

Assessment of the Stress History of Quaternary Clay from Piezocone Tests

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Abstract. This paper highlights the importance of linking regional geology to geotechnical ground investigation when estimating the pre-consolidation pressure σ'_p of Quaternary clay deposits from piezocone tests. The work comprises a comprehensive site characterization from boring logs, piezocone tests and laboratory oedometer tests carried out at the Tubarão experimental testing site, in Southern Brazil. Geological characterization includes radiocarbon dating of samples from these clayey sediments. The approach developed at the testing site was later extended to 12 well characterized clay sites along the Brazilian coast to demonstrate that net cone penetration $q_t - \sigma_{v0}$ can provide reliable estimations of pre-consolidation pressure σ'_p in Quaternary plastic, compressible, non-fissured clays. However, the $\sigma'_p/(q_t - \sigma_{v0})$ ratio is not a constant (typically ranging from 0.1 to 0.4) and, as a consequence, pairwise parameter correlations considering σ'_p and $q_t - \sigma_{v0}$ lead to inaccurate predictions. Independent assessment of the void ratio e_0 is needed in order to produce more realistic first order estimates of σ'_p from piezocone data.

Keywords: CPT, overconsolidation ratio, pre-consolidation pressure, stress history.

1. Introduction

Geological and geotechnical assessment of the stress history of clay sediments is regarded as a key stage in the design of geo-infrastructures. Since stress history controls the strength and stiffness of geo-materials, evaluation of the depositional processes of clay deposits linked to geotechnical properties impacts the prediction of long-term consolidation settlements as well as short-term stability problems.

Given the importance of the subject, there has been considerable research developments in the past two decades. Correlations of the stress history pre-consolidation pressure and the net field penetration resistance have been reported (Wroth, 1984; Mayne & Mitchell, 1988; Mayne, 1991) and a critical appraisal of standard engineering practice has been reviewed by recent state-of-the art publications (e.g. Schnaid, 2005; Mayne *et al.*, 2009). However, few comprehensive case studies regarding geological and geotechnical data are available in the literature, and consequences are that engineering practice often adopts simplified, empirical recommendations for the estimation of the pre-consolidation pressure. The limitations of the state-of-practice are highlighted in the present paper by demonstrating that the predicted pre-consolidation pressure σ'_p from the piezocone net field penetration resistance $q_t - \sigma_{v0}$ requires independent assessment of the soil void ratio e_0 .

2. Background Information

The pre-consolidation pressure σ'_p is defined as the maximum effective vertical stress to which a soil has been

subjected along its stress history and is considered as one of the most important parameters required to assess the deformation of soft clays. Often the term is used to define the effective stress at which an undisturbed sample yields during an oedometer test, or it represents the critical stress at which a clayey soil becomes destructured and where the subsequent compression curve is initially steeper than the standard virgin line (e.g. Burland, 1990). For an idealized elasto-plastic soil, σ'_p defines the transition from overconsolidated (OC) to normally consolidated (NC) soil states, characterizing a reloading region where strains are predominantly elastic from a region of irrecoverable plastic strains.

The relative magnitude of the pre-consolidation pressure is often described by a normalized parameter termed the overconsolidation ratio $OCR = \sigma'_p/\sigma'_{v0}$, in which σ'_{v0} is the current effective vertical stress in the ground.

In addition to the oedometer test, σ'_p (or OCR) can be assessed directly from field tests such as through the use of a piezocone, vane or dilatometer following research efforts developed during the 1980s (Marchetti, 1980; Wroth, 1984; Konrad & Law, 1987; Mayne, 1987; Crooks *et al.*, 1988; Mayne & Mitchell, 1988; Mayne & Bachus, 1988; Sandven *et al.*, 1988; Sully *et al.*, 1988). Unfortunately, it is generally recognized that large strain measurements provided by cone penetration or shear torsion are not very sensitive to the *stress history* (e.g. Baldi *et al.*, 1982 Lunne *et al.*, 1997; Schnaid *et al.*, 2016) and disregarding the primary influence of past straining in field measurements in-

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roduces severe limitations in the accuracy of predictive methods of *OCR*.

Acknowledging the approximate nature of the correlations between q_c and *OCR*, a recommended practice to guide engineering judgment is to estimate the *OCR* from the undrained shear strength ratio ($s_u - \sigma'_{v0}$), as suggested by Schmertmann (1978) and Ladd *et al.* (1977). The method consists simply of estimating s_u from the CPT data and σ'_{v0} from soil profile to compute ($s_u - \sigma'_{v0}$). The ratio is then compared to the corresponding normally consolidated undrained shear strength, adopting Shansep's type of approach for comparison (Ladd *et al.*, 1977). Alternatively, predictions of the *OCR* directly from piezocone data can be made using either theoretical solutions or empirically based approaches (Senneset *et al.*, 1982; Wroth, 1984; Konrad & Law, 1987; Tavenas & Leroueil, 1987; Mayne, 1991; Schneider *et al.*, 2001; Long *et al.*, 2010). A brief overview of current practice is presented and discussed herein and new recommendations are provided for Quaternary clay sediments from the experience gathered in Brazil over the last decade.

3. Tubarão Coastline Sediments

Sedimentary deposits formed along the coastline of Brazil are mainly a product of the general Eustatic sea level variations over the last 1 million years, during the so called Quaternary Period (*e.g.* Angulo & Lessa, 1997; Angulo *et al.*, 1999 and 2006; Milne *et al.*, 2005). Sediments from the upper 20 m layers were predominantly formed after the most recent glaciation, during the last 8,000 years in the Holocene Period (Giannini, 1993; Nascimento, 2011). Located in the Southern Hemisphere and relatively close to the equator, these formations in Brazil are not influenced by glacial loading and unloading.

