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Estimation of Geotechnical Parameters of Santos Marine Clays using Piezocone and Vane Tests in Statistical Basis

Faiçal Massad
Escola Politécnica of São Paulo University, São Paulo, Brazil, faissal@usp.br

Abstract. The paper deals with the estimation of geotechnical parameters such as pre-consolidation pressure (σ'_p), undrained shear strength (s_u) and Young´s moduli (E_{oed} e E_{ur}) of marine clays of Santos Coastal Plain ("Baixada Santista"), Brazil, based on field and laboratory tests and in the light of the geological history of these sediments, in particular, their preconsolidation mechanisms. Simple formulae are proposed for the estimation of these parameters supported by the observation of linearly increasing variations, with depth, both the CPTU corrected point resistance (q_t) and the Vane Test undrained shear strength (s_u). A practical application of these formulae is presented, using field and laboratory tests, showing their potentiality. Evaluations of the mean, the variance and the coefficient of variation values are carried out for comparisons, based on the First Order Second Moment (FOSM) method.

KEYWORDS. Geological History; soft clays, CPTU, Vane Test, Consolidation Test

1 INTRODUCTION

The estimation of geotechnical parameters such as pre-consolidation pressure (σ'_a) and undrained shear strength (s_u) of marine clays has been made based on field tests (CPTU and Vane Test) and in the light of their geological history. Supported by the observation of a linear variation with depth of the CPTU corrected tip resistance (q_t), the author (Massad, 2009 and 2010) presented a simple formula to estimate the Kulhaway and Mayne (1990) empirical factor $N_{\sigma t}$ successfully applied to Santos clays. As it is known, this $N_{\sigma t}$ factor depends on the type of soil, its origin and correlation with results of consolidation tests on undisturbed samples of good quality. The same was observed with the undrained shear strengths from Vane Tests that increase linearly with depth, with growth rates (c_1) that depend on the submerged densities (γ') of the clays (Massad, 2009).

It is in this context that the knowledge of the marine clays origin is introduced and, in particular, their preconsolidation mechanisms, chiefly, preterit sea level variations and dune action. These mechanisms are reflected in correlations with depth of pre-consolidation pressures (σ'_a), the undrained shear strength (s_u) and oedometer Young´s moduli (E_{oed} and E_{ur}), of great importance in the application of some rheological models of soils, such as Hardening Soil Model (Schanz et.al. 2013). As recommended by Demers and Lerouiel (2002), geological and geotechnical knowledge should be considered when dealing with such correlations.

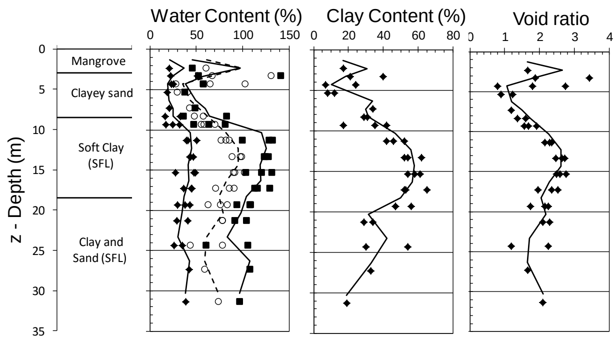

Figure 1: Subsoil data close to Barnabé Island

Figure 1 shows a subsoil profile close to Barnabé Island, in Santos, that will be referenced later on. An extensive field investigation (Massad, 2009 and 2010) revealed the following Holocene strata: a fluvial sedimentation that led to a sandy or clayey mangrove deposition, up to 2m width (SPT=0), followed by an intermediate sedimentation of a fluvial-bay type (SFL), 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. Not shown there was the presence of layers of the so called Transitional Pleistocene Clay (AT) at greater depths, with SPTs>5; and, at last, the occurrence of sands with gravel and residual soils from gneiss.

