Geotechnical characterization of a soft soil deposit in the west city limit of Recife - PE, Brazil

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ABSTRACT: Soft soil deposits have special behavior characteristics that require an adequate geotechnical characterization. This paper aims to study the soft soil geotechnical parameters, whose deposit location is in the Recife Metropolitan Region, through field and laboratory investigation, and to discuss the results with the Recife database and the international literature. It was performed the following tests on four field-distributed investigation sites: Vane shear, SPT, Piezocone (CPTu), and Shelby tube (ϕ4 ”). It is noteworthy that this article will focus on one investigation site (investigation site 2). Undisturbed samples submitted to laboratory tests (4.5, 8.5, and 12.5 m) allowed the geotechnical analysis of the layers L2 and L3. The results presented that the L2 layer has characteristics of organic clays (CH) and organic soils (OH), and L3 layer has similarities to silty and clays (MH and CL). In general, the measured (qt, fs, u2) and derived (Fr, Rf, Bq, Qt1) parameters profiles from the Piezocone test were in agreement with the SPT profile. The L1 layer presented qt values ranging from 2.0 MPa to 1.0 MPa; L2 layer an average of 0.7 ± 0.05 MPa, with some peak values; L3 layer an increasing and linear trend of 0.7 to 1.5 MPa. Regarding the Vane test, the estimated results presented a satisfactory application. However, concerning laboratory results, the estimated values were higher, which may be associated with the presence of organic matter, sand and seashells lenses in the torque readings of the vane test.

Keywords: Soft soil; Vane test, Piezocone; Soil behavior type (SBT), Cone factor.

1. Introduction

Soft soil deposits have special behavior characteristics that require an adequate geotechnical characterization. Estimation of geotechnical parameters in this type of material requires good quality samples, adequate and reference tests, such as the Piezocone test. (CPTu). In the Recife Metropolitan Region, Northeastern Brazilian coast (Figure 1), it is common to find soft soil deposits in the plains. Coutinho et al. (1998); Coutinho (2007), Coutinho & Bello (2012) present more information about geotechnical studies of the Recife soft clay.

This paper aims to study the soft soil geotechnical parameters, whose deposit location is in the Recife Metropolitan Region, through field and laboratory investigation, and to discuss the results with the Recife database and the international literature.

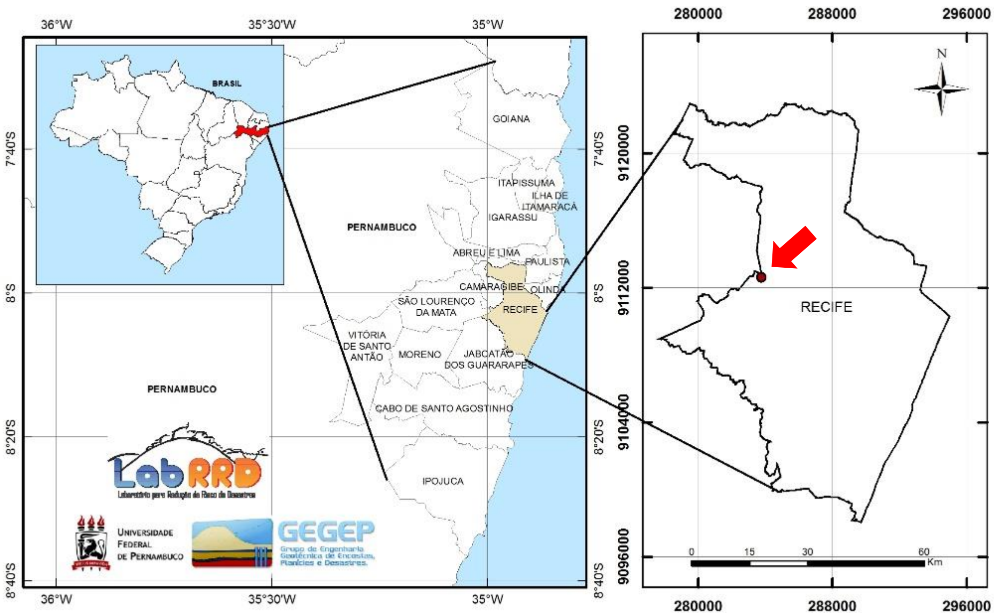


Figure 1. Study area localization

2. Experimental program

2.1. *In situ* tests

It was performed the following tests on four field-distributed investigation sites (Figure 2): Vane shear, SPT, Piezocone (CPTu), and Shelby tube (**ϕ**4 ”). All the tests were performed according to Brazilian and international standards.

Preliminarily, the SPT survey identified the profile consisting of soft soils, with emphasis on an intermediate layer of very soft organic soil of 8 m thickness with N_{SPT} values of 0/45 (no blows). From this identification, it was taken Shelby samples at depths of 4.5, 8.5, and 12.5 meters for laboratory tests. It was performed Vane tests every meter of the profile, until 15 meters deep. It was performed CPTu tests until about 20 meters deep, with parameters measured every 0.03 m. It is important to highlight that this article will focus on a specific investigation site. Future papers will present other results.

