Settlements of Earth Fills on Thick Layers of Overconsolidated Soft Clays without Geodrains

Tassements des remblais sur d’épaisses couches d'argile molle, surconsolidée, sans géodrains

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ABSTRACT: The monitoring of earth fills built on soft clays has been done frequently through the Brazilian coastline. As the most common measurement is the settlement along time, the interpretation of the results is usually done by Asaoka’s Method, generally involving extrapolations that have given rise to doubts (for instance, about the secondary consolidation effect) and to a double interpretation, and even to controversies, especially when it comes to evaluating the effectiveness of vertical geodrains to accelerate settlements. Doubts about the soil disturbances around the geodrains that have been of concern among us and abroad. The paper is based on data from a work in Santos Harbor, in São Paulo State, Brazil, in which 3 experimental fills were built and monitored, one of them partially with geodrains. Many laboratory and field tests were available besides local experience that proved decisive in the evaluation of the measurements and in making decision. It is shown that the controversies can be overcome with information of the soil and of similar works in the region and details of geodrain installation, confirmed by the behavior of the landfills of the work.

RÉSUMÉ: La surveillance des remblais construits sur argiles molles a souvent été effectuée le long de la côte brésilienne. Comme la mesure la plus courante est le tassement au cours du temps, l'interprétation des résultats est généralement faite par la méthode d´Asaoka, impliquant généralement des extrapolations qui ont donné lieu à des doutes (par exemple, à propos de l'effet de la consolidation secondaire), à une double interprétation, et même à des controverses, surtout quand il s'agit d'évaluer l'efficacité des géodrains verticaux pour accélérer les tassements. Ces doutes sur les remaniements du sol autour des géodrains ont été une préoccupation pour nous et à l'étranger. L´article est basé sur les données de travaux au Port de Santos, dans l'État de São Paulo, au Brésil, au cours duquel trois remblais expérimentaux ont été construits et surveillés, l'un d'entre eux avec des géodrains. De nombreux essais en laboratoire et in situ étaient disponibles en plus de l'expérience locale qui s'est avérée décisive dans l'évaluation des mesures et en prise de décisions. Il est démontré que les controverses peuvent être surmontées avec la connaissance des sols,des travaux similaires dans la région, et le mode d´installation des géodrains. Ceci est confirmé par le comportement des remblais en service.

1 INTRODUCTION

A port terminal (Embraport) is under construction in the left side of the Santos Harbor Channel, close to the Barnabe Island, as shown in Figure 1. The total area that is being filled, roughly 800,000m², is delimited by Sandi and Diana Rivers. The Area 3 of Figure 1, alongside the Santos Channel, will be used for containers storage and part of it was reclaimed underwater. The final level of the earth fills in the area will be 3.5m.

2 GEOLOGICAL AND GEOTECHNICAL ASPECTS

Many geological evidences show that the sedimentary clays of the Santos Coastal Plain (“Baixada Santista”) were formed during two Quaternary depositional cycles, with an intermediate erosive process. This gave origin to two different types of clays: the Pleistocene (Transitional) Clays and the Holocene Clays. The former ones, also called Transitional Clays (AT), 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 dune action. Included in this last category are the mangrove sediments, which are still forming.

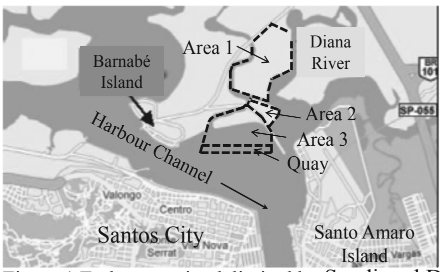

Figure 1.Embraport site delimited by Sandi and Diana Rivers.

In the site of the terminal occur fluvial sediments, originating alternate and discontinuous layers of sand and clay. But it is close to Santo Amaro Island, where a lagoon-bay type of sedimentation took place, with deep layers of SFL (SPT ~1 to 4). This way, both characteristics were found.

In fact, an extensive field investigation, including SPT percussion borings, Vane Tests and CPTUs, revealed: a) a fluvial sedimentation that led to a sandy or clayey mangrove deposition, 0 to 2m width (SPT=0); b) an intermediate sedimentation of a fluvial-bay type, 25 to 35m width, in a mix environment (turbulent and calm), that gave origin to layers of clay with sand lenses, with SPTs varying from 1 to 4; c) the presence of layers of Transitional Clay (AT) at greater depths, with SPTs>5; and d) at last, the occurrence of sands with gravel

and residual soils from gneiss. Figure 2 illustrates the local subsoil, without the Transitional Clay and the residual soils.
Eolic deposits were always present in the area, including Santo Amaro Island and Santos City Plain. Their weights were responsible for the higher values of SPT, ranging from 2 to 4 as well as the overconsolidation of the deposits.

