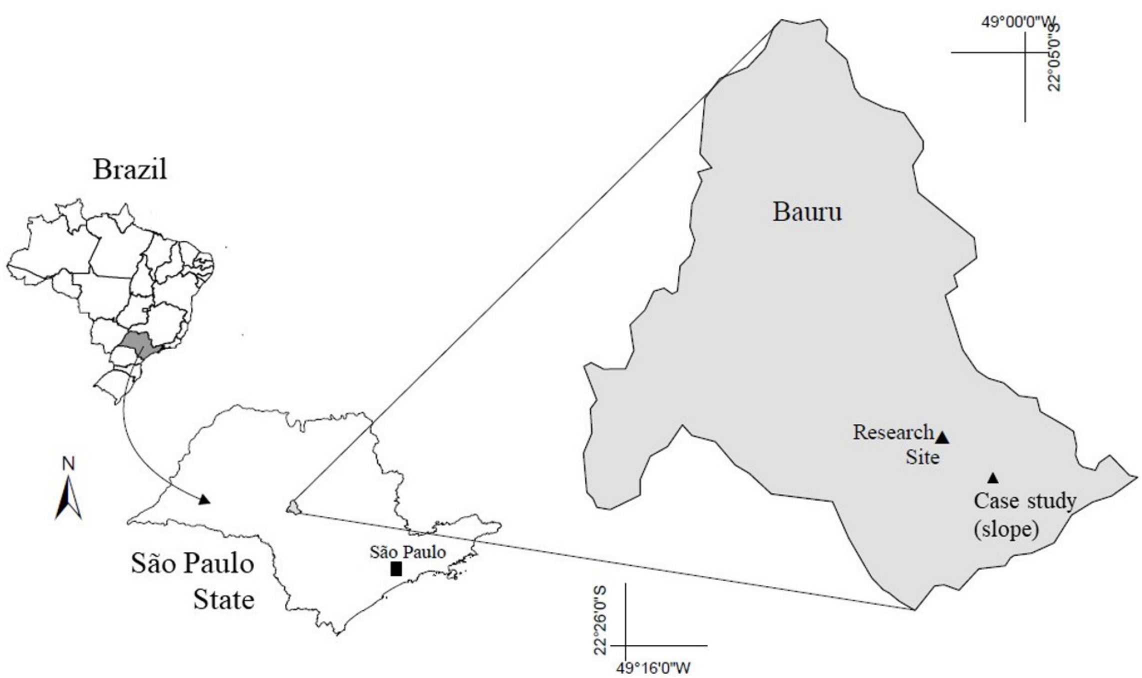

Figure 2. Schematic representation of the Unesp research site and the cut slope in the city of Bauru, São Paulo State, Brazil.

