Influence of stress state and seasonal variability in a DMT campaign for a tunnel project in a porous tropical Brazilian clay

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ABSTRACT: The paper presents a discussion of the effect of field stress state modifications on the geotechnical predicted Marchetti DMT parameters, via results from a test located inside the settlement basin of the excavation (Location A) and from a location free from the interferences caused by the excavation (Location B) of a tunnel in the city of Brasília, Brazil. These results showed that the soil of Location A has suffered significant reductions in the values of the geotechnical predicted parameters, when compared to similar values from the other location (Location B). This situation should somehow be considered in tunnel design projects, and field-testing programs, for areas with similar conditions as the one presented herein. In fact, the difference of predicted results from one location to the other can be appreciable, although distinct (different magnitudes) are observed from one parameter to the other. The paper also presents a discussion of the effect of seasonal variations on the DMT predicted geotechnical parameters. To achieve that, two field-testing campaigns were carried out, the first during the wet (rainy) season of the year and the second during dry season. Surprisingly, it was noticed that seasonality didn't cause important modifications in the DMT predicted results (at least no appreciable *engineering* differences), indicating that field-testing campaigns for underground or tunnel design projects can be organized and carried out at any time of the year.

1 INTRODUCTION

Great part of the Federal District of Brazil, where its capital Brasília is located, presents a meta-stable porous and collapsible soil, commonly known as the Brasilia “porous clay”. This soil is constituted by a superficial layer of silty clay that, when submitted to stress alterations or water content variations (or both), suffers a considerable volume change and structural breakdown. This phenomenon is defined as “soil collapse”, and it was visibly observed during the underground construction works that took place in this city some recent years ago – in particular within the superficial settlement basin (or influence zone) of the excavated tunnel of this major governmental enterprise. Of course, this was caused during tunnel construction by the associated effects of stress state and humidity changes (wet versus dry seasons) that took place, respectively, internally and externally to the natural soil layers of this city.

Therefore, a jointed research project between Brazil and Portugal was established, with the aim to study these effects and its prediction or detection via *in situ* testing. This common project has produced an on going PhD (Marques 2005), a MSc thesis (Santos 2003) and an international paper in the recent ISC´2 Conference (Marques et al. 2004), and it was conducted with field tests in the Brasilia porous clay, in areas within and outside the influence zone of the already existing underground tunnel, and at different times of the year, i.e., during wet and dry seasons, as will be detailed next.

As presented by Marques et al. (2004), the Brasilia metro has a total length of 42 km, which has been built using several construction methods. About 6.8 km of those were built in tunnel (D_{eq} = 9.6 m), excavated in a layer of porous clay with collapsible characteristics, using the NATM. The on going PhD thesis has the purpose of better understanding the particular behavior of the Brasilia porous clay for further numerical simulations of the tunnel construction, using the Finite Element Method. The geotechnical characterization of the soil affected by the tunnel excavation was made via in situ testing as well as via an extensive program of laboratory tests that included oedometric and drained triaxial tests. In this paper, however, only the DMT results are presented, given the focus of the present international Conference.

Since the porous clay is generally in an unsaturated field condition, suction is a very important factor in its behavior. Once its known that suction varies with soil water content, the study tried to evaluate the effect of moisture content changes on soil behavior (hence on in situ testing) during distinct time (or season) of the year, as already commented before. For such, field works were divided in two stages. One of them was carried out during the rainy season (October-March) and the other when the soil water content was lower (dry season, April-September).

The investigation also evaluated the effect of the tunnel excavation on the behavior of the surrounding soil, because it was foreseen that this particular tunnel excavation would induce soil collapse. Thus, in both stages (rainy and dry seasons), identical in situ tests were accomplished in two locations. One of those was defined in the lateral of the tunnel (Location A), inside of the area affected by the excavation works. The other location was in the same cross section, but at a sufficient far away distance to be out of the subsidence basin (hence, located 75 m apart from the tunnel axis, i.e., Location B). These testing locations were defined as close as possible to the instrumented section of this tunnel (which, by the way, has served to other University of Brasília theses).

