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Marine soft clays of Santos, Brazil: Building settlements and geological history

Argiles marine de Santos, Brésil: Tassements des bâtiments et l'histoire géologique

Faiçal Massad
Department of Structural and Foundations Engineering
Escola Politécnica da Universidade de S. Paulo, Brazil

ABSTRACT
The paper deals with the settlement of tall buildings, supported by shallow foundations, in the City of Santos, Brazil. After describing the Geological History of the clayey sediments of Santos Coastal Plain, the paper presents briefly their Geotechnical Properties, emphasizing the pre-consolidation mechanisms and the 4 classes of soft marine clays. With this background it is shown that the soft clays of Santos City, deposited before 7.000 years BP, overlaid with a 8-12 m thick sand deposit, were submitted to dune action that may explain: a) the differences in settlements of buildings with the same height and thickness of soft layer, in some cases in a proportion of 1:3; and b) some occurrences of inclined buildings.

RÉSUMÉ
Cet article traite le tassement des bâtiments hauts de la cité de Santos, Brésil, appuyés sur fondations rases. Après une description de l'histoire géologique des sediments argileux de la plaine côtière de Santos, ses proprietés géotechniques sont presentées, en dêtachant les mécanismes de préconsolidation et les 4 classes des argiles molles. A partir de cette base-là il est montré que les argiles molles de la Cité de Santos, qui ont été déposées 7.000 annés BP (avant aujourd'hui), par-dessous une couche de sable de 8 à 12 m d'épaisseur, ont été soumises a l'action des dunes. Ce fait-là peut expliquer: a) la dispersion des tassements des bâtiments, même quand ils presentent de pareil hauteur et épaisseur de la couche d'argile molle; et b) l'inclinaison de quelques bâtiments.

1 INTRODUCTION

The City of Santos is located in the Southeastern Brazilian coast, in the State of São Paulo. With more than 600,000 inhabitants, the city has the biggest harbor area of Latin America. In the 1940's up to the 1970's a booming tourist industry led to the construction of many tall buildings along the beach shore, up to 18 floors or even more. They were supported by shallow foundations built on a layer of medium to compact sand overlaying more than 50 m of soft to medium and even stiff clays. In general, the maximum settlements ranged from 0.4 to 1.2 m (Teixeira, 1994), in some cases with an unexpected scatter of values: buildings with the same height and thickness of soft layer settled differently, in proportions as 1:3. Moreover, today about 100 buildings are inclined and in one extreme case a 2.2^o tilted building was plumbed as reported by Maffei et al. (2001). The cause of these tiltings has been imputed to: a) the shape of the loaded area ("T" and "L" forms not recommended); b) highly non uniform loads; and c) the construction of nearby buildings, as close as 4 to 10 m (Teixeira, 1994). Nevertheless tilting has occurred without a rational explanation, as was the case of Building SA, reported by Teixeira (1994).

Based on the geological history and some geotechnical properties, it is shown that the marine soft clays of Santos may present different OCR values due to sea level oscillations and dune action in the last 5,000 years. The paper stresses that this dune action may explain some occurrences of the inclined buildings and the mentioned settlement scattering.

2 GEOLOGICAL HISTORY

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. Included in this last category are the mangrove sediments, that are still forming.

The soft marine clays of Santos City were deposited before 7.000 years BP. They are overlaid with a 8-12 m thick sand deposit, originated from the displacement of barrier islands,

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- CPTU 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- CPTU Friction ratio.

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	Consolidation (12 SHP)	Santos Coastal Plain	20-30	5-20 (VT)
2	Outcropping	Dune Action	1-4	>2.0	Consolidation (2 SHP+10 CPTU)	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	Consolidation (4 SHP+ 1CPTU0	Santos City Shoreline	15-30	10-20 (UU)
4	Beneath 8-12 m of sand layer	Dune Action	1-4	>1.4	Consolidation (2 SHP)	Santos City Inland	40-80	>35 (VT)

Legend: *OCR*-over consolidation ratio; c_o-constant of expression (2); *SHP*-Stress History Profiles; *CPTU*-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

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 plains 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 Tab. 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). 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

