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Undrained shear strength correlation analysis based on vane tests in the Jacarepaguá Lowlands, Brazil

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Technical Note

Keywords
Organic soil
Piezocone test
Plasticity index
Undrained shear strength
Vane test
Soft soil

Abstract

The test sites analyzed here consist of clay deposits located in the Jacarepaguá Lowlands in Rio de Janeiro, characterized by high plasticity, high compressibility and low undrained shear strength. The deposits are made up of lightly overconsolidated aged clays, montmorillonite being the predominant clay mineral. Soft clay deposits are usually superficial, with thicknesses generally varying between 6 m and 17 m and geologically recent and originated from marine regressions and transgressions, that occurred between 6000 and 3500 years ago. The objective of this study is to analyze a large database of undrained shear strength measurements obtained by 461 vane tests performed at 15 different sites. In general, most of the data correspond to very soft clays, with undrained shear strength values lower than 25 kPa. The undrained shear strength measurements are correlated with plasticity index and with maximum excess pore pressure, measured with piezocone tests. The method for estimating the undrained shear strength $s_{u(DT)}$ of soil from the excess pore pressure generated during piezocone dissipation tests proposed by Mantaras et al. (2015) was validated against the vane test database.

1. Introduction

The Jacarepaguá Lowlands, shown in Figure 1, is a coastal region formed mainly by thick deposits of soft and very soft organic clays with high plasticity, high compressibility, and low undrained shear strength (e.g. Baroni & Almeida, 2017; Riccio et al., 2013; Almeida et al., 2008; Futai et al., 2008; Almeida et al., 2007). It is limited to the South by the Atlantic Ocean, to the West and North by the Pedra Branca Massif, and to the East by the Tijuca Massif. It extends around 22 km along the East-West axis and 4 to 6 km along the North-South axis, with a total area of 120 km^2. Due to the scarcity of land with better subsoil conditions, several infrastructure projects were carried out in this region in the last decade, such in 2007 the Pan-American Games, in 2014 the FIFA World Cup and in 2016 the Olympic and Paralympic Games.

The undrained shear strength s_u of soft soil is a fundamental parameter controlling the stability of structures built on these soils. However, s_u is dependent on various factors affecting soil behavior such as the mode of failure, stress paths, strain rate, anisotropy, temperature, stress history, clay structure, among other factors (Bjerrum, 1973; Ladd et al., 1977; Wroth, 1984). The undrained shear strength of soft clays is often obtained using in situ vane tests, especially in very soft clay deposits, due to the difficulty of extracting undisturbed samples. Correlations of the s_u with the stress history (e.g., overconsolidation ratio, preconsolidation stress) have been presented by various authors (e.g., Mesri, 1975; Ladd et al., 1977; Ng et al., 2017). However, such correlations require good quality undisturbed samples, which are not easily obtained in very soft soil deposits, and for this reason are not addressed in the present technical note. The objective of this study is to analyze the results of 461 good quality in situ vane shear tests performed at 15 different sites located in the Jacarepaguá Lowlands. The undrained shear strength measurements are then correlated with soil parameters including Atterberg limits and piezocone measurements. Compressibility studies in this region have recently been reported (Baroni & Almeida, 2017).

2. Jacarepaguá Lowlands general characteristics

The subsoil of Jacarepaguá Lowlands is composed of deposits of very soft clay with high organic matter content, formed in the Quaternary period (Suguio & Martin, 1981). The deposits are geologically recent and originated from marine regressions

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Figure 1. Location of the Jacarepaguá Lowlands and studied sites.

and transgressions, that occurred between 6000 and 3500 years before present (Costa Maia et al., 1984). Soft clay deposits are usually superficial, with thicknesses generally varying between 6 m and 17 m, although deposits of 22 m (Riccio et al., 2013) and 28 m (Almeida et al., 2008) have been reported. Superficial fill sand layers, deposited for the temporary traffic of vehicles, are commonly found at some sites.