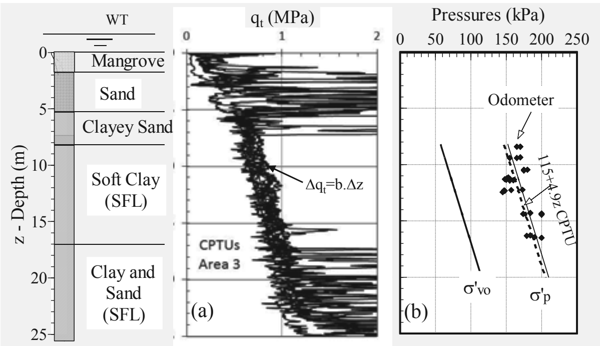

Figure 2. Odometer tests vs. 7 CPTUs at Area 3 of Figure 1.

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 and they differ in their "state properties", like undrained shear strength, void ratio and SPT. It is interesting to mention that negative B_q values were observed for the Pleistocene Clays, whose preconsolidation, with high OCR, was confirmed by consolidation tests on undisturbed samples (Massad 2009-a).

Table 1.Properties of the Marine Holocene and Pleistocene Clays

Group	Item	Man-grove	SFL	AT
Differences	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	1.5-2.0
	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
Similarities	γ_n(kN/m^3)	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
	$C_c/(1+e_o)$	0.36	0.43	0.39
	Cr/Cc(%)	12	8-12	9
	R_f(%)	-	1.5-4.0	1.5-2.0

Legend: SI Symbols used

Data from 3 borings in Area 3 are presented in Figure 3.

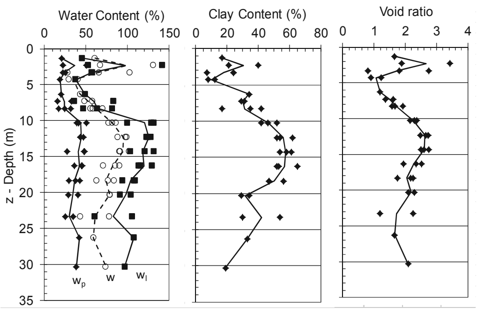

Figure 3. Data from 3 borings (SS110; SS115;SS120) in Area 3.

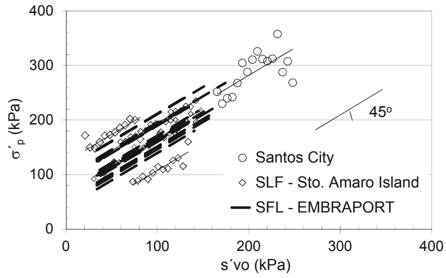

Figure 4. σ'$_p$ from CPTUs as a function of the σ'$_{vo}$.

About 20 stress history profiles, from odometer tests and CPTUs, carried out in sites of the Santos Plain, like Figure 2, showed that equation (1) holds; C_1 and C_2 are constants.

$$\sigma'_p - \sigma'_{vo} = C_1 \qquad \text{or} \qquad \sigma'_p = C_2 + \gamma'.z \qquad (1)$$

Figure 4 illustrates its validity and Table 2 shows values of C_1 for the 4 Classes of SFL Clays (Massad 2009-a). These findings have a practical consequence: more than 12 experimental earth fills settled in a wide range of values (ε_{EOP}=1 to 12%) and of velocities ($c_v \cong c_h$~3.10^{-3} to 5.10^{-2} cm^2/s), depending on *OCR*. Note that for the SFL clays $c_v \cong c_h$ (Massad 2009-a).

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

Class	Clay Profile	Site	Consolidation Mechanism	OCR	σ'p- σ'vo (co)kPa
1	Out-cropping	Baixada Santista	Neg. Sea level Osc.	1.3-2.0	20-30 (5-20)
2	Out-cropping	St.Amaro I Embraport.	Dune Action	>2.0	50-120 (25-45)
3	Beneath 8-12m of sand layer	Santos City	Neg. Sea level Osc	1.0-1.3	15-30 (10-30)
4	Beneath 8-12m of sand layer	Santos City	Dune Action	>1.4	40-80 (>35)

Legend: SI Symbols used; stresses and c_o(of Eq. 3) in kPa;

