Geotechnical characterization of a Recife soft clay – Laboratory and in-situ tests

Caractéristiques géotechniques d'une argile molle de Récife – Essais de laboratoire et en place

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ABSTRACT: This paper presents the results of an investigation of laboratory tests (characterization, compressibility, and, strength) and in situ tests (SPT, piezocone, and dilatometer) that were performed in one of the deposits of Recife soft clays (Brazil). Soil classification, stress history, in situ horizontal stress (K_0), compressibility parameters (e_0, C_C, C_S, M), and strength parameters (S_U and ϕ') will be presented, discussed, and analysed. The selected site is located near the center of the city in the area of the Clube Internacional. The soil profile consists of about 6-7 meters of a clayey sand underlain by an organic soft clay layer with a thickness of 20 meters, subdivided into 2 layers, with SPT values usually varying from 1 to 3. All laboratory and in situ tests were well performed and the results were satisfactorily good and, in general, they compared very well.

RESUME: Cet article présente les résultats d'éssais de laboratoire (caracterisation des sols, compressibilité, resistence) et in situ (SPT, piezocone, dilatométre) realizés avec les argiles moles de Recife (Brésil). La classification des sols, histoire des contraintes et la contrainte horizontale in situ (k_0), paramétres de compressibilité (e_0, C_C , C_S, M) et de resistence (Su, ϕ') sont présentées et analysées. L'endroit choisi est proche du centre de la ville de Recife. Le profil du sol est formé par 6-7 mètres de sables argileux sur une couche d'argile organique mole de 20 mètres d'épaisseur, avec des valeurs de SPT entre 1 et 3. Touts les éssais de laboratorie et in situ ont été bien éxécutés et les résultats sont bons et en général sont comparables.

1 INTRODUCTION

The presence of soft clay deposits usually require the evaluation of soil parameters to analyse the performance of the foundation in a geotechnical problem. Laboratory and in situ tests are usually used to obtain the soil properties. This paper presents results of a research project, developed in the Geotechnical Group of the Federal University of Pernambuco-Brazil, to study the soft soil deposits of the lowland area of Recife, creating a database to support foundation design. The results of the geotechnical parameters in relation to characterization, stress history, in situ horizontal stress, one-dimensional compression, and shear strength, obtained in a research site through laboratory and in situ tests (SPT, piezocone and Marchetti flat dilatometer) are presented, discussed, and analysed.

2 SITE DESCRIPTION AND CHARACTERIZATION

Recife is situated on the Northeastern coast of Brazil (Figure 1) and presents a plain formed in the Quaternary period with the influence of salt and fresh water. Soft clay and organic soil deposits are found in about fifty percent of the lowland area, more frequently in the sub-surface, formed in the Holocene period, having a maximum age of about 10,000 years. The land level is close to sea-level, thus the soft soil deposits, in general, are almost totally below the water table level.

The selected site (Recife research site 1) is located near the center of the city in the area of the Clube Internacional. The soil profile (Figure 2) consists of 6-7 meters of clayey sand / sandy clay, underlain by an organic soft clay with a thickness of about 20 meters, subdivided into two layers, with SPT (N-value) usually varying from 1-3. Underneath this, there are alternate layers of sand and clay where the SPT N-value increases with depth. The water table level is located in the range of 1-2 meters depending on the season. Sampling was done by means of a stainless steel thin-walled sampler ("shelby") 800 mm long, internal diameter of 101.6 mm, area ratio of 5%, and a clearance of 1.5%. Steps were taken to minimize the disturbance of the samples in the field and in the laboratory.

The results of the characterization tests were usually quite different for each soft clay layer (Figure 2). The plasticity index of the first soft layer (6-16 meters) presents values in the range of 70.4 ± 12.4%, while in the second soft layer (16-26 meters) the values are in the range of 33.0 ± 5.7%. The natural water content is usually presented slightly below the liquid limit in both layers, showing values in the range of 65-100% in layer 1 and in the range of 45-65% in layer 2. The organic content is also higher in layer 1 (7.0 ± 1.5%) than in layer 2 (3.7 ± 1.7%). The grain size distribution for both layers can be described as 65% clay, 25% silt, and 10% sand, with Kaolinite being the main clay mineral.

