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IN SITU TESTING OF SOFT BRAZILIAN SOILS

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Abstract: An overview of in situ tests performed on soft Brazilian soils is presented. Special emphasis is given to the Sarapuí test site and to the test sites in Rio de Janeiro of very high plasticity. Some lessons related to the use of a piezocone with two filters are presented.

1. INTRODUCTION

A recent report on the Brazilian test sites has been presented at the XIII Brazilian Conference on Soil Mechanics and Geotechnical Engineering, XIII COBRAMSEG, held in Curitiba in 2006 (CAVALCANTE et al. [21]). The requirements for a test site to be included in the report were: (i) it should be involved in activity and (ii) it should provide information about foundations. A map of those sites is shown in figure 1. The

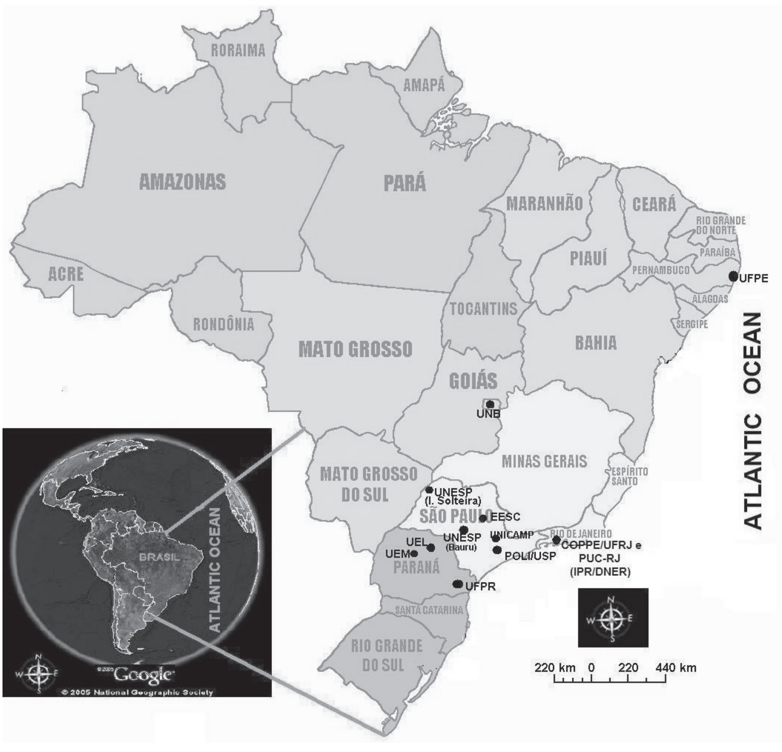

Fig. 1. Brazilian test sites in activity (adapted from CAVALCANTE et al. [21])

report provides, for each site, information on the origin of the soils, the soil investigations carried out (especially in situ tests) and the experience related to foundations. The perspectives envisaged by researchers with respect to new developments have also been included in the report.

As can be seen in figure 1, the test sites are concentrated in the southeast region, which is the most developed part of the country. The reasons for the test sites were (CAVALCANTE et al. [21]): (i) special geotechnical engineering projects; (ii) university research, not necessarily connected with applied engineering. Almost all test sites were established in 1988, except the Sarapuí test site, which was established in 1974 (table 1). It can also be seen in table 1 that only 2 out of the 11 test sites are soft clay sites; the others are tropical soils sites, in which the behaviour of the unsaturated part of the profile concentrates most of the research.

Table 1

General information on Brazilian test sites (adapted from CAVALCANTE et al. [21])

	Institution/Test site	Starting year	Area (m^2)	Soft clay
01	COPPE/UFRJ – PUC/RJ (IPR-DNER)	1974	42,000	Yes
02	POLI/USP (EPUSP/LMS)	1988	5,000	No
03	EESC/USP	1988	1,200	No
04	UNICAMP	1989	1,700	No
05	UNESP/FEB	1991	50,000	No
06	UNESP/FEIS	1988	1,650	No
07	UNB	1990–1995	1,000	No
08	UFPR	1997	3,600	No
09	UEL/PR	1998	2,975	No
10	UEM/PR	1992	1,000	No
11	UFPE (SESI)	1996	1,650	Yes

As the XIII COBRAMSEG was held together with the III Portuguese–Brazilian Conference on Soil Mechanics and Geotechnical Engineering, a similar report on the Portuguese test sites was included in the same volume of the Proceedings (VIANA da FONSECA [64], SANTOS [53]).

A number of other soft clay sites have been reported. They are related to important engineering projects, like Sesc-Senac in Rio de Janeiro (ALMEIDA [3]) and Ceasa in Porto Alegre (SOARES [56], SCHNAID et al. [54]). There are soft clay test sites that have not been included in the mentioned report due to the lack of information on foundation experience (e.g., Clube Internacional, in Recife, PE, COUTINHO et al. [25]). Some data from these test sites will be presented in the next sections.