The diverse Holocene morphological features along the coast include lagoons and residual lakes, barriers, deltas and pre-existing incised valleys that have been flooded and filled. The deposition therefore results from transgression integrated bay-lagoon sedimentary systems formed behind a transgressive barrier during the Holocene maximum flooding (Giannini, 1993; Giannini *et al.*, 2007).

The geomorphological evolution of these areas has been comprehensively investigated using a combination of morphology, stratigraphic analysis of rotary push cores, vibracores and trenches with radiocarbon dating, taxonomic determination and taphonomic characterization of Holocene fossil mollusks (Guedes *et al.*, 2011; Giannini *et al.*, 1993, 2007), as well as geotechnical site investigation testing data (*e.g.* Schnaid, 2005; Mantaras *et al.*, 2014; Jannuzzi *et al.*, 2015). Figure 1 is used to illustrate how a bay along the coast evolved over the last 8000 years (Giannini *et al.*, 2010). The Holocene sedimentary succession began with deposits of transgressive sandsheets. These deposits correspond to the initial marine flooding surface that was formed while the relative sea-level rose at a higher rate

than the input of sediments, prior to the formation of the coastal barrier (Fig. 1a). The change from a bay to a lagoon system occurred at approximately 5500 and 4000 cal BP in the mid-Holocene highstand with the formation of the barrier during the falling of the sea level and the achievement of a balance between sea-level and sedimentary supply (Fig. 1b). The presence of this barrier was followed by a gentle decline in sea level and the initial emergence of back-barrier features restricted the hydro-dynamic circulation inside the bay. This geological process transformed the bay into a lagoon system (Fig. 1c). The final stage, during the last 1700 years, was marked by the increase of the back-barrier width, with the establishment of salt marshes, the arrival of the delta in the back-barrier, and the advance of aeolian dunes along the outer lagoon margins (Fig. 1d). These marine-lacustrine environmental conditions resulted in normally consolidated to lightly overconsolidated soft soils with high water content, some organic matter content, high compressibility and low shear strength properties.

Once this geological background is properly understood, specific prediction can be made of the local ground conditions which is generally based on independent results from geotechnical site investigation. Examples of how to link the geological information with the geotechnical data are given and possible interpretations of the stress history are explored.

4. Case Study

A comprehensive site investigation in the Tubarão Lagoon system located in southern Brazil is described as a means of developing possible ways for linking geological and geotechnical sciences. Geotechnical investigation comprises both field and laboratory tests. Piezocone, vane, dilatometer, shear wave velocity and SPT measurements were performed to identify the soil type and stratigraphy. Measured cone resistance q_c , sleeve friction f_s and pore pressure u_z , as well as dilatometer readings p_0 and p_1 are shown in Fig. 2, revealing a typical soil profile with superficial sand-silty layers, overlying an approximately 20 m thick, very soft, essentially normally consolidated clay layer. The normalized soil behavior index I_c proposed by Robertson (1990) and the dilatometer material index I_b proposed by Marchetti (1980) are also shown in Fig. 2. These indices are essentially CPT and DMT predictive methods of Soil Behaviour Type based directly on q_c and f_s measurements for the CPTU or on p_0 and p_1 pressures for the DMT.

The superficial layer 2 m to 3 m in thickness is characterized as silty-sand and sandy-silt soils ($1.90 < I_c < 2.82$), from 3 to 6 m the soil is predominantly sandy-silt, and below 6 m, the soil is typically clay ($2.82 < I_c < 3.22$). The piezometric profile is approximately hydrostatic with groundwater at a depth of 1 m. Shear wave velocity measurements and cone resistance show monotonic increase with depth. The Atterberg Limits and the *in situ* water contents are shown in this figure, a common feature begin that

water content is generally slightly greater than the liquid limit, and both are relatively constant with depth.

Thin wall, *stationary piston samplers* were used to retrieve undisturbed samples at depths of 5, 9, 13 and 16 m,



Figure 1 - The Tubarão Quaternary depositional system representative from the mid-south coast of Brazil (1-Rocky headlands or bedrock; 2-Sand Barrier and Back-barrier; 3-Delta Plain (modified from Giannini, 1993 and Carvalho do Amaral *et al.*, 2012). a) Deposits of transgressive sandsheets. b) Change from a bay to a lagoon system. c) Lagoon system. d) Current coastal conditions.

