Prediction of Load-Settlement Curves by the DMT in an Unsaturated Tropical Soil Site

N.M. Silva, B.P. Rocha, H.L. Giacheti

Abstract. Several methods for prediction of the load-settlement curves of shallow foundations have been proposed based on *in-situ* testing data. However, the good accuracy of such prediction depends on the definition of appropriate soil stiffness. Seasonal variability and its influence on the soil behavior need to be considered for unsaturated tropical soils. In this context, this study uses a procedure to determine the complete load-settlement curves of shallow foundations by the flat dilatometer test (DMT) in an unsaturated tropical soil site, considering seasonal variability. The DMT and the plate load tests carried out at the experimental research site of the University of São Paulo (São Carlos, Brazil) are presented and discussed. It was found that the DMT is an adequate test for predicting soil stiffness, and the presented procedure allows a good estimate of the complete load-settlement curves. It was also observed that seasonal variability should be considered in the prediction of such curves for the studied site.

Keywords: flat dilatometer test (DMT), *in-situ* tests, load-settlement curve, seasonal variability, tropical soils.

1. Introduction

Several methods are available to predict the load-settlement curve based on *in-situ* test data (Schmertmann, 1986; Mayne *et al.*, 2000; Briaud, 2007). However, in most cases, these methods consider that the deformability modulus is constant (Lehane & Fahey, 2004). Moreover, the accuracy of these curves' prediction depends on the adequate definition of soil stiffness for the deformation level imposed by the foundation element (Mayne, 2001, Shin & Das, 2011).

The plate load test has been commonly used to represent the behavior of shallow foundations (Consoli *et al.*, 1998; Menegotto, 2004, Tang *et al.*, 2018). The utilization of plate load test results allows minimization of the effects of the "scale" factor, soil sample disturbance, and selected technique on the input information for a foundation design (Reznik, 1993).

The flat dilatometer (DMT) has been shown to be an accurate test technique for site characterization (Marchetti *et al.*, 2001; Marchetti & Monaco, 2018), compacted fill analyses (Queiroz *et al.*, 2012; Amoroso *et al.*, 2015), laterally loaded pile analyses (Robertson *et al.*, 1987; Marchetti *et al.*, 1991), as well as to predict foundation settlements (Schmertmann, 1986; Monaco *et al.*, 2006; Anderson *et al.*, 2007; Monaco *et al.*, 2014). Very few studies evaluating the applicability of such test for predicting the complete load-settlement curves of shallow foundations in unsaturated tropical soils have been found in the literature.

Soils formed in tropical weather regions are influenced by drying and wetting cycles, which lead to the formation of thick profiles of unsaturated soils. It is important to consider seasonal variability in these soil sites caused by soil suction, which is related to the water content through a soil-water retention curve (SWRC). Therefore, the behavior of unsaturated soils cannot be considered without taking into account soil suction (ψ) and the site variability (Giacheti *et al.*, 2019).

This study presents the results of flat dilatometer and plate load tests for prediction of the load-settlement curves of shallow foundations in an unsaturated tropical sandy soil. The DMT and plate load tests were carried out in different months of the year to better understand the influence of seasonal variability on the load-settlement curve prediction in the studied site.

2. Flat Dilatometer Test (DMT)

2.1. Principles of test procedure and interpretation

Marchetti (1980) and Marchetti *et al.* (2001) describe the flat dilatometer, which has a steel blade 14 mm thick, 94 mm wide and an expandable circular steel membrane (60 mm diameter) mounted on one face. The blade is connected, by an electro-pneumatic tube, running through the insertion rods, to a control unit on the surface. The authors also describe the test procedure which starts by inserting the dilatometer into the ground. By use of a control unit with a pressure regulator, a gauge and an audio signal, the operator determines the p_0-pressure required to just begin to

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move the membrane and the p_1-pressure required to move it 1.1 mm into the ground. The blade is then advanced into the ground by one depth increment, typically 200 mm, using common field equipment.

The DMT interpretation starts by first determining three intermediate parameters (Marchetti, 1980; Marchetti *et al.*, 2001): the material index (I_D), the horizontal stress index (K_D) and the dilatometer modulus (E_D), which are defined as:

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

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

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

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

A detailed description of the DMT equipment and test procedure can be found in Marchetti (1980), Marchetti *et al.* (2001) and Marchetti & Monaco (2018).

2.2. Prediction of shallow foundation settlements by the DMT

Predicting the settlements of shallow foundations is often considered the main application of the DMT (Schmertmann, 1986; Monaco *et al.*, 2006; Failmezger *et al.*, 2015). The accumulated experience suggests that the constrained modulus (M_{DMT}), which is determined according to Marchetti (1980), can be assumed as an adequate operative or the working strain modulus for most practical purposes. This modulus is defined by Eq. 4:

$$M_{DMT} = R_M \cdot E_D \quad (4)$$

where M_{DMT} = constrained modulus from DMT, R_M = correction factor, a function of I_D and K_D.

Lehane & Fahey (2004) investigated the influence of the disturbance caused by the DMT blade installation on the constrained modulus prediction in sands. The authors proposed an equation for estimating the constrained modulus for working condition (M_{DV}). According to Lehane and Fahey (2004), M_{DV} is more relevant to settlement prediction than E_D, and can be considered an operational modulus applied by the dilatometer at a 1.8 % settlement ratio (δ/B_{eq}), according to Eq. 5:

$$M_{DV} = 1.3 f_{aniso} \frac{E_D}{\sqrt{K_D}} \quad \text{at} \quad \frac{\delta}{B_{eq}} = 1.8\ \% \quad (5)$$

where δ = settlement, B_{eq} = the square root of the base width of the foundation element, f_{aniso} = inherent anisotropy factor.

Décourt (1999) proposed an approach to extrapolate the plate load test data by analyzing the results of 145 load tests on shallow foundations and on rigid steel plates carried out all over the world in very different soils.

