Stress history and preconsolidation pressure evaluation from SCPTU

Histoire géologique et l´évaluation de la contrainte de consolidation par le piézocone

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ABSTRACT
The paper deals with the evaluation of the preconsolidation pressure (σ'_p) of marine clays of Santos, Brazil, from Static Cone Penetration Tests (SCPTUs), in the light of their geological history. It starts with a brief account of the origin, the evolution and the geotechnical properties of the marine sediments. Many SCPTUs have been carried out in the Holocene Clays (SFL Clays), pre-consolidated chiefly by negative sea-level oscillations or dune action. The estimation of σ'_p was done by means of the Kulhaway and Mayne's equation, that uses the net tip resistance and an empirical factor ($N_{\sigma t}$) that depends on soil type and also on the kind of sampler used to extract undisturbed samples. In this paper its value was determined using a criteria that takes into account the stress history: the correlations with odometer test results were considered in a geological and geotechnical context. It is shown that $N_{\sigma t}$ ranged from 3.0 to 3.9 for the SFL Clays. A confirmation of these figures is presented in two ways: indirectly, using field tests, and directly, by comparing the computed σ'_p values with the measured ones by means of odometer tests on undisturbed samples. Finally, the same basic procedure is applied to another marine clay of the Rio de Janeiro Coastal Plain.

RÉSUMÉ
Cet article traite de l'évaluation de la contrainte de consolidation (σ'_p) des sediments argileux de la plaine côtière de Santos, Brésil, par le piézocone, sous la lumière de leur histoire géologique. Il commence avec un relevé de l'origine et l'évolution des sédiments marins. Leurs propriétés géotechniques sont presentées, en détachant les principales mécanismes de surconsolidation des argiles molles (SFL): l'oscilation négative du niveau de la mer et l'action des dunes. A partir de cette base-là, il est montré que l'évaluation de σ'_p peut s'accomplir avec l'équation de Kulhaway et Mayne, qui utilise la résistence de point nette et un facteur empirique ($N_{\sigma t}$), qui depend du type de sol et de l'appareil utilisé par le prélèvement des échantillons intacts. Dans cet article la valeur de $N_{\sigma t}$ est déterminée, en considérant l'histoire des contraintes: les corrélations avec les résultats des essais oedométrique ont été considerées dans un contexte géologique et géotechnique. Il est montré que $N_{\sigma t}$ varie de 3,0 à 3,9 pour les argiles molles (SFL). Une confirmation de ces valeurs est présentée de deux manières: indirectement, par des tests sur terrain, et directement, par les resultats des essais oedométriques. Finalemente, le même procédé est appliqué a un autre sediment argileux de la plaine côtière de Rio de Janeiro.

Keywords: Piezocone; stress history; preconsolidation pressure; soft clays

1 INTRODUCTION

The Santos Coastal Plain ("Baixada Santista") is located in the Southeastern Brazilian coast, in the State of São Paulo, Brazil. Its importance is due to the presence of many industries and the biggest harbour of Latin America. In the second half of the last century a booming tourist industry led to the construction of many tall buildings along the beach shore in the cities of Santos and São Vicente, up to 18 floors or even more.

The occurrence of thick deposits of soft Holocene clays (SFL Clays) is the major problem in the design of civil works in the area. They present different OCR values due to sea level oscillations and dune action in the last 5.000 years.

Since the 1990's, many Static Cone Penetration Test (SCPTU) have been carried out in the SFL Clays. As a first approach, the estimation of preconsolidation pressure was done by means of the equation (Kulhaway and Mayne 1990):

$$\sigma'_a = \frac{q_t - \sigma_{vo}}{N_{\sigma t}} \quad (1)$$

where q_t is the SCPTU corrected point resistance, σ_{vo} is the in Situ Vertical Total Stress and $N_{\sigma t}$ an empirical factor, taken as 3,3 (Mayne et al. 1998) or 3.4 (Demers and Lerouiel, 2002). According to the latter authors, Equation (1), that uses the net tip resistance, is the simplest and most effective method to evaluate the preconsolidation pressure.

As the $N_{\sigma t}$ empirical factor depends on soil type and the kind of sampler used to extract undisturbed samples, a proposition is made to determine it in the light of their geological history. This approach was recommended by Demers and Lerouiel (2002): geological and geotechnical contexts should be considered when dealing with correlations with odometer test results.

