Geotechnical properties of Brazilian marine clays

Propriétés géotechniques des argiles marines brésiliennes

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ABSTRACT
This paper presents the main results obtained from an extensive laboratory investigation on Brazilian marine clays. Samples were collected from different depths in eight petroleum fields (Marlim, Marlim Leste, Marlim Sul, Espadarte, Jabuti, Jubarte, Cachalote and Roncador) located in Campos basin and one petroleum field (Piranema) located in Sergipe - Alagoas basin, offshore Brazil. Grain size analyses, Atterberg limits, oedometer tests, isotropically consolidated undrained compression (CIUC) and K_0-consolidated undrained compression (CK_0UC) triaxial tests, direct simple shear (DSS) and resonant column tests were carried out in samples from 56 cores. Moreover, in some of CIUC triaxial tests, maximum shear moduli (G_{max}) were determined by using bender elements inserted into the specimens. The SHANSEP technique was used in the investigation to study the undrained behavior of the marine clays. A summary of the main characteristics of compressibility, deformability and undrained strength (s_u) of the soils investigated is presented. Finally, a correlation between G_{max} values obtained with bender elements and s_u from CIUC tests is shown in the paper.

RÉSUMÉ
Cet article présente des principaux résultats obtenus d'une large investigation de laboratoire sur des argiles marines brésiliennes. Des échantillons ont été extraits de différentes profondeurs dans huit champs de pétrole Marlim Leste, Marlim Sul, Espadarte, Jabuti, Jubarte, Cachalote, Roncador et Marlim) localisés dans le Bassin Campos et un champ de pétrole (Piranema) localisé à Sergipe – Bassin Alagoas (Brésil). L'analyse granulométrique, limites d'Atterberg, essais de consolidation, essais de compression triaxiale isotropiquement consolidés et non drainés (CIUC), essais de compression triaxiale K_0 (CK_0UC) et essais de cisaillement simple direct (DSS), essais à la colonne résonnante ont été effectués sur 56 différents échantillons. En plus, dans quelques essais triaxiaux CIUC, le module de cisaillement maximum (G_{max}) a été déterminé par l'usage d'éléments fléchissants insérés dans les éprouvettes. La technique SHANSEP a été utilisée dans l'investigation pour l'étude du comportement non drainé des argiles marines. Un résumé des caractéristiques de compressibilité, déformabilité et résistance non drainée (s_u) des sols examinés est présenté. Finalement, une corrélation entre valeurs de G_{max} obtenus par des éléments fléchissants et s_u obtenus des essais CIUC est présentée dans cet article.

Keywords : marine Brazilian clays, undrained shear strength, soil compressibility, maximum shear modulus

1 INTRODUCTION

The oil industry in Brazil is in large expansion, boosted by its recently discovered deepwater fields. As a result, every effort has been made to provide the necessary geotechnical knowledge of the marine subsoil, so that the offshore structures can be constructed and the fields can start producing. With this aim, an extensive laboratory investigation on the geotechnical properties of Brazilian marine clays has been developed and part of the results is presented in this paper.

Samples were collected in a total of 56 cores from eight petroleum fields (Roncador, Marlim, Marlim Sul, Marlim Leste, Jubarte, Cachalote, Espadarte and Jabuti) located in Campos basin and one petroleum field (Piranema) located in Sergipe - Alagoas basin, offshore Brazil. The locations of the petroleum fields are presented in Figure 1. As shown in Table 1, the water depth in these fields varies from 600 to 2000 m. Table 1 also shows the number of cores and the depth sampled in each field. In Roncador and Marlim fields, the samples were collected with Kullemberg corers, while in the remaining fields Jumbo Piston Corers were used. It is impossible not to recognize the enormous difficulty in collecting undisturbed samples in so deep seabed and that an inevitable disturbance should be occurred.

Grain size analyses, Atterberg limits, oedometer tests, isotropically consolidated undrained compression (CIUC) and K_0-consolidated undrained compression (CK_0UC) triaxial tests, direct simple shear and resonant column tests were carried out. Moreover, in some CIUC triaxial tests, maximum shear moduli (G_{max}) were determined by using bender elements inserted into the specimens.