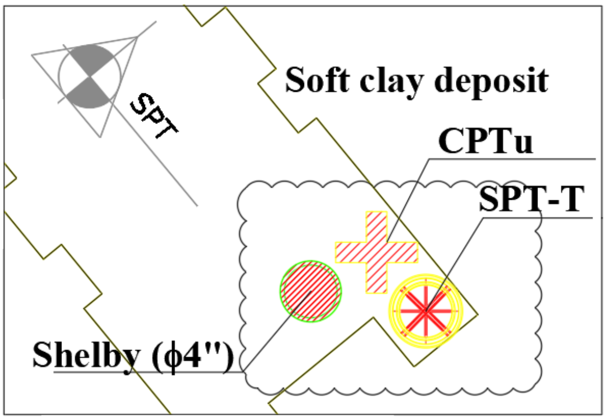


Figure 2. Experimental program – study area (investigation site 2)

2.2. Laboratory tests

Following the Brazilian standards, it was performed characterization tests on the undisturbed Shelby samples, such as unit weight (γn), organic matter content (OC), oedometer, and triaxial UU-C. An integrated analysis between the laboratory test results and the in situ test results (Vane and CPTu) was made.

3. Site characterization

3.1. Location and soil profile

With approximately 60,000 square meters (14,8 acres), the area is located in Recife, bordering the city of Camaragibe, Pernambuco State, Brazil. The area is about 850 m from one of the region’s largest rivers, the Capibaribe River, an important transporter of organic sediments in the soft soil deposits formation in the Recife plain (Coutinho 2007).

The 19 SPT results were verified to analyze the geotechnical profile of the study area, 3 of them belong to the investigation site 2.

Figure 3 presents the three-dimensional profile of the total land area, highlighting the representative area of investigation site 2. The profile indicates that the stratigraphy is quite diverse over the extension of the region.

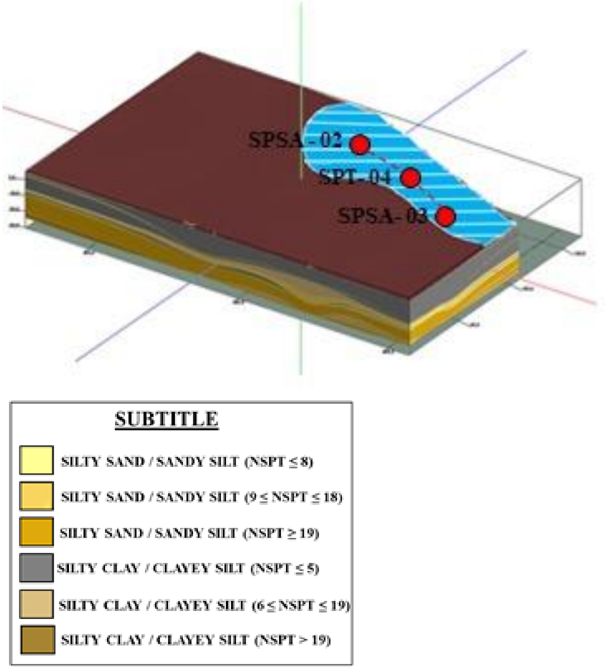


Figure 3. Three - dimensional profile of the total area of the enterprise, highlighting the representative area of the investigation site

On the surface, sometimes, it can be found a layer of silty sand/sandy silt with $N_{SPT} \leq 8$, sometimes a layer of silty clay/clayey silt with sand and gravels, very soft to soft, suggesting a probable landfill of up to 3.14 m thick. In sequence, there are a series of intercalations of clayey silt and silty clays, predominantly with sand and organic matter at various levels of decomposition, whose penetration resistance index $N_{SPT} = 5$. Taken together, these layers, known as soft soils, have varying thicknesses and can reach values higher than 25 m.

Subsequently, it can be found a layer of the same material, but with higher consistencies ($6 \leq N_{SPT} \leq 19$), up to 8.77 m thick that has an alternation, being proceeded or replaced by layers of silty sand/sandy silt ($9 \leq N_{SPT} \leq 18$). Soft sandy silt/silty sand lenses of 1.91 m in average thickness may emerge from the aforementioned layers. Finally, there is sandy silt/silty sand layer ($N_{SPT} \geq 19$) up to 13 m thick, which can cover or proceed/precede layers of clayey silts/silty clays ($N_{SPT} > 19$) up to 6.06 m thick. The water table is generally at the same level as the ground and around 30 meters deep. The ground is impenetrable to percussion.

Figure 4 shows a section obtained through the analysis of the boreholes located in the investigation site 2.

At the study site, it can be found a layer of silty sand with gravels up to 1 m deep; it is followed by a layer of silty clay with sand and organic matter, with the presence of tree roots and branches, and/or seashells fragments with very soft to soft consistency and thicknesses ranging from 9.00 to 25.00 m, reaching an average depth of 17.00 meters.

Then, there is a layer of silty sand/sandy silt with gravels and/or mica up to 22 (± 4.00) m deep, and $9 \leq N_{SPT} \leq 18$. It can be found lenses of clayey silt or silty up to 2 m thick by interspersing or overlapping this layer.

Finally, there is a layer of sandy silt ($N_{SPT} \geq 19$) that alternates with a layer of silty clay with sand ($N_{SPT} > 19$) up to 30.00 m deep, which corresponds to impenetrable to percussion.

