DMT Tests at Sarapuí Soft Clay Deposit: from 1985 to 2012

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ABSTRACT: Dilatometer tests were performed in the very soft clay of Sarapuí test site, near Rio de Janeiro, Brazil, from 1985 to 2012. Different equipment has been used, from the initial Marchetti version to the most recent seismic DMT, in four series of tests. Careful procedures were always used. However, significant scatter was obtained for the "intermediate" DMT parameters I_D and E_D, and less for K_D, which however still needs to be improved. When p_0 and p_1 values are separately considered, the scatter is not very significant. However, when the difference Δp is considered, a significant scatter is obtained, explaining the significant scatter in the geotechnical parameters which depend on Δp and less scatter in those which depend only on p_0. Besides special procedures, the test results indicate that a much softer membrane is required for testing in very soft clays. The chart for estimating soil type and unit weight should be extended to cover very soft clays. Values of v_s from the SDMT presented very good repeatability.

1 INTRODUCTION

Dilatometer tests were performed at Sarapuí test site, near Rio de Janeiro, Brazil, from 1985 to 2012. Different equipment has been used, and Table 1 presents a summary of the tests performed. The results from all tests performed are analyzed herein.

2 TESTS PERFORMED

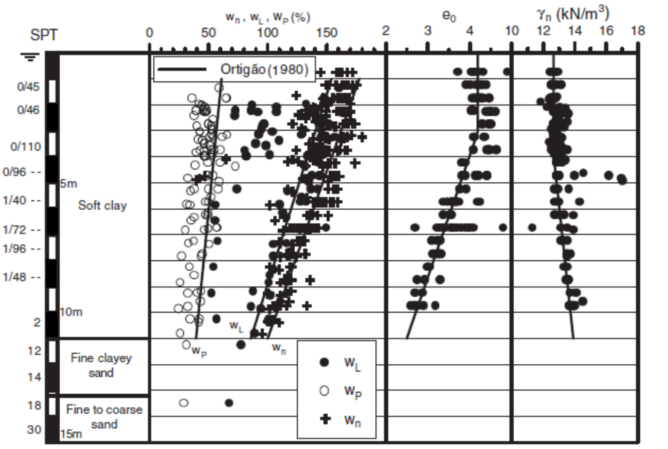
2.1 *The Test Site*

The early studies on the very soft clay of the region where the Sarapuí test site is located were conducted by Pacheco Silva (1953).

Table 1. Tests performed at Sarapuí test site.

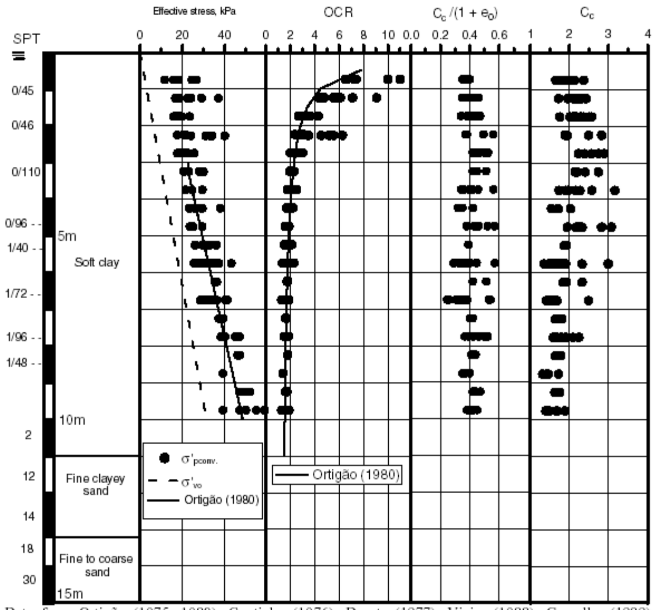
Series	Date	Test Site	Number of tests performed	Equipment owner
1	Oct. 1985	Sarapuí I	4	NGI
2	July 1992	Sarapuí I	5	Geomecânica
3	June 2012	Sarapuí II	2	COPPE/UFRJ
4	Dec. 2012	Sarapuí II	2	COPPE/UFRJ