2 SOIL CHARACTERIZATION

The range of the index parameters of the soils from the nine fields investigated is presented in Table 2. As it can be seen, there are several types of soils with void ratios varying from 0.90 to 4.2, plasticity index from 5 to 70% and clay fraction from 5 to 80%.

Table 1. Identification of the petroleum fields.

Field	number of cores	depth sampled (m)	water depth (m)
Marlim Leste	8	4 to12	940 to 1350
Marlim Sul	6	12 to 19	1590 to 1970
Espadarte	3	8 to 16	1260 to 1610
Jabuti	9	2 to 5	1100 to 1250
Jubarte	6	18 to 20	1170 to 1440
Cachalote	2	17 to 19	1370 to 1500
Piranema	7	3 to 21	1230 to 1670
Roncador	10	3 to 5	1500 to 2000
Marlim	5	3 to 5	600 to 1000

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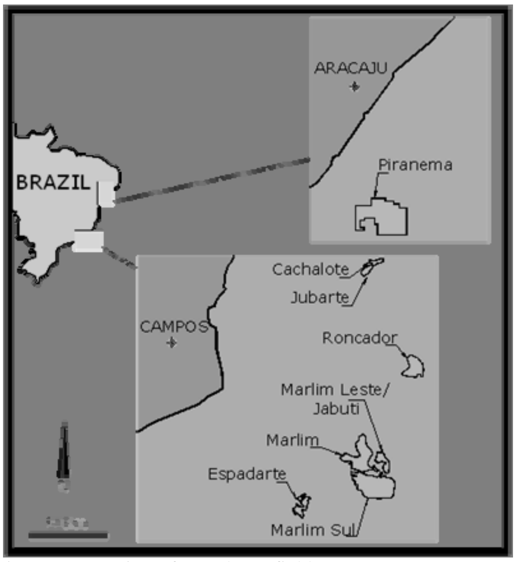

Figure 1. Location of petroleum fields.

Table 2. Index parameters.

Field	γ (kN/m^3)	w (%)	e	LL (%)	PI (%)	Clay fraction (%)
Marlim Leste	14.29	30.8	0.90	35	15	24
	18.65	96.1	2.81	94	62	63
Marlim Sul	13.64	54.6	1.57	58	28	43
	16.50	122	3.56	107	70	70
Espadarte	13.01	50.2	1.37	48	19	45
	16.86	151	4.20	97	65	67
Jabuti	13.50	43.6	1.21	28	5	5
	17.38	90.2	2.61	72	43	50
Jubarte	13.68	39.1	1,25	55	28	9
	16.91	121	3.41	108	66	68
Cachalote	13.98	71.6	2.03	65	32	6
	15.40	112	3.10	96	58	69
Piranema	13.34	31.7	0.88	28	10	15
	18.37	120	3.46	91	58	80
Roncador	14.21	77.7	2.09	46	23	32
	15.46	105	2.86	83	51	55
Marlim	15.48	64.4	1.81	54	23	37
	18.04	71.7	1.97	68	37	43

Note: The minimum and maximum values of each parameter are indicated in the table.

The position of the soils in the plasticity chart is shown in Figure 2. It is well-known that the "A" line equation is PI = 0.73(LL-20). Nagaraj and Jayadeva (1983) obtained the correlation PI = 0.74(LL-8) for organic clays. Almeida et al. (2008), in a study on Rio de Janeiro soft clays, obtained for the majority of the soils analyzed results that were well fitted by "A" line. For the set of 463 samples analyzed in this investigation, the correlation obtained was:

$$PI = 0.74(LL - 17) \tag{1}$$

with a coefficient of determination (R^2) of 0.91.

With regard to the activity index, the soil from Piranema Field presents a different behavior in comparison with the data set. For this reason, the results are presented separately (Figures 3 and 4). The activity index for Piranema soil is about 0.65 (inactive) and for the remaining fields is about 0.82 (normal activity).

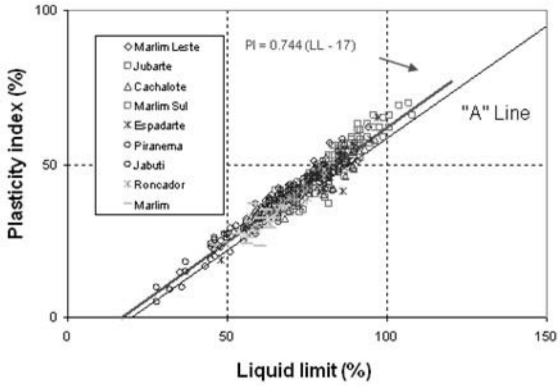

Figure 2. Position of Brazilian marine soils in the Plasticity Chart.