2 PRECONSOLIDATION PRESSURE (σ'_a)

Since the 90´s CPTUs are being executed in Santos Plain, especially for the design of port terminals. For the SFL Clays it was possible to observe a linear relationship between the corrected tip resistance (q_t) of CPTUs and depth (z), i.e., a and b being constants:

$$q_t = a + b \cdot z \tag{1}$$

Table 1: SFL Clays- Baixada Santista (Massad, 2010)

CPTU	γ_n (kN/m^3)	q_t (kPa)	$N_{\sigma t}$	$\sigma'_a - \sigma'_{vo}$ (kPa)
901(Cubatão)	15.0	204+30.8	~3.2	0
9 (Sto. Amaro)	15.5	268+31.4z	~3.0	81
10(Sto.Amaro)	15.5	154+31.4z	~3.0	8
12(Sto.Amaro)	15.5	224+31.4z	~3.0	42
2 (Santos)	15.5	564+32.0z	3.0	81
101(I.Barnabé)	14.9	472+34.0z	3.9	95

Table 1 shows some of these relationships. On the other hand, about 20 underground profiles, from different sites of Santos Plain (Massad, 2010) showed that there is a sound parallelism between the preconsolidation pressure (σ'_a) and the effective earth pressure (σ'_{vo}), i.e.:

$$\sigma'_a = const + \sigma'_{vo} = \sigma'^{\,z=0}_a + \gamma' \cdot z \tag{2}$$

This finding suggests an over consolidation due to preloading, which can be attributed to the lowering of water sea level or dune action during the Holocene, which is consistent with the geological history of the region (Massad, 2010).

For the determination of σ'_a through CPTU data an empirical correlation proposed by Kulhawy and Mayne (1990) has been employed:

$$\sigma'_a = \frac{q_t - \sigma_{vo}}{N_{\sigma t}} \tag{3}$$

where σ_{vo} is the initial total vertical pressure and $N_{\sigma t}$ an empirical factor, usually taken equals to 3.3 (Kulhaway & Mayne, 1990) or 3.4 (Demers & Leroueil, 2002), among other values.

If γ_n and γ' are respectively the natural and effective unit weights of the soil the following linear relationships hold:

$$\sigma_{vo} = \sigma^{z=0}_{vo} + \gamma_n \cdot z \tag{4}$$

$$\sigma'_{vo} = \sigma'^{\,z=0}_{vo} + \gamma' \cdot z \tag{5}$$

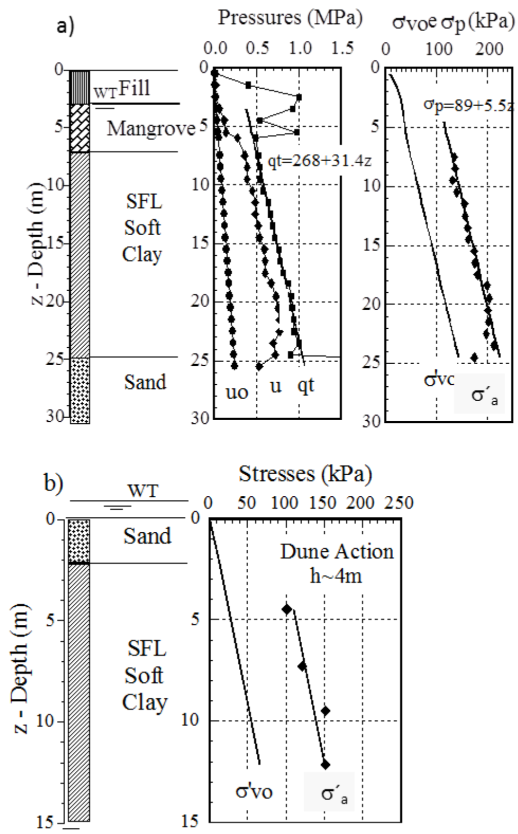

Figure 2. a) CPTU 09 e b) Oedometer test - Santo Amaro Island, Baixada Santista.

where the first terms on the right-hand sides are constants. From Eqs. (1) to (4) it follows (Massad 2009 and 2010):

$$N_{\sigma t} = \frac{b-\gamma_n}{\gamma'} \quad \text{and} \quad \sigma'^{z=0}_{a} = \frac{a-\sigma^{z=0}_{vo}}{N_{\sigma t}} \qquad (6)$$

Figure 2 illustrates the application of these equations to a CPTU in Santo Amaro Island, Santos Plain. Using Eq. (3) with $N_{\sigma t}$ given by Eqs. (6) values of σ'_a were obtained and they compare very well with the results of oedometer tests (see Figure 2-b) carried out in undisturbed samples. In this region the preconsolidation mechanism is due to the action of dunes and $N_{\sigma t}$ assumed a figure of 3.0.