The Sarapuí test site is situated in a flat swampy area, around Guanabara Bay, on the left bank of Sarapuí river, some 7km from Rio de Janeiro City, with average coordinates 22°44'41'' (S) and 43°17'23'' (W). It was established in the mid-1970s as a research site by the Transportation Research Institute of the Brazilian Federal Highway Department (IPR-DNER), with focus on the study of embankments on soft soils, an issue faced by this Department throughout Brazil (Ortigão & Lacerda 1979). A number of in situ and laboratory tests have been performed (e.g., Lacerda et al. 1977, Werneck et al. 1977, Ortigão et al. 1983). A comprehensive report about the deposit has been provided by Almeida & Marques (2002). Geotechnical characteristics of the soil are included in Fig. 1, based on investigations carried out near the trial embankments sites. The very soft organic clay layer is about 11 m thick, and overlyes sand layers. The plasticity index (IP) of the Sarapuí clay decreases with depth, from around 100% to 50%. Stress history and compressibility characteristics of the deposit are shown in Fig. 2.



Data from Ortigão (1975, 1980), Coutinho (1976), Duarte (1977), Collet (1978), Vieira (1988), Barbosa (1990) and Lima (1993).

Fig. 1. Characteristics of Sarapuí soft clay deposit (Almeida & Marques 2002).



Data from Ortigão (1975, 1980), Coutinho (1976), Duarte (1977), Vieira (1988), Carvalho (1989), Barbosa (1990), Lima (1993) and Bezerra (1996).

Fig. 2. Stresses and compressibility parameter profiles (Almeida & Marques 2002).

In the last fifteen years, however, security reasons have prevented the use of the test site. A new area (named Sarapuí II) in the same deposit, 1.5 km from the previous area and inside of a Navy Facility, has been used since then (Fig. 3). Two studies on pile behaviour have been carried out at Sarapuí II site (Alves 2004, Francisco 2004, Alves et al. 2009). The initial tests with the torpedo piezocone (Porto et al. 2010) have also been performed at Sarapuí II test site. Although the whole deposit can be considered fairly homogeneous in horizontal directions, a number of in situ tests have been performed in this new area, which is being used by the Research Center of the Brazilian Oil Company (CENPES/PETROBRAS) and Federal University of Rio de Janeiro as a state-of-the-art test site on very soft organic clay. The very soft clayer in the test area

Fig.3. Sarapuí II test site with respect to the early Sarapuí I test site.

is around 8 m deep, and a clayey-silt layer underlies the very soft clay. Some geotechnical characteristics of the soil are included in Fig. 4. A comprehensive study about the deposit of Sarapuí II has been undertaken by Jannuzzi (2009, 2013).

The geotechnical characteristics of Sarapuí I and Sarapuí II are generally very similar.

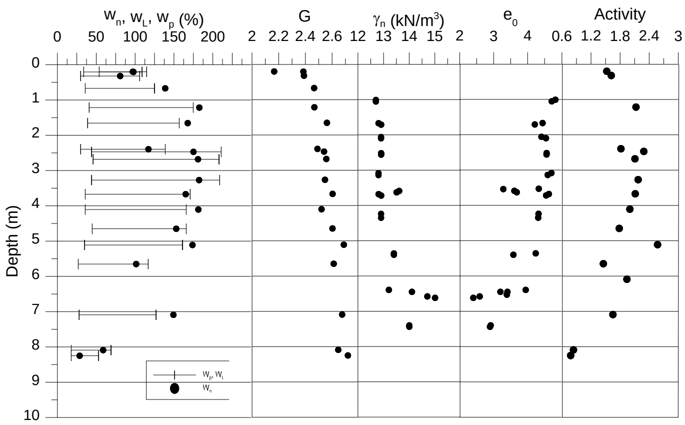


Fig. 4. Liquid limit, plastic limit and natural water content; specific gravity; total unit weight; initial void ratio; activity versus depth (adapted from Jannuzzi 2013).

2.2 *First series of tests*

The dilatometer test (DMT) was performed the first time in Brazil in 1985, by Tom Lunne (NGI) and the late Marcio Miranda Soares (COPPE/UFRJ) at Sarapuí I deposit. The tests were performed in a joint research project on in situ tests in very soft clays between the Norwegian Geotechnical Institute (NGI) and Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia from Federal University of Rio de Janeiro (COPPE/UFRJ). The research project also included tests with four piezocones used in the North Sea and brought to Brazil by Tom Lunne. The first prototype of a COPPE piezocone was also tested in the same series of tests (Soares et al. 1986, 1987).