Details of the Brasília porous clay have already been extensively published elsewhere (Cunha et al. 1999, Marques et al. 2004) and will not be again presented herein. It will however be briefly commented next just to aid the unaware reader to visualize its main characteristics.

2 MAIN SITE CHARACTERISTICS

The Brazilian capital Brasília and its neighboring areas (Federal District) are located in the Central Plateau of Brazil, as presented in Figure 1. This district has a total area of 5814 km^2 and is limited in the north by the 15°30’ parallel and in the south by the 16°03’ parallel. The University of Brasília (UnB) campus is located within the city of Brasília in its “north wing”, portrayed in this figure by an “airplane” shape like form. The tunnel is also located in this same city, however at its “south wing”, as portrayed in Figure 1.

Within the Federal District extensive areas (more than 80 % of the total area) are covered by a weathered latosoil of the tertiary-quaternary age. This latosoil has been extensively subjected to a laterization process and it presents a variable thickness throughout the District, varying from few centimeters to around 40 meters. There is a predominance of the clay mineral caulinite, and oxides and hydroxides of iron and aluminum. The variability of the characteristics of this latosoil depends on several factors, such as the topography, the vegetal cover, and the parent rock. In localized points of the Federal District the top latosoil overlays a saprolitic/residual soil with a strong anisotropic mechanical behavior and high (SPT) penetration resistance, which originated from a weathered, folded and foliate slate, the typical parent rock of the region. In other points this latosoil overlays a thick layer of metamorphic rocks, known as “metarithimitics” (sandstones, claystones, etc.). This latter case is the case found in the location of the studied conducted herein. The thickness of the top latosoil is evaluated as around 24 m according to SPT results at site.

The surficial latosoil is locally known as the Brasília “porous” clay, being geotechnically constituted by sandy clay with traces of silt, forming a lateritic horizon of low unit weight and high void ratio, as well as an extremely high coefficient of collapse. Although these characteristics vary from site to site at this city, its main geotechnical characteristics are generally similar. These characteristics are illustrated in Table 1, obtained from a comprehensive site and laboratory investigation program at the UnB research site. In the particular area of the tunnel, Locations A and B, the soil has similar (but slight distinct) geotechnical values as those of Table 1, as already presented by Marques et al. (2004).

Table 1. Main geotechnical values for the Brasília porous clay (Cunha et al. 1999)

Parameter	Units	Range of Values
Sand percentage	%	12-27
Silt percentage	%	8-36
Clay percentage	%	80-37
Moisture content	%	20-34
Nat. unit weight	kN/m^3	17-19
Degree of saturation	%	50-86
Void ratio	--	1.0-2.0
Liquid limit	%	25-78
Plasticity limit	%	20-34
Plasticity index	%	5-44
Young Modulus	MPa	2-14
Drained Cohesion	kPa	10-34
Drained Friction angle	degrees	25-33
Coefficient of Collapse	%	0-12
Coef. earth pressure	--	0.4-0.6
Coef. of permeability	cm/s	10^{-6}-10^{-3}

Figures 2 and 3, in the next page, respectively present the specific area of the in situ tests (Locations A and B) and their position in relation to the tunnel cross section and its (superficial) measured settlement deployment basin (with a maximum settlement at tunnel centerline of 16.8 cm, this section).