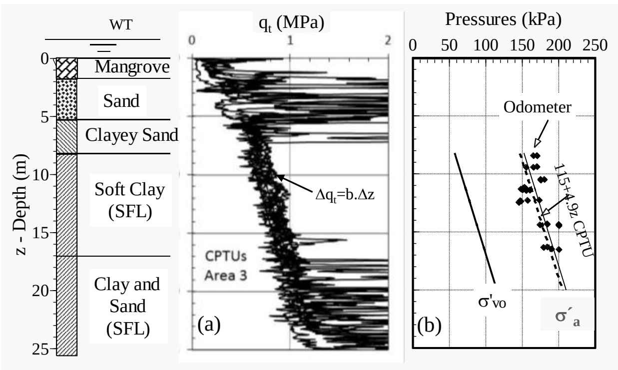

Figure 3. CPTUs close to Barnabé Island vs oedometer Tests - Baixada Santista (Massad et. al., 2013).

Figure 3-a displays various CPTUs in a site close to Barnabé Island with the subsoil presented in Fig. 1. A good agreement of σ'_a from a CPTU and oedometer tests are shown in Fig. 3-b for the Soft Clay. Table 2 shows the values of *a* and *b* (Eq. 1).

The following values were found: $N_{\sigma t}$=3.9, *b*=34 and *a* ranging from 210 to 470 kPa (mean of 335 kPa and a standard deviation of 86 kPa). Table 1 shows results obtained by Massad (2010) in other sites of Santos Plain.

Reporting again to the data of Figure 3 and Table 2, Tables 3 and 4 present the results of a geo-statistical analysis applying the FOSM ("First Order Second Moment") method (Christian et. al., 1992) to Eqs. (3) and (6).

Table 2: Values of *a* and *b* (Eq. 1) for the Soft Clay (SFL) of Fig. 3 - Close to Barnabé Island

CPTU	a	b
1	300	34
2	210	34
3	220	34
4	300	34
5	407	34
6	320	34
7	280	34
8	278	34
9	231	34
10	472	34
11	407	34
12	463	34
13	400	34
14	407	34

Table 3. Statistical analysis of data of the Soft Clay layer close to Barnabé Island- Input Data

Item		Average	CV (input)	Variance
γ_n *(kN/m3)*		14.9	5.0%	0.56
$\sigma_{vo}^{z=0}$ *(kPa)*		15.2	0	0
$q_t=a+b.z$ *(CPTU)*	*a (kPa)*	335	25.7%	7396
	b(kPa/m)	34.0	0	0
$s_u=c_o+c_1.z$ *(Vane Test)*	c_o *(kPa)*	28.0	18.9%	28.1
	c_1*(kPa/m)*	1.47	0	0

Table 4. Statistical analysis of data close to Barnabé Island- Output Data

Item		Average	Variance	CV (output)
$N_{\sigma t}$		3.9	0.55	19.1%
N_{kt}		13.0	0.26	3.9%
σ'_a-γ'.z		82.0	732	33.0%
$s_u=c_o+c_1.z$ *(CPTU)*	c_o *(kPa)*	24.6	44.7	27.2%
	c_1*(kPa/m)*	1.47	-	-

Coefficient of variations (*CV*) of 5% and 0% were assigned to γ_n and *b*, respectively. It was concluded that $N_{\sigma t}$=3.9 *(CV=19.1%)* and σ'_a*=82.0+4.9.z (CV=33%)*. Under the adopted premises, the contributions of *a* and $N_{\sigma t}$ to the variance of σ'_a amounted to 66% and 34%, respectively.

3 UNDRAINED SHEAR STRENGTH (s_u)

Hundreds of Vane Tests have revealed s_u varying linearly with depth, i.e.:

$$s_u = c_o + c_1 . z \tag{7}$$

where c_o and c_1 are constants. Again, this fact is consistent with the Geological History of the Santos marine clays and applies in their "virgin" states.

In cases where CPTUs are available, the undrained shear strength can be obtained by the known expression derived from the Theory of Cylindrical Cavity Expansion:

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \tag{8}$$

where N_{kt} is an empirical factor, usually varying in a wide range of values, determined by reference to s_u measurements through other types of testing.

