Evaluation of Sample Quality and Correction of Compressibility and Strength Parameters-Experience with Brazil Soft Soils

M.I.M.C.V. Bello, R.Q. Coutinho, A.S. Norberto

Abstract. Sample quality has a direct influence on the results of geo-mechanical parameters obtained in laboratory and *in situ* tests, potentially causing serious technical and economic consequences. In the study of soft soil behavior using laboratory tests, it is important to evaluate, and be able to quantify sample quality, and if necessary and possible, to correct the effects of sample disturbance and to obtain geotechnical parameters appropriate and necessary for engineering projects. This paper presents and discusses the Brazilian results of sample quality evaluation and the correction of compressibility and strength parameter results to account for the effects of sample disturbance, as well as a review of several papers that address correction and sample quality issues. Proposals presented by Coutinho (2007) and Futai (2010) were used to evaluate sample quality. Proposals presented by Schmertmann (1955), Oliveira (2002), Coutinho (2007) and Futai (2010) were used for correction of compressibility parameters that were altered by the effects of sample disturbance. The results from these study areas were satisfactory for all the proposals. It was possible to obtain compression parameters corresponding to good quality samples using the proposals for correcting the effects of sample disturbance.

Keywords: compressibility parameters, oedometer test, sample quality.

1. Introduction

The qualitative study of soft clay samples is very important in order to be able to obtain the appropriate values for geotechnical parameters resulting from laboratory and *in situ* tests used in engineering projects and in empirical correlations. The quantitative effect of inappropriate sampling can bring serious consequences both technical and economic.

Efforts have been made during research projects to understand, quantify, minimize, and whenever possible, correct the geotechnical parameters resulting from sample disturbance of Recife soft clays (Coutinho, 1976; Ferreira, 1982; Ferreira & Coutinho, 1988; Coutinho *et al.*, 1998; Oliveira *et al.*, 2000, Oliveira, 2002; Coutinho, 2007; Bello, 2011; Coutinho & Bello, 2012). The studies cited above were carried out by the Geotechnical Research Group (GEGEP/UFPE) coordinated by the second author.

This article presents and discusses a review of the Brazilian results of sample quality evaluation, and correction of the effects of sample disturbance. Proposals presented by Coutinho (2007) and Futai (2010) were used to evaluate sample quality. Proposals presented by Schmertmann (1955), Oliveira (2002), Coutinho (2007) and Futai (2010) were used in order to correct compressibility parameters that were influenced by the effects of sample disturbance.

2. Analyses of the Sampling Process

Sample disturbance occurs in all sampling processes and, if sampling is carried out well, the effects of disturbance will hopefully be more subtle. Whatever its magnitude, sampling disturbance normally affects both undrained strength and compressibility. In addition, chemical effects may cause changes in the plasticity and sensitivity of the soil sample.

Hvorslev (1949) classified the sample disturbance according to five categories: (a) variations in the stress conditions; (b) variations in the water content and in the initial void ratio; (c) alteration of the soil structure; (d) chemical variations; and (e) mixture and separation of the soil constituents. The influence of the disturbance on the results of laboratory tests depends on the type and degree of disturbance, the soil characteristics, and the technique used in the tests.

Ladd & Lambe (1963) (see also Sandroni, 1977) defined that perfect sampling is correlated to the process where the disturbance is limited only to the effects caused by relieving field stress, however the real sampling presents additional disturbance. The sampling procedure varies the stress state and induces disturbance of the soil (Fig. 1).

Jamiolkowski *et al.* (1985) considered some of the factors that result in alterations during the sampling procedure and preparation of the sample specimens: (a) variations in stress caused by opening of the hole; (b) removal of

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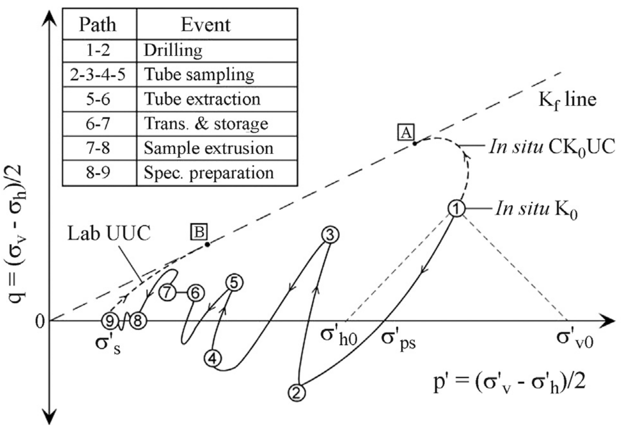


Figure 1 - Stress Paths during the tube sampling process (Ladd & Lambe, 1963).

the field strength stress; (c) geometry and type of the sample extraction equipment; (d) method used by the sample extraction equipment; (e) relation between diameter of the sample extraction equipment and the sample specimens; (f) transport, storage, and laboratory manipulation.

Leroueil & Jamiolkowski (1991) defined the disturbance as destruction of the agglutinate between the points of contact of the grains, and indicated that the two main causes of the disturbance are the distortion mechanics associated with the operation of sampling, and the relief of the total stress field.

Hight (2000) examined the effect of sampling on the behavior of soft clays, stiff clays and sands, and described improvements that have been made to the methods of sampling, which have enabled higher quality samples to be obtained.

Coutinho (2007) reported that in practical and research works in Brazil, sampling has normally been carried out by means of a thin walled stainless-steel tube (Shelby), or by using a stationary piston sampler, 800 to 1000 mm in length, with an internal diameter measuring 100 to 110 mm, and an area ratio of 7% respectively, in order to obtain samples of satisfactory quality. According to Coutinho (2008), complementary procedures in each case must be established by updating the knowledge base in the literature. Aspects of the disturbance process of the sample are inevitable, but the degree of disturbance can be minimized through improvements in sampling procedures in the field, along with proper manipulation in the laboratory.

Oliveira (2002) comments that better-quality samples can be obtained by adequately trained teams using Sherbrooke sampling. Tanaka (2008) concluded that it is possible to obtain high quality samples of soft clays to depths of 400 meters using standard sampling methods that follow technical recommendations.

Futai (2010) indicates that, the solutions adopted to eliminate the unwanted effects on samples often include the use of the method suggested by Ladd & Foot (1974): SHANSEP ("Stress History and Normalized Soil Engineering Properties").

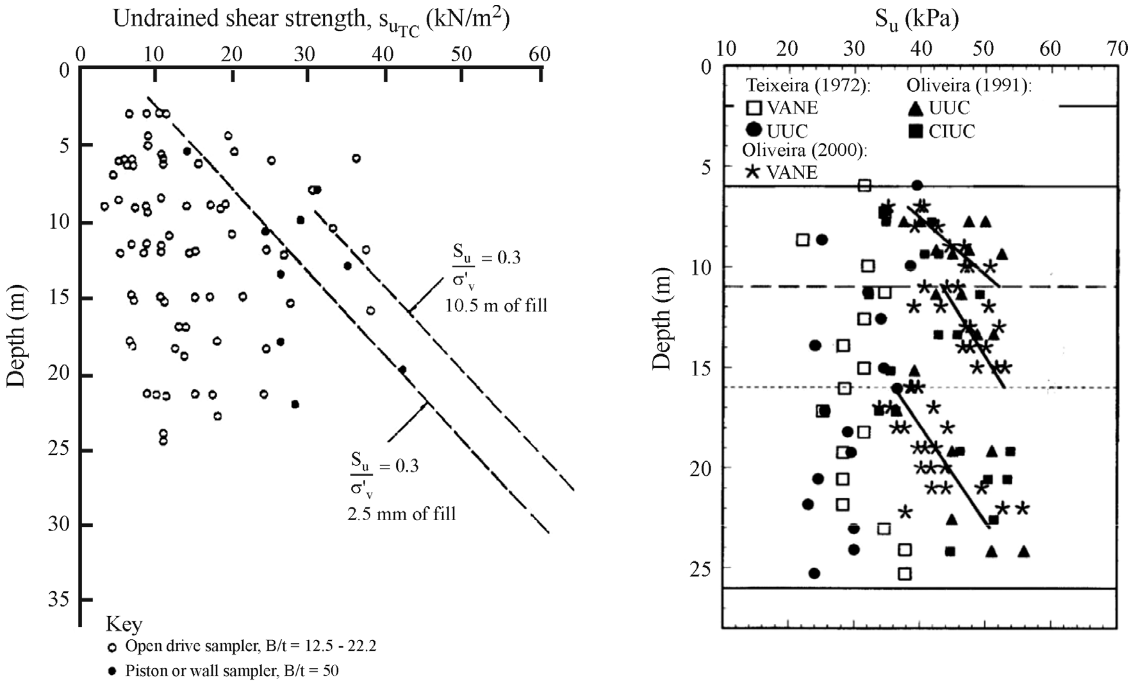
Okumura (1971) listed some quantitative requirements for parameters to be used in evaluating sampling disturbance. Such parameters must be: (a) Easy to determine for perfectly undisturbed conditions; (b) Regularly variable with disturbance, regardless of the depth of extraction, the stress system experienced, and the soil type; (c) Sensitive to change due to disturbance; (d) Easily and accurately measured.

3. Influence of the Sample Quality on Strength Parameters

The sample quality has direct influence on the strength parameters obtained in laboratory testing. Many researchers have investigated ways to understand and avoid the disturbance processes. Santagata *et al.* (2006) present the discussion about the effect of the sampling tube in results of triaxial CIU-C tests. Hight (2000) presents the familiar results of a conventional soft clay site investigation, involving sampling and laboratory testing (Fig. 2a). It shows the results of unconsolidated undrained (UU) triaxial compression (TC) tests on samples of Singapore marine clay, the majority of which were taken with a thich-walled open drive sampler. There is a large scatter in the data, most of which falls below the best estimate of *in situ* shear strength in compression. Samples taken with a thin-walled piston sampler lead to higher strength. Figure 2b shows the comparison between the results of undrained strength obtained from UU-C e CIU-C triaxial tests and *in situ* field vane tests obtained by Teixeira (1972), Oliveira (1991) and Oliveira *et al.* (2000) in Clube Internacional of Recife. The lower S_u values, obtained by Teixeira (1972), were caused by the disturbance of samples (Shelby type samples with diameter of 60 mm) and test conditions (procedure and equipment). The reduction of S_u values was in the order of 50% in comparison with the results obtained by Oliveira (1991) and Oliveira *et al.* (2000).

Ortigão (1980) performed UU triaxial tests and registered the variation of S_u value with the diameter of samplers, using piston samplers with different diameters. This effect was studied theoretically by Baligh (1986), when was introduced the concept of stress path. Baligh (1986) showed that the disturbance increases when the relation between the thickness and diameter of the tube also increase. Tube sampling can be causing yielding by compression and shear because the cycles of compression-extension-compression can be causing the destructuring of the soil. These effects and the theoretical prediction of Baligh (1986) were confirmed experimentally by La Rochelle & Lefebvre (1971), Ortigão (1980), Tavenas & Leroueil (1987) and Hight *et al.* (1992).