3 IN SITU TESTS

The piezocone and the Marchetti dilatometer testing procedures used, were in accordance with what was suggested in the literature (e.g. ASTM, 1986; Schmertmann, 1988; Campanella & Robertson, 1988). Both equipment were pushed into the ground at an approximate rate of 20 mm/s, using a CPT rig, with a capacity of 5-8 tons. The dilatometer was stopped every 200mm and pressure measurements were taken. The dissipation tests were performed at some depths using both equipment (CPTU and DMT). The piezocone and the dilatometer tests, performed in the Recife soft clays, represents a joint effort of the Geotechnical Groups of the UFPE, COPPE/UFRJ, and Geomecânica Ltd - Rio de Janeiro. All in situ tests were well performed and the results were satisfactorily good.

Typical results and parameters from the piezocone tests are shown in Figure 3. Due to unbalanced pore water pressure, correction was applied to the original recordings of cone resistance and sleeve friction, using the proposal of Lunne et al. (1985) and Konrad (1987). The three tests, that were performed, presented similar results with very good repeatability, identification of soil type, strattigraphy, and classification. Results of the dilatometer index parameters for the three tests performed are shown in Figure 4. They also presented a very good

Figure 1 - Location of Recife - Pernambuco / Brazil.

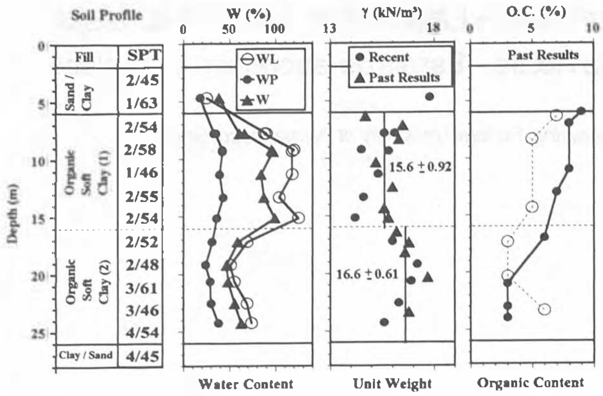

Figure 2 - Results of characterization tests vs Depth (Coutinho et al., 1993).

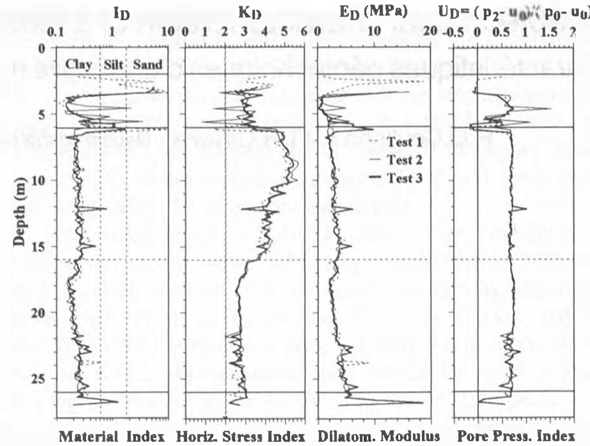

Figure 4 - Dilatometer tests results - I_D, K_D, E_D, U_D vs Depth

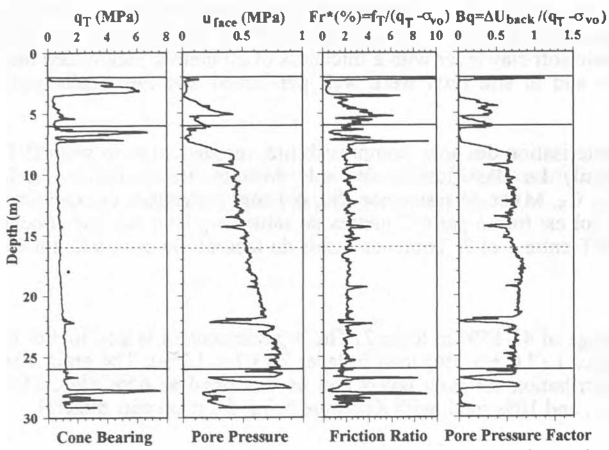

Figure 3 - Typical piezocone results - (Oliveira, 1991; Coutinho et al., 1993).