Dos Santos *et al.* (2019) integrated Décourt's (1999) approach for the representation of the normalized load-settlement curve and Lehane & Fahey's (2004) considerations about M_{DV}, to predict a complete load-settlement curve. This approach was tested and compared with plate load tests carried out in a tropical sandy soil from an experimental research site in Bauru-SP, Brazil. Good agreement between the load-settlement curve predicted by the DMT and those determined by the plate load tests was found.

Figure 1 shows the representation of a typical curve, defined according to the approach used (Dos Santos *et al.*, 2019), where q = applied stress; q_{app} = applied stress at working condition; q_{uc} = load at conventional soil failure; δ = settlement; B_{eq} = square root of the base width of the foundation element.

The normalized load-settlement curve is represented together with the data point where the conventional rupture occurs. It is also possible to observe the representation of the DMT working load condition (δ/B_{eq} = 1.8 %) in this curve. Since the DMT membrane is 60 mm (B) in diameter and expands 1.1 mm (δ), a settlement ratio (δ/B) equal to 1.8 % is mobilized during the test.

3. Study Site

The DMT and plate load tests were carried out at the experimental research site of the University of São Paulo, in São Carlos-SP (Brazil). In this site, the subsoil is a clayey fine sand with two well-defined layers: Cenozoic Sediments with lateritic behavior (up to around 6.0 m depth) overlaying the residual soil derived from Sandstone with non-lateritic behavior. The groundwater level varies sea-

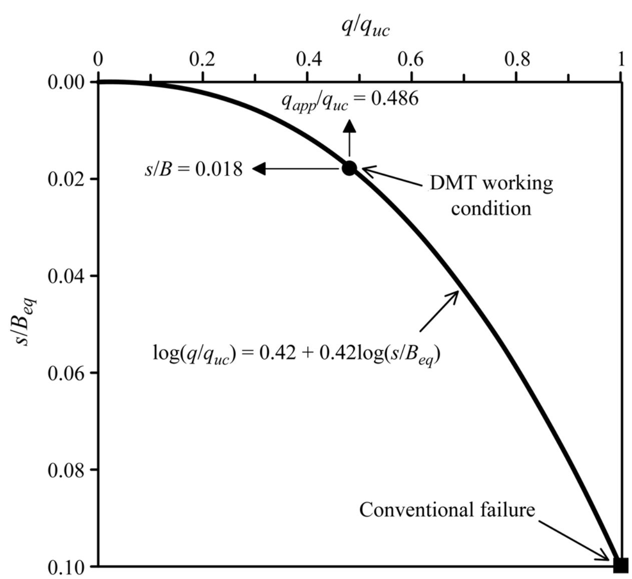

Figure 1 - Representation of the load-settlement curve based on the DMT (Dos Santos *et al.*, 2019).

sonally between 9 and 12 m below the ground surface. Both horizons can be classified as clayey sand (SC) according to USCS.

The tropical climate provides wet and hot seasons (October to April) that are followed by dry winters. This type of tropical weather can lead to variations in the *in-situ* soil suction since it features high annual temperatures with wet summers and dry winters. The seasonal variation's influence on soil suction can lead to significant changes in the *in-situ* test data, as discussed by Giacheti *et al.* (2019) based on CPT data. Figure 2 shows the soil profile together with dry unit weight (γ_d), void ratio (e) and Atterberg limits (w_L and w_P) of the studied site up to 12 m depth.

The soil-water retention curves (SWRCs) at 2.0, 5.0 and 8.0 m depths were determined by Machado & Vilar (1998) to examine the influence of soil suction on the soil strength and stiffness parameters (Fig. 3). The purpose of the laboratory investigation was to assess the influence of suction on the soil behavior. Figure 4 shows the data of the unsaturated oedometer tests carried out on undisturbed soil samples collected at 2.0, 5.0 and 8.0 m depths for different soil suction values. It shows that the pre-consolidation stress (σ'_p) values increase as the soil suction increases.

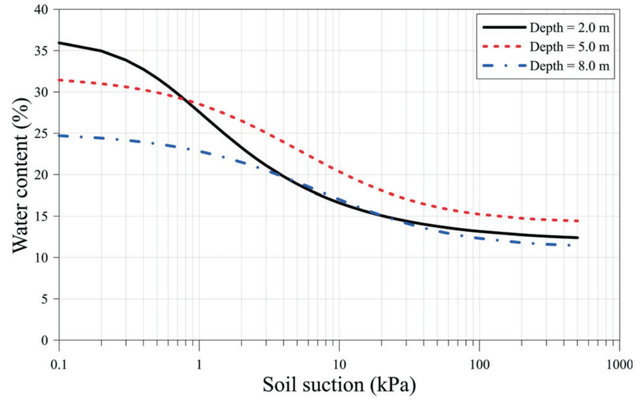

Figure 3 - Soil-water retention curves for the soil collected at 2.0 m, 5.0 m and 8.0 m depths (adapted from Machado & Vilar, 1998).

4. In-Situ Tests

4.1. DMT and plate load tests

The plate load tests were carried out on a rigid steel plate (25 mm thick and with 0.80 m diameter) at 1.5, 4.0, 6.0 and 8.0 m depths by Costa (1999) and Macacari (2001). The tests were carried out in natural and inundated conditions, allowing the evaluation of the influence of suction on the load-settlement curve. A total of 18 plate load tests were considered. A summary of the plate load tests used in this study is presented in Table 1. It should be mentioned that an average curve was considered for the inundated condition at 1.5 and 6.0 m depths. These tests were selected by considering the soil suction and water content profile by means of the SWRCs during the DMTs.