Hight (2000) comments that the advantage of both UC and UU tests is that they show the full imprint of sam-



(a) (b)

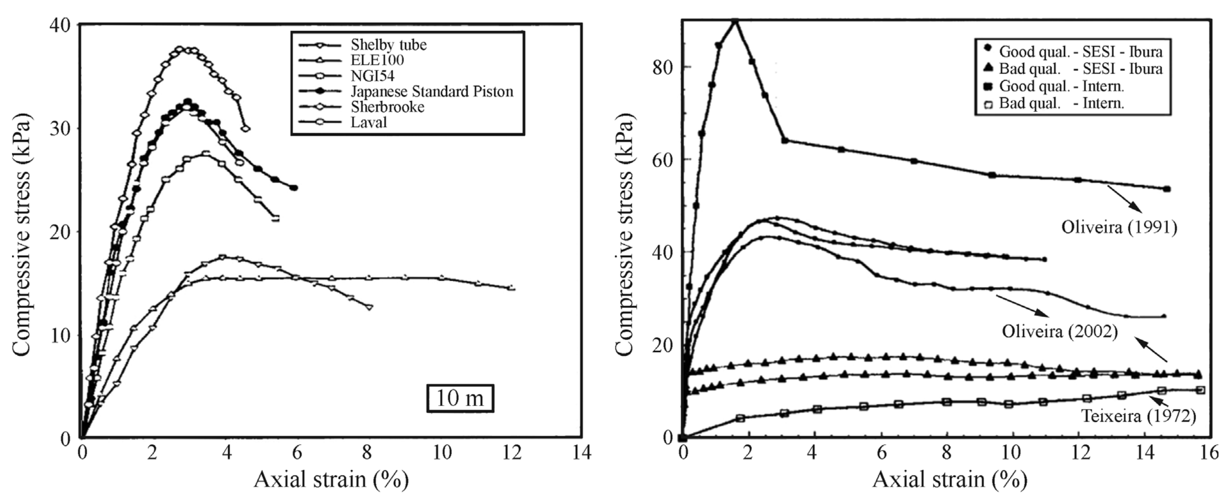
Figure 2 - (a) Results of unconsolidated undrained triaxial compression tests on thick-walled and thin-walled tube samples of Singapure marine clay (Hight, 2000); (b) Undrained strength profile of the Clube Internacional -Recife (Coutinho *et al.*, 1998).

pling effects, and the UC data in Fig. 3a confirms that "block" samples taken by rotary methods can be of higher quality than even the best tube samples. Between tube samples, there is a significant difference in measured strengths, and, therefore, in levels of sample disturbance.

Coutinho *et al.* (1998) show results of the stress-strength curve of UU triaxial tests performed in Recife soft clays (samples of good and bad quality). It can be observed the difference in the S_u and ε_f values obtained (Fig. 3b).

Figure 4 shows the influence of sample quality in the obtained S_u value. This influence is represented for difference between the sampler diameter and the relation of the sampler/specimen's diameters for Sarapuí-RJ deposit (Ortigão, 1980) and Clube Internacional - Recife deposit (Coutinho *et al.*, 1993).

For the Sarapuí deposit, the S_u values for 8.0 m depth, using sampler and specimens with diameters of 50 mm (S_u = 4.5 kPa), and sampler and specimens with diameters



(a) (b)

Figure 3 - (a) Unconfined compression tests on Ariake Clay (Hight, 2000); (b) Triaxial UU tests performed in poor and good samples - Recife (Coutinho *et al.*, 1998).

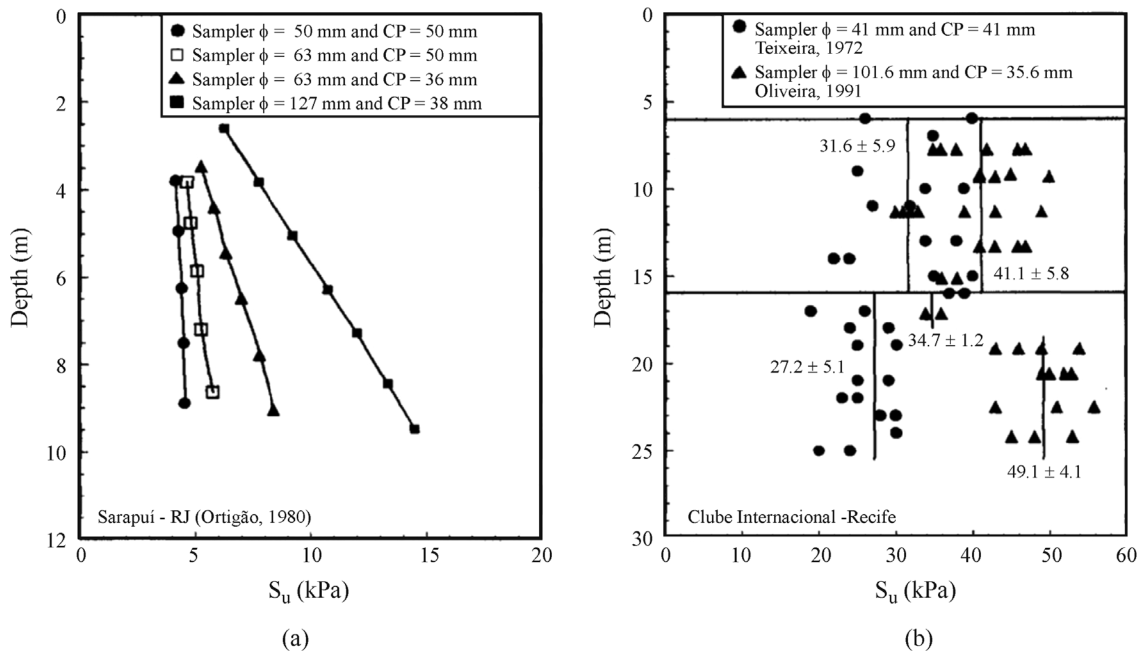


Figure 4 - UU Triaxial tests results: (a) Sarapuí (Ortigão, 1980); (b) Clube Internacional do Recife (Coutinho *et al.*, 1993).

of 125 mm and 38 mm, respectively (S_u = 13 kPa), provided the relation of $S_{u\phi127}/S_{u\phi50}$ = 2.9. For Clube Internacional, the relation for the second layer was equal to $S_{u\phi101.6}/S_{u\phi41}$ = 1.8 (sampler of 101.6 mm diameter and specimen of 35.6 mm; and sampler of = 41 mm and specimen of 41 mm). It is observed that the larger the diameter of the sampler and the relationship between the diameters of the sampler and the specimen, the greater the S_u value.

Clayton *et al.* (1992) show comparisons of stress paths of Bothkennar clay sampled in different ways (Sherbrook, Laval and piston samples) of Bothkennar clay. The authors found that provided tube sampling strain excursions were limited to ± 2% and that appropriate stress paths were used to reconsolidate the material back to its *in situ* stress state, the undrained strength of the Bothkennar clay would be within ± 10% of its undisturbed value. Strain path tests on high quality (Laval and Sherbrook) undisturbed samples of natural clay by Clayton *et al.* (1992) have confirmed that, in normally and lightly over-consolidated clays, stiffness is greatly affected by tube sampling, but undrained strength reductions are less significant and can, in any case, be recovered by good reconsolidation procedures.

Hight (2000) shows that the strength available around the critical potential failure surface A-B-C beneath an embankment constructed on this clay will vary by an amount reflecting the level of anisotropy of the soil (Fig. 5). The average mobilized strength is indicated as S_u. Experience has shown that S_u is often close to the average strength measured in simple shear, which in this case is similar to the strength measured in UU tests on poor quality samples, so that, when UUTC data is combined with a conventional factor of safety, a safe design results. An improvement in sample quality will lead to a higher UUTC strength profile, and if the same design procedure is adopted, *i.e.* using UUTC strengths to represent an average mobilised

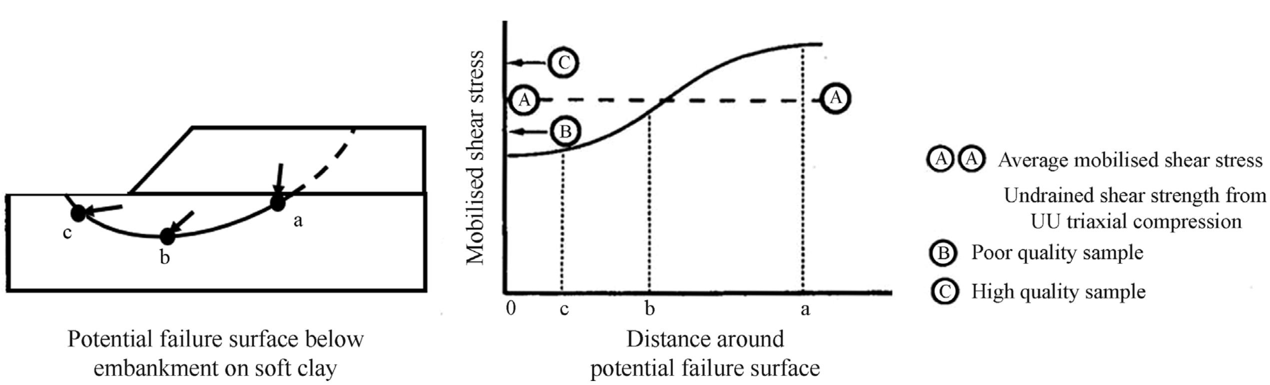


Figure 5 - Inherent dangers in improving sample quality while neglecting anisotropy (Hight, 2000).

strength, an unsafe design may result, unless the factor of safety is modified.

4. Influence of the Sample Quality on Compressibility Parameters

The quality of the sample directly influences the edometric compression test. Skempton & Sowa (1963) analyzed the compressibility through the relations between *in situ* void ratio subjected to the same vertical stress σ'_{vo} (usually consolidation) for more than 20 clays of different lithologies. The authors observed that the void ratio can be correlated with limits of liquidity, plasticity and depth, and concluded that: (a) the relationship between e_0 and log σ'_{vo} is essentially linear; (b) for a certain value of (σ'_{vo}, e_0) normally consolidation depends fundamentally on the nature and mineralogy of the clays and can be represented by the liquid limit; (c) the compressibility curves tend to converge; (d) the use of the liquidity index reduces dispersion.