In general, the local clay deposits present a superficial layer varying from 1.0 m to 4.0 m in thickness, which may reach organic matter content values up to 60% (Baroni & Almeida, 2017). These deposits have high water content (w) reaching 950% for the top crust organic layers, then decreasing to around 100% for deeper layers. These deposits are classified as organic soils and not as peat soils (Landva & Pheeney, 1980).

The soil bulk unit weight (γ) was generally very low, with average values on the order of 13 kN/m^3, while the specific gravity of soil particles (G_s) varied between 2.44 and 2.66. In general, the grain size distribution showed more than 50% of fines and X-ray diffraction analysis indicated that montmorillonite was the predominant clay mineral, which is compatible with the high activity value presented in Table 1. The presence of quartz, kaolinite and muscovite were also detected by the X-ray diffraction measurements.

A summary of typical soil properties is also presented in Table 1, with the soil being classified as a black, high plasticity, very soft, high-organic, sandy silty clay with extremely low undrained shear strength (BS, 2018a, b). The presence of humic acids associated with a low pH value was also detected (see Table 1). The low values of the specific gravity of soil particles (G_s) and of the bulk unit weight (γ) result from high values of organic matter content (OM), and are compatible with the literature (Coutinho & Lacerda, 1987; Mitchell & Soga, 2005).

All clay deposits in this region have high water content, plasticity and compressibility, with compression ratios

Table 1. Typical properties of the soil tested.

Properties	Range/Value
pH	3.36
Activity, $A = I_p$/%<0.002mm	6-6.4
Electrical conductivity, EC (mS/cm)	6.59
Salinity (%)	0.35
Sulphate (mg/L)	4551
Chloride (mg/L)	505

($CR = CC/(1+e_o)$) typically around 0.45 (Almeida & Marques, 2013). In the superficial layers, where high organic clay soils and roots are found, the overconsolidation ratio (OCR) values may reach high values on the order of 8 (Baroni & Almeida, 2017). The OCR decreases with increasing depth, reaching typical values between 1 and 2 (Baroni & Almeida, 2017) as a result of aging and water level fluctuations (Parry & Wroth, 1981). The values of the coefficient of consolidation (c_v) are generally very low, on the order of 3×10^{-8} m^2/s (Almeida & Marques, 2013).

The typical values of water content (w) and liquid limit (w_L) below the crust layer are w = 175% and w_L = 150%, respectively. Clays with natural moisture close to or above the liquidity limit are found along the entire Brazilian coast (Coutinho & Lacerda, 1987; Almeida & Marques, 2003; Oliveira et al., 2010; Coutinho & Bello, 2014; Jannuzzi et al., 2015; Baroni & Almeida, 2017).

In general, the soil parameters are more scattered in the top organic clay layers. The plasticity index ($I_P = w_L - w_P$) is greater than 80% in the deeper layers of clay, reaching 500% in the shallower clay layers, indicating that the deposits have a high plasticity. Below a depth of 3 m the average I_P value is 110% (Baroni & Almeida, 2017). Equation 1 shows the local relationship (Baroni, 2016) between the plasticity index and the liquid limit, the 0.7 angular coefficient obtained is similar to the well-known 0.73 Casagrande's coefficient.

$$I_P = 0.7w_L - 6.12 \quad (1)$$

Table 2 presents the range of geotechnical parameters for the 15 sites studied. It shows that the average value of the liquidity index ($I_L = (w - w_P)/I_P$) is typically greater than unity, suggesting that clays may be sensitive (Mitchell & Soga, 2005). Some data are limited, such as clay sensitivity and liquidity index, and therefore are not correlated with vane undrained shear strength.

3. Undrained shear strength data bank

Most vane tests presented here were performed using vane borer equipment, having been used with excellent results in the last two decades in Brazil (Baroni & Almeida, 2012; Coutinho & Bello, 2014), and considered in the literature to be quite reliable for measuring low undrained shear strength values (e.g. Selänpää et al., 2017).