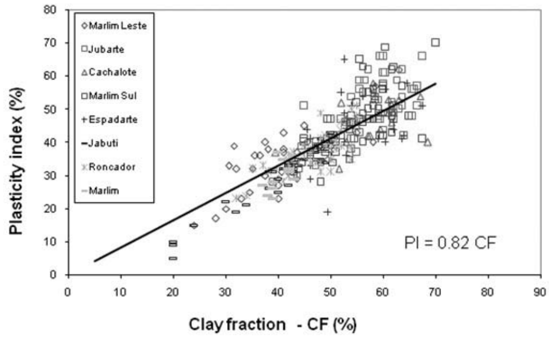

Figure 3. Plasticity index as a function of clay fraction – all fields with exception of Piranema

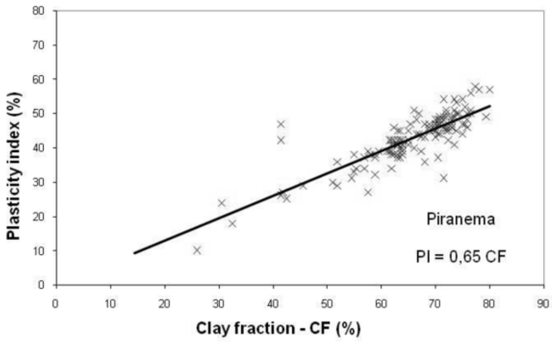

Figure 4. Plasticity index as a function of clay fraction – Piranema Field.

3 COMPRESSIBILITY AND STRESS HISTORY

A total of 165 oedometer tests were performed on the soils analyzed. Table 3 shows values of compression index (C_c), swelling index (C_e), compression ratio (CR = C_c / (1+e_0)) and overconsolidation ratio (OCR).

As shown in Table 3, CR values vary from 0.16 to 0.39. It was observed that CR has the tendency to increase with the liquid limit (CR = 0.0035LL). The OCR values are in general smaller than 2 but in three fields higher values are also observed: Marlim Leste, Marlim Sul and Espadarte.

The obtained average value of C_e/C_c is 0.14. Marlim Leste, Piranema and Jabuti fields present the highest average values (0.16 to 0.18) whereas Roncador and Marlim fields present the smallest ones (0.10 to 0.12).

Table 3. Parameters of compressibility.

Field	C_c	C_e	CR	OCR
Marlim Leste	0.34 1.2	0.06 0.15	0.16 0.37	< 5
Marlim Sul	0.53 1.20	0.08 0.20	0.20 0.36	< 5
Espadarte	0.7 1.06	0.09 0.16	0.20 0.33	< 3
Jabuti	0.66	0.12	0.23	~ 1
Jubarte	0.56 1.17	0.08 0.20	0.19 0.37	< 2
Cachalote	0.6 1.07	0.08 0.14	0.20 0.30	~ 1
Piranema	0.41 1.31	0.06 0.20	0.18 0.39	< 2
Roncador	0.67 1.26	0.07 0.17	0.21 0.34	< 2
Marlim	0.62 0.7	0.05 0.08	0.22 0.24	< 2

Note: The minimum and maximum values of each parameter are indicated in the table.

Figure 5 shows the relationship between compression index and water content. This correlation presented a better fit than the usual correlation between C_c and LL. The correlation found is:

$$C_c = 0.0106w \tag{2}$$

which is very similar to those presented by Koppula (1981) and Bowles (1979). Almeida et al. (2008) and Coutinho et al. (2000) presented correlations between C_c and w for Rio de Janeiro and Recife soft clays, respectively, that result in a little higher C_c values.

