Laboratory Behaviour of Rio de Janeiro Soft Clays. Part 1: Index and Compression Properties

Discussion by

Kátia Vanessa Bicalho, Reno Reine Castello

The authors presented a comprehensive and useful synthesis of index and compression properties of Rio de Janeiro soft clays. It is useful not only for Rio de Janeiro but for most of Brazil, whose coastal plains share the same origin. The writers congratulate the authors for the work.

Of minor practical importance, but not so for teaching purposes, there is a mistake (maybe a mistyping) on the plasticity classification of clays of the so called Region IV (Fig. 4 and Table 2). They probably are the same clays of Regions II and III (medium to high plasticity) displaced to the right in the Casagrande's chart by a larger content of organic matter. They are not low plasticity clays. The results presented in Fig. 4 have the plasticity index (I_p) limits for each region different from those specified in Table 2. The organic matter increases plastic and liquid limits, but not the plasticity index (Casagrande, 1948; Bain, 1971).

Another point is about the correlation between compression index (C_c) and natural gravimetric water content (w). The writers have also found (Castello & Polido, 1986) better correlations for water contents (a state) than for liquid limits (a soil characteristic). On the other hand Terzaghi & Peck (1948), possibly the pioneers on this type of correlation, tried the liquid limit ($Cc = (w_L - 10)\ 0.009$), which seems more rational. Do the authors have an explanation why the water content works better?

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Laboratory Behaviour of Rio de Janeiro Soft Clays. Part 1 : Index and Compression Properties by Almeida, Futai, Lacerda and Marques. Published in Soils and Rocks v. 32(2), p. 69-75.
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Laboratory Behaviour of Rio de Janeiro Soft Clays. Part 1 : Index and Compression Properties

Discussion by

Ian Schumann Marques Martins, Paulo Eduardo Lima de Santa Maria, Flavia Cristina Martins de Santa Maria

1. Introduction

The authors are to be congratulated for presenting a paper with a significant amount of data on soft soils. The kind of data presented is of great value for geotechnical engineering practice, particularly for those involved with soft soils.

To facilitate the discussion's follow-up, the discussers have used the same items that have been used by the authors in the paper.

2. Soil Characterization

As one of the main aims of the paper is to provide practical data for pre-design purposes, it would be adequate to more precisely locate each place studied. Being so, it is suggested to replace the name "Uruguaiana Clay" by "Uruguaiana Street Clay in the Neighbourhood of the Uruguaiana Subway Station" (Vilela, 1976). In a similar way, it is also suggested to use "Botafogo Clay near Botafogo Subway Station" (Lins & Lacerda, 1980), instead of "Botafogo Clay" and so on.

It would be also adequate to present the geotechnical profiles shown in Fig. 1 in a more detailed way because some of them do not reproduce field conditions or do not unveil important information. These are the cases of Caju, Uruguaiana, Botafogo and Barra da Tijuca profiles.

Concerning "Caju Clay", the samples were taken from a soft clay layer beneath a failed embankment. The undrained shearing strains that took place in the soft clay layer due to failure were of such a magnitude that the clay structure was destroyed. Then, despite the care taken during sampling, the retrieved samples could never represent the natural conditions under which the deposit was formed. Although these conditions were reported by Cunha & Lacerda (1991), this information was neglected by the authors. Notwithstanding, if one of the main aims of the paper is to establish a comparison between parameters and properties of Rio de Janeiro soft clays, the conditions under which the determination of such properties and parameters were carried out must be clearly stated.

As a contribution to Table 1, Cunha & Lacerda (1991) have reported that "Caju Clay" has an organic matter content of the order of 5% and the amount of clay given by the grain size analysis is above 60%. Besides, the consolidation tests carried out by Carvalho (1989) have shown that in the normally consolidated domain the average value of the coefficient of consolidation is of the order of 1×10^{-8} m^2/s.

The average value of 9×10^{-8} m^2/s presented in Table 1 for the coefficient of consolidation (c_v) of "Sarapuí Clay" seems to be inadequate since for this clay the values of c_v range from 40×10^{-8} m^2/s in the recompression branch to 1×10^{-8} m^2/s in the virgin compression domain (see, for example, Coutinho, 1976).