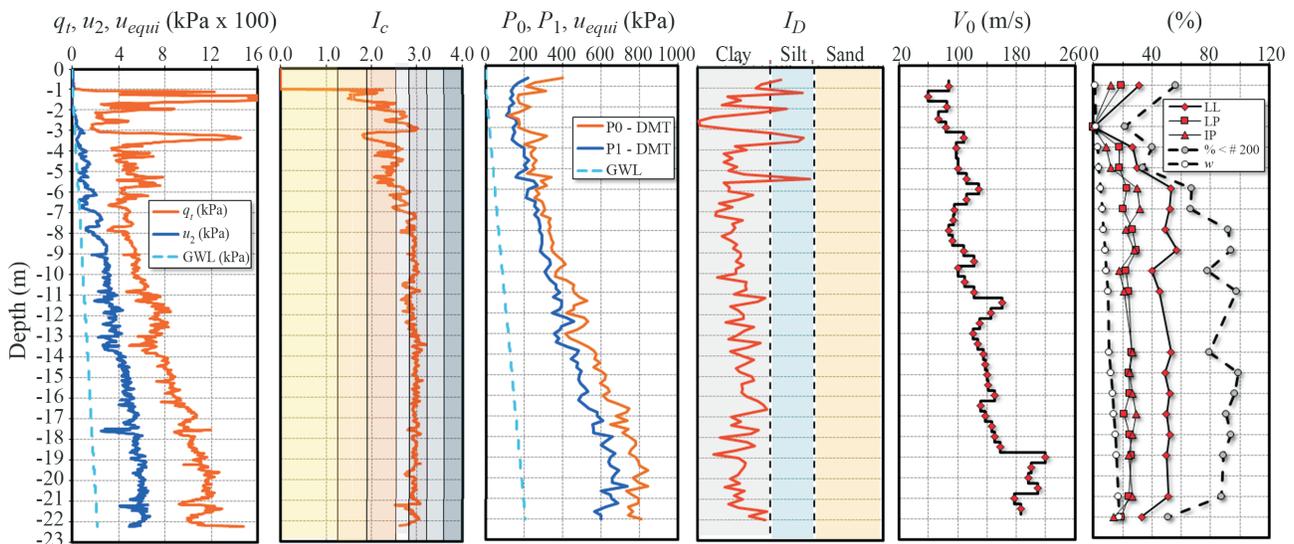


Figure 2 - Typical soil profile from CPTU and DMT measurements.

according to ASTM D1587 (2000). Incremental loading oedometer tests were performed according to the ASTM D2435 (2011) standard to determine the pre-consolidation pressure σ'_p , the compression index C_c , the recompression index C_r and the coefficient of consolidation c_v .

Figure 3 combines the geotechnical profile to the paleoenvironmental reconstruction of the lagoon system of the area. Elemental and isotopic carbon and nitrogen analyses were conducted at the Stable Isotope Laboratory of CENA/USP (Nascimento, 2011) to characterize the sediment age of the different layers (estimated in time intervals and expressed in terms of time before measurement: BP = Before Present). The analysis performed by Giannini *et al.* (2010) is based on total organic carbon (TOC) content, total nitrogen (TN) content, and stable isotopes of carbon (d13C) and nitrogen (d15N) from peat, wood and organic matter. As previously discussed, the results suggest sedimentary processes formed by three facies, with depositions occurring during the last 8000 years (Nascimento, 2011).

A remarkable feature in the analysis of the data shown in Fig. 3 is the recognition that CPTU measurements capture the characteristic features of the three facies representative of the profile, reflecting the changes in aging and soil type. The oldest, fairly homogenous, lower clay layer, of depth ranging from 6 m to 22 m, is dated from 8013-7800 to 3838-3576 year cal BP and is identified by B_q values ranging from 0.4 to 0.6 and q_t increasing linearly with depth (representative of normally consolidated clays). The paleoenvironmental classification identifies a bay deposition

(BD) formed by clay particles with siliceous shells (Cs). Geochemical data indicative of the intermediate sediment layer is from the period of 2445-2306 year cal BP that was formed by transport sediments of the active channel of the Tubarão River (AC), deposited in sand and clay thin layers or lenses with occasional shells (SCs). These sand lenses are essentially drained reducing the B_q values to the range of 0.1 to 0.2. The superficial, recently deposited sediments (2563-2359 to 909-733 year cal BP are also layered (sand and clay), showing a predominantly drained response ($B_q \approx 0$).

5. Stress History

Correlations between the soil stress history and the piezocone measurements were established in terms of critical-state concepts, using either cone resistance or penetration pore pressure. For shoulder filter elements (u_2) the overconsolidation ratio can be expressed in terms of the normalized cone tip resistance $(q_t - u_2)/\sigma'_{v0}$ and the critical state material constants $M = (6\sin(\phi'))/(3 - \sin(\phi'))$ and $\Lambda = 1/(C_r/C_c)$ (e.g. Mayne, 1991):

$$OCR = \frac{\sigma'_p}{\sigma'_{v0}} = 2 \left[\frac{1}{1.95M + 1} \left(\frac{q_t - u_2}{\sigma'_{v0}} \right) \right]^{\frac{1}{\Lambda}} \quad (1)$$

In practice, under a number of simplifications and based on representative soil parameters, the predicted σ'_p is often expressed as:

$$\sigma'_p = k(q_t - \sigma'_{v0}) \quad (2)$$

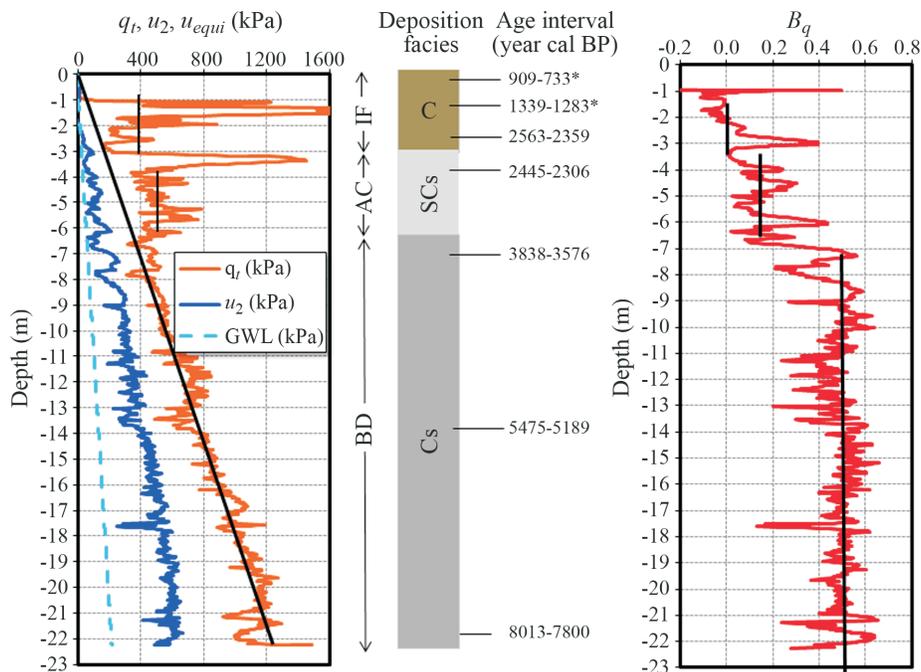


Figure 3 - CPTU profile combined to the paleoenvironmental reconstruction of the Tubarão lagoon system. (* nearby borehole; BD bay deposition; AC active channel; IF inter-channel fines; Cs clay with shells; SCs sand and clay layers with occasional shells; C clay).

where coefficient k is obtained from site specific correlations and is shown to range from 0.1 to 0.5 (e.g. Konrad & Law, 1987; Mayne & Holtz, 1988; Demers & Leroueil, 2002;).

The Tubarão case study provides a unique opportunity to evaluate this type of approach given the fact that the stress history of the deposit is known and supported by radiocarbon dating. The incremental loading oedometer test is the standard method of obtaining the pre-consolidation pressure in the laboratory and the measured values were used as a reference. Typical results of tests performed using a fixed-ring oedometer with drainage at the bottom and top of the test specimen are presented in Fig. 4. The test procedure includes overnight loadings under constant effective stress to determine the position of the virgin compression line using the Casagrande method (1936). The sample quality shown in the figure has been assessed by the $\Delta e/e_0$ ratio, where Δe is the change in void ratio during the recompression process to the *in situ* effective stresses and e_0 is the initial void ratio, as proposed by Lunne *et al.* (1997).

The field vane OCR was calculated using the lower limit of the proposed correlation of Mayne & Mitchell (1988) which, according to the authors experience, is consistent with Brazilian practice: $OCR = 4.5(s_u/\sigma'_{v0})$ for $0 < Z \leq 5$ m and $OCR = 3.8(s_u/\sigma'_{v0})$ for $5 < Z \leq 22$ m. Estimated OCR from dilatometer tests is based on Lunne *et al.* (1989), considering $OCR = (0.3K_D)^{1.17}$ for $(s_u/\sigma'_{v0}) < 0.8$ and $OCR = (0.27K_D)^{1.17}$ for $(s_u/\sigma'_{v0}) > 0.8$.

The calibrated value of the piezocone coefficient k is 0.22 for the soft clay layer (Cs). Note that $k = 0.22$ is easily justified. From the modified Cam Clay (Wroth, 1984), the relationship between s_u and OCR is expressed as:

$$\frac{s_u}{\sigma'_0} = \left(\frac{M}{2} \right) \left(\frac{OCR}{2} \right)^\lambda \quad (3)$$

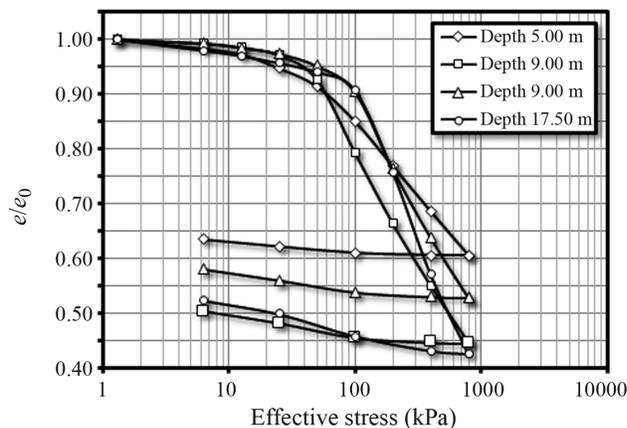
The value of s_u is calculated from the measured net penetration:

$$(q_t - \sigma'_{v0}) = s_u N_{KT} \quad (4)$$

assuming N_{KT} as derived by Baligh (1975) from the strain path method:

$$N_{KT} = 12 + \ln(I_r) \quad (5)$$

By combining these three equations and adopting $\phi' = 28^\circ$ and $I_r = 100$, the calculated value of $k = 1/(0.25MN_{KT}) = 0.22$. The rigidity index is defined as $I_r = G/s_u$, where G is the shear modulus and s_u is the undrained shear strength. In the present work an average I_r was estimated as 100 using strength and stiffness measured from the stress-strain response of unconsolidated undrained triaxial compression tests (UU). In general, s_u values from UU tests are similar to those measured by vane tests. Note that $I_r = 100$ is often adopted as the default value for soft



Depth (m)	e_0	σ'_p (kPa)	e at σ'_p (kPa)	$\Delta e/e_0$	Sample quality
5.00	0.946	20.00	0.901	0.048	Good to fair
9.00	1.664	32.00	1.600	0.038	Very good to excellent
13.00	1.110	44.00	1.080	0.027	Very good to excellent
17.50	1.734	57.50	1.620	0.066	Good to fair

Figure 4 - Incremental load oedometer test data at the Tubarão testing site.

clays and is in line with previous reported data in the region (Schnaid *et al.*, 1997). The friction angle was measured via the triaxial tests. In a similar approach, but using a different set of parameters, Mayne (2007) derived an average k value of 0.33.