Four tests have been performed in this first series, and the same blade was used in all tests. The COPPE rig, designed and manufactured at COPPE machine shop specifically for these tests (Fig. 5), was used for all tests, which have been performed with the standard rate of 20 mm/s. The water table was 0.30 m above ground level during this first series of tests.

Fig. 5. Readings taken by Tom Lunne in the first series of dilatometer tests at Sarapuí I deposit.

Results of the "intermediate" parameters I_D, K_D and E_D (equations 1, 2 and 3, respectively) for the four tests performed are shown in Fig. 6.

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

$$K_D = \frac{p_0 - u_0}{\sigma'_{v0}} \quad (2)$$

$$E_D = 34.7\,(p_1 - p_0) \quad (3)$$

where

I_D = material index
K_D = horizontal stress index
E_D = dilatometer modulus
p_0 = the corrected first reading
p_1 = the corrected second reading
u_0 = in situ pore pressure
σ'_{v0} = vertical effective stress

There is a significant scatter in the results in all parameters. K_D values (related just to p_0) for DMT1 and DMT3 are, respectively, above and below the average trend of the other 2 tests. The smaller values of K_D from DMT3 were attributed to inadequate or insufficient cycling (or "exercising") of a new membrane before the test, although the cycling recommendations (Marchetti & Crapps 1981) had been followed. As far as DMT1, it was hypothesized that the higher values of K_D could be related to the proximity to the road access (2.7 m). When just DMT2 and DMT4 are considered, the scatter has been significantly reduced.

However, when I_D and E_D (which depend both on the difference between p_1 and p_0) are now considered, even DMT2 and DMT4 present some scatter. This subject is further discussed in section 3.

2.3 *Second series of tests*

Soon after the first series of tests at Sarapuí I deposit, in 1986, Geomecânica, a Brazilian geotechnical company, purchased the equipment and a partnership was established between Geomecânica and COPPE/UFRJ. In this partnership COPPE/UFRJ was allowed to use the Geomecânica equipment, and joint research would be performed. The second series of tests, a Master Thesis (Vieira 1994), was in this way carried out by both Geomecânica and COPPE/UFRJ personnel.

The same rig used in the first series of tests was also used in the second one, which was performed in Sarapuí I deposit. The water table varied between 0.32 m and 0.36 m above ground level at the occasion of the tests.

Since insufficient cycling of the membrane was a possible cause of inaccuracy of one test from the first series, a study was undertaken by Vieira (1994) on this subject. 11 membranes (type H, nominal thickness of 0.2 mm) were cycled with different number of cycles and the variations of ΔA and ΔB (membrane stiffness) values due to the cycling process were evaluated. The tests performed provided the information required to be sure that in the second series of tests any scatter in the data could not be attributed to inadequate or insufficient cycling of the membranes.

Values of I_D, K_D and E_D for four tests performed are shown in Fig. 7. The numbering of the tests performed followed the sequence of the first series. Data from DMT9 were not included in the figure, because the test was performed in remoulded material.

Significant scatter was still also found for all intermediate parameters, more pronounced in I_D and E_D, which will have a consequence on the geotechnical parameters estimated, as shown in section 3, see also Vieira et al. (1997).

The C readings were also taken, as well as dissipation tests performed in this series of tests, but these are not included herein.

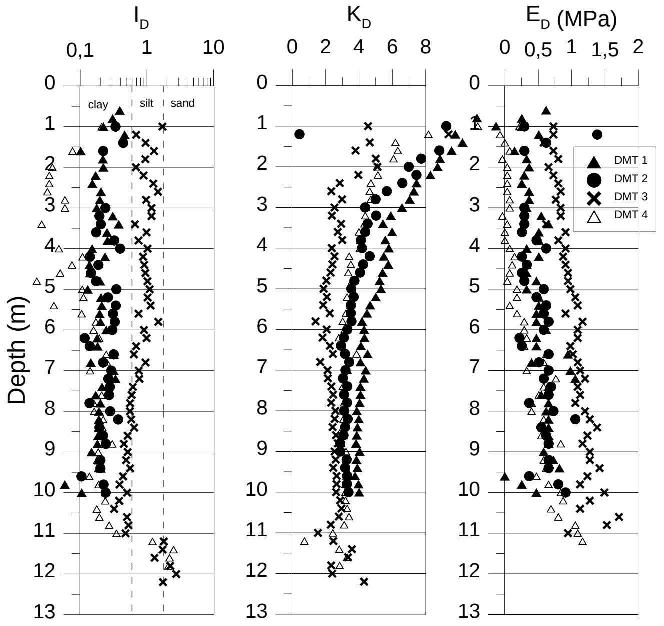


Fig. 6. I_D, K_D and E_D from the first series of tests at Sarapuí I test site.