2. THE SARAPUÍ TEST SITE

The Sarapuí test site was the part of a major research project conducted by the Brazilian Highway Research Institute, IPR-DNER, involving laboratory, in situ testing and trial embankments (LACERDA et al. [38]). The soft clay deposit is about 11 m thick and overlies sand layers. Results from SPT as well as the natural water content w_n, liquid limit w_L and plastic limit w_P, void ratio e_0 and natural unit weight γ_n are shown in figure 2 (according to ALMEIDA and MARQUES [6]). The Sarapuí clay is an organic marine clay, dark grey, the organic content varies from 4 to 6%. The clay content is about 65%. The clay particles are predominantly of the kaolinitic group (ANTUNES [12[). The content of soluble salts of Sarapuí clay ranges from 4.7 g/dm^3 to 8.5 g/dm^3. The plasticity index (I_P) of Sarapuí clay decreases with depth from about 100% to 50%. The water content is slightly higher than the liquid limit, which is a typical behaviour of sensitive clays, however its sensitivity, measured in vane tests (ORTIGÃO and COLLET [48]), is about 4.4. The void ratio decreases with depth from about 4.2 to 2.5, and the natural unit weight varies from about 12.5 to 14.5 kN/m^3. The overconsolidation ratio (OCR) decreases with the depth in the clay crust (about 3.5 m), and becomes constant below the crust (OCR about 1.5, MARTINS et al. [44]).

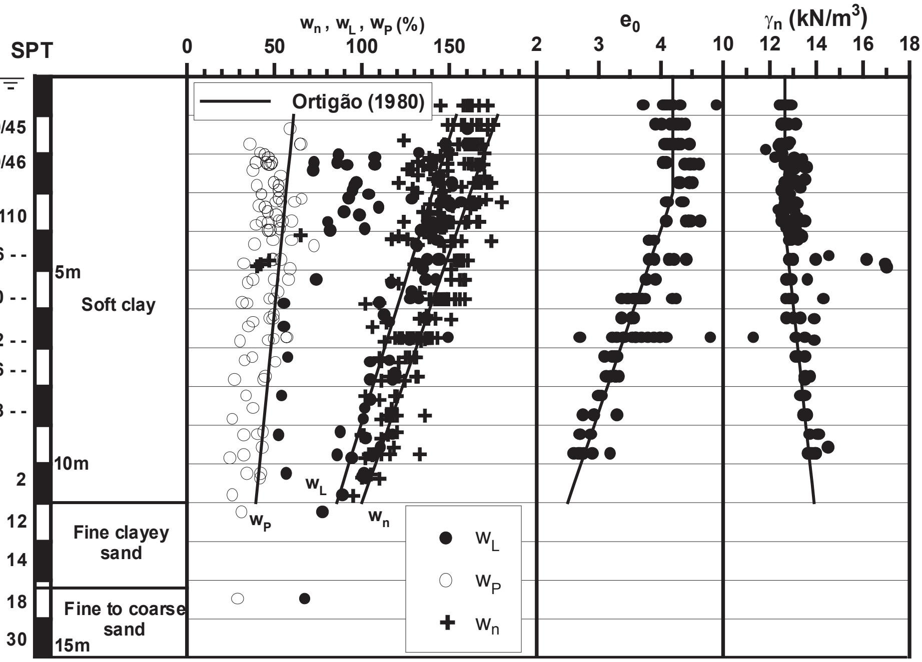

Fig. 2. Characteristics of the Sarapuí clay deposit. Data from ORTIGÃO [46], [47], COUTINHO [24], DUARTE [34], COLLET [22], VIEIRA [65], BARBOSA [15] and LIMA [41], obtained from ALMEIDA and MARQUES [6]

Recent papers summarizing the main information about the Sarapuí test site have been presented by ALMEIDA and MARQUES [6], ALMEIDA et al. [7] and MARTINS et al. [44].

A number of in situ tests have been performed in the Sarapuí test site, and table 2 lists those tests and the corresponding references. Unfortunately, some of these researches (or a significant part of them) are only available in theses (in Portuguese). Otherwise, papers have been presented only at Brazilian geotechnical conferences.

