Laboratory Behaviour of Rio de Janeiro Soft Clays. Part 2: Strength and Yield

Marcos Massao Futai, Márcio de Souza Soares de Almeida, Willy Alvarenga Lacerda

Abstract. This paper summarizes the yield and strength behaviour of clays studied in the State of Rio de Janeiro in the last forty years, with emphasis on the role of the clay structure on strength and yield. The undrained strength normalised by the overconsolidation stress is analyzed against the plasticity index I_p. Values of the clay friction angle ϕ' are also analyzed against the plasticity index I_p. Both data are compared with the available literature data, but the Rio de Janeiro clays have higher I_p and also show more data scatter. As far as yield is concerned, it is shown that the use of the SHANSEP method results in the destruction of the clay structure with the loss of its anisotropic characteristics. An evaluation of the level of structure destruction is presented.

Key words: properties of sedimentary clays, laboratory tests, Rio de Janeiro soft clays.

1. Introduction

The sedimentary deposits found in the coastal plains of the Rio de Janeiro State consist mostly of alluvia and marine deposits of the Quaternary Age. A number of soft clays deposits have been studied in the last 30 years in the City of Rio de Janeiro (Botafogo and Uruguaiana, Barra da Tijuca, Caju and St. Cruz) and vicinity (Fluminense Plains, Sarapuí, Itaipu and Juturnaíba dam), in association with some engineering works. In some of these deposits it was possible to perform research projects, by means of master or doctoral studies which generated a good quality data bank. Using this data bank, Almeida *et al.* (2008) summarized index and compression properties of well studied Rio de Janeiro sedimentary clay deposits in the last four decades. This paper complements this study and presents strength and yield behaviour of these clays. Emphasis is given to the role of the clay structure on both strength and yield. Table 1 summarizes the main geotechnical properties of the clays analyzed in the present paper, with emphasis on strength properties. Additional information on these clays may be obtained on Almeida *et al.* (2008).

2. Strength

2.1. The sample quality

It is initially useful to analyse the relationship between the undrained strength and the specimen diameter. Figure 1 shows the variation of undrained strength S_u of Sarapuí clay measured (Ortigão, 1980) by unconsolidated undrained triaxial UU tests normalised by S_{uref}, which is the undrained strength of UU tests carried out on the reference 127 mm diameter samples. The average values of S_u/S_{uref}, increase with a D_1/D_2 ratio expressed by:

$$\frac{\dfrac{D_{sh}}{D_{ts}}}{\dfrac{D_{shref}}{D_{sh}}} = \frac{D_1}{D_2} \qquad (1)$$

where D_{sh} = shelby diameter; D_{shref} = reference shelby diameter (in this case, 127 mm) and D_{ts} = test specimen diameter.

The quality of test data depends on sampler diameter relationship (relation between the diameter of the shelby sampler used and the diameter of the reference shelby sampler) and also on the specimen diameter relationship (relation between the diameter of the sampler and the diameter

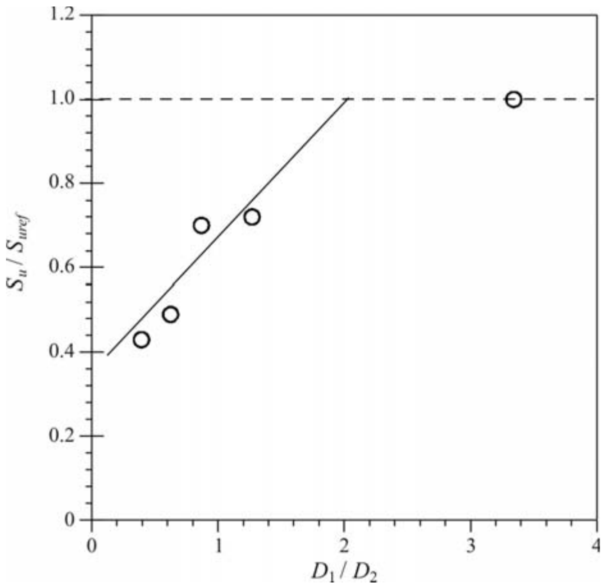

Figure 1 - Variation of S_u/S_{ust} with D_1/D_2 (Futai, 1999).

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Table 1 - Geotechnical properties of Rio de Janeiro clays.