2 ORIGIN AND EVOLUTION OF THE SEDIMENTS

Many geological evidences shows that the sedimentary clays of the Santos Coastal Plains ("Baixada Santista") were formed during two Quaternary depositional cycles, with an intermediate erosive process (Suguio et al., 1981). This gave origin to two different types of clays: the Pleistocene (Transitional) Clays and the Holocene Clays. The former ones, also called Transitional Clays, deposited 100,000 to 120,000 years BP (Before Present), are medium to hard clays, pre-consolidated due to a sea-level lowering of 130 m at the peak of the last glaciation (15,000 years BP); as a consequence, these sediments were also deeply eroded. The latter ones, also called SFL clays (from Sediments-Fluvial-Lagoon-Bay), originated since 10,000 years BP by sedimentation where the Pleistocene sediments had been eroded, are very soft to soft clays, lightly over consolidated due to such occurrences as short negative sea-level oscillations (i.e., bellow present sea level) or the action of dunes. A third category are the mangrove sediments, that are still forming.

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Table 1. Some Properties of the Marine Clays of Santos Coastal Plains

Item	Holocene Mangrove	Clays SFL	Pleistocene Clays AT
Depth (m)	≤5	≤50	20-45
SPT	0	0-4	5-25
B_q	-	0.4-0.9	-0.1-0.2
q_t (MPa)	-	0.5-1.5	1.5 a 2.0
e	>4	2-4	<2
σ'_p (kPa)	<30	30-200	200-700
OCR	1	1.1-2.5	>2.5
s_u (kPa)	3	10-60	>100
γ_n (kN/m3)	13.0	13.5-16.3	15.0-16.3
%<5µ	-	20-90	20-70
w_L	40-150	40-150	40-150
I_P	30-90	20-90	40-90
$Cc/(1+e_o)$	0.36	0.43	0.39
Cr/Cc (%)	12	8-12	9
R_f(%)	-	1.5-4.0	1.5-2.0

Legend: B_q- SCPTU pore pressure coefficient; q_t- Corrected cone bearing; *e*- void ratio; σ'_p- max. past vertical effective stress; *OCR*- overconsolidation *ratio;* s_u- *u*ndrained shear strength; γ_n- natural specific unit weight; w_L- Liquid Limit; I_P- Plasticity Index*;* *Cc*- Compression Index; *Cr*- Recompression Index; and R_f- SCPTU Friction ratio.

The soft marine clays of Santos City were deposited before 7.000 years BP. They are overlaid with a 8-12 m thick sand, originated from the displacement of barrier islands, developed in the last 7,000 years BP, during periods of land submergence. These barrier-islands shaped lagoons on their backside, that lasted partially isolated for relatively long periods of almost stable sea-level. With the rapid lowering of the sea-level (periods of land emersion), the barrier-islands displaced toward the continent and regressive beach-ridges were formed, isolating completely the lagoons from the open sea and causing their desiccation. Later on, the intra-lagoon river deltas developed in quiet sea-waters, giving origin to the plain of Santos, the so called "Baixada Santista". Eolic deposits (fossil and active dunes) were present in many sectors of the Santos coastline.

3 GEOTECHNICAL PROPERTIES

The main properties of the marine clays are presented in Table 1, separated in two parts: the upper one emphasizes the differences and the lower one stresses the similarities. As it can be seen, their index properties are almost the same (lower part) and they differ in their "state properties", like undrained shear strength, void ratio and SPT (upper part), that also reveal the great heterogeneity of these soils.

Three aspects will be considered next: a) the soil classification; b) the pre-consolidation mechanisms; and c) the undrained shear strength.

As far as soil classification is concerned, to differentiate the Holocene from the Pleistocene Clays one may use a criterion based on SPT values (see Table 1) rather than plasticity or grain size characteristics. The classification proposed by Robertson et al. (1983) based on Cone Penetration Tests (SCPTU) parameters B_q and q_t helped in defining the bounds of this criterion (Massad, 2004). The values of these parameters, shown in Table 1, led to classify the Holocene Clays (SFL) as soft to medium clays and the Pleistocene Clays as stiff clays. It is interesting to mention that negative B_q values were observed for the Pleistocene Clays, confirming their higher OCR.

For the Pleistocene Clays (AT), the max. past vertical effective stresses (σ'_p) from consolidation tests on undisturbed samples, taken out from 6 boreholes, are in agreement with the total overburden pressures, which is consistent with their geological history (Massad, 1999).

With reference to the Holocene Clays (SFL Clays), Massad (1999) identified the following pre-consolidation mechanisms: a) negative sea-level oscillations; b) dune action; and c) aging.