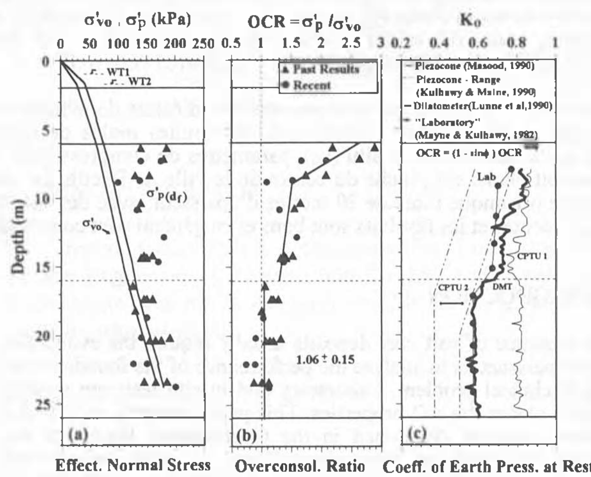

Figure 5 - Stress history and in situ horizontal stress parameters

repeatability and identification of soil type and classification (soft clay).

4 STRESS HISTORY AND IN SITU HORIZONTAL STRESS

The laboratory oedometer tests were performed in soil specimens with a diameter of 87mm, a height of 20mm, using a Bishop's type apparatus, with double drainage. Loads were doubled for each stage, beginning with 5-10 kPa until 1280 kPa and then decreased down to 10 kPa. Each stage usually lasted 24 hours. Figure 5(a and b) shows results of the effective overburden pressure, the preconsolidation stress σ'_P determined by Casagrande's method, and the values of the overconsolidation ratio, OCR. Layer 1 is slightly overconsolidated (OCR $\leq$ 2.5) and layer 2 is close to a normally consolidated state (OCR < 1.3). In some specimens from each soft layer, the preconsolidation stress σ'_P was also determined according to the deformation at the end of the primary consolidation ("d_{100}"), showing values higher by 3-26% (average 16%) than the values obtained conventionally, with the deformations measured at the end of the stage ("d_f"-Fig. 5a).

The results of σ'_P and OCR were also obtained from the piezocone and dilatometer tests through empirical correlations (Lunne et al., 1989; Kulhawy and Mayne, 1990). Table 1 shows all the results obtained from σ'_P and OCR in eight depths of the soft deposit. The volumetric strain for σ'_{VO} is also presented giving one idea of the quality of the soil specimens tested. In general, the results of OCR from both in situ tests' correlations are similar and in the same order than the range of laboratory results. The average result obtained by the piezocone through the Lunne et al. correlations seems to be the closest to the laboratory results. The differences between each piezocone estimation are a good index of the reliability of estimated OCR (Sugawara, 1988). Lunne et al. (1989) stated that the uncertainty in the OCR, determined by using the correlation from DMT to young clays, is about 30%.

In situ horizontal stress, σ_{ho} (or coefficient of earth pressure at rest, k_0) is an important geotechnical parameter but very difficult to get good measurements with any device. In general, there is an uncertain reliability, because of the scarcity of referent values (Lunne et al,1990). Values of K_0 were obtained using correlations from laboratory, dilatometer, and piezocone tests. The equations that were used are presented below:

a) Piezocone:

$K_0 = (1\text{-sen}\phi')\,(OCR)^{\text{sen}\phi'}$; $\phi' = f(f_S$ - CPTU) (Masood, 1990) (1)

$K_0 = 0.1Q = 0.1\,(q_T - \sigma_{VO})/\sigma'_{VO}$ (Kulhawy and Mayne, 1990) (2)

b) Dilatometer:

"young" clays - $K_0 = 0.34\,K_D^{\,0.54}$ (Lunne et al., 1990) (3)

c) Laboratory:

$K_0 = (1\text{-sen}\phi')\,(OCR)^{\text{sen}\phi'}$ (Mayne and Kulhawy, 1982) (4)

ϕ' - Table 2 - Amorim Jr. 1975; OCR - Table 1 (lab / average).