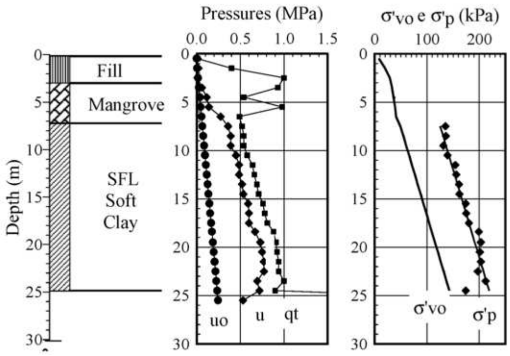

Figura 1: CPTU-9, Santo Amaro Island, Conceiçãozinha Quay

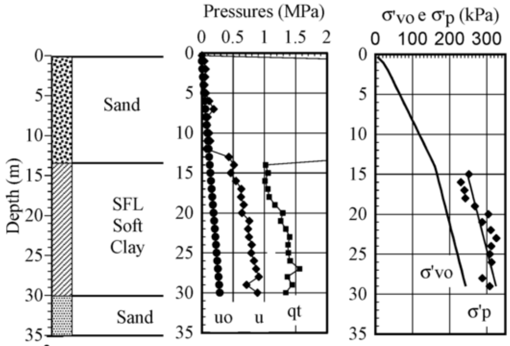

Figure 2: CPTU - Site of Building UNISANTA – Santos City

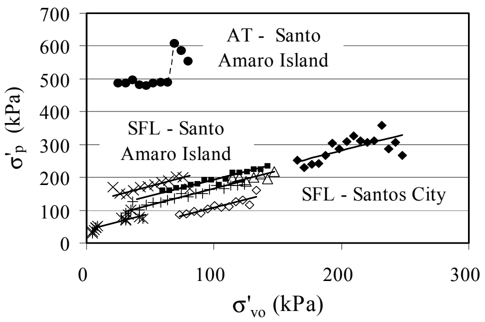

Figure 3: Max. past vertical effective pressure (σ'_p) from CPTUs as a function of the vertical effective pressure (σ'_{vo}) – Santos Coastal Plain

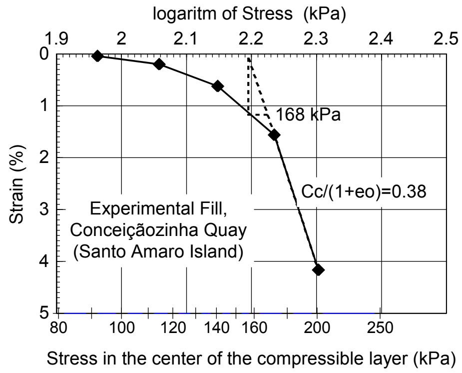

Figura 4: Stress-strain curve for an Experimental Fill

based on SPT values (see Tab. 1) rather than plasticity or grain size characteristics. The classification proposed by Robertson et al. (1983) based on Cone Penetration Tests (CPTU) parameters B_q and q_t helped in defining the bounds of this criterion (Massad, 2004). The values of these parameters, displayed in Tab. 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 maximum 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 both by oedometer tests on undisturbed samples and by Cone Penetration Tests (CPTU), like those of Figs. 1 and 2, the following relationship holds:

$$\sigma'_p - \sigma'_{vo} = constant \quad (1)$$

Table 3: Some Buildings of Santos City: General Data and Results of Settlement Analysis of the Critical Columns (the Most Settled Columns)

Building	Total Load MN	N	H (m)	OCR	σ_{vf}/σ_{vo}	Primary Consolidation Results: Settlement 900 days (mm)	Settlement EOP (mm)	Final Strain (%)	$C_v.10^3$ (cm^2/s)	Secondary Consolidation: $C_{\alpha\varepsilon}$ (%)	Starting Time (days)	U %	ε'_{EOP} (10^{-11}/s)	Reference
B	51	15	8.0	1.17	1.36	225	258	3.2	3.0	3.8	900	95	21	Machado (1961)
C	62	12	12.0	1.25	1.39	315	345	2.9	5.2	3.0	950	91	16	Machado (1961)
D	60	12	12.0	1.25	1.36	274	315	2.6	5.2	2.8	1100	93	13	Machado (1961)
IA	49	8	13.5	-	1.14	113	121	0.9	7.3	1.2	1000	95	5	Teixeira (1960)
IB	78	15	13.5	-	1.26	202	215	1.6	7.4	1.8	1000	94	9.	Teixeira (1960)
SC	64	14	15.0	-	1.19	206	237	1.6	7.7	1.3	1200	95	6	Teixeira (1960)
SA	75	15	15.0	-	-	450	754	5.0	2.6	4.6	1800	83	13	Teixeira (1960)
U	79	10	16.0	1.13	1.26	253	436	2.7	3.3	2.3	1700	85	7	Teixeira (1960)
UNISANTA	129	7(10)	16.0	1.41	1.27	110	140	0.9	5.5	-	-	-	-	Gonçalves et al. (2002)
3 Macuco	~60	12	9.0	-	-	60	-		-	-	-	-	-	Reis (2000)

Legend: N - number of floors; H - thickness of Holocene Clay (SFL); *OCR* - Over Consolidation Ratio; σ_{vf} and σ_{vo} - respectively, the final and initial vertical effective stresses on the center of the compressible layer; *EOP*-End Of Primary; C_v and $C_{\alpha\varepsilon}$ - Coefficients of Primary and Secondary Consolidation, respectively; *U*- Degree of Consolidation; and ε'_{EOP} - Strain Rate at the End of Primary Consolidation.

where σ'_{vo} is the initial vertical effective stress. Fig. 3 illustrates the validity of expression (1) for various CPTUs carried out in two sites of the Santos Coastal Plain. Tab. 2 shows values of the constant of expression (1) 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 Tab. 2, has a geological meaning: the maximum lowering during those negative sea-level oscillations was 2 to 3 m (Massad, 1999). The aging effect may result in a rate $\Delta\sigma'_p/\Delta\sigma'_{vo}$=1.15 rather than 1, as revealed by expression (1). For the aim of this paper it will be neglected.