Parameter/clay	Caju (b)	Sarapuí (c)	Itaipú (g)	Juturnaíba (h)	Uruguaiana (i)	Botafogo (j)	Barra da Tijuca (k)
References	Lira (1988); Cunha & Lacerda (1991)	Lacerda *et al.* (1977); Ortigão (1980); Almeida & Marques (2002)	Carvalho (1980); Sandroni *et al.* (1984)	Coutinho & Lacerda (1987)	Vilela (1976)	Lins & Lacerda (1980)	Almeida *et al.* (2000)
w (%)	88	143 ± 21.7	240 ± 110	154 ± 95.6	54.8 ± 15.9	35	100-500
I_P (%)	67.5	73.08 ± 16.1	74.5 ± 30.1	63.59 ± 22.1	40.5 ± 22.03	11	120-250
g (kN/m^3)	14.81	13.1 ± 0,49	12 ± 1,85	12.5 ± 1.87	16.1 ± 1.39	17.04	12.5
S_t	3	2,59 ± 0,69	4-6	5-10	3.00	-	5.0
% organic matter	-	4.13 - 5.54	32.63 ± 20.46	19 ± 10.63	2.56 ± 1.04	-	-
S_u (UU) (kPa)	6-12	8.64 ± 3.26	7.5 ± 3.53	18.7 ± 5.43	70.9 ± 25.1	20-90	15.5 ± 6
S_u vane (kPa)	-	8-20		6-30	-	70-110	6-30
S_u/σ'_{vm} (UU)		0.35	0.49	0.34	0.33	0.30	0.42
φ' (degrees)	27	25-30	21-65	25-65	34 ± 5	28	40
E_u/σ'_{v0} (UU)	171.5 ± 119	101 ± 154	59.7 ± 34.5	21 ± 0.16	40.4 ± 34.9	234 ± 123(CIU)	-
E_u/S_u	403.5 ± 47	129.7 ± 69.1	33.7 ± 12.1	101.7 ± 87.9	69.6 ± 29	292 ± 117(CIU)	-
e_o	2.38	3.71 ± 0.57	6.72 ± 3.1	3.74 ± 1.89	1.42 ± 0.36	1.1	-

of the test specimen). For higher D_{sh}/D_{ts} ratio, the specimen will be far enough from the sample edges, thus clay structure disturbance due to sample insertion is lower. Even though there is few data, the analysis of Sarapuí clay data suggests that D_1/D_2 values were equal or higher than 2. The test specimen diameter, therefore, should be less than:

$$D_{ts} = \frac{D_{sh}^2}{254} \tag{2}$$

Substituting in Eq. (2) the more commonly used 4" shelby tube D_{sh} = 100 mm, it is concluded that a test specimen with a 38 mm diameter should be adopted. As this is the minimum test specimen adopted in triaxial tests, it is also concluded that the sampler must have diameters equal or higher than 100 mm, as recommended in the Brazilian Code of Practice for soil sampling (NBR 9820, 1997). This finding is valid for the standard specimen preparation procedure of sample extrusion from the shelby used for the present data analysis (Ortigão, 1980).

More recently a new procedure of sample preparation has been proposed (Ladd & De Groot, 2003) which is in increasing acceptance (Sandroni, 2006) and does not involve sample extrusion from the shelby. Therefore the above finding may not be valid if this procedure is used and further studies are necessary. The Soil Mechanics Laboratories of USP (LMS-EPUSP) and COPPE-UFRJ have used the Ladd and De Groot (2003) proposed procedure.

This finding is restricted to homogeneous non-fissured clays. For fissured clays, the sample should be large enough to include a representative number of fissures. Thus, a small sample is usually not representative.

2.2. The influence of the stress level on the natural clay structure

The influence of high stresses on the structure and anisotropy of clays will be further illustrated at this point. For this purpose, data of CIU triaxial tests, more easily available than CK$_o$U triaxial tests, will be used together with the clay structure disturbance index (Futai, 1999), ID, defined by:

$$ID = \frac{\sigma'_c}{\sigma'_{cm}} \tag{3}$$

in which σ'_c is the confining stress applied to the triaxial specimen and σ'_{cm} is the isotropic overconsolidation pressure.

Figure 2 presents the variation of the normalised deviator stress $q/M\sigma'_c$ with ID for four clays, where q and M are respectively the deviator stress and the slope of the critical state line as used by Atkinson & Bransby (1978). Generally the structure disturbance index is defined as the relationship between the maximum confining stress and the isotropic overonsolidation pressure. However in this analysis, due to the lack of data of isotropic overconsolidation pressure, the overconsolidation pressures obtained after oedometer tests were used. Since the relationship between isotropic and oedometric overconsolidation pressure for natural clays varies in the range of 0.44 to 0.66 (Díaz-Rodriguez *et al.*, 1992), depending on the friction angle, the ratio between the ID presented in Fig. 2 and ID of Eq. (3) lies also in this range.