Table 2

In situ tests performed at the Sarapuí test site

In situ testing	Reference
SPT	ORTIGÃO [47]
Hydraulic fracture testing	WERNECK et al. [68]
CPT	BORGES NETO [18], GUIMARÃES [37]
CPTU	ALENCAR [1], LEHTOLA [40], ROCHA FILHO and ALENCAR [50], SOARES et al. [6], [62], [59], SILLS et al. [55], DANZIGER [27], ÁRABE [13], BEZERRA [17], DANZIGER et al. [28], [30], ALVES [9]
DMT	SOARES et al. [61], VIEIRA [66], VIEIRA et al. [67]
VT	COSTA FILHO et al. [23], COLLET [22], ORTIGÃO and COLLET [48]
SCPT	FRANCISCO [36]

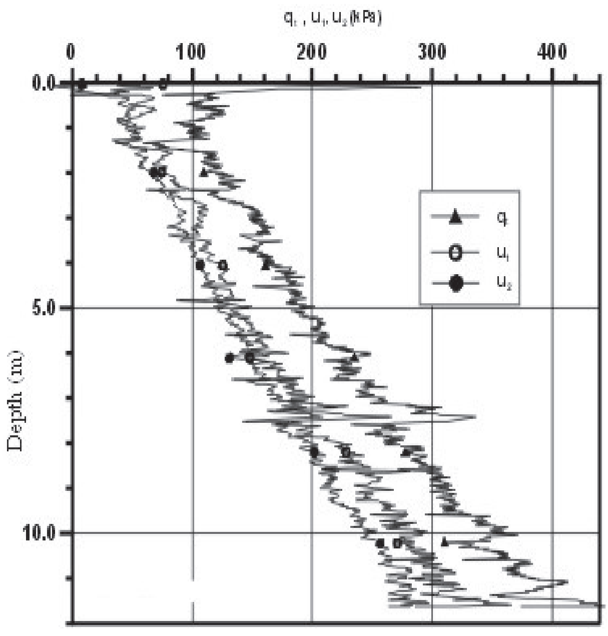

Fig. 3. Piezocone test in the Sarapuí clay. The values of q_T, u_1 and u_2 versus depth (BEZERRA [17])

In the particular case of the piezocone test, probes having 5, 10 and 15 cm^2 in area have been used. Moreover, as far as filter location is concerned, not only a single filter was used, but probes with 2 and 4 filters have been used as well. Actually, the piezocone with 2 filters became a standard at COPPE/UFRJ in 1996 (BEZERRA [17], DANZIGER et al. [28]). The corresponding advantages due to the use of a single filter are described in a next section. Both the piezocone test and the dilatometer test have been performed for the first time in Brazil at the Sarapuí test site. The values of q_T, u_2, u_1 from a piezocone test with 2 filters are shown in figure 3, where q_T is obtained from expression (1), (CAMPANELLA et al. [20]):

$$q_T = q_c + u_2(1 - a)\,, \tag{1}$$

where:

q_c – the cone resistance measured,
u_2 – the pore pressure measured at the cone shoulder,
u_1 – the pore pressure measured at the cone face,
a – the area ratio.

The values of p_0, p_1 and p_2 from a dilatometer test are presented in figure 4.

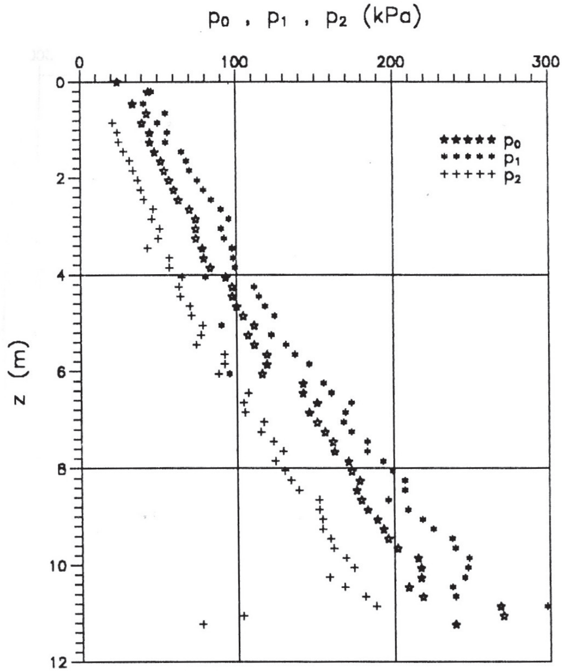

Fig. 4. Dilatometer test. Values of p_0, p_1 and p_2 versus depth (VIEIRA [66]).
p_0 – corrected A reading, p_1 – corrected B reading, p_2 – corrected C reading