Figure 2 presents water content and undrained shear strength profiles for the studied deposits. Higher values of water content are observed (Figure 2a) for the top 3 m deep superficial layer as these present higher organic matter content values. Figure 2b shows data from the 461 vane test results used herein. The water level variation at the surface and associated soil dryness, in addition to the presence of roots in this region, result in higher values of s_u (Figure 2b). Below depths of 3 m the expected trend of decreasing

Table 2. Physical properties and undrained shear strength - average values from 15 sites.

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13	Site 14	Site 15
w (%)	294	247	277	244	174	130	115	149	108	94	104	-	250	-	-
w_P (%)	76	64	67	80	71	42	44	56	-	-	21	-	84	-	-
w_L (%)	223	289	204	206	200	123	132	150	-	-	43	-	243	-	-
I_P (%)	148	224	139	124	135	80	88	94	-	-	13	-	159	-	-
I_L (%)	1.58	0.85	1.51	1.29	1.13	1.08	0.82	0.81	-	-	2.63	-	1.52	-	-
γ (kN/m^3)	11.5	12.3	12.5	12.4	14.2	13.7	14.1	14.0	13.4	13.6	13.3	-	12.1	-	-
OM (%)[a]	16.8	18.7		-	12.4	-	-	-	-	-	-	-	-	-	-
s_u (kPa)	11.8	13.8	10.1	17.5	12.8	5.4	40.5	4.0	9.8	8.4	43.4	13.6	17.4	10.6	24.5
[N° of points]	[41]	[43]	[26]	[103]	[42]	[10]	[50]	[14]	[15]	[12]	[25]	[13]	[33]	[13]	[21]
$s_{t\,(average)}$[b]	10.1	6.4	10.5	-	9.3	4.2	-	7.5	5.3	11.1	3.4	4.5	5.6	10.3	-