For higher ID, thus lower $q_f/M\sigma'_c$ ratios, structure disturbance is caused by isotropic consolidation with a loss of strength, associated to the loss of anisotropy. For ID lower than 1, the soil is at an overconsolidated state, where structure is very important.

Figure 2a presents the variation in $q/M\sigma'_c$ for Juturnaíba clay. The value of $q/M\sigma'_c$ decreases rapidly for ID smaller than 1, and then it gets about constant. Figure 2b shows a similar behaviour for other Rio de Janeiro clays.

The conclusion that may be taken from Fig. 2 is that when these clays are consolidated to about three times the overconsolidation pressure, there is a tendency for $q_f/M\sigma'_c$ to become constant. After this stress level is achieved, the clay structure is destroyed.

The interpretation and meaning of ID is illustrated in Fig. 3, in which the deviator stress normalised by the confining stress is plotted against ID. A low value of ID means that the soil is at an overconsolidated state, while a very high ID value is associated to a normally consolidated state of the soil. The strengths at points A and B represent the natural condition and remoulded strengths, respectively. Soil sensitivity can be related to the ID value. The strength of a sensitive soil drops from A to B, with small variations of axial deformation, indicating that soils with lower ID value presents higher sensitivity.

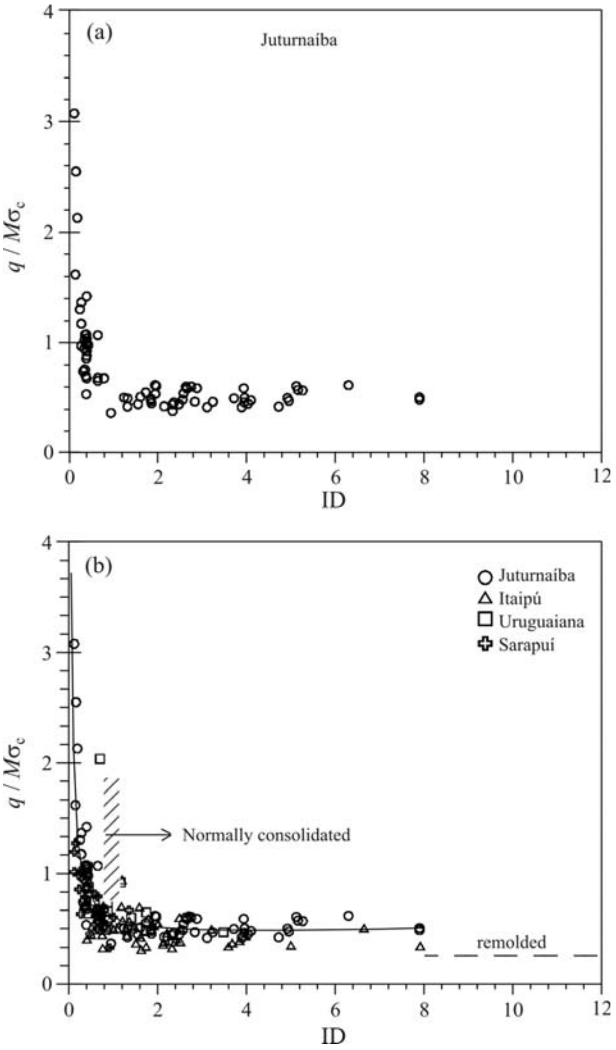

Figure 2 - Influence of structure and anisotropy on undrained behaviour of Rio de Janeiro clays (Futai, 1999).

2.3. Undrained strength

The normalised undrained strength (S_u/σ'_{vm}, laboratory data, where σ'_{vm} is the overconsolidation pressure)