The DMTs were performed in March and October, 2016 and April and October, 2017 by Rocha (2018). Three DMT tests and one soil sampling were performed in each of these periods. Soil sampling was carried out up to 7.75 m

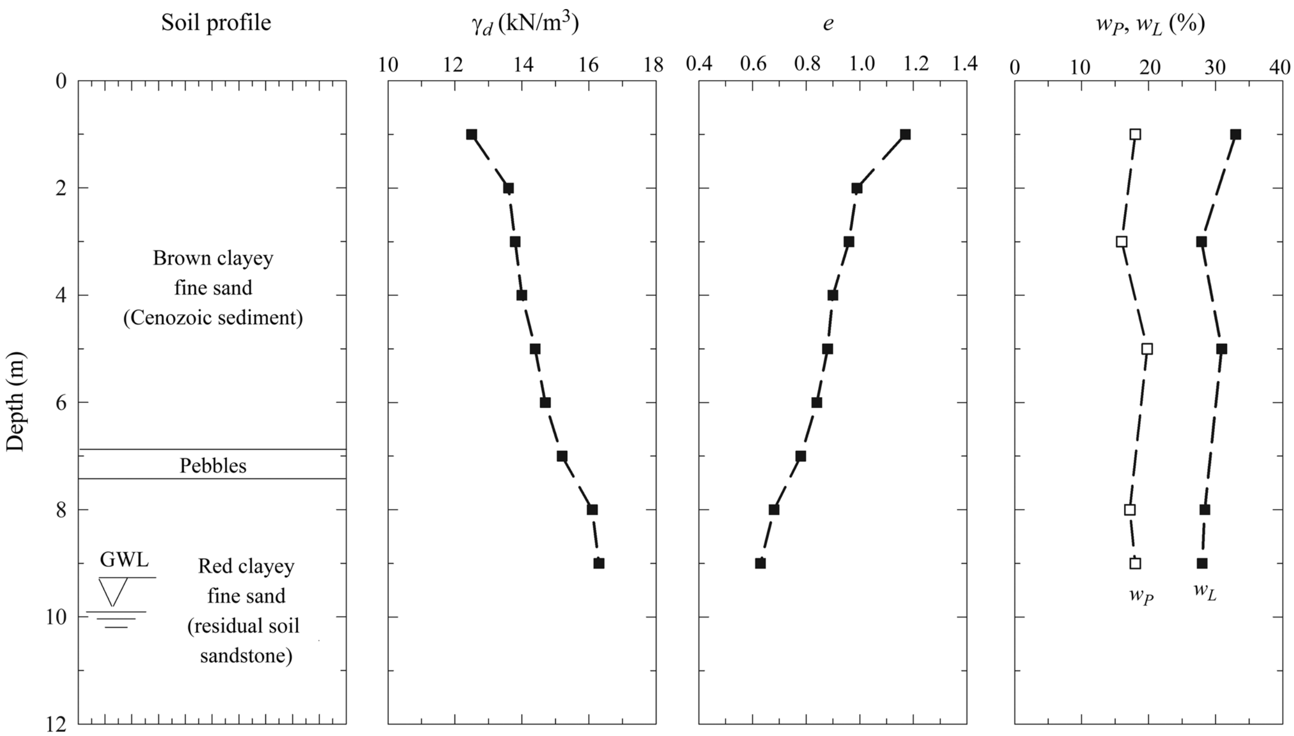

Figure 2 - Soil profile and some index properties of the studied site (adapted from Machado & Vilar, 2003).