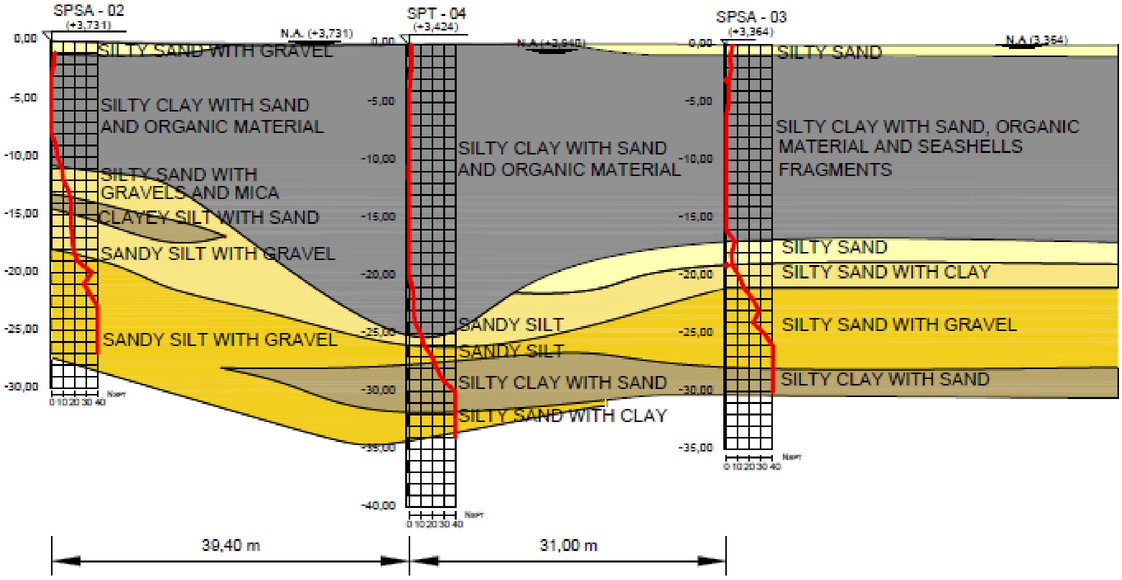
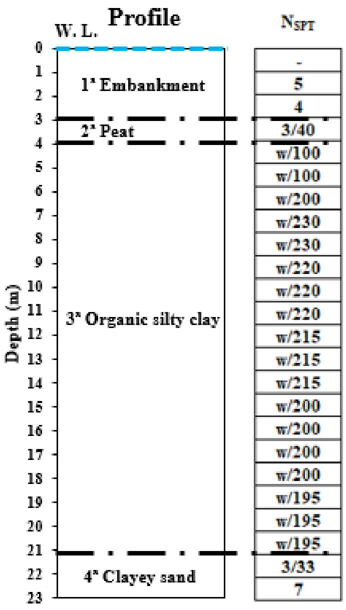


Figure 4. Geotechnical Profile– study area (investigation site 2)

Through the integrated analysis of all tests performed, three layers were identified on the soil profile. Layer 1 (L1: 0.0-3.0m), a sand clay; layer 2 (L2: 3.0-11.0m), a very soft organic silty clay; layer 3 (L3: z > 11m), a soft to medium silty clay with seashells fragments. According to Coutinho and Barbosa (2018), the soil profile of the present study agrees with the location and geotechnical characteristics of the fluvial-lagoon deposits (Qfl) that occur in the Recife plain, which tends to have thick layers of soft (to very soft) organic soils (Figure 5).

Typical Profile "Qfl" - Fluvial-Lagoon Deposits								
Layer	Possible occurrence	Occurrence	Faixas de espessura (m) Extreme	Faixas de espessura (m) Most frequently	N_{SPT}	W_n (%)	OMC (%)	e_0
1ª	Sand	50%	0.5 - 16.2	02/ago	4 + 10	-	-	-
	Embankment	40%	0.15 - 6	01/mar	04/ago	-	-	-
	Organic clay	5%	0.3 - 6.9	1.8 - 5.5	w/100 - 4	50 - 80	5 - 15	1.3 - 1.96
	Silty clay	5%	0.4 - 6	1.2 - 3	4 - 10	-	-	-
2ª	Sand	35%	0.6 - 10	0.5 - 4	4 - 10	-	-	-
	Organic clay	30%	0.3 - 15	1 - 5.5	1 - 3	-	5 - 15	-
	Silty clay	23%	0.15 - 7	1.2 - 2	1 - 4	-	3 - 9	0.92 - 2.35
	Peat	12%	0.2 - 6.8	2.1 - 4.7	3/40 - 2	150 - 300	>30	-
3ª	Sand	50%	0.41 - 14.9	1.5 - 6.8	3 - 12	-	-	-
	Silty clay	21%	0.45 - 8.25	1.5 - 4.5	2 - 5	-	-	-
	Organic clay	18%	0.2 - 7.5	1.5 - 4.5	w/220 - 1	140 - 200	4 - 12	2 - 4.5
	Peat	11%	0.95 - 5.3	1.2 - 3	w/34 - 1	100 - 300	30 - 70	3 - 6
4ª	Sand	56%	0.7 - 14.9	1.5 - 6	6 - 20	-	-	-
	Silty clay	23%	0.5 - 12	1.1 - 4.5	w/100 - 8	70 - 100	1 - 5	1.5 - 2.5
	Organic clay	21%	0.3 - 25.9	3 - 12	w/215 - 1	80 - 120	9 - 12	1.5 - 2.5
5ª	Sand	57%	0.15 - 15	2.1 - 7.5	6 - 22	-	-	-
	Silty clay	30%	0.5 - 12	1.1 - 4.5	w/100 - 8	70 - 100	1 - 5	1.5 - 2.5
	Organic clay	13%	0.3 - 25.9	3 - 12	w/215 - 1	80 - 120	9 - 12	1.5 - 2.5
6ª	Sand	51%	0.45 - 8.8	1.5 - 5	10 - 32	-	-	-
	Silty clay	36%	0.35 - 6	1.5 - 4.5	1 - 3	-	-	-
	Organic clay	13%	1 - 6.5	2 - 7	w/100 - 2	-	-	-
7ª	Sand	69%	0.45 - 8.8	1.5 - 5	10 - 32	-	-	-
	Silty clay	19%	1 - 6.5	2 - 4.5	1 - 3	-	-	-
	Organic clay	12%	1.6 - 11	2.5 - 6	w/100 - 2	-	-	-