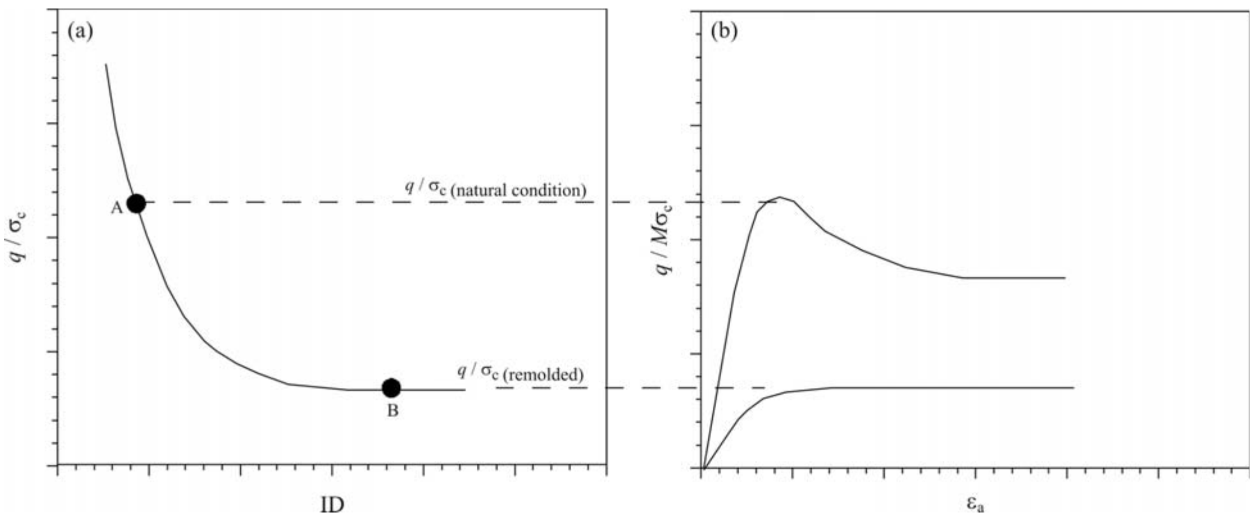

Figure 3 - Interpretation of ID parameter (Futai, 1999).

variation with plasticity index (I_P) for Rio de Janeiro clays is shown in Fig. 4, together with data from Eastern Canadian clays (Leroueil *et al.*, 1983; Marques *et al.*, 2004). The range of I_P for the Rio de Janeiro clay is higher than that of Canadian clays and because of scatter of the data a good fit is not easily obtained. Some of the of S_u/σ'_{vm} values for Rio de Janeiro clays are higher than the proposed relationship, which can be explained by sampling quality, since lower S_u/σ'_{vm} values reflect a higher quality of sampling with the increase of σ'_{vm}. In any case, it may be observed a trend of the increase of S_u/σ'_{vm} with I_P.

2.4. Drained strength

Kenney (1959) obtained a relationship between clay friction angle (ϕ') and I_P and concluded that ϕ' decreases with I_P. Rio de Janeiro clays present this behavior just for I_P less than 40%. However, for values of plasticity index greater than 40% a significant scatter can be observed, as shown in Fig. 5, since ϕ' can be higher due to influence of fibres in the organic matter. Pinto (1992) also presented similar results for other Brazilian clays. Coutinho & Lacerda (1987) and Mitchell and Coutinho (1991) showed that the friction angle increases with organic matter content.

3. Yield

Yield curves obtained from CIU triaxial tests performed on Sarapuí (Ortigão, 1980) and Botafogo (Lins & Lacerda, 1980) clays are shown in Fig. 6. In these tests the natural clay structure was destroyed because of the application of stresses up to eight times the overconsolidation stresses, in a procedure similar to the SHANSEP (Ladd & Foot, 1974) method. In this figure *q* and *p*' are respectively the deviator stress and the average effective stress as used in the Critical State Theory. These variables are normalized against p'_e the Hvorslev equivalent pressure (Atkinson & Bransby, 1978) and *M*, the slope of the critical state line. As a result of high isotropic consolidation stresses have been applied, which destroyed the natural clay structure, the yield envelope is centred in the hydrostatic axis. This point is further discussed below.

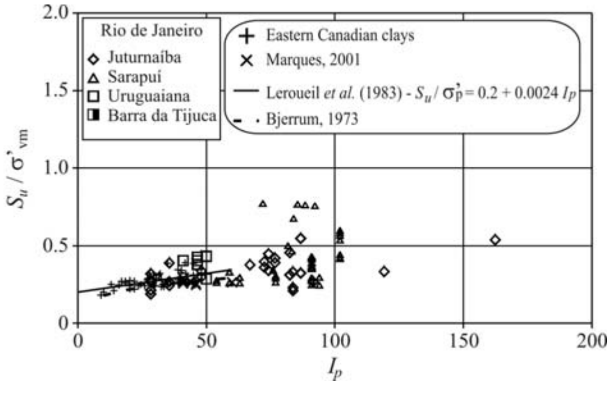

Figure 4 - Variation of S_u/σ'_{vm} with I_P.