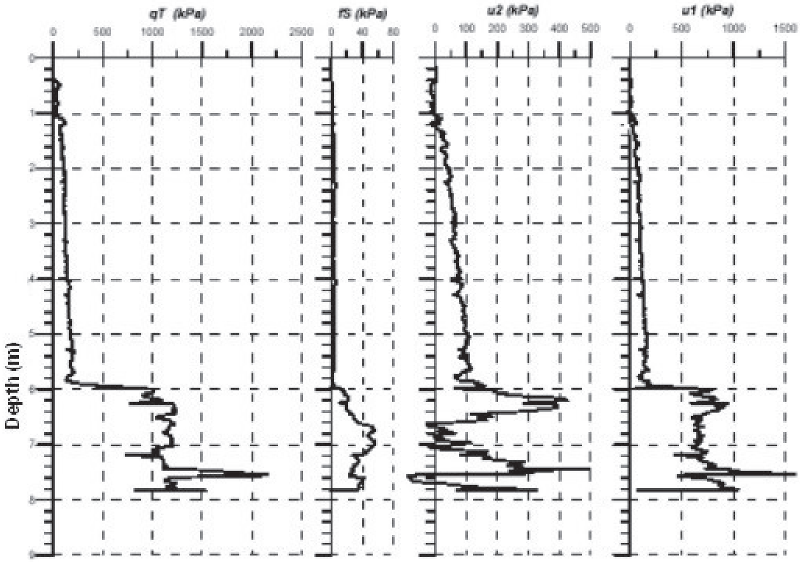

Fig. 5. Piezocone test in Sarapuí-II clay. Values of q_T, f_s, u_1 and u_2 versus depth (ALVES [9])

For the sake of safety, the Sarapuí test site stayed less active for a while, and another area, Sarapuí-II (owned by the Navy, on the opposite side of the motorway), was used, mainly for a research on piles. Although the same geotechnical parameters are obtained in the new test site, the soft clay deposit is about 6 m thick, as can be seen from a piezocone test shown in figure 5 (after ALVES [9]).

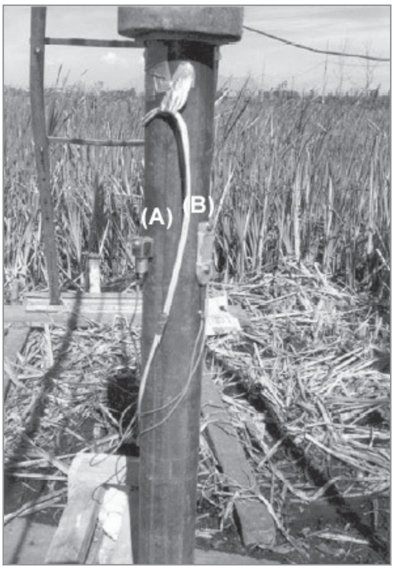

Fig. 6. Model pile instrumented with accelerometers and strain gages (ALVES [9])

A closed-end steel pile, 4.5 m length, 114 mm in diameter (figure 6) was dynamically driven and subjected to both dynamic and static loading (ALVES [9], ALVES et al. [11], [10]). The load–settlement curve obtained in a static load test is shown in figure 7.

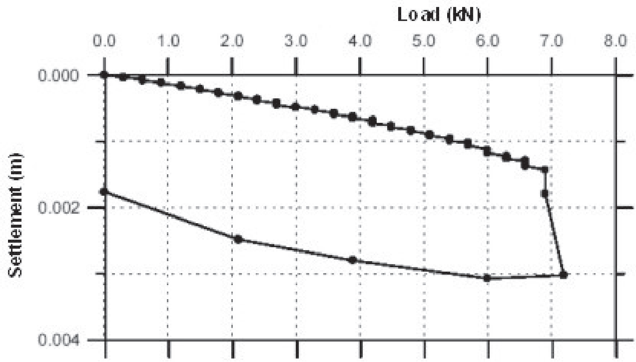

Fig. 7. Load test result in a steel pile (ALVES [9], ALVES et al. [11])

ALVES [9] and ALVES et al. [11] have compared the ultimate load measured in the test with the failure load predicted based by three methods proposed by ALMEIDA et al. [4], ESLAMI and FELLENIUS [35] and LEHANE et al. [39]. They have concluded that the three methods allowed us to predict similar shaft resistances, but the measured load was underestimated by 25–35%. The toe resistance predicted based on the papers by ALMEIDA et al. [4] and ESLAMI and FELLENIUS [35] were about 90% and 70%, respectively, the measured value.

3. IN SITU TESTS PERFORMED AT BRAZILIAN SOFT CLAY SITES

3.1. GENERAL

A number of in situ tests have been performed at soft clay sites, both for research and for engineering applications. Engineering applications have mainly been related to the design of embankments. In this particular case, the vane test and the piezocone test became routine design tools, and the piezocone experience and widespread use followed university research. Table 3, according to DANZIGER and SCHNAID [32], summarises the cone factor N_{KT} values (LUNNE et al. [42]) obtained in several deposits along the Brazilian territory:

$$N_{KT} = \frac{q_T - \sigma_{v0}}{s_u}, \tag{2}$$

Table 3

N_{KT} values, Brazilian soft clays (adapted from DANZIGER and SCHNAID [32])