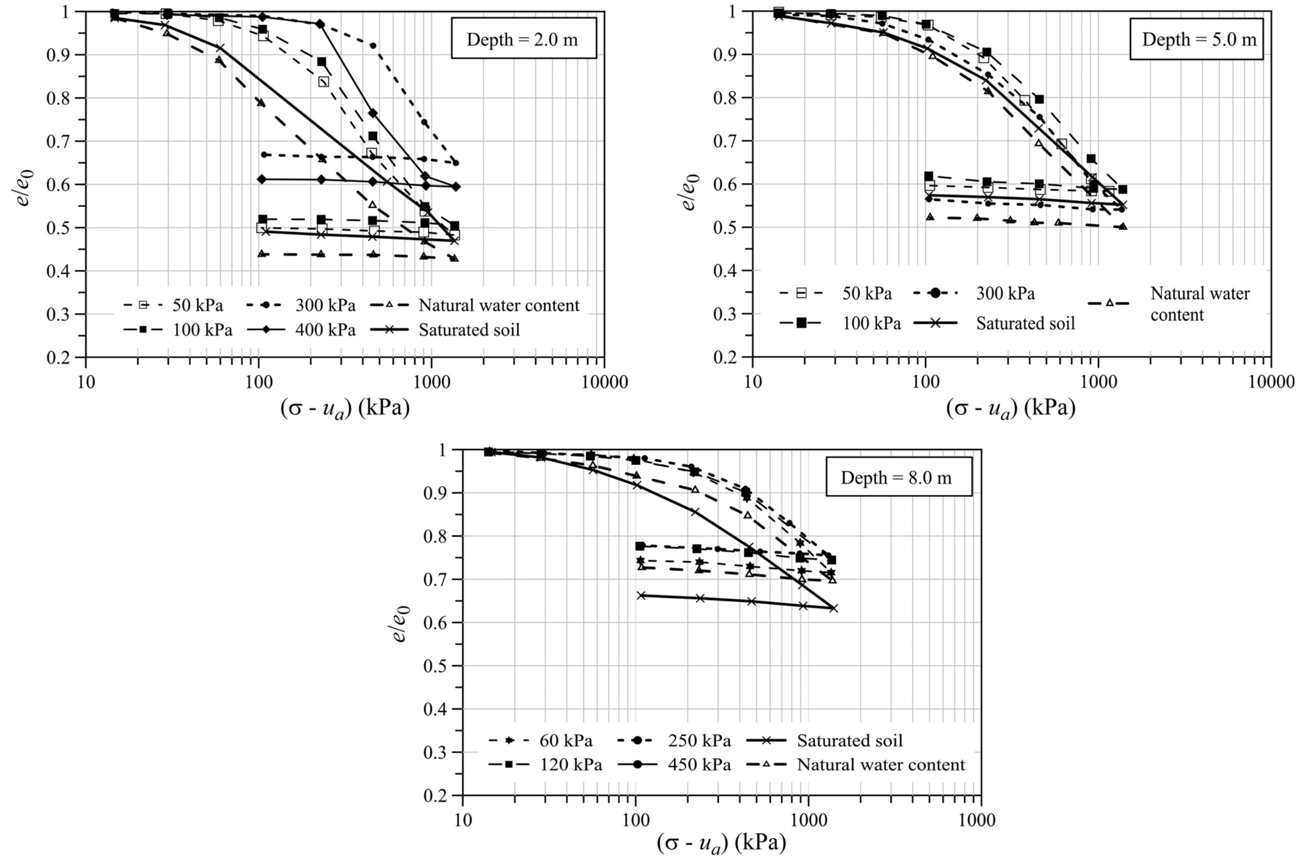

Figure 4 - Data of the oedometer tests performed on undisturbed soil samples collected at 2.0, 5.0 and 8.0 depths for soil suction values (Machado, 1998).

depth by using a helical auger to collect samples at 0.75 m intervals, to determine the water content profile and its variation in each test. The DMTs, soil sampling (undisturbed and disturbed samples), and plate load test locations are presented in Fig. 5. The average I_D, K_D and E_D profiles determined in each campaign are presented in Fig. 6.

4.2. Seasonal variability

The seasonal variability of the DMT data was assessed while considering the variation in the soil suction and water content values by means of the SWRCs. Figure 7 shows the soil suction and the water content profiles deter-

Table 1 - A summary of the plate load tests previously carried out in the study site.

Depth (m)	Designation	Loading procedure	Soil condition	Soil suction (kPa)	Author
1.5	Average curve (Q1, Q2, QS1, QS2, SS1, SS2, SS3, S-40)	Slow/Quick	Inundated	-	Costa (1999)
1.5	S1	Slow	Natural	10	Costa (1999)
1.5	S2	Slow	Natural	31	Costa (1999)
4.0	N4C1	Quick	Natural	18	Macacari (2001)
4.0	N4C2	Quick	Inundated	-	Macacari (2001)
6.0	N6C1	Quick	Natural	16	Macacari (2001)
6.0	Average curve (N6C2, S6C3, S6C4)	Quick	Inundated	-	Macacari (2001)
8.0	N8C1	Quick	Natural	4	Macacari (2001)
8.0	N8C2	Quick	Natural	6	Macacari (2001)

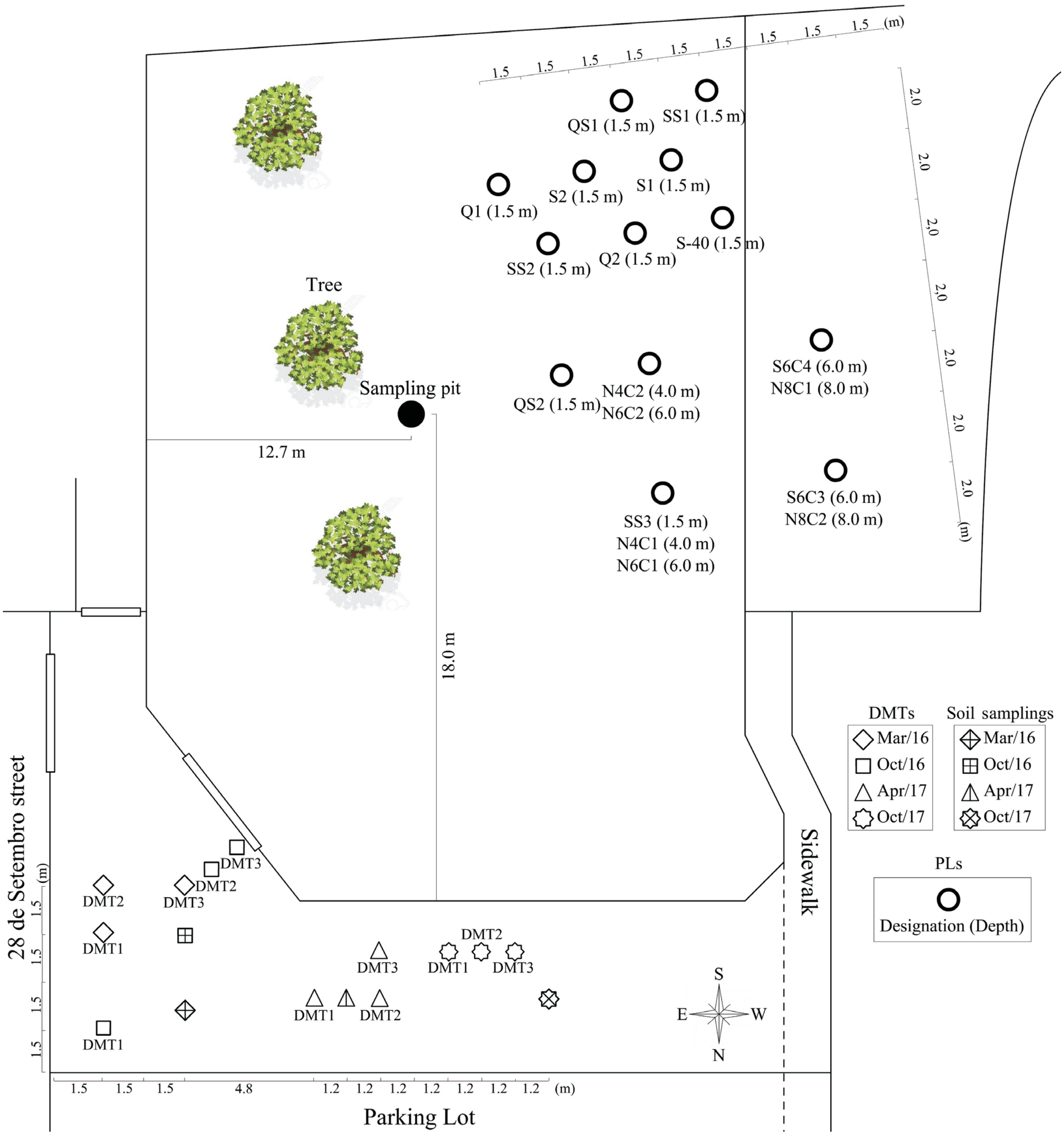

Figure 5 - Schematic representation of DMT, soil sampling and plate load tests positions at the study site.