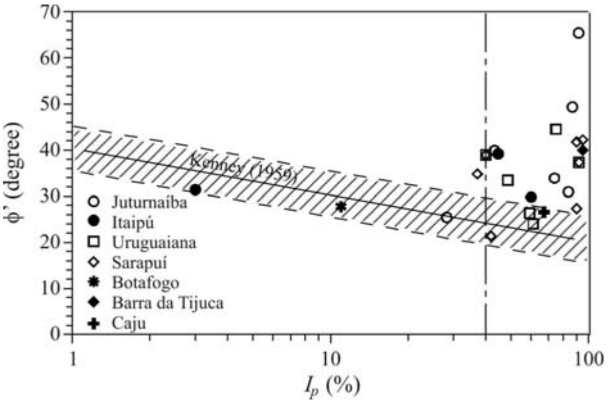

Figure 5 - Relationship between friction angle and I_P of Rio de Janeiro clays.

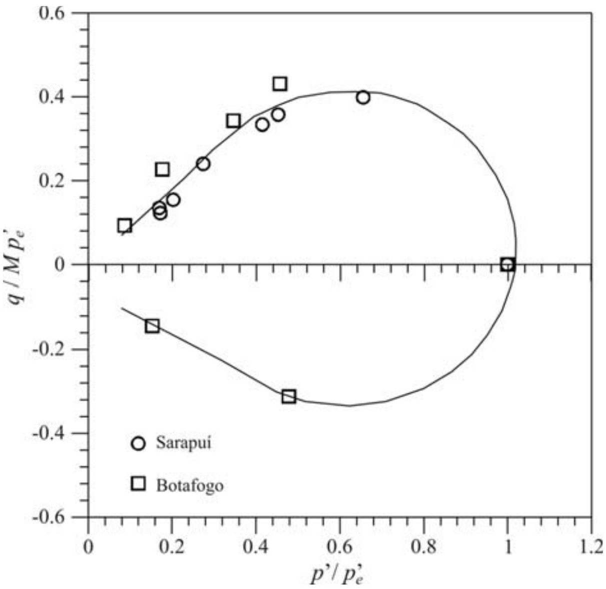

Figure 6 - Normalised yield curves of Sarapuí and Botafogo clays from CIU tests (Futai, 1999).

Yield curves of natural clays are usually normalised by the overconsolidation stress σ'_{vm} (*e.g.*, Díaz-Rodriguez *et al.*, 1992). For Rio de Janeiro clays, however, better representations of the yield envelopes were obtained by normalising data by the product $M\sigma'_{vm}$ (Graham *et al.*, 1988), where *M* is the inclination of the critical state line in the Cambridge *q*:*p*' plot, given by (Atkinson & Bransby, 1978):

$$M = \frac{6 \sin\phi'}{3 - \sin\phi'} \tag{4}$$

Figure 7 illustrates how *M* may be a useful normalising parameter of clay behaviour. The yield curves obtained using data from triaxial tests on overconsolidated specimens are shown in Fig. 8. Despite the lack of data for extension triaxial conditions, it is observed that all clays analysed

