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Influence of suction on the parameters of the Marchetti Dilatometer Test on a compacted residual soil

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Article

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Unsaturated soils
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Abstract

This study had the objective to evaluate the application of the Marchetti Dilatometer Test (DMT) on compacted residual soil, analyzing the influence of suction on the parameters obtained. For this, a sample of residual diabase soil was collected and compacted in the laboratory at its optimum moisture content. Granular matrix suction sensors (GMS) were installed inside the compacted sample to monitor the suction during the experiment. The GMS allowed the monitoring of suction profile variations during the drying of the specimen submitted to ambient conditions. The DMT blade was statically inserted at 6 different points of the specimen surface with measurement of parameters *A* and *B* at every 10 cm deep. It was observed that with the increase of suction, there is an increase in both: material index value (I_D) and dilatometric module (E_D), but a reduction in the horizontal stress index (K_D) value. The increase in E_D value and reduction in K_D value indicates that there is an increase in deformability modulus (E) and a decrease in coefficient of at-rest earth pressure (K_0). The DMT correctly detected the trend in variations in geotechnical parameters as a function of variation in soil suction profiles.

1. Introduction

Technological control of soil embankment is a great importance during and after construction. This control is verified by determining the compaction humidity in relation to the optimum moisture content, as well as the degree of compaction reached. However, the information provided by this technique does not always reflect the authentic behavior of the soil, in addition to being applicable only during the construction stage. Thus, there is a need for more representative tests for the provision of control parameters of compacted soils.

The Marchetti Dilatometer Test (DMT) is a good alternative, among field tests, to assess the behavior of embankments, since it is a relatively simple test, easy to perform, and allows to estimate the geotechnical parameters of the soils (Marchetti & Monaco, 2018).

Initial studies with the DMT were based on readings and interpretations made in sedimentary soils (Marchetti, 1980). The DMT showed to be very useful to estimate the geotechnical parameters of these soils, such as overconsolidation ratio (*OCR*), the effective angle of internal friction (ϕ') and undrained shear strength (*Su*).

There are several studies in residual soils (Cruz & Fonseca, 2006; Borden et al. 1985; Giacheti et al. 2006; Silva, 2008), but only a few have proposed correlations. In general, it is common to apply the correlations of sedimentary soils to residual soils, resulting in inconsistent interpretations of its geotechnical behavior. This problem is evidenced in the studies by Cruz (2010, 2012), which explain that residual soils present unconventional mechanical behavior when compared with sedimentary soils. The presence of cementation and suction interferes with the interpretation of the results obtained in field tests.

Cruz et al. (2014) obtained a correlation to obtain the cohesion intercept that takes into account the *OCR* value obtained from the DMT, which proved to be satisfactory in relation to the experimental results obtained for a residual granite soil. A reduction in the values of p_1, E_D, I_D, and K_D was also observed as the tests with DMT were closer to the water level inside the soil, thus decreasing the suction value.

Rocha et al. (2021) incorporated the effect of suction in the equations proposed by Marchetti et al. (2001) following a different path from the research proposal presented here, noting that the mean values of K_D and E_D were twice as high in the active zone of the soil due to the influence of suction with smaller variations in *Id* values. This research was developed with the objective to better understand the influence of suction on the behavior of compacted soils, by analyzing the parameters obtained through the DMT. This

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2. Dilatometer Marchetti Test - DMT

Developed by Silvano Marchetti in the mid-1970s in Italy, the DMT is commonly used in the area of geotechnical investigations. The original articles published by Marchetti (1975, 1980) provide a detailed description of the test and a series of empirical correlations between test results and common geotechnical parameters. According to Lutenegger (1988), the DMT is a simple tool, quick measurement and has low acquisition and installation costs, besides being resistant and used in several types of soils. Marchetti et al. (2001) state that the DMT is suitable for a wide range of soils, from sands, soft soils, rigid clays to soft rocks, natural or even compacted soils. The test provides estimates of soil parameters, which can be used to predict the performance of engineering structures.

The DMT equipment consists of a flat stainless-steel blade with a flexible circular membrane on one side of the blade. The blade is connected to the control unit, located on the ground surface, through a pneumatic-electric cable inserted inside the thrust rods. This control unit reads the pressures, *A* and *B*, required to just begin to move the membrane ('lift-off' pressure) and expand the membrane center of 1.1 mm against the soil (ASTM, 2015).

Pressure readings *A* and *B* are corrected by the membrane stiffness, which was inferred prior to the start of the test, yielding the values of p_0 and p_1 as described in Equations 1 and 2.

$$p_0 = 1.05 \cdot \left(A - z_m + \Delta A\right) - 0.05 \cdot \left(B - z_m - \Delta B\right) \quad (1)$$

$$p_1 = B - z_m - \Delta B \quad (2)$$

2.1 Intermediate parameters of the DMT

By obtaining the corrected pressure readings, p_0 and p_1, along with the estimate of the vertical effective stress (σ'_v) and the pore pressure (u_0), Marchetti (1980) defined three interpretation indexes of the dilatometer test: the material index (I_D), the horizontal stress index (K_D) and the dilatometer modulus (E_D), respectively presented in Equations 3, 4 and 5.

$$I_D = \frac{p_1 - p_0}{p_0 - u_0} \quad (3)$$

$$K_D = \frac{p_0 - u_0}{\sigma'_v} \quad (4)$$

$$E_D = 34.7 \cdot \left(p_1 - p_0\right) \quad (5)$$

The parameter I_D is related to soil type, and the K_D parameter is related to the overconsolidation ratio (OCR) and coefficient of earth pressure at-rest (K_0) and the parameter E_D relates to the soil deformability modulus.

2.2 Correlations with geotechnical parameters

There are several semi-empirical correlations using the K_D and E_D values to estimate the geotechnical parameters of the soil. In the literature, there are correlations to obtain the coefficient of earth pressure at-rest (K_0), overconsolidation ratio (*OCR*), deformability or Young's modulus (*E*) and oedometric modulus (M_{DMT}), effective angle of internal friction (ϕ'), among others. In this paper, emphasis will be given to parameter K_0, a parameter that relates to the stresses acting on the soil in the at-rest condition.

There are some proposals de correlations to obtain the K_0 parameter, using the data found with the DMT. Equation 6 was proposed by Marchetti (1980) for clay soils. According to Jamiolkowski et al. (1988), this correlation can only be used for soft or median clays, without signs of aging, cementation or preconsolidation, with $I_D \leq 1.2$. For Lacasse & Lunne (1988), the Marchetti equation provides overestimated K_0 values for $1.5 < K_D < 4$. They suggest that Equation 6 is valid for $K_D > 4$.

$$K_0 = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.6 \quad (6)$$

With the advances in the study of unsaturated soils, formulations for the definition of parameter K_0 appeared, considering the variable suction, with the objective of describing their geotechnical behavior more realistically.

According to Lu & Likos (2004), the relationship between the different stress components, such as horizontal and vertical stresses, is based on constitutive stress-deformation laws. The commonly used linear stress-deformation equation in elasticity is Hooke's Law.