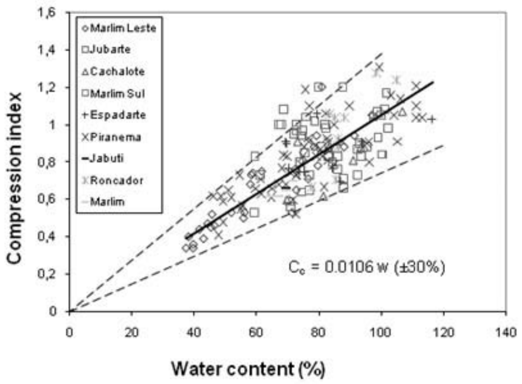

Figure 5. Compression index and water content relationship.

4 MAXIMUM SHEAR MODULUS

A correlation was determined between G_{max}, void ratio at the end of primary consolidation (e) and confining stress (σ_0), valid for the normally consolidated condition. For this purpose 80 tests on soils from eleven cores of Marlim Leste, Marlim Sul e Jubarte were considered (40 G_{max} values obtained from resonant column tests and 40 G_{max} values obtained from bender elements). The following expression was determined:

$$G_{max} = 1.83\sigma_0^{0.62} e^{-0.83} \tag{3}$$

where σ_0 is in kPa and G_{max} in MPa (see also Barros et al., 2008). The R^2 coefficient of expression (2) is equal to 0.87.

Figure 6 shows a comparison between expression (3) and the well-known expression of Kokusho et al. (1982):

$$G_{max} = 14.2\frac{(7.32-e)^2}{1+e} p_a^{0.4}\sigma_0^{0.6} \tag{4}$$

where p_a is the atmospheric pressure. Expression (4) was obtained for normally consolidated alluvial clays with void ratios varying from 1.4 to 4. As can be noticed, the expression obtained in the present investigation leads to greater values of G_{max} (approximately 30%).

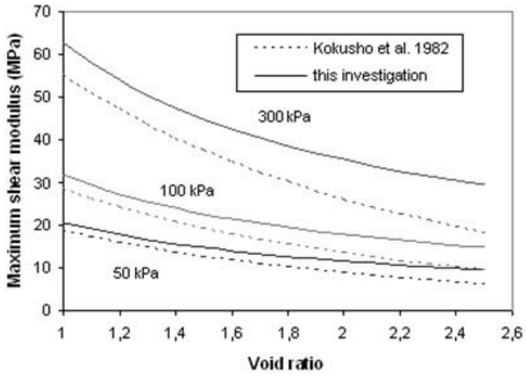

Figure 6. Comparison between expressions (3) and (4) for three different confining stresses.

5 SHEAR STRENGTH

5.1 *The use of SHANSEP technique*

Three cores, two from Roncador field and one from Marlim field, were selected to verify the applicability of the SHANSEP technique (Ladd and Foott, 1974) for Brazilian marine clays.

The results are presented in Table 4. The n value in the expression $s_u/\sigma'_{vo}=A(OCR)^n$ varied from 0.69 to 1.02. In Table 4, the expressions are presented setting n=0.8, which is the typical value found in the literature.

Table 4. Correlations obtained for s_u/σ'_{vo} (Barros et al., 2006).

Field	Cores	Test	Correlation
Roncador	K04A	CK_0UC DSS	$s_u/\sigma'_{vo}=0.356(OCR)^{0.8}$ $s_u/\sigma'_{vo}=0.304(OCR)^{0.8}$
Roncador	K05	CK_0UC DSS	$s_u/\sigma'_{vo}=0.320(OCR)^{0.8}$ $s_u/\sigma'_{vo}=0.278(OCR)^{0.8}$
Marlim	03	CK_0UC DSS	$s_u/\sigma'_{vo}=0.381(OCR)^{0.8}$ $s_u/\sigma'_{vo}=0.325(OCR)^{0.8}$

5.2 *Undrained shear strength for normally consolidated condition*

For Marlim Sul, Marlim Leste, Jubarte, Cachalote, Espadarte and Piranema fields, CIUC, CK_0UC and direct simple shear (DSS) tests were carried out with effective vertical stresses higher than the preconsolidation stress, in order to evaluate the ratio s_u/σ'_{vo} for the normally consolidated condition. Table 5 shows the mean values of s_u/σ'_{vo} obtained in each type of test.

With regard to the s_u/σ'_{vo} values from CK_0UC tests, it can be seen that the average value, 0.311, is close to the value 0.32 indicated by Ladd (1991). However, for the DSS tests the values obtained in this investigation (average of 0.29) are considerably higher than that suggested by Ladd (0.22 to 0.27).