For the SFL clays of Santos Coastal Plain there is a linear increase of q_t with depth, with a rate b. Massad (2009-b) used this fact and equation (1) to estimate the empirical factor $N_{\sigma t}$ of Kulhaway and Mayne (1990), as shown in Equation 2.

$$\sigma'_p = \frac{q_t - \sigma_{vo}}{N_{\sigma t}} \quad \text{with} \quad N_{\sigma t} = \frac{b - \gamma_n}{\gamma'} \qquad (2)$$

The use of equation 2 with *b*=34MPa/m for the SFL clay layer of Embraport site (see Figure 2-a) resulted in $N_{\sigma t}$ =3.9 and the constant C_2 of equation 1 varying from 80 to 115kPa, revealing the great heterogeneity of the soil (see also Teixeira 1960 on this feature). The high values of σ'$_P$ for the Embraport site are associated with *OCR*>2 at mid height of the layer, as shown in Table 2. Furthermore, Figure 2-b shows also data of odometer tests (dashed line is the average) carried out by Andrade (2009) that agree with the σ'_p of the nearest CPTU.
The shear strength of the SFL clays follows the equation $s_u=c_o+c_1.z$, with $c_1=0.4\gamma'$.For Embraport site the c_o values are higher (Table 2), as those found in Santos City (Teixeira 1994).
Figure 5 shows that: a) the c_h for the overconsolidated range (o.c.) varies from 4.7x10^{-3} to 1.5x10^{-1} cm^2/s (mean value of 2.1x10^{-2} cm^2/s) for the soft clay (SFL) layer (8 to 17m depth); and b) the upper sand and the lower clay/sand layers are highly permeable. In cases like this there is no need to use drains, as shown by Pilot (1991) besides local practice (Massad, 2009-a).

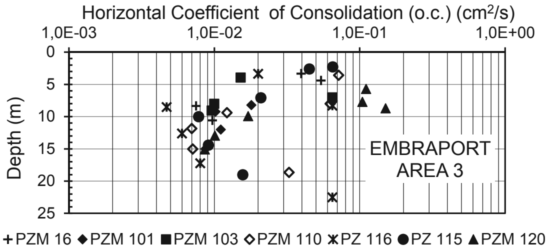

Figure 5: Data from dissipation tests of 7 CPTUs at Area 3.

3 PILOT EMBANKMENT 1

An experimental earth fill – the Pilot Embankment 1 - was built in the Area 3 before it was reclaimed underwater. It was divided in three parts (see Figure 6), Segments 1 and 2 with square meshes of geodrains 25m length, spaced 1,2m and 2.4m, respectively, and Segment 3, without vertical drains.

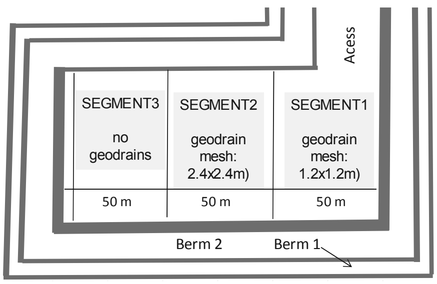

Figure 6: Relative positions of the Segments. Pilot Embankment 1

Detailed information about the construction and the instrumentation is found in Rémy et al (2010). It is worth mentioning that the rate of loading was distinct among the segments. And it was also distinct in Segment 3, comprising two sides, North and South, with different heights. Figure 2 shows the subsoil in the site.

Many difficulties arose in the interpretation of the data of the Embankment Pilot 1. They refer to the following drawbacks:

a) the Segments 1, 2 and 3 were too close and the earth fill loads were applied at different rates; for Segments 1 and 2, the 4 loading stages were applied during 354 and 452 days, respectively; for Segment 1, the 2 stages required 142 days;
b) the installation of the geodrains involved the use of a temporary casing 2 inches inside diameter and flushing water to pass through the upper sand layers (see Figure 2) besides the fact that the soil resistance was high; and
c) there occurred two problems with the measuring probe of the magnet extensometers. The first one in Nov., 13th, 2008 (day 400 in Figure 7) when the measuring probe was changed; ant the second one between Feb.,19th, 2009 (day 485) and Sept., 16th, 2009 (day 694), that is, 209 days with no measurements, due to damage in the probe device.

Figure 7 shows the measured settlements of the Soft Clay (SFL) layer, between 8 and 17m (see Figure 2) of Segment 3. The plot reveals: a) the interference between the Segments 2 and 3, due to their proximity and the differences in the rate of loading, as mentioned above; and b) the 3 stages of loading that occurred, making it possible to apply Asaoka's Method, as shown in Figure 8. Table 3 presents the results of this analysis.