Ladd (1973) listed the following structural disarrangement effects in the oedometer compression curve: (a) decrease of the void ratio (or increase in deformation) for a σ'_v value;

(b) difficulty in defining the point of smaller curvature; (c) reduction of the pre-consolidation pressure value; (d) increase of compressibility in the recompression region, and decrease in the compression region. Hight (2000) shows in Fig. 6a, the bounding surfaces found for Saint Louis clay, from East Canada, in block samplers, Laval samples and 50 mm diameter piston samples. Tests on the block and Laval samples define the same bounding surface, which sits well outside the equivalent surface defined on the basis of the poorer quality piston samples.

Coutinho (1976, 2007) presents a study with examples of comparative oedometer curves for samples taken by different samplers (Sherbrooke, Shelby 60 and 100 mm), and their corresponding properties (Fig. 6b).

Oedometer curves are also shown for a completely disturbed sample obtained from the laboratory. It is observed that the better-quality sample was obtained with Sherbrooke samplers (Coutinho *et al.*, 2000). The results confirmed all the effects caused by the disturbance described by Ladd (1973). It also shows that the normally consolidation range of a good quality curve is not linear, as usually described ("straight virgin"), but rather presents itself as a curve. The line recognized as a straight (virgin) line is in fact curved.

The void ratio relation *vs.* the effective pressure becomes linear with the disturbance. Compression curves are similar for effective pressures reaching high values. The relation between pre-consolidation pressures of good and poor-quality samples was found to be as high as 3, although initial void ratios do not seem to be significantly influenced by sampling quality. Significant reductions were also observed in the compression index C_c, in the permeability and in the coefficient of vertical consolidation c_v values as the soil was disturbed through poor quality sampling procedures (Table 1). In general, the swell index C_s showed a slight increase with sampling disturbance (Coutinho, 1976, 2007). These effects cause errors in the evaluation of the evolution of the settlements through time (the periods predicted for stabilization can be greater when based on sample disturbance).

The use of geotechnical parameters obtained from poor quality samples can lead to serious technical and economic consequences (Martins, 1983; Coutinho *et al.*, 1998; Oliveira, 2002; Coutinho, 2007, 2008; Almeida & Marques, 2010).

Figures 7a and 7b (Coutinho *et al.*, 1998) show the behavior of geotechnical parameters of depth compressibility for the SESI - Ibura (Recife) and Sarapuí (Rio de Janeiro) sites, respectively. For both sites, the values obtained for the compression index (C_c), the pre- consolidation stress

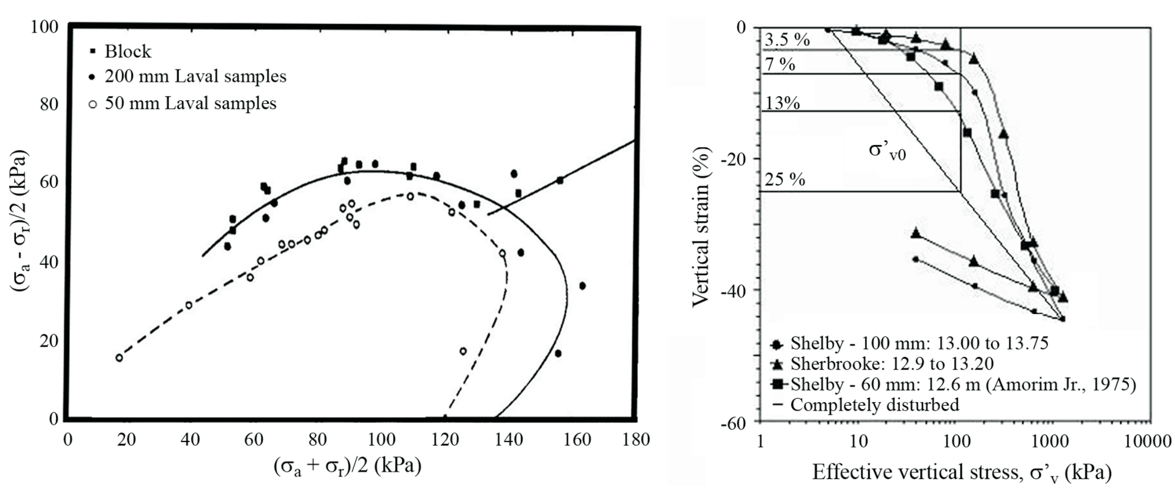


Figure 6 - (a) Shrinking of the bounding surface for Saint Clay as a result of disturbance during sampling (Hight, 2000); (b) Oedometer curves from samples taken using differing methods (Coutinho, 2007).

Table 1 - Effect of sampling on one-dimensional consolidation for Recife and Sarapuí-RJ clays (Coutinho *et al.*, 1998).

	Recife (International Club)		Sarapuí (Rio de Janeiro)	
Parameters	Good/poor	Good/disturbed	Good/poor	Good/disturbed
σ'_p	1.5-3.0	3.0-5.0	1.5-2.0	1.5-2.5
C_S	0.8-1.0	0.7-1.2	0.9-1.2	1.0-1.1
C_c	1.2-2.0	1.2-2.1	1.2-1.5	1.4-1.7
C_v (water level)	1.21	1.93	1.26	1.37

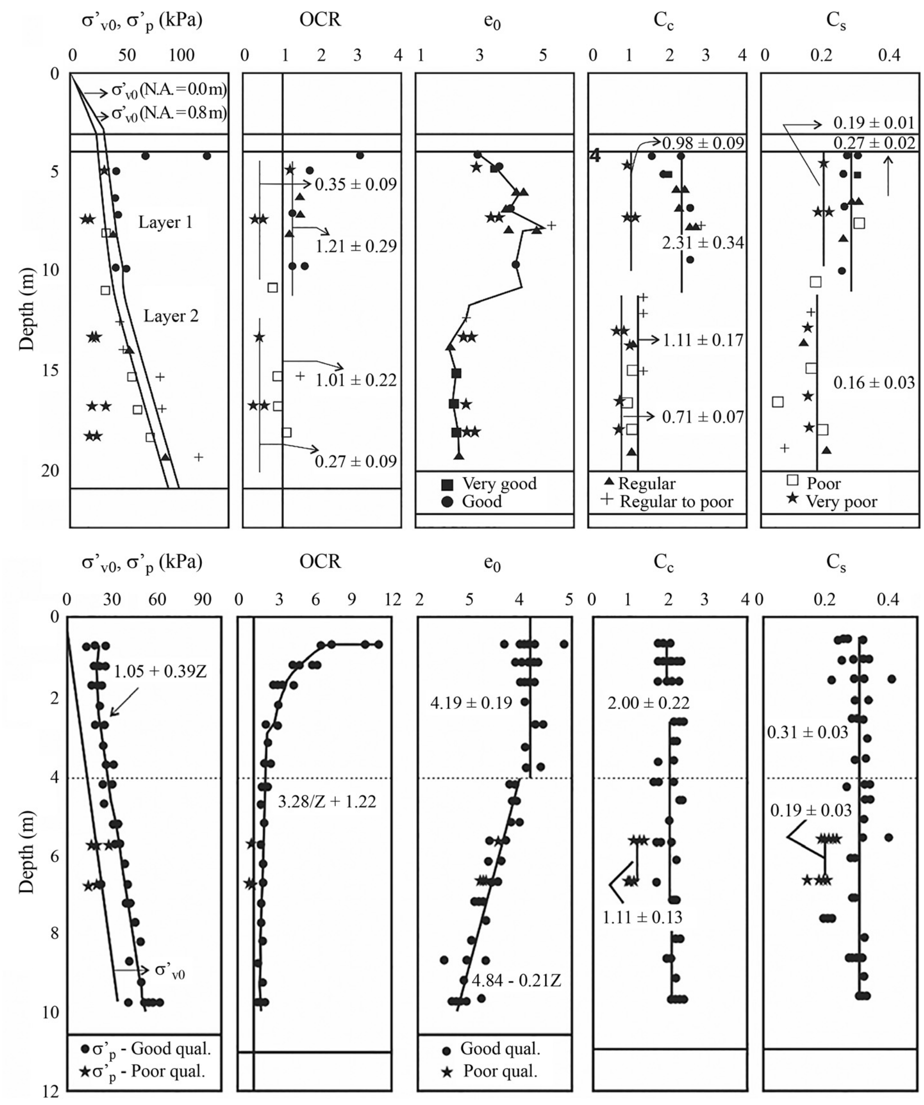


Figure 7 - Compressibility parameters *vs.* depth; (a) SESI-Ibura - Recife (b) Sarapuí-Rio de Janeiro (Oliveira, 2000).

(σ'_p) and OCR, for the samples of better quality were higher compared to the disturbed/poor quality samples. The relationships obtained were as follows: SESI - Ibura: (a) $C_{c\ satisfactory}/C_{c\ poor\ quality}$ = 2.4 for the 1st layer and 1.6 for the 2nd layer; (b) $OCR_{satisfactory}/OCR_{poor\ quality}$ = 3.6 (on average) for both layers; (c) $C_{s\ satisfactory}/C_{s\ poor\ quality}$ = 1.2 for the 1st layer, not varying for the 2nd layer; Sarapuí: (a) $C_{c\ satisfactory}/C_{c\ poor\ quality}$ = 1.8; (b) $OCR_{satisfactory}/OCR_{poor\ quality}$ = 1.8. The initial void ratio (e_0), the influence of the disturbance is not significant, in both deposits.

Ferreira & Coutinho (1988) results show the influence of disturbance on the coefficient of consolidation (c_v), which causes a large drop in c_v values in the recompression region, and a lower quantitative effect in the virgin compression region (Ladd, 1973). In the normally consolidated region the ratios found for mean values of c_v for samples of good quality, poor quality and completely disturbed were for the International Club, 2.3/1.9/1.0; and for Sarapuí, 1.7/1.4/1.0, respectively.

Figure 8 shows correlations between C_C and e_0, considering the sample quality, for the SESI - Ibura and Internacional Club sites. The samples were classified as Very Good to Excellent (VG), Good (G), Regular (R), Transition range between Regular and Poor (T), Poor (P) and Very Poor (VP). In this way, we attempted to perform correlations with all samples obtained, separating what is called satisfactory / adequate quality (VG, G and R) from what is called inadequate quality (T, P and VP). It was also sought to verify the quantitative effect of the transition band (T) on the correlation of samples with satisfactory quality.

It is easily observed in Fig. 8 the effect of sample disturbance in obtaining the C_c. Considering $e_0 = 3.0$, C_c values of 1.67 (SESI - Ibura) and 2.43 (International Club) are obtained for samples of satisfactory quality (VG + G + R) and for very poor samples, values of C_c of 0.88 (SESI - Ibura) and 1.44 (International Club). There was a decrease in the value of C_c of 90% for SESI-Ibura and 70% for the International Club, due to the poor quality of the samples.

Table 2 presents the results of the statistical correlations performed for the two sites of Recife. As can be observed, the correlation coefficients (r^2) are larger for the SESI-Ibura deposit than the International Club results, as the standard deviations are smaller. The quantitative effect of the transition range (T) on the correlation of samples with satisfactory quality was higher for the International Club deposit.

