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New Methodologies for the Determination of Yield Pressure of Marine Clays Through the CPTU

Faiçal Massad

Senior Full Professor, Polytechnic School of São Paulo University, São Paulo, Brazil, faical.massad@usp.br

ABSTRACT: The paper deals with the use of empirical formulas for the determination of the yield pressure of marine clays through the CPTU. Kulhawy and Mayne's formula is one of them, which has already been the subject of analysis by the author (Massad, 2010), who proposed a methodology for the determination of its empirical factor for soils with known stress history and with cone resistance (q_t) varying linearly with depth. These conditions have been observed in marine clays in Brazil and abroad. In the present work the author extends this methodology to two other formulas of Mayne (2017), which make use of q_t, pore water pressure (u_2) and hydrostatic pressure (u_o), adjusting the empirical factors for cases of linear relationships of q_t and u_2 with depth. The paper shows two successful cases of application to marine clays, in which the results of CPTUs and oedometer tests were available, as well as knowledge about their geological history.

KEYWORDS: yield pressure, CPTU, marine clays.

RESUMO. O artigo trata do uso de fórmulas empíricas para a determinação da pressão de preadensamento de argilas marinhas através do CPTU. Uma dessas fórmulas é a de Kulhawy e Mayne, que já foi objeto de análise pelo autor (Massad, 2010), que propôs uma metodologia para a determinação de seu fator empírico para solos com história de tensões conhecida e com resistência do cone (q_t) variando linearmente com a profundidade. Essas condições têm sido observadas em algumas argilas marinhas no Brasil e no exterior. No presente trabalho o autor estende essa metodologia para duas outras fórmulas de Mayne (2017), que fazem uso de q_t, da poropressão (u_2) e da pressão hidrostática (u_o), ajustando os fatores empíricos para casos de relações lineares de q_t e u_2 com profundidade. O artigo mostra dois casos bem-sucedidos de aplicação concomitante destes métodos em que se dispunha de resultados de CPTUs e de ensaios de adensamento, além de conhecimentos sobre as suas histórias geológicas.

PALAVRAS-CHAVE: pressão de preadensamento, CPTU, argilas marinhas.

1 INTRODUCTION

Piezocone tests (CPTU) have been used to determine the yield pressure (σ'_a) of marine soils in Brazil and around the world. And this is done with few mathematical models and many empirical correlations. But it is worthy to consider the geological and geotechnical contexts when establishing these correlations for a given soil, as suggested by Demers and Lerouiel (2002), and more recently re-emphasized by Mayne (2017).

One of the most used empirical correlations is that of Kulhawy and Mayne, quoted by Coutinho et al (2000), given by the equation:

$$\sigma'_a = \frac{q_t - \sigma_{vo}}{N_{\sigma t}} \tag{1}$$

where q_t is the corrected tip resistance, σ_{vo}, the total vertical pressure and $N_{\sigma t}$, an empirical factor equals to 3.3 (Mayne et al, 1998) or 3.4 (Demers and Lerouiel, 2002).

Mayne (2017) presented two other formulas, valid for inorganic clays, with low sensitivity, as follows:

$$\sigma'_a = k_2 \cdot (q_t - u_2) \tag{2}$$

$$\sigma'_a = k_3 \cdot (u_2 - u_o) \quad (3)$$

where u_o and u_2 are, respectively, the hydrostatic pressure and the pore-pressure measured at the base of the cone. And he indicated the following values $N_{\sigma t}$=3,0, k_2=0,60 and k_3=0, 54, warning on the possible need for adjustments for each "geomaterial".

Based on the geological history of marine clays, Massad (2009) showed that there is a parallelism between yield pressure (σ'_a) and the effective vertical initial pressure (σ'_{vo}), that is:

$$\sigma'_a = \sigma'_{vo} + \Delta p \quad (4\text{-a})$$

where Δp is a constant, which can be due to overloads from: a) lowering of the water level; b) sediment erosion; and d) dune weight.

