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Soil Behaviour Type of the Sarapuí II Test Site

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ABSTRACT: One of the major applications of the CPTU test has been the determination of soil stratigraphy and the identification of soil behaviour type. The present paper uses piezocone data from Sarapuí II soft clay test site to evaluate the soil behaviour type charts that have been suggested by Robertson and coauthors from a long time (Robertson et al. 1986, Robertson, 1990), and recently updated (Robertson, 2012). Two lightly overconsolidated clay layers, 3.0-7.5m, and 7.5-10m, for which detailed geotechnical data are available, have been used as references. The trend of both layers to be lightly overconsolidated was properly identified in the Q_{tn} versus F_r chart, which did not occur in the Q_{tn} versus B_q chart. Both layers fall into the undrained behaviour, which is consistent with their behaviour. However, layer 1 was classified as contractive and layer 2 as dilative, which is not right. It is suggested to move the limit between dilative and contractive behaviour towards the top of SBTn 4.

1 INTRODUCTION

One of the major applications of the piezocone test (CPTU) has been the determination of soil stratigraphy and the identification of soil type. This has typically been accomplished using charts that link cone parameters to soil type. The trend of a normally consolidated behaviour can also be obtained from some of those charts (e.g. Robertson 1990). Recently, Robertson (2012) proposed a chart where a more generous behaviour, i.e a dilative – contractive and drained –undrained behaviour can be obtained from the Normalized cone resistance versus Normalized friction ratio chart.

A number of very good quality piezocone tests have been performed in a soft clay test site and have been used to verify the reliability of the most common identification methods, by using the software CPeT-IT.

2 SOIL CLASSIFICATION FROM CPT AND CPTU

2.1 *Historical*

To the authors´ knowledge, Begemann (1965) proposed the first chart that link soil type to the cone parameters cone resistance (q_c) and sleeve friction (f_s), which was based on the mechanical cone. Other suggestions have been presented, based both on the mechanical CPT (e.g., Sanglerat et al. 1974, Schmertmann, 1978) and the electrical CPT (e.g. Douglas and Olsen, 1981).

The measurement of the pore pressure in the CPTU allowed the appearance of classification charts where the sleeve friction – considered a less reliable parameter, with respect to the cone resistance and the pore pressure – was replaced by the pore pressure (e.g., Jones et al. 1981, Jones & Rust, 1982, Senneset & Janbu, 1984).

The combination on the three piezocone parameters was first introduced by Robertson et al. (1986), through the use of two charts, the first one relating the corrected cone resistance q_t with pore pressure parameter B_q (equation 1), and the second q_t with friction ratio, $R_f=f_s/q_t$.

The Robertson et al. (1986) method has become very popular. Normalized parameters suggested by Wroth (1984), were used (Q_t and F_r, equations 2 and 3, in addition to B_q) in 1990 (Robertson, 1990), to take into account the soil stress state.

$$B_q = \frac{u_2 - u_o}{q_t - \sigma_{vo}} \tag{1}$$

$$Q_t = \frac{q_t - \sigma_{vo}}{\sigma'_{vo}} \tag{2}$$

$$F_r = \frac{f_s}{q_t - \sigma_{vo}} \tag{3}$$

Occasionally, soils will fall within different zones on each chart; in these cases, judgement is required to properly classify the soil (Lunne et al. 1997).

Robertson et al (1986) and Robertson (1990) stressed that the CPT-based charts were predictive of soil behaviour, and suggested the term 'soil behaviour type', because the cone responds to the in-situ mechanical behavior of the soil and not directly to soil classification criteria.

Twelve ´soil behaviour type` (SBT) zones were proposed by Robertson et al. (1986) and nine (SBTn) by Robertson (1990). Later, Robertson (2010) updated the early Robertson et al.´s (1986) method including a dimensionless cone resistance (q_c/p_a, where p_a=atmospheric pressure) and reducing the number of SBT zones from 12 to 9 in order to match the SBTn zones.

According to Robertson (2009), the normalized charts provide more reliable identification than the non-normalized charts, although when the in situ vertical stress is between 50 and 150 kPa the difference is very small.