Hooke's Law can be extended to the concept of suction stress. Two general conditions can be imposed for homogeneous unsaturated soil. Assuming that $\sigma_x = \sigma_y = \sigma_h$ and that the deformations $\varepsilon_x = \varepsilon_y = \varepsilon_h = 0$ gives Equation 7. This equation gives the value of the coefficient of earth pressure at-rest, or K_0, as a function of suction and vertical stress.

$$K_0 = \frac{\upsilon}{1-\upsilon} - \frac{1-2\upsilon}{1-\upsilon} \cdot \frac{\chi \cdot \left(u_a - u_w\right)}{\left(\sigma_v - u_a\right)} \quad (7)$$

The parameter χ of Equation 7 was proposed by Bishop (1959) to represent the effective stresses in unsaturated soils. The value is 1 for saturated soil and 0 for dry soil. The value depends mainly on the degree of saturation, and secondarily it is a function of soil structure and drying and wetting cycles (Bishop et al., 1960). Bishop's (1959) proposal is presented in Equation 8.

$$\sigma' = (\sigma - u_a) + \chi \cdot (u_a - u_w) \quad (8)$$

Applying the Mohr-Coulomb criterion for the effective stress equation proposed by Bishop (1959), the shear strength for unsaturated soils is represented by Equation 9. When the soil is saturated the value of $u_a = u_w$ and Equation 9 is reduced to Equation 10. The difference between Equations 9 and 10 represents the increase in resistance attributed to matrix suction. This difference is given by Equation 11.

$$\tau = c' + \left[(\sigma - u_a) + \chi \cdot (u_a - u_w) \right] \cdot tg\phi' \quad (9)$$

$$\tau_0 = c' + (\sigma - u_a) \cdot tg\phi' \quad (10)$$

$$\tau - \tau_0 = \chi \cdot (u_a - u_w) \cdot tg\phi' \quad (11)$$

Thus, the parameter χ can be obtained from Equation 11 being the same represented by Equation 12. Using this equation, the variation of χ as a function of suction can be obtained by performing shear strength tests. Figure 1 shows how this parameter is graphically obtained for different suction values. The τ_0 value shown in this figure represents the effective soil cohesion obtained from the test under the saturated condition. The relationship between shear strength and suction is obtained through unsaturated shear strength tests.

$$\chi = \frac{\tau - \tau_0}{(u_a - u_w) \cdot tg\phi'} \quad (12)$$

The parameter χ is dependent on the degree of saturation and the void ratio of the soil. For soils where the water retention curve is independent of the void ratio, the parameter χ can be considered equal to the degree of saturation S, however this is not normally found (Einav & Liu, 2020; Vaunat & Casini, 2017). In the work presented by Jennings & Burland (1962) it was verified for several types of soil that the variation of the parameter value χ in function of the suction is different from the variation of the saturation degree. Pereira et al. (2010) point out that the relationship χ=S should be viewed with caution as it loses its validity for silty and clayey soils.

In this research was determined the cohesion intercept that represents the relationship between shear strength and suction for zero net normal stress (σ - u_a = 0). This cohesion intercept was obtained by performing unconfined compressive strength tests using specimens with different initial suction values. For the definition of the cohesion intercept there is a need to determine the effective cohesion (*c'*) and effective angle of internal friction (ϕ›) obtained from direct shear tests performed under the saturated condition. The cohesion intercepts were defined by the intersection of the rupture surface with the plane represented by shear strength as a function of suction (σ - u_a = 0). According to Figure 2, the cohesion intercepts were determined by the intersection of the lines that are tangent to the Mohr circle obtained by unconfined compressive strength tests with the shear strength plane as a function of the suction. These straight lines have a slope equal to ϕ', effective angle of internal friction of the soils, considered constant as the suction increases. This constant value of the effective angle of internal friction was obtained in studies carried out by Massocco (2017) on the same residual diabase soil of this research.

Equations 3 and 4 were modified based on the effective stress equation (see Equation 8) proposed by Bishop (1959). The value of u_0, related to the pore water pressure for the saturated soil, was replaced by the term *(υ / 1 - υ).χ.(*u_a - u_w) which will be added to the value of p_0. The modifications proposed to obtain parameters I_D and K_D are shown in Equations 13 and 14.

$$I_D = \frac{p_1 - p_0}{p_0 + \left(\frac{v}{1-v} \right) . \chi \cdot (u_a - u_w)} \quad (13)$$

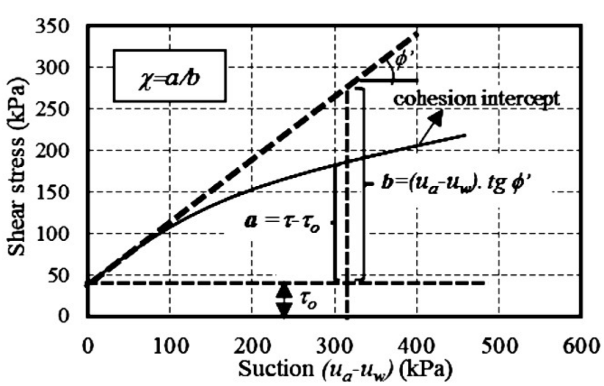

Figure 1. Graphical representation of the determination of the variation of the parameter χ as a function of suction using the cohesion intercept (modified from Khalili & Khabbaz,1998).

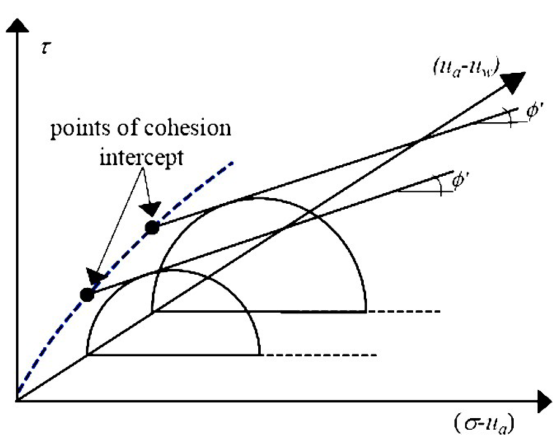

Figure 2. Determining the cohesion intercepts, Pecapedra et al. (2018).

$$K_D = \frac{p_0 + \left(\frac{\nu}{1-\nu}\right) \cdot \chi \cdot (u_a - u_w)}{(\sigma - u_a) + \chi \cdot (u_a - u_w)} \tag{14}$$

Fredlund & Rahardjo (1993) and Fredlund et al. (2012), also consider that elastic behavior within a soil mass may provide some information on the earth pressure at-rest of the soil. According to the authors, the theory of elasticity can be used to calculate the changes of stress acting on the soil, with Young's modulus and Poisson's ratio added to the equations. For the authors, in the resting condition, the K_0 parameter of a homogeneous and unsaturated soil mass takes the form of Equation 15.

$$K_0 = \frac{\nu}{1-\nu} - \frac{E}{(1-\nu) \cdot H} \cdot \frac{(u_a - u_w)}{(\sigma_v - u_a)} \tag{15}$$

Equations 7 and 15 show that the coefficient of earth pressure at-rest decreases with the increasing of suction value. This soil behavior, based on the theory of elasticity, has been experimentally proven by several researchers using different techniques to obtain K_0 as a function of suction (Mesri & Hayat, 1993; Daylac, 1994; Machado & Vilar, 1998; Oliveira, 1998; Peixoto, 1999; Zhang et al., 2009; Oh et al., 2013; Pirjalili et al., 2016; Abrantes & Campos, 2019).