mined during the execution of the DMT and the plate load tests.

The water content values determined in the plate load tests are similar to the water content profiles determined with the tests carried out in March and October, 2016 and April, 2017. The results of these plate load tests were those that best characterized the soil water content conditions (Fig. 7a), and they were considered in this study.

Figure 7b shows that the water content determined in the tests (ranging from 15 to 20 %) tends to be in a region of the SWRCs where a little change in water content causes a considerable change in soil suction. The tests which resulted in higher water content profiles (Mar/16 and Apr/17) showed soil suction values always lower than 10 kPa. There were significant changes in soil suction, ranging from 13 to 130 kPa up to 5.0 m depth in the dry seasons (Oct/16 and

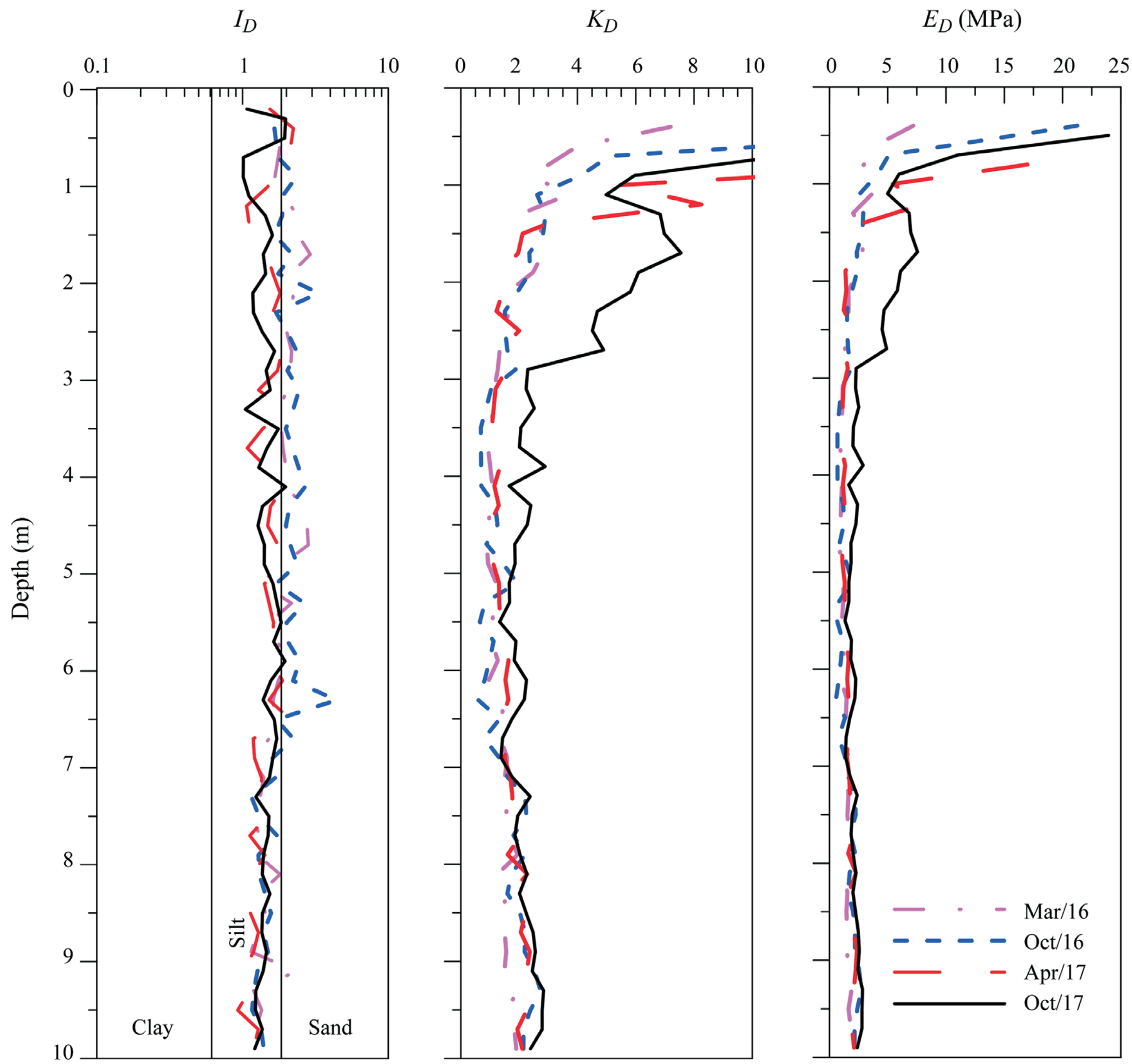

Figure 6 - I_D, K_D and E_D profiles at the study site (adapted from Rocha, 2018).

Oct/17). It is important to investigate the changes in soil suction, mainly for the design of foundations because the bearing capacity of shallow foundations is directly influenced by soil suction (Costa, 1999 and Reznik, 1994).