The compilation of the piezocone, vane and oedometer testing data plotted together with the calculated s_u , σ'_p and OCR is shown in Fig. 5. The values of s_u and σ'_p increase linearly with depth and, in addition, the value of OCR is relatively constant and equal to unity below 6 m.

Reliable predictions of the pre-consolidation pressure and the overconsolidation ratio encouraged the use of the piezocone in other areas. Besides the Tubarão Site, similar research was performed in 12 different normally to slightly overconsolidated clay sites spread along the Brazilian coast (Fig. 6). Note that all tests were performed and supervised by the same personnel, following strictly the recommendations from the IRTP (1999) and international codes of practice (Eurocode, 1997; ASTM, 1999, ABNT, 1991) in order to minimize the possible sources of errors. The primary sources of data, as summarized in Table 1, are: (1) borehole logs with SPT and undisturbed (4" Shelby tubes) samples, (2) CPTU soundings, and (3) laboratory consolidation and shear strength tests obtained in a variety of locations. Sample quality has been assessed from the change in the void ratio during the recompression process to the *in situ* effective stresses, as already mentioned.

The collected data allowed for a direct comparison between the laboratory measured pre-consolidation pressure σ'_p and the net field penetration resistance $q_t - \sigma'_{v0}$, as presented in Fig. 6, showing that there is no unique average trend to correlate these quantities. The poor correlation in

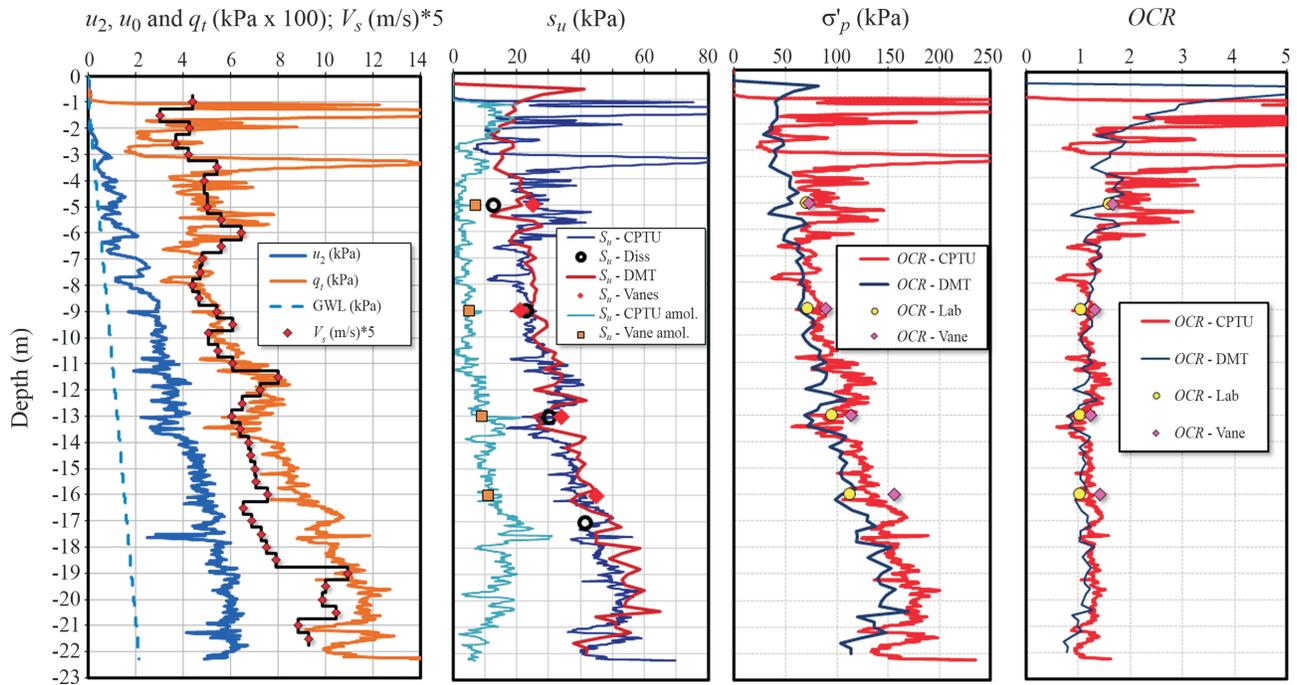


Figure 5 - Strength and stress history of the Tubarão lagoon system.

Table 1 - Summary of the site tests for 166 samples.