As far as "Santa Cruz Clay" is concerned, a complete set of properties and parameters listed in Table 1 can be found in the careful work of De Campos (2006). This is an important additional source of information to all those who intend to deal with soft clays from Rio de Janeiro State coast.

The geotechnical profile near Botafogo Station of Rio de Janeiro Subway is not as simplified as shown in Fig. 1. Besides, it should be once more reminded that if one of the main aims of the paper is to compare soft clays from different places of the Rio de Janeiro State coast, one should give as much information as possible regarding the conditions under which samples were withdrawn. In the case of "Botafogo Clay", Lins & Lacerda (1980) have reported the following information, which must be added to that given by the authors:

a) The tested samples were taken from the depth of 10 m and in the middle of a 6 m-thick clayey-sand layer.

b) Grain size analysis has shown that "Botafogo Clay" was made up of 54% fine sand, 18% silt and 28% clay. So, even showing an appearance of a sandy-clay, "Botafogo Clay" is, in fact, a clayey-sand.

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c) The coefficient of consolidation of "Botafogo Clay" in the normally consolidated range is greater than 20 x 10^{-8} m^2/s (*e.g.* twenty times the typical value found for the Brazilian coastal soft clays).

d) Sampling was carried out one year after the local water table was lowered.

The preceding information suggest that at least part of the data obtained for "Botafogo Clay" could be possibly affected by consolidation caused by water table lowering. This has probably occurred because "Botafogo Clay" with its 28% of clay content and its high c_v is in the boundary between the soils with predominantly undrained or drained behaviour. Being so, the discussers are of the opinion that it is inadequate to compare "Botafogo Clay" to the other ones shown in Table 1. It would be more adequate to compare the remaining clays in Table 1 to that one also found in the neighbourhood of Botafogo subway station, between 13 m and 19 m. According to some strength parameters that have been shown by Lins & Lacerda (1980), the referred clay could be more properly classified as a soft clay than that described by the authors. It would be interesting to hear from the authors some comments about this clay layer.

In the case of the geotechnical profile of the subsoil in the neighbourhood of Uruguaiana Station of Rio de Janeiro Subway, there is a mistake. It is not shown in Fig. 1 the 10 m-thick sand layer existing above the soft clay layer, as described by Vilela (1976). Besides, the transition from the sand layer to the clay layer occurs at a depth greater than 10 m. This statement is supported by the grain size analysis of a sample taken between the depths of 11.0 m and 11.45 m, which has shown 70%, 25% and 5% for sand, silt and clay fractions, respectively. On the other hand, samples taken between the depths of 13.0 m and 18.45 m are predominantly clayey. So, if only these samples were taken into account to characterize "Uruguaiana Clay", values shown in Table 1 would undergo a substantial change, as shown in Table 3.

Yet, as a contribution to Table 1, it is worth reminding that the best quality samples tested by Vilela (1976), *e.g.* those obtained at depths greater than 13.0 m with 4" (100 mm) diameter tube samplers, gave $C_c/(1 + e_o) = 0.36 \pm 0.03$ and a c_v of the order of magnitude of 1 x 10^{-8} m^2/s in the normally consolidated range.

The discussers have another set of comments to make on the so-called "Barra da Tijuca Clay", whose parameters and properties are also shown in Table 1. Depending on the place and depth, "Barra da Tijuca Clay" may show many different characteristics. In the region that includes SENAC headquarters, Barra da Tijuca Roundabout and the Panamerican Games Athletes' Village, for example, there is a superficial 3-m thick peat layer whose water content can be higher than 600%. This soil is easily recognized by its dark brown colour and peculiar smell. It is also identified by its specific gravity $G < 2.0$, liquid limit $w_l > 450\%$ and plasticity index (*PI*) of the order of 250% (Da Mota, 1996 and Garcia,1996). In the vicinity of Barra da Tijuca Roundabout, this superficial peat layer looks like a dark pudding and exhibits a natural water content of 630%, a unit weight of 10 kN/m^3 and a void ratio $e_o = 12$. One-dimensional consolidation tests carried out by the discussers on this material have revealed overconsolidation stresses σ'_{vm} of the order of 5 kPa and a $C_c/(1 + e_o) = 0.45 \pm 0.03$. An unusual feature of this soil that must be highlighted is its extremely low coefficient of consolidation (c_v), which may reach a value of 4 x 10^{-10} m^2/s, *e.g.* twenty-five times smaller than the typical value of c_v in the virgin compression range, found for clays of the Brazilian coast.