Table 3: Results of the Application of Asaoka's Method

Stage	c_v (cm^2/s)	ρ_f EOP(cm)	ρ_f/H (%)	$\sigma'_{vf}/\sigma'_{vo}$ (*)
1	3.10^{-2}	3.5	0.37	1.29
2	2.10^{-2}	13.5	1.42	1.88
3	2.10^{-2}	15.3	-	-

Note: (*) in the center of the SFL Clay layer

With the preconsolidation pressures indicated in Figure 2-b it follows an average *OCR*=2.2 for the center of the Soft Clay (SFL) layer. The conclusion is that the SFL Soft Clay of Embraport site behaved as an overconsolidated clay, of Class 2 of Table 2. Moreover, note that the c_h~c_v given by Figure 5 agrees with the values of Table 3 and with local experience.

Due to the second difficulty and to the highly permeable layers, the geodrains of Segments 1 and 2 were disregarded, a position that differs from that of Rémy et al (2010) being a different view. Table 4 endorses this position: the indicated plates were installedat the base of the earth fills and the values of c_v are equivalent in the sense that they refer to all layers. It can be seen that the drain installation greatly affected the *EOP* settlements but lesser the time of its occurrence. These conclusions are in consonance with the research by Saye (2001) with the Florence Lake Clay, in Omaha, Nebraska (USA).

Table 4: Influence of soil disturbance due to drain installation

Segment	Geodrains	Plate	Max. Level	c_v/H_d^2	ρ_f EOP(cm)
1	2.4x2.4m	PR 02	7.27m	4.2*10^{-3}/day	194
2	1.2x1.2m	PR 08	6.95m	3.5*10^{-3}/day	~137
3	without	PR 11	7.70m	7.0*10^{-3}/day	89

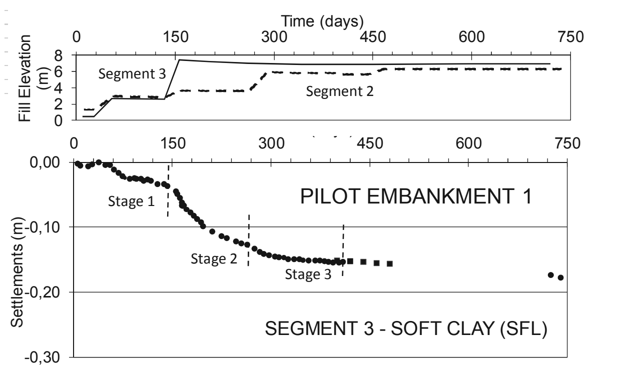

Figure 7: Compression of the Soft Clay (SFL) layer. Segment 3

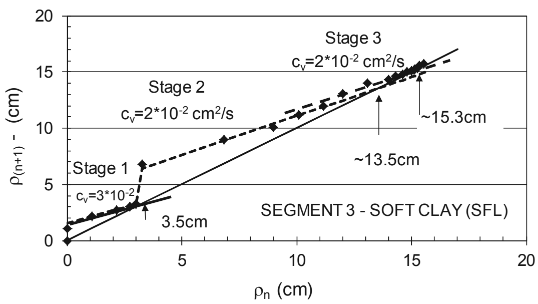

Figure 8: Asaoka's Method - Pilot Embankment 1

4 PILOT EMBANKMENTS 2 AND 3

A second experimental fill (Pilot Embankment 2) was built in Area 3, with a maximum height of 5.2m. Figure 9 displays de subsoil profile and gives information about the initial and final stresses, the preconsolidation pressures and the *OCR*.

The values of the end of primary settlement (ρ_f) and c_v/H^2_d were determined as illustrated in Figure 10 for one of the 4 plates installed at the earth fill base for the two stages shown in Figure 11-a. Note again that c_v is equivalent in the sense that it refers to all layers and that, after roughly 5 month, at least 95% of the primary settlement was reached.

The Figures 11-a and 11-b show also the very good fittings of the theoretical and measured values of settlements and the product *v.t* (velocity*time) along the primary consolidation time. For the secondary range, *v.t* reached a constant value, allowing the estimation of $C_{\alpha\varepsilon}$=0,85%, consistent with the values obtained for the Santos' Buildings (for more details, Massad 2005 2010).

A third experimental fill (Pilot Embankment 3), built also in Area 3, with a maximum height of 6.7m, behaved in a similar way, with c_v/H^2_d averaging $1.8.10^{-2}$/day; the *EOP* settlement was ~80 cm and 95% of this value was reached after ~6 month.