[a] Organic Matter; [b] Clay Sensitivity - s_t

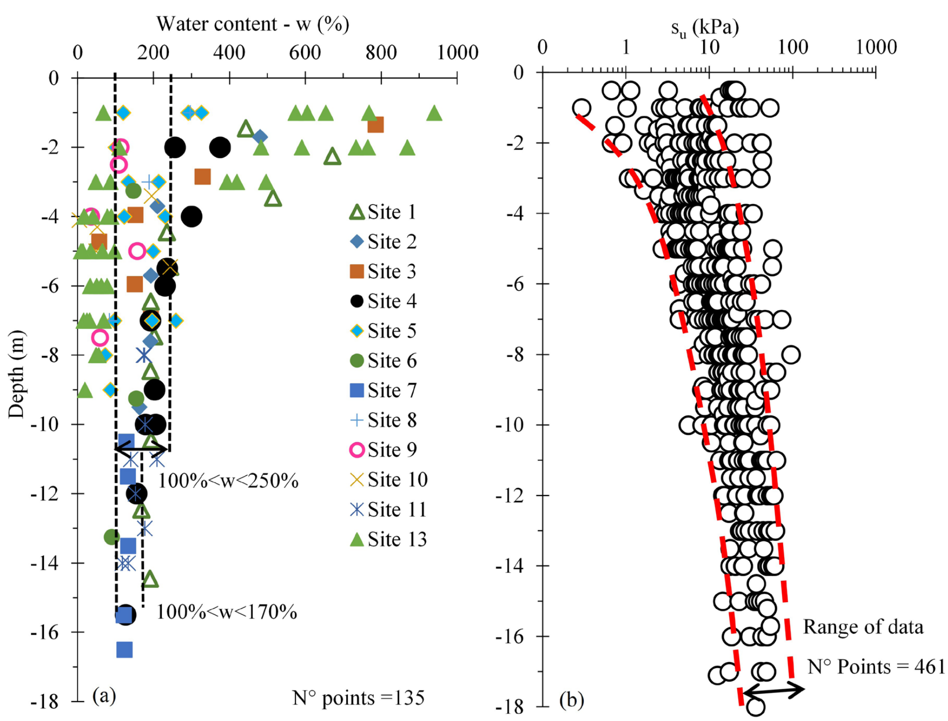
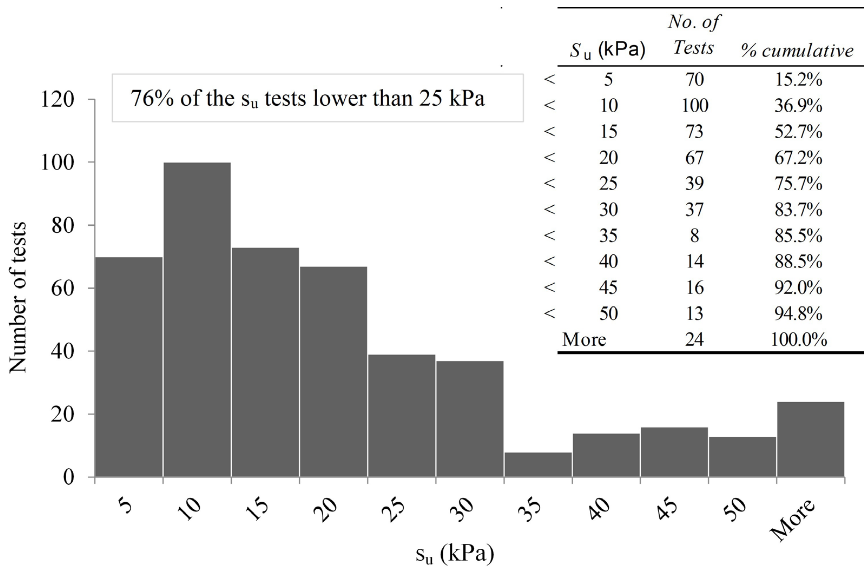


Figure 2. (a) Soil moisture content, 12 sites and (b) undrained shear strength.



	S_u (kPa)	No. of Tests	% cumulative
<	5	70	15.2%
<	10	100	36.9%
<	15	73	52.7%
<	20	67	67.2%
<	25	39	75.7%
<	30	37	83.7%
<	35	8	85.5%
<	40	14	88.5%
<	45	16	92.0%
<	50	13	94.8%
More		24	100.0%

Figure 3. Histogram of undrained shear strength values measured.

water content (w) with increasing effective stresses and the consequent increase in undrained shear strength (Atkinson, 1981) is observed.

The histogram shown in Figure 3 indicates that 70 out of the 461 measurements of s_u presented values of s_u lower than 5 kPa. Approximately 76% of the tests resulted in values of s_u lower than 25 kPa, which classifies the deposits studied here as very soft clay (Terzaghi & Peck, 1967). This range of strength variation is consistent with values found in other Brazilian deposits (e.g. Lacerda & Almeida, 1995; Almeida & Marques, 2003; Schnaid, 2009; Coutinho & Bello, 2014; Jannuzzi et al., 2015).

4. Undrained shear strength versus plasticity index

The relationship between the undrained strength normalized by the vertical in situ effective stress s_u/σ'_{vo} and the plasticity index I_P of the studied clays is presented in Figure 4, with the curves of young and aged clays proposed by Bjerrum (1973) and Chandler (1988) for OCR = 1 “young” clay and m_{fv} = 0.95, in order to predict OCR from field vane test data. It is extended here for a wider range of plasticity index values. Although some scatter is observed for the available data, the points are distributed in a regular pattern in Figure 4, generally falling between the two proposed curves for young and aged clays, which is consistent with the geology of the clay deposit. The points outside the range of variation, indicate the presence of sand lenses or shells fragments in the soil. The linear relationship between s_u/σ'_{vo} and I_P proposed by Skempton (1957) for stiffer, less plastic clays does not fit well with the present database for very soft high plasticity clays.

