Effects of overconsolidation ratio on undrained shear strength of clay considering pressuremeter of limited length: cases study

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Abstract. Undrained shear strength ($s_u$) of foundation soils were estimated from the results of pressuremeter tests conducted on slightly overconsolidated and overconsolidated clays in two test sites. To investigate the effects of overconsolidation ratio ($OCR$) and pressuremeter of limited length on the undrained shear strength of clays, three kinds of evaluation methods based on the cavity expansion theory were used in this study. Where the direct traditional method suggested by Gibson and Anderson ignores the effect of pressuremeter of limited length and $OCR$, the analytic method based on modified Cambridge model proposed by Cao only considers the effect of $OCR$, the finite element method (FEM) in view of the modified Cambridge model take the effects both of pressuremeter of limited length and $OCR$ into account. The results show that the undrained shear strength obtained from the direct traditional method is significantly smaller than that obtained from the analytic method due to the effect of $OCR$, and with the increase of $OCR$, the difference between the two increases. The undrained shear strength estimated from the analytical method is larger than that estimated from the FEM in virtue of the effect of pressuremeter of unlimited length, and with the increase in $OCR$, the effect of pressuremeter of limited length rapidly decreased. When performing a PMT in clay with pressuremeter of limited length, there is a critical value of $OCR$, where the length effect is higher than the $OCR$ effect when the $OCR$ is below this critical value, while the effect of $OCR$ and the length cancel each other out when the $OCR$ is above this critical value. The threshold value is predicted to be 23 for the OC silty clay in case 1, and the actual value of the threshold is 34 for the OC silty clay in case 2.

1. Introduction
Cavity expansion theory was introduced into the field of geotechnical engineering by Gibson and Anderson (1961). With the development of cavity expansion theory, it has been widely used in geotechnical engineering, such as in situ soil testing, pile foundations and earth anchors, underground excavations and tunneling, and wellbore instability (Yu 2000).
Most of the abovementioned interpretation methods developed for PMT results are based on the following fundamental assumption (Carter et al.1993; Iskander 2013): 1) the soil around the pressuremeter membrane is an elastic-perfectly plastic material. 2) the soil is under an axisymmetric plane strain condition during the expansion. (i.e., an infinite length for pressuremeter membranes). 3) no volume change occurs within the clay (i.e., an undrained expansion test). The effect of stress history (OCR) on soil behavior cannot be considered when evaluating undrained shear strength with an elastic-perfectly plastic model, but in the actual situation, the stress history plays an important role in the undrained shear strength of soil (Gutierrez et al.2008; Ching et al.2010). The modified Cam Clay (MCC) model is a volume hardening-softening model based on the concept of critical state and has been commonly used to describe the nonlinear behavior of clay prior to the failure or deformation behavior depending on the stress level and stress path. This is more appropriate for modeling the mechanical behavior of normal consolidated clay and overconsolidated (OC) clay (Wood 1990; Yu 2000; Chen and Abousleiman 2012). In addition, the soil around the pressuremeter membrane does not maintain the axisymmetric plane strain state, because PMT is carried out using a finite-length pressuremeter membrane. Many previous studies (Mair and Wood 1987; Yu 2000; Yu et al.2005; Silvestri et al.2008; Nihat et al.2015) suggested that the pressuremeter of unlimited length is the main reason for the undrained shear strengths determined from the conventional interpretation methods of PMT generally higher than those estimated from field or laboratory tests. It is necessary to study the effect of a pressuremeter of limited length on undrained shear strength using the finite element method (FEM) while considering the stress history of the soil.

A consistent conclusion was obtained from many studies (Yu 2005; Soleimanbeigi 2013; Nihat 2015) indicating that the assumption of infinite pressuremeter length in traditional methods results in the overprediction of undrained shear strength, and OCR is also an important factor affecting undrained shear strength while its effect cannot be considered through traditional methods. But it is unclear how much overestimation is due to the pressuremeter geometry and how much is due to the OCR. In other words, the effects of pressuremeter geometry and OCR on undrained shear strength should be studied separately. Actually, the pressuremeter geometry (L/D) is fixed when PMT are carried out in a field investigation, while the OCR of tested soil varies greatly. Research should be focused on the effects of OCR and pressuremeter of limited length on undrained shear strength. In this study, the undrained shear strength of foundation soil was evaluated from the results of PMT conducted on SOC and OC clays in two test sites. The efficiencies of three evaluation methods for undrained shear strength based on the cavity expansion theory are summarized, and the undrained shear strengths obtained from these three evaluation methods were compared.