Underneath the superficial peat layer described above, there is a 10 m-thick organic soft clay layer of dark grey colour with natural water content $w = 215\% \pm 85\%$, liquid limit (without previous drying) $w_l = 240\% \pm 80\%$, plasticity index $PI = 165\% \pm 75\%$, specific gravity $G = 2.42 \pm 0.18$ and natural void ratio $e_o = 5.6 \pm 0.6$. One-dimensional consolidation tests carried out by the discussers on this clay have revealed overconsolidation stresses ranging from 7 kPa to 32 kPa and $C_c/(1 + e_o)$ values determined at the beginning of the virgin compression branch of the *e* x log (σ'_v) plot, between 0.36 and 0.67. The coefficient of consolidation in the normally consolidated range is of the order of 1 x 10^{-8} m^2/s.

Finally, it would be convenient to hear from the authors about the criterium used to determine *CR* and C_c values presented in Table 1 since the values of both parameters vary with vertical effective stress (σ'_v).

3. Compressibility and Stress History

The features of the *OCR* x depth plot shown in Fig. 5 are indeed very interesting. According to the authors, there are three of them that stand out, namely:

a) The *OCR* profile for all clays is within a narrow zone.

b) The narrow zone of *OCR* values with depth suggests that soft clay deposits of Rio de Janeiro State coastal zone have similar stress histories.

c) Some deposits show a desiccated crust that may reach a thickness as great as 4 m and where *OCR* values are higher.

Table 3 - Geotechnical data of Uruguaiana Clay (taken into account only the samples between the depths of 13.0 m and 18.45 m).

Clay layer thickness (m)	Water content *w* (%)	Liquid limit w_l (%)	Plasticity index *PI* (%)	Clay content (% < 2 μ)	Unit weight γ (kN/m^3)
7	61 ± 7	83 ± 17	51 ± 9	48 ± 8	15.6 ± 0.3

The discussers are of the opinion that three other observations should be added to the above list, as follows:

i) When clay deposits reach surface (cases where the desiccated crusts show up), the *OCR* trend is to be constant with depth as soon as the crust zone is left behind.

ii) *OCR* values' trend to be constant with depth (see Fig. 5) suggests that clay deposits of Rio de Janeiro State coast have not been affected by the 2 m to 3 m lowering of sea level that occurred 4000 years ago, as estimated by Massad (1994).

iii) Except for "Itaipu Clay", there is a trend for *OCR* values to reach a constant value in the neighbourhood of 1.7, provided the depth considered is out of the desiccated crust zone. This feature suggests that the main cause (perhaps the unique) of overconsolidation of Rio de Janeiro coastal clays was secondary consolidation (aging).

As far as Fig. 6 is concerned, it would be convenient to review C_c and C_r values because they are not correct, at least those given for "Sarapuí Clay".

Finally, the discussers would like to present a more detailed discussion on the relationship between natural water content w and compression index C_c shown in Fig. 7.

It is well known that e x σ'_v (log) plots obtained from one-dimensional consolidation tests carried out on good quality samples are rather curvilinear in the virgin compression range. This means that compression index C_c is not a constant. For this reason, the use of C_c as a characteristic parameter for compressibility may not be suitable (see Fig. 8).