It is interesting to note a change of hierarchy on the use of the pore pressure with respect to friction sleeve. In fact, Table 1, adapted from Liao (2005), provides a list of several soil classification charts found in literature. They are divided into three groups: a) charts based on cone resistance and sleeve friction; b) charts based on cone resistance and pore pressure; c) charts based on all three quantities of CPTU data. The trend of using the three CPTU quantities more recently can be seen from the table.

Table 1. Soil classification charts found in the literature (adapted from Liao, 2005)

Methods based on:
a) cone resistance and sleeve friction: Begemann (1965), Sanglerat et al (1974), Schmertmann (1978), Douglas & Olsen (1981), Vos (1982), Robertson & Campanella (1983), Erwing (1988), Olsen & Malone (1988), Olsen & Mitchell (1995), Zhang & Tumay (1999), Eslami & Fellenius (1997)
b) cone resistance and porewater pressure: Jones et al (1981), Jones & Rust (1982), Senneset & Janbu (1984), Parez & Fauriel (1988), Senneset et al (1989), Chang-hou et al (1990), Jian et al (1992) and Schneider et al (2008)
c) all three quantities of CPTU data: Robertson et al. (1986), Robertson (1990, 1991), Larsson & Mulabdic (1991), Jefferies & Davies (1991, 1993) and Ramsey (2002)

However, the trend of going back to the use of a single chart cone resistance versus sleeve friction (through normalized parameters) was justified in detail by Robertson (2012), based on the following (simplified) reasons:

i) In the case of onshore tests, the penetration is carried out through unsaturated soils before reaching saturated soil. The use of viscous liquids, like silicon oil, has minimized the loss of saturation but has not completely solved the problem. Also, few commercial CPT operators pre-drill the sounding and fill it with water.

ii) Although it has been documented (e.g., Lunne et al. 1986) that the sleeve friction is less accurate than the cone resistance, a number of measures on the cone design can provide reliable f_s measurements.

This chart is shown in Figure 1 below, where a more generalized cone parameter Q_{tn}, defined in Equation (4), is suggested. The chart is particularly useful, because a direct dilative-contractive and drained-undrained behaviour can be obtained.

$$Q_{tn} = \frac{q_t - \sigma_{vo}}{p_a} \cdot \frac{p_a}{\sigma'_{vo}} \qquad (4)$$

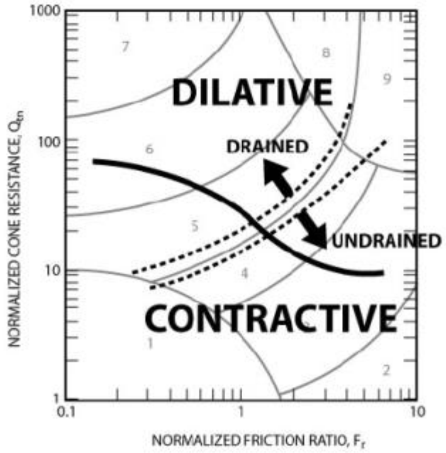

Figure 1. Approximate boundaries between dilative-contractive behaviour and drained-undrained CPT response on normalized SBTn $Q_{tn} – F_r$ chart (after Robertson 2012).

3 THE TEST SITE

3.1 *General*

The early studies on the very soft clay of the region where the Sarapuí test site is located were conducted by Pacheco Silva (1953). 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). A comprehensive report about the deposit has been provided by Almeida and 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. Two studies on pile behaviour have been carried out at Sarapuí II site (Alves 2004, Francisco 2004). The initial tests with the torpedo piezocone (Porto et al. 2010) have also been performed at Sarapuí II test site. 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 clay in the test area is around 8 m deep, and a clayey-silt layer underlies the very soft clay. A comprehensive study about the deposit of Sarapuí II was undertaken by Jannuzzi (2009, 2013) and Jannuzzi et al. (2015).

The liquid limit, plastic limit and natural water content, specific gravity, total unit weight, initial void ratio, activity versus depth are included in Figure 2. The grain size distribution, organic content, total salt content and NaCl content, relative percentage of clay minerals versus depth are shown in Figure 3.