2. Three evaluation methods for undrained shear strength

2.1 Direct traditional method

Gibson and Anderson (1961) regarded the soil as an elastic-perfectly plastic Tresca material and assumed that the soil is under an axisymmetric plane strain condition during the expansion. The analytical solution of the expansion in a small cavity in the plastic stage was briefly obtained using the total stress analysis method as follows:

\[ p_{ca} = \sigma_{ho} + s_u [1 + \ln(G/s_u)] + s_u [\ln(\Delta V/V)] \]  \( \text{(1)} \)

Where \( p_{ca} \) is the applied pressure using the pressuremeter; \( \sigma_{ho} \) is the horizontal at rest pressure; \( s_u \) is the undrained shear strength; \( G \) is the shear modulus, and \( \Delta V/V \) is the volumetric strain. It was assumed that \( \Delta V/V = 1 \) when the expansion membrane was infinitely expanded (Gibson and Anderson 1961); then, the plastic deformation of the surrounding soil reached the limit. Therefore, the third expression in Eq. (1) was omitted, and the limiting cavity pressure \( p_L \) can be expressed as follows:

\[ p_L = \sigma_{ho} + s_u [1 + \ln(G/s_u)] \]  \( \text{(2)} \)

By substituting Eq. (2) into Eq. (1), we obtained:

\[ p_{ca} = p_L + s_u [\ln(\Delta V/V)] \]  \( \text{(3)} \)
By plotting the $p_{ca}$ vs. ln($\Delta V/V$) curve, the slope of the plastic phase of the curve (almost a straight line) was estimated as the undrained shear strength $s_u$ of the soil, and the intercept of the straight line on the y-axis was the limiting pressure $p_L$ (Alzubaidi 2013). The schematic of PMT device and typical cavity pressure vs. ln($\Delta V/V$) to estimate the undrained shear strength is shown in Fig. 1.

Because the effective stress was replaced with the total stress, the effects of OCR and pressuremeter of limited length were neglected; therefore, the undrained shear strength determined from the direct traditional method was generally higher than that obtained from high-quality field or laboratory tests. However, the direct traditional method is widely used to estimate the undrained shear strength for its simplicity and intuition, and the most direct use of the original data of PMT.

Fig 1. (a) Schematic of PMT device  
Fig 1. (b) typical cavity pressure vs. ln($\Delta V/V$) curve

2.2 Analytical method based on MCC model
The plastic zone stress path was obtained by Cao (2001) through combining the formulas of elastic and plastic body strain on the plastic zone of MCC model and assuming that the volume strain is zero under undrained expansion. Then, the ultimate deviator stress of cylindrical cavity expansion was determined by intersecting the stress path and limit state line.

$$q_u = Mp'_0 (OCR/2)^\Lambda$$  \hspace{1cm} (4)

For the isotropic initial stress state, the relationship between undrained shear strength and deviator stress on the critical state can be expressed as follows:

$$s_u = \frac{q_u}{m} = \frac{Mp'_0 (OCR/2)^\Lambda}{m}$$  \hspace{1cm} (5)

Fig. 2 shows the schematic of the MCC model and model parameters. The yield surface of the model in $p' - q$ plane has an elliptical shape. After the soil has yielded, the yield surface expands to the model stress hardening behavior of NC soil, while shrinking to the model stress softening of OC soil.