It is important to mention that while in the DSS test the deformation rate was that recommended by Ladd and Foott

(1974) (5% / hour), in the CIUC and CK_0UC triaxial tests, the deformation rate was 8%/hour, about ten times that indicated by Ladd and Foott (0.5 a 1.0 % / hour).

It can be estimated that the s_u/σ'_{vo} values from CIUC and CK_0UC tests obtained in this investigation should be reduced in 4 to 8% (Chandler, 1988 & Bjerrum, 1973) in order to be compared with data from literature.

If this correction is done, the s_u/σ'_{vo} values from CK_0UC and DSS tests become very close. These results suggest that the investigated Brazilian marine clays present a very small degree of anisotropy.

Table 5 - s_u/σ'_{vo} values for normally consolidated condition

Field	CIUC	CK_0UC	DSS
Marlim Leste	--	0.33 (10)	0.33 (9)
Marlim Sul	0.41 (14)	0.31 (9)	0.30 (16)
Espadarte	0.39 (12)	0.33 (5)	0.29 (4)
Jubarte	0.37 (41)	0.31 (16)	0.28 (15)
Cachalote	0.40 (10)	0.32 (4)	0.28 (4)
Piranema	0.34 (109)	0.30 (24)	0.29 (96)

Note: the number in parentheses indicates the totality of tests.

5.3 *Relationship between G_{max} and s_u*

In an attempt to determine a correlation between G_{max} and s_u, G_{max} values were obtained from bender elements in 60 CIUC tests performed in normally consolidated conditions on soils from 19 cores of Marlim Leste, Marlim Sul, Jubarte, Cachalote and Espadarte fields.

Figure 7 shows the relationship between G_{max} and s_u. The correlation found is:

$$G_{\max} = 573 s_u \tag{5}$$

with a R^2 coefficient equal to 0.83.

Several correlations between G_{max} and s_u are presented in the technical literature. However, it is difficult to compare the results here obtained with others, since different ways of determining both s_u and G_{max} are usually employed.

Expression (5) is similar to the one obtained by Arango *et al.* (1978) in tests on different types of soils, varying from low compressibility silts to high compressibility clays: G_{max}= 813s_u. They determined the undrained strength, s_u, from triaxial CIUC tests, but obtained G_{max} from *in situ* tests. The greater value of the ratio G_{max}/s_u obtained by them can be explained by the fact that they determined G_{max} *in situ*, what usually results in values greater than the ones determined in laboratory.

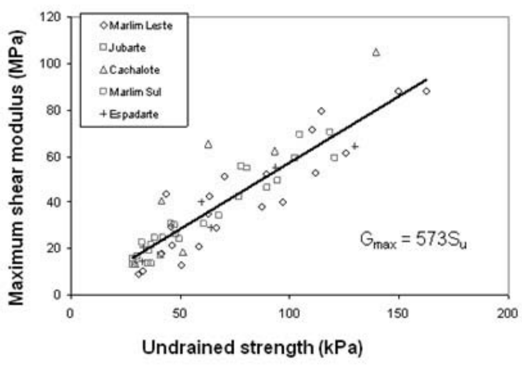

Figure 7. Maximum shear modulus and undrained strength relationship.

6 CONCLUSIONS

This paper presented the results of an extensive laboratory investigation on the behavior of Brazilian marine clays. The main conclusions are:

- these soils show a large variability of void ratios (0.9 to 4.2), plasticity indexes (5 to 70%) and clay fractions (5 to 80%).
- the mean line that indicates the position of these soils in the plasticity chart lies slightly above and is parallel to the “A” line.
- the activity index of these soils is about 0.82 (normal activity) with exception of Piranema field, which is approximately 0.65 (inactive).
- the OCR values are in general smaller than 2, but in three fields there are higher values.
- the relationship between C_c and water content obtained is very similar to those found in the literature.
- it was possible to establish a correlation of G_{max} with confining pressure and void ratio for the normally consolidated condition.
- the very similar s_u/σ'_{vo} values from CK_0UC and DSS tests obtained ins this investigation suggest that Brazilian marine clays present a very small degree of anisotropy.
- it was possible to establish a correlation of G_{max} with the undrained strength obtained in CIUC test.

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