Figure 5(c) presents the average values of K_0 that were obtained for all correlations, showing that the DMT results were very close to the "laboratory" and that the K_0 values from piezocone are very dependent on the correlation used (see also Coutinho et al.,1993). Lunne et al. (1990) estimated that for the "young" clays the uncertainty associated with K_0 from DMT is about 20%.

Bezerra (1996) using a piezocone with two porous stones, found that the Sully & Campanella (1991) correlation [$K_O = 0.5 + 0.11\,(u_1 - u_2)/\sigma'_{VO}$] presented very close results to the dilatometer and laboratory values for the Recife soft clay.

5 ONE - DIMENSIONAL COMPRESSION

Typical curves of void ratio versus consolidation pressure from oedometer tests for both soft layers are shown in Figure 6. It can be seen that the "virgin" portion is not linear. This is consistent

Table 1. Results of OCR and σ'_p - Laboratory, Piezocone, and Dilatometer Tests

Layer	Depth	Laboratory		Piezocone (1)				Piezocone (2)			Piezocone		DMT (3)
		Average		OCR				σ'_p(kPa) / OCR *(a)			Average		OCR *(b)
		$\varepsilon_V / \sigma'_{vo}$	OCR	Lunne et al.(1989)				Kulhawy & Mayne(1990)			OCR		Average
	(m)	(d_{100})	d_f / d_{100}	Q	$\Delta u/\sigma'_{vo}$	Bq	F_r^*	Q	(q_T-σ_{vo})	Δu_{face}	(1)	(2)	
	8.0	2.7	1.88 / 2.18	2.11	1.00	3.00	1.00	2.12	160 / 2.19	92 / 1.25	1.78	1.85	2.03
1	9.2	3.7	1.50 / 1.74	2.12	1.38	1.93	1.00	2.13	174 / 2.20	158 / 2.00	1.61	2.11	2.07
	11.4	3.0	1.44 / 1.67	1.73	1.20	1.70	1.00	1.73	161 / 1.78	163 / 1.81	1.41	1.77	1.62
	13.4	5.6	1.38 / 1.60	1.52	1.00	1.73	1.00	1.51	157 / 1.56	155 / 1.54	1.31	1.54	1.58
	19.2	4.2	1.06 / 1.23	1.26	1.00	1.53	1.00	1.31	182 / 1.35	199 / 1.48	1.20	1.38	0.94
2	20.7	5.2	1.06 / 1.23	1.40	1.00	1.54	1.00	1.33	197 / 1.37	211 / 1.46	1.24	1.39	1.00
	22.6	6.0	1.06 / 1.23	1.52	1.00	1.74	1.00	1.56	249 / 1.60	243 / 1.56	1.32	1.57	1.00
	24.3	6.0	1.06 / 1.23	1.54	1.00	1.69	1.00	1.50	255 / 1.52	262 / 1.57	1.31	1.53	0.97

(*)Note: a) Piezocone (2): Kulhawy & Mayne, (1990) average of results: OCR = 0.32 x Q; $\sigma'_p = 0.33 \times (q_T - \sigma_{vo})$; $\sigma'_p = 0.47 \times \Delta u_{face}$
b) DMT (3): Lunne et al. (1989) average of results: OCR = $0.3 \times K_D^{1.17}$ (± 30%)

with findings in many other investigations (Coutinho & Lacerda, 1987; Mesri & Choi, 1985), and it seems to be universal. In this study, the virgin portion curve was simplified by two linear parts to obtain the compression index C_C (C_{C1} and C_{C2}).

Figure 7 shows the results obtained for the compressibility parameters: void ratio e_0, compression index C_{C1} (first part), and swell index C_S. They are basically constant in each soft layer but presenting higher values and a higher dispersion in layer 1. The average result of the compressibility index in layer 1 (C_{C1}=1.55), for instance, is twice the average result observed in layer 2 (C_{C1}= 0.75). In relation to the difference between the inclination of the two parts of the virgin curve, the results obtained were: layer 1 - $C_{C1} / C_{C2} = 2.08 \pm 0.41$; and layer 2 - $C_{C1} / C_{C2} = 1.15 \pm 0.13$, showing a higher non-linearity in the soft clay of layer 1.