(a)



(b)

Figure 5. (a) Typical profile “Qfl”; (b) SPT Result Example - ID 48: SESI-Ibura (Coutinho and Barbosa, 2018)

3.2. Laboratory results

The samples submitted to laboratory tests (4.5, 8.5 and 12.5m), allowed the geotechnical analysis of the L2 and L3 layers. The natural moisture (W_n) in L2 varied from 164% to 180%, in L3 was 84%. The plasticity limit (Wp) varied from 70% to 109% in L2, in L3 was 41%. The liquid limit (Wl) presented values around 190% in L2, and L3 was 95%. As expected, L2 (“organic soils”) presents higher plasticity limit values (Figure 7).

The plasticity chart of some Brazilian clays, proposed by Coutinho et al. (1998), includes Jurtunaíba and Recife clay (Figure 6). The comparison of the present study results with this chart revealed that the L2 layer presented characteristics of organic clays (CH) and organic soils (OH) and the L3 layer with similarities to silty and clays (MH and CL).

The organic matter content (OC) of the L2 layer varied from 17% to 19%; in L3 presented a value of 9%. According to Huang et al. (2009) proposal, the L2 layer can be classified as "organic soils" and the L3 as "mineral soils with organic matter". The initial voids (e_0) on L2 showed values close to 4.0, while on L3 close to 2.0. The OCR values of the L2 and L3 layers suggest a tendency for the condition normally consolidated preceding 5 meters deep (Figure 7). The compression index of the L2 layer presented values close to 2.0, while the L3 layer presented a value of 0.85. The S_u values, obtained from triaxial compression tests (UU), were 12.5 kPa on L2, and 9.5 kPa on L3.

All results are consistent with the database (Coutinho, 2007), as shown in Figure 6, for clays with very low N_{SPT} and the presence of organic matter.

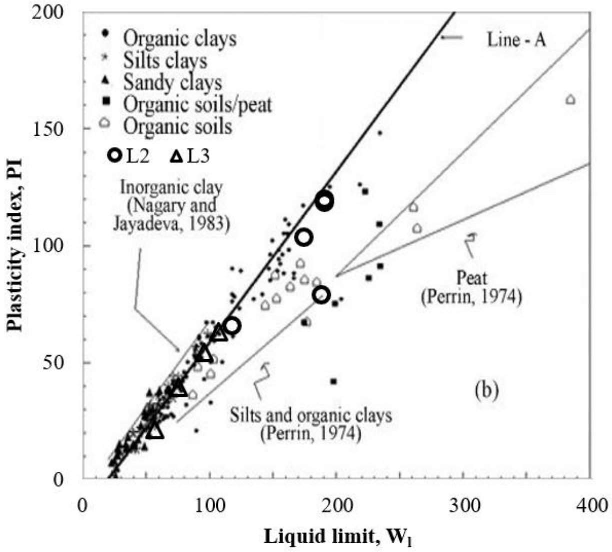


Figure 6. Casagrande plasticity chart (from Coutinho et al. 1998).