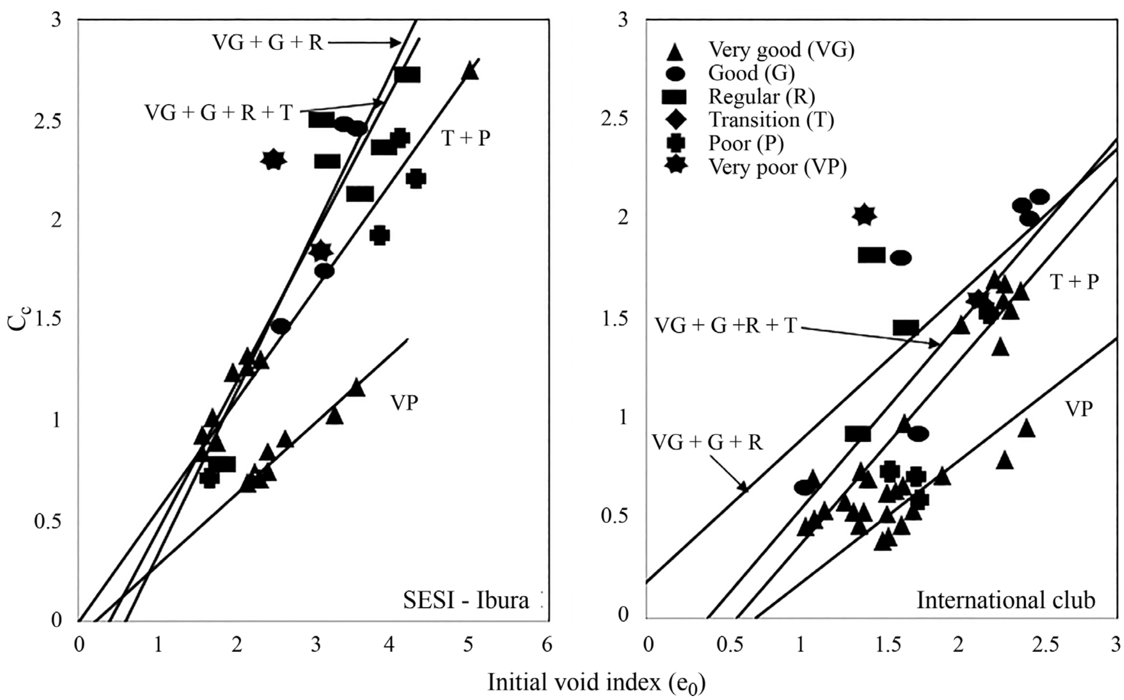


Figure 8 - Statistical correlation between C_c and e_0: SESI-Ibura and International Club - Recife (Coutinho *et al.*, 1998).

Table 2 - Results of statistical correlations for the deposits studied in Recife (Coutinho *et al.*, 1998).

Site	Correlation C_C *vs.* e_0	Equation	r^2	Standard deviation
SESI - Ibura	VG + G + R	$C_C = 0.695\ (e_0 - 0.604)$	0.92	0.18
	VG + G + R + T	$C_C = 0.638\ (e_0 - 0.373)$	0.95	0.16
	T + P	$C_C = 0.520\ (e_0 - 0.011)$	0.96	0.13
	VP	$C_C = 0.308\ (e_0 - 0.127)$	0.88	0.06
International Club	VB + G + R	$C_C = 0.757\ (e_0 + 0.210)$	0.61	0.29
	VG + G + R + T	$C_C = 0.947\ (e_0 - 0.388)$	0.77	0.27
	T + P	$C_C = 0.923\ (e_0 - 0.557)$	0.86	0.17
	VP	$C_C = 0\ 620\ (e_0 - 0\ 668)$	0.64	0.18

5. Evaluation of Sample Quality

5.1. Proposal of Coutinho (2007) from Lunne *et al.* (1997)

A quantitative procedure for evaluation of the quality of samples has been defined by NGI-the Norwegian Geotechnical Institute (Lacasse, 1988). This procedure uses volumetric deformation (ε_{vo}) corresponding to the initial effective vertical stress (σ'_{vo}) (Eq. 1). This criterion was later modified using the ratio $\Delta e/e_0$ by Lunne *et al.* (1997) (Table 3). Lunne *et al.* (1997) justify that a variation in void ratio (Δe) is more detrimental to the soil structure the lower the initial void ratio (e_0). In accordance with the proposal, the relation $\Delta e/e_0$ is used as criterion for evaluating sample disturbance, with Δe being the void ratio variation, and e_0 being the initial void ratio.

$$\varepsilon_{\sigma'_{v0}} = \frac{e_0 - e_{\sigma'_{v0}}}{1 + e_0} \tag{1}$$

Coutinho (2007), from Coutinho *et al.* (1998) and Oliveira (2002), based in Lunne *et al.* (1997) presented a proposal for Brazilian clays (Table 3).

The proposal presents four groups used for the classification of samples: very good to excellent, good to regular, poor, and very poor. Figure 9 shows the volumetric (ε_{vo}) to σ'_{vo} profile obtained in oedometric tests in the two research areas of UFPE (Internacional Club and SESI-Ibura). Results of Sherbrooke samples and completely dented samples were included. The straight vertical line presented corresponds to the limits suggested by Lunne *et al.* (1997), separating the samples in satisfactory to unsatisfactory, for the material investigated.

5.2. Proposal of Futai (2010)

Futai (2010) presented a proposal for evaluation of sample quality through application of a normalized compression curve using data from Brazilian deposits (Fig. 10a). According to this proposal, the normalized curve (ID x $(e_y - e)/e_y$) allows direct evaluation of sample quality, distinguishing between good quality samples, and those remolded or disturbed, for ID > 1 (clays that are normally consolidated).

The restructuring index (ID) is presented in Eq. 2, while Eqs. 3 and 4 make it possible to evaluate sample quality, and make comparisons using the results of compression tests to adopt ID values, or classify them by direct use of the curve limit presented in Fig. 10a.

$$\mathrm{ID} = \sigma'_v / \sigma'_{vy} \tag{2}$$

where σ'_v is the effective pressure, σ'_{vy} is the pressure of the oedometer tests, and e_y is the void ratio in the effective procedure.

Good quality samples must present:

$$0.22 < (e_y - e)/e_y < 0.32 \text{ (for ID = 3)}; \tag{3}$$

$$0.48 < (e_y - e)/e_y < 0.58 \text{ (for ID = 10)}. \tag{4}$$

Table 4 presents values of (ID x $(e_y - e)/e_y$) for Recife and Sarapuí clays taking into account different sample conditions. Good quality samples are situated in the range of recommended values (Eqs. 3 and 4).

The proposals presented by Coutinho (2007) and Futai (2010) were used to classify the soft clay samples from the Suape study areas (Bello, 2011). In the AE-1 and AE-2 study areas, 43% and 62% of the samples, respectively, were classified as being of satisfactory quality according to the Coutinho (2007) proposal (Table 5).

In spite of all the care taken during sampling and handling procedures used for laboratory and field samples, many were still classified as poor and very poor (unsatisfactory). The presence of decomposing material in the study area, as well as the difficulties encountered when dealing with this type and consistency of soil, causes greater difficulty when attempting to obtain good quality samples.

6. Correction of compression parameters to account for sample disturbance

Three proposals for correction of the effects from disturbance of the samples are presented and discussed in this study: (a) Schmertmann (1955)-construction of the field curve; (b) Oliveira (2002) - construction of new laboratory compression curves (c) Coutinho (2007) - correction of compression ratio (CR) and overconsolidation ratios (OCR) or σ'_{vm} parameters.

Table 3 - Proposed criteria for evaluation of sample disturbance by Coutinho (2007) and Lunne *et al.* (1997).

Overconsolidation ratio	$\Delta e/e_0$ (Coutinho 2007)			
(OCR)	Very good to excellent	Good to regular	Poor	Very poor
1-2.5	< 0.05	0.05-0.08	0.08-0.14	> 0.14
	$\Delta e/e_0$ (Lunne *et al.*	1997)		
(OCR)	Very good to excellent	Good to regular	Poor	Very poor
1-2	< 0.04	0.04-0.07	0.07-0.14	> 0.14
2-4	< 0.03	0.03-0.05	0.05-0.10	> 0.10

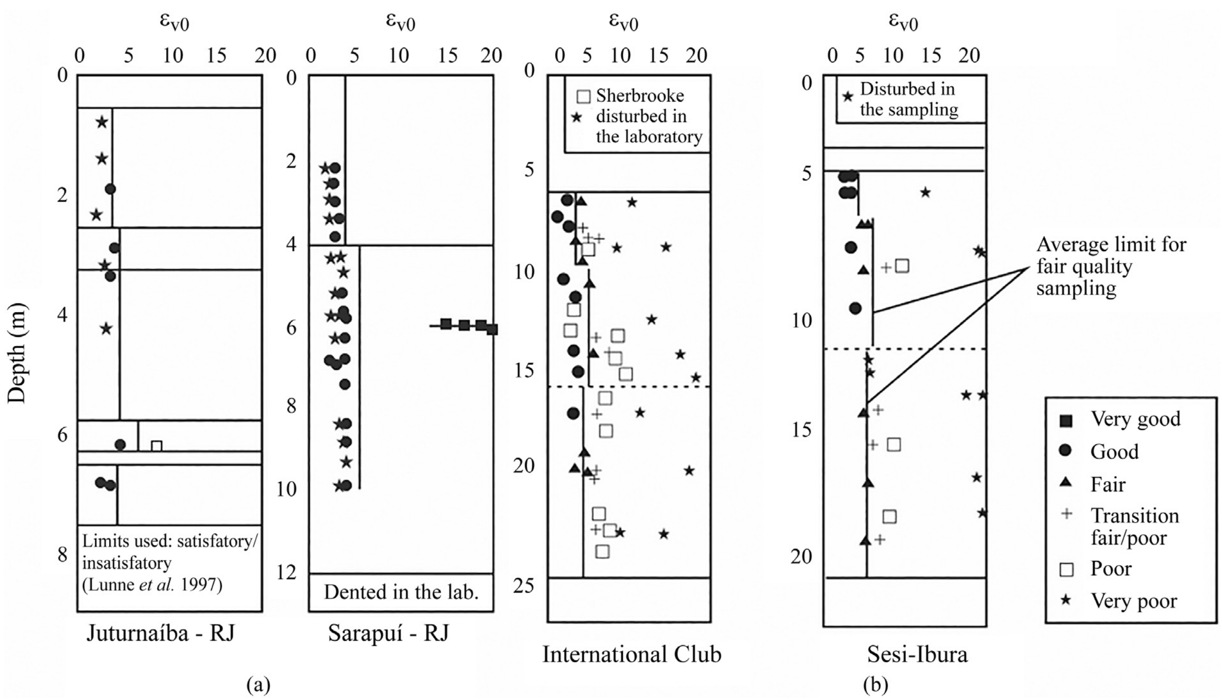


Figure 9 - Sample quality classification: (a) Rio de Janeiro deposits; (b) research areas of Recife (from Coutinho *et al.*, 1998; Oliveira, 2002).