$M$ is the slope of the critical state line (CSL) in $p' - q$ plane; for cylindrical cavity, $m = 1$, $M = 2\phi'_c$, and $\phi'_c$ is the critical state friction angle (Wood 1990). $p'_c$ is the effective overconsolidation pressure, and $p'_0$ is the initial average effective stress. The isotropic $OCR = p'_c/p'_0$. Plastic body strain ratio $\Lambda = 1 - \kappa/\lambda$, where $\kappa$ is the slope of the virgin compression line, and $\lambda$ is the slope of the swelling line.
2.3 FEM based on MCC model

The analytical solution based on MCC considers the effect of stress history on the soil behavior, but it neglects the effects of pressuremeter of limited length on the undrained shear strength in a cylindrical cavity. The FEM based on MCC model can be used to simulate the pressuremeter of limited length to compensate the abovementioned shortcomings.

The in-situ vertical effective stress $\sigma_0$ and horizontal effective stress $\sigma_{10}$ were used to express the initial stress state of the test location. The coefficients of the horizontal at rest pressure $K_0$ is expressed by the famous empirical formula reported by Mayne and Kulhawy (1982) as follows:

$$K_0 = (1 - \sin \phi') OCR \sin \phi'$$  \hspace{1cm} (6)

The loading pressures were corrected to consider the volume change and pressure loss within the pressuremeter system, and the probe pressures at each stage were normalized with respect to the maximum applied pressure during the test. After the volume change of the probe is recorded, the duration time for each pressure level is 60 s, and the pressure applied for each stage is 10 s (Fig. 3a). Considering the pore water pressure, the soil body adopts the axisymmetric pore fluid eight-node shrinkage integral unit CAX8RP, and the sweeping meshing technique is used to divide the model mesh. The typical finite element model of borehole PB-3 for PMT is shown in Fig. 3b.

3. Case analysis 1

The proposed offshore wind farm project is located in the coastal waters of Heidao town, Zhuanghe
county, Dalian city. These foundation types of the fans are high-pile cap and jacket, and the test piles were selected in fan F40, Fan F64 and F70 (as shown in Fig. 4). Drilling and sampling, in situ tests (standard penetration tests, heavy dynamic penetration tests, pressuremeter tests), and laboratory tests were carried out around the three seats. Three boreholes were drilled in the position of fan F40 and named PB-1, PB-2, and PB-3, and many PMTs were conducted on the SOC organic silt in these holes. Three boreholes were drilled in the position of fan F70 and named as PB-4, PB-5, and PB-6, and many PMTs were conducted on the OC silty clay in these holes. The PMTs were conducted using a Menard-G pressuremeter with a pressuremeter membrane of 0.66 m long and 0.074 m of the initial radius. The average depths of the PMTs are shown in column 3 of Table 1.

Typical $p_{ca}-\ln(\Delta V/V)$ curves from the PMT were plotted to estimate $s_u$ using the direct traditional method shown in Fig. 1(b). The initial flat part of the curve reflects the soil disturbance during the boring and pressuremeter installation in the boreholes. This does not affect the slope of the straight segment of the curve (i.e., $s_{ca}$-value). The slope of the fitted straight line generally decreased with the increase in the strain in the complete $p_{ca}-\ln(\Delta V/V)$ curve. The undrained shear strength will be lower if the large strain of the soil is considered. Thus, it is usually 5-15% of the strain area in the $p_{ca}-\ln(\Delta V/V)$ curve derived undrained shear strength. The estimated $s_u$ values obtained from the slope of the best fitting line over the datapoints corresponding to 5-15% of the strain area are summarized in column 5 of Table 1.

The consolidation and triaxial compression tests were carried out on the soil samples corresponding to the PMT points. In this study, axisymmetric finite element (FEM) analyses were conducted using the ABAQUS software. The actual loading time and pressure duration of the pressure membrane were used to simulate the graded loading. $\sigma_{h0}', \kappa, \lambda$, and $e_0$ were assigned to the FE model as shown in Fig. 6 for simulating PMT on 8.6 m in BP-3. For the cavity expansion problem, the radial stress ($\sigma_r$) and circumferential stress ($\sigma_\theta$) at the cavity wall are the maximum and minimum principal stresses, respectively. The values of $\sigma_r$ and $\sigma_\theta$ during each simulated PMT were estimated from the FE analyses, and the deviator stress is defined as follows:

$$q = \sigma_\theta - \sigma_r$$

The deviator stress vs. cavity strain ($q-\varepsilon_c$) curve for the PMTs conducted in borehole PB-3 is plotted in Fig. 5. The undrained shear strength is equal to half of the maximum deviator stress $q_{max}$, and the simulation results obtained from the FEM based on the MCC model are summarized in column 10, Table 1.