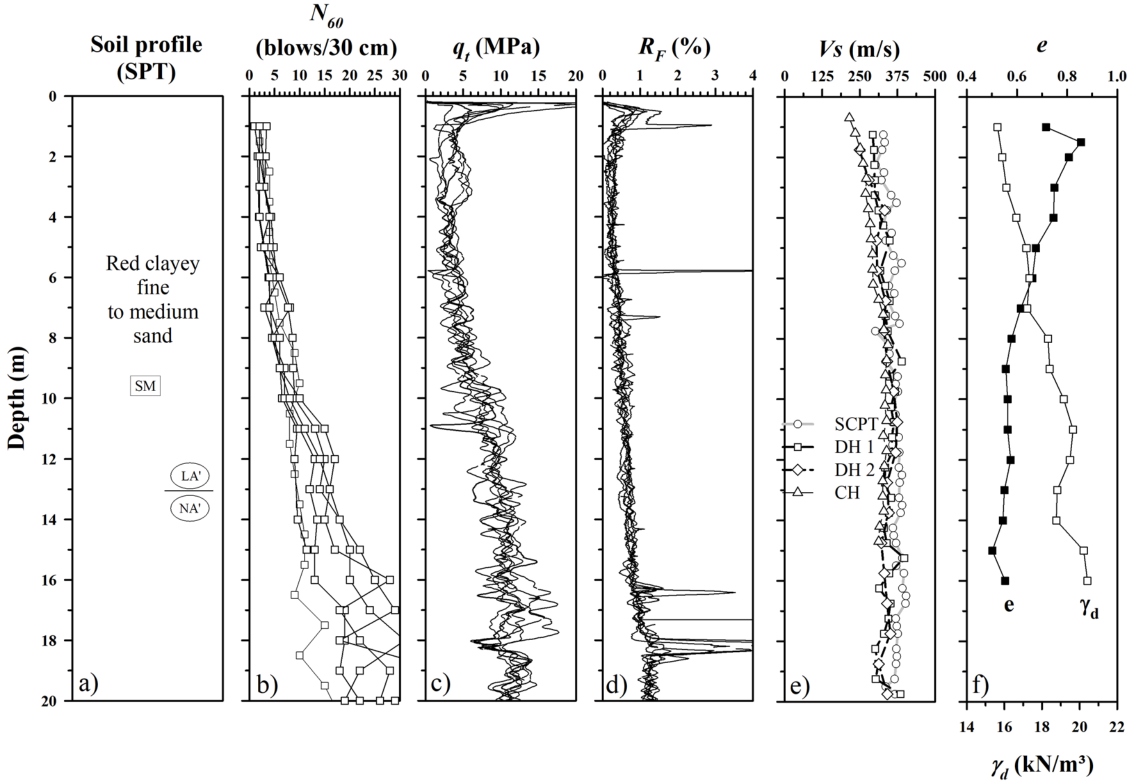

Figure 3. In situ and laboratory tests data for the experimental research site. The water level is deeper than 30 mat this location [adapted from Rocha & Giacheti (2018)].

4. Results and analysis

Six DMTs were carried out at the site and Figure 4 presents the DMT profiles in terms of I_D, K_D and E_D data plotted as an average profile as well as plus and minus one standard deviation (*SD*). The I_D, K_D and E_D parameters were calculated using Equations 1, 2, and 3, respectively (Marchetti, 1980).

From the interpretation of the laboratory and in situ tests (Figure 3) it is observed that the site profile is relatively homogeneous, and that possible variations observed in the mechanical parameters of the soil may be associated with soil suction, as well as its variation over time. In this sense, the interpretation of in situ tests, as well as the design of geotechnical works (e.g., slope stability) should consider the effect of soil suction.

Since the DMT does not provide soil sample, the soil type can be defined based on the material index (I_D) and by means of the chart proposed by Marchetti & Crapps (1981) relating I_D and E_D . Geotechnical parameters can be estimated by using classical correlations and these parameters can be compared with laboratory-determined reference values obtained by triaxial tests on undisturbed soil samples.

4.1 Soil classification

The first step of the site characterization in the slope stability analysis consists of defining the representative site profile. The definition of the soil type was done by means of grain size distribution tests in the laboratory. Tropical soils normally present a macroaggregate structure, due to the cementing action of iron and aluminum oxides and hydroxides. It is recommended to carry out grain size distribution tests with and without the use of dispersant, to have a textural classification of the soil in these two conditions to better understand how this aggregation occurs.

Figure 5 shows the particle size distribution curves with and without the use of dispersant for samples collected at 0.25 m, 3.50 m, 5.50 m, and 8.00 m depth using a helical auger. It can be seen in this figure a significant difference between the clay and silt fractions for these two conditions, with implications for the soil classification. For instance, the sample collected at 8 m depth is classified as a clayey sand (78% Sand; 5% Silt; 17% Clay) with the use of dispersant and as a silty sand (65% Sand; 35% Silt) without the use of dispersant. It is due to the action of iron and aluminum oxides and hydroxides, present in tropical soils, which produce agglutination of the clay fraction, leading to a macroaggregate structure.

The soil classification by means of the DMT uses the Material Index (I_D) and the Dilatometric Modulus (E_D) as proposed by Marchetti & Crapps (1981). The site profile is classified as a sandy silt by the DMT data, as shown in Figure 4 and Figure 6. This classification is not in agreement with the grain size of the soil obtained by the test with