Butterfield (1979) and Martins (1983) have shown that when data from one-dimensional compression tests are presented in a v(log) x σ'_v (log) plot (v being the specific volume $v = 1 + e$), the virgin compression branch of the compression curve appears as a straight line in such a kind of plot. Being so, the compressibility parameter in the virgin compression range, denoted by $\not\subset_c$, is a constant given by:

$$\not\subset_c = \frac{-d \log v}{d \log \sigma'_v} = \text{constant} \quad (2)$$

It is easy to show that (see, for example, Martins *et al.*, 2006).

$$\not\subset_c = 0.434 \frac{C_c}{1+e} \quad (3)$$

Assuming that C_c values shown in Fig. 7 have been obtained at the beginning of the virgin compression branch of the e x σ'_v (log) plots (as C_{cM} shown in Fig. 8) and keeping in mind that all clays presented in the paper have a saturation degree of 100%, one can replace the void ratio e in Eq. (3) by the product Gw between specific gravity G and water content w. Then,

$$\not\subset_c = 0.434 \frac{C_c}{1+Gw} \quad (4)$$

or

$$C_c = \frac{\not\subset_c}{0.434}(1+Gw) \quad (5)$$

The pairs (C_c, w) which satisfy Eq. (5) are, according to Fig. 8, those pertaining to the virgin domain of the one-dimensional compression curve (as, for example, C_{cM} and w_M). Nevertheless, the plot of Fig. 7 does not give the relationship between C_c and w within the virgin compression range but between C_{cM} and the sample water content. Due to sampling operations, the sample water content w is slightly higher than the water content in the field w_o. If the sample water content w is assumed to be equal to the field water content w_o (w_o associated to the vertical effective stress in the field, σ'_{v0}) and if the water content associated to the overconsolidation stress is denoted by w_Y, then w can be evaluated by (see also Fig. 8):

$$G(w - w_Y) \cong G(w_0 - w_Y) = e_0 - e_Y = C_r \log \frac{\sigma'_{vm}}{\sigma'_{v0}} = C_r \log OCR \quad (6)$$

The value of the compression index associated to the water content w_Y, which satisfies Eq. (5), is:

$$C_{c_Y} = \frac{\not\subset_c}{0.434}(1+Gw_Y) \quad (7)$$

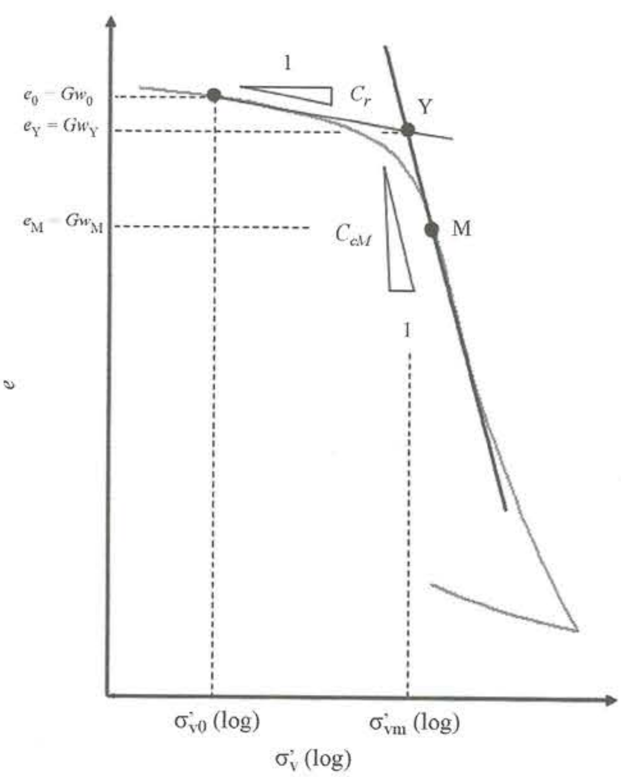

Figure 8 - Typical e x σ'_v (log) plot from an oedometer test carried out on a good quality sample of an organic clay from Rio de Janeiro State coastal zone.