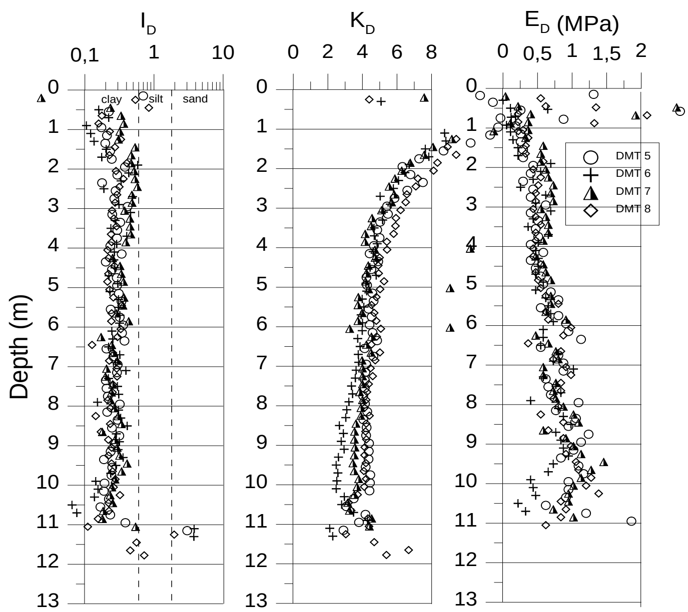


Fig. 7. I_D, K_D and E_D from the second series of tests at Sarapuí I test site.

2.4 *Third series of tests*

The addition of the seismic device in the DMT equipment (Marchetti et al. 2008) lead COPPE/UFRJ to purchase in 2011 its own equipment. Thus the third series of tests was carried out in 2012, with the same rig used in the previous series of tests. The water table was 0.28 m above ground level at this occasion. The seismic DMT poses an additional difficulty with respect to the regular DMT, because the seismic device requires a larger distance between the rig and the soil, as illustrated in Fig. 8. The procedure of performing seismic DMT in Sarapuí II deposit is very cumbersome, which was described in detail, together with the test results, by Jannuzzi et al. (2014).

Fig. 8. Seismic DMT at Sarapuí II test site (Jannuzzi et al. 2014).

An error was made in the first test by the senior author, related to the fact that in the case of very shallow depth the soil pressure is not sufficient for getting the membrane to the "zero" position. Since the audio signal could not be heard, it was thought that some mistake had happened, and then the membrane was pressurized. This process caused the membrane to be damaged, which was verified after the test, where a bulging was observed in the membrane.

Apparently, this was forgotten from the experience gained in the second series of tests. In fact, the data from the first series of tests (Fig. 6) show that DMT tests started at 0.8 m depth, while in the second series tests at 0.2 m depth are available (see Fig. 7).

Irrespectively the damage with the membrane, the seismic test could be carried out.

It must be pointed out that when using the seismic DMT no more manual readings are required, and the values of A and B are automatically recorded in the acquisition data system. A comparison was undertaken between the recorded values and readings taken in the regular way, and good results were obtained. The only difference is that the recorded values consider the zero shift in the manometer automatically.

Values of I_D, K_D and E_D for the two tests performed are shown in Fig. 9. The numbering of the tests performed followed Jannuzzi´s (2013) research, where SDMT 01/01 means the first test of her first seismic DMT series of tests.

The results show a significant scatter both on K_D (higher scatter) and I_D, but unexpectedly not in E_D. The reason for this behavior is provided in section 3.

