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Evaluation of pre-consolidation pressure and undrained shear strength of marine clays from CPTu data

Évaluation de la pression de préconsolidation et de la résistance au cisaillement non drainé des argiles marines à partir des données du CPTu

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ABSTRACT: The paper presents comparisons between different semi empirical methods for the estimation of pre-consolidation pressure and undrained shear strength of soft clays from CPTu data. The methods have been recently published by Massad (2009, 2010, 2016), Mayne (2016) and Odebrecht & Schnaid (2018) and were applied to the marine clays of the Bothkennar (UK) and of a region close to the Barnabé Island, in the Coastal plain of Santos, Brazil, referred to herein as Barnabé Island clay. It is intended to verify if these methods are consistent with each other, with the results from other field and laboratory tests and with the known stress history (ageing and unloading). Overall, for Bothkennar clay, there was good agreement between the different methods and the different types of tests (field and laboratory). For the Barnabé Island clay, the application of the Mayne's Method resulted in pre-consolidation pressures and undrained shear strength significantly higher than those obtained by the other methods and tests, due to the great effect of B_q parameter on the analyzes. The paper confirms the importance of trying to validate methods that estimate geotechnical parameters from CPTu with tests that measure them directly and bearing in mind the stress history of the soils.

RÉSUMÉ: L'article présente des comparaisons entre différentes méthodes semi-empirique pour l'estimation de la pression de pré-consolidation et de la resistance non drainée de cisaillement des argiles molles à partir des données du CPTu. Ces méthodes, récemment publiées par Massad (2009, 2010, 2016), Mayne (2016) et Odebrecht & Schnaid (2018), ont été appliquées aux argiles marines molle de Bothkennar (UK) et de la région de l'Ile de Barnabé (Santos, Brésil), ici appelée argile de l'île Barnabé. Il est destiné à vérifier si ces méthodes sont compatibles d'abord les uns avec les autres et aussi avec les résultats d'autres essais et de l'histoire des contraintes de ces sols (vieillissement et déchargement). Dans l'ensemble, pour l'argile Bothkennar, il y avait un bon accord entre les différentes méthodes et les différents types d'essais (champ et laboratoire). Pour l'argile de l'Ile Barnabé, l'application de la méthode de Mayne a entraîné des pressions de pré-consolidation et résistances de cisaillement non drainée beaucoup plus élevée que celles obtenues par les autres méthodes et essais, en raison du grand effet du paramètre B_q sur les analyses. Par conséquent, il est toujours important d'essayer de valider les méthodes basées sur le CPTu avec autres essais et en tenant compte l'histoire des contraintes des sols.

KEYWORDS: Piezocone; stress history; pre-consolidation pressure; undrained shear strength; marine clays.

1 INTRODUCTION

As the CPTu is a very usual test in field investigations, it is interesting to use its results in a more embracing way for the determination of several geotechnical parameters, to exempt a large quantity of specific tests. It is important to highlight that, although in a reduced quantity, the tests that directly measure parameters, such as the pre-consolidation pressure and undrained shear strength, are essential for the validation of estimates from CPTu data on an empirical basis.

Demers & Leroueil (2002) recommended that the geological knowledge (deposition processes, erosion / thawing, sea level variations and ageing) should also be considered when establishing correlations between CPTu results and oedometer tests.

Based on the CPTu data, Eq. 1 is one of the most used for the estimation of the pre-consolidation pressure (σ'_a). It was proposed by Kulhawy & Mayne (1990, apud Coutinho & Oliveira 1993):

$$\sigma'_a = \frac{q_t - \sigma_{v0}}{N_{\sigma t}} \quad (1)$$

where q_t is the corrected cone tip resistance, σ_{v0}, the total overburden pressure, and $N_{\sigma t}$, an empirical factor that, in general, is in the order of 3.3 (Mayne et al. 1998) to 3.4 (Demers & Leroueil 2002), among other values.

To estimate the undrained shear strength (S_u) from CPTu, Lunne et al. (1985) proposed an expression as a function of the net cone tip resistance (q_t-σ_{v0}) (second term of Eq. 2). Tavenas et al. (1982) recommended its determination in function of the excess pore pressure (Δu) induced by the cone penetration (third term of Eq. 2).

$$S_u = \frac{q_t - \sigma_{v0}}{N_{kt}} = \frac{\Delta u}{N_{\Delta u}} \quad (2)$$

In Eq. 2 N_{kt} and $N_{\Delta u}$ are empirical factors, $\Delta u = u_2 - u_0$, being u_2 the pore pressure measured at the base of the cone and u_0 the hydrostatic pressure.

The most used empirical factor is the N_{kt}, which is usually determined from reference values of the undrained shear strength, obtained with the Vane Test or the Unconsolidated Undrained Triaxial Compression Test (UU). According to Senneset et al. (1989), values of N_{kt} range from 10 to 15 for normally over-consolidated clay and from 15 to 19 for heavily overconsolidated clay.

Mayne & Mitchell (1988) proposed a correlation between S_u/σ'_a and the plasticity index (IP) of a clay, shown in Eq. 3, with a great dispersion.

$$\frac{S_u}{\sigma'_a} = \frac{\sqrt{IP}}{22} \quad (3)$$

Recent studies have been carried out to estimate these parameters from CPTu data, some of which were presented by Massad (2009, 2010, 2016), Mayne (2016), Odebrecht & Schnaid (2018). Their calculation methodologies will be evaluated in this paper, in the context of the marine clays of the Bothkennar (UK) and of the region close to Barnabé Island, (Santos, Brazil), with known geological histories.

2 MAYNE'S METHOD (2016)

Mayne (2016) proposed the estimation of the pre-consolidation pressure and the undrained shear strength based on the combination of Critical-State Model and the Spherical Cavity Expansion Theory of Vésic (1972 and 1977).

2.1 Pre-consolidation pressure

The Critical-State Model provides the following relationship between undrained shear strength (S_u) and the over consolidation ratio (OCR):

$$S_u = \left(\frac{M_c}{2}\right)\left(\frac{OCR}{2}\right)^{\Lambda} \sigma'_{v0} \tag{4}$$

where M_c=6.sinØ'/(3-sinØ') is the frictional parameter for triaxial compression (Ø' is the effective friction angle), σ'_{v0}, the vertical effective pressure and Λ=1-C_r/C_c, the plastic volumetric strain ratio, being C_c and C_r, the virgin compression and recompression indexes, respectively. Mayne (2016) assumed Λ=1 in a simplified way.

From the Spherical Cavity Expansion Theory, developed by Vésic (1972 and 1977), the following equations were written for determining the empirical cone factors N_{kt} and $N_{\sigma t}$:

$$N_{kt} = \frac{4}{3}\ [ln(I_R) + 1] + \frac{\pi}{2} + 1 \tag{5}$$

$$N_{\Delta u} = \frac{4}{3}\ ln(I_R) \tag{6}$$

where I_R is the rigidity index and B_q, the normalized pore pressure parameter, given by B_q=Δu/(q_t-σ_{v0}).

With the combination of Eqs. 2 and 4 with Eq. 5 or 6, Mayne (2016) obtained the Eqs. 7 and 8 for estimating σ'_a as a function of the cone tip resistance or the penetration pore pressure, respectively.

$$\sigma'_a = \frac{q_t - \sigma_{v0}}{M_c\ .\left(1 + \frac{1}{3} ln\, I_R\right)} \tag{7}$$

$$\sigma'_a = \frac{\Delta u}{\frac{1}{3} M_c\ .ln\, I_R} \tag{8}$$

It is important to highlight that, the denominator of Eq. 7 is the $N_{\sigma t}$ of Eq. 1.

As the estimates are based on I_R, Mayne (2016) presented a simplified equation given in terms of a single parameter, B_q:

$$I_R = \exp\left(\frac{2.93\ .B_q}{1 - B_q}\right) \tag{9}$$

2.2 Undrained shear strength

When replacing Eq. 9 in Eqs. 5 and 6, Mayne (2016) obtained the formulas for the empirical factors based only on B_q. The combination of these formulas with the expressions presented in Eq. 2 and replacing B_q with Δu/(q_t-σ_{v0}) lead him to a single simple equation to determine the undrained shear strength:

$$S_u = \frac{q_t - u_2 - \sigma'_{v0}}{3{,}90} \tag{10}$$

3 MASSAD's METHOD (2009, 2010, 2016)

Massad (2009, 2010, 2016) presented, for the Holocene clays of Santos Coastal Plain (Brazil), a method for estimating the pre-consolidation pressure and the undrained shear strength based on their geological history.

3.1 Pre-consolidation pressure

Massad (2009) evaluated many underground profiles in homogeneous clay deposits, and observed a linear relationship between the cone tip resistance (q_t) and the depth (z) at a rate "b", that is:

$$q_t = a + b.z \tag{11}$$

where "a" is a constant.

The author also noted that it is possible to assume a linear relationship between the pre-consolidation pressure (σ'_a) of oedometer tests and the vertical effective pressure (σ'_{v0}). This relationship depends on events that occurred during the Quaternary, such as the preloading (Δp) due to negative sea level oscillations or dune action, and the r factor that considers the effect of the ageing, so that:

$$\sigma'_a = r\ (\Delta p + \sigma'_{v0}) \tag{12}$$

It is interesting to mention that, when admitting only ageing influencing the overconsolidation (Δp =0), σ'_a and σ'_{v0} would be proportional, therefore with OCR constant with depth and greater than 1 (Massad 2009), without physical meaning for the Santos Holocene clays. Otherwise, when admitting that r=1 (no aging effect), with preloading causing the overconsolidation, the difference σ'_a-σ'_{v0} is constant at any depth z.

From the combination of Eqs. 1, 11 and 12 and finally by matching the depth-dependent terms, Massad (2009) obtained the following expression for $N_{\sigma t}$ estimation:

$$N_{\sigma t} = \frac{b - \gamma_n}{r.\gamma'} \tag{13}$$

where γ_n and γ' are, respectively, the natural and effective unit weights of the clay deposit.

The r factor can be obtained by the Mesri & Choi (1979) equation:

$$r = \left(\frac{t}{t_p}\right)^{\frac{C_{\alpha e}/C_c}{1 - C_r/C_c}} \tag{14}$$

where t is the time of secondary compression, t_p, the time of primary compression; C_c and C_r, the virgin compression and recompression indexes; and $C_{\alpha e}$, the coefficient of secondary compression in terms of void ratio (e).

3.2 Undrained shear strength

Hundreds of Vane Test (VT) performed on the Santos Holocene clays, gathered by Massad (2009, 2010), revealed that the undrained shear strength varies linearly with depth, as follows.

$$S_u = c_o + c_1.z \tag{15}$$

While the constant c_o may range from 5 kPa to 60 kPa, the rate c_1 is a fraction of γ' (30 do 50%).

The linearity of both the cone tip resistance (Eq. 11) and the undrained shear strength (Eq.15) lead Massad (2016) to propose a simplified expression for the estimation of the N_{kt} factor:

$$N_{kt} = \frac{b - \gamma_n}{c_1} \tag{16}$$

4 ODEBRECHT & SCHNAID'S METHOD (2018)

Odebrecht & Schnaid (2018) collected test results (SPT, CPTu, laboratory consolidation and shear strength tests) from 12 different locations on the Brazilian coast containing normally to slightly overconsolidated clays. When plotting a graph, to verify the existence of a direct relationship between laboratory results of σ'_a and net field penetration resistance (q_t- σ_{v0}), the authors obtained a weak correlation (R^2 = 0.47), concluding that there is no unique relationship between these parameters, suggesting that this correlation involves a more complex dependency.

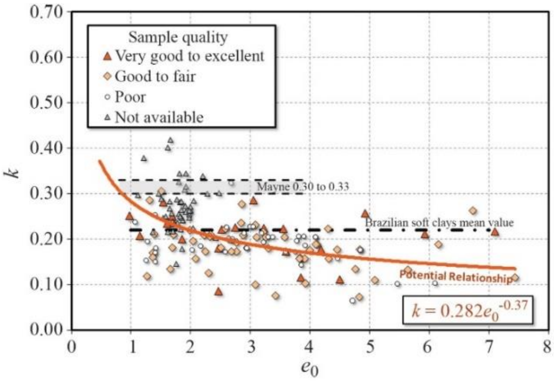

Figure 1. Variation of $k=1/N_{\sigma t}$ with void ratio (e_o) for Quaternary Brazilian clays (Odebrecht & Schnaid 2018).

As is known (Massad 2009; Odebrecht & Schnaid 2018), for the Brazilian Quaternary clays, the pre-consolidation pressure obtained from oedometer tests decreases with the increase of the void ratio (e_0). For Odebrecht & Schnaid (2018) this dependency is feasible because the strength of the soil structure due to ageing is not so significant and the pre-consolidation pressure can be associated with the void ratio only. From this assumption, Odebrecht & Schnaid (2018) included the void ratio in the relationship between σ'_a and q_t- σ_{vo} by doing empirical tests to improve the correlation, resulting in the graph presented in Figure 1.

The authors expressed $k=\sigma'_a/(q_t-\sigma_{vo})=1/N_{\sigma t}$ as a potential function of the void ratio (e_0), proposing an estimate of the pre-consolidation pressure of Quaternary Brazilian clays according to the equation:

$$\sigma'_a = k \ .(q_t - \sigma_{v0}) = (0.282 e_0^{-0.37})(qt - \sigma_{v0}) \tag{17}$$

5 BOTHKENNAR CLAY

The soft silty clay at Bothkennar, situated between Edinburgh and Glasgow, UK, on the edge of the River Forth, attracted the interest of many researchers due to its homogeneity, described by Nash et al. (1992-a) as being "remarkably uniform".

5.1 Geological history and overconsolidation mechanism

According to Nash et al. (1992-a), it is estimated that between 8,500 to 6,000 years before present the sediment deposition process on the test bed site reached a maximum level around +4.5m in relation to the current sea level. These authors considered the possibility that the soft clay was overconsolidated, because of both an erosive process caused by sea level regression and ground level fluctuations, implying that $\sigma'_a=\sigma'_{v0}+15$ kPa, that is, a preload equivalent to $\Delta p=15$ kPa. It is worth mentioning the existence of a dry crust of 2 to 3 m thick, which would have been deposited in subtidal or intertidal conditions (Nash et al. 1992-a).

When plotting the curve given by $\sigma'_a=\sigma'_{v0}+15$ kPa as a function of depth (Figure 2), it is noted OCR values decreasing with depth from 1,5 to 1.1. As the oedometer tests revealed an average OCR of 1.55, Nash et al. (1992-a) proposed that, for Bothkennar clay, $\sigma'a=1.55\sigma'_{v0}$, originating a second curve in Figure 2. With the divergence in the results between the two curves, these authors suggested that most of the apparent overconsolidation would be due to ageing.

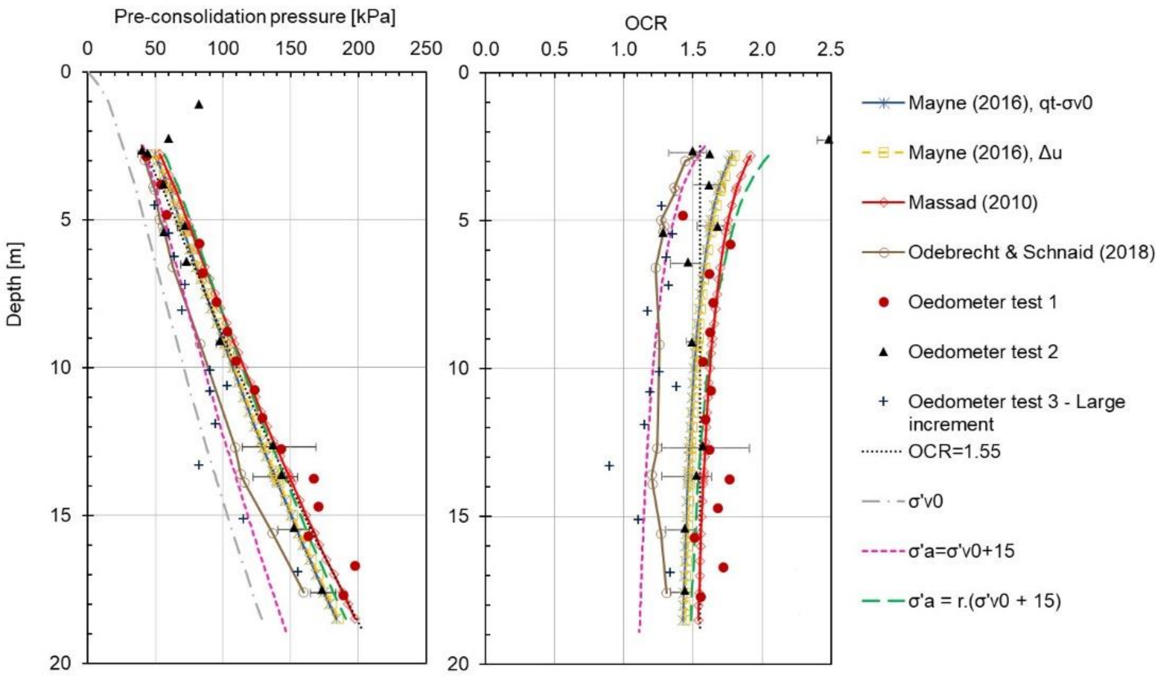

Figure 2. Estimate of the pre-consolidation pressure and the OCR of Bothkennar clay (test results: Nash et al. 1992-a).

However, it is important to highlight that each curve considers only an isolated overconsolidation mechanism: for $\sigma'_a=1.55\sigma'_{v0}$, than OCR is constant due solely to ageing, whereas for the curve $\sigma'_a=\sigma'_{v0}+15$, only the 15 kPa preload affected the over-consolidation.

Therefore, to consider the combined effect of ageing and preload, it is proposed to adapt the expression $\sigma'_a=\sigma'_{v0}+15$ by inserting the r factor, estimated at 1.33 by Eq. (14), so that:

$$\sigma'_a = r\ .(\sigma'_{v0} + 15) \quad (18)$$

To estimate the r factor, the following data were used, gotten from Nash et al. (1992-a and 1992-b): $C_{\alpha e}/C_c=0.04$ and $C_r/C_c=0.10$. The t_p value has been figured out at 10 years and t was assumed as being 6,000 years.

5.2 *CPTu data*

The Figure 3 shows the results of two CPTus performed at the test bed site of Bothkennar clay, confirming that the underground is quite uniform. The specific unit weight (γ) was taken as 16.7 kN/m³ and the water table at 0.8 m depth.

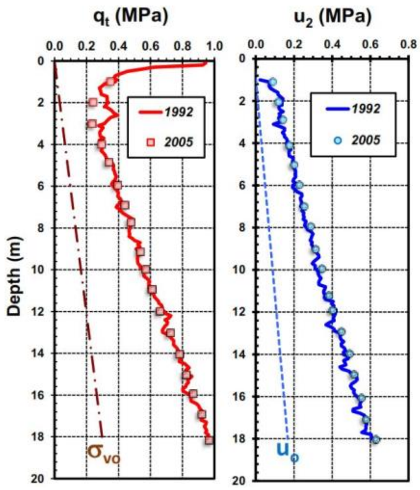

Figure 3. Results of two CPTus in Bothkennar clay (prepared by Mayne 2016, with data from Nash et al. 1992-a; Powell & Lunne 2005).

5.3 *Analysis of results*

The application of the methods presented above to estimate σ'_a and S_u to the Bothkennar clay resulted in the graphs of Figures 2 and 4. Note that for σ'_a comparisons were made with oedometer test results and for S_u with Vane Test, Triaxial Test and Dilatometer Test (DMT).

5.3.1 *Preconsolidation pressure*

From the analysis of Figure 2, the curves of the Massad's and Mayne's Methods were the closest to the adapted curve with the introduction of the r factor (Eq. 18). For greater depths they also fitted well the oedometer results. The OCR for Bothkennar clay varied between 1.3 and 1.7.

For the Odebrecht & Schnaid's Method, the e_0 data available from the paper of Nash et al. (1992-b) were not enough to obtain an acceptable correlation of the type $k=f(e_0)$ as proposed by the authors. The large dispersion of data possibly occurred due to the limited range of e_0 values ($1.0\leq e_0\leq 2.1$), when compared to the wide one used in the Odebrecht & Schnaid's study ($0.7\leq e_0\leq 12.4$).

Although the expression provided by Odebrecht & Schnaid (Eq. 17) refers to Quaternary Brazilian clays, the method was applied to Bothkennar clay to assess the similarity in the behavior between marine clays from different locations. Through the results shown in Figure 2, it can be noticed that the curve was closer to the one proposed by Nash et al. (1992-a) which consider only the effect of preload ($\sigma'_a=\sigma'_{v0}+15$) and to one specific oedometer test, which was performed with large increments of load, reflecting in lower values of pre-consolidation pressures.

From the $N_{\sigma t}$ values gotten by the Massad's and Mayne's Methods, 3.30 and 3.56, respectively, it is evident the proximity between them and to the reference values given in item 1. The value 4.3 of $N_{\sigma t}$ obtained by the Odebrecht & Schnaid's Method was quite high, resulting in considerably lower pre-consolidation pressures when compared to the other methods, indicating an average OCR of 1.3.

5.3.2 *Undrained shear strength*

From the analysis of Figure 4, it can be said that the curves of Massad's and Mayne's Methods practically coincided each other and had a good agreement with the resistance values obtained from the pressiometer and the Average VT (Vane Test) bellow the dry crust.

When evaluating the S_u/σ'_a relationship it was obtained 0.33 by the Massad's Method and, by the Mayne's Method, 0.35 in terms of (q_t-σ_{v0}) and 0.34 in terms of Δu. Therefore, the results were quite close between these methods.

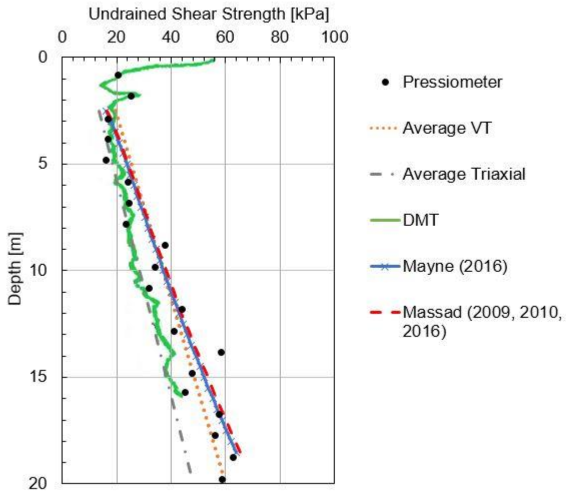

Figure 4. Estimate of the undrained shear strength of Bothkennar clay (test results: Nash et al. 1992-a).

From the empirical correlation of the $S_u/\sigma'_a=f(IP)$ (Eq. 3) proposed by Mayne & Mitchell (1988) and knowing that, for Bothkennar clay IP = 40% (Nash et al. 1992-a), results $S_u/\sigma'_a = 0.29$, a little below to those indicated above.

6 BARNABÉ ISLAND CLAY (SANTOS)

The Santos Coastal Plain in the southeast coast of São Paulo State, Brazil, presents thick layers of very soft to soft and medium marine clays. In addition to the urbanized areas, as Santos City, there are several industries installed in the region, and the largest port in Latin America. The Barnabé Island is in the left side of the Santos Harbor Channel, close to the Bertioga Channel.

6.1 *Geological history and overconsolidation mechanism*

The soft marine clays of the region of Barnabé Island were deposited during the Holocene, 8,000 to 7,000 years before present. They are overconsolidated due to the action of dunes, that were present up to almost the middle of the last century. They were probably used in the expansion of Santos Port.

This overconsolidation presents itself in an erratic way, due to the different heights of the dunes, thus giving a great heterogeneity to these clays. OCR values higher than 2 were reported (Massad 2009 and 2016), implying coefficients of secondary compression ($C_{\alpha\varepsilon}$ in terms of deformation) of the order of 0.1% (Lambe & Whitman 1979; Massad 2009). This figure and the time the dunes were removed (50 to 100 year) allow to estimate r≅ 1 from Eq (14). In other words, the effect of aging became negligible.

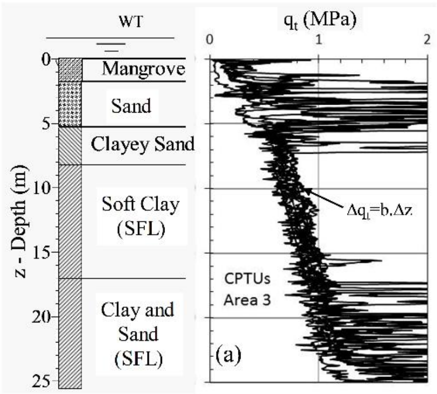

Figure 5. CPTu data in an area close to Barnabé Island (Massad et al. 2013).

6.2 CPTu data

The Figure 5 shows the results of 14 CPTus performed in an area close to Barnabé Island, with an approximate soil profile. Close to the surface there are an initial layer of 1 to 3m of a very soft clay (mangrove) followed by sand until the contact with the studied clay, at a depth of 5 to 6m. The specific unit weight (γ) of the clay was taken as 14.9 kN/m³ and the water table at 0.8 to 1.5 m above soil surface. It is seen that for the whole data parameter b of Eq. 11 is constant and equal to 34 kPa/m. The application of Eq. 13 gives $N_{\sigma t}$= (34-14.9)/4.9=3.9.

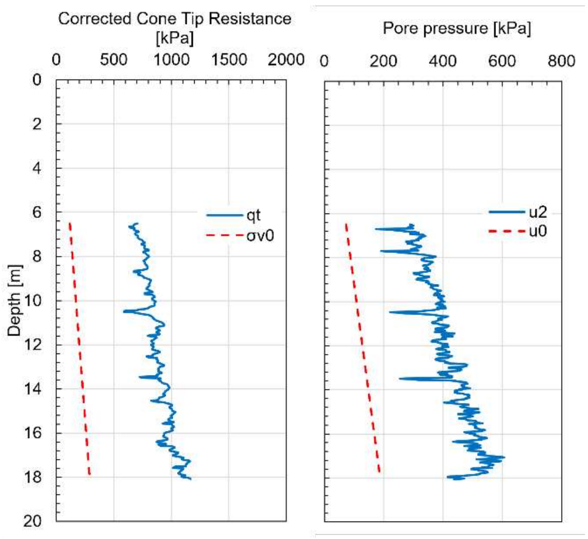

Figure 6. CPTu data of Barnabé Island clay.

The Figure 6 shows the result of one of these CPTus considering only the Barnabé Island clay, starting at 6 m and extending to a depth of 18 m.

6.3 Analysis of the results

The application of the methods presented to estimate σ'ₐ and S_u for the Barnabé Island clay resulted in the graphs of Figures 7 and 8, in which the results of oedometer or Vane Tests are also presented. It is important to say that while the consolidation tests were made in shelby samples extracted at a certain distance from the CPTu borehole, with regular to good qualities, the Vane Test was executed close to it, that is. in the same local.

6.3.1 Pre-consolidation pressure

From the analysis of Figure 7, the points of the oedometer tests were located between the curves of the Massad's and Odebrecht & Schnaid's Methods. OCR varied roughly between 2 and 3, a fact observed in other locations in Santos Coastal Plain, more specifically in Santo Amaro Island (Massad 2009).

It can also be noted that the pre-consolidation pressure is overestimated by the Mayne's Method, with OCR ranging from 4 to 7. An evaluation of Eq. 9 shows that variations in the B_q coefficient excessively impact the I_R value, impairing the analyzes. According to Massad (2009), for example, the B_q values for the Holocene sediments in Santos Coastal Plain vary from 0.4 to 0.9, which, through Eq. 9, would result in a great I_R variation from 7.0 to 2.8×10^{11}. For the elaboration of the method, Mayne (2016) used a data set in which B_q varied from 0.45 to 0.75 (roughly equivalent to 10 <I_R <1,000). As the value obtained in the present case study was B_q = 0.42, the lower limit indicated by Mayne (2016) was adopted (B_q = 0.45) and, even so, the great influence of this parameter remained.

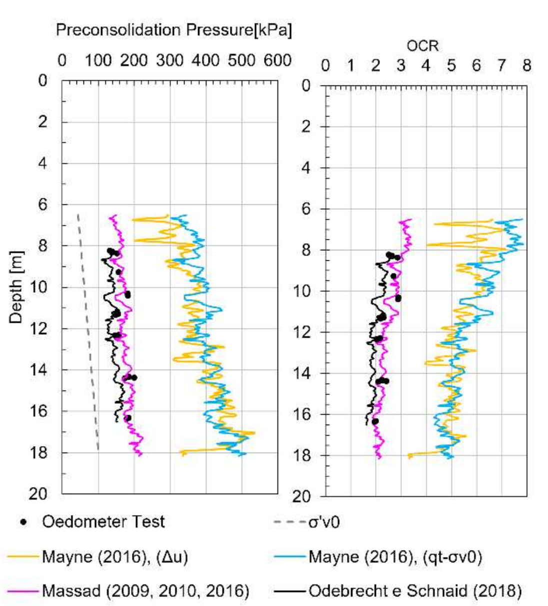

Figure 7. Estimate of the pre-consolidation pressure and OCR to the clay of Barnabé Island (test results: Andrade 2009).

For the Massad's Method, the calculated $N_{\sigma t}$ was 3.9, as seen above. For the Mayne's Method (2016), the low B_q value was decisive to obtain an underestimated $N_{\sigma t}$ of 1.69. Lately, Mayne (2017) stated that coefficients like $N_{\sigma t}$ "should be adjusted based on local geologies and site-specific geomaterials, where possible".

For the Odebrecht & Schnaid's Method, the value found was quite high, $N_{\sigma t}$ = 4.73, leading to lower σ'ₐ when compared to the other methods, but still close to the values of oedometer tests with regular to good qualities. For its application in this study, the potential function of Eq. 17 regarding the Quaternary Brazilian clays was considered.

6.3.2 Undrained shear strength

From the analysis of Figure 8, it is noted that the estimated values of S_u were slightly higher for Massad's Method when compared with the local Vane Test data but in the range of VT results in the whole area. The same cannot be said of the Mayne's Method, which has led to extremely high S_u values.

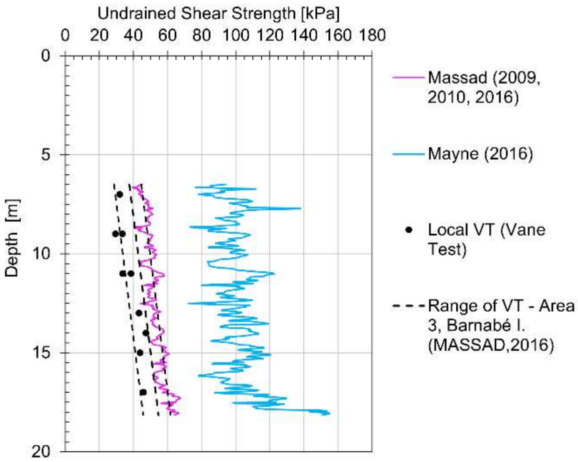

Figure 8. Estimate of the undrained shear strength of Barnabé Island clay.

When assessing the S_u/σ'_a relationship, for the Massad's Method a figure of 0.30 was obtained, whereas for the Mayne's Method 0.25, in terms of (q_t-σ_{v0}), and 0.30, in terms of Δu.

From the empirical correlation of the S_u/σ'_a=f(IP) proposed by Mayne & Mitchell (1988) (Eq. 3) and assuming IP = 75% (Andrade 2009), S_u/σ'_a=0.39, much higher than those obtained through the application of both methods.

The N_{kt} was of the order of 13 for the Massad's Method, and 7 for Mayne's Method.

7 CONCLUSIONS

The use of semi empirical methods to estimate parameters that are not directly measured by CPTu reduces the total amount of specific tests needed, such as the Vane Test and the oedometer test; the latter requires the extraction of undisturbed samples of good quality, which elevates the costs and time of the geotechnical investigation. However, the CPTu does not replace those specific tests because they are essential for validation purposes, along with the stress history of the site.

For two sites with known geological history the article allowed to reach the following conclusions.

7.1 *Preconsolidation pressure (σ'_a)*

For Bothkennar clay, the results of the Mayne's and Massad's Methods showed better adjustments when comparing them with the data of the available tests and by associating them with what is known of the geological history of the deposits. The OCR for Bothkennar clay varied between 1.3 and 1.7. The Odebrecht & Schnaid's Method (2018), on the other hand, using the equation k=f(e) of Brazilian Quaternary clays, led to lower OCR values, averaging 1.3.

For the Barnabé Island clay, the results of the Odebrecht & Schnaid's and Massad's Methods showed better adjustments when comparing them with the data of the available oedometer tests, with regular to good quality, and with the geological history of the deposit. The OCR for Barnabé Island clay ranged roughly from 2 to 3. For the Mayne's Method, it was noticed that variations in the B_q coefficient affected too much the I_R index, impairing the analyses.

7.2 *Undrained shear strength (S_u)*

For Bothkennar clay the results of the Mayne's and Massad's Methods showed good agreement each other and when comparing them with the Vane Test and pressiometer data.

For the Barnabé Island clay, estimates of S_u by Massad's Method showed reasonable adjustments to the available test data. The results of the application of the Mayne's Method led to extremely high values of undrained resistance.

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