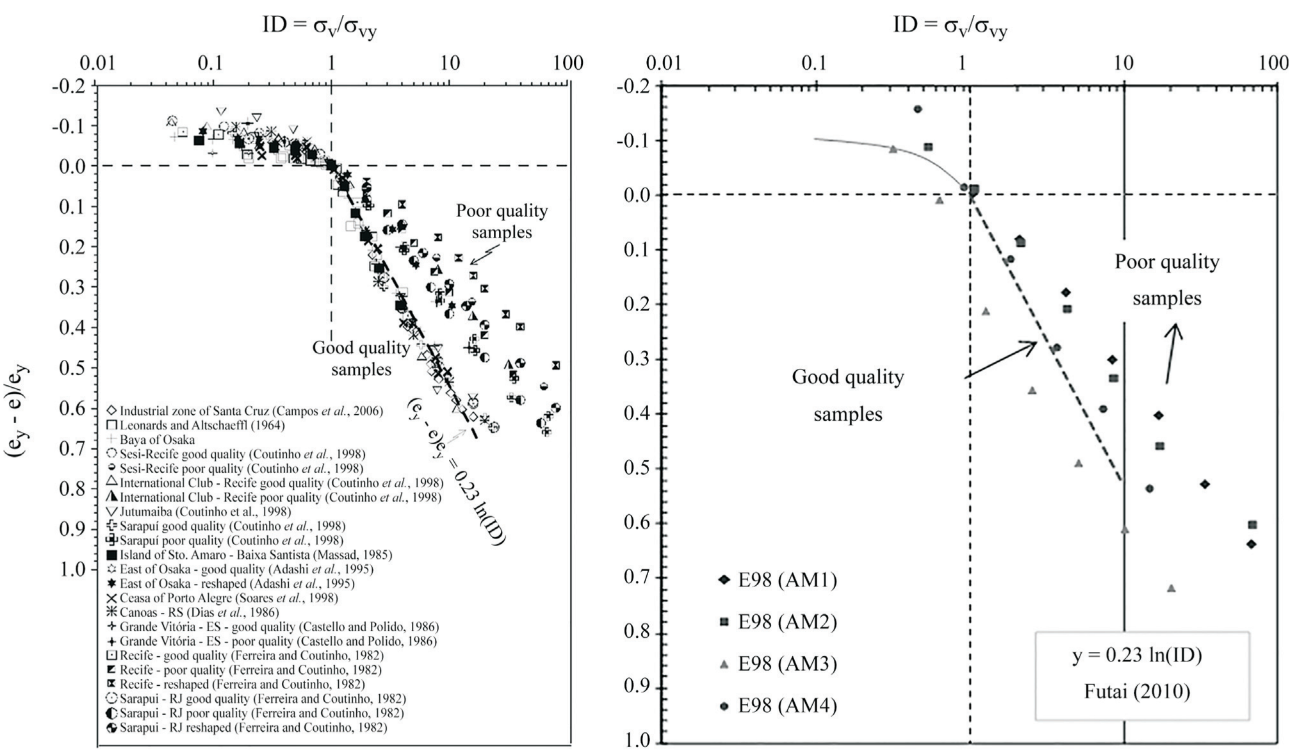


Figure 10 - (a) Standard compression curves of good and poor quality curves (Futai, 2010); (b) Evaluation of sample quality, proposal Futai (2010): Suape study area AE-1 - E98 (Bello, 2011).

Table 4 - Evaluation of sample quality (Futai, 2010).

Local and reference	Sample quality	$(e_y - e)/e_y$	
		ID = 3	ID = 10
Recife (Ferreira & Coutinho, 1988)	Completely disturbed	0.07	0.20
	Poor quality	0.12	0.31
	Good quality	0.25	-
Rio de Janeiro (Ferreira & Coutinho, 1988)	Completely disturbed	0.10	0.30
	Poor quality	0.16	0.37
	Good quality	0.25	0.50

Table 5 - Classification of sample quality according to Coutinho (2007) proposal: results of Suape (Bello, 2011).

Areas	Classification	Samples	(%)
AE-1 30 samples	Very good to excellent	4	13.3
	Good to regular	9	30.0
	Poor	13	43.3
	Very poor	4	13.3
AE-2 50 samples	Very good to excellent	5	10.0
	Good to regular	26	52.0
	Poor	15	30.0
	Very poor	4	8.0

A comparative study was performed with the objective of verifying the efficiency of corrections for geotechnical parameters/compression curves. The results obtained were then compared with experimental values/curves from good quality samples.

6.1. Schmertmann proposal (1955)

The Schmertmann (1955) proposal made it possible to predict the curve for field compression. The pre-consolidation pressure (σ'_{vm}) can be corrected in an interactive manner, using the void ratio (e_0) in the oedometer curve as a base for differentiation between the corrected and laboratory curves for different pre-consolidation pressure values. The symmetry point of the curve e_0 supposedly represents the actual preconsolidation pressure (without disturbance).

Oliveira (2002) evaluated the effect of the Schmertmann (1955) correction on the good, poor quality curves constructed through the abacus for the three clays (Sarapuí, Ibura and Juturnaíba) by estimating the relationship between the other pre-consolidation curves and the preconsolidation stress of the good quality curve corrected by Schmertmann (1955), which was taken as a reference (Table 6). The same was done for the compression ratio of the first straight stretch (C_{C1}). By analyzing the data in this ta-

Table 6 - Geotechnical parameters obtained from the curves corrected by the Schmertmann (1955) methodology (good and poor quality experimental and built by the abacus) (Oliveira, 2002).

Clay	Curve	σ'_{vm}	C_{c1}	C_r	Relation of C_{c1}/C_{c1} good quality	C_r/C_r good quality
Sarapuí (e_0 = 3.54)	Good quality	42	2.9	0.33	1	1
	Poor quality	25	1.64	-	0.75	0.59
	Built by abacus	40	1.94	0.33	0.95	0.67
SESI-Ibura (e_0 = 3.84)	Good quality	55	2.75	0.20	1	1
	Poor quality	42	1.96	0.22	0.76	0.71
	Built by abacus	40	2.14	0.20	0.72	0.78
Juturnaíba (e_0 = 4.24)	Good quality	40	2.24	0.23	1	1
	Built by abacus	32	2.49	0.23	0.80	1.11

ble, it can be seen that the σ'_{vm} and C_{C1} ratios of the abacus-constructed curves corrected by Schmertmann (1955) range from 0.72 to 0.95 for σ'_{vm} and from 0.67 to 1.11 for C_{C1}. This means that the curves constructed by the abacus and corrected by the Schmertmann (1955) methodology, can reproduce these parameters in at least 67% of their value corrected from good quality experimental curves, the results being well above a poor sample quality. The correction still approximates the curves of good quality and built by the abacus.

By removing the poor quality samples, the mean corrections and ranges of variation for each parameter are: (a) Pre-consolidation pressure σ'_{vm}: average of 25% for more and range of 8-39%; (b) Compression index C_{C1}: average of 16% for more and range of 8-26%; (c) C_r recompression index: mean of 20% for less and range of -68 to + 50%.

Jamiolkowski *et al.* (1985) state that the correction typically increases between 10 and 20% the value of the compression index C_c for samples of good quality of soft and medium clays. In the clays studied by Oliveira (2002), the results obtained for good quality samples are within this range (8-16%). Oliveira (2002) also comments that some authors recommend that Schmertmann (1955) correction be made, as Jamiolkowski *et al.* (1985), while Lunne *et al.* (1997) only cite its existence without detailing or recommending its use. Recently, Almeida & Marques (2010) indicate the correction of Schmertmann (1955) in the compression curves.

Bello (2011) presents in Figs. 11a and 11b the experimental oedometer curves representing good and poor quality samples, together with the corrected curves according to the proposal from Schmertmann (1955). In good quality samples, a small correction is observed in the compressibility parameters, however in poor quality samples significant correction of these parameters is noted. The curves corrected by the Schmertmann methodology (1955) are always above the good quality curves.

6.2. Oliveira proposal (2002)

Oliveira (2002) suggested a simple method for construction of a proper oedometer curve, using the results of oedometer tests performed in Sherbrooke soft clay samples from Rio de Janeiro and Recife. These curves are compared with the experimental curves, and can be used to estimate the first calculations. The method adopts the initial void ratio for use as input data, since its value is approximately constant, and does not depend on disturbance. A calculation method was developed for the curves considering the final and initial void ratio (e_f/e_0) *vs.* the initial void ratio (e_0) for each stress normally used in the laboratory (Fig. 12).

The following steps describe the methodology needed to construct the curve: (a) identify the void ratio of the sample; (b) enter the void ratio into the calculations in order to determine the e_f/e_o relation for each stress normally used in the oedometer tests; (c) calculate the final void ratio for each load period; (d) construct a new oedometer curve.

The abacus proposed by Oliveira (2000) has the objective of constructing curves equivalent to those of good experimental quality, which are not free of even slight denting. The compressibility parameters are corrected by rereading the oedometric curve.

In order to evaluate this proposal, Oliveira (2000) selected samples from three Brazilian clays: Sarapuí-RJ, Ibura-PE and Juturnaíba-RJ. The constructed curves are shown in Figs. 13 (a), (b) and (c), together with experimentally obtained oedometric curves.