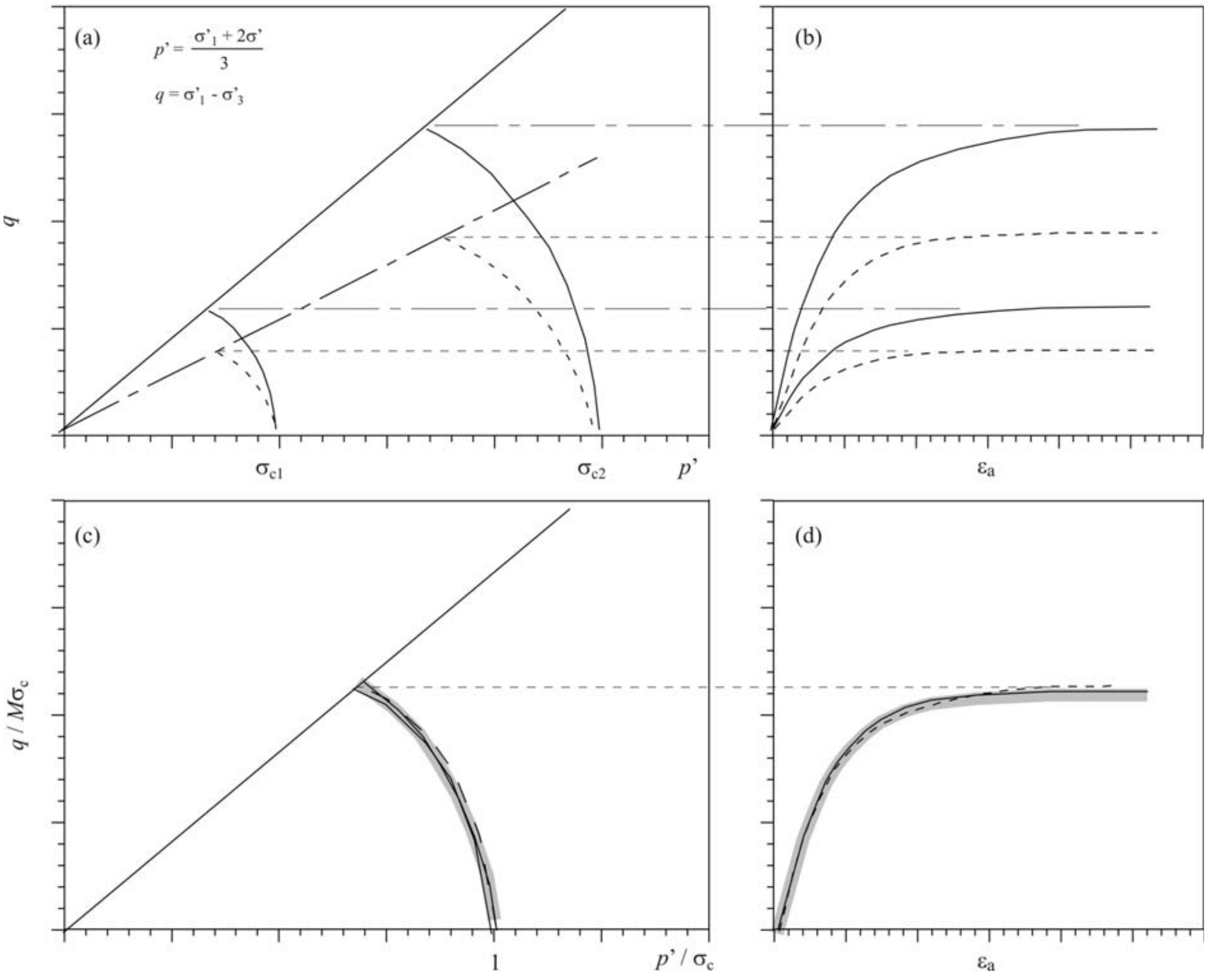

Figure 7 - Normalisation of clay behaviour.

show yield envelopes asymmetrical with respect to the hydrostatic line (p'/σ'_{vm} axis). These yield envelopes are in accordance with previous findings (*e.g.*, Díaz-Rodriguez *et al.*, 1992) and reflect the influence of the structure and anisotropy of natural clays.

Figure 9(a) shows all yield curves normalised with respect to overconsolidation pressure, in a single plot (Futai, 1999). However, the scatter shown in this figure is reduced when normalisation is made with respect to the average effective yield stress p'_m, as shown in Fig. 9b (Graham *et al.*, 1988), p'_m being defined by:

$$p'_m = \frac{\sigma'_{vm}}{3}(1+2K_0) \qquad (5)$$

where

$$K_0 = 1 - \sin\phi' \qquad (6)$$

Graham *et al.* (1988) proposed that this kind of normalization decreases the effects of mineralogy on the yield curve. Figure 9(b) shows that for the clays presented in this study, there are two well defined trends: the lower normalized yield curve represents soft clays and the other yield curve represents medium clays and organic clays, with high concentration of fibres and organic matter. The mineralogical composition of these clays is very similar; however, the organic matter has an important influence on the behaviour and may be responsible for the differences on the normalised yield curves. The data scatter in Fig. 9 is similar to that found by Graham *et al.* (1988) for clays less plastic than Brazilian clays.

The yield envelopes for Sarapuí clay presented in Figs. 8 and 9 are put together in Fig. 10 and the differences observed result from the high stresses used in the SHANSEP approach, which destroy the structure and anisotropy of natural clays. This behaviour is presented schematically in Fig. 11, where the stress increase expands and changes the shape of the yield envelope, which then becomes symmetrical with respect to the hydrostatic axis.