State	Site	Sample number	Sample quality	e_o	OCR	ω (%)	LL (%)	LP (%)	PI (%)	k	Reference
São Paulo	Santos	16	V-E = 4	{1.77}	{1.33}	{60}	{79}	{39}	{40}	{0.18}	Present work
			G-F = 9	[3.42]	[2.32]	[113]	[124]	[65]	[59]	[0.25]	
			Po = 3	(1.15)	(0.91)	(35)	(26)	(17)	(9)	(0.07)	
			V-P = 0								
Rio Grande do Sul	Porto Alegre	8	V-E = 3	{1.77}	{1.35}	{122}	{120}	{60}	{60}	{0.31}	Schnaid (2005)
			G-F = 4	[3.42]	[1.76]	[130]	[125]	[75]	[75]	[0.32]	
			Po = 1	(1.15)	(1.17)	(60)	(100)	(50)	(50)	(0.21)	
			V-P = 0								
Rio de Janeiro	Barra da Tijuca CM1 & CM2	11	V-E =	{4.84}	{1.03}	{192}	{196}	{50}	{146}	{0.14}	Baroni (2010)
			G-F = 6	[10.67]	[2.31]	[784]	[610]	[173]	[497]	[0.24]	
			Po = 5	(1.42)	(0.9)	(56)	(67)	(20)	(47)	(0.07)	
			V-P = 0								
Rio de Janeiro	Barra da Tijuca Gleba F	11	V-E = 2	{5.47}	{1.15}	{200}	{169}	{47}	{124}	{0.14}	Baroni (2010)
			G-F = 5	[12.37]	[8.77]	[670]	[521]	[212]	[308]	[0.24]	
			Po = 4	(3.84)	(0.53)	(167)	(147)	(38)	(95)	(0.11)	
			V-P = 0								
Recife	Clube Internacional	11	-	{1.66}	{1.30}	{90}	{70}	{36}	{35}	{0.28}	Coutinho <i>et al.</i> (2000)
				[2.47]	[2.08]	[125]	[99]	[44]	[63]	[0.42]	
				(1.11)	(0.89)	(51)	(45)	(24)	(17)	(0.20)	
Sergipe	Sergipe	34	-	{1.84}	{1.67}	{66}	{66}	{31}	{34}	{0.31}	Brugger <i>et al.</i> (1994)
				[2.05]	[2.26]	[75]	[85]	[34]	[50]	[0.40]	
				(1.51)	(1.01)	(53)	(52)	(25)	(28)	(0.15)	
Rio de Janeiro	Barra da Tijuca	8	V-E = 6	{5.42}	{1.45}	{166}	{128}	{45}	{86}	{0.20}	Teixeira <i>et al.</i> (2012)
			G-F = 2	[7.01]	[3.00]	[269]	[193]	[67]	[127]	[0.26]	
			Po = 0	(3.55)	(1.20)	(136)	(115)	(37)	(69)	(0.17)	
			V-P = 0								

Table 1 (cont.)

State	Site	Sample number	Sample quality	e_0	OCR	ω (%)	LL (%)	LP (%)	PI (%)	k	Reference
Rio de Janeiro	Sarapuí	37	V-E = 1 G-F = 14 Po = 22 V-P = 0	{3.38} [4.46] (2.46)	{1.70} [3.10] (1.30)	{133} [171] (106)	{113} [145] (86)	{50} [73] (33)	{59} [91] (44)	{0.19} [0.23] (0.16)	Ortigão (1980)
Santa Catarina	Navegantes	19	V-E = 2 G-F = 11 Po = 5 V-P = 1	{2.24} [2.84] (0.98)	{1.54} [3.89] (0.49)	{79} [100] (36)	-	-	-	{0.20} [0.29] (0.13)	Present work
Rio de Janeiro	Barra do Furado	3	V-E = 0 G-F = 3 Po = 0 V-P = 0	{2.32} [4.46] (1.71)	{1.40} [1.92] (1.11)	{83} [187] (56)	{91} [117] (63)	{38} [47] (32)	{58} [70] (24)	{0.20} [0.21] (0.18)	Present work
Santa Catarina	Araquari	4	V-E = 1 G-F = 1 Po = 2 V-P = 0	{1.60} [1.71] (1.41)	{1.53} [1.91] (1.04)	{59} [61] (47)	{69} [75] (55)	{32} [34] (20)	{35} [41] (28)	{0.20} [0.25] (0.15)	Present work
Santa Catarina	Tubarão	4	V-E = 1 G-F = 1 Po = 2 V-P = 0	{1.35} [1.80] (0.70)	{1.18} [1.60] (1.04)	{80} [98] (33)	{45} [27] (17)	{22} [29] (18)	{22} [32] (9)	{0.20} [0.22] (0.18)	Present work

Legend: V-E (Very good to Excellent); G-F (Good to Fair); Po (Poor); V-P (Very Poor); { average value }; [maximum value] and (minimum value).

given locations ($r^2 < 0.5$) is partially attributed to sample quality; however, as demonstrated later, sample quality is not the only factor to be considered. Part of the observed scatter may be attributed to organic matter influence on the measured q_p , inducing variations in the σ'_p vs. q_t relationship.

Because there is no unique relationship between q_t and changes in σ'_p , it becomes evident that this correlation involves a more complex measurement-property dependence. From a purely empirical basis, some attempts are made to smooth the observed trend between q_t and σ'_p (or OCR) by incorporating the influence of the void ratio e_0 .

In Quaternary clays, it is well established that σ'_p obtained in the conventional laboratory oedometer tests reduces with increasing e_0 , as shown in Fig. 7 (modified from Massad, 2009). This observation suggests that strengthening of the soil structure with time due to effects of secondary compression are not so severe in recently deposited clays and that pre-consolidation pressures can be associated to void ratio only. Departing from this experience, an attempt is made to express the coefficient k as a function of void ratio, as illustrated in Fig. 8. The values of k reduce with the increase in void ratio from 0.4 to 0.1, yielding a mean value of 0.22 (recommended by Schnaid *et al.*, 1997 and Mantaras *et al.*, 2014 and calculated from $\phi' = 28^\circ$ and $I_r = 100$). Note that the 166 samples database comprises many specimens of poor-quality retrieved from soils of

very high void ratio (greater than 4), but disregarding results from the low quality samples does not change the aforementioned conclusions. It is also worth mentioning that this range of k values is similar to that reported by Larsson & Mulabdic (1991) for 9 Swedish clays, which suggest an alternative correlation of k tracked with liquid limit.