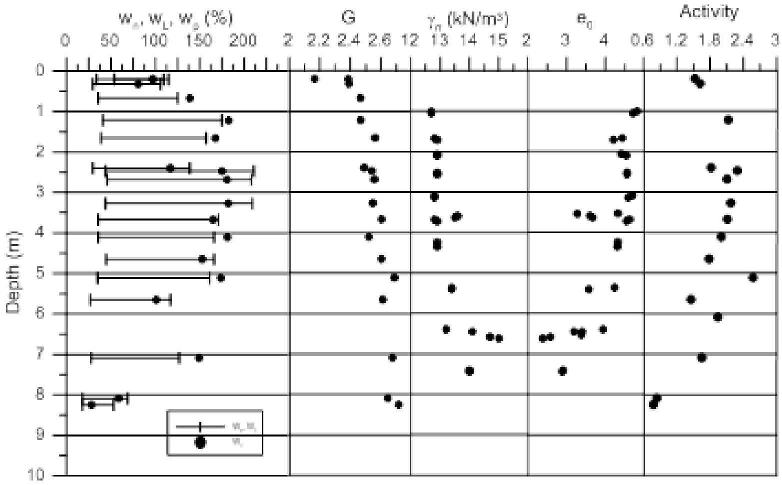

Figure 2. Liquid limit, plastic limit and natural water content; specific gravity; total unit weight; initial void ratio; activity versus depth (adapted from Jannuzzi 2013, Jannuzzi et al. 2015).

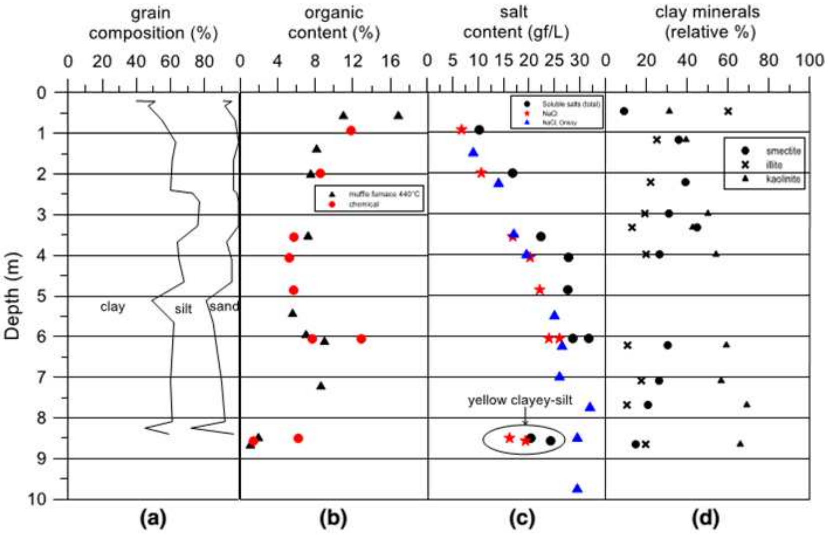

Figure 3. (a) Grain size distribution; (b) organic content; (c) total salt content and NaCl content (data from Onsøy clay also included); (d) relative percentage of clay minerals versus depth (Jannuzzi et al. 2015).

The overconsolidation ratio (OCR) versus depth, from 24h incremental loading tests performed in very good quality samples, is shown in Figure 4. The specimens in the depth range 4.0 – 5.5 presented a significant number of shells, providing meaningless results. It can be observed that the deposit is lightly overconsolidated below 3 m depth, approximately, with OCR around 2.

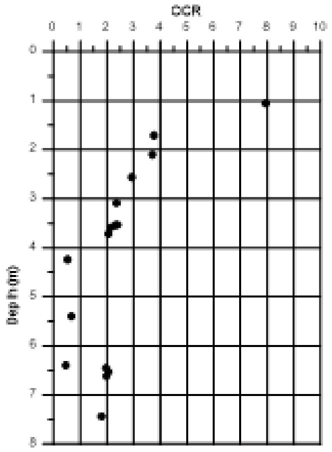

Figure 4. OCR versus depth, Sarapuí II test site.