This parallelism may suffer slight deviations, in cases of occurrence of the "aging" phenomenon, which implies the introduction of the term r in the expression (4-a) as follows:

$$\sigma'_a = r \cdot (\Delta p + \sigma'_{vo}) \quad (4\text{-b})$$

Massad (2009) proposed the following equation using expression of Mesri and Choi (1979):

$$r = \frac{\sigma'_a}{\sigma'_{vo} + \Delta p} = \left(\frac{t}{t_p}\right)^{\frac{C_{\alpha e}/C_c}{1 - C_r/C_c}} \quad (4\text{-c})$$

where $C_{\alpha e}$ is the secondary consolidation coefficient; C_c, the soil compression index; C_r, the recompression index; t_p, the time required for the development of primary consolidation; and t, the time of aging. Usually r can range from 1 (without aging) to 1.4. It should be noted that if only aging were to be acted, with Δp=0, the term r of Eq. (4-c) would be equal to the OCR (Over-Consolidation Ratio), i.e., the yield pressure would be proportional to the initial effective stress. In other words, OCR would be constant with depth and greater than 1 (Massad, 2009).

In addition, it has been found that both q_t and u_2 vary linearly with depth in marine clays, that is:

$$q_t = a + b.z \quad (5)$$

$$u_2 = c + d.z \quad (6)$$

where a,b, c and d are constants. Assuming a water table at a depth equal to z_{wl}, the hydrostatic pressure (u_o) may be written as:

$$u_0 = \gamma_o.(z - z_{wl}) \quad (7)$$

The application of the Eqs. (1), (2) e (3) can be done in the context of geological and geotechnical history, or, in geotechnical terms, through the Eq. (4-b).

2 DETERMINATIONS OF THE EMPIRICAL FACTORS OF MAYNE´S FORMULAS

The empirical factors of Mayne's formulas can be determined based on the Eqs. (4-b), (5) e (6).

2.1 Determination of the factor $N_{\sigma t}$ of Eq. (1)

Assuming that the specific unit weight (γ_n) is constant along depth (z), the total and the effective initial stresses can be written:

$$\sigma_{vo} = \sigma_{vo}^{z=0} + \gamma_n . z \quad (8)$$

$$\sigma'_{vo} = \sigma'^{z=0}_{vo} + \gamma' . z \quad (9)$$

where γ' is the submerged unit weight. If γ_n is not constant, it should be replaced at a depth z by $\bar{\gamma}_n$, the weighted average, given by:

$$\bar{\gamma}_n = \frac{\int_0^z \gamma_n . dz}{z} \quad (10)$$

Substituting Eq. (1) into Eq. (4-b) and considering Eqs (5), (8) and (9) the following expression may be derived, after some transformations:

$$N_{\sigma t} = \frac{b - \gamma_n}{r . \gamma'} \quad (11)$$

This equation was presented earlier by Massad (2009 and 2010).

2.2 Determination of the factor k_2 of Eq. (2)

Similarly, substituting Eqs (2) into Eq. (4-b) and bearing in mind Eqs. (5), (6) and (9), the following expression results, after some transformations:

$$k_2 = \frac{r . \gamma'}{(b - d)} \quad (12)$$

2.3 Determination of factor k_3 of Eq. (3)

Finally, replacing Eq. (3) in Eq. (4-b) and in view of Eqs. (6). (7) and (9), the following expression may be written, after some transformations:

$$k_3 = \frac{r . \gamma'}{(d - \gamma_o)} \quad (13)$$

2.4 Summary of the results so far

Table 1 summarizes the formulas of the 3 empirical factors.

Table 1: The empirical factors of Eqs. (1), (2) and (3)

Eq. (1)	Eq. (2)	Eq. (3)
$N_{\sigma t} = \frac{b - \gamma_n}{r . \gamma'}$	$k_2 = \frac{r . \gamma'}{(b - d)}$	$k_3 = \frac{r . \gamma'}{(d - \gamma_o)}$

See the attached list of symbols.

3 TWO CASE HISTORIES

Two cases of marine clays will be analyzed, namely: a) Bothkennar Clay (UK); e b) Torp Clay (Sweden).

3.1 Bothkennar Clay (UK)

The silty soft clay of Bothkennar is located on the banks of the River Forth between Edinburgh and

Glasgow (UK). It has been the subject of many studies over the years, due to its homogeneity and uniformity. In 1992, volume XLII, no. 2 of the Geotéchnique Journal was dedicated to it and, more recently, it was addressed by Mayne (2016), in an article on the determination of the history of stresses in soils through piezocone tests. In this same context, it was also the subject of studies by Ferreira (2021).

According to Nash et al. (1992-a), Bothkennar Clay is overconsolidated due to processes that occurred after its deposition between 8,500 and 6,000 years BP, including erosion, sea level fluctuation and surface drying, but that aging would have been its main cause. These authors presented three sets of consolidation tests (oedometer), which were entitled as: "First set (piston)", "Large increment" and "Laval". Only the first and third sets will be considered next.