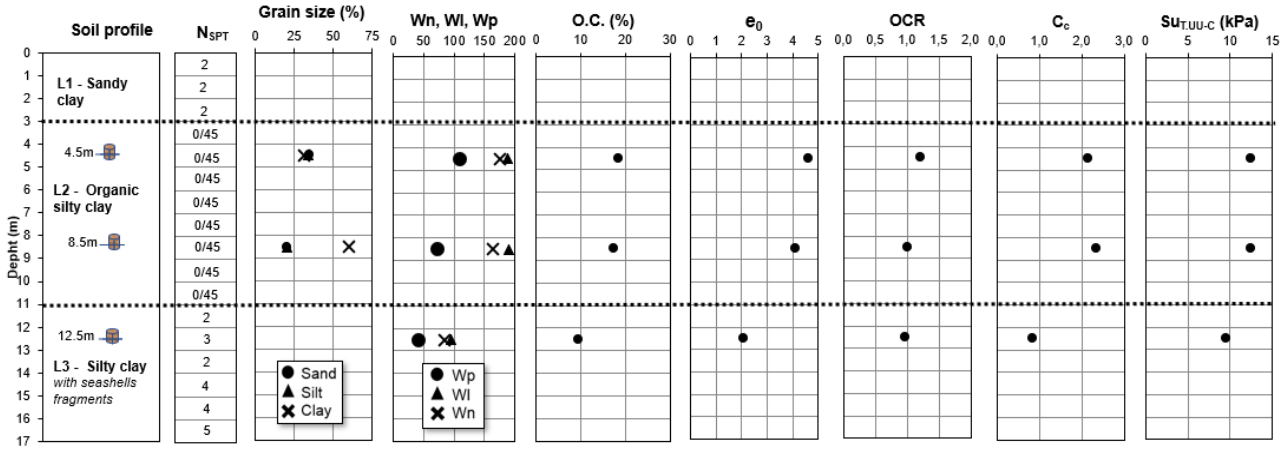


Figure 7. Profile geotechnical characteristics – investigation site 2.

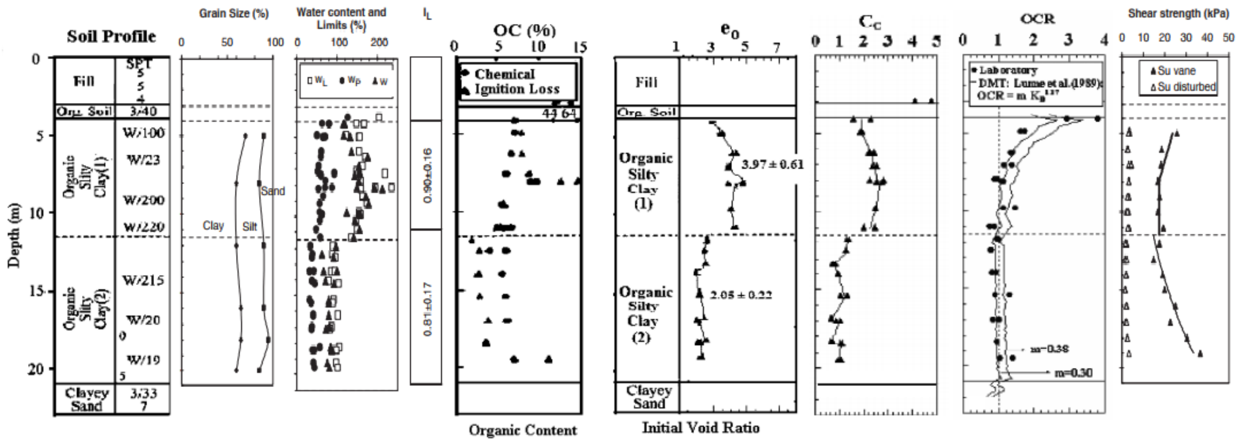


Figure 8. Profile geotechnical characteristics – SESI-Ibura (Coutinho, 2007).

3.3. Vane test results

The L1 layer presented an average S_u value of 41 ± 0.9 kPa. In L2, S_u values varied following a decreasing trend with depth (47.5-2.57z). In L3, an increasing trend with depth was observed (4.55z-29.5). Regarding sensitivity, the L1, L2, and L3 layers presented mean values of 2.76 ± 0.0.33, 1.9 ± 0.1, and 2.17 ± 0.4, respectively (Figure 9). These values classify soils as "medium sensitivity", according to Skempton and Northey (1952).

Coutinho et al. (2000) and Coutinho and Bello (2012) present a resistance ratio modified from Skempton (1957), with results from several Brazilian clays, including Recife and Suape clays. In this study, the points were among the correlations of Coutinho et al. (2000) and Larsson (1980) (Figure 10).

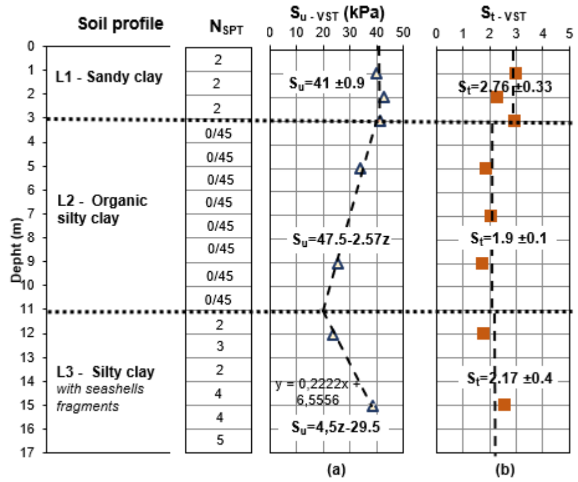


Figure 9. Vane tests result profiles: (a) S_u; (b) S_t.

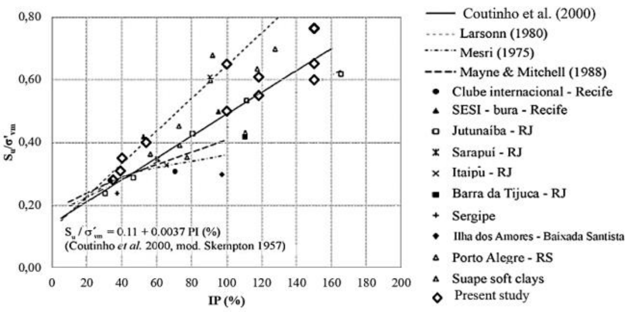


Figure 10. Resistance-ratio, S_u/σ'_{vm} (Coutinho and Bello 2012).