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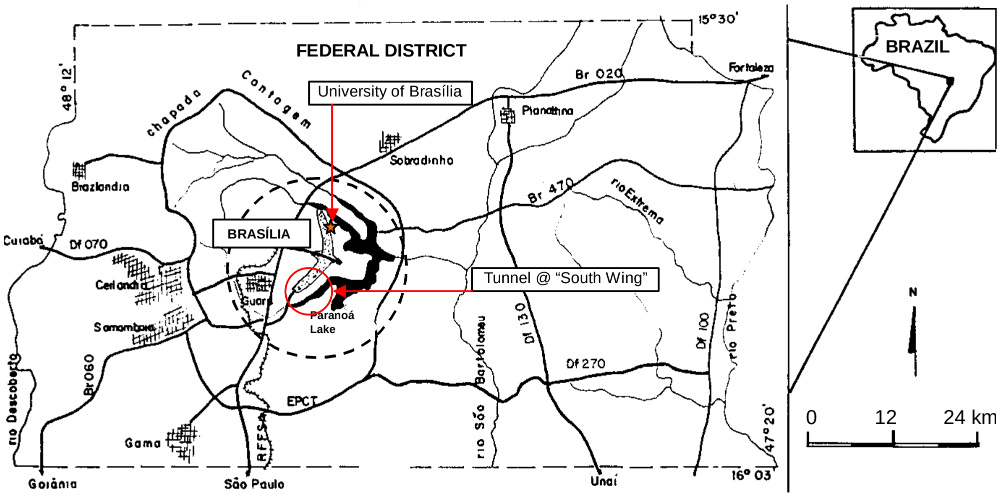

Figure 1. Location map of Brasília city and tunnel position

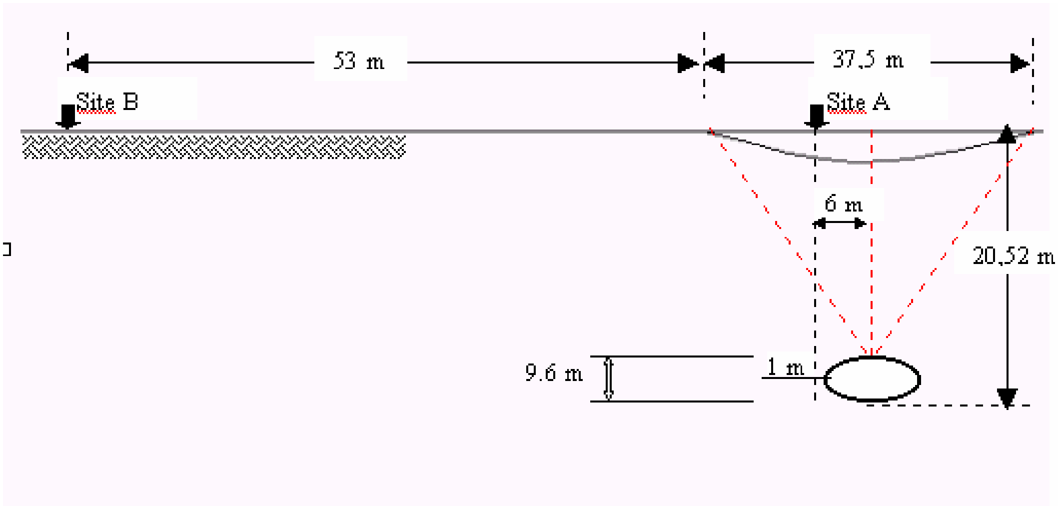

Figure 2. Locations A and B in relation to tunnel axis and settlement basin

Figure 3. Specific in situ testing areas and tunnel S 4294 cross section

3 DMT RESULTS

3.1 *Stress state influence on results (A vs. B)*

In order to study the influence of the stress state of the soil into DMT corrected (by calibration values) and interpreted results (standard empirical correlations) a set of DMT tests was carried out at each distinct site location, A and B. Site A was chosen to be within the displacement basin of the tunnel, at around 1 m from the tunnel's face (6 m from its centerline). Site B on the other hand was chosen to be at around 67 m from the tunnel's face (72 m from its centerline), where it is believed that the soil is unaffected by the tunnel's overall displacement vectors and stress changes. Figure 2 clearly depicts both site locations A and B.

