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Use of piezocone tests to predict consolidation yield stress and overconsolidation ratio of lagoonal deposit soil

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Abstract: Existing empirical methods for interpreting the consolidation yield stress and the overconsolidation ratio (OCR) in clays from piezocone tests are briefly reviewed. It can be seen that no universal correlation exists for all worldwide sites. However, for a given clay deposit, there does exist a most appropriate method to reflect the consolidation yield stress and the OCR based on piezocone test data. Three empirical methods are compared based on the piezocone test data collected on Lixia River lagoonal deposit soil sites in the north of Jiangsu province. The objective of this study is to evaluate the validity of the existing relationships linking the consolidation yield stress to piezocone test data and identify the appropriate method for Lixia River lagoonal deposit soil. It is shown that the correlation based on the net tip resistance has much higher accuracy for estimating the consolidation yield stress of lagoonal deposit soil than other methods.

Key words: piezocone (CPTU); consolidation yield stress; overconsolidation ratio; lagoonal deposit; correlation

The consolidation yield stress (σ'_p) and the overconsolidation ratio (OCR) of lagoonal deposit soil are fundamental characteristics used for geotechnical design. They are generally obtained by laboratory oedometer tests on undisturbed soil samples. However, these parameters determined in the laboratory are influenced by sample disturbance, test procedure, and the interpretation method. If a near-continuous profile of the stress history with depth is required, the conventional laboratory method becomes time consuming and expensive.

These difficulties may be overcome by using an in situ testing device such as the piezocone penetration test, which provides continuous profiles of the cone resistance, sleeve friction, and pore water pressure. Piezocone test data have been used in the past to estimate the stress history of cohesive soil deposits[1-2]. Compared to oedometer tests, piezocone tests are fast, economical, and give continuous profiles of the stress history in depth.

Currently, numerous correlations, mostly empirical, have been proposed to predict these two parameters from separate or combined piezocone measurements. This paper briefly reviews existing methods of interpreting the stress history of clays from piezocone tests. Three empirical methods are compared on the basis of the piezocone test data collected in Lixia River ages-old lagoon facies soft soils with the OCR ranging from 0. 8 to 3. 0. The objective of this paper is to investigate the potential use of piezocone test data for determining the stress history of lagoonal deposits and identify the most appropriate method for Lixia River ages-old lagoon facies soft soils deposits.

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1 Review of Existing Methods

Mayne[3] reported different methods of interpreting the consolidation yield stress and the OCR of clays from piezocone tests. Different researchers have given different categories. Chen and Mayne[4] divided existing methods into three groups: ① Empirical approaches; ② Analytical models; ③ Numerical simulations. Demers and Leroueil[2] divided those into three groups: ① Methods based on tip resistance measurements alone; ② Methods based on pore water pressure measurements alone; ③ Methods combining both types of measurements. Kurup and Dudani[5] gave the following categories: ① Empirical methods based on pore pressure parameters; ② Theoretical methods based on cavity expansion theories and critical-state soil mechanics; ③ Analytical methods based on yield stress and bearing capacity; ④ Artificial neural network (ANN) models. Due to length limitations, only a brief review of the empirical methods is given here.

1.1 Methods based on net cone resistance

Mayne[6] proposed an empirical relationship between the net cone resistance ($q_t - \sigma_{v0}$) and the consolidation yield stress by introducing the parameter $N_{\sigma t}$ and obtained a very good correlation between these two parameters:

$$\sigma_p' = \frac{q_t - \sigma_{v0}}{N_{\sigma t}} \tag{1}$$

where $N_{\sigma t}$ is an empirical coefficient and dependent on soil properties and types, q_t is the cone resistance corrected for the unequal end area ratio and pore pressure effects, and σ_{v0} is the total vertical stress. Mayne et al. showed that there was a clear trend between $(q_t - \sigma_{v0})$ and σ_p' based on 36 test sites around the world[7].

Mayne[6] proposed the normalized net tip resistance with respect to the effective vertical stress by introducing the parameter Q_t:

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma_{v0}'} \tag{2}$$

where σ_{v0}' is the effective vertical stress.

The analysis of world data by Chen and Mayne[8] gives a Q_t/OCR value of 3.1, but with a relatively low coefficient of determination ($r^2 = 0.67$) for intact clays and a great deal of scattering ($r^2 = 0.47$) when fissured clays are included.

1.2 Methods based on excess pore pressure

Mayne[6] showed relationships between the normalized excess pore pressure (N_{EPP}) and the OCR, or between the excess pore pressure and the consolidation yield stress, using the following equations:

$$N_{EPP} = \frac{u - u_0}{\sigma_{v0}'} \tag{3}$$

$$\sigma_p' = K_{EPP}(u - u_0) \tag{4}$$

where K_{EPP} is an empirical coefficient and dependent on soil properties and types, u is the pore pressure reading from various pressure transducer locations induced during the penetration, and u_0 is the initial pore pressure. Current correlations using the excess pore water pressure gave more scattered results than those with the net tip resistance.

The above correlations for K_{EPP} were derived for normally to lightly overconsolidated clays and should not be extrapolated to heavily overconsolidated deposits or fissured clays where the excess pore water pressure is small or even negative.