Hence, evaluating w_Y from expression (6) and introducing it in Eq. (7), one obtains:

$$C_{c_Y} \cong \frac{\not{\subset}_c}{0.434}(1 + Gw - C_r \log OCR) \quad (8)$$

Since $C_{c_Y} \cong C_{c_M} = C_c$, the relationship between C_c and w can be expressed approximately by:

$$C_c \cong \frac{\not{\subset}_c}{0.434}(1 + Gw - C_r \log OCR) \quad (9)$$

Taking into account only Juturnaíba, Sarapuí and Uruguaiana clays, for which $\not{\subset}_c$ values have been determined by the discussers, it can be assumed the following average values for the terms in Eq. (9): $\not{\subset}_c = 0.21$, $G \cong 2.57$, $C_r \cong C_c / 8$ and $OCR \cong 1.7$. With these average values kept in mind, assuming also that $w_0 \cong w$ and that C_c values presented by the authors have been determined as C_{cM} in Fig. 8, Eq. (9) gives:

$$C_c \cong 0.48 + 1.23w \quad (10)$$

which is a similar expression to that presented by the authors.

It should be emphasized that for the studied clays, $0.180 \leq \not{\subset}_c \leq 0.240$. Thus, expression (10) represents an average line through a set of points with a considerable amount of scattering, as shown in Fig. 7. For this reason, both Eq. (10) and the expression presented by the authors should be used with caution.

4. Summary and Conclusions

The discussers would like to emphasize the important contribution given by the authors regarding the pattern of *OCR* profiles. As pointed out by the discussers, the shape shown by the *OCR* profiles suggests that clay deposits from Rio de Janeiro State coast were not affected by sea level lowering that occurred 4000 years ago, as reported by Massad (1994). Besides, the *OCR* trend to be constant with depth towards a value of approximately 1.7 seems to indicate that the overconsolidation observed in Rio de Janeiro State coastal clays are due to secondary consolidation (aging). In the discussers' opinion, this is a subject that deserves a deeper study, which may throw new lights on the understanding of the processes under which the clay deposits of Rio de Janeiro coast were formed.

The empirical expression $C_c = 1.3w$, found by the authors to the set of clays studied, is of great practical interest. The referred expression is similar to the expression $C_c \cong 0.48 + 1.23w$, deduced herein by the discussers. Although very attractive from the practical point of view, both expressions should be used with caution since there is a considerable amount of scattering in the relationship between w and C_c that both expressions intend to represent.

As for the rest, the remaining conclusions stated by the authors should be viewed with caution in face of the questions raised by the discussers herein.

Finally, the discussers would like to clearly state that this discussion was written keeping in mind the purpose of exchanging ideas viewing at a deeper understanding of soil formation for a better practice of geotechnical engineering.

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Authors' reply to the discussions presented by Bicalho, K. & Castello, R.R, and by Martins, Santa Maria & Santa Maria.

Initially the authors would like to thank the two discussions presented by the above writers and for their interest in the paper. The replies to the writers are presented separately below.

Reply to Bicalho & Castello

With respect to the first point raised by these discussers regarding Region IV, there is indeed a mistyping in Table 2 and the last line should read $I_p > 50\%$ (instead of $I_p > 130\%$). However, contrary to the discussers' statement, the clay of Region IV (basically Itaipu clay) is different from the clays of Regions II and III as all layers assessed have higher liquid limit and also higher organic matter. As a consequence of the higher organic content (presence of fibers) Itaipu clay has shown higher friction angle than the clays from Regions II and III.

The other point raised by Bicalho and Castello regards the correlation between the water content w with the compression index C_c. The reason to use this correlation rather than the correlation between C_c and liquid limit w_L is because it has become common practice recently (*e.g.*, Sandroni, 2006; Almeida *et al.*, 2008) to measure water content using SPT samples. This low-cost and simple procedure also provides a first assessment of the variation of soil characteristics in extensive areas and can be used for preliminary geotechnical design. Therefore, the authors have not in fact assessed the correlation between C_c and liquid limit w_L, simply because the determination of the liquid limit is more time consuming than the determination of the water content. Thus, there is no such conclusion that the w x C_c correlations works better than any C_c x w_L correlation, it is just because the former is simpler and straightforward. More recent work including only data on Barra da Tijuca and Recreio dos Bandeirantes clays (Almeida *et al.*, 2008) has changed slightly the correlation to $C_c = 0.012w$ (w_o in %), as shown in Fig. 9.