The DMT tests were carried out in distinct membrane positions in relation to the tunnel's longitudinal axis. In this particular sub item it is solely presented the results for the tests in which the membrane was positioned at 45° to the tunnel's longitudinal axis, but the results are valid for all positions tested in this research. Although not shown herein, it can be said that the main difference between distinct membrane positions was related to the sensitivity of the DMT obtained results, i.e., the closer is the membrane to a perpendicular position in regard to the tunnel's long. axis (parallel to the horizontal displacement vectors) the higher is the sensitivity of the DMT obtained results to the tunnel's stress changes around the soil.

As observed before, the study was carried out for the two main seasons of Brasília city, i.e., wet and dry seasons. It is noticed in Figure 4 that during the wet season there was a slight increase in the soil's water content in relation to those of the dry season. This increase was higher for the upper portions of the strata, and tends to disappear as deeper we go into the profile.

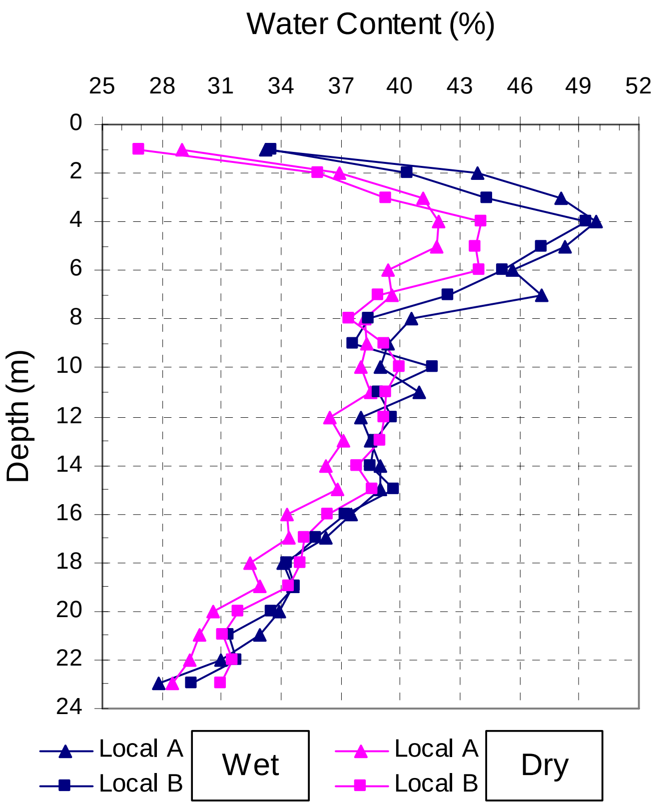

Figure 4. Water content variation at each location and season

Therefore, two sets of DMT results for p_0 and p_1 pressures were obtained, each respectively for sites A and B at wet and dry seasons.

From this set of results it was noticed that there seams to be three distinct geotechnical layers, herein defined as layers I, II and III, although the strata can be considered as "homogeneous" in pedological terms. This was noticed to be more pronounced in Site A, although some layer discretization is also possible in Site B. Most probably, distinct laterization and pedogenetic processes that have occurred distinctively along the profile during the geological times give the difference in results. These layers are depicted in Figure 5.

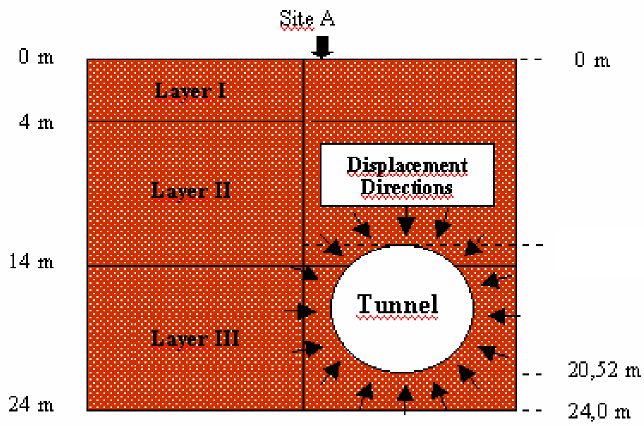

Figure 5. Distinct soil layers idealized for the profile

Figures 6 and 7 present the DMT p_0 and p_1 results for both dry and wet seasons, while Figures 8 and 9 present interpreted results for K_0 (Lunne et al. 1990) and M (Marchetti 1980) solely for wet season.