3.4. Piezocone results

According to EN-ISO 22476-1, the Piezocone measurements of the soils of the study area are in class 1, referring to soft soil deposits. For better interpretation integrated with laboratory and vane results, a Piezocone measurement profile was adopted, corresponding to investigation site 2.

In general, the measured (q_t, f_s, u_2) and derived (F_r, R_f, B_q, Q_{t1}) parameters profiles from the Piezocone test were in agreement with the SPT profile (Figure 11). The L1 layer presented qt values ranging from 2.0 MPa to 1.0 MPa; L2 layer an average of 0.7 ± 0.05 MPa, with some peak values; L3 layer an increasing and linear trend of 0.7 to 1.5 MPa. Sleeve friction (f_s) showed an upward trend in the L3 layer.

3.4.1. Soil behavior type (SBT)

For this analysis, proposals that use normalized (Robertson, 2009) and non-normalized (Robertson, 2010) parameters were applied. The proposal that presented the highest agreement with the other results (laboratory and vane) was the non-normalized.

The L1 layer presented I_{SBT} profile values varying linearly with a depth between 1.7 and 2.8, classified as "silty sand" to "silty clay". In the L2 layer, these values ranged from 3 to 2.7, with a great occurrence of points in classification zone 4 that is "clayey silt to silty clay". In the L3 layer, the points showed a small tendency of decreasing the I_{SBT} value with the depth, being classified in zone 5 (silty sand to sandy silt), as shown in Figure 12.

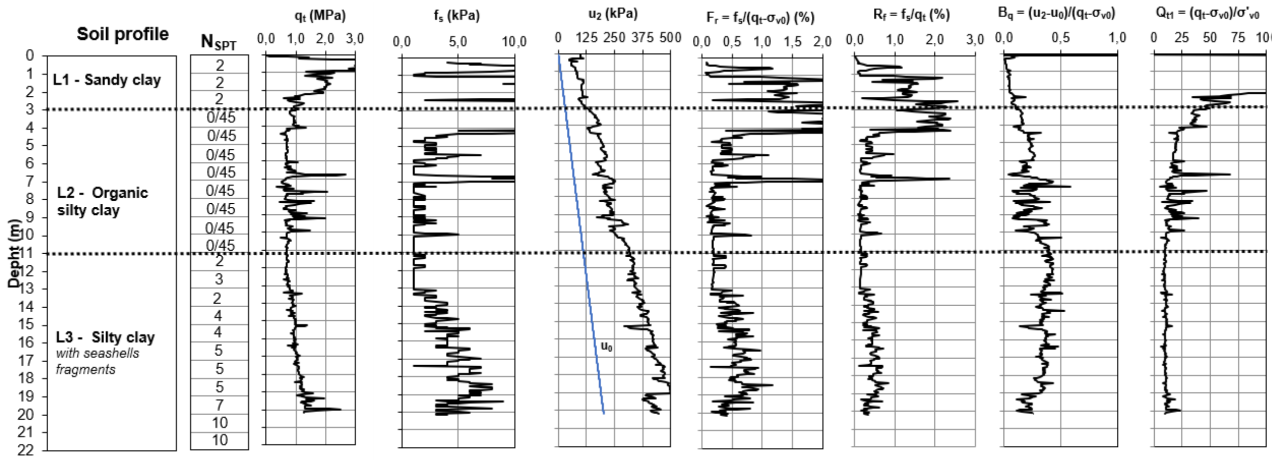


Figure 11. Measurements and derived parameters from piezocone test – investigation site 2.

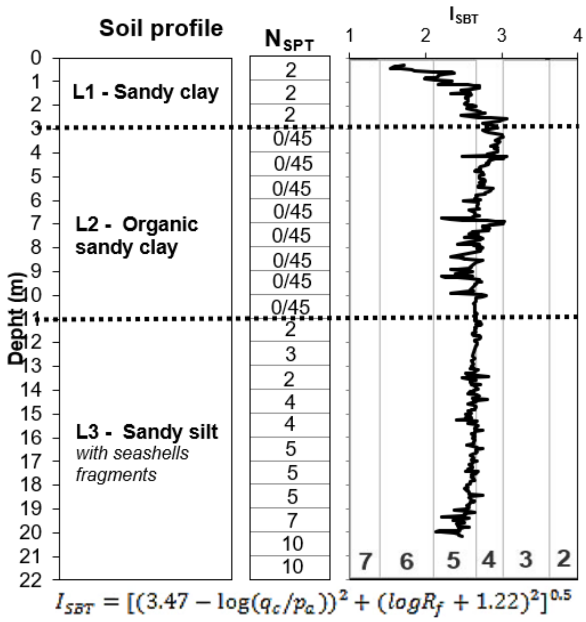


Figure 12. I_{SBT} profile, from Robertson (2010).

The non-normalized chart (Figure 13) revealed a higher concentration of points between SBT zones 4 (clayey silt to silty clay) and 5 (silty sand to sandy silt).