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Soil characterization

These writers have presented a number of interesting comments and suggestions, most of which have now been included in the updated version of Table 1 shown below. In fact, Uruguaiana Street clay has a clay content varying with depth (Villela, 1976). It varies from 5% at a depth of 10.5 m reaching a maximum of 54% at a depth of 16 m. The paper shows results of the entire layer, while the writers focused on the material below 13 m, with higher clay content. Therefore, Table 3 provided by the writers is a detail of Table 1 of the paper. Fig. 1 shows a soft clay layer above the mentioned layer, which was clearly a mistake. The authors thank the writers for this important correction.

As far as Barra da Tijuca clay is concerned, the paper is based on the data compiled by Futai (1999) until the late nineties. Later on, a large number of dissertations and theses have dealt with Barra da Tijuca clay (*e.g.*, Macedo, 2004; Nascimento, 2009) and also Recreio dos Bandei-

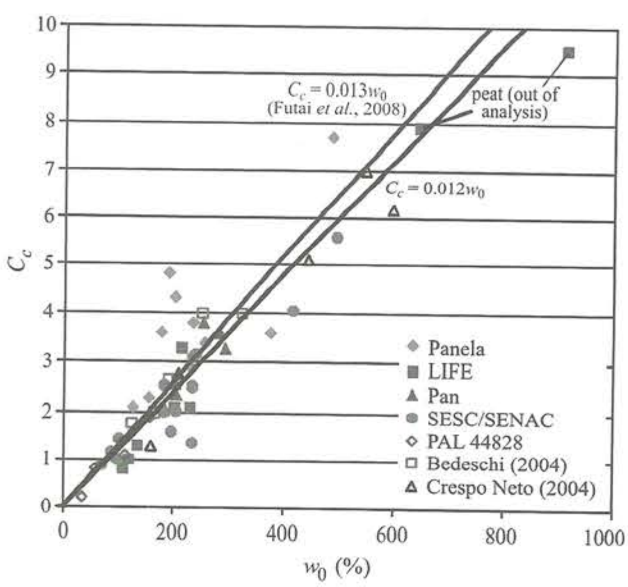

Figure 9 - Compression index C_c *vs.* in situ water content w_o for Barra and Recreio clays.

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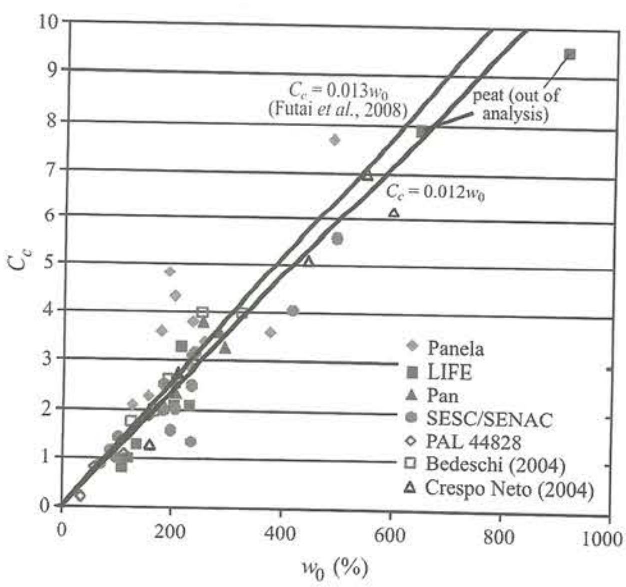

Figure 9 - Compression index C_c *vs.* in situ water content w_0 for Barra and Recreio clays.

rantes (Crespo Neto, 2004). Most of the data mentioned by the discussers regarding water content, liquid limit, plasticity index and compressibility are within the range shown in Table 1. More recently, Almeida *et al.* (2008) presented data with very high water content as shown in Fig. 9. There is indeed a clear difference of behavior depending on the soil depth. However, the purpose of the paper is to present typical and overall data without emphasis on the differences in behavior between different depths.