3.2 *Piezocone tests*

Seven CPTU tests have been performed, one of them under an existing embankment. The standard rate of 20 mm/s has been used in all tests. The equipment used has been developed by COPPE – Federal University of Rio de Janeiro (UFRJ) and Grom Eng., and is able to measure cone resistance, q_c, sleeve friction, f_s and pore pressure at cone face, u_1, and cone shoulder, u_2. The advantages of measuring pore pressure at 2 positions have been recognized throughout the last 15 years at COPPE/UFRJ and have been reported by e.g. Danziger (2007).

Calibration has been carried out before and after every test series in the range of load /pressure values expected in the field. Water was used – as COPPE/UFRJ regular practice – as saturation fluid.

A typical result is shown in Figure 5.

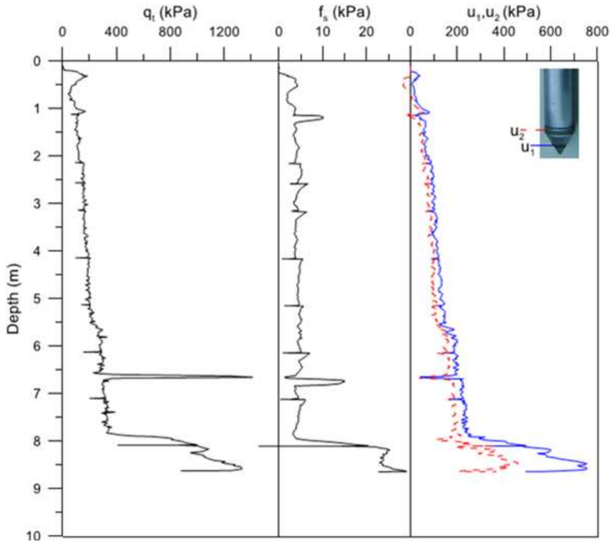

Figure 5. Corrected cone resistance (q_t), friction sleeve (f_s) and pore pressures at cone face (u_1) and cone shoulder (u_2) from a typical piezocone test at Sarapuí II site (Jannuzzi et al. 2015).

4 SBT FROM SARAPUÍ II TEST SITE

The analysis herein performed is related to two layers, the first 3 - 7.5 m (layer 1) and the second 7.5 - 9 m (layer 2). This choice was due to the fact that the upper 3 m of the deposit is overconsolidated, and the purpose of the paper is to analyze the material which can be said to be lightly overconsolidated. It must be pointed out that geological evidences show that the whole deposit was formed underwater. In other words, the OCR values of the material below 3 m has been attributed to secondary consolidation (Martins et al. 2009). Also, no reasons are known so far to justify the OCR values obtained in the upper 3 m of the deposit.

The data from six piezocone tests, with excellent repeatability, were plotted in the Robertson et al. (1990) chart, using the the software CPeT-IT, and the results are found in Figure 6. Layer 1 (organic clay), in grey, is mostly included in SBTn 3 – clays: clay to silty clay, in both charts, which is consistent with the tested material, although one should expect that the high organic content would indicate At least part of the data in SBTn 2 - clay-organic soil. Layer 2 (clayey silt), in green, falls mostly in the SBTn 4 in the case of the Q_{tn} x F_r chart, whereas the data spread in SBTn 3, 4 and 5 in the case of Q_{tn} x B_q chart. The SBTn 4 is consistent with the expected behaviour of the material, and the classification in different SBTn categories may be explained by the fact that the friction sleeve (and consequently F_r) is a value obtained over a certain length, and the pore pressure (and consequently B_q) is more localized, reflecting sudden changes in the soil profile.

The OCR trend is consistent with the data plotted in the Q_{tn} versus F_r chart, indicating approximately that both layers are lightly overconsolidated. The data plotted in the Q_{tn} versus B_q chart, however, do not reflect properly the differences between the two layers, because it indicates a higher OCR in the case of layer 2.

The data have also been plotted in the Robertson´s (2012) chart, where the drained-undrained and dilative-contractive behaviour are shown (Figure 7), with limits that have been included in the chart provided by the software CPeT-IT.

A quite interesting picture can be observed. Both layers fall into the undrained behaviour, which would be expected, because the separation between the two types of behaviour is approximately the line between SBTn 4 and 5, i.e. the separation between the clay type of behaviour and the sand type of behaviour. The results are consistent with the soil behaviour of both layers.