This set of oedometer tests for the Quaternary clays yields the following equation for $(q_t - \sigma_{v0})$ and e_0 :

$$\sigma'_p = k(q_t - \sigma_{v0}) = (0.282e_0^{-0.37})(q_t - \sigma_{v0}) \quad (6)$$

that produces k values reducing typically from 0.5 to 0.1, with a mean value of 0.22 (Fig. 8).

Alternatively, Eq. 6 can be used to predict the overconsolidation ratio directly:

$$OCR = (0.282e_0^{-0.37}) \frac{(q_t - \sigma_{v0})}{\sigma'_{v0}} \quad (7)$$

To conclude, Fig. 9 exemplifies the applicability of Eqs. 7 and 8 to the described ground conditions reported from the Tubarão testing site in section 3. In this figure, the net cone resistance $(q_t - \sigma_{v0})$, overconsolidation ratio OCR and parameter k (Eq. 6) are plotted against depth. Although $(q_t - \sigma_{v0})$ increases with depth (showing a direct dependency on mean effective stress), the OCR remains approximately constant and equal to unity, representing the normally consolidated conditions reported by the sedimentation process.

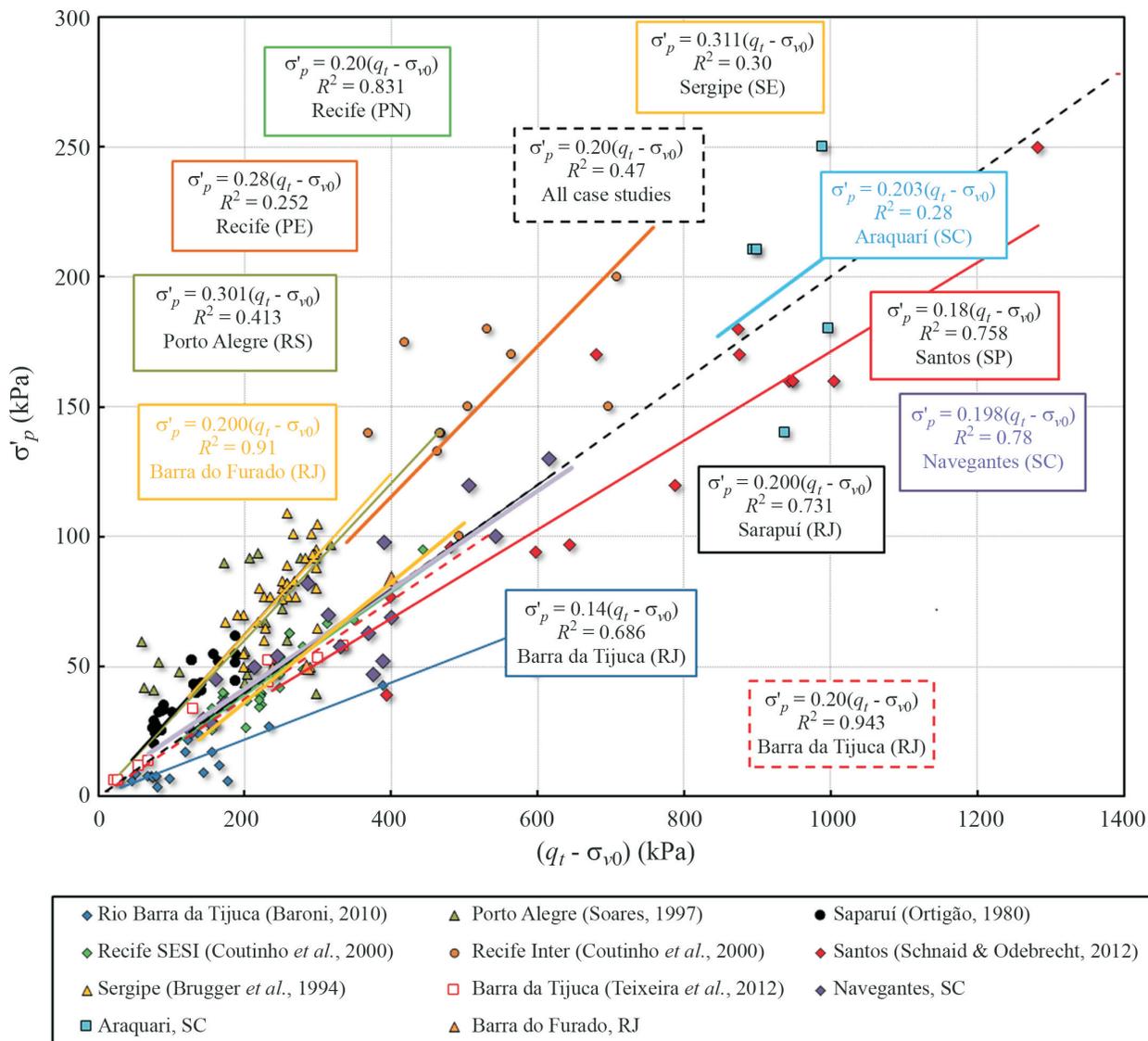


Figure 6 - Correlation of pre-consolidation pressure σ'_p and the net field penetration resistance $q_t - \sigma_{v0}$ for Quaternary Brazilian clays.