Compressibility and stress history

Regarding the values of C_c and C_r shown, there are indeed some mistakes and Fig. 10 presents the correct data.

With respect to the *OCR vs.* depth plot, the authors agree with the added contributions and also that aging is the main cause of overconsolidation of Rio de Janeiro clays.

Regarding C_c values, the authors used the same criterion used by the writers, *i.e.*, C_c was determined at the beginning of the virgin compression line.

With respect to the correlation between compression index C_c and water content w, the writers have developed an interesting and new relationship based on the log (e) *vs.* log (σ'_v) plot (previously used by Almeida, 1981 and 1982, for Sarapuí clay). The equation $C_c = 0.43 + 0.0123w$ (w in%) developed by the writers has sound theoretical basis. However, this equation differs from the correlationships developed by a number of authors (Almeida *et al.*, 2008; Bowles, 1979; Kopula, 1981; Nagaraj & Miura, 2001) which are of the type $C_c = K.w$ (*i.e.*, without intercept) with K values in quite a narrow range 0.010-0.013. The equation developed by the writers is plotted in Fig. 11 together with the authors data. The theoretical relationship proposed by the writers is very interesting, but it is not a good fit for the data, as show in Fig. 11.

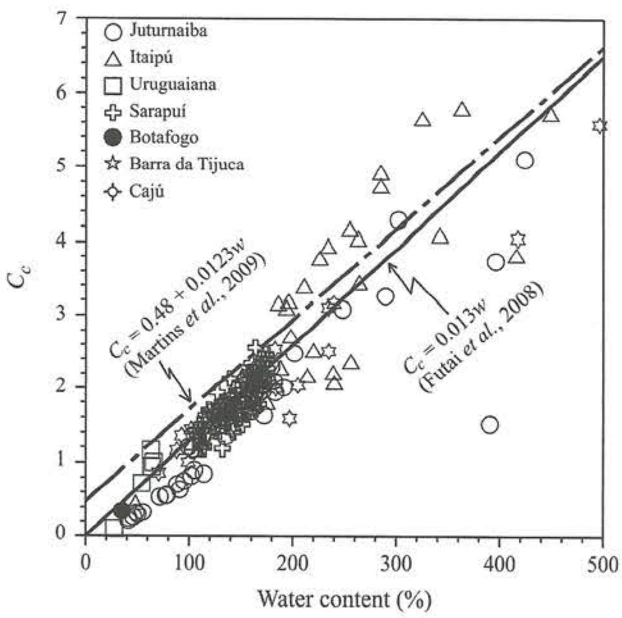

Figure 11 - Compression index C_c *vs.* in situ water content w_0 for Rio de Janeiro clays and the correlation proposed by Martins *et al.* (2009).