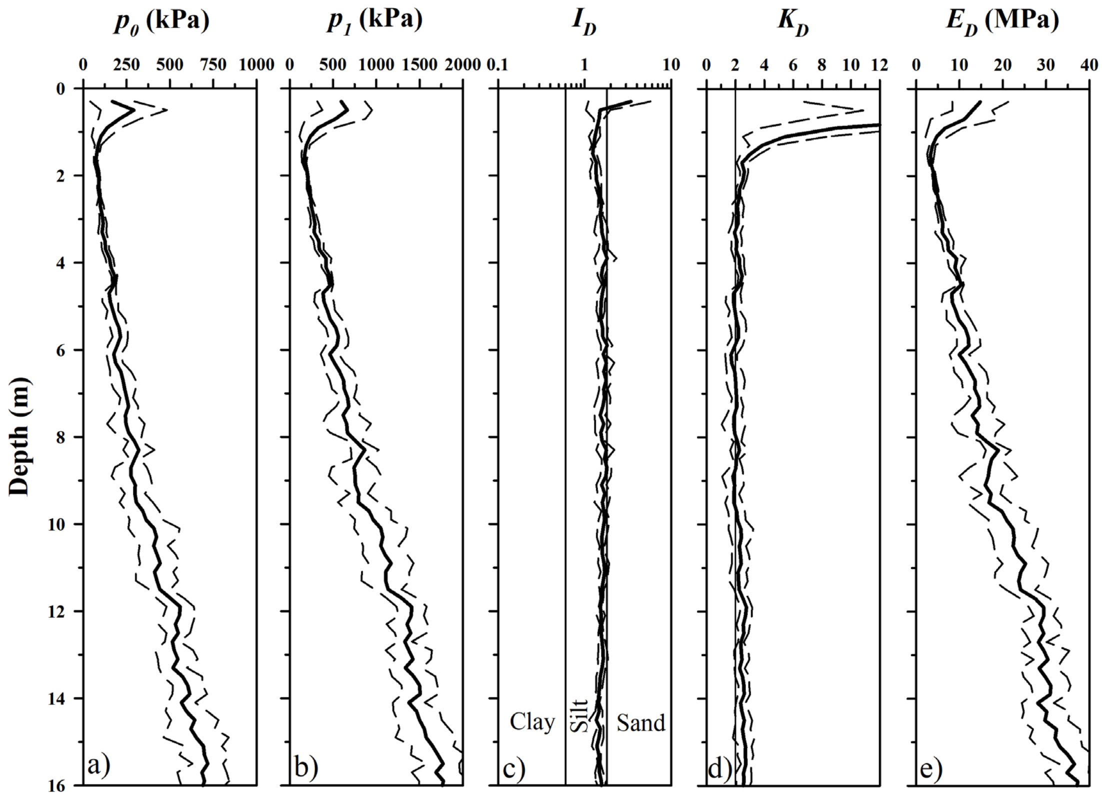

Figure 4. DMT data and interpretation for the study site. a) Corrected first reading, b) Corrected second reading, c) Material index, d) Horizontal stress index, e) Dilatometer modulus.

dispersant (Figure 5), which classifies the soil as a fine sand with little clay. However, the soil is classified as a silty sand when the grain size distribution curve is determined without the use of the dispersant. That classification is more consistent with the behavior identified by the DMT. It is important to note that the I_D index is a parameter that reflects the mechanical behavior of the soil, as a stiffness index, and not the grain size composition of the soil (Marchetti et al., 2001). Furthermore, the I_D index indicates that mixtures of sand and clay are usually classified as silts, as observed for the study site (Marchetti et al., 2001).

4.2 Geomechanical parameters

The geomechanical parameters estimative by means of the average profiles ± standard deviation of I_D, K_D and E_D was done considering the six DMTs. It is important to emphasize that the investigated profile is unsaturated. Thus, the mechanical soil parameters were determined by triaxial tests both in saturated and unsaturated condition for a soil suction equal to 50 kPa (Fernandes, 2022; Saab, 2016) through the axis translation technique (Hilf, 1956). This value was used in laboratory to represent the field condition as it was measured in situ by tensiometers and granular matrix sensors.

Figure 7 shows the profiles of total unit weight (γ_n), friction angle (ϕ), and cohesion intercept (c) estimated by the DMT. These values were compared with reference values determined in laboratory from undisturbed samples (Fagundes & Rodrigues, 2015; Fernandes, 2022). The γ_n values were estimated by Schmertmann (1986)'s equation (Equation 4) while friction angle was estimated by equation suggested by Marchetti (1997). The cohesion intercept values were calculated from Equation 6 proposed by Cruz & Viana Da Fonseca (2006). It is worth noting that the proposed equation was developed for a residual silty sand from Granite.

$$\frac{\gamma_n}{\gamma_w}=1.12\ .\left(\frac{E_D}{p_a}\right)^{0.1}.\left(I_D\right)^{-0.05} \tag{4}$$

$$\phi=28+14.6\ .\log K_D-2.1\ .\log^2 K_D \tag{5}$$

$$c=0.376\ .\ \nu_{OCR}+3.08 \tag{6}$$

γ_w is the specific weight of water, p_a is the atmospheric reference pressure (100 kPa), and ν_{OCR} is the virtual overconsolidation ratio obtained from Marchetti & Crapps (1981) approach.