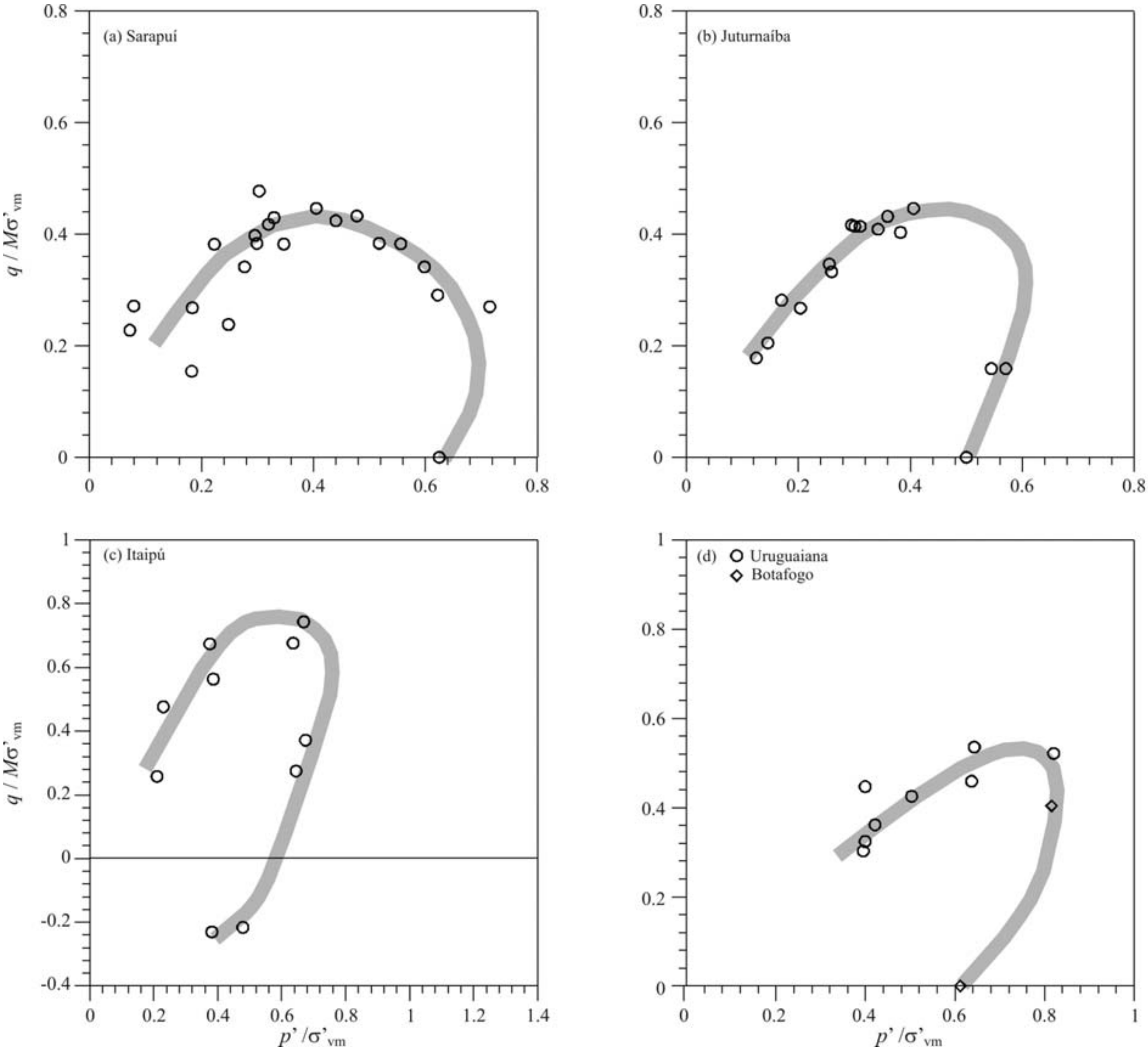

Figure 8 - Limit state curves of five Rio de Janeiro soft clays (Futai, 1999).