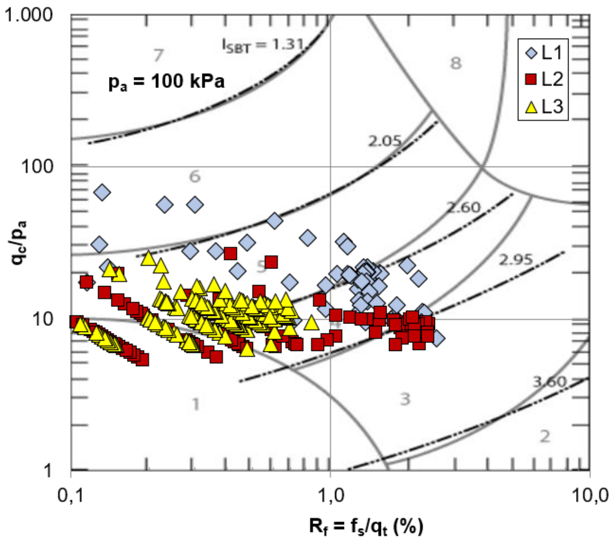


Figure 13. Non-normalized SBT chart, from Robertson (2010).

3.4.2. Cone factor (N_{kt})

The cone factor (N_{kt}), in terms of total stress, is defined by the ratio of the net point resistance to the undrained resistance obtained by some reference test. In the present study, it was adopted, as a reference, the results of undrained resistance obtained by the Vane test, as in Eq. (1).

$$N_{kt} = \frac{(q_t - \sigma_{v0})}{Su_{VST}} \quad (1)$$

Where Nkt = cone factor, qt = corrected cone resistance, σv0 = vertical total stress in situ and Su_{VST} = undrained strength from Vane shear test.

N_{kt} values ranged from 9.5 to 23.5, with a decreasing trend (24.36-1.92z) to a depth of 8m. Above this depth, the values of N_{kt} presented an average of 20 ± 2, as in Figure 8a. With reasonable dispersion, an average value of N_{kt} was obtained by linear regression of 16 ±7, as in Figure 8b.

Mayne and Peuchen (2018) proposed an estimate of Nkt through the values of pore pressure ratio, as in Eq. (2).

$$N_{kt} = 10.5 - 4.6\ln(B_q + 0.1) \quad (2)$$

Where N_{kt} = cone factor, B_q = pore pressure ratio (>-0.1).

The N_{kt} values estimated by Mayne and Peuchen (2018) showed a linear regression mean of 16.3 ±3, in agreement with the mean value obtained by the vane test, but with less dispersion (Figures 14a and 14b).

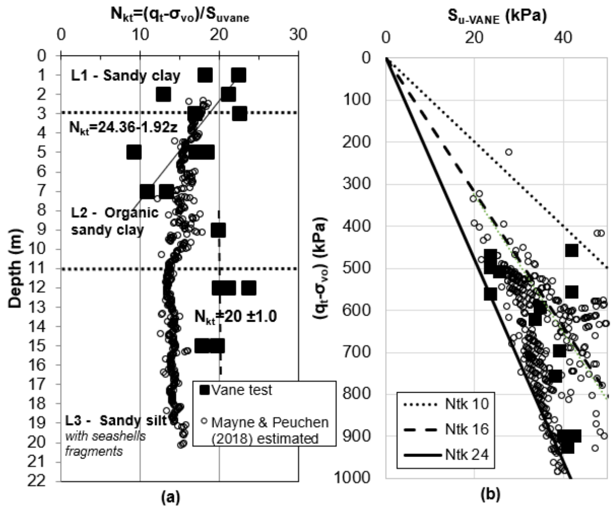


Figure 14. Cone factor study: (a) along the profile; (b) general analysis.

3.4.3. Estimated parameters

In this study, the profiles of preconsolidation pressure (σ'p), over consolidation ratio (OCR), in situ stress ratio (K_0), and undrained shear strength (S_u) were estimated by CPTu, according to Figure 15.

To estimate the preconsolidation pressure, Mayne's (2017) proposal adapted for the Recife clays presented in Eq. (3) was applied, which uses the exponent m', a function of soil grain size. The higher the number of fines in the soil, the higher the exponent m', as in Eq (4).

$$\sigma'_p = K_1(q_t - \sigma_{v0})^{m'} . \left({p_a}/{100}\right)^{1-m'} \quad (3)$$

$$m' = 1 - \frac{0.28}{1 + \left({I_{SBTn}}/{2.65}\right)^{25}} \quad (4)$$

Where K1 = constant, qt = corrected cone resistance, σv0 = vertical total stress in situ, pa = atmospheric pressure (100 kPa), ISBTn=soil behavior type index normalized (=Ic)