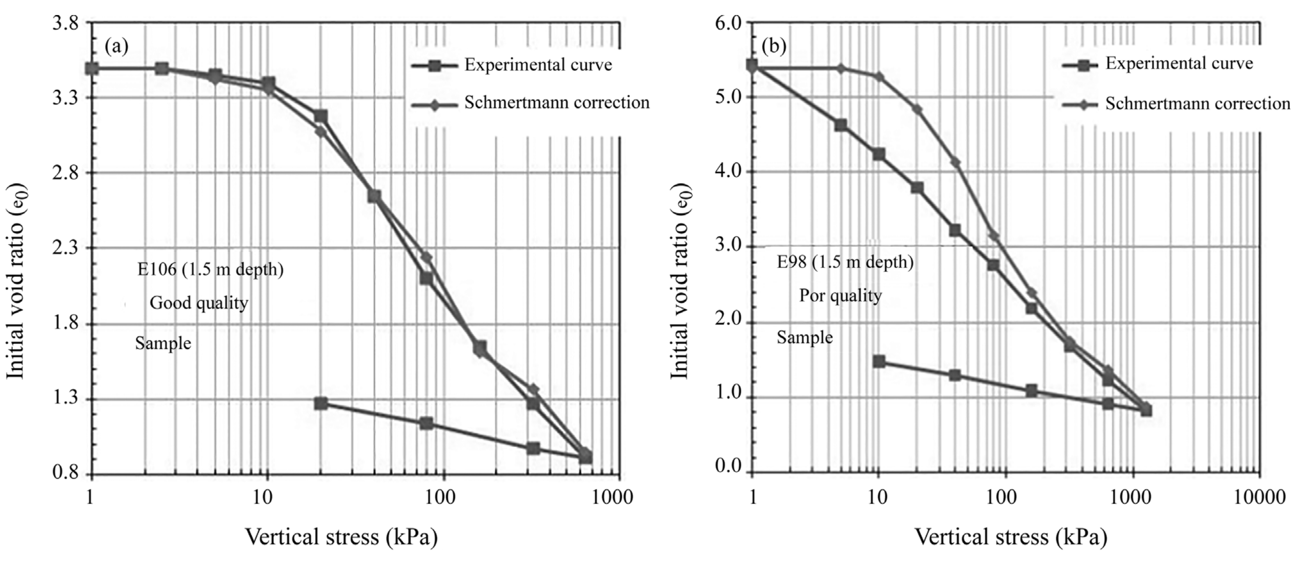


Figure 11 - Experimental oedometer curves, and curves constructed by Oliveira (2002) calculations: (a) good quality, AE-1 study area; (b) poor quality, AE-2 study area (Bello, 2011).

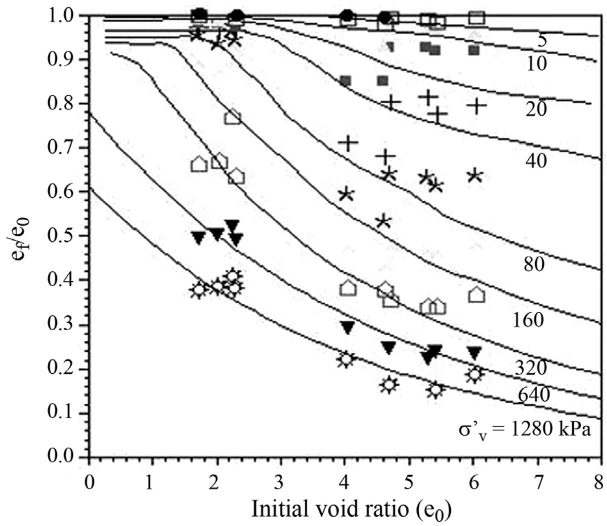


Figure 12 - Calculations used to construct the oedometer curve (Oliveira, 2002).

The curves constructed from the proposed abacus approximated the experimental curves of good quality. In the case of Sarapuí clay, the agreement between the good quality curves and those built by the abacus is very good at low stress, up to about 100 kPa; from this value the agreement reduces, presenting a smaller setback. In the Ibura clay, the curve constructed by the abacus lies below the experimental curve up to about 160 kPa, when the curves meet. Despite this fact, the curves have good agreement. In both cases, the shape of the curves is similar and distinct from the poor quality curve. In the Juturnaíba clay, the curves are practically parallel from the stress of 20 kPa, with a final void ratio difference for each pressure, approximately equal to 0.3 (or 7% of the initial void ratio e_0 = 4.24), in the sense of greater (see results in Table 7).

Figure 14 presents curves constructed by using the calculations based on experimental oedometer curves obtained in good and poor-quality samples from the Suape study areas (Bello, 2011; Coutinho & Bello, 2012). The curves produced from the calculations feature characteristics of curves from good quality samples. The compressibility parameters are obtained from the corrected curve.

Table 8 presents geotechnical parameters obtained from the experimental curves, and the curves constructed from the Oliveira (2002) calculations. The experimental recompression index (C_s) is greater than that of the constructed curve. The experimental preconsolidation stress and the compression index (C_c) are smaller than that of the constructed curve. In the AE-1 study area, the C_s, σ'_{vm}, C_c relations (experimental curves / curves constructed) varied from 1.25 to 3.17 for C_s, from 0.23 to 0.94 for σ'_{vm} and from 0.55 to 0.97 for C_c. In the AE-2 study area, the C_s, σ'_{vm}, C_c relations varied from 1.80 to 3.89 for C_s, from 0.19 to 0.80 for σ'_{vm}, and from 0.51 to 0.99 for C_c. The results show an improvement in the constructed curve, particularly for those relating to poor quality samples. Considering the previous studies performed by Oliveira (2002) and the results obtained for Suape soft clays, the potential can be seen for this methodology, along with its usefulness in correcting the oedometer curves, and obtaining compressibility parameters that correspond to good quality samples.

6.3. Proposal of Coutinho (2007)

Coutinho (2007) presented a correction proposal based on the relation involving the compression ratio (CR) and the overconsolidation ratio (OCR) with specific defor-

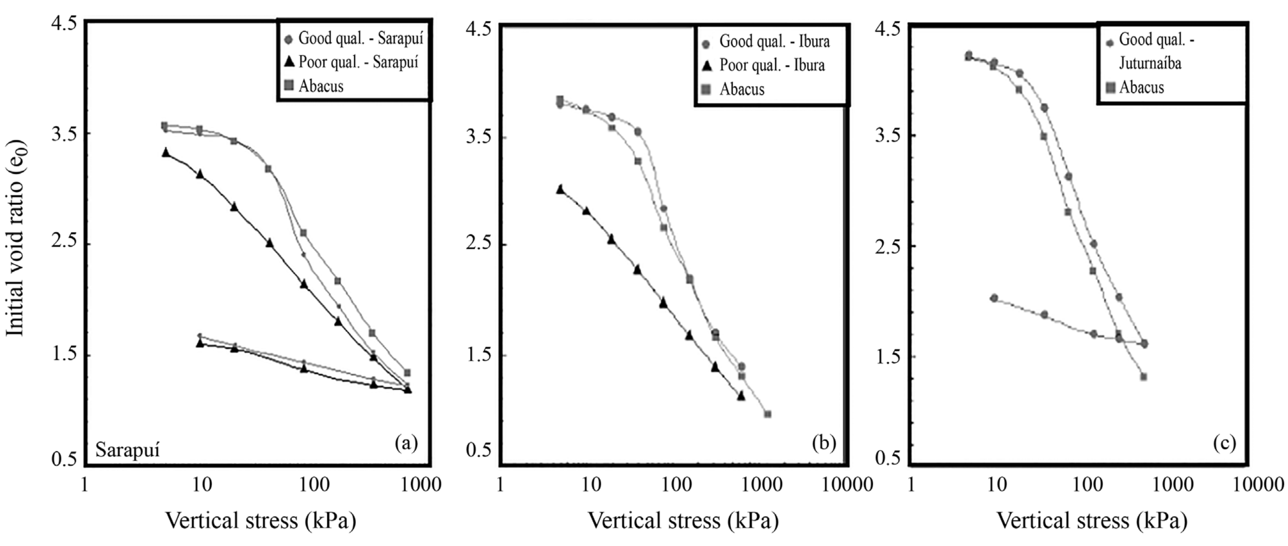


Figure 13 - Experimental oedometer curves (Coutinho *et al.* (1998) and constructed by the abacus (good and poor quality): (a) (e_0 = 3.54), Sarapuí; (b) (e_0 = 3.84), SESI-Ibura; (c) (e_0 = 4.24), Juturnaíba (Oliveira, 2002).

Table 7 - Geotechnical parameters obtained from the experimental oedometric curves and constructed by the abacus (Oliveira, 2002).

Clay	Curve	σ'_{vo}	C_{c1}	C_r (beginning of the curve)	Relation of to σ'_{vo} good quality	Relation of to C_{c1} good quality	C_r/C_r good quality
Sarapuí (e_0 = 3.54)	Good quality	39	2.5	0.12	1	1	1
	Poor quality	21	1.12	0.63	0.54	0.45	5.25
	Built by abacus	30	1.6	0.22	0.77	0.64	1.83
SESI-Ibura (e_0 = 3.84)	Good quality	43	2.55	0.16	1	1	1
	Poor quality	11	0.95	0.68	0.26	0.37	4.25
	Built by abacus	32	1.84	0.50	0.74	0.72	3.12
Juturnaíba (e_0 = 4.24)	Good quality	33	2.03	0.27	1	1	1
	Built by abacus	23	1.98	0.48	0.70	0.98	1.78

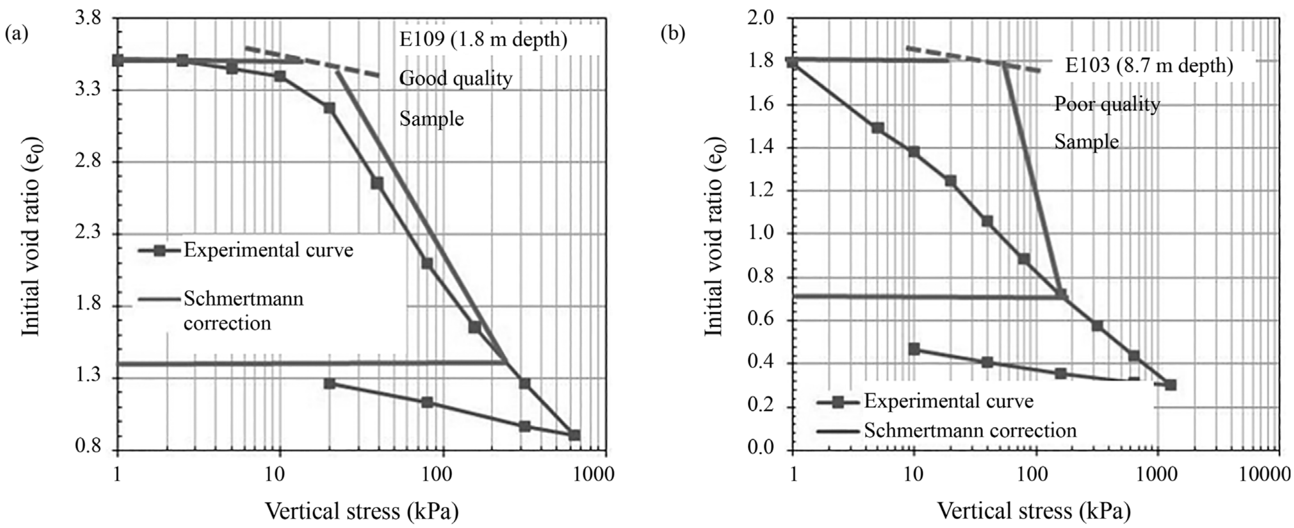


Figure 14 - Experimental curves and curves constructed by use of the Schmertmann proposal (1955): (a) good quality, study area AE-2; (b) poor quality, study area AE-1 (Bello, 2011).

Table 8 - Corrected compressibility parameters values from Oliveira (2002) proposal: AE-2 study area, Suape (Bello, 2011).