Constrained tangent modulus values (M) correspondent to the in situ overburden stresses, were obtained from laboratory and dilatometer tests. The Marchetti (1980) correlation for clays (I_D < 0.6) was used:

$$M = R_M . E_D \text{ ; where } R_M = 0.14 + 2.36 \log K_D \quad (5)$$

The results (Figure 7) show a very reasonable agreement in the soft layer 2. In the soft layer 1, the DMT values were slightly higher than the oedometer results. Lunne et al. (1989) stated that for clays, at that time, it was recommended to use the Marchetti (1980) correlation. Marchetti (1997) concluded that the comparisons both in terms of M_{DMT} - $M_{reference}$ or in terms of predicted vs measured settlements are very encouraging in the use of the correlation M - E_D.

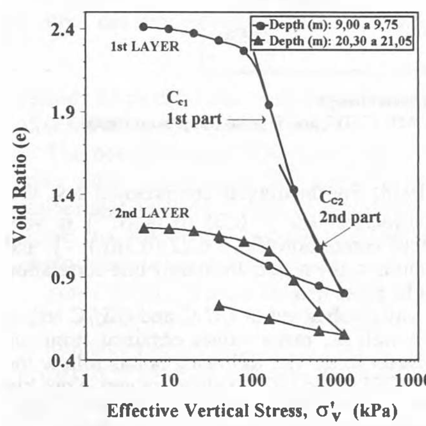

Figure 6 - Typical e vs Log σ'_v curves - oedometer tests.

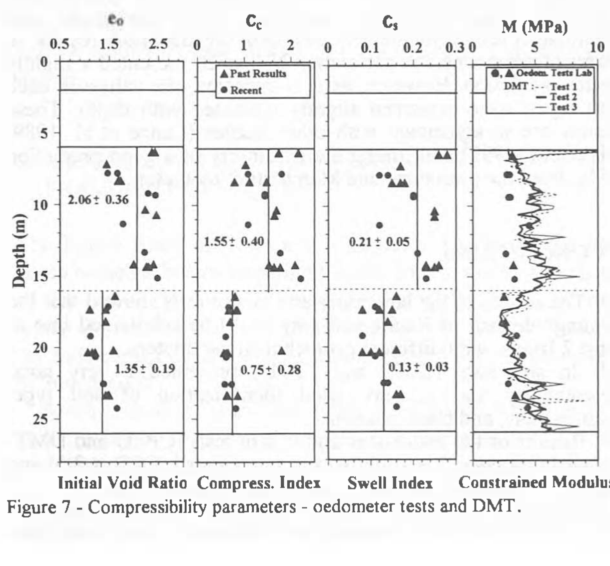

Figure 7 - Compressibility parameters - oedometer tests and DMT.

6 SHEAR STRENGTH

The laboratory shear strength parameters were obtained through UU-C and CIU-C triaxial tests, using Wikeham Farrance type equipment, with specimens of 37.5 mm in diameter and 80 mm long (see Coutinho & Lacerda, 1989). The shear strength parameters, in drained (ϕ') and undrained conditions (S_U), were also obtained from piezocone and dilatometer tests. The S_U empirical correlations used for both in situ tests are referenced to the triaxial compression test.

Table 2 shows the results of the effective friction angle ϕ' obtained from the triaxial CIU-C tests, and from the piezocone tests using Senneset & Janbu (1984) and Lunne et al. (1985) methods. No one piezocone method alone presented good results. The average result, considering both piezocone methods, is reasonably close to the laboratory results; however, the uncertainty is very high. There is also some difference in the laboratory results from the two studies performed.Campanella & Robertson (1988) concluded that reliable estimates of ϕ' of clays can not be made from the results of undrained CPTU penetration.