In view of Eqs (1) and (4), equation (8) can be transformed into:

$$s_u = \frac{a - \sigma_{vo}^{z=0}}{N_{kt}} + \frac{b - \gamma_n}{N_{kt}} \cdot z \tag{9}$$

Imposing to Eq (9) the same growth rate with depth (c_1) of Eq (7), it follows:

$$N_{kt} = \frac{b - \gamma_n}{c_1} \quad \text{and} \quad c_o = \frac{a - \sigma_{vo}^{z=0}}{N_{kt}} \tag{10}$$

Besides the already mentioned 14 CPTUs (Fig. 3) almost 300 Vane Tests (Figure 4) were carried out in 32 points in a site close to Barnabé Island. Reporting to Eq. 7 and Figure 4, it is noticeable that c_o ranged roughly between 19 and 35 kPa (averaging 28 kPa) and c_1=1.47 kPa/m. The resulting residual deviation was figured out 5.3 kPa.

The application of FOSM method ("First Order Second Moment") to Eqs. (10) allows stating (see Tables 3 and 4) that the average value of the c_o obtained through CPTUs (24.6 kPa) was slightly lower than the corresponding value of Vane Tests (28.0 kPa), but with a greater dispersion: CV of 27% (CPTUs) versus 19% (Vane Tests) in rounded numbers. Under the adopted premises, the contributions of a and $N_{\kappa t}$ to the variance of c_o amounted to 98% and 2%, respectively.

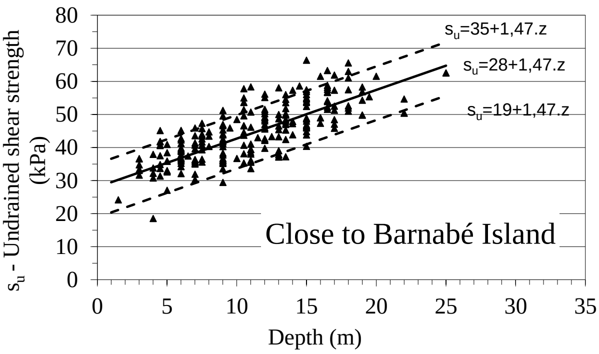

Figure 4: Undrained shear strength from Vane Tests vs depth (SFL Clays)

4 OEDOMETER MODULI (E_{oed} e E_{ur})

The oedometer test provides the tangent oedometer moduli - E_{oed} for loading and E_{ur} for unloading-reloading - and the pre-consolidation pressure (σ'_a), which are references to define the parameters α and β of Kuwalhay and Mayne (1990):

$$E_{oed} = \alpha \cdot (q_t - \sigma_{vo}) \tag{11}$$

$$E_{ur} = \beta \cdot (q_t - \sigma_{vo}) \tag{12}$$

Using the Eqs. (3), (11) and (12), the following relations hold for α and β:

$$\alpha = \frac{(E_{oed} / \sigma'_{vo})_{LAB}}{N_{\sigma t} \cdot OCR} \tag{13}$$

$$\beta = \frac{(E_{ur} / \sigma'_{a})_{LAB}}{N_{\sigma t}} \tag{14}$$

The E tangent modulus can be determined in oedometer tests by the expressions:

$$\frac{E}{\sigma'_v} = -\frac{d\sigma'_v}{de} \cdot \frac{1+e_o}{\sigma'_v} = -(1+e_o) \cdot \frac{d(\ln \sigma'_v)}{de} \quad (15)$$

If, during testing the load is doubled from one stage to the next, Eq (15) can be replaced by:

$$\frac{E}{\overline{\sigma}_v} = \frac{2.\ln(2) \cdot (1+e_o)}{e_1 - e_3} \quad (16)$$

where e_1 and e_3 are respectively the void ratios at the end of the forward and subsequent stages of the considered stage.

Figure 5 illustrates the application of Eq. 16 to a consolidation test in a good quality undisturbed sample, extracted close to Barnabé Island, at a depth of 8.4 m (Aguiar [8]). The preconsolidation pressure (σ'_a) was 170kPa.