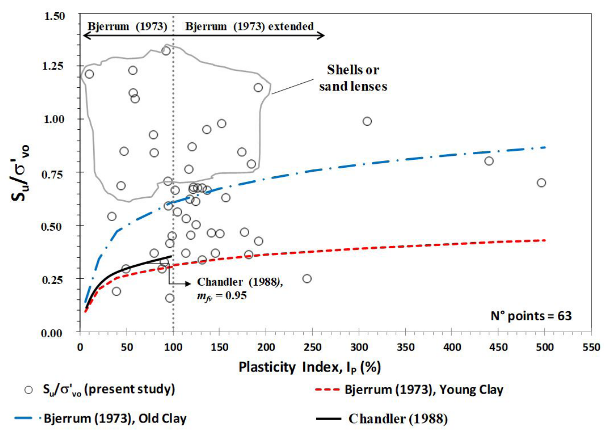


Figure 4. Correlation between s_u/σ'_{vo} and soil plasticity index (I_P).

5. Undrained strength versus excess pore pressure

A method for estimating the undrained shear strength $s_{u(DT)}$ of soil from the excess pore pressure generated during piezocone dissipation tests was proposed by Mantaras et al. (2015). Using the principles of cavity expansion and critical state soil theory, the authors obtained consistent estimates of s_u according to Equation 2.

$$s_{u(DT)} = Du_{max} \; / \; 4.2' log\left(I_r\right) \tag{2}$$

The values of $s_{u(DT)}$ obtained from Equation 2 are compared here with values of $s_{u(VT)}$ obtained by means of the vane equipment (reference test), and the $s_{u(CPTU)}$ obtained with the

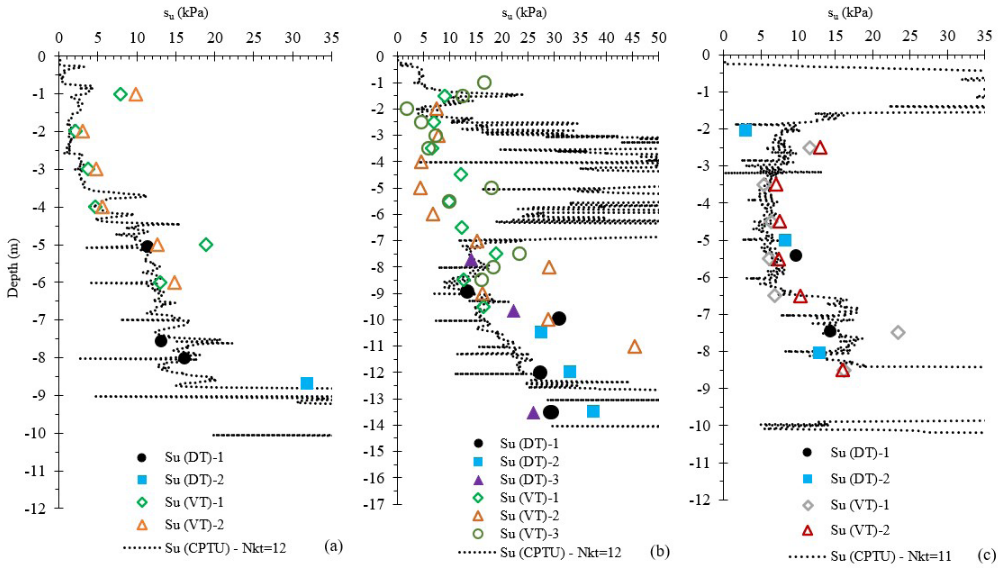


Figure 5. Comparison of s_u obtained through different methodologies: (a) site 10, (b) site 13 and (c) site 14.