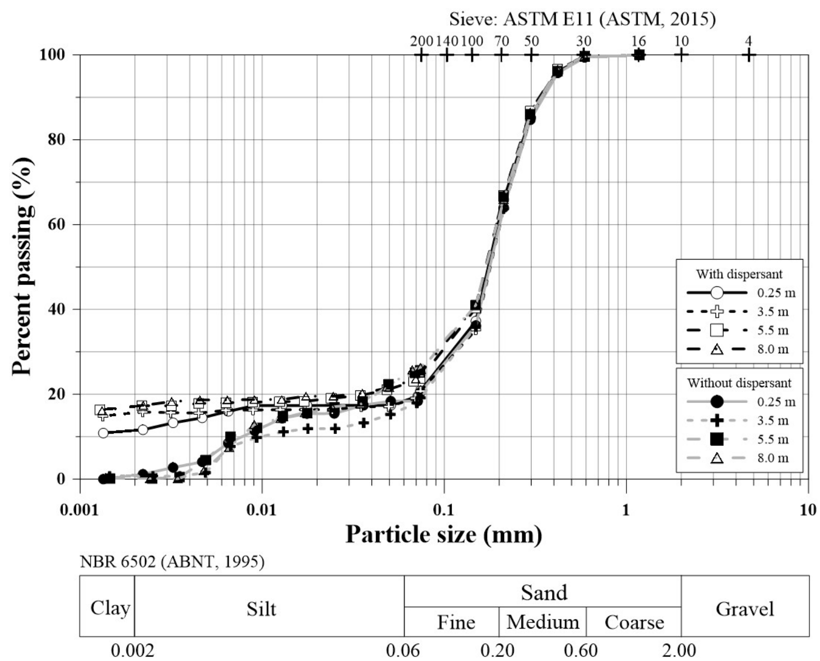

Figure 5. Grain size distribution curves with and without dispersant for the soil samples collected at 0.25, 3.50, 5.50, and 8.00 m depth [adapted from Rocha (2018)].

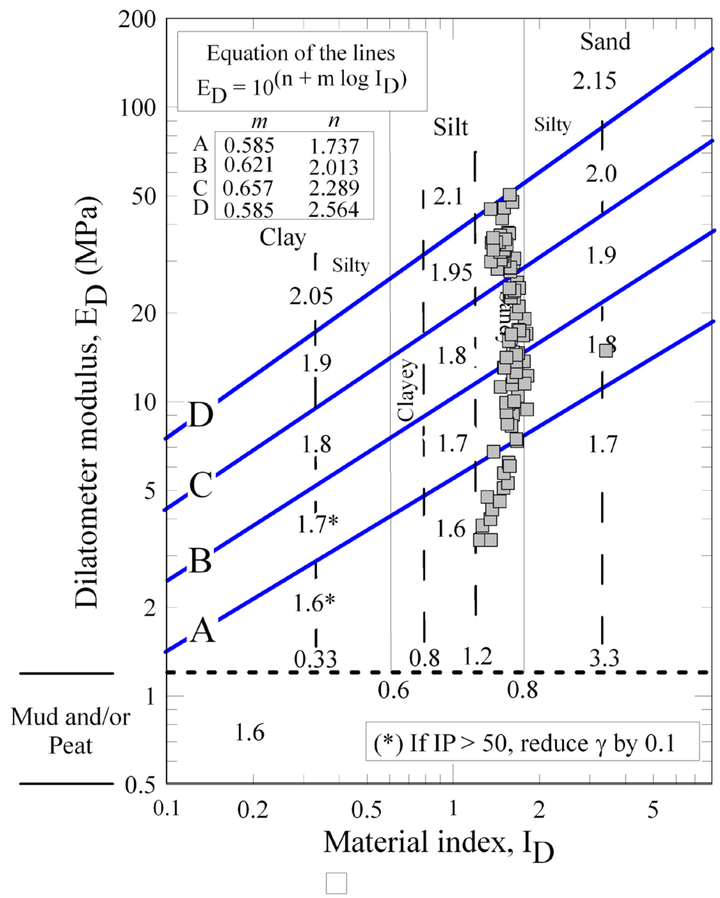

Figure 6. Soil classification for the soils from the study site in the DMT chart [adapted from Marchetti & Crapps (1981)].