Pirjalili et al. (2016) investigated the variation of parameter K_0 as a function of the suction of a compacted clay soil with two different void ratios. The tests were performed with the soil sample molded inside a metal ring instrumented with strain gauges to monitor lateral deformations, being the suction imposed on a triaxial test cell. Figure 3 presents the results obtained, indicating the reduction linear of the K_0 value with the increase of the suction. The highest values of K_0 were obtained for the specimen with a higher void ratio ($e = 0.92$).

The interpretation of the DMT in saturated sands and clays is well established, with many studies and methodologies, but the interpretation of the tests in unsaturated soils still needs further studies.

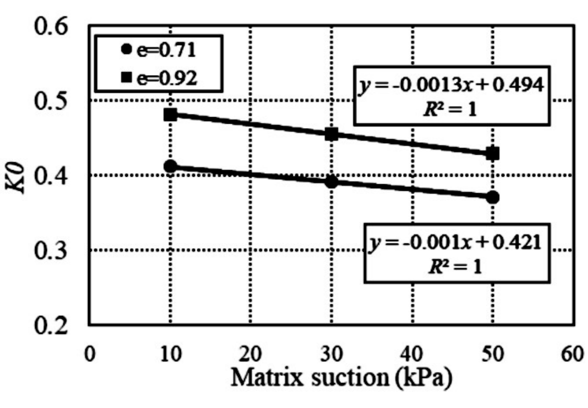

Figure 3. Variations of K_0 as a function of suction (modified from Pirjalili et al., 2016).

Frequently, the interpretation of field tests in unsaturated soils neglecting the contribution of suction. Failure to consider the influence of suction on the results may lead to an inadequate definition of the stratigraphic profile, and in particular, incorrect estimation of soil geotechnical parameters.

3. Materials and methods

This section presents the methodology used to perform the tests. It explains the procedures for conducting direct shear and unconfined compressive strength tests, detailing the procedure for the compaction and execution of the DMT in the laboratory and the procedures for suction monitoring.

3.1 Shear strength tests

To determine the soil resistance parameters, direct shear and unconfined compressive strength tests were performed. The direct shear strength test was performed in consolidated and drained conditions to determine cohesion (*c'*) and effective angle of internal friction (ϕ›), following the recommendations of ASTM (2011). For the procedure, a soil sample at optimum moisture conditions was compacted in a Proctor cylinder. From this sample, three specimens were molded with the aid of metallic shear molds, which present dimensions of 101.6 x 101.6 x 20.0 mm. The test specimens were submitted to the stages of flooding, consolidation and subsequent rupture, adopting the vertical normal stresses of 32.7, 77.4 and 126.8 kPa. The unconfined compressive strength test follows normative ASTM (2016). The samples were compacted in a steel three-part mold, with an internal diameter of 38 mm and height of 80.2 mm, in five equal layers, in optimum moisture conditions. Subsequently, they were submitted to different suction values, by wetting and/or drying process. Suction was determined using the filter paper method. For each specimen, two suction values were determined, and the mean value was adopted.

The initial suction values of the specimens were obtained with the use of Whatman No. 42 quantitative filter paper placed in direct contact with the surface of the specimen, being then involved in plastic film and aluminum paper, remaining at rest in a styrofoam box for a minimum period of 7 days. To determine the matrix suction value, the calibration proposed by Chandler et al. (1992) was used. Following this methodology, the cohesion intercept was obtained for the initial suction of the specimen, considering that its value remains constant during the test.

3.2 Experiment equipment – GMS and DMT

The mechanical equipment of the Large-Scale Triaxial (LST) test, located at the Soil Mechanics Laboratory at Federal University of Santa Catarina (UFSC), was adapted to perform the DMT in compacted soil. This equipment is used to obtain resistance and compressibility parameters of rockfill dams, to test specimens with dimensions of 66 cm in diameter and 165 cm in height (Hummes & Maccarini, 2009; Espíndola, 2016).

The reaction gantry, the hydraulic cylinder and the compaction mold were used for the experiment, with dimensions of 66 cm in diameter and 86 cm in height, formed by 16 windows screwed together and supported on a circular steel base. The soil sample was compacted within the mold using the socket of the Proctor compaction test. The sample had a total height of 72 cm, divided into 24 equal layers of 3 cm each. Were applied 293 blows per layer to achieve the level of compaction required in normal energy and optimum moisture content.

Four granular matrix suction sensors (GMS), manufactured by Irrometer Company, model 200SS sensors were installed in the center of the compacted sample at the depths of 9, 27, 45 and 63 cm. The GMS were screwed into PVC pipes where the wire that should be connected to the data acquisition system. This set was inserted into the holes that were hand-drilled with an earth auger with the same diameter of the GMS. To ensure good hydraulic continuity between the water present in the soil structure and the GMS, a mud was produced with the same soil, and it was used before the installation. The data acquisition was through Monitor 900M, via RS232 connection, using the Watergraph software.

Figure 4a presents the equipment used for the conducting of DMT. Figure 4b shows a schematic representation of the test indicating the position where the GMS was installed and the depths where it was taken as DMT readings. The nominal dimensions of the DMT blade, made of stainless steel, are 22 cm high and 9.3 cm wide. On one side has a flat expandable steel membrane with 6 cm in diameter. The reading intervals were defined every 10 cm, and seven readings were taken at 5, 15, 25, 35, 45, 55 and 65 cm deep. These test depths correspond to the center of the expandable membrane of the DMT blade.

For the process of inserting the DMT blade, it was necessary to make a piece of solid steel, 35 cm long, 10 cm high and 8 cm wide. One end of the piece was bolted to the hydraulic cylinder of the portico and the other end was connected to the dynamometer ring, along with the connections for setting the rods with the blade. The function of the steel piece was to enable driving in the blade from different positions within the mold. Figure 5a presents the schematic drawing of the pieces made. The picture of the moment at the beginning of the insertion of the DMT slide is presented in Figure 5b. Figure 6 shows the locations where the DMTs were performed. It is observed that the expansion of the steel membrane is directed to the center of the specimen. This avoids possible interference with the test results since it is close to the mold wall (10 cm).