For each of about 20 stress history profiles, obtained by oedometer tests on undisturbed samples and by Cone Penetration Tests (SCPTU), like those of Figures 1 to 4 (see also Figure 5), the following relationship holds:

$$\sigma'_p - \sigma'_{vo} = cons\tan t \qquad (2)$$

where σ'_p and σ'_{vo} are, respectively, the Pre-Consolidation Pressure and the in Situ Vertical Effective Stress. Equation (2) means that in a stress history profile, there is a parallelism between σ'_p and σ'_{vo} lines. Values of σ'_p were evaluated from SCPTUs with $N_{\sigma t}$=3. Later on this figure will be validated.

Table 2 shows values of the constant of Equation (2) for the 4 Classes in which the Holocene SFL Clays may be classified, according to both, the type of outcropping layer and the prevailing pre-consolidation mechanism. While Classes 1 and 2 predominate mainly in the inner parts of the Santos Coastal Plain, Classes 3 and 4 occur in the Santos City. For Classes 1 and 3, the range 20-30 kPa for this constant, shown on Table 2, has a geological meaning: the maximum lowering during those negative sea-level oscillations was 2 to 3 m (Massad, 1999).

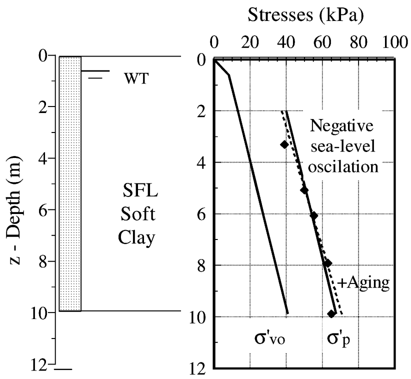

Figure 1. Odometer tests - Piaçaguera-Guarujá Road

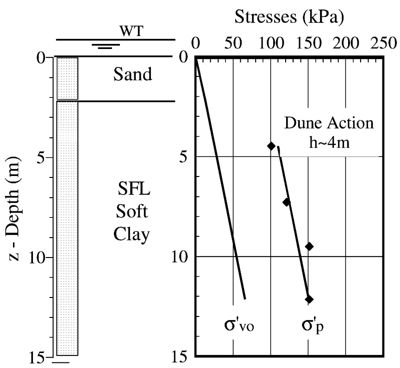

Figure 2. Odometer tests - Santo Amaro Island, Conceiçãozinha Quay

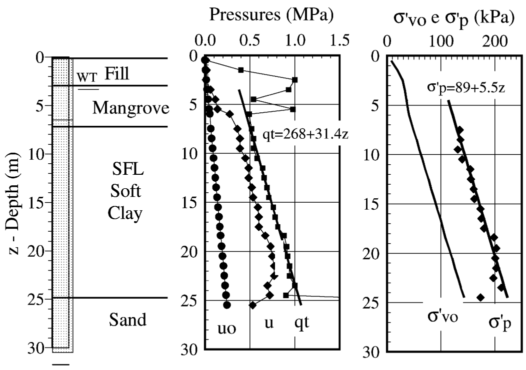

Figure 3. SCPTU-9, Santo Amaro Island, Conceiçãozinha Quay

Table 2. Classes of Holocene Clays (SFL). Santos Coastal Plains

Nº.	Clay Location	Over Consolidation Mechanism	*SPT*	*OCR*	Type of test	Site	σ'_p-σ'_{vo} (kPa)	c_o (kPa)
1	Outcropping	Negative Sea-level Oscilation	0	1.3-2.0	12 Odometers	Santos Coastal Plain	20-30	5-20 (VT)
2	Outcropping	Dune Action	1-4	>2.0	2 Odometers +10 SCPTUs	Santo Amaro Island	50-120	25-35 (VT)
3	Beneath 8-12 m of sand layer	Negative Sea-level Oscilation	1-4	1.0-1.3	4 Odometers	Santos City Shoreline	15-30	10-20 (UU)
4	Beneath 8-12 m of sand layer	Dune Action	1-4	>1.4	2 Odometers + 1SCPTU	Santos City Inland	40-90	>35 (VT)

Legend: *OCR*-over consolidation ratio; c_o-constant of Equation (3); *SCPTU*-Static Cone Penetration Test, with pore pressure measurement; *VT*-Vane Test; *UU*-Unconfined Undrained Triaxial Test; σ'_p and σ'_{vo}-max. past and initial vertical effective stresses, respectively