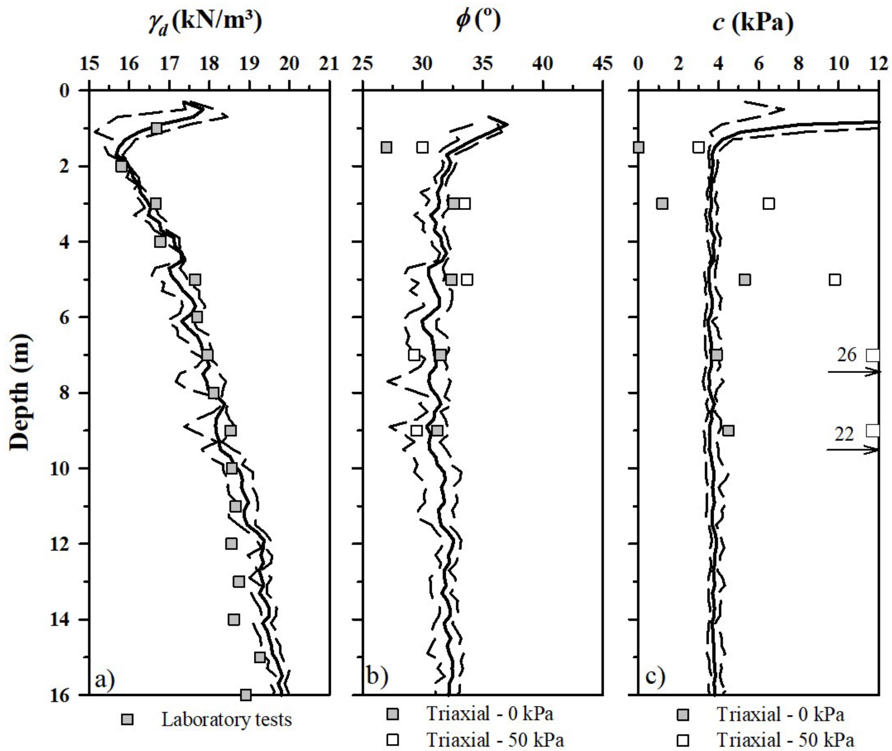

Figure 7. Estimated parameters from DMT for the study site and reference values determined by triaxial tests.

Figure 7a shows that the density values estimated by Equation 4 are in good agreement with those determined from undisturbed soil samples, especially between 1 and 11 m depth. The ϕ value varied from 27.0º for 1 m depth to 31.2º for 9 m depth at the saturated condition and varied from 30.0º for 1 m depth to 29.5º for 9 m depth at the unsaturated condition (Figure 7b and Table 1). So, an average ϕ value equal to 30.9º in the saturated condition, and 31.2º in the unsaturated condition were calculated from the triaxial tests. The ϕ values determined from the average profiles of I_D, $K_{D,}$ and E_D agree relatively well with the reference values from triaxial tests below 2 m depth. It did not occur above 2 m depth, and it could be related to the effect of high soil suction values, which increased p_0 and p_1 values, mainly in the topsoil due to the soil-atmosphere interaction, which reflect in the estimative of geomechanical parameters by DMT (Giacheti et al., 2019; Rocha, 2018; Rocha et al., 2021).

Cohesion intercept values estimated from the DMT were compared with those determined in the laboratory by triaxial tests on undisturbed soil samples (Figure 7c). It should be mentioned that a soil suction value equal to 20 kPa to estimate the cohesion intercept from the DMT. This suction value was assumed from moisture content profiles and soil water retention curves available for the site and will be discussed latter on. The cohesion intercept values increased with depth and with soil suction (Table 1). The cohesion value was equal to 0 kPa in the saturated condition, and 3.0 kPa for 50 kPa suction for the sample collected at 1.5 m depth. The cohesion intercept was equal to 4.5 kPa in the saturated condition, and 22 kPa for 50 kPa suction for the sample collected at 9.0 m depth.

It is important to mention that the cohesion intercept for tropical sandy soils is mainly related to the cementing structures and the effect of the unsaturated condition and this parameter varies seasonally depending on the rainfall regime and water infiltration in the soil mass.

5. Slope stability analysis

The stability analysis of a cut slope in the city of Bauru, São Paulo state, which has a site profile and mechanical parameters like those found in the experimental research site at the Unesp, will be performed. DMT (Figure 4) and the triaxial tests (Table 1) previously presented will be used in these analyses.

The slope is 6.6 m high and has an approximate slope gradient of around 55°. The slope geometry was defined from planialtimetric surveys, and the groundwater was assumed at the slope foot, based on SPT data carried out at this location. No groundwater flow was considered in the stability analysis. Figure 8 shows the defined geometry and the assumed groundwater position for the slope stability analysis.

Table 1. Strength parameters obtained by triaxial tests for different test depth for saturated and unsaturated conditions (Fernandes, 2022; Fernandes et al., 2022).

Depth (m)	Cohesion intercept (kPa)		Friction angle (°)	
	s = 0 kPa	s = 50 kPa	s = 0 kPa	s = 50 kPa
1.5	0.0	3.0	27.0	30.0
3.0	1.2	6.5	32.6	33.5
5.0	5.3	9.8	32.4	33.7
7.0	3.9	26.0	31.5	29.3
9.0	4.5	22.0	31.2	29.5