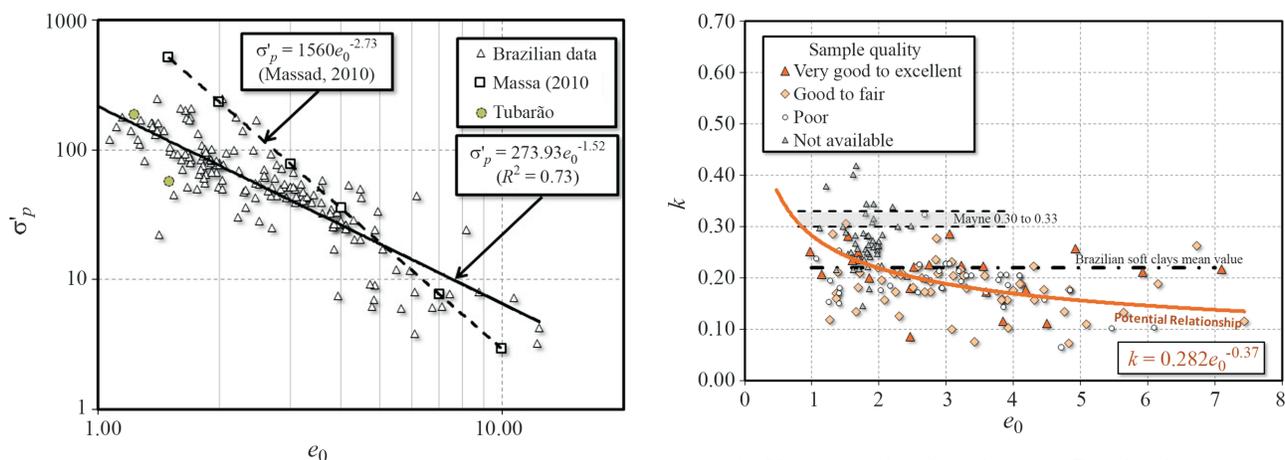


Figure 7 - Variation of e_0 vs. σ'_p (modified from Massad, 2009).

Figure 8 - Variation of k with void ratio for Brazilian low sensitivity clays.

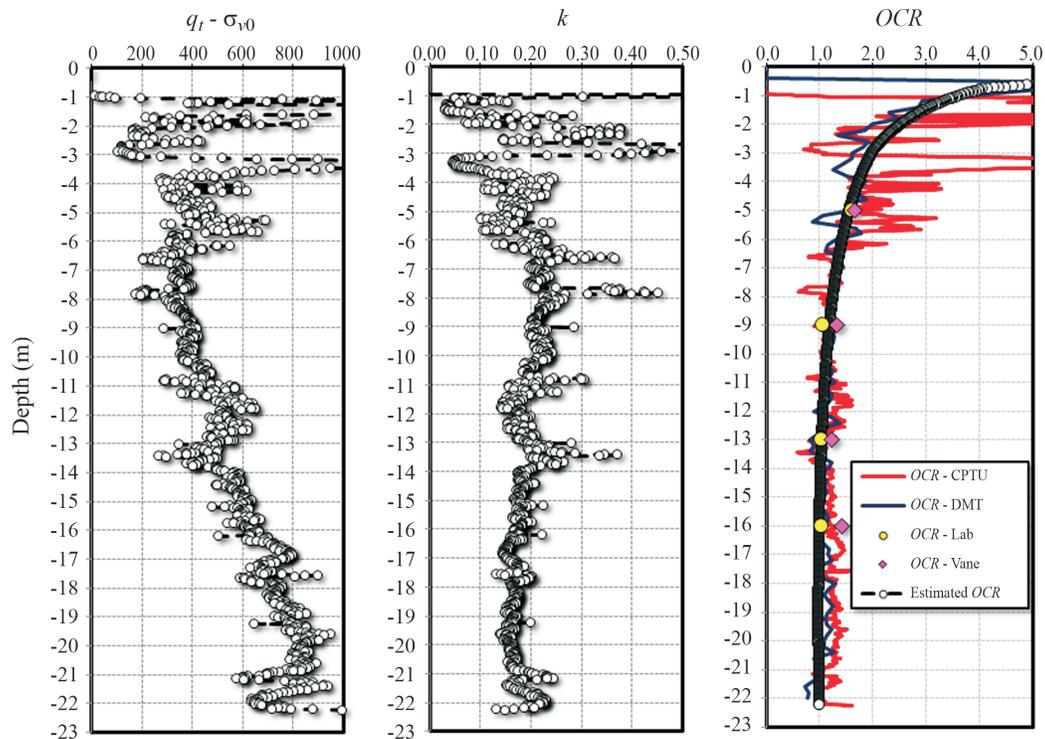


Figure 9 - Variation of k and OCR with depth for the Tubarão Experimental Testing Site.

Eq. 7 produces predicted OCR values in conformity with DMT and oedometer tests. The average k value calculated as a function of void ratio is on the order of 0.22 and is constant with depth, being lower than the 0.3 value often assumed in design (Chen & Mayne, 1996).

6. Concluding Remarks

The present paper presents detailed characterization of Quaternary, normally to slightly overconsolidated clay deposits, including high quality data from field and laboratory tests that comprises profiles with void ratios ranging from 1.0 to 12 and water contents from 30% to 400%. Based on tests from 12 well-documented sites it was found that piezocone field data should be used with caution when predicting the pre-consolidation pressure σ'_p (or OCR). A possible explanation is that σ'_p is strongly affected by soil structure emerging from the effects of secondary compression, aging and cementation, whereas q_t (as a large strain measurement) is not very sensitive to these effects. As a consequence, the ratio of σ'_p and q_t cannot be expressed as a constant, as often assumed in engineering practice. Correlations between σ'_p and q_t should be preferably expressed through the void ratio, which is an indirect form of compensating for the lack of sensitivity of cone penetration to stress history. In terms of engineering practice, an expression was proposed for interpretation of piezocone tests that provides realistic first order estimates of σ'_p .

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