Based on these tests and on settlement observation data, Ferreira, and Massad (2022-a and b) assigned the parameter r of Eq. (4-c) the value 1.33. In fact, data from Nash et al (1992-a and 1992-b) reveals $C_{\alpha e}/C_c$=0.04; C_r/C_c=0.1; t_p=10 years, than r=$(6{,}000/10)^{0.04/(1-0.1)}$=1,33 from Eq. (4-c). For t=8,500 years r=1.35.

Mayne (2016) analyzed the results of two CPTUs, presented by Nash et al (1992-b) and Powell and Lunne (2005), partially reproduced in Figure 1. The water level was at a depth of 0.8 m and the average natural specific unit weight of the clay (γ_n) was 16.7 kN/m^3.

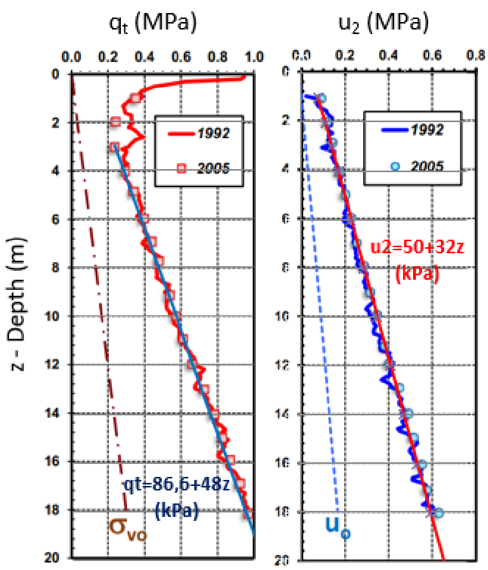

Figure 1. Two CPTUs in Bothkennar
Modified from Mayne (2016).

Below the desiccated crust, about 3.5 m thick, the values of q_t and u_2 vary linearly with depth, as shown in Figure 1, so Eqs (1), (2) and (3) can be used, with the corresponding empirical factors summarized in Table 1. The values of the empirical factors ($N_{\sigma t}$, k_2, k_3) and of the σ'_a, are presented in Table 2 and Figure 2, respectively.

Table 2: Results obtained for the 3 empirical factors of Eqs. (1), (2) and (3) - Bothkennar Clay

Item	$N_{\sigma t}$	k_2	k_3
Indicated by Mayne (2017)	3.0	0.60	0.54
Calculated	3.5	0.56	0.41

From the analysis of these results, it can be concluded that:

a) The σ'_a calculated through Eqs. (1), (2) and (3), with the empirical factors of Table 2, are very close to the values obtained through the consolidation tests, indicated in Figure 2; below the desiccated crust, the over consolidation ratios (OCR) vary roughly between 1.8 and 1.5, averaging around 1.6.

b) The empirical factors calculated for Bothkennar Clay (Table 2) differ from those indicated by Mayne (2017). The differences, in terms of σ'_a, would be +17%, -7% and -24% for Eqs. (1), (2) and (3), respectively.

c) Reporting again to Figure 2 and taking as reference the σ'$_a$ from Eq. (1), the corresponding values of Eq. (2) average 4% below, as opposed to the σ'$_a$ of Eq. (3), about 3% above.
d) Even on the dried crust, there is a good agreement between the σ'$_a$ of the Eqs. (1) and (2) and those of the consolidation tests.

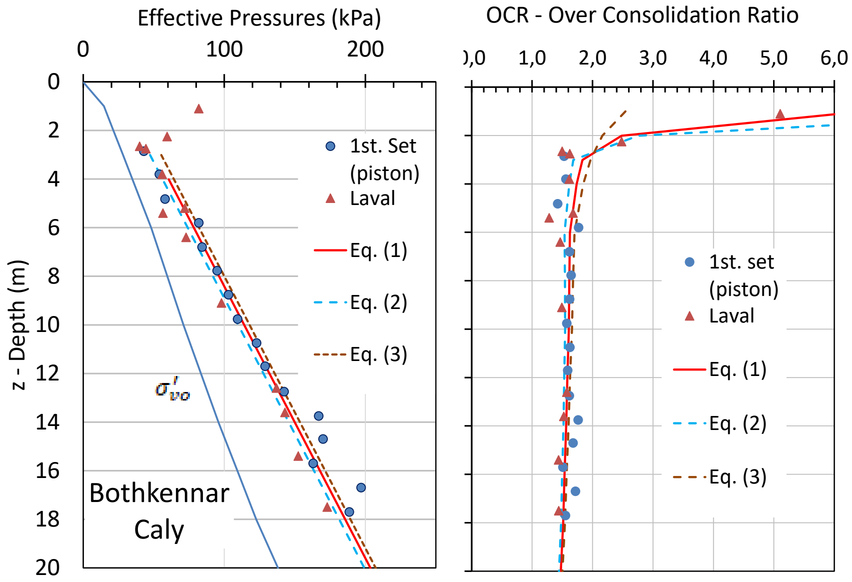

Figure 2: Pressures and OCR – Bothkennar Clay (UK)