![Fig 4. Wind farm site and fan layout plan](image1)

![Fig 5. Deviator stress vs cavity strain at the cavity wall in borehole PB-3](image2)
Table 1. Soil description and engineering properties from PMTs

| Soil type          | Boring name | Average depth(m) | OCR | \( s_u/kPa \) (direct traditional method) | \( s_u/kPa \) (the analytical method) | \( \lambda \) | \( \kappa \) | \( w_o \) | \( s_u/kPa \) (FEM) |
|--------------------|-------------|------------------|-----|------------------------------------------|----------------------------------------|------------|--------|---------|------------------|
| SOC organic silt   | PB-1        | 3.3              | 1.6 | 67                                       | 69                                     | 0.20       | 0.01   | 1.55    | 24               |
|                    | PB-2        | 4.8              | 2.2 | 170                                      | 182                                    | 0.35       | 0.035  | 1.17    | 64               |
|                    | PB-3        | 6.0              | 2.1 | 239                                      | 254                                    | 0.35       | 0.0175 | 1.17    | 89               |
|                    | PB-4        | 11.7             | 1.3 | 163                                      | 166                                    | 0.35       | 0.07   | 1.29    | 54               |
| OC silty clay      | PB-5        | 10.3             | 1.1 | 83                                       | 84                                     | 0.35       | 0.0175 | 2.86    | 26               |
|                    | PB-6        | 4.8              | 2.5 | 452                                      | 491                                    | 0.03       | 0.003  | 0.46    | 174              |
|                    |             | 6.2              | 1.8 | 171                                      | 179                                    | 0.35       | 0.01   | 0.46    | 62               |
|                    |             | 8.6              | 1.5 | 150                                      | 155                                    | 0.15       | 0.025  | 1.65    | 52               |
|                    |             | 1.1              | 4.0 | 1469                                     | 617                                    | 0.04       | 0.005  | 0.32    | 1310             |
|                    |             | 3.3              | 5.2 | 1010                                     | 1247                                   | 0.08       | 0.01   | 0.49    | 552              |
|                    |             | 5.1              | 14.1| 807                                      | 1136                                   | 0.08       | 0.004  | 0.49    | 654              |
|                    |             | 8.5              | 13.0| 1310                                     | 1819                                   | 0.08       | 0.004  | 0.49    | 1019             |
|                    |             | 3.3              | 6.5 | 1610                                     | 2064                                   | 0.03       | 0.005  | 0.4     | 960              |
|                    |             | 4.8              | 11.8| 1328                                     | 1823                                   | 0.06       | 0.004  | 0.49    | 995              |
|                    |             | 6.6              | 3.4 | 1182                                     | 1374                                   | 0.07       | 0.0035 | 0.48    | 544              |
|                    |             | 12.1             | 7.0 | 2042                                     | 2635                                   | 0.02       | 0.007  | 0.48    | 1281             |
|                    |             | 1.1              | 2.7 | 538                                      | 604                                    | 0.03       | 0.002  | 0.41    | 224              |
|                    |             | 5.3              | 15.0| 923                                      | 1300                                   | 0.04       | 0.003  | 0.59    | 768              |
|                    |             | 7.4              | 7.4 | 739                                      | 960                                    | 0.12       | 0.007  | 0.59    | 486              |
|                    |             | 13.6             | 8.6 | 1243                                     | 1646                                   | 0.12       | 0.001  | 0.54    | 864              |

The shear strength was estimated using three different methods based on the cylindrical cavity expansion theory in the undrained clay. Compared to the direct traditional method, the analytical method considers the effect of OCR on the undrained shear strength of the soil alone. Scatter plots of the ratio of \( s_u \) values obtained from the direct traditional method (\( s_{ud} \)) to the \( s_u \) values obtained from the analytical method (\( s_{ua} \)) with OCR are shown in Fig. 6. As shown in the diagram, \( s_{ud} \) is less than \( s_{ua} \) in both SOC organic silt and OC silty clay, and the difference between \( s_{ud} \) and \( s_{ua} \) increased with the increase in OCR. For SOC organic silt, the \( s_{ud} \) is ~1-8% lower than \( s_{ua} \). For OC silty clay, the \( s_{ud} \) is ~11-29% lower than \( s_{ua} \). This indicates that the undrained strength obtained from the direct traditional method will be underestimated without considering the influence of OCR, and this phenomenon is more obvious in the OC soil.