The cone resistance is related to undrained shear strength by the cone factor $N_{KT} = (q_T - \sigma_{VO})/S_U$, despite theoretical advances, empirical correlation is still the most commonly used for the interpretation of piezocone tests. In this study, the empirical correlation proposal by Lacasse (1988) - N_{KT} vs IP, and the correlation proposal by Lunne et al. (1985) - $N_{\Delta U}$ vs B_q, where $S_U = \Delta U/N_{\Delta U}$ were used. Due to the high plasticity of the soft clay in layer 1, a graphical extrapolation of the Lacasse (1988) correlation was necessary.

The interpretation of dilatometer results was done in this study using the empirical correlations proposal by Marchetti (1980) and

Table 2. Results of φ' - Laboratory and Piezocone Tests

Layer	Depth (m)	φ (°) Piezocone Senneset and Janbu(1984)	Lunne et al.(1985)	φ' (°) triaxial CIU - C Coutinho et al (1993)	Amorim Jr. (1975)
1	7-16	25 - 33	18-23	26	25
2	16-26	31 - 33	24-27	23	28

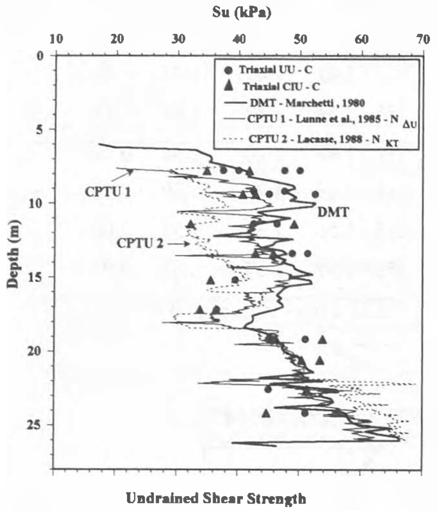

Figure 8 - S_U vs Depth - DMT, CPTU, and Triaxial compression tests

Lacasse & Lunne (1988). For the triaxial compression test, the Lacasse & Lunne correlation [S_U = 0.20 $(0.5K_D)^{1.25}$] is very similar to the Marchetti correlation [S_U = 0.22 $(0.5K_D)^{1.25}$]; and for limited space conditions, the results from only one correlation (Marchetti,1980) will be presented.

Figure 8 shows S_U values obtained in UU-C and CIU-C ($\sigma'_c \cong \sigma'_{oct}$ in situ) tests; as well as, mean values obtained from the piezocone and dilatometer tests. The following points follow the analysis of the data: 1) CIU-C and UU-C values are very close but present some dispersion (see Coutinho & Lacerda,1989 for more discussions). 2) the mean laboratory results are basically constant with depth and present different values in each soft layer (layer 1 - S_U = 42 ± 5.4 kPa); layer 2 - S_U = 49.2 ± 4.5 kPa); 3) the results obtained using empirical correlations from piezocone and dilatometer tests compare very well with the laboratory results. In terms of piezocone, the correlation $N_{\Delta U}$ vs B_q presented a slightly better prediction. However, as it is expected, the values in each soft layer, were presented slightly increased with depth. These results are in agreement with other studies (Lunne et al. 1989; Marchetti, 1997) confirming the possibility of a good prediction of S_U from the piezocone and Marchetti dilatometer.

7 CONCLUSIONS

1. The results of the laboratory and in situ tests showed that the "young" deposit of Recife soft clay could be subdivided into at least 2 layers, with different geotechnical parameters.
2. In situ tests (DMT and CPTU) presented a very good repeatability and as very good identification of soil type, strattigraphy, and classification.
3. Results of the oedometer and in situ tests (CPTU and DMT) showed that layer 1 is slightly overconsolidated (OCR ≤ 2.5) and layer 2 is basically normally consolidated (OCR < 1.3).
4. The values of K_O, that were obtained, showed that the DMT results were relatively close to the "laboratory" results and that the K_O values from CPTU are very dependent on the correlation used.
5. The average result of the compression index in layer 1 (C_{C1} = 1.55) is twice the average result observed in layer 2 (C_{C2} = 0.75). Constrained tangent modulus values (M) were obtained from laboratory and DMT tests. The results especially show a reasonable agreement in the soft layer 2.
6. With relation to undrained shear strength, the results obtained using empirical correlations from CPTU and DMT, compare very well with the laboratory results.

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