Changes in soil structure related to the process of inserting the DMT blade and its influence on test results are not well known. However, the thickness of the DMT blade

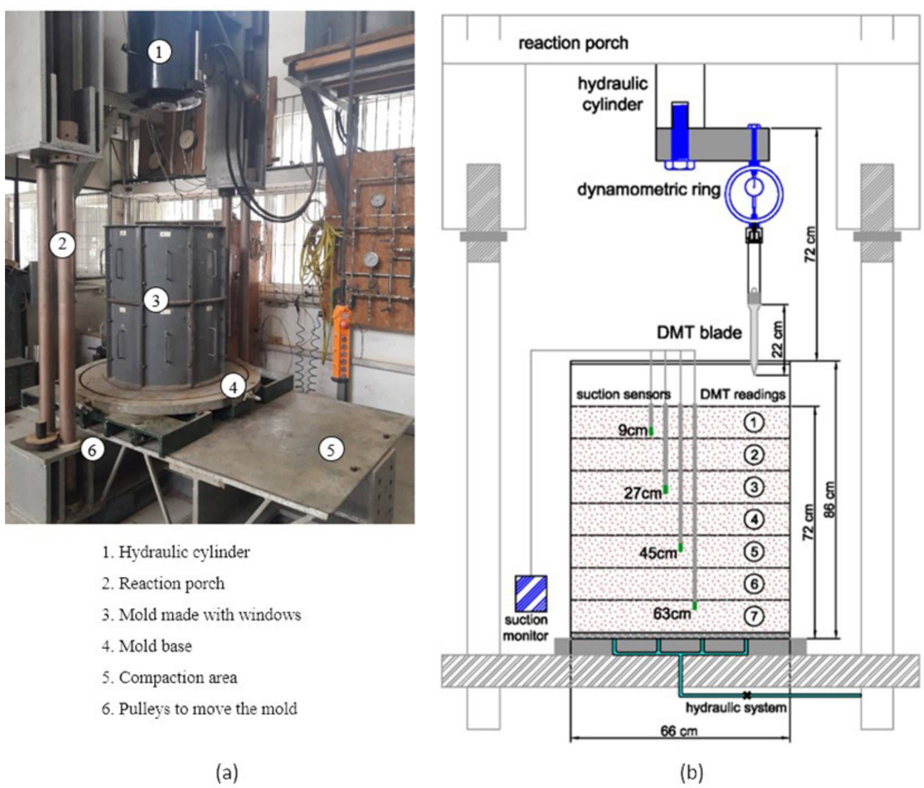

Figure 4. Equipment used for conducting the DMT in the laboratory: (a) general view; (b) schematic section.

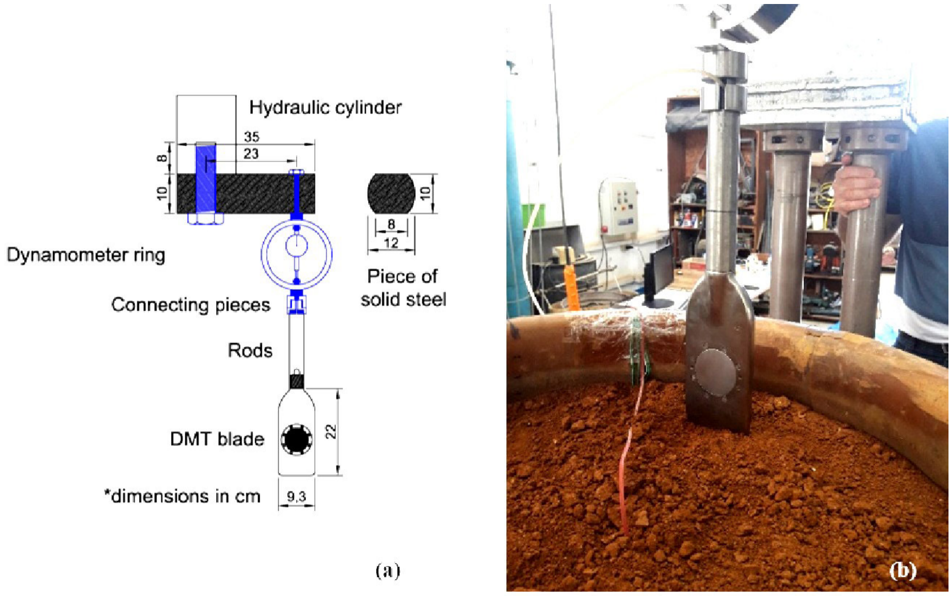

Figure 5. Parts made for driving in the DMT blade: (a) schematic layout (b) DMT blade.

(10-15 cm), the shape of its tip and the measuring system on the side minimize changes to the soil structure. Some experimental studies in sandy soils and mathematical modeling have been carried out to quantify the effect of DMT blade insertion in the soil (Zhongqing et al., 2021; Frost et al., 2016; Melnikov & Boldyrev, 2014). Zhongqing et al. 2021 measured horizontal displacements of 2 mm at a distance of 70 mm from the DMT blade with vertical displacements of 1 to 3 mm in the region close to the diaphragm.

Six tests were performed with the DMT positioned at different locations on the specimen surface (Figure 6), obtaining in each of them 7 readings of parameters *A* and *B*. The first test was performed for the molding conditions, corresponding to the optimum moisture content and maximum dry density of the compaction curve determined with Proctor normal energy.

The second DMT was carried out after sample saturation. The sample saturation was performed with the aid of water flow valves located at the base of the mold, where the water was inserted by low pressure (36 kPa) in the base and top directions of the sample. Saturation was confirmed when all GMS presented suction values are equal to zero. The other 4 DMT were performed as the specimen lost moisture and started to present different suction profiles. The suction profile was continuously monitored and the timing of the DMTs was selected, considering the GMS limit that can measure suctions up to 200 kPa. The insertion of the DMT blade was made statically with a velocity of 20 mm/s, this value being within the range of variation recommended by different standards (TC16 DMT, 2001; ASTM, 2015; Eurocode, 1997; ISO, 2017). In this laboratory experiment, many of the variables could be controlled, such as specimen homogeneity, better control of DMT slide insertion, and ambient conditions

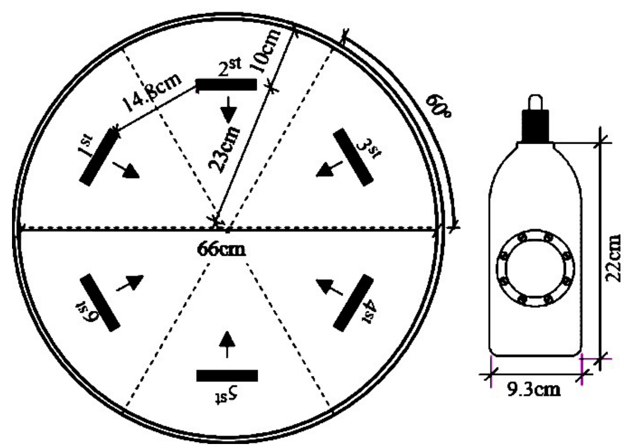

Figure 6. DMT blade insertion position.

related to temperature and relative humidity. There are some limitations such as the small specimen height that allows readings to a depth of 65 cm where the vertical stresses are small. However, the purpose of DMTs is to verify the influence of suction on test results that are all subjected to the same boundary conditions. Thus, suction is the only variable of the tests.