4.3. Constrained modulus by the DMT

Seasonal variability influences the average *MDMT* and *MDV* profiles determined in each *in situ* test campaign, as shown in Fig. 8. M_{DV} is not really affected by seasonal variability, while M_{DMT} is, mainly up to 5.0 m depth in the tests conducted in Oct/17. This occurs because both parameters (E_D and K_D) are influenced by soil suction in the studied soil, as shown by Rocha (2018). The ratio between E_D and K_D is used to calculate M_{DV} (Eq. 5), and it hides the influence of suction on the prediction of the load-settlement curve. Another relevant aspect of M_{DV} is the possibility of considering the soil anisotropy by using the inherent anisotropy factor (f_{aniso}). As the investigated soil suffered intense pedogenetic and morphogenetic processes during its formation (tropical soil), which led to a homogeneous and isotropic soil (Vaz, 1996), corrections due to the soil anisotropy are not relevant.

5. Load-Settlement Curves

The DMT and plate load test data obtained in different periods of the year were used to predict the complete load-settlement curves as described by Dos Santos *et al.* (2019).

The DMTs carried out in Mar/16 and Apr/17 were considered representative of the wet season, and the tests carried out in Oct/16 were considered representative of the dry season based on the water content profile and soil water retention curves (Fig. 7). Considering the unsaturated condition makes it possible to assess the seasonal variability influence on the prediction of the load-settlement curves by the DMT. The DMTs carried out in Oct/17 were not considered to predict the complete load-settlement curves because the *in-situ* soil suction values measured by tensiometers (4

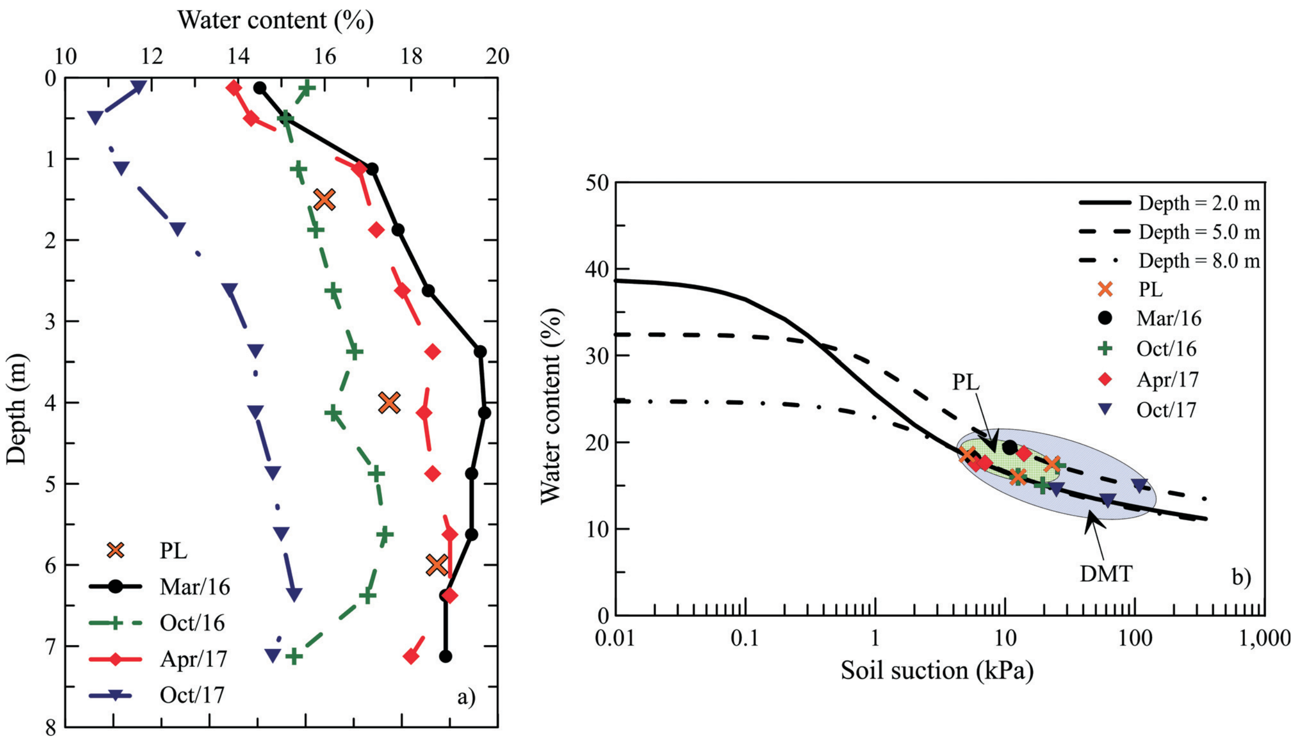

Figure 7 - a) Water content profiles determined during the execution of the DMT and the plate load tests (PL); b) Soil suction for each DMT and plate load tests (PL) by means of the SWRCs.

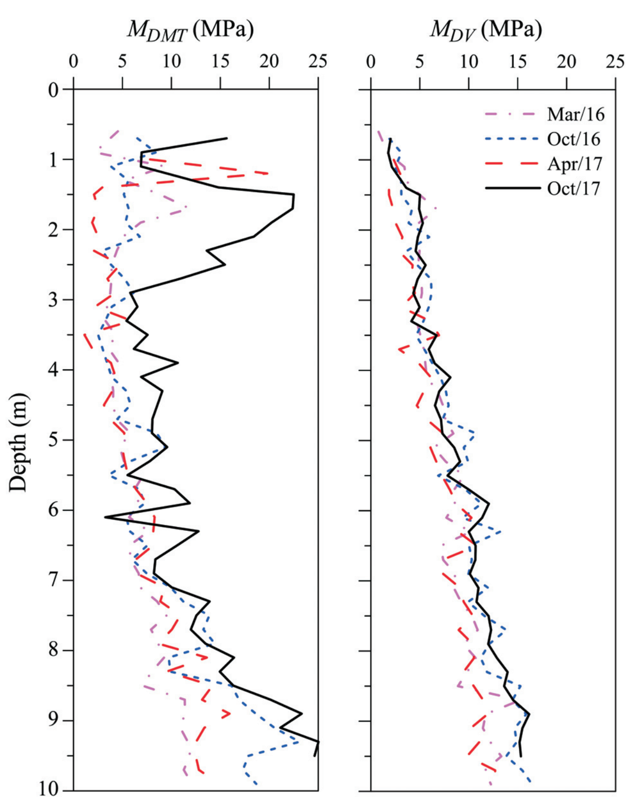

Figure 8 - Average M_{DMT} and M_{DV} profiles determined by DMT tests.