Vertical	Depth (m)	σ'_{vo}	Classification Coutinho (2007)	Parameters							
				Experimentals				Corrected (Oliveira, 2002)			
				σ'_{vm}	OCR	C_c	C_s	σ'_{vm}	OCR	C_c	C_s
SP102	1.5	6.2	Good to regular	20.0	3.2	0.8	3.1	30.0	4.84	0.81	1.80
	6.0	15.2	Good to regular	9.0	0.6	1.3	0.2	12.0	0.79	1.31	0.17
SP105	5.5	27.3	Poor	6.0	0.2	1.1	0.1	14.0	0.51	1.25	0.08
SP106	4.5	19.5	Good to regular	6.0	0.3	1.4	0.2	32.0	1.64	1.51	0.18
SP109	6.3	30.0	Very poor	16.0	0.5	2.1	0.4	18.0	0.60	2.50	0.09
SP123	1.7	6.1	Poor	12.0	2.0	0.6	0.1	26.0	4.26	0.86	0.10
SP121	2.5	19.6	Poor	16.0	0.8	1.6	0.2	45.0	2.30	2.45	0.19
SP128	3.5	10.5	Poor	13.0	1.2	0.9	0.2	20.0	1.90	1.10	0.17
SP137	0.4	5.5	Poor	8.0	1.5	1.8	0.2	20.0	3.64	3.60	0.07
SP138	2.9	5.7	Good to regular	10.0	1.8	2.0	0.4	20.0	3.51	3.80	0.22
	3.9	11.1	Very poor	20.0	1.8	2.2	0.2	25.0	2.25	2.30	0.12

mation (ε_{vo}), that represents the quality of the sample. A greater decrease can be verified in the CR and OCR values when ε_{vo} increases and a minimum limit exists where the samples are almost totally disturbed.

Figures 15a and 15b show, respectively, the compression ratio (CR) and overconsolidation ratio (OCR) *vs.* ε_{vo} for the SESI-Ibura deposit. Coutinho *et al.* (1998) and Coutinho *et al.* (2000) comment that, as expected, CR and OCR values decrease strongly when ε_{vo} increases. There is a minimum limit for CR values (20%) and for OCR values (0.25), where the samples are almost completely dented. This type of correlation may be useful for an approximate correction of CR and OCR values, considering the quality of sampling in practical projects. In this type of work, the sampling process often does not utilize the recommended procedures and field teams with adequate training.

Figures 16 (a) and 16 (b) present the correlations between CR and σ'_{vm} *vs.* ε_{vo}, respectively, for the AE-2 study area (SUB-AREA A). Each layer is represented by a curve correlating to soft soil deposits containing different compressibility layers (different CR and σ'_{vm} values for each layer). Results found in SUB-AREA A seem consistent with the observations of Coutinho (2007) on the behavior of soft clays of Recife. The relation between the value of σ'_{vm} obtained in samples of good quality and in samples of poor quality was in the order of 3 (considered high), however e_o does not appear to be significantly influenced by the quality of the sample.

The results obtained in the Suape areas showed reasonable correlations of CR and σ'_{vm} *vs.* ε_{vo} for soft layers, allowing for correction of the CR and σ'_{vm} values by considering ε_{vo} values corresponding to very good - excellent quality samples. The correction can be particularly important when considering poor quality samples in practical projects.

6.4. Proposal of the normalized oedometric curve presented by Futai (2010)

Futai (2010) proposed to use normalization of the compression curves in calculations of repression. The

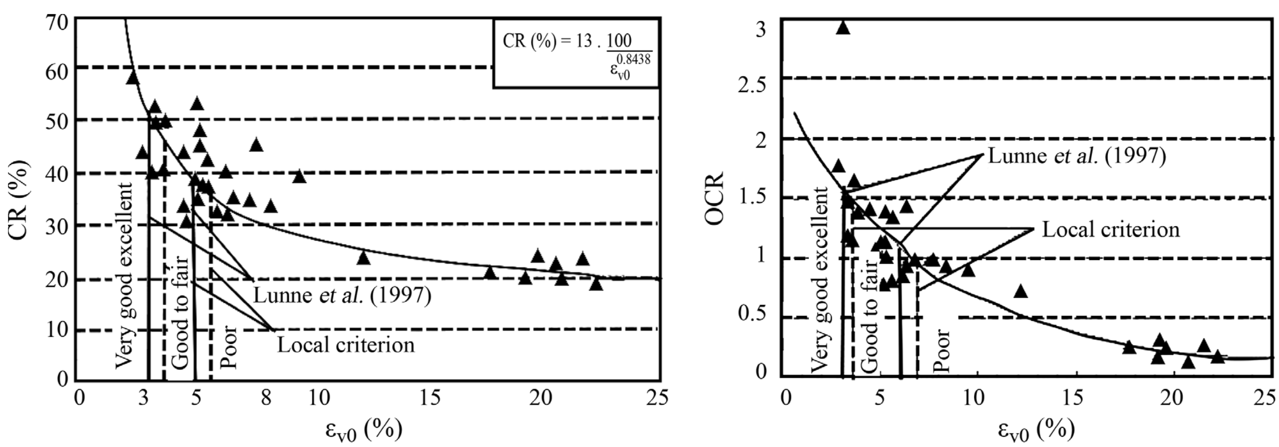


Figure 15 - (a) Curve CR *vs.* ε_{vo} ; (b) Curve OCR *vs.* ε_{vo} for the SESI-Ibura deposit -PE (Coutinho *et al.*, 1998).

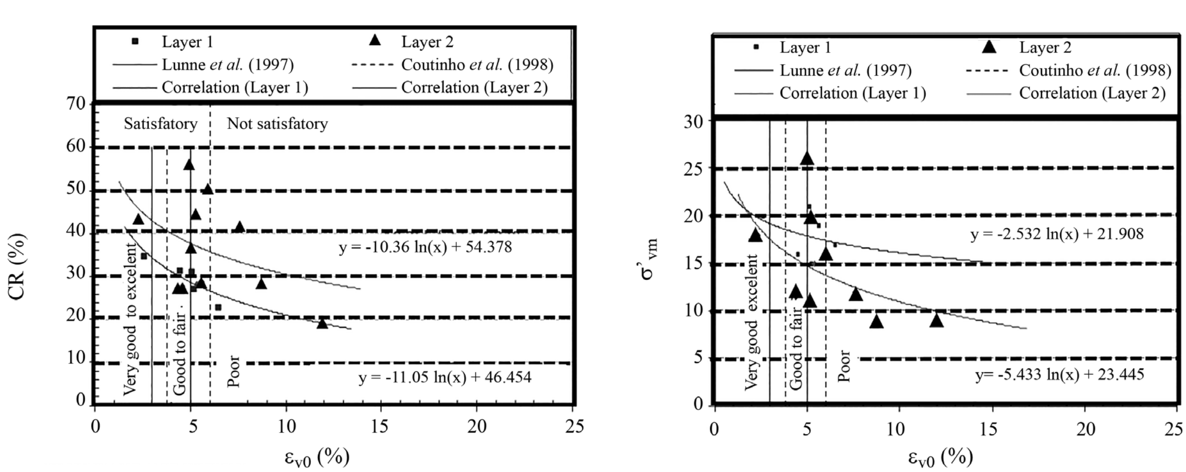


Figure 16 - Evaluation of sample quality, study area AE-2, SUB-AREA A: (a) Curves CR *vs.* ε_{vo}; (b) Curves σ'_{vm} *vs.* ε_{vo} (Bello 2011, from Coutinho *et al.*, 1998; Coutinho, 2007).

equations to estimate settlements do not require the values of C_c ou $C_c/(1 + e_0)$ and nor of correlations. It is only necessary to know the initial void ratio, the history of stress and the loading. Therefore, the author believes that this is a more rational way of calculating settlements, and emphasizes the need to verify if the normalized compression curve of the soil falls within the classification range of good quality sample before applying the proposed calculation of setbacks. However, the author does not comment on the correction of sample curves classified as poor quality for use in the calculation of settlements.

From the data of tests in clays of different Brazilian localities and collected in the international literature, Futai (2010) applied the normalization of oedometric compression curves to evaluate the sample quality.

In the proposal, two sections were considered: ID > 1 (usually consolidation), and ID > 1 (final vertical stress greater than the yield stress). The normalized compression curve, for ID > 1, can be represented by a logarithmic function (Eq. 5). In the section ID < 1, the relation is linear, and the field void ratio is used as reference (Eq. 6).

$$e = e_y \,.\, (1\text{-}\ \xi .\ \ln\,(\mathrm{ID})) \tag{5}$$

$$\frac{e_y - e}{e_y} = \chi.(\mathrm{ID}_0 - 1) \tag{6}$$

where ξ is an adjustment coefficient equal to 0.23, and χ is the angular coefficient of the line equal to 0.06.

And so it is possible to calculate the void ratio for yielding (Eq. 7).

$$e_y = \frac{e_0}{1.06 - (0.06\mathrm{ID}_0)} \tag{7}$$

where ID_0 equals the relation of the effective vertical field stress (σ'_{vo}) with the yield stress (σ'_{vy}).

Based on these criteria, it is suggested that samples that were not included in the good quality bands proposed by Futai (2010), be corrected to obtain a new value of the yield stress (σ'_{vy}). In Eq. 7, the parameters e_0, ID_o and σ'_{vo} are known, as well as σ'_{vy} obtained directly from the test, thus obtaining e_y in a simple way. In the second stage of the procedure, Eq. 5 would be used, since it is a reference for samples of good quality. The void ratio used would correspond to the final loading pressure, where it coincides with the reference line. By developing the equation, we arrive at the value of the yield stress.

Table 9 shows the results of the σ'_{vm} correction by the proposed Futai standard curve (2010) obtained in the AE-1 study area (E98 and E137) and in the AE-2 study area (E109 and E138, together with the results of the correction proposed by Oliveira (2002).

Table 9 - Correction of the preconsolidation stress according to criteria of Futai (2010)-Suape (Bello, 2011).