Site	Geotechnical parameters			N_{KT} average (range)	Note	References	
	Ip (%)	OCR	s_u (kPa)			Geotechnical parameters	Piezocone testing
Sarapuí, Rio de Janeiro, RJ	30–110	1.5 (below the 3.5 m crust)	8–18, VT	9.0 (8–10)–3.0 to 6.5 m 10.5 (10–11)–6.5 to 10.0 m	Other piezocone tests at the site (under the embankment): ALENCAR Jr. [1], ROCHA FILHO and ALENCAR [50]	ORTIGÃO [47], ORTIGÃO et al. [49], ORTIGÃO and COLLET [48]	SOARES et al. [60], [62], [59], SILLS et al. [55], DANZIGER [27], DANZIGER et al. [28], [30]
				14 (11–16)			BEZERRA [17]
Senac, Rio de Janeiro, RJ	100–250	1.5 (below the 3 m crust)	8–30, VT	9 (5–11)		ALMEIDA [3]	
Clube Internacional, Recife, PE	25–90	1–2	35–55, UU	12.5–7 to 16 m 13.0–16 to 26 m total variation: 10.0 to 15.5		COUTINHO et al. [25]	OLIVEIRA [45], COUTINHO et al. [25]
				(11–17)–7 to 16 m (12–16)–16 to 26 m			BEZERRA [17]
Ibura, Recife, PE	45–115	≈1 (below the crust)	9–27, UU	14.0–4.0 to 11.1 m 13.5–11.1 to 21.0 m		COUTINHO et al. [26]	
Aracaju Harbour, SE	25–45	1–2	10–30, VT	15.5 (14.5–16.5)	Tests performed from a jack-up platform, about 2.5 km from the shoreline	BRUGGER et al. [19], SANDRONI et al. [52]	DANZIGER et al. [31], BRUGGER et al. [19], SANDRONI et al. [52]
Santos Harbour, SP	40–80	1.3–2.0	5–50, VT	18 (15–21)	Sand layers throughout the profile. Clay parameters from other site in the same region.	SAMARA et al. [51]	BEZERRA [16], ALMEIDA [2]
Enseada do Cabrito, Salvador, BA	50	1.5–3	9–17, VT	15 (12–18)		BAPTISTA and SAYÃO [14]	
Ceasa, Porto Alegre, RS	20–70	1–1.5	10–20, VT	12 (8–16)		SOARES et al. [57], [58], SOARES [56]	
Salgado Filho Airport, Porto Alegre, RS	20–70	1–5	10–15, UU-CIU	12 (10–16)		SCHNAID et al. [54]	

where:

s_u – undrained shear strength,

σ_{v0} – total vertical stress.

Most of the data presented in table 3 comes from lightly overconsolidated clays, with OCR in the range of 1–2. There is a significant scatter of N_{KT} in table 3, and part of it is attributed to different tests used to obtain the reference values of s_u.

3.2. EXPERIENCE WITH SOFT SOILS OF VERY HIGH PLASTICITY

The city of Rio de Janeiro is growing up towards west, and a number of very soft deposits with high plasticity can be found there. An important project SESC/SENAC that started in the mid 90's required a number of geotechnical studies for the design of embankments (ALMEIDA [3], ALMEIDA et al. [8]). A number of facilities related to the Panamerican Games, to be held in 2007 in Rio de Janeiro, are in the same area (figure 8).

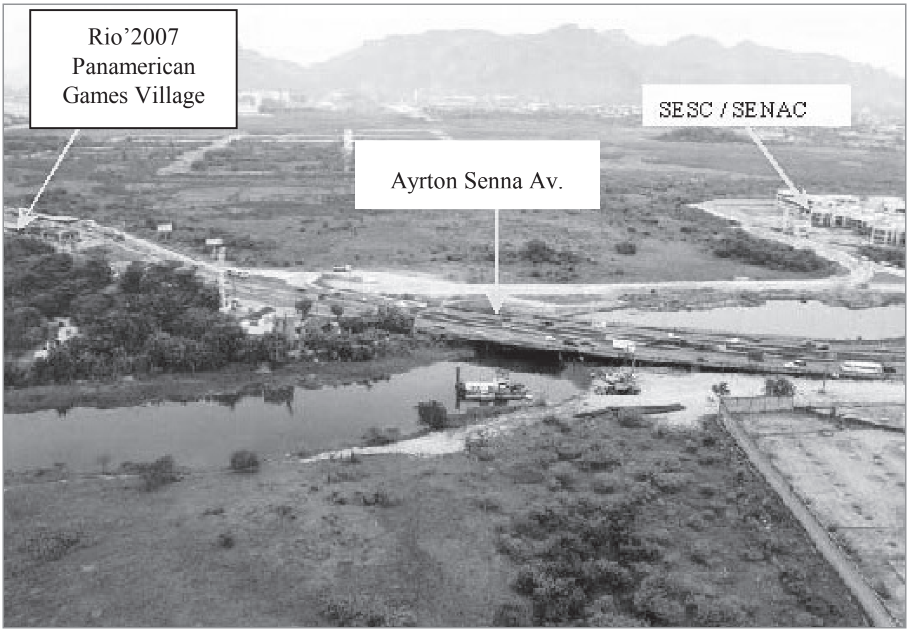

Fig. 8. View of part of the west region of the city of Rio de Janeiro, SESC/SENAC project, and Rio'2007 Panamerican Games Village

The geotechnical parameters of the soft soil in the SESC/SENAC area are presented in figure 9. Ground conditions can be defined as follows: very soft grey clay of fluvial-marine origin and with shell fragments, with a top layer of peat. ALMEIDA et al. [8] have divided the soil profile into three sublayers: a first sublayer (the depth of

0–3 m) with water content of about 500%; a second sublayer (the depth of 3–7 m) with water content of about 200%; and a third sublayer (the depth of 7–12 m) with water content of about 100%. Piezocone and vane tests and a number of laboratory tests have been performed in the area. The Sherbrooke sampler has been compared to piston samplers in a NGI-COPPE/UFRJ joint research project.