From these figures it can be noticed:

- There seems to be a much larger influence of the stress state relief during wet rather than dry season, and in particular more concentrated to layer III. It is believed that this was caused by the proximity of the tunnel's face to the testing positions in this particular layer, and by the fact that, during dry season, there is another effect taking place and influencing the results;
- There seems, therefore, that during dry season there is also the variable (along profile) influence of suction in the obtained DMT raw and interpreted results. This effect tends to "mask" the stress state effects, decreasing differences between results from sites A and B. This is clearly noticed by a close comparison between these figures;
- There also seems to be some influence of the stress state relief in layer I, where the settlement basin is located (Site A). This influence was also noticed to be more pronounced during wet rather than dry season, for the same aforementioned reasons. It reveals that, from the three distinct layers of the profile, only the intermediate (4-14 m) one was not influenced by displacement vectors and stress change variations caused by the presence of the tunnel.

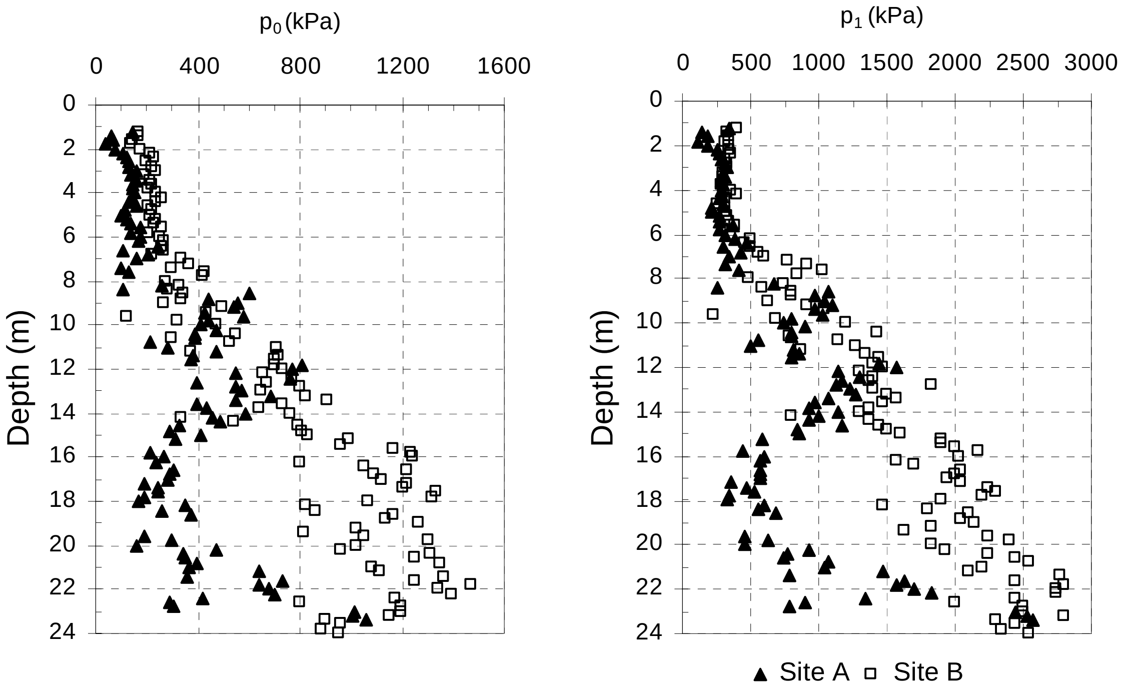

Figure 6. DMT p_0 and p_1 results for wet season

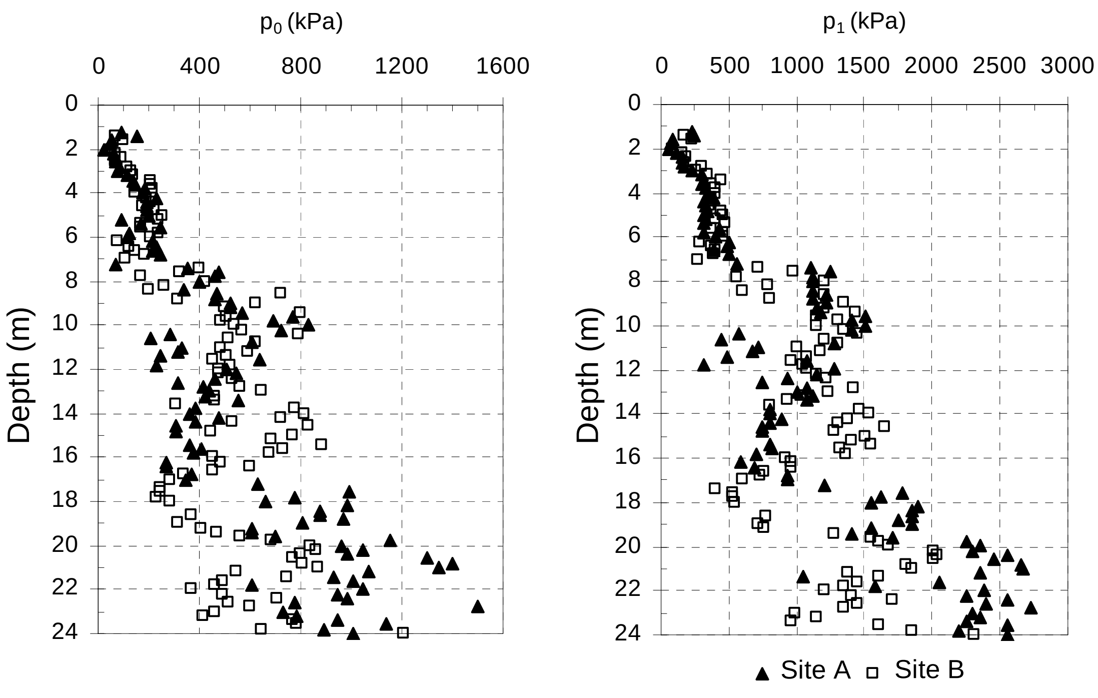

Figure 7. DMT p_0 and p_1 results for dry season

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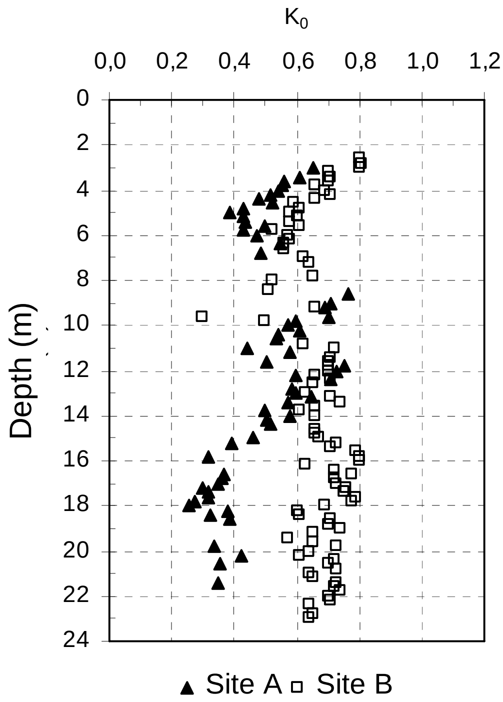

Figure 8. DMT interpreted K_0 results at distinct locations (wet season)