Compared to the analytical method, the effect of pressuremeter of limited length on the undrained shear strength of the soil can be considered alone by simulating the expansion of pressuremeter membrane with a particular length using the FEM. Scatter plots of the ratio of \( s_u \) values obtained from the FEM (\( s_{uf} \)) to those obtained from the analytical method (\( s_{ua} \)) with OCR are shown in Fig. 6. The \( s_{uf} \) values are less than \( s_{ua} \) in both the SOC organic silt and OC silty clay, and the difference between \( s_{uf} \) and \( s_{ua} \) decreased with the increase in OCR. For SOC organic silt, the \( s_{uf} \) is ~69-64% lower than \( s_{ua} \). For OC silty clay, the \( s_{uf} \) is ~62-41% lower than \( s_{ua} \). The results show that the undrained strength obtained from the analytical method will be overestimated by ignoring the effect of pressuremeter of limited length, and the pressuremeter of limited length effect rapidly decreased with the increase in OCR. This is probably because the larger the OCR, the smaller the possibility of vertical deformation of the soil around the pressuremeter membrane, and the closer the soil to the plane strain state.

According to the above discussion, the undrained shear strength increases with the increase in OCR and decrease in the pressuremeter of limited length. To comprehensively consider both the influence on undrained shear strength, it is necessary to compare the \( s_u \) values obtained from the direct
traditional method \( (s_{ud}) \) with those obtained from the FEM \( (s_{uf}) \). The scatter plots of the ratio of \( s_{uf} \) to \( s_{ud} \) with OCR are shown in Fig. 6. The values of \( s_{uf} \) are less than \( s_{ud} \) in both the SOC organic silt and OC silty clay, and the ratio of \( s_{uf} \) to \( s_{ud} \) increases with the increase in OCR. This indicates that the effect of pressuremeter of limited length is greater than that of OCR in the tested soil. However, with the decrease in pressuremeter of limited length effect and increase in OCR, the effect of OCR will cancel out the effect of pressuremeter of limited length at a certain OCR, and the ratio of \( s_{uf} \) to \( s_{ud} \) is equal to 1. In the nonlinear fitting of the scatter points of the ratio of \( s_{uf} \) to \( s_{ud} \) for the OC silty clay, the x value corresponds to the intersection of the fitting straight and \( y = 1 \) is equal to 23, predicting that the effects of OCR and pressuremeter of limited length on undrained shear strength are offset by each other when \( OCR = 23 \).

![Fig 6. Scatter plots of the ratio of calculated results obtained from three different methods](image)

4. Case analysis 2

The Wuhan Tianhe Airport is located in Huangpi district, Wuhan city, Hubei province. To obtain the parameters of soil strength, deformation, etc., a series of PMTs were carried out in boreholes. Three boreholes, HZX228, HZX233, and HZX321, were located in the SOC silty clay, and the other three boreholes, HZX360, HZX410, and HZX435, were located in the OC silty clay. The layout of the boreholes is shown in Figure 7. The PMTs were conducted using a Menard-GA pressuremeter with a pressuremeter membrane of 0.6 m long and 0.07 m of the initial radius. The acquisition process of each parameter is reported in the last chapter, and the calculation results are summarized in Table 2.