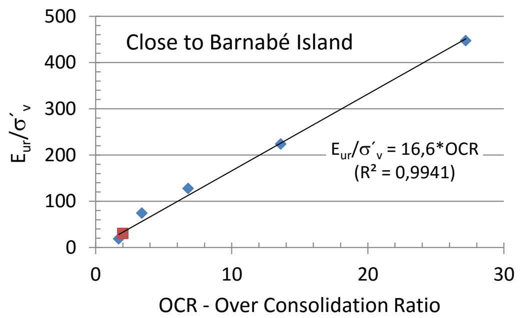

Figure 5: Interpretation of an oedometer test - Sample 4-A

The value of E_{oed}/σ'_v associated to OCR=1 resulted in 5.7. On the other hand, for the loading and unloading ranges ($OCR > 1$) Figure 5 provides the relationship E_{ur}/σ'_v=16.6*OCR, whence E_{ur}/σ'_a=16.6.

This type of analysis was applied to other undisturbed samples [8], yielding the results shown in Table 5.

For the universe of all samples of Table 5 the average of the relation E_{ur}/σ'_a was about 18.0 with a standard deviation of 3.0. Based on Eq. 14 and $N_{\sigma t}$ data of Table 4 it followed β=18.0/3.9=4.6 on average with a variance of about 1.37 and CV = 25.4%. These figures resulted from implementing the FOSM method ("First Order Second Moment") to Eq. (14) and are summarized in Table 6. Under the adopted premises, the contributions of $N_{\sigma t}$ and E_{ur}/σ'_a to the variance of β were 57% and 43%, respectively.

Table 5. E_{oed} e E_{ur} from Consolidation Tests in a site Close to Barnabé Island (Apud Aguiar [8])

Depth (m)	Sample	E_{ur}/σ'_a	E_{oed}/σ'_v	OCR	(E_{oed}/σ'_v)/ OCR	(E_{oed}/σ'_v)/ OCR
5.6	1-A	19.84	11.1	2.5	4.44	-
	1-B	22.10	10.5	2.5	4.20	-
	1-C	16.60	10	2.3	4.35	-
	1-D	15.38	9.1	2.4	3.79	-
7.3	3A	14.23	7.9	2.1	3.76	-
	3B	23.16	9.1	2.0	4.55	-
	3C	20.23	10.5	2.4	4.38	-
8.4	4A	16.60	5.7	3.1	-	1.84
9.4	5-A	14.90	7	2.8	-	2.50
10.5	6-A	16.43	5.1	2.7	-	1.89
	Average	17.95	-	-	4.21	2.08
	Standard Deviation	2.98	-	-	0.29	0.30

Table 6. Statistical analysis of -α and β parameters, close to Barnabé Island

Item		Average	CV (input)	Vari-ance	CV (output)
$N_{\sigma t}$		3.9	19.2%	0.55	-
E_{ur}/σ'_a		18.0	16.7%	9.0	-
β		4.6	-	1.37	25.4%
For z<8m	(E_{oed}/σ'_v)/ *OCR*	4.21	6.9%	0.08	-
	α	1.08	-	0.05	20.3%
For z>8m	(E_{oed}/σ'_v)/ *OCR*	2.08	14.4%	0.09	-
	α	0.53	-	0.02	23.9%

For similar estimates of α (Eq. 13), the data presented in the last two columns of Table 5 were used. The separation into two universes was necessary and is justified by the type of soil: sandy to about 8m deep (z) and clayey below this value (see Fig. 1). Table 6 summarizes the results. It is seen that α ranged from 0.5 to 1.0 with $CV \cong 24\%$.

5 FINAL REMARKS

Based on the geological history of marine sediments from Santos Plain, Brazil, the work presented formulae to estimate the empirical factors $N_{\sigma t}$ (of Kulhaway and Mayne) and N_{kt} and thus determine both the pre-consolidation pressure (σ'_a) and the undrained shear strength (s_u) through CPTUs. In both cases, the formulae are very simple and that for N_{kt} brings in equivalence to the growth rate with depth of the s_u Vane Tests.

A practical application was made using the FOSM method for comparisons. In addition, it was shown that the α and β parameters of Kuwalhay and Mayne, which allow the estimate of the E_{oed} and E_{ur} moduli through CPTUs, can be determined by the results of consolidation tests on undisturbed samples of good quality Again, simple mathematical expressions have been provided, which facilitate the interpretation of consolidation tests, as shown in the practical application.

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