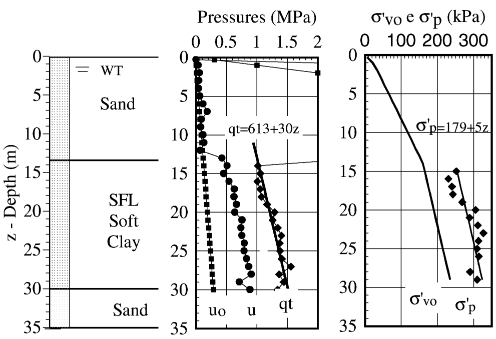

Figure 4. SCPTU-2 - Site of Building UNISANTA – Santos City

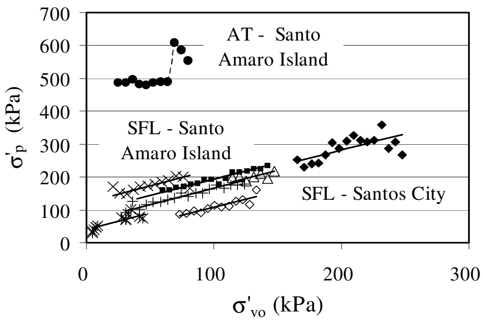

Figure 5. Max. past vertical effective pressure (σ'_p) from SCPTUs as a function of the vertical effective pressure (σ'_{vo}) – Santos Coastal Plain

The aging effect may result in a rate $\Delta\sigma'_p/\Delta\sigma'_{vo}$=1.15 rather than 1, as revealed by Equation (2) (see also Figure 1). For the aim of this paper it will be neglected for the SFL Clays of Santos.

Finally, undrained shear strength (s_u) were obtained by means of Vane Tests, carried out in more than 50 sites in Baixada Santista, reaching depths of 15 to 20m, or even more. As a secure relation, these tests have shown that (Massad, 1999):

$$s_u = c_o + 0.4 \cdot \gamma' \cdot z \tag{3}$$

where c_o is a constant, γ' is the effective unit weight of the soil and z is the depth. Values of c_o (Table 2) for the 4 Classes of SFL Clays are consistent with their pre-consolidation mechanisms.

4 CRITERIA TO DEFINE THE EMPIRICAL FACTOR $N_{\sigma t}$

The application of Equation (1) was done considering the stress history, or, in geotechnical terms, the Equation (2).

Reporting again to Figures 3 and 4, one can see that for the SFL Clays the SCPTU point resistance (q_t) varies almost linerarly with depth (z), that is:

$$q_t = a + b \cdot z \tag{4}$$

where a and b are constants.

If γ_n and γ' are respectively the natural and effective unit weights of the soil, than:

$$\sigma_{vo} = \alpha + \gamma_n \cdot z \tag{5}$$

and:

$$\sigma'_{vo} = \alpha' + \gamma' \cdot z \tag{6}$$

where α and α' are constants.

Combining Equations (1), (2), (4), (5) and (6), the following expression holds:

$$N_{\sigma t} = \frac{b - \gamma_n}{\gamma'} \tag{7}$$

Table 3, prepared using this equation, confirms the value of $N_{\sigma t}=3$ adopted to estimate σ'_p from the SCPTUs of Santo Amaro Island (Figure 3) and Santos City (Figure 4).

Table 3. SCPTU's results – SFL Clays of Santos Coastal Plain

Place	SCPTU	γ_n (kN/m³)	q_t (kPa)	$N_{\sigma t}$	σ'_p- σ'_{vo} (kPa)
Sto. Amaro I.	9	15.5	q_t=268+31.4z	~3.0	81
UNISANTA	2	15.0	q_t=268+31.4z	3.0	89
Barnabé I.	101	14.9	q_t=472+34.0z	3.9	95

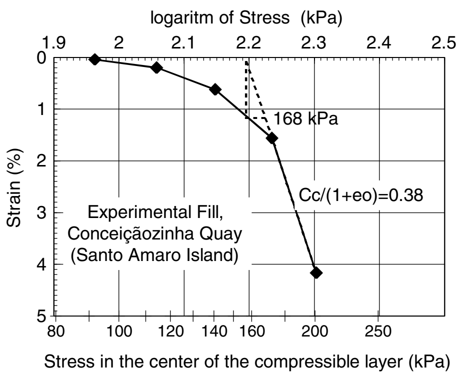

Figure 6. Stress-strain curve for an Experimental Fill

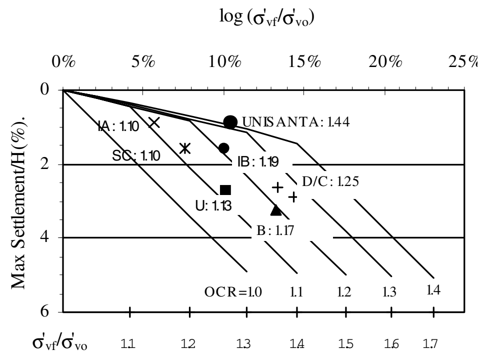

Figure 7. Max. EOP settlements of Santos Buildings as a function of maximum load and OCR (σ'_{vf} and σ'_{vo}: are, respectively, the final and initial vertical effective stresses on the center of the compressible layer)