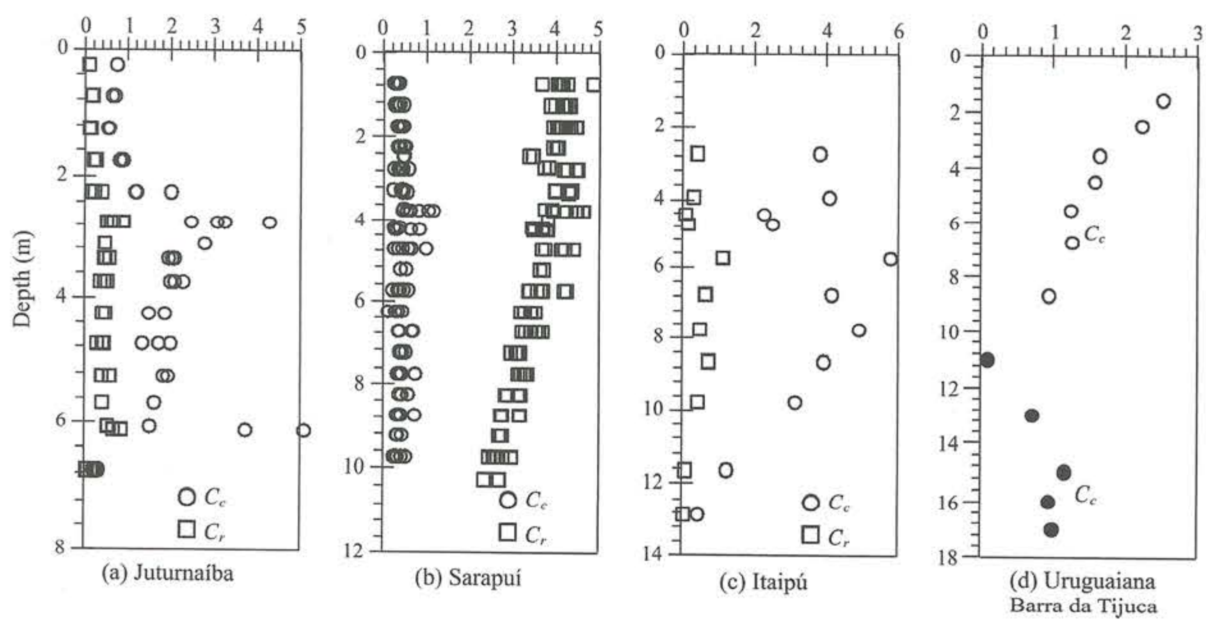

Figure 10 - Compressibility parameter profiles.

Table 1 (altered) - Geotechnical properties of Rio de Janeiro clays.

Parameter / clay	Caju (b)	Sarapuí (c)	Santa Cruz (IZ) (d)	Santa Cruz (SZ) (e)	Nothern coast of Guanabara (f)	Itaipú (g)	Juturnaíba (h)	Uruguaiana Street clay (i)	Botafogo (near the Subway station) (j)	Barra da Tijuca (k)
References	Lira, 1988; Cunha & Lacerda, 1991	Lacerda *et al.*, 1977; Ortigão, 1980; Almeida & Marques, 2002)	Aragão, 1975	Aragão, 1975	Aragão, 1975	Carvalho, 1980; Sandroni *et al.*, (1984)	Coutinho & Lacerda, 1987	Vilela, 1976	Lins & Lacerda, 1980	Almeida *et al.*, 2000
Clay layer thickness (m)	12	12	15	10	8.5	10	7	9	6	12
w (%)	88	143 ± 21.7	112	130	113	240 ± 110	154 ± 95.6	54.8 ± 15.9	35	100-500
w_L (%)	107.5	120.3 ± 18.0	59.6	125.4	122	175.4 ± 82.6	132.5 ± 43.8	71.3 ± 30.0	38	70-450
I_p (%)	67.5	73.08 ± 16.1	32	89	81	74.5 ± 30.1	63.59 ± 22.1	40.5 ± 22.03	11	120-250
% clay	60	70	-	54	35	-	60.7 ± 12.74	39.4 ± 10.11	28	28-80
γ (kN/m^3)	14.81	13.1 ± 0.49	13.24	13.44	13.24	12 ± 1.85	12.5 ± 1.87	16.1 ± 1.39	17.04	12.5
S_t	3	2.59 ± 0.69	3.39	2-6	-	4-6	5-10	3.00	-	5.0
% organic matter	5	4.13 - 5.54	-	-	-	32.63 ± 20.46	19 ± 10.63	2.56 ± 1.04	-	-
$CR = C_c / (1 + e_o)$	0.27	0.41 ± 0.07	0.32	-	0.26 ± 0.15	0.41 ± 0.12	0.31 ± 0.12	0.31 ± 0.15	0.16	0.52
C_s/C_c	0.21	0.15 ± 0.02	0.10	-	0.16 ± 0.04	-	0.07 ± 0.06	-	0.19	0.10
c_v (m^2/s) x 10^{-8}	1	1-40	0.2-18.2	-	0.4	5	1-10		30	2-80
e_o	2.38	3.71 ± 0.57	3.09	3.37	2.91	6.72 ± 3.1	3.74 ± 1.89	1.42 ± 0.36	1.1	-

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