However, layer 1 was classified as contractive and layer 2 as dilative, which is not true. Both layers are contractive, as found in DSS tests carried out in samples reconstituted for the in situ stresses. Also, the geological evidences indicate that the whole deposit was formed underwater, and there are no evidences of significant layers that have been removed to justify a high OCR. Therefore, the limit between dilative and contractive behaviour should be moved towards the top of SBTn 4, as also indicated in Figure 7.

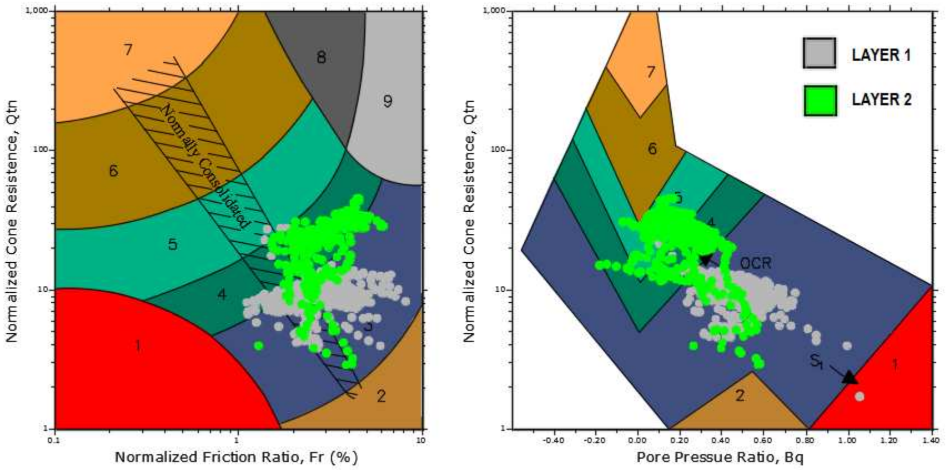

Figure 6. Two clay layers' data plotted at Robertson´s (1990) normalized charts.

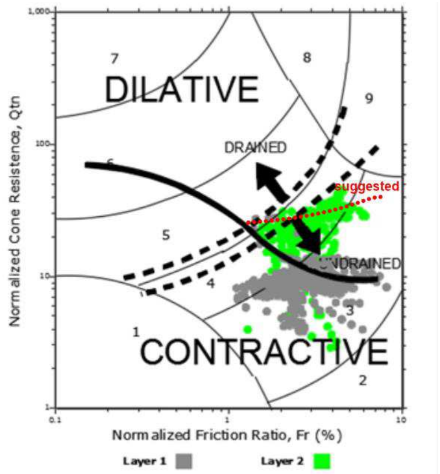

Figure 7. Two clay layers' data plotted at Robertson´s (2012) chart; suggested trend for dilative-contractive behaviour.

5 CONCLUSIONS

The results of six piezocone tests, carefully performed in a clay test site, were used to evaluate the reliability of the soil behaviour type which have been suggested by Robertson and coauthors from a long time (Robertson et al. 1986, Robertson 1990), recently updated (Robertson, 2012).

Two lightly overconsolidated layers were chosen to be used as references, the first one a dark grey very soft, very plastic, organic (layer 1), and the second one a yellow clayey-silt, stiffer, with a smaller organic content and plasticity index (layer 2). Both layers were properly classified as SBTn 3 (layer 1) and SBTn 4 (layer 2) in both normalized charts Q_{tn} versus F_r and Q_{tn} versus B_q. In fact, one would expect that layer 1 would have been classified as SBTn 2, because it presents a high organic content, which was not the case.

The trend of both layers to be lightly overconsolidated was properly identified in the Q_{tn} versus F_r chart, which did not occur in the Q_{tn} versus B_q chart. In fact, in this case there was an indication that layer 2 has a higher OCR than layer 1, which is not the case.

Both layers fall into the undrained behaviour, which is consistent with their behaviour. However, layer 1 was classified as contractive and layer 2 as dilative, which is not right. It is suggested to move the limit between dilative and contractive behaviour towards the top of SBTn 4.

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