4. Results and discussions

4.1 Characterization of the soil

The soil sample collection point is in the city of Florianópolis/SC, Brazil. According to the geological map by Tomazzoli & Pellerin (2018), in the exact location of the collection point is a diabase dike. The surrounding geological unit is granite.

The laboratory tests carried out had the objective of characterizing the sample collected for the research. Table 1 presents a summary of the results of the granulometric curve, Atterberg limits, unit weight of solids, compaction test, direct shear test and soil classifications. The results of the saturated direct shear tests, obtained for the compacted specimens under the optimum moisture content conditions, are presented in Figure 7. The effective cohesion value and effective angle of internal friction were respectively 8.1 kPa and 34.7°.

4.2 Determination of vertical effective stress profiles

Figure 8 shows the results of the unconfined compressive strength tests as a function of the respective initial suction values obtained with the filter paper technique. The experimental points of this figure represent the projection of each of the 17 tests in the plane defined by the shear strength as a function of suction. This procedure is shown schematically in Figure 2. The curvilinear envelope (Figure 8) fitted to these experimental points represents the cohesion intercept.

For the compacted diabase residual soil used in this study, the variation of the parameter χ, obtained by the relationship between "a" and "b", presented in Figure 8, for different suction values, was defined by Equation 16. This equation was substituted in Equation 14 to determine the effective vertical stress. The effective vertical stresses, given by Equation 17, were obtained by substituting the value of χ, represented by Equation 16, in Equation 8.

$$\chi = -0.201 \cdot \ln\left(u_a - u_w\right) + 1.5194 \quad (16)$$

$$\sigma'_v = \left(\sigma - u_a\right) + \left[-0.201 \cdot \ln\left(u_a - u_w\right) + 1.5194\right] \cdot \left(u_a - u_w\right) \quad (17)$$

The suction profiles obtained with the GMS and the effective vertical stress profiles are shown in Figure 9. The suction values were defined for the depths of the DMT by interpolation of the GMS readings. It can be observed in Figure 9 that the suction profiles present small variations of values. This indicates that for the maximum depth of the tests (0.65 m) the specimen drying occurred homogeneously. As expected, the effective vertical stresses increase with increasing depth and suction, reaching a maximum value of 85 kPa.

Figure 10 shows the suction monitoring during the 182 days period of the experiment. The results presented in this figure demonstrate the good functioning of the GMS. After the first DMT was performed, for the compaction condition, the specimen saturation was performed. GMS indicated a rapid reduction in suction value to zero. After this step, the specimen was closed to homogenize the moisture content in all its volume. During this period, an initial suction profile was defined, and the top of the specimen was opened.

No variations were observed in the suction values measured by the MSG after the DMT insertion. This can be

Table 1. Summary of the soil characterization tests.

Grain Size Analysis	Clay (%)	27.8
	Silt (%)	29.8
	Fine Sand (%)	16.3
	Medium Sand (%)	20.0
	Coarse Sand (%)	3.9
	Gravel (%)	2.2
Atterberg Limits	W_L (%)	47
	W_P (%)	44
	I_P (%)	3
	GI (Group Index)	3
Unit weight of solids	γ_s (kN/m³)	28.0
Compaction Test	W_{opt} (%)	30
	γ_d (kN/m³)	13.9
Direct Shear Test	c' (kPa)	8.1
	ϕ' (°)	34.7
Classifications	HRB	A-5
	USCS	ML

Legend: see List of Symbols

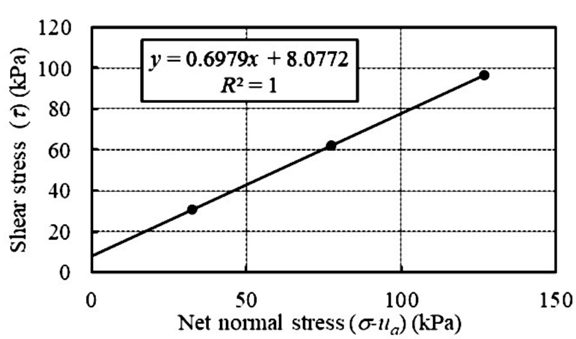

Figure 7. Results of direct shear tests performed under saturated conditions.

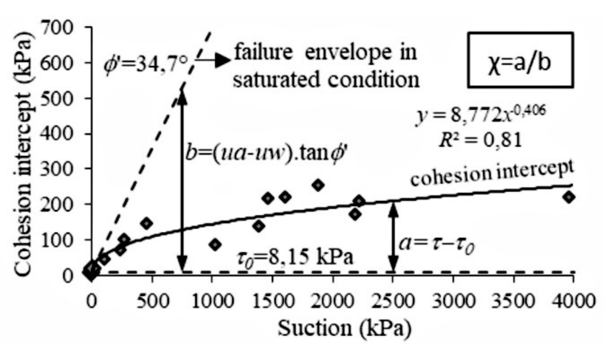

Figure 8. Obtaining parameter χ using the results of unconfined compressive strength tests.

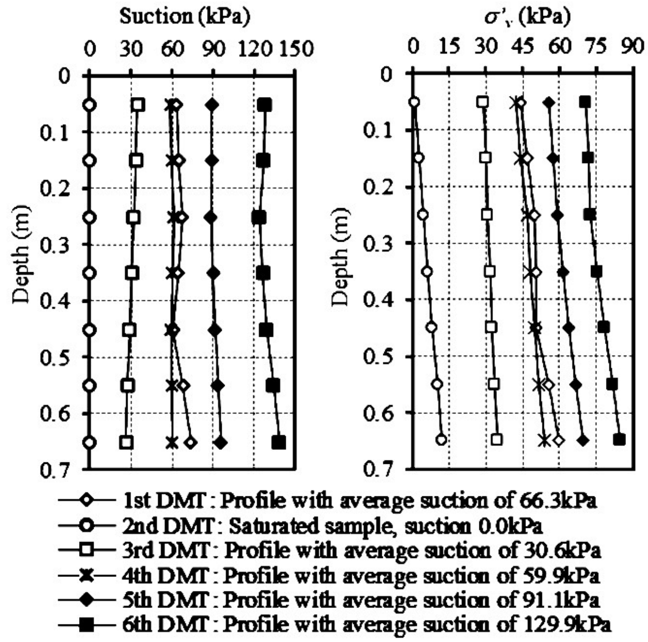

Figure 9. Profiles of suction and effective vertical stress.