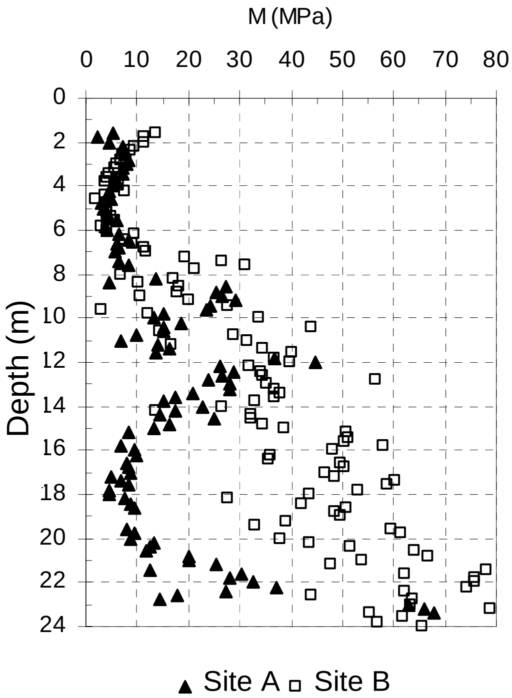

Figure 9. DMT interpreted M results at distinct locations (wet season)

- There seems to be the same stress state influence in both interpreted K_0 and M results, also concentrated for layers I and III. In terms of K_0 (coeff. of stress state at rest) the average decrease of values from Site B to A was respectively 50 and 24%, for layers III and I, denoting higher stress state influence at points closer to the tunnel's face. For layer II this average decrease was only 5%, which is negligible considering possible natural stratigraphic variations from one site to another. In terms of the M (constrained modulus) parameter the average values of decrease were respectively 72 and 30% for layers III and I, whereas for layer II this decrease was in the range of 19% (in this case not so negligible, but lower than the other layers).

3.2 *Seasonal variability influence on results (wet vs. dry season)*

In order to study the influence of the seasonal variability on the obtained DMT corrected (by calibration values) and interpreted results, it was applied herein the same procedures as applied before. That means, the direct comparison of initial and intermediate DMT parameters as well as interpreted, via empirical correlations, geotechnical values.

For the sake of simplicity, and given the fact that all the comparisons have similar trends, it will be presented herein only the comparison between the K_0 and M values derived at Site A respectively at wet and dry seasons. In this particular case the DMT membrane was located parallel to the tunnel's longitudinal axis, but, as already commented before, this set of comparative results express similar trends and conclusions as those obtained in other (not shown) data from this same site.

Figures 10 and 11 respectively show the results for K_0 and M, at distinct seasons. From these figures it can be said:

- The average difference of values for all the profile from K_0 results at wet and dry seasons was in the range of 9%, with slight lower values for the dry season. This comparison, therefore, indicates that the influence of the moisture content variation from one season to another was not enough to induce appreciable variations, or a perceptible "trend", in the obtained DMT initial, intermediate and empirically derived parameters. This is perhaps related to the fact that, indeed, soil moisture variations from one season to another was not appreciable (see Figure 4), and its influence was lower than the influence of other factors (as stratigraphy);

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- Similar results were obtained for M. In this case the average difference was in the range of 30% (however with large scatter), with slight lower values for the dry season. Again the same aforementioned observations can be applied here;

It is believed that the large scatter of data for all the comparisons presented in this sub item are primordially related to stratigraphic differences of the tropical soil tested in each season. Although the site was the same (Site A) there was a distance difference between the geographic points tested from one season to another. This could, perhaps, indicate the non-expected trend of slight lower geotechnical values obtained for the dry rather than the wet season (which was not initially expected). Suction has influenced the results, given the average soil´s moisture content variation from one season to another. It however did not appear to be enough to produce a clear trend in the comparisons from wet to dry seasons.

Given the discussion of sub item 3.1 it is also observed that suction effects were solely markedly noticed to "mask" the difference of results from one site to another, i.e., to approximate DMT results from site A to B (hence decreasing stress state effects) during dry season. During the wet season this approximation of values was not noticed, as observed before.