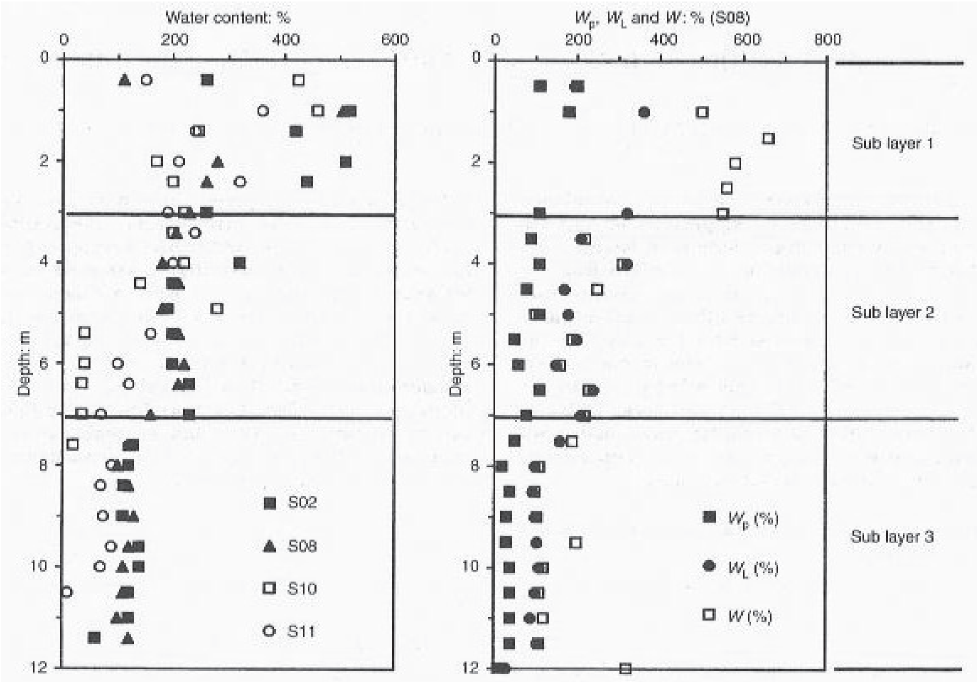

Fig. 9. Geotechnical parameters in the SESC/SENAC area (ALMEIDA [3], ALMEIDA et al. [8])

T-bar tests, piezocone tests and vane tests have been performed in the Panamerican Games Village area. The deposit is overconsolidated in a 3-m upper layer (OCR decreasing with depth), and lightly overconsolidated (OCR about 1.4) below this 3-m layer. The values of s_u obtained from those tests are compared in figure 10.

The values s_u from the T-bar tests have been obtained at the bar factor $N_b = 10.5$, which is the value suggested by STEWART and RANDOLPH [63] for any soil:

$$N_b = \frac{P}{s_u\, d}, \tag{3}$$

where:

P – the load per unit length acting in the T-bar,

d – the T-bar diameter.