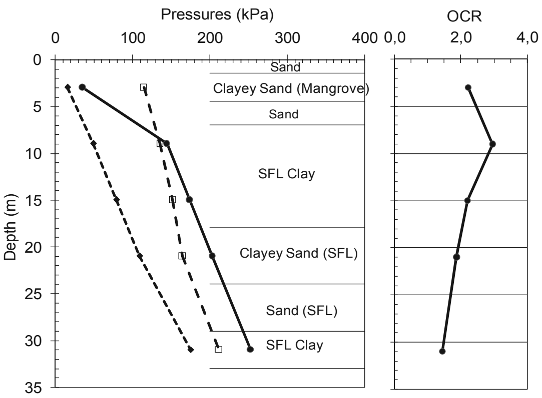

Figure 9: Subsoil profile, pressures and OCR – Pilot Embankment 2

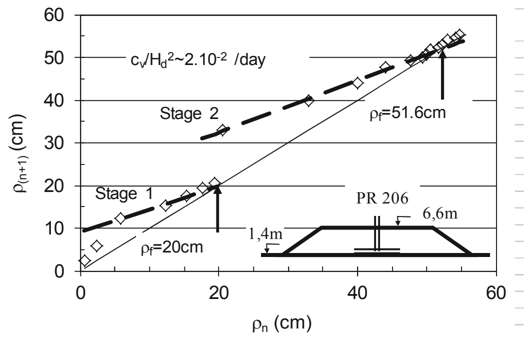

Figure 10: Asaoka's Method - Pilot Embankment 2

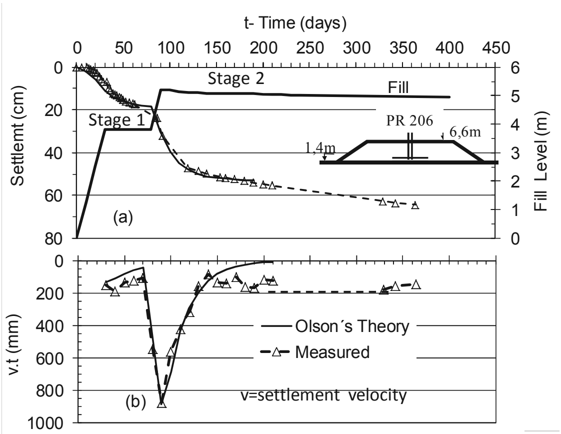

Figure 11:Results of the Pilot Embankment 2 – Plate PR 206

5 BEHAVIOR OF THE EARTH FILLS OF THE WORK

The earth fills in Area 3 of Figure 1 were built with a temporary surcharge, in general of 80kPa. Tens of plates were installed to monitor the settlements. The time of surcharge removal, set to reach 95% of consolidation, was fixed between 6 and 8 months, or even more, depending on the time of construction.

The settlements of two of these plates are shown in Figures 12-a and 12-b, together with the fittings with Olson´s Theory of Consolidation; the c_v/H^2_d values were determined using the Method of Baguelin (1999), alternative to Asaoka´s Method. In these cases, 6 months was enough for surcharge removal.

6 CONCLUSIONS

Due to the high *OCR* values of the SFL Clays, the c_v were also high, of the order or $10^{-2}cm^2/s$. As a consequence, there was no need to use geodrains in the Embraport site.

This conclusion was supported by 3 experimental earth fills without geodrains and, more important, by the monitoring of settlements in Area 3, where temporary surcharges were used.

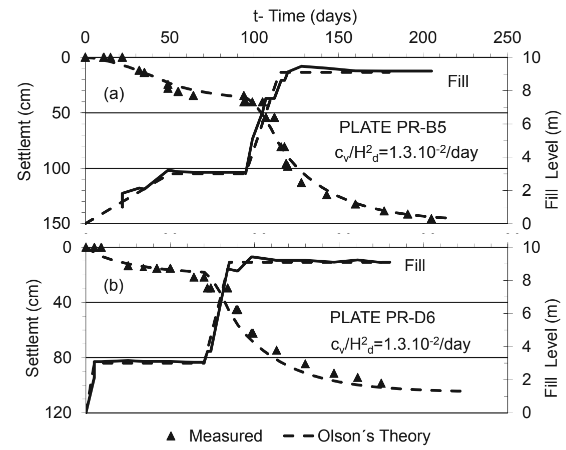

Figure 12:Analysis of settlements of earth fills of Area 3

7 ACKNOWLEDGEMENTS

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