It is worth mentioning the data of Fig. 4, which shows the stress-strain curve related to a field test. As a matter of fact, an experimental field 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 Tab. 2) over 18m Pleistocene Clay (AT). While for the latter strata $\sigma'_p\cong$500kPa (see Fig. 3), for the former σ'_p=164kPa, which was extracted from Fig. 1 and is very close to the value σ'_p=168kPa, presented on Fig. 4. This result was taken by the author as a validation on the use of CPTUs results to determine σ'_p by means of Kulhaway and Mayne (1990) equation.

Finally, undrained shear strength (s_u) were obtained by means of UU Triaxial Tests, Vane Tests and, more recently, by the CPTU. These tests have shown that (Massad, 1999):

$$s_u = c_o + 0.4 \cdot \gamma' \cdot z \quad (2)$$

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

4 BUILDING SETTLEMENTS OF SANTOS CITY

Tab. 3 presents the results of a recent reinterpretation of settlements of many buildings, supported by shallow foundations, mostly with 5 to 10 years of continuous measurements. They were built in the period 1947-1954, except UNISANTA Building and the 3 Macuco Buildings, constructed at the end of the 1990's. As an illustration of the type of analysis that was carried out, Fig. 5-a shows the settlements of the most settled column of Building SA and Fig. 5-b the correspondent values of the settlement velocities. In these figures, the theoretical values were computed, firstly, by applying Asaoka's Method to the measured settlements; and secondly, by using Olson's Consolidation Theory (Olson, 1977), considering the construction time, roughly 400 days. The agreement is remarkable along the primary consolidation time. With this approach the values of the end of primary settlement and C_v were determined (see Tab. 3).

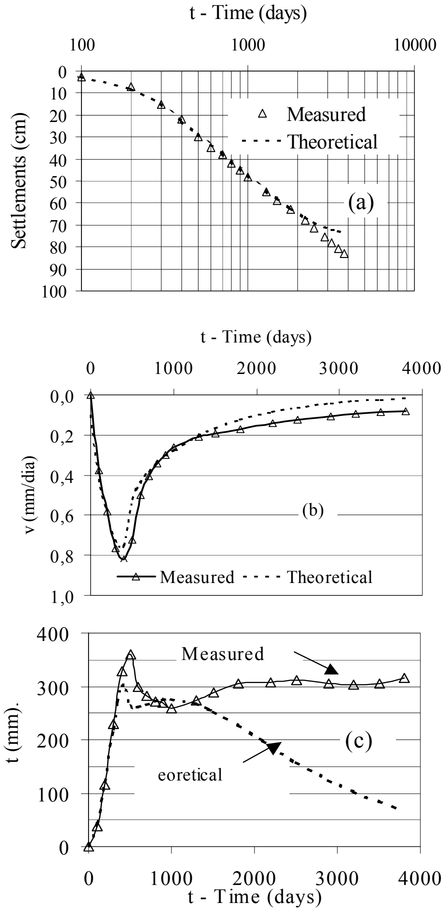

Figure 5: Settlements and Settlement Velocities (v) - Building SA

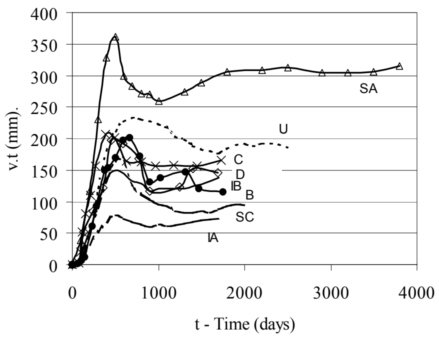

Figure 6: Product v.t for the most settled columns

From Fig. 5-a it is seen that the secondary settlements (ρ_{sec}) follows a straight line of the form:

$$\rho_{sec} = \rho_p + C_{\alpha\varepsilon} \cdot H \cdot log(t/t_p) \quad (3)$$

where ρ_p is the end of primary settlement at time t_p. Therefore, for the settlement velocity (v) one may write, in sequence:

$$v = \frac{d\rho}{dt} = C_{\alpha\varepsilon} \cdot \frac{H}{2.3 \cdot t} \quad (4)$$

$$v \cdot t = C_{\alpha\varepsilon} \cdot \frac{H}{2.3} \quad (5)$$

that is, $v.t$=constant. Fig. 5-c confirms this finding and allows the following conclusions to be drawn:

a) $v.t$=300mm and then $C_{\alpha\varepsilon}$=300x2.3/15,000=4.6%;
b) the secondary consolidation started at a time of 1,800 days, corresponding to a theoretical degree of primary consolidation (U) of 83%; this means that Hypothesis B of Jamiolkowski et al. (1985) holds true for this SFL Clay;
c) $C_{\alpha\varepsilon}$ may be figured out at any time t by simply measuring v, therefore without complete series of settlement records.

Fig. 6 shows that expression (5) is true for other buildings.
From the results presented on Tab. 3 it may be concluded:

a) buildings with almost the same N and H values showed very different EOP settlements (compare U and UNI-SANTA Buildings in Tab. 3: the EOP settlements are in a proportion of 3:1); otherwise, the final strain (at EOP consolidation) ranged between 1 and 5%;
b) the 3 Macuco Buildings revealed a maximum settlement of 60 mm after 900 days recording. This figure is very low as compared to that of Building B at 900 days;
c) the C_v values are in the range 3 10^{-3} to 8. 10^{-3} cm^2/s, of the same order of magnitude as those of the CPTU (Massad, 2004) and also those published by Teixeira (1994); and
d) the $C_{\alpha\varepsilon}$ varied between 1.2 and 4.6%, averaging 2.5%.

Fig. 7 presents the correlation between the settlements of the most settled columns, the maximum applied loads and OCR. The full lines were determined using mean soil parameters (24 h oedometer tests), like those given in Tab. 1, without any correction, despite the ε'_{EOP} low values (see Tab. 3), probably due to some sample disturbance (Lerouiel, 1966). 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: they depend on the pre-consolidation mechanism (sea level oscillation or dune action), and, consequently, on the class 3 or 4 of Tab. 2.

In the 1950's, dunes 1 to 5 m in height were seen along a beach close to Santos City. The maxima pressures they exerted could be of the same order of magnitude as those of 2 to 10 floor buildings! This fact could explain the settlement scattering mentioned above. Besides, the non uniform pressure they exerted may be the cause of tilting, as photo 1 illustrates.

5 CONCLUSIONS

The paper gave a new insight into the old problem of building settlements in Santos City. The site where this city grew up was affected by dunes in the last 5,000 years and this fact may explain some occurrences of inclined buildings. The observed scatter in the total primary settlements of the buildings, even with the same height and width of compressible layer, was due to the differences in OCR values, which depends on the preconsolidation mechanisms: negative sea level oscillation and the just mentioned dune action. The continuous settlement monitoring of 9 buildings, over 5 to 10 years, showed that EOP consolidation occurred mostly around 1,000 days, except in 2 cases; the C_v ranged between $3x10^{-3}$ and $8x10^{-3}$ cm^2/s. Secondary consolidation started at a theoretical primary consolidation degree of 85 to 95%, confirming Hypothesis B of Jamiolkowski et al.(1985). The coefficient of secondary compression reached a mean value of 2.5%.

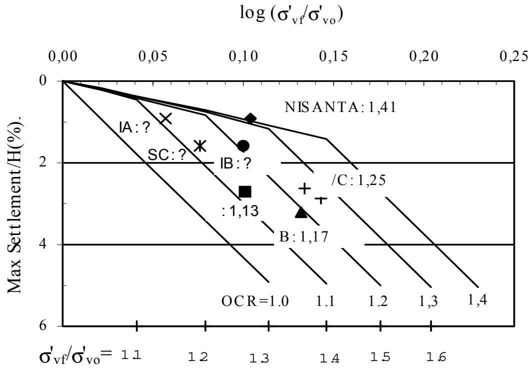

Figure 7: Max. EOP settlements of Santos Buildings as a function of maximum load and OCR (σ_{vf} and σ_{vo} : see Legend of Tab. 3)

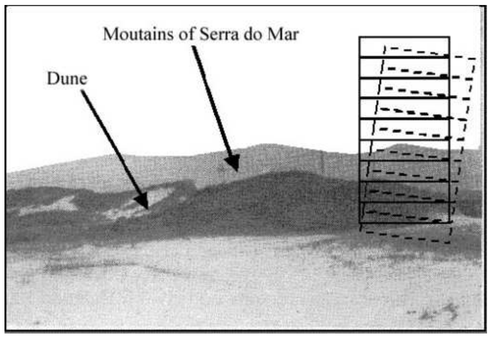

Photo 1: Dune at Praia Grande (Adapted from Rodrigues, 1965)

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