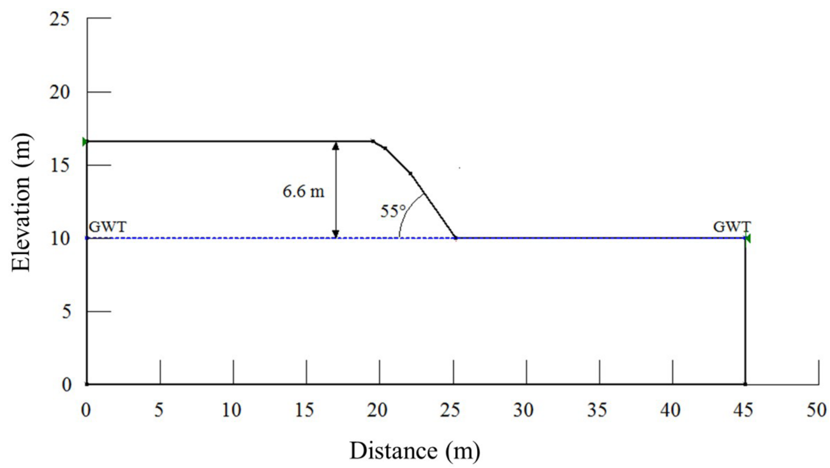

Figure 8. Slope geometry.

The GeoStudio software was used to perform the slope stability analysis using the Simplified Bishop's stability method. The shear strength criterion is that one proposed by Fredlund et al. (1978) for the unsaturated soil.

5.1 The analysis with DMT data

At the time the DMTs were carried out, disturbed soil samples were taken using a helical auger to determine the moisture content profiles (Figure 9a) to estimate the soil suction. The moisture content profile ranges from 4.0 to 11.2%, and the estimated soil suction varies from 4.2 to 50 kPa, with an average value equal to 20 kPa. These values were estimated from the soil water retention curves (SWRCs) determined from undisturbed samples collected at 1, 3, 5, and 7 m depth (Figure 9b) by Fernandes (2022). Table 2 presents the input parameters for the stability analyses by DMT and triaxial tests. In these analyses, the suction was assumed not to affect the internal friction angle (ϕ) of the soil.

Figure 10 presents the safety factor (*FS*) equal to 0.943, as well as the possible rupture surfaces considering the soil parameters obtained by DMT. This value is lower than one, i.e., the slope is in an unstable condition for the assumed boundary conditions, stresses, and soil parameters. It is worth noting that the geomechanical parameters (c and ϕ) were obtained using empirical correlations, and they may not adequately represent the mechanical behavior of the studied unsaturated tropical soil.

5.2 The analysis with triaxial test data

To compare the *FS* values calculated from the interpretation of DMT data, the cohesion intercept value determined using the triaxial test data for the same field suction value (i.e., 20 kPa) was estimated. For this, the model of Fredlund et al. (1978) was used to estimate the unsaturated cohesion for 20 kPa of suction (Equation 7), which resulted in a cohesion intercept value equal to 4.7 kPa.

In order to apply Equation 7 the values of cohesion intercept versus suction (Table 1) were reinterpreted to define ϕ^B that resulted in the value of 5.10° (tg ϕ^b = 0.089). Hence, the calculated *FS* was equal to 1.035, close to that found from the interpretation of the DMT data (Figure 11).

$$c = c_{sat} + \left(u_a - u_w\right) . \tan\phi^b \tag{7}$$

where c_{sat} is the saturated cohesion, $u_a - u_w$ is the soil suction and ϕ^b is the angle indicating the increase in shear strength due to soil suction.

Following the same approach, another stability analysis was performed considering an average cohesion value obtained for the suction condition equal to 50 kPa (Table 1). In this case, the calculated *FS* was 2.161 (Figure 12).

Table 2. Average soil parameters assumed for slope analysis stability by DMT and triaxial tests for different soil suctions.

Type of test	Soil parameters		
	γ (kN/m³)	c (kPa)	ϕ (°)
DMT *s* = 20 kPa	16.8	3.7	32.0
Triaxial *s* = 20 kPa	16.8	4.7	32.5
Triaxial *s* = 50 kPa	16.8	13.4	32.5

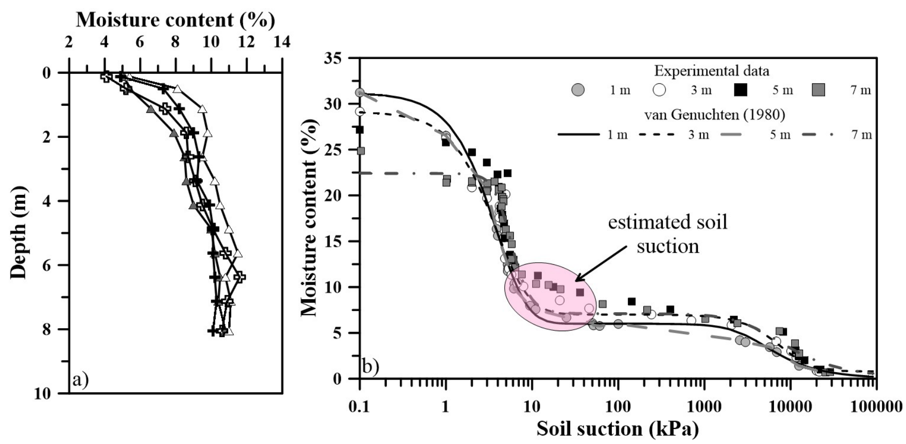

Figure 9. Moisture content profiles (a) and the soil water retention curves (b) [adapted form Fernandes (2022)].