to 31 kPa) or estimated by the water content profile and the SWRCs (5 to 23 kPa) during the plate load tests did not reach values as high as those estimated by the water content profile and the SWRCs during the DMT campaign (25 to 130 kPa), as can be seen in Fig. 7.

The prediction of the load-settlement curves for the wet and dry conditions was made by using the average M_{DMT} values within the zone of influence of the foundation element, considered equal to $2B$ ($B = 0.80$ m). The curves were also predicted by considering the average M_{DMT} values plus and minus one standard deviation, to represent the site variability.

The load-settlement predictions for the wet condition were compared with the inundated plate load tests and the plate load tests with soil suction (ψ) lower than 10 kPa (Fig. 9). The load-settlement predictions for the dry condition were compared with the plate load tests carried out with soil suction (ψ) values between 15, 18 and 31 kPa (Fig. 10). For both conditions, the load-settlement curve prediction was carried out for different embedment depths (1.5, 4.0, 6.0 and 8.0 m depths).

The load-settlement curves determined with the DMT are in good agreement with the plate load test results (Fig. 9 and Fig. 10), mainly for the dry condition. All the load-settlement curves were in the region delimited by the average M_{DMT} values plus and minus one standard deviation (σ),

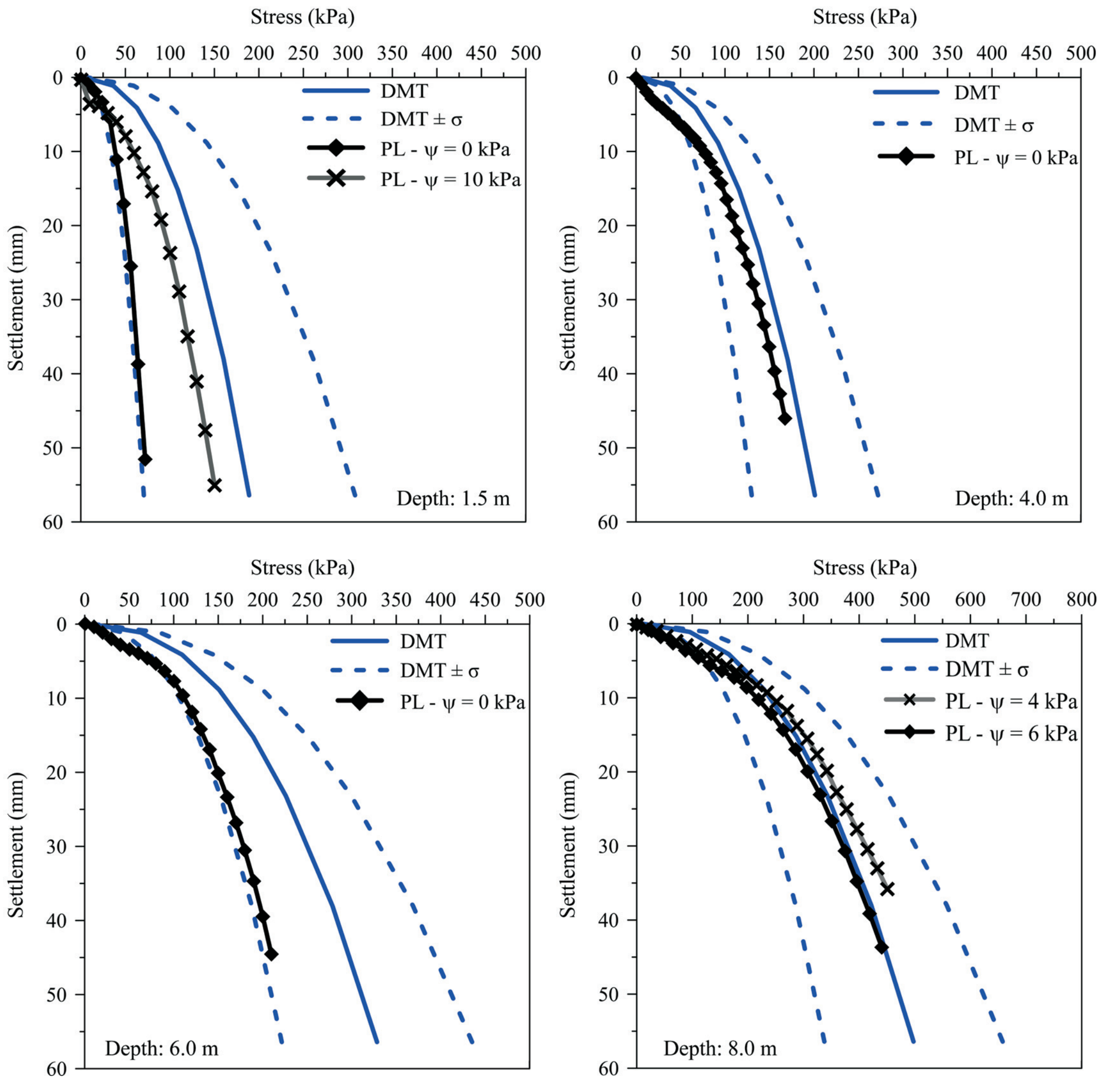

Figure 9 - Load-settlement curves predicted by the DMT and determined by the plate load tests for the wet season condition (Costa, 1999; Macacari, 2001; Rocha, 2018).