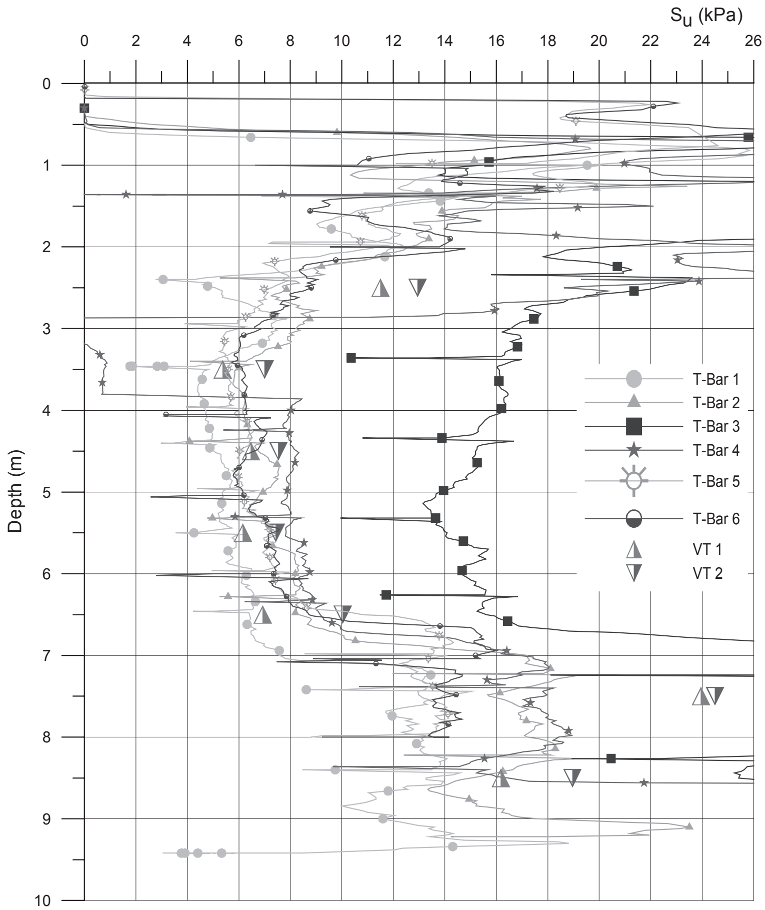

Fig. 10. Undrained shear strength s_u obtained from vane tests and T-bar tests (MACEDO [43], ALMEIDA et al. [5])

A significant scatter found in one of T-bar tests was attributed to the load exerted by roots found in the top soil, as can be seen in figure 11. There is good agreement between the values s_u obtained from the vane tests and the T-bar tests in the 3.5–6.5-m layer, the most homogeneous part of the profile. In the remaining part of the profile, the values s_u from the vane tests are from 15 to 65% greater than the s_u provided by the T-bar.

A good agreement between the values s_u obtained from the piezocone tests and the T-bar tests in the 3.5–6.5-m layer has also been obtained, as shown in figure 12. However, this agreement was possible due to a local correlation between the vane tests and the piezocone tests, providing a cone factor N_{KT} of about 7, which is in the lower limit of the N_{KT} values obtained in similar deposits.

Therefore the T-bar test was found to be less dependent on the bar factor N_b than the piezocone on the cone factor N_{KT}.

Fig. 11. T-bar at the beginning of a test; roots in the top soil can be observed (MACEDO [43], ALMEIDA et al. [5])

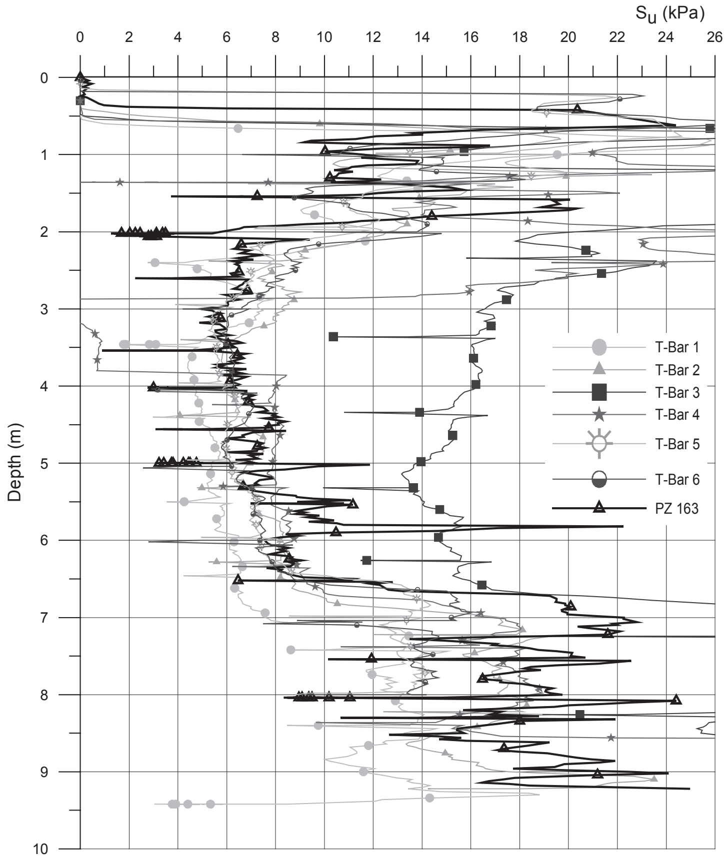

Fig. 12. Undrained shear strength s_u obtained from piezocone tests and T-bar tests (MACEDO [43], ALMEIDA et al. [5])

3.3. SOME LESSONS LEARNED FROM A PIEZOCONE WITH 2 FILTERS

Since the piezocone probe with two filters became a standard at COPPE/UFRJ, the advantage of its use compared to the single-filter probe became very clear under a number of circumstances, some of them being mentioned below.

In a number of cases, the equilibrium pore pressure as measured by the piezocone dissipation test was found to be different from the hydrostatic pore pressures. In these situations, the possibility of having two pore pressure dissipation curves provides more reliability with respect to the data obtained. Had the piezocone only one pore pressure measurement the doubts associated with possible errors related to the reference (zero) readings would be always present. Two situations are illustrated below.