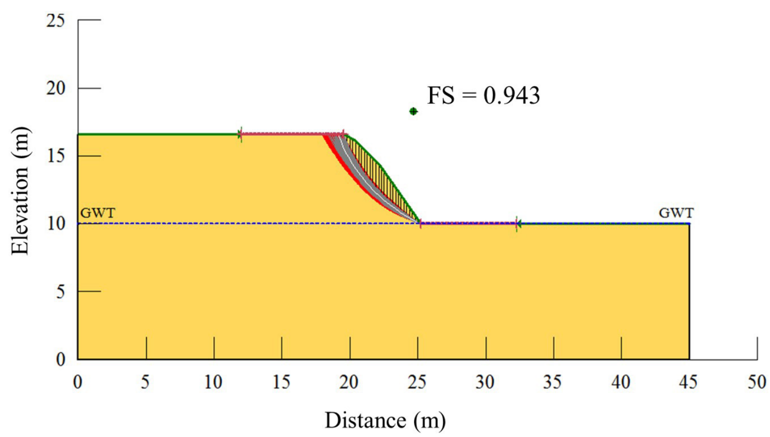

Figure 10. Minimum safety factor (*FS*) and slip surfaces tested assuming shear strength parameters by DMT.

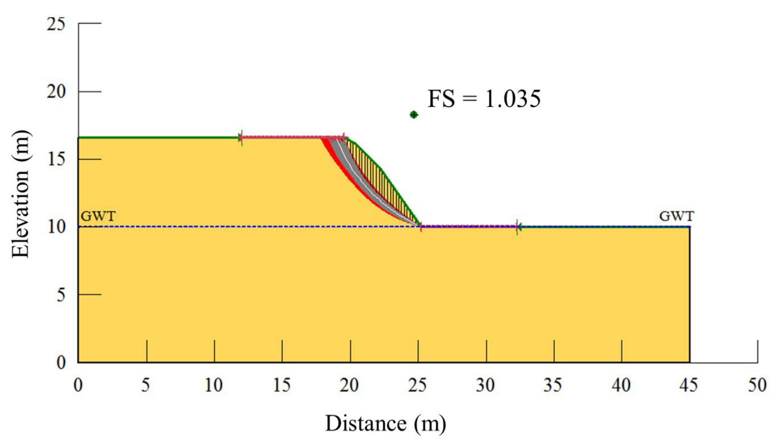

Figure 11. Minimum safety factor and slip surfaces tested assuming shear strength parameters from the unsaturated triaxial tests with a suction value equal to 20 kPa.

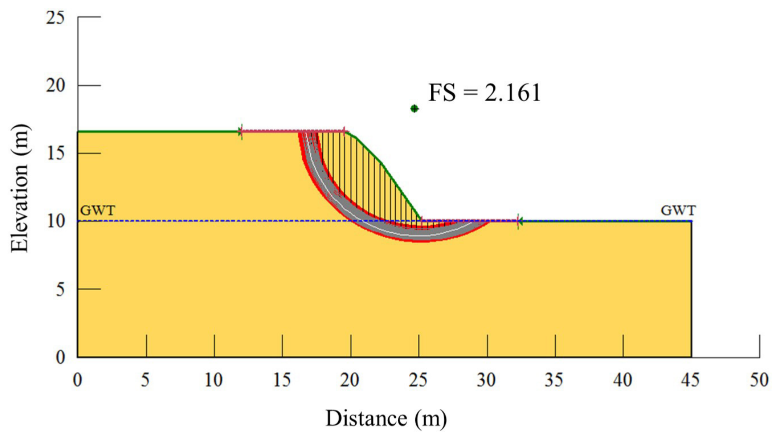

Figure 12. Minimum safety factor and slip surfaces tested assuming shear strength parameters from the unsaturated triaxial tests with a suction value equal to 50 kPa.

Figure 13. The slope after failure [adapted from Vieira (2021)].

The results of this and other similar studies have led to a general consensus that unsaturated condition, with its associated soil suction, tend to increase slope stability due to increase in apparent cohesion (Dai et al., 2022; Kang et al., 2020; Sivakumar Babu & Murthy, 2005).