To validate this figure of 3 for $N_{\sigma t}$, two case histories will be presented, one in Santo Amaro Island e the other in Santos City.

a) An experimental fill 5.8m height was built in 5 stages, in Santo Amaro Island, close to the Conceiçãozinha Quay. In this place the subsoil consisted of 22m of Holocene Clay (SFL of Class 2 of Table 2) over 18m of Pleistocene Clay (AT). While for the latter strata $\sigma'_p \cong 500$kPa (see Figure 5), for the former σ'_p=164kPa, which was extracted from Figure 3 and is very close to the value σ'_p=168kPa, presented on Figure 6, which shows the field stress-strain curve of this experimental test.
b) Building settlements in the Santos City has been monitoring since de 1940´s decade. They were supported by shallow foundations built on a layer of medium to compact sand overlaying soft clays, as shown in Figure 4. Figure 7, extracted from Massad (2005), presents the correlation between the settlements of the most settled columns, the maximum applied loads and the mean OCR for many buildings. The full lines were determined using mean soil parameters (24 h oedometer tests), like those given in Table 1. The numbers associated to the letters identifying the buildings are the measured OCR in each site. These results give a fair explanation of the scatter of EOP settlements of Santos´ buildings: they depend on the pre-consolidation mechanism (sea level oscillation or dune action) and, consequently, on the class, 3 or 4, of Table 2. For the UNISANTA building, the OCR value was estimated from Figure 4: in the center of the compressible layer, its value is about 1.44.

These results were taken by the author as a validation on the use Equation (1) with $N_{\sigma t}=3$ for both places.

In another place of "Baixada Santista", offshore Barnabé Island, high quality samples were taken and odometer tests were carried out by Aguiar (2008), with the results displayed on Figure 8. Also shown in this figure is the result of a SCTPU,

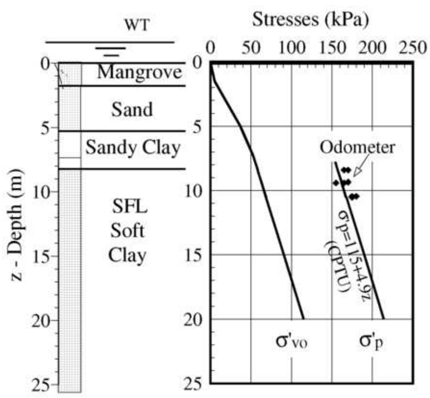

Figure 8. Odometer tests x SCPTU – Barnabé Island – Baixada Santista

performed in the same soil, but onshore. Table 3 shows other results of this test, including the value of $N_{\sigma t}$=3.9, computed using Equation 7. There is a good agreement between laboratory and field results.

It is interesting to mention the analysis made by Almeida et al. (2005) working with the Sarapuí Clay, in the Coastal Plain of Rio de Janeiro (Brazil), known as "Baixada Fluminense". They used $N_{\sigma t}$ =3.4 and found a good agreement with the odometer tests results. For this clay, the aging effect led to a rate $r=\Delta\sigma'_p/\Delta\sigma'_{vo}$=1.31 rather than 1, as revealed by Equation (2). This effect implies in changing Equation (7) to:

$$N_{\sigma t} = \frac{b-\gamma_n}{r\cdot\gamma'} \tag{8}$$

which gives $N_{\sigma t}$=3.45 (see Table 4), practically the same value used by Almeida et al. (2005), and $\sigma'_p=17+3.8z$, also roughly coincident with the plot presented by these authors.

Table 4. SCPTU's results – Sarapuí Clay – Rio de Janeiro, Brazil

Place	Clay	γ_n (kN/m^3)	q_t (kPa)	$N_{\sigma t}$	σ'_p-σ'_{vo} (kPa)
Baixada Fluminense	Sarapuí.	12.9	q_t=60+26z	3.45	17

5 CONCLUSIONS

Based on the knowledge of the geological history of the marine sediments, the criteria presented in this paper to figure out the $N_{\sigma t}$ empirical factor and thus the estimation of σ'_p from SCPTU is valid. For the Santos Marine Clays (SFL), this factor ranged from 3.0 to 3.9, probably due to soil heterogeneity.

The validation was done by means of laboratory – that is, oedometer tests - and field data, involving two case histories.

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