![Fig 7. Plan and drilling arrangement of Tianhe Airport](image)
The undrained shear strength of the soil can be considered alone by simulating the expansion of pressuremeter membrane with a particular length using the FEM. The scatter plots of the ratio of $s_u$ values obtained from the FEM ($s_{uf}$) to those obtained from the analytical method ($s_{ud}$) with OCR are shown in Fig. 8. The values of $s_{uf}$ are less than $s_{ud}$ in both the SOC and OC silty clays, and the difference between $s_{uf}$ and $s_{ud}$ increased with the increase in OCR. For the SOC silty clay, the $s_{uf}$ is ~1-10% lower than $s_{ud}$. For the OC silty clay, the $s_{uf}$ is ~13-48% lower than $s_{ud}$. This indicates that the undrained shear strength obtained from the direct traditional method will be underestimated without considering the effect of OCR, and this phenomenon is more obvious in the OC soil.

Compared to the analytical method, the effect of pressuremeter of limited length on the undrained shear strength of the soil can be considered alone by simulating the expansion of pressuremeter membrane with a particular length using the FEM. The scatter plots of the ratio of $s_u$ values obtained from the FEM ($s_{uf}$) to those obtained from the analytical method ($s_{ud}$) with OCR are shown in Fig. 8. The values of $s_{uf}$ are less than $s_{ud}$ in both the SOC and OC silty clays, and the difference between $s_{uf}$ and $s_{ud}$ decreased with the increase in OCR. For the SOC silty clay, the $s_{uf}$ is ~63-52% lower than $s_{ud}$. For the OC silty clay, the $s_{uf}$ is ~48-35% lower than $s_{ud}$. The results show that the undrained shear strength obtained from the analytical method will be overestimated by ignoring the effect of OCR.
pressuremeter of limited length, and the pressuremeter of limited length effect decreased rapidly with the increase in OCR. This is probably because the larger the OCR, the smaller the possibility of vertical deformation of the soil around the pressuremeter membrane, and the soil is closer to the plane strain state.

According to the above discussion, the undrained shear strength increases with the increase in OCR and decreases with the pressuremeter of limited length. To comprehensively consider both the influence on undrained shear strength, it is necessary to compare the $s_u$-values obtained from the FEM ($s_{uf}$) with those obtained from the direct traditional method ($s_{ud}$). The scatter plots of the ratio of $s_{uf}$ to $s_{ud}$ with OCR are shown in Fig. 8. The ratio of $s_{uf}$ to $s_{ud}$ increased with the increase in OCR until the ratio reached 1 while the corresponding OCR is equal to 34. Thereafter, the ratio became stable around 1. This indicates that the effect of pressuremeter of limited length is greater than that of OCR when $OCR < 34$, and the effect of OCR is neutralized with the effect of pressuremeter of limited length when $OCR ≥ 34$. Interestingly, the scatter plots of the ratio $s_{ud}/s_{uf}$ and $s_{df}/s_{uf}$ intersect when $OCR = 34$. It is reasonable to calculate the undrained strength using the directional method for silty clay with $OCR > 34$.

![Fig 8. Scatter plots of the ratio of calculated results obtained from three different methods](image)

### 5. Conclusion

(1) When the cylindrical cavity expansion theory was used to explain the undrained shear strength obtained from PMTs conducted on different types of clays, the direct traditional method suggested by Gibson and Anderson ignores the effect of pressuremeter of limited length and OCR, the analytic method based on modified Cambridge model proposed by Cao only considers the effect of OCR, the finite element method (FEM) in view of the modified Cambridge model take the effects both of pressuremeter of limited length and OCR into account.

(2) The undrained shear strength obtained from the direct traditional method is significantly smaller than that obtained from the analytic method due to the effect of OCR, and with the increase of OCR, the difference between the two increases.

(3) The undrained shear strength estimated from the analytical method is larger than that estimated from the FEM in virtue of the effect of pressuremeter of unlimited length, and with the increase in OCR, the effect of pressuremeter of limited length rapidly decreased.

(4) When performing a PMT in clay with pressuremeter of limited length, There is a critical value of OCR, where the length effect is higher than the OCR effect when the OCR is below this critical value, while the effect of OCR and the length cancel each other out when the OCR is above this critical value. The threshold value is predicted to be 23 for the OC silty clay in case 1, and the actual value of the threshold is 34 for the OC silty clay in case 2.

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