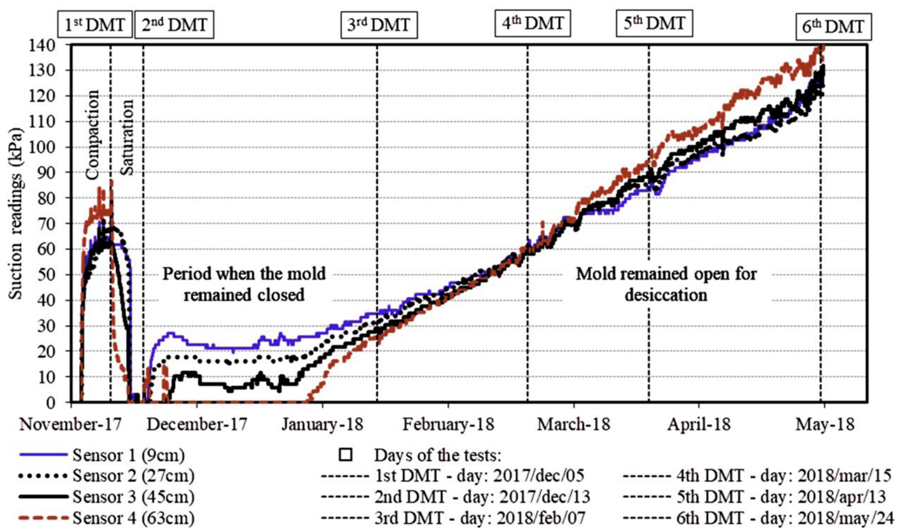

Figure 10. Monitoring of the suction sensors during the experiment.

seen in Figure 10 where the increase in suction in all GMS occurred at a constant rate. This fact indicates that there were no changes in the soil structure at a distance from the DMT blade of the order of 20 cm. Therefore, the distance between the DMT insertion points, indicated in Figure 6, is sufficient to prevent interference between the tests performed on each of the 6 suction profiles. At the end of the tests, the metallic compaction mold was removed, and no cracks were observed on the lateral surface of the specimen, which is at a distance of 10 cm from the DMT driving points (see Figure 6).

4.3 Results of the DMT

This item presents and analyzes the results of the DMT performed on compacted soils for different suction profiles. The results of all tests performed are presented in Table 2. In this table are the test parameters proposed by Marchetti (1980) and the suction profiles associated with each of the 6 DMTs.

Figure 11 presents the values of the pressure readings p_0 and p_1 and q_D, obtained from the DMT blade thrust

Table 2. Parameters of DMT obtained for different suction profiles.

Test	Depth (m)	A (kPa)	B (kPa)	Suction (kPa)	I_D	K_D	E_D (MPa)
1st DMT (Molding)	0.05	160	750	63.3	3.32	3.64	18.6
	0.15	485	1340	64.7	1.72	10.11	28.2
	0.25	490	1370	67.6	1.76	9.55	29.1
	0.35	540	1570	64.6	1.92	10.31	34.6
	0.45	330	1200	60.8	2.62	6.29	28.8
	0.55	550	1540	67.9	1.79	9.58	33.1
	0.65	490	1650	73.6	2.44	7.75	39.3
2nd DMT (Saturation)	0.05	155	610	0.0	2.77	157.50	13.9
	0.15	400	1000	0.0	1.45	138.88	19.2
	0.25	340	960	0.0	1.79	70.03	19.9
	0.35	465	1050	0.0	1.20	69.76	18.6
	0.45	360	1000	0.0	1.75	41.21	20.6
	0.55	440	1080	0.0	1.42	41.64	20.6
	0.65	290	970	0.0	2.37	22.49	22.1
3rd DMT (Drying)	0.05	155	640	34.7	2.80	5.34	15.0
	0.15	410	1080	33.8	1.57	13.24	21.7
	0.25	330	1020	32.2	2.03	10.27	22.5
	0.35	495	1230	30.8	1.44	15.06	24.1
	0.45	380	1040	29.0	1.67	11.32	21.4
	0.55	410	1040	27.6	1.46	11.93	20.3
	0.65	380	1130	26.5	1.95	10.51	24.6
4th DMT (Drying)	0.05	300	1040	58.8	2.40	6.95	24.3
	0.15	480	1330	59.6	1.75	10.55	28.3
	0.25	435	1430	61.2	2.33	8.86	33.6
	0.35	630	1660	60.4	1.65	12.59	34.9
	0.45	510	1400	59.4	1.73	9.98	29.8
	0.55	500	1350	59.9	1.68	9.42	28.3
	0.65	485	1490	60.4	2.11	8.65	34.0
5th DMT (Drying)	0.05	245	780	88.9	1.91	4.55	16.8
	0.15	410	1300	88.8	2.14	6.97	29.7
	0.25	450	1580	88.5	2.59	7.24	38.5
	0.35	580	1770	89.8	2.11	9.04	40.7
	0.45	445	1520	91.3	2.46	6.68	36.5
	0.55	520	1640	93.7	2.20	7.49	38.1
	0.65	580	1730	95.7	2.02	8.06	39.2
6th DMT (Drying)	0.05	440	1000	128.1	1.13	6.43	17.7
	0.15	455	1410	126.7	2.06	6.24	32.1
	0.25	470	1550	124.0	2.31	6.28	36.7
	0.35	530	1780	126.2	2.43	6.76	42.9
	0.45	460	1710	129.0	2.81	5.63	42.9
	0.55	645	1850	134.2	1.89	7.68	41.2
	0.65	580	1920	138.4	2.39	6.56	46.1

resistance with the dynamometric ring, mounted on the thrust rods. There is an influence of suction both in the pressure profiles p_0 and p_1, and in the DMT blade thrust resistance (q_D). Regarding pressures p_0 and p_1, the values of p_1 have the highest variations concerning suction increase. Parameter p_0 presents the lowest variations, probably because the reading being carried out in a region of the sample disturbed by the insertion of the blade. The value of the parameter p_1, obtained when the movement of the membrane center reaches 1.1 mm, is directly associated with the stiffness of the soil resulting from the compaction process. It can be observed in Figure 11c that the tip resistance (q_D) increases with depth. This fact is associated with the increase in confining pressure and suction. However, suction has a greater influence on the increase in tip resistance (q_D). The values of p_0 and p_1 of each of the profiles presented in Figure 11, obtained for different