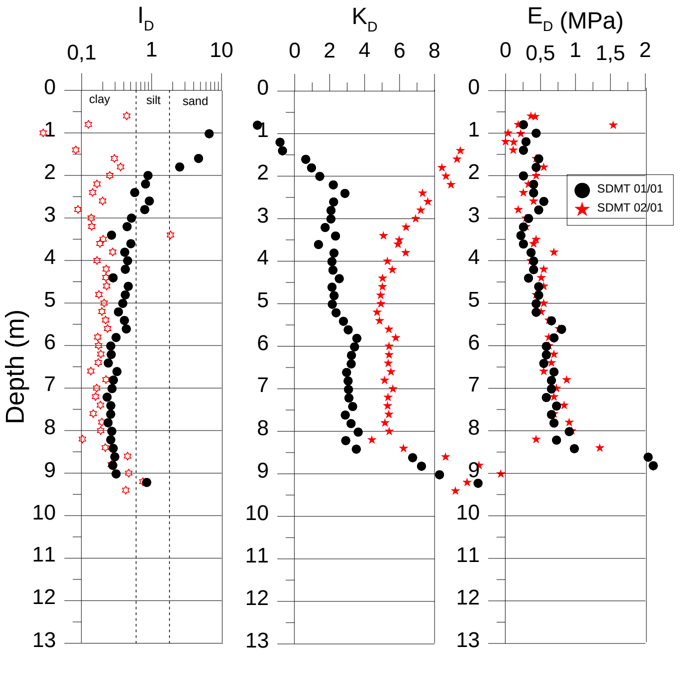


Fig. 9. I_D, K_D and E_D from the third series of tests at Sarapuí II test site.

2.5 *Fourth series of tests*

The main purpose of the third series of tests was to obtain shear wave velocity measurements. However, the shape of the waves was not smooth in all tests, and it was decided that the hammer and the plank needed to be improved and more tests would be performed (Jannuzzi et al. 2014). This was done and the results of I_D, K_D and E_D for the two tests of the fourth series are presented in Fig. 10. The water table was at ground level at the occasion of the tests.

A significant scatter was observed for all three parameters in this case, with the only possible explanation the fact that the second test could not be performed continuously. In fact, heavy showers with lightening occurred, and the test needed to be interrupted and continued the next day. Despite the scatter on the DMT data, the shear wave velocity, v_s, from the seismic device from both tests was quite similar, as shown in Fig. 11.

3 DISCUSSION

A possible explanation related to the data in Fig. 9 is that when the membrane was pressurized too much, there was a shift in both A and B (and consequently p_0 and p_1) values, but it continued to work with the same stiffness, providing proper values of the difference p_1-p_0. Provided E_D is proportional to the difference p_1-p_0, similar values with data from the other test were obtained. However I_D is affected both by the difference p_1-p_0 and p_0 itself, thus I_D values were not the same as in the other test.

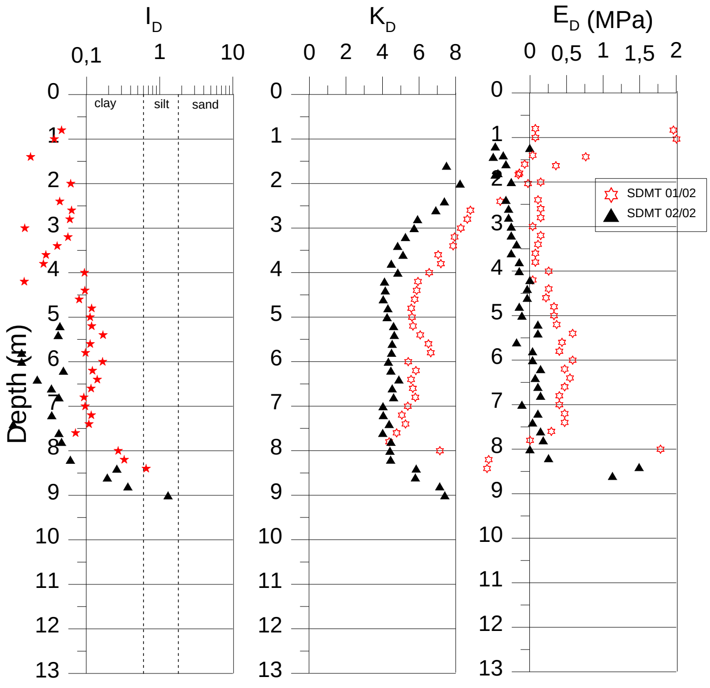


Fig. 10. I_D, K_D and E_D from the fourth series of tests at Sarapuí II test site.