Stake	Sample	Quality Coutinho (2007)	Pre-consolidation stress σ'_p (kPa)		
			Oedometric	Futai (2010)	Oliveira (2002)
E98	AM1	Poor	9.0	20.4	27.0
	AM2	Very poor	7.0	37.8	30.0
	AM3	Good to regular	4.0	8.9	15.0
	AM4	Very good	6.0	16.8	19.0
E137	AM1	Good to regular	21.0	19.91	22.0
	AM2	Poor	22.0	23.34	26.0
	AM3	Very good	9.0	14.91	13.0
	AM4	Good to regular	35.0	40.47	36.0
	AM5	Good to regular	30.0	42.23	31.0
E109	AM1	Good to regular	19.0	25.9	21.0
	AM2	Good to regular	16.0	17.97	17.0
	AM3	Good to regular	20.0	21.02	22.0
	AM4	Good to regular	26.0	25.37	26.0
	AM5	Very poor	16.0	26.51	18.0
E138	AM1	Good to regular	8.0	15.12	12.0
	AM2	Very poor	10.0	16.47	20.0
	AM3	Good to regular	14.0	25.26	17.0
	AM4	Very poor	20.0	22.30	23.0
	AM5	Good to regular	28.0	30.10	28.0

In samples of good quality the proposal reached values of σ'$_{vm}$ higher than the values obtained experimentally. In samples of poor quality the values of σ'$_{vm}$ corrected by the proposal were significantly higher than the values obtained experimentally. Comparing the proposed correction of σ'$_{vm}$ with the Futai (2010) normalized curve and the proposal for the construction of new oedometric curves suggested by Oliveira (2002), the results of σ'$_{vm}$ were alternated in each sample tested, concluding that in the application of the two corrections satisfactory results can be obtained.

The proposed correction of σ'$_{vm}$ by the normalized curve of Futai (2010) constitutes a tool of simple application to obtain values of σ'$_{vm}$ not influenced by the molding. In general the results of the application of the σ'$_{vm}$ correction by the normalized curve were stimulating in Suape soft clays. It is suggested to use in other Brazilian clays reported in the literature.

The initial proposal of Futai (2010) had as objective to use air standard curves to evaluate samples and calculate settlements. It is only necessary to know the initial void ratio, the stress history and the loading. Apparently there was no interest in constructing the curves to obtain other parameters. In this work, it is suggested to construct the corrected oedometric curves from this proposal to obtain the parameters.

Bello (2011) and Coutinho & Bello (2012) comparing the results of the correction proposal for Suape soft clay samples, made some observations:

(a) The Oliveira (2002) proposal amounts to a simple procedure, where only the initial void ratio and the oedometer test pressures are needed. All of the curve's corresponding points must be determined. Considering the studies carried out by Oliveira (2002) applied in the clays of Recife, Juturnaíba and Sarapuí, and the results found in the clays of Suape, the potential of the proposal for correction of the oedomometric curves is verified.

(b) The σ'$_{vm}$ value obtained by the Schmertmann (1955) proposal was practically unmodified when considering good quality samples. A significant difference was observed in the σ'$_{vm}$ corrected value when dealing with poor quality samples.

(c) In the Coutinho (2007) proposal, it was possible to obtain corrected CR and OCR values by considering the ε_{vo} value corresponding to very good and excellent quality samples. Correlations for each soft soil layer of the deposit must be constructed.

Figure 17 for the AE-1 Suape study area shows a comparison between the experimental oedometer curve (poor quality samples), and the curves constructed by the Oliveira (2002) calculations and Schmertmann proposal (1955) (Coutinho & Bello, 2012). It can be observed that the corrected curve for good quality experimental samples approximates the Schmertmann (1955) curve (field curve). The σ'$_{vm}$ values obtained from the two corrected curves are similar (around 24 kPa), and the recompression ratio is slightly greater in the Schmertmann curve.

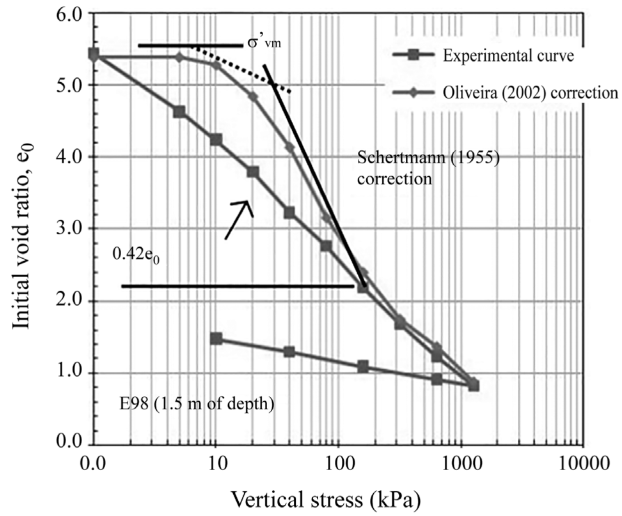


Figure 17 - Oedometer curve and curves constructed by Oliveira (2002) and Schmertmann (1955) proposals (Coutinho & Bello, 2012).

7. Correction of Strength Parameters to Account for Sample Disturbance

For correction of the value of S_u is proposed the use of the relationship of resistance (S_u/σ'$_{vm}$) *vs.* the IP plasticity index. The values of σ'$_{vm}$ are considered corrected for the effect of the sample's denting (see Schmertmann, 1955; Oliveira, 2000; Coutinho, 2007; Futai, 2010).

Figure 18 shows the relation $S_{u\,vane}$/σ'$_{vm}$ *vs.* IP proposed by Mesri (1975), Coutinho *et al.* (2000) modified from Skempton (1957), Larsson (1980) and Mayne & Mitchell (1988), together with the mean values of various Brazilian clays, including Recife and Suape (SUB-AREAS A and C). For Recife and Suape clays, the points fall between the correlations of Larsson (1980) and Mesri (1975), forming upper and lower limits respectively. The proposal from Coutinho *et al.* (2000) represents clays from Recife, Juturnaíba-RJ, Sarapuí-RJ and satisfactorily for Suape. The poor quality samples had the σ'$_{vm}$ value corrected (see Coutinho & Bello, 2012; Bello, 2011).

The equation of the resistance relationship obtained by Coutinho *et al.* (2000) modified from Skempton (1957) is proposed in this work to be used as a criterion for correcting the value of S_u. Table 10 presents a summary of the results of the S_u correction of Suape's AE-1 study area. The corrected S_u values were around ± 16% higher in relation to the S_u values obtained in the field vane tests.

This new proposal constitutes an efficient tool and easy to apply to obtain the S_u value, indicative of samples of good quality.

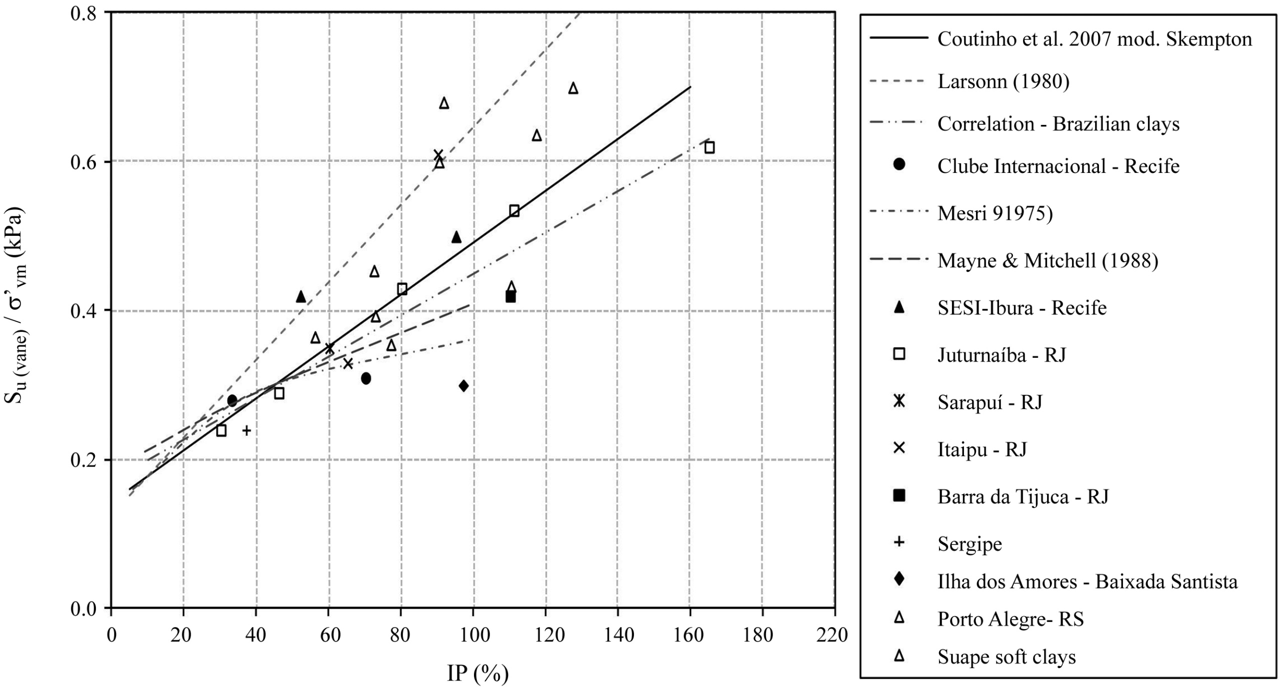


Figure 18 - Resistance ratio several brazilian soft clays: $S_{u\ vane}/\sigma'_{vm}$ and IP (Coutinho *et al.*, 2000; Coutinho & Bello, 2012).

Table 10 - Summary of S_u values corrected according to Coutinho *et al.* (2000) modified from Skempton (area of study AE-1 - Suape).

	$S_{u\ vane}/\sigma'_{vm}$	Equation (Coutinho *et al.*, 2000 apud Skempton, 1957)	σ'_{vm}	IP	$S_{u\ vane}$	$S_{u\ corr}$
1st stretch	0.30	0.539	27.0	116.04	8.20	14.56
	0.73	0.546	20.0	117.72	14.60	18.91
	0.27	0.469	17.0	96.92	4.53	7.97
	0.26	0.391	30.0	75.91	7.90	11.73
	0.15	0.421	29.2	83.98	8.00	12.29
	0.27	0.373	33.0	71.11	8.82	12.31
2nd stretch	0.34	0.557	31.0	120.93	10.51	17.28
	0.47	0.535	25.8	114.83	12.04	13.80
	0.69	0.527	28.4	112.65	14.71	14.96
	0.43	0.495	22.0	104.15	9.40	10.90
	0.28	0.591	21.0	130.00	6.00	12.41

8. Conclusions

This study presented and discussed results from sample quality evaluations, and correction of the effects of sample disturbance of Brazilian soft clays.

Results from the Coutinho (2007) and Futai (2010) proposals were similar, and may be considered satisfactory for evaluating and quantifying the quality of Suape soft clay samples. Overall, within this study, more than 50% of the samples were classified as being of satisfactory quality (very good to excellent, and good to regular).

The Schmertmann (1955), Oliveira (2002) and Coutinho (2007) proposals were used for correcting the compressibility parameters from samples whose quality was classified as unsatisfactory. The proposals studied for correction use produced parameters corresponding to very good / excellent field curves. The corrections can be particularly important for use with poor quality samples. For use in project, the corrections must be utilized for all of the important parameters, or simply throughout the complete curve.

In a study of sample quality, it is very important to make use of a regional / local data base in order to obtain proper correlations, and to be able to verify standard behavior.

Acknowledgments

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