3.2. Torp Clay, Sweden

Torp Clay, which occurs in Munkedal, Sweden, in the valley of the Örekilsälven River, was deposited in the post-glacial period. At the top there is a sandy layer, followed by clay, with silt and sand lenses, and, at greater depths, layers of silt and sand (Larsson and Åhnberg, 2003 and 2005). Originally, the clay was normally or only slightly overconsolidated. But it became overconsolidated due to erosive processes, landslides, and excavations in the 1980s. In summary, the overconsolidation is a result of recent real unloading. But they proposed for σ'$_a$ an expression similar to Eq. (4-b), that is:

$$\sigma'_a = 1{,}15 \cdot (\sigma'_{vo} + 100) \quad (14)$$

However, creep effects could not be inferred from the test results (page 88 of Larsson and Åhnberg 2003). In view of this statement, it was adopted r=1 in this paper as a working hypothesis.

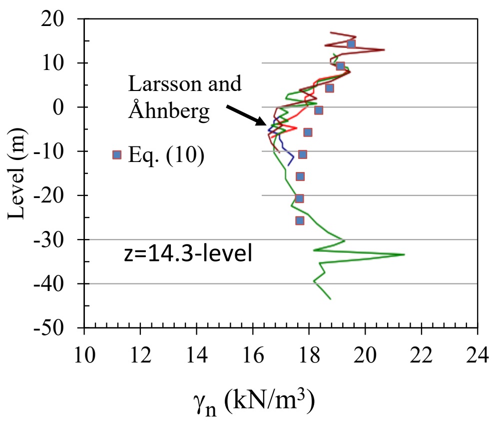

Figure 3: Laboratory Specific Unit Weight – Torp Clay - Modified from Larsson and Åhnberg (2003)

Unlike Bothkennar clay, Torp Clay presents a certain heterogeneity, which is manifested, for example, in the natural specific unit weights (γ_n) of good quality undisturbed samples, varying roughly between 16.5 and 20.0 kN/m^3, as shown in Figure 3.

Larsson and Åhnberg presented results from CPTUs done in various sections in the Torp area. Of interest to the present study is the CPTU-S9 (Figure 4), executed in an excavated area, with water level at a depth of 2m, and which was the object of studies by Mayne (2017) and Ferreira (2021), already mentioned. The values of q_t e u_2 vary linearly with depth, as shown in Figure 4, and the Eqs (1), (2) and (3) can be used again, with the corresponding empirical factors summarized in Table 1, with r=1.0, as admitted above.

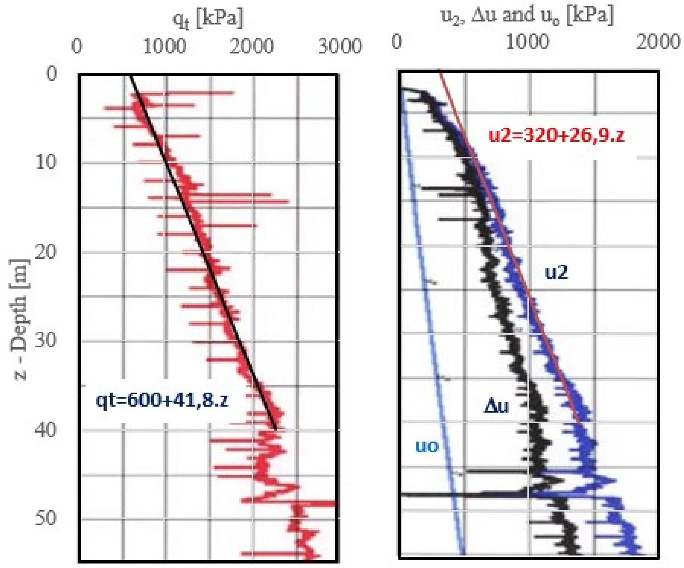

Figure 4: CPTU-S9 – Torp Clay (Sweden)
Adapted from Larsson e Åhnberg (2003) and Ferreira (2021).