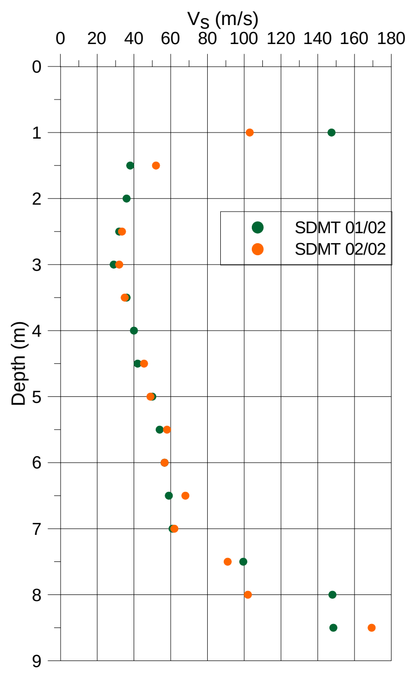


Fig. 11. v_s from fourth series of tests.

When the results of the two tests that may be considered the best ones from third and fourth series of tests are plotted together, Fig. 12 is obtained. Scatter is still observed for all three parameters, especially in the upper 4 m of the deposit.

Fig. 13 presents the results of all tests in the four series of tests for which no errors or nonconformities could be attributed. It must be pointed out that the thickness of the very soft material is around 11 m in the case of Sarapuí I test site, whereas is around 8 m in the case of Sarapuí II test site. Therefore, values with greater depths must be disregarded in each deposit.

A significant scatter is found for I_D and E_D, and less for K_D. In fact, when Sarapuí I and Sarapuí II are considered separately, a trend of higher values is observed for Sarapuí II. This subject is treated below, through the values of the undrained shear strength, provided it depends only on K_D.

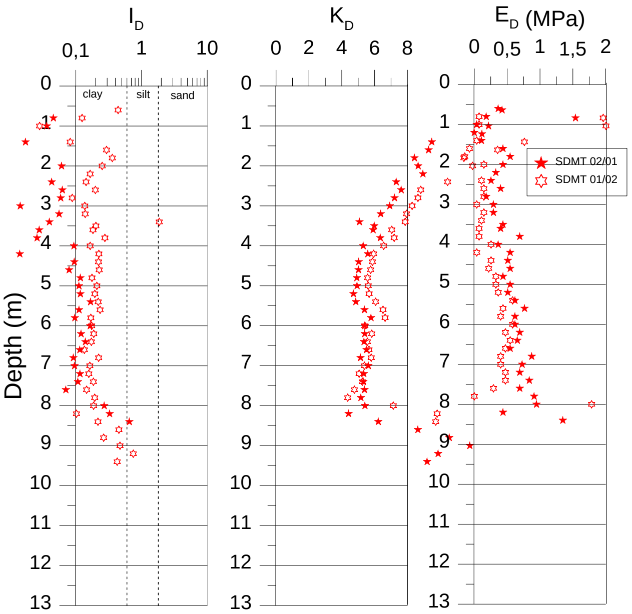


Fig. 12. I_D, K_D and E_D from the best tests in third and fourth series of tests at Sarapuí II test site.

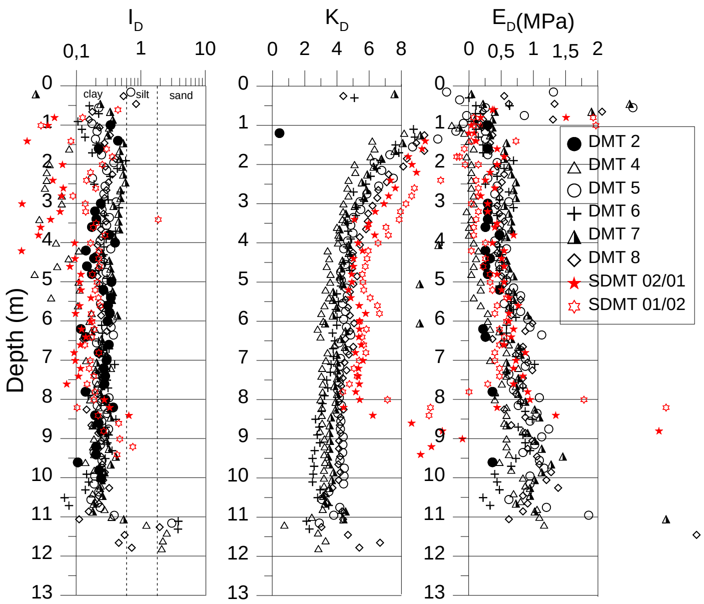


Fig. 13. I_D, K_D and E_D from all tests (from Sarapuí I and Sarapuí II sites) with no errors or nonconformities.