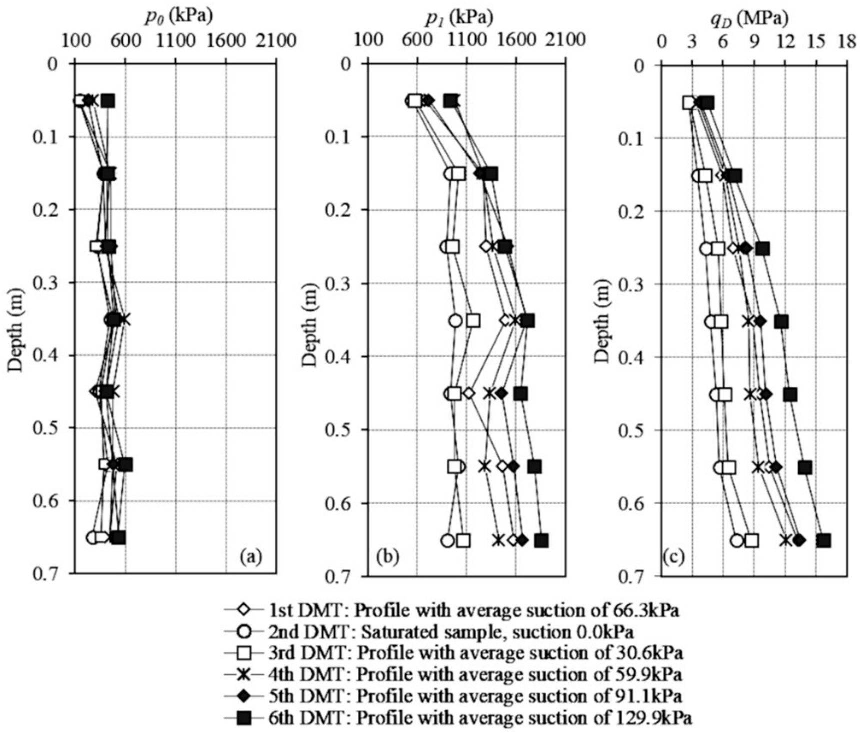

Figure 11. Readings of pressures (a) p_0 and (b) p_1 and tip resistance (c) q_D.

levels of suction, are plotted in Figure 12. This graph shows an increasing trend for pressures p_0 and p_1 as a function of suction when compared to the linear adjustments applied to the experimental points.

Figure 13 presents the profiles for the intermediate parameters I_D, K_D and E_D, obtained from the data from the DMT. The I_D and K_D parameters were obtained by Equations 13 and 14, respectively. When the suction value is equal to zero (2nd DMT) these equations become equal to the equations proposed by Marchetti (1980) for saturated soils.

For the calculation of I_D and K_D, the value of Poisson's ratio (ν), in Equations 13 and 14, was considered constant and equal to 0.3. This value was obtained by equating the equation for the value of K_0, proposed by Jaky (1944), with Equation 15 considering suction equal to zero in this equation. In this way, the value of Poisson's ratio was calculated by Equation 18.

$$K_0 = 1 - sen\phi' = \frac{v}{1 - v} \tag{18}$$

The material index parameter (I_D), presented in Figure 13a, varies around an average value for each of the suction profiles, without presenting an increasing or decreasing trend according to depth. However, there is a slight influence of suction, and so the I_D values are higher for higher suction values, as can be seen in Figure 14.

The parameter I_D classified the compacted sample between sandy silt and silty sand, different from the particle

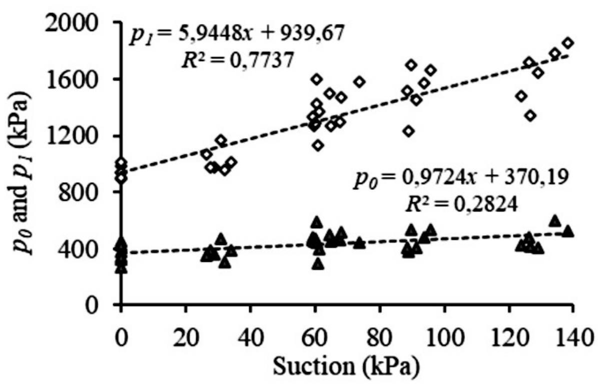

Figure 12. Relationship between the readings p_0 and p_1 and suction.

size distribution test conducted in the soil sample, which classified the soil as silty clay. This behavior is justified by the fact that the I_D parameter reflects the mechanical performance of the soil.

As for the horizontal stress index parameter (K_D), presented in Figure 13b, the values obtained experimentally show a great influence from increases in suction values. The results of 2nd DMT are not plotted in this figure. The profile of the 2nd DMT, in the saturated condition, shows a value of 157.5 on the surface of the specimen followed by a reduction of value to 22.5 at a depth of 0.65 m. Those values are very high and are directly related to the small values of vertical stresses (σ'_v) limited by the maximum depth of the laboratory test,

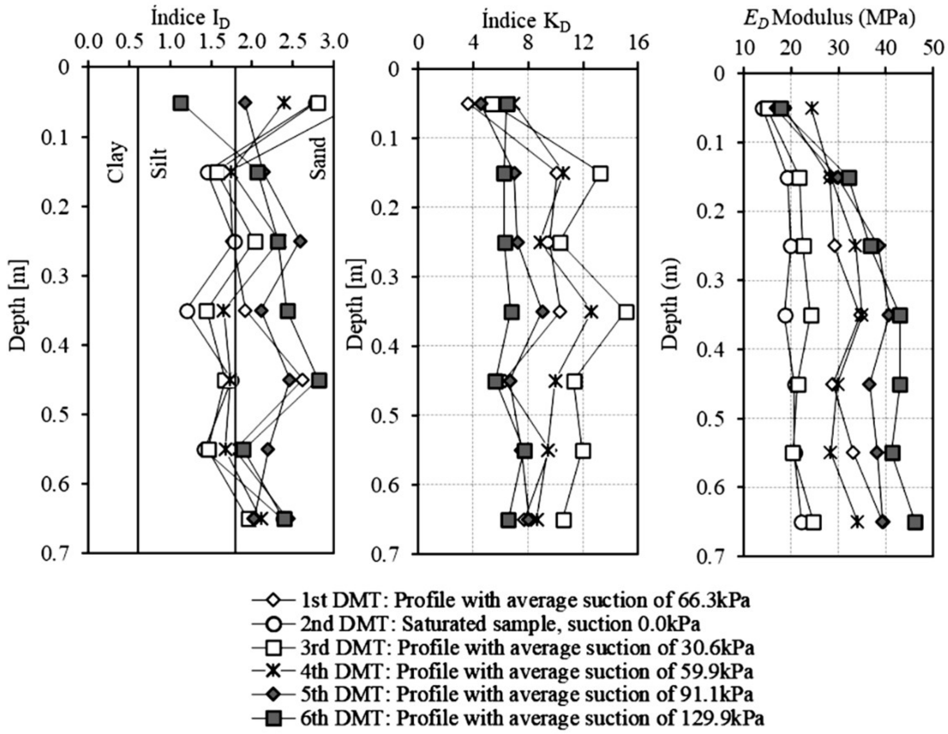

Figure 13. Profiles for the parameters: (a) I_D, (b) K_D and (c) E_D.

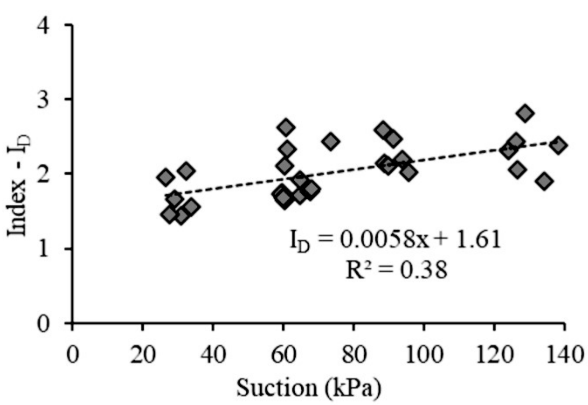

Figure 14. Relationship between I_D and suction.