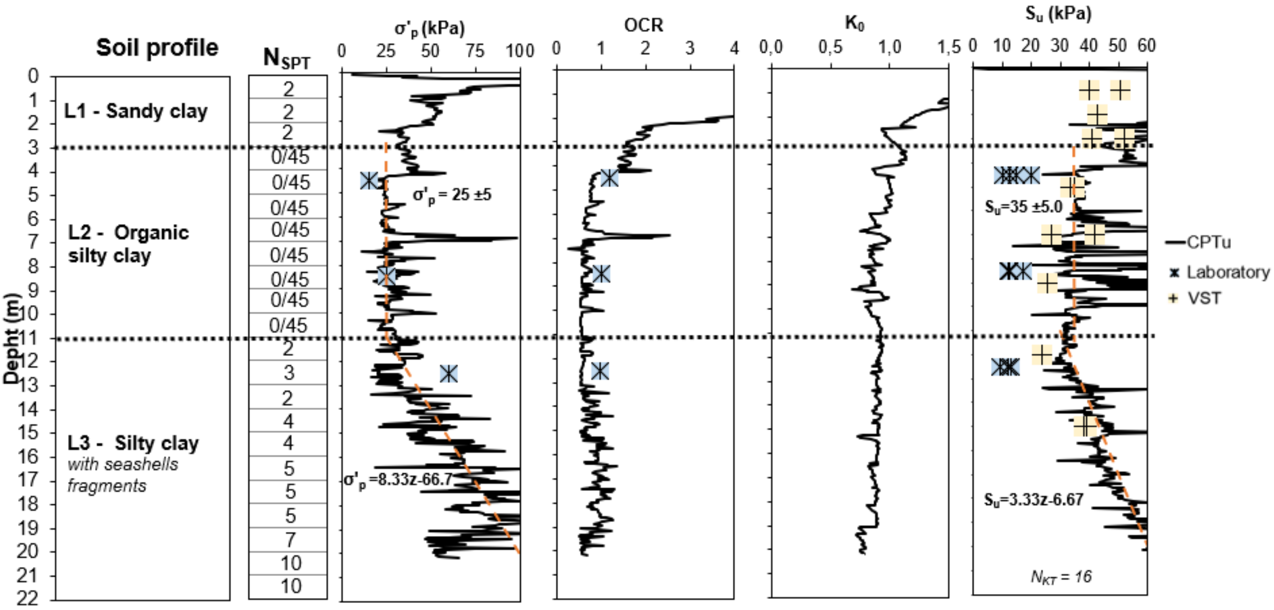


Figure 15. Estimated parameters from piezocone test.

The original proposal (Mayne, 2017) uses a K_1 constant of 0.33. In the present study, it was used the value of 0.25, according to Coutinho (2007).

The K_0 values were estimated by Sully and Campanella (1991), $K_0=0.5+0.11(u_1-u_2)\sigma'_{v0}$. The OCR values were estimated by the ratio of the estimated preconsolidation pressure (Eq. 3) by the effective pressure. The undrained strength (S_u) was estimated from the N_{kt} obtained by the Vane test ($S_u=(q_t-\sigma_{vo})/N_{ktVST}$).

The estimated L1 layer preconsolidation pressure ranged from 75 kPa to 35 kPa at the intersection with the L2 layer. The L2 layer presented a clear concentration of values around 25 ± 5.0 kPa, with some peaks. The L3 layer showed an increasing tendency (8.33z-66.7) of preconsolidation pressure with depth. The estimation of preconsolidation pressure was consistent with the values obtained by laboratory tests.

The estimated value profile of OCR presented a preconsolidation characteristic in the L1 layer and a tendency to normally consolidated condition (NC) in the L2 and L3 layers, in agreement with local experiments, where this tendency is verified for depths greater than 4m (Coutinho, 2007). Compared with the laboratory test results, the estimate was slightly lower.

The estimated K_0 values presented a concentration of points close to 1.0 in the L2 and L3 layers.

Using the N_{kt} equal to 16, the estimated values of Su in the L2 layer varied from 30 kPa to 40 kPa, with an average of 35 ± 5.0 kPa. In the L3 layer, the estimated Su values assumed an increasing trend with depth (3.33z-6.67). Regarding the vane test, the estimated results presented a satisfactory application. However, concerning laboratory results, the estimated values were higher, which may be associated with the presence of organic matter, sand and seashells lenses in the torque readings of the vane test.

4. Conclusions

From the data presented in this paper, all results are consistent with the database (Coutinho, 2007) for clays with very low N_{SPT} and the presence of organic matter.
In general, the measured (qt, fs, u2) and derived (Fr, Rf, Bq, Qt1) parameters profiles from the Piezocone test were in agreement with the typical profile of the study area. The L1 layer presented qt values ranging from 2.0 MPa to 1.0 MPa; L2 layer an average of 0.7 MPa ±0.05 with some peak values; L3 layer an increasing and linear trend of 0.7 to 1.5 MPa. Sleeve friction (fs) showed an upward trend in the L3 layer.

The L1 layer presented ISBT profile values varying linearly with a depth between 1.7 and 2.8, classified as "silty sand" to "silty clay". In the L2 layer, these values ranged from 3 to 2.7, with a great occurrence of points in classification zone 4 that is "clayey silt to silty clay". In the L3 layer, the points showed a small tendency of decreasing the ISBT value with the depth, being classified in zone 5 (silty sand to sandy silt). Due to the complexity of this soil, a broad program of geological-geotechnical studies is necessary for its adequate characterization and understanding, which will be presented and discussed in future papers.

The estimated L1 layer preconsolidation pressure ranged from 75 kPa to 35 kPa at the intersection with the L2 layer. The L2 layer presented a clear concentration of values around 25 kPa, with some peaks. The L3 layer showed an increasing tendency (8.33z-66.7) of preconsolidation pressure with depth. The estimation of preconsolidation pressure was consistent with the values obtained by laboratory tests.

The Su values, obtained from triaxial compression tests (UU), are more appropriate with local / regional experiences. This study confirms how important it is to obtain parameters through laboratory and in situ tests with correlations suited to local/regional experiences.

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