Tests in Aracaju harbour from a jack-up platform

Piezocone tests with a single filter have been carried out from a jack-up platform some 2.5 km from the shoreline (figure 13). In the second series of tests, dissipation tests in the sand layer below the soft clay layer revealed equilibrium pore pressures at the depth by 3 m greater than it was expected. At the time the dissipation test was performed, the possibility of artesian pressures in the situation like this, i.e., no visible mountains (figure 14), was not regarded as available, and the whole team stayed a long while trying to understand what has actually happened. Since the number of tests was limited, it took some time until it was realized that the measured artesian pressures were considered to represent a real situation.

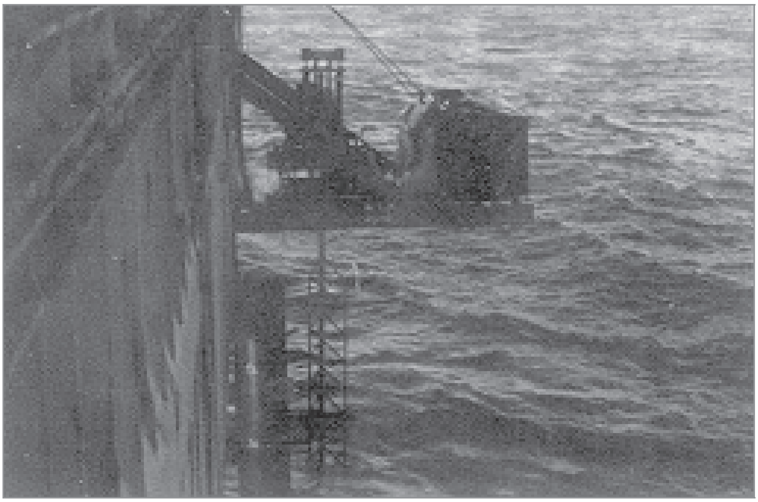

Fig. 13. Piezocone tests performed from a jack-up platform, in shallow waters, 2.5 km from the shoreline of Aracaju, northeast Brazil

Fig. 14. The shoreline view from the platform

Tests in the main Brazilian Motorway

The second case was related to the dissipation tests performed in the central part of the Rio de Janeiro – São Paulo Motorway (the main Brazilian Motorway), where series of accidents have been recorded due to the uneven surface in a certain area.

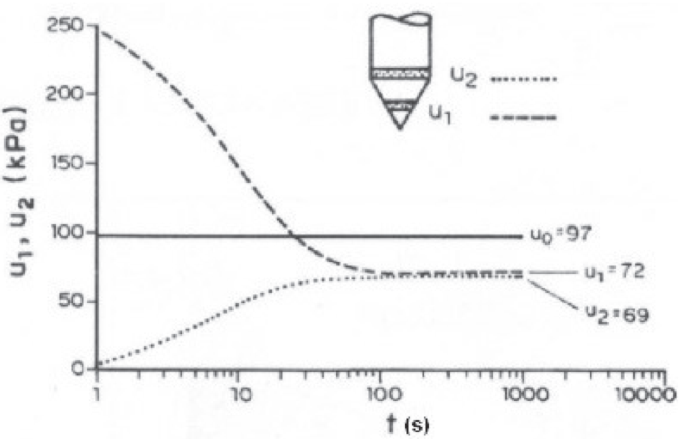

Fig. 15. Dissipation tests performed in Rio de Janeiro–São Paulo Motorway (DANZIGER et al. [29])

The interest was to check whether there was any layer of soft clay – which was supposed to have been removed – in the profile. The piezocone tests have shown no soft clay layer, however a quite particular situation arose (DANZIGER et al. [29]), as shown in figure 15. In fact, both pore pressures u_1 and u_2 obtained by dissipation tests were smaller than the equilibrium pore pressure u_0, calculated assuming the water level observed. Moreover, u_1 and u_2 provided very close final values, so a reliable result was obtained, indicating that it was a real situation. Had the piezocone a single filter, much more time would have to be spent to confirm the values obtained. The installation of piezometers has confirmed, as expected, the piezocone data. The pore pressure conditions have been attributed to pumping water for beer production by a beer plant (De MELLO [33]).

4. CONCLUSIONS

In situ tests on soft soils have increasingly been used in Brazil for the last 30 years in order to design embankments. Vane tests and piezocone tests are used as routine design tools, while other in situ tests are still restricted to research activities.

Piezocone tests have been performed on a number of soft soil deposits, which in most cases are plastic marine organic clays, slightly overconsolidated. A significant database is now available.

The advantage of using a piezocone with two filters in the dissipation tests has been illustrated.

The recent use of T-bar in one deposit of very soft soil with very high plasticity has been found to be promising. Actually, the T-bar was found to be less dependent on the bar factor than the piezocone on the cone factor.

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