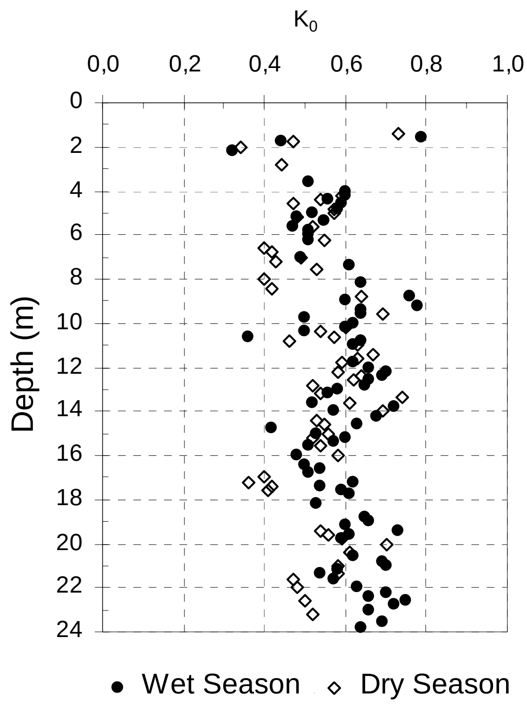

Figure 10. DMT interpreted K_0 results at distinct seasons (site A)

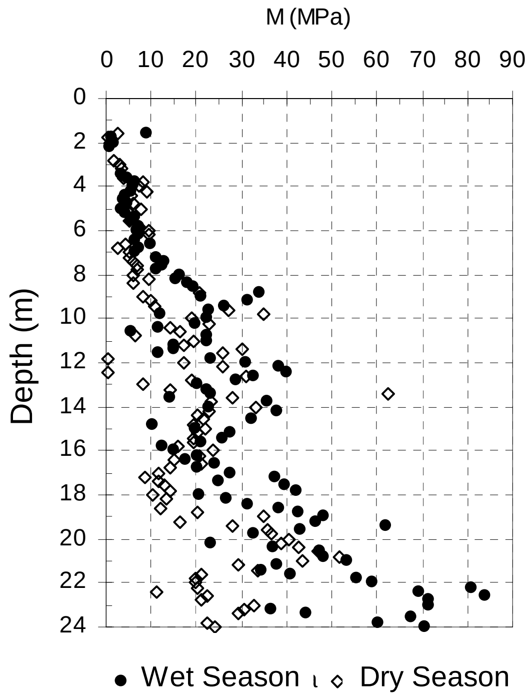

Figure 11. DMT interpreted M results at distinc seasons (site A)

4 CONCLUSIONS

This study has emphasized the importance of a better understanding of the effects of stress and suction (indirectly measured by the soil's moisture content) generated around tunnels constructed in tropical soils, and their influence into the derived soil's parameters.

Although limited, the study has indicated initial points and preliminary conclusions of value, which still have to be tested against future numerical analyses with the data and site characteristics presented in this paper.

It is initially concluded that the excavation of the tunnel influences the state of stress in soil layers around it. It was noticed that the DMT empirically interpreted geotechnical values have substantially decreased from a point close to the tunnel's face in relation to another point in an area unaffected by the tunnel's excavation. Besides, this influence was hindered by suction effects, i.e., it could not be clearly noticed during the dry season of the year, as observed with tests during the wet season.

This therefore indicates that the stress state influence around the tunnel, given its construction, should somehow be incorporated into DMT interpre-

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tative correlations, at least for tunnel projects in soil deposits of this particular type.

The influence of soil's suction or moisture content variation, from one season to another, has shown to be limited because for tests at similar site location (close or distant to tunnel's face) there was no appreciable difference in the results of the DMT empirically interpreted values. The observed large data scatter at the same site appears to be related to stratigraphic differences of this tropical soil.

This therefore tends to indicate that in situ testing programs can be carried out at any season of the year for soil deposits of this particular type.

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