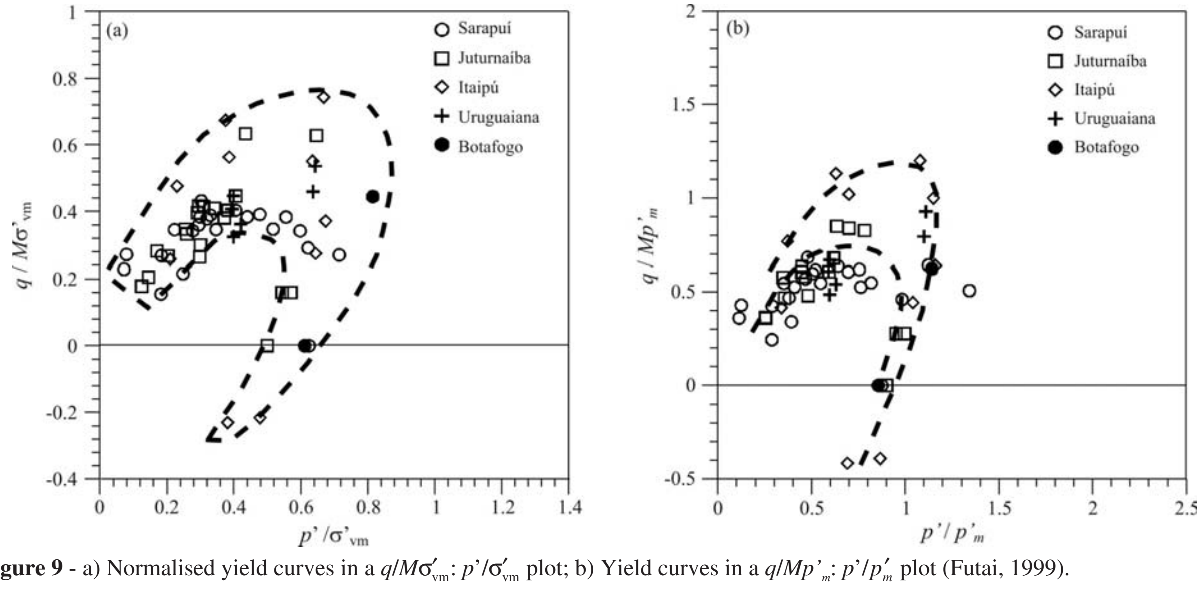

Figure 9 - a) Normalised yield curves in a $q/M\sigma'_{vm}$: p'/σ'_{vm} plot; b) Yield curves in a q/Mp'_m: p'/p'_m plot (Futai, 1999).

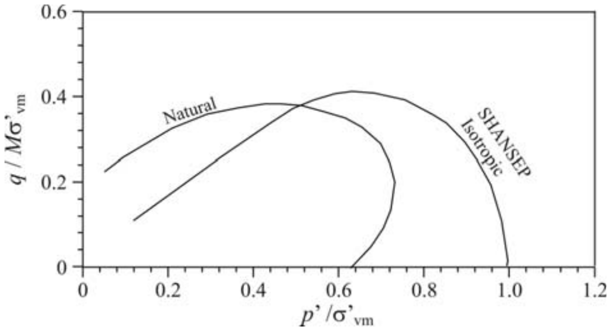

Figure 10 - Yield curves for Sarapuí clay (Futai, 1999).

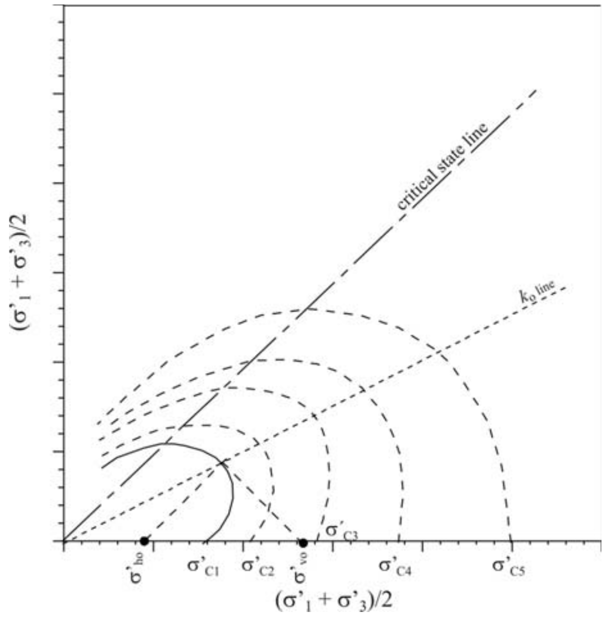

Figure 11 - Variations on the shape of yield curves with isotropic loading (Futai, 1999).

4. Conclusions

This paper summarized a study on the strength and yield behaviour of Rio de Janeiro sedimentary clays. Emphasis was given to the role of the clay structure on both strength and yield.

Regarding strength the following main conclusions were reached:

1. The specimen disturbance increases with the increase of the specimen diameter for the conventional technique of sample extrusion; further studies should be carried out to investigate the new technique for specimen preparation proposed by Ladd & De Groot (2003);

2. The normalised undrained strength S_u/σ'_{vm} plotted against the plasticity index showed that for the high I_P range of Rio de Janeiro clays S_u/σ'_{vm} values are higher than those of Canadian and Scandinavian clays.

3. It is shown that, for I_P values higher than 40%, the friction angle ϕ' increases with I_P due to the presence of the organic matter, which can contain fibers.

Regarding yield, the following main conclusions were reached:

1. It is observed that when high stresses are used, such as in the SHANSEP approach, the structure and the anisotropy of the natural clays are destroyed, which will influence its behaviour.

2. At lower stress levels the yield curves obtained were asymmetrical with respect to the hydrostatic axis *p*' due to the influence of anisotropy and structure of these clays.

3. The use of the ratio between maximum consolidation stress used in the test and clay overconsolidation pressure made possible to assess the influence of the degree of structuring caused by the consolidation process in the laboratory.

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