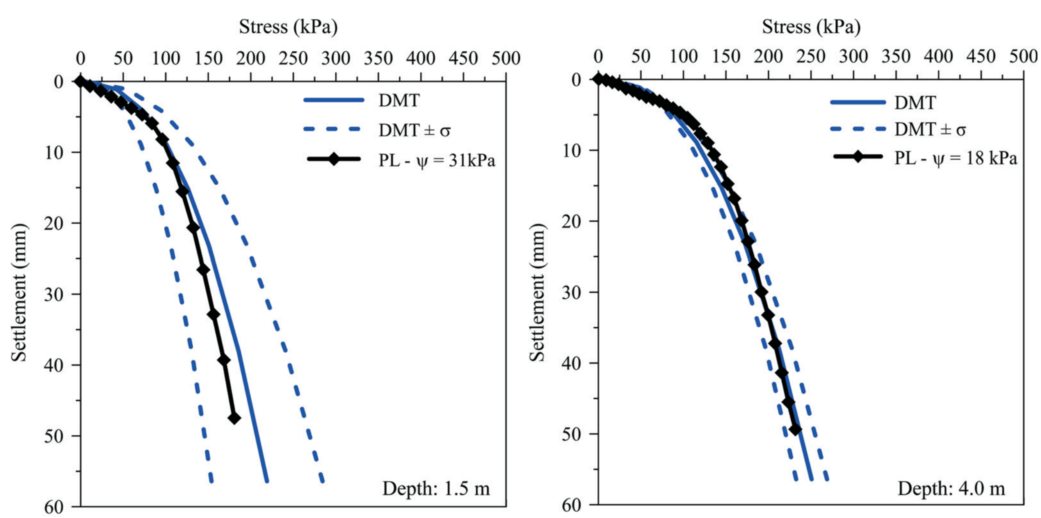

Figure 10 - Load-settlement curves predicted by the DMT and determined by the plate load tests for the dry season condition (Costa, 1999; Macacari, 2001; Rocha, 2018).

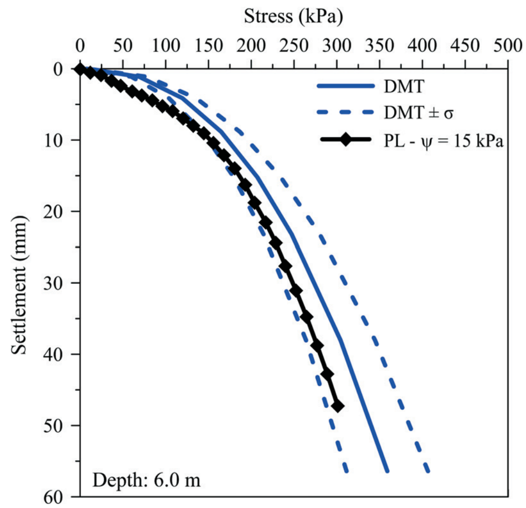

Figure 10 (cont.) - Load-settlement curves predicted by the DMT and determined by the plate load tests for the dry season condition (Costa, 1999; Macacari, 2001; Rocha, 2018).

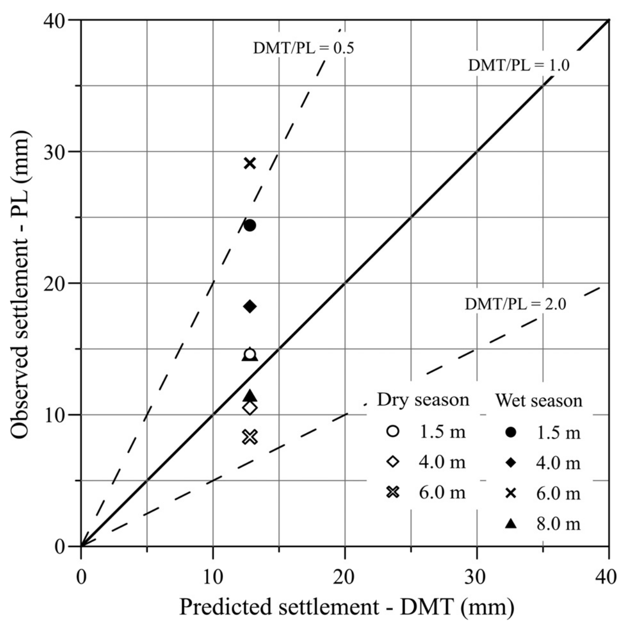

Figure 11 - Settlements predicted by the DMT *vs.* those measured by the plate load tests for the wet and dry seasons.

which is expected considering the (seasonal and spatial) variability of the investigated site.

Figure 11 shows the differences between the settlements predicted by the DMT for the working condition (δ/B_{eq} = 1.8 %, *i.e.* for 12.78 mm) and those measured by the plate load tests for both the wet and dry conditions. Good agreement was observed, since most of the data points are within the satisfactory range indicated by Monaco *et al.* (2006).

6. Conclusions

The prediction of the complete load-settlement curves for shallow foundations using the DMT and the influence of seasonal variability on this prediction was discussed.

The DMT is an adequate test for predicting soil stiffness, and the presented procedure allows providing a good estimate of the complete load-settlement curves for the study site.

The DMT also works well for predicting settlements in the working conditions, as presented and discussed by Marchetti *et al.* (2001), with the advantage of not requiring the collection of undisturbed samples and performance of laboratory tests.

In addition, the M_{DMT} profiles were influenced by soil suction (ψ) up to around 5.0 m depth in the study site. For this reason, seasonal variability should be considered in the prediction of load-settlement curves in unsaturated tropical soils, as the one herein.

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