When the dilatometer intermediate parameters are used for the estimation of geotechnical parameters, some conclusions can also be drawn.

Firstly, when the chart for estimating soil type and unit weight is considered (Marchetti & Crapps 1981), it is clear that it should be extended to cover very soft clays. In fact, values of the material index I_D smaller than 0.1 have been obtained, as well as values of the dilatometer modulus E_D smaller than 5 bar (roughly 500 kPa). Moreover, suggestions of values of unit weight should consider values smaller than 14 kPa (for IP greater than 50%).

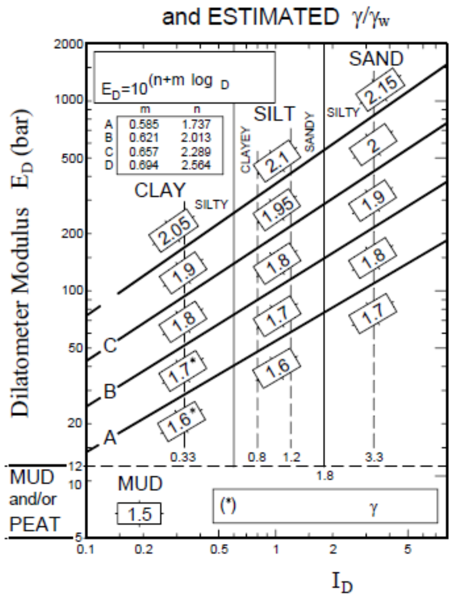


Fig. 14. Chart for estimating soil type and unit weight (Marchetti & Crapps 1981, Marchetti et al. 2001).

One of the most useful geotechnical parameter estimated from the dilatometer is the undrained shear strength, s_u (or c_u). It is well known that different types of in situ and laboratory tests provided different stress paths (and rate of shear) and consequently different values of s_u (e.g. Wroth 1984). The original correlation suggested for this case (Marchetti 1980, equation 4) was based on relationships found in laboratory tests, but it is outside the scope of the present paper to discuss this subject. The present paper will use s_u values from vane tests, as a reference, provided very good quality are available for the Sarapuí deposit. The corresponding results are shown in Fig. 15.

$$s_u = 0.22\sigma'_{v0}(0.5K_D)^{1.25} \quad (4)$$

First of all, it can be observed a slight trend of higher values of s_u from vane tests in Sarapuí II than Sarapuí I, which could be explained by different types of equipment. In fact, although research tests have been performed by Ortigão & Collet (1986) at Sarapuí I site, an equipment able to measure the torque closed to the blade was used at Sarapuí II (Jannuzzi 2013), which could have provided more accurate results. However, the s_u values estimated from the DMT seemed to have captured the same feature, i.e., slightly higher values from Sarapuí II than from Sarapuí I site.

As far as the values themselves are concerned, DMT values of s_u are in the range – average values and 50% the average values – in the case of Sarapuí I, whereas the best DMT tests in Sarapuí II provided results in the same range of the vane data.

Therefore, despite the trend of the data has been captured by the dilatometer, the scatter of the data still needs to be reduced.

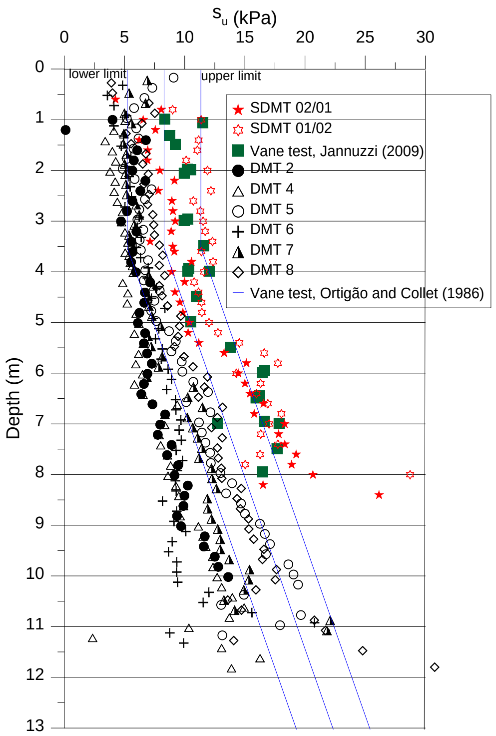


Fig. 14. Undrained shear strength from vane and DMT data.