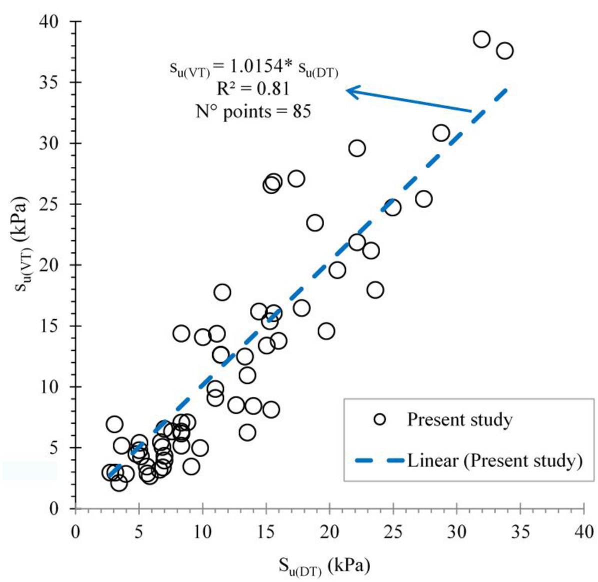


Figure 6. s_u measured with vane tests versus $s_{u(DT)}$ estimated with the CPTU dissipation test.

piezocone test using calibrated N_{kt} parameters (Lunne et al., 1997). Figure 5 shows the profiles obtained for three of the studied sites. The results of the correlation proposed by Mantaras et al. (2015) are in good agreement with the measured values from the vane tests and piezocone tests (CPTU). In the region under study, the cone factor N_{kt} varies randomly with the depth, and it is not uncommon to use different N_{kt} values for the estimation of the s_u profile in the same location. The tests performed indicate that the lower limit and upper limit values of N_{kt} are 6 and 18, respectively, with N_{kt} = 12 a typical average value.

Figure 6 correlates 85 results of $s_{u(VT)}$ and $s_{u(DT)}$ for tests at nearby boreholes carried out at similar depths. As shown in Figure 6, the $s_{u(DT)}$ values are around 1.5% lower than the $s_{u(VT)}$ values, indicating that Equation 2 can be applied for estimation of s_u for the Jacarepaguá Lowlands.

6. Conclusions

Results of 461 vane tests performed at 15 different sites located in the Jacarepaguá Lowlands in Rio de Janeiro were analyzed here. In general, most of the data correspond to very soft clays, with undrained shear strength values lower than 25 kPa. The soil profiles show, as expected, a decrease in water content and a corresponding increase in undrained shear strength with depth.

As expected, the undrained shear strength, normalized with effective stresses, increased with the plasticity index in a nonlinear trend, within the range of young and aged clays proposed by Bjerrum (1973) and Chandler (1988).

A correlation proposed in the literature to obtain the undrained shear strength from the maximum excess pore pressure measured with piezocone tests was validated against the vane test database.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Magnos Baroni: conceptualization, methodology, investigation, data curation, writing – original draft, validation, writing – review & editing. Marcio Almeida: conceptualization, data curation, methodology, supervision, validation, writing – review & editing.

List of symbols

A	Activity
CC	compression index
CPTU	piezocone test
EC	electrical conductivity
G_s	specific gravity of soil particles
G	soil shear modulus
I_L	liquidity index
I_r	soil rigidity index
I_P	plasticity index
OM	organic matter
OCR	overconsolidation ratio
c_v	coefficient of consolidation
e_o	initial void ratio
s_u	undrained shear strength
$s_{u\,(DT)}$	undrained shear strength of soil from the excess pore pressure generated during piezocone dissipation
s_t	clay sensitivity
w_L	liquid limit
w	natural water contentw_P plastic limits
Δu_{max}	maximum normalized excess pore pressure
γ	soil bulk unit weight
σ'_{v0}	vertical in situ effective stress

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