1.3 Methods based on effective tip resistance

Senneset et al. proposed a resistance parameter which represents the difference between the measured tip resistance and the measured pore water pressure, called "effective tip resistance". Houlsby suggested that the following factor, the normalized effective tip resistance (L), could be a useful indicator of OCR[9]:

$$L = \frac{q_t - u}{\sigma_{v0}'} \tag{5}$$

where q_t is the cone resistance corrected for unequal end area ratio and pore pressure effects, and u is the pore water pressure reading from various pressure transducer locations induced during the penetration.

Refs. [10 - 11] investigated the relationships between L and OCR, and between the consolidation yield stress and the effective tip resistance. The latter relationship can be defined as

$$\sigma_p' = \frac{q_t - u}{N_{\sigma e}} \tag{6}$$

where $N_{\sigma e}$ is an empirical coefficient and dependent on soil properties and types.

For some deposits this method works well but, in general, it is not recommended in estimating the consolidation yield stress using the "effective" cone resistance. In soft normally consolidated clays , using the excess pore pressure to interpret the consolidation yield stress may therefore be more accurate.

2 Site Description and CPTU Results

2.1 Description of site

For this study, the piezocone test site was selected in Huai-yan expressway at Yancheng city in the eastern Jiangsu province. The ancient Lixia River lagoon is a transgression and regression integrated barrier-lagoon sedimentary system was reached, based on the previous achievement on lagoon and through detailed investigation of the areal geology of Jiangsu. The Lixia River lagoon soft soils developed under such a sedimentary environment and was influenced by the alluvium of the old Huanghe River; therefore, there formed the typical lagoon facies soft soil with high water content, high organic matter content, high compressibility and inferior engineering properties. The laboratory tests for this study were done for the site. The soil samples were collected by means of a stationary piston sampler 76 mm in diameter before embankment construction at 1 m intervals between the depths of 2 and 14 m. The consolidation yield stress was interpreted using the Casagrande method by conventional oedometer tests using a daily load (every 24 h) increment of 0.5. It can be seen from the test results that the subsoil is lightly overconsolidated, with an OCR of about 1.8. The plasticity index ranges from 23.5 to 36.9, and the natural water content of the clay is about 83.3%, which is 25% to 35% of its liquid limit. Tab. 1 gives the typical values of the properties of the soil layers studied.

Tab. 1 Typical properties of the soil layers studied

Layer	Bulk density/ ($kN \cdot m^{-3}$)	Specific gravity	Water content/%	Liquid limit	Plasticity index
Clay	18. 2	2. 74	38. 9	41. 4	18. 6
Muck	15. 1	2. 74	83. 3	48. 3	36. 9
Mucky clay	17. 5	2. 74	46. 6	46. 4	23. 5
Clay	18. 7	2. 74	26. 7	39. 2	19. 6

2. 2 Piezocone test results

The piezocone penetration device used in this study was produced by Vertek-Hogentogler Co. of USA. The equipment is the versatile piezocone system equipped with advanced digital cone penetrometers fabricated with 60° tapered 10 cm^2 tip area cone which provided measurements of q_t, f_s, and u_2 with a 5-mm-thick porous filter located just behind the cone tip. Water pressures can act over a part of the base area of the cone in a direction opposite to the resisting forces developed during pushing, thus the measured total stress q_c will be reduced. To obtain the actual total stress q_t, a correction must be applied to account for the design of the cone. This correction is done directly by the field computer data acquisition system E4FCS during data processing for each set of readings, using the following equation[12]:

$$q_t = q_c + 0.2 u_2 \tag{7}$$

The rate of penetration for all tests in this study is 2 cm/s. At this rate, one set of readings can be obtained for every 5 cm of penetration.

The typical profiles of q_t, f_s and u_2 with depth for the test is presented in Fig. 1. The water-table is also indicated in the figure. Soil layers can be identified from the piezocone reading profiles. The piezocone test results from Fig. 2 indicate clearly the homogeneity of the lagoonal deposit soil. The soil profiles show a surface crust to a depth of about 2. 0 m in which the cone tip resistance is about 1. 0 MPa and decreases slightly with depth. Two soft soil layers are detected below the crust: the first, relatively thick, extends to a depth of 11. 5 m and corresponds to a water content of about 83. 3 %. Below this layer, the average water content is about 46. 6%. In the mucky layer, the pore water pressure generated during penetration increases dramatically with depth, while q_t increases slightly with depth between 2 and 12 m. Below 12 m, q_t increases drastically with depth; however, the pore pressure decreases remarkably under the depth of 14 m. The soil boundary between extremely sensitive and moderately sensitive clay is found approximately at 13 m, which is in close agreement with the boundary obtained from the exploration drilling report.

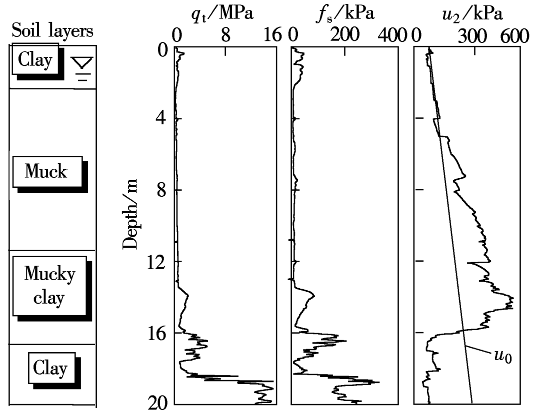

Fig. 1 Typical results from piezocone tests