5.3 Slope failure back analysis

Vieira (2021) performed the back analysis of similar shear slope slides by integrating data from laboratory tests and numerical modeling. The author analyzed a rupture that occurred after a 124.7 mm rainfall. Figure 13 shows the slope after rupture. The GeoStudio software (SLOPE/W and SEEP/W) was used to perform the numerical simulations in a time-dependent analysis. The approach adopted considered the Simplified Bishop's stability method, as well as the Mohr-Coulomb criterion that incorporates the effect of the saturated condition, as proposed by Fredlund et al. (1978). The slope geometry and the failure surface were obtained from planialtimetric surveys. The rainfall history of the region during the slope failure period was obtained from a meteorological station near the slope. The slope failure back analysis was performed by combining the cohesion intercept and friction angle values to obtain them, considering the unitary safety factor (*FS* = 1) at the time of the 124.7 mm rain that caused the slope failure.

It is worth noting that slope stability analyses that use geomechanical parameters determined by triaxial compression tests with controlled suction in numerical simulations that incorporate the hydraulic properties of the soil, and flow conditions to simulate rainfall and its interaction with the soil mass are unusual in the practice of geotechnical jobs.

6. Conclusion

The main conclusions are:

- The DMT allowed to define the site profile and to give a preliminary estimative of the strength parameters of the soils;
- The natural specific weight profile (γ_n), friction angle (ϕ) and the cohesion intercept (c) presented reasonable agreement with the reference values;
- The DMT was an interesting tool in defining the site profile for the case study as well as for estimating the strength parameters required in the slope stability analyses in the preliminary design phase;
- The slope stability analyses performed considering the geometry, stresses and parameters estimated by the DMT and by the triaxial tests for a suction value of 20 kPa indicated that the slope is at the eminence of rupture ($FS \approx 1$). In addition, the slope was found to be stable for a suction value of 50 kPa based on the triaxial test data, since the factor of safety in this case is greater than 2.0 ($FS \approx 2.2$);
- The back analysis of a slope with similar characteristics to those in this study confirms that the failure occurs due to the reduced contribution to soil shear strength by the effect of rainfall and its interaction with the soil mass;
- The DMT can be used as logging test in the preliminary site characterization of unsaturated tropical soil sites specially to define the stratigraphical profile, site variability, select the regions to collect disturbed and undisturbed soil samples and as the first attempt to estimate the geotechnical design parameters via correlations;
- The ideal condition is to characterize the site using a logging test like the SPT, CPT or DMT and refine it with triaxial compression tests with controlled suction to determine the shear strength parameters to have a better understanding of the suction effect during the lifetime of the slope considering the hydraulic properties of the soil and the influence of rainfall regime, infiltration and drainage conditions.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Breno Padovezi Rocha: conceptualization, data curation, visualization, formal analysis, investigation, methodology, writing – original draft, writing – review & editing. Jhaber Dahsan Yacoub: conceptualization, data curation validation, writing – review & editing. Jeferson Brito Fernandes: conceptualization, data curation validation, writing – review & editing. Roger Augusto Rodrigues: conceptualization, experimental supervision, methodology, writing – review. Heraldo Luiz Giacheti: conceptualization, methodology, supervision, funding acquisition, project administration, writing – review.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

List of symbols

c	Cohesion
c_h	Coefficient of consolidation
c_{sat}	Saturated cohesion
e	Void ratio
f_s	Sleeve friction
p_a	Atmospheric reference pressure (100 kPa)
p_0	Corrected first reading
p_1	Corrected second reading
q_t	Cone resistance
s	Soil suction
A-	Pressure required to just begin to move the membrane into the soil
B-	Pressure required to move the membrane center 1.1 mm against the soil
C-	Pressure taken by slowly deflating the membrane immediately after *B-pressure* is reached
CH	Crosshole test
DH	Downhole test
DMT	Flat dilatometer tests
E_D	Dilatometer modulus
FS	Safety factor
I_D	Material index

K_D Horizontal stress index
K_h Coefficient of permeability
K_0 In situ coefficient of lateral earth pressure
LA' Lateritic soil behavior
M_{DMT} Vertical drained constrained modulus
NA' Non-lateritic soil behavior
OCR Overconsolidation ratio
PMT Pressuremeter tests
R_f Friction ratio
SCPT Seismic cone test
SM Silty sand
SPT Standard penetration tests
SPT-T Standard penetration tests with torque measurements
S-SPT Seismic SPT
SWRC Soil water retention curve
S_u Undrained shear strength
Vs Shear wave velocity
ϕ Friction angle
ϕ^b Angle indicating the increase in shear strength due to soil suction
γ_d Dry unit weight
γ_n Total unit weight
γ_w Specific weight of water
u_0 Hydrostatic pressure
$u_a - u_w$ Soil suction
v_{OCR} Virtual overconsolidation ratio
σ'_v Effective vertical stress
ΔA Calibration parameters used to correct the *A*, *B* pressure
ΔB Calibration parameters used to correct the *A*, *B* pressure

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