While s_u values depend just on p_0 values, the constrained modulus M depends both on p_0 and p_1. The values of M obtained for all tests with no errors or nonconformities are presented in Fig. 15. A comparison with laboratory tests is outside the scope of the present paper, and Fig. 15 is presented just to show the scatter problem, which is very significant.

In fact, if only the values of p_0 for all tests are now compared, the scatter is not very significant, the same occurring for p_1. In fact, both p_0 and p_1 have been able to capture the trend of higher values in Sarapuí II with respect to Sarapuí I. However, when the difference $\Delta p = p_1 - p_0$ is plotted, a significant scatter is found, which explains the scatter found in the associated geotechnical parameters. Besides special procedures, a much softer membrane is required for testing in very soft clays.

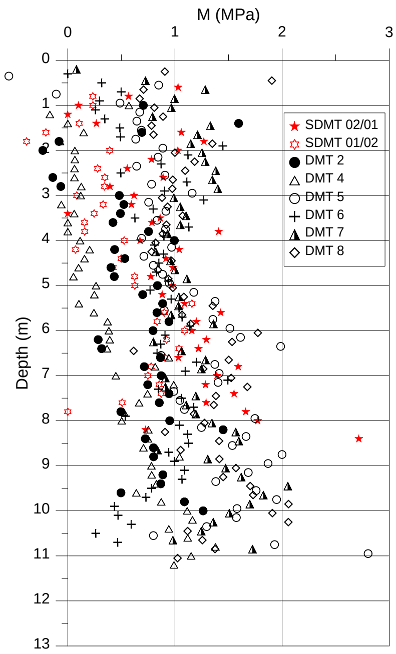


Fig. 15. M values for Sarapuí I and Sarapuí II sites.

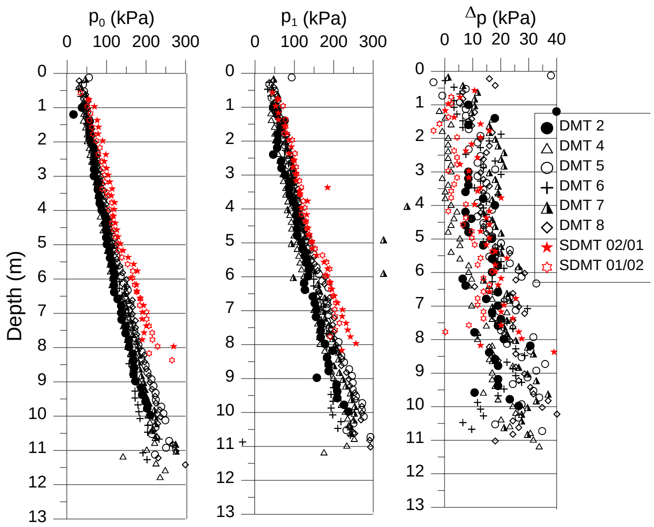


Fig. 16. p_0, p_1 and Δp values for all tests with no errors or nonconformities.

4 FINAL REMARKS AND CONCLUSIONS

Dilatometer tests were performed in the very soft clay of Sarapuí test site, near Rio de Janeiro, Brazil, from 1985 to 2012. Different equipment has been used, from the initial version to the most recent seismic DMT, in four series of tests. Careful procedures were always used. However, significant scatter was obtained for the "intermediate" DMT parameters I_D and E_D, and less for K_D, which however still needs to be improved. When p_0 and p_1

values are separately considered, the scatter is not very significant. However, when the difference Δp is considered, a significant scatter is obtained, explaining the significant scatter in the geotechnical parameters which depend on Δp and less scatter in those which depend only on p_0. Besides special procedures, the test results indicate that a much softer and sensitive membrane is required for testing in very soft clays. The chart for estimating soil type and unit weight (Marchetti & Crapps 1981) should be extended to cover very soft clays. In fact, values of the material index I_D smaller than 0.1 have been obtained, as well as values of the dilatometer modulus E_D smaller than 5 bar (roughly 500 kPa). Moreover, suggestions of values of unit weight should consider values smaller than 14 kPa.

DMT tests will be performed still in the first semester of 2015 in a joint research project between COPPE/UFRJ and Marchetti Inc. aiming at the development of procedures to be recommended in very soft soils.

Despite the scatter found in the DMT results, values of v_s from the SDMT presented very good repeatability.

5 ACKNOWLEDGEMENTS

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