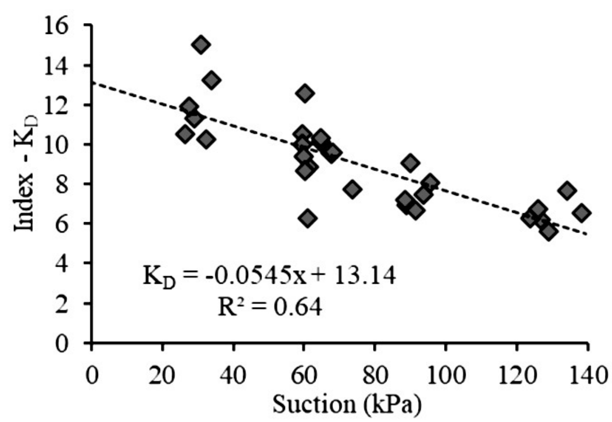

Figure 15. Relationship between K_D and suction.

which is a limitation of this research. To avoid anomalous K_D values, they are often plotted to depths greater than 1 m.

For profiles that have a specific suction value, the K_D values do not tend to increase or decrease with depth, oscillating around an average value. The K_D values of these profiles ranged from 4.2 to 15.5. However, as can be observed in Figure 15, there is a tendency of decreasing K_D values with an increase of suction. As the matrix suction of the soil increases, there is a reduction in horizontal stress (Fredlund & Rahardjo, 1993). This reduction in horizontal stress, which varies as a function of depth, causes a reduction in the K_0 value.

The profiles for the dilatometer modulus parameter (E_D), presented in Figure 13c, show that E_D increases up to the depth of 35 cm, with a tendency to remain constant at further depths. The E_D range varied between 13.9 and 46.1 MPa, with a mean of 28.8 MPa. In Figure 16 are plotted the values of E_D as a function of suction in all the experimental points. The E_D values increase with increasing suction, showing a good correlation coefficient (R^2 = 0.82). Many studies have verified an increase in the modulus of deformability and shear resistance in compacted residual soils as a function of an increase in suction (Oliveira, 2004; Pecapedra, 2016; Bernardi, 2018).

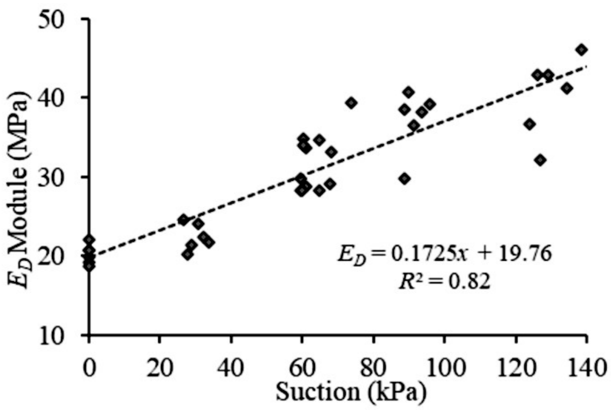

Figure 16. Relationship between E_D and suction.

5. Conclusions

The experimental results of this research verified the suction influence on the readings measured during the DMT in the compacted soil. It was suggested that the equations for material index I_D and horizontal stress index K_D should be adapted, inserting the variable suction in them. This had the objective to adapt the equation to be used in data from tests carried out on unsaturated soils. The use of the effective vertical stress equation proposed Bishop (1959), which incorporates suction, has also been suggested. In this equation, the variation of the parameter *c'* as a function of suction was defined using the cohesion intercept obtained with the results of uniaxial compression tests. In this equation, the variation of the parameter χ as a function of the suction was defined using the cohesion intercept obtained with the results of uniaxial compression tests. In these tests, the initial suction of the specimens were determined using the filter paper technique. As a simplifying hypothesis, the value of Poisson's ratio of the equations obtained for I_D and k_D was considered constant and equal to 0.3.

With the increase in the suction value, the parameters I_D and E_D showed a tendency to increase values and the K_D value showed a tendency to decrease in value. When going from the saturated condition (2nd DMT) to the suction of the order of 130 kPa (6th DMT) the Id value changed from 1.8 to 2.1, showing an increase of 18%. For this same suction interval, the value of *Ed* increased from 19.3 kPa to 37.1 kPa, showing an increase of 92%. The K_D value obtained for the saturated condition was equal to 12, reducing to 6.5 when the average suction of the soil profile was equal to 130 kPa, thus presenting a reduction of 46%. The variations in the I_D, K_D and E_D values, with the increase of suction, are compatible with the mathematical models and the experimental results obtained by other researchers. The relationships proposed in this research for the calculation of I_D and K_D, incorporating the suction value, provided coherent values. It was found that the DMT correctly detected the influence of suction on the geotechnical parameters analyzed.

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Declaration of interest

There were no competing interests or conflicts of interest associated with the conduct of this research or the development of this paper.

Authors' contributions

Cândida Bernardi: conceptualization, data curation, formal analysis investigation, methodology, resources, project administration, supervision, validation, visualization, writing – original draft, writing – review & editing. Orlando Martini de Oliveira: conceptualization, investigation, methodology, resources, project administration, supervision, validation, writing – review & editing. Murilo da Silva Espíndola: investigation, resources. Rafael Augusto dos Reis Higashi: funding acquisition, resources.

List of symbols

c'	Effective cohesion
DMT	Marchetti dilatometer test
E_D	Parameter related to the soil deformability modulus
E	Modulus of elasticity for the soil structure related to a change in (σ-u_a)
HRB	Highway Research Board soil classification
H	Modulus of elasticity for the soil structure related to a change in (u_a-u_w)
I_D	Parameter related to soil type
I_p	Plasticity index
K_D	Parameter related to the over-consolidation ratio (OCR) and coefficient of earth pressure at-rest (K_0)
K_0	Coefficient of earth pressure at-rest
K_D	Horizontal stress index
OCR	Overconsolidation ratio
p_1	Pressure obtained from the DMT
p_0	Pressure obtained from the DMT
USCS	Unified Soil Classification System
u_a	Air pressure
u_w	Pore water pressure
(u_a-u_w)	Suction
w_l	liquid limit
$w_{opt.}$	Optimum moisture content
w_p	Plastic limit
Z_m	Gage reading when vented to atmospheric pressure
Z	Reading depth

ΔA	DMT membrane calibration readings
ΔB	DMT membrane calibration readings
ϕ'	Effective angle of internal friction
γ_d	Dry unit weight
γ_s	Unit weight of the solid particles
σ'	Effective stress
σ	Total stress
σ_v	Normal vertical stress
S	Degree of saturation
Su	Undrained shear strengths
τ	Shear strength
τ_0	Shear strength in saturated conditions
υ	Poisson's ratio
χ	Coefficient related to the degree of saturation of the soil

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