Table 3: Results obtained for the 3 empirical factors of Eqs. (1), (2) and (3) - Torp Clay

Item	$N_{\sigma t}$	k_2	k_3
Indicated by Mayne (2017)	3.0	0.60	0.54
Calculated	2.35 to 3.15 Average=2,87	0.51 to 0.64 Average=0.56	0.45 to 0.56 Average=0.49

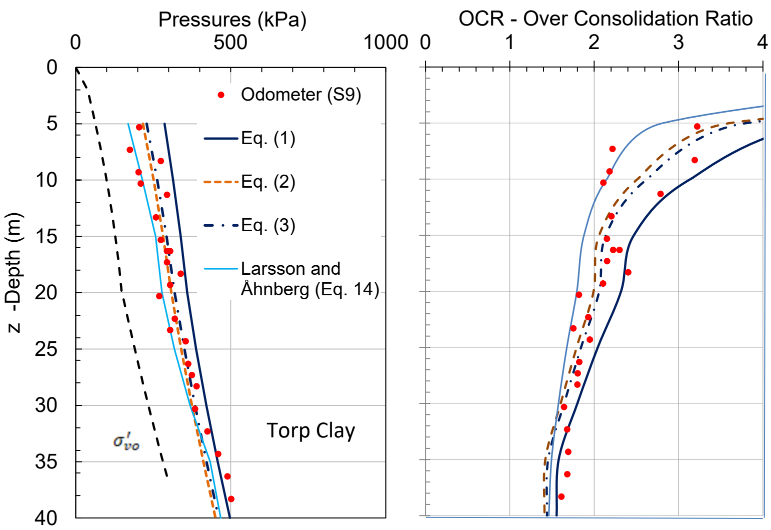

Figure 5: Pressures and OCR – Torp Clay (Sweden)

The values of the empirical factors ($N_{\sigma t}$, k_2, k_3) are presented in Table 3. Figure 5 shows how σ'_a and the OCR vary with depth. From these results it can be concluded that:

a) The working hypothesis that r=1 was validated.
b) Eqs. (1), (2) and (3), with the empirical factors of Table 1, can be used even for soils with a certain heterogeneity, with specific unit weights varying with depth as shown in Figure 3; hence the shape of the representative lines of the σ'_a have inflections and are curvilinear.
c) This heterogeneity affected the empirical factors, as shown in Table 3; in average terms, they deviate from the values indicated by Mayne (2017) by 7% for $N_{\sigma t}$, -13% for k_2 and -17% for k_3.
d) The σ'_a calculated by the Eq. (2) e (3) are better fitted to the oedometer points than Eq (1) in this case history.
e) The OCR (Over Consolidation Ratio) of Torp Clay ranges from 4.0 to 1.4.

4 CONCLUSIONS

The yield pressures can be determined based on the CPTU, through the 3 formulas indicated by Mayne, provided that their empirical factors are adjusted, considering the geological history of the marine soils with linearity between q_t and u_2 with depth.

These conditions were met in two cases of marine clays that have been widely studied, Bothkennar Clay and Torp Clay, which allowed a very good fitting between the calculated yield pressures and those obtained through oedometer tests.

The proposed empirical factors can be applied even to cases of marine clays with some heterogeneity as to their specific unit weights, as was the case of Torp Clay.

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LIST OF SYMBOLS

a; b	: Constants of Eq. (5)
c; d	: Constants of Eq. (6)
C_r, C_r	: Compression and recompression indexes
CPTU	: Cone Penetration Test
$C_{\alpha e}$	: Coefficient of secondary consolidation
k_2 e k_3	: Empirical factors (Eqs. 2 e 3)
$N_{\sigma t}$	: Empirical factor of Eq. (1)
q_t:	: Corrected Cone Point Resistance
r	: Term of Eq. (4-b)
OCR	: Over Consolidation Ratio
t	: Aging time
t_p	: Time for primary consolidation to occur
u_o	: Hydrostatic pressure
u_2	: Poro-pressure at the cone base
z; z_{wl}	Depth; depth of water level
Δp	: Overload
γ_o	: Specific weight of water
γ_n and γ'	: Natural and effective specific unit weights of soil
$\bar{\gamma}_n$	: Weighted average of γ_n (Eq. 10)

σ'_a	: Yield pressure
σ_{vo}	: Initial Total Vertical Pressure
σ'_{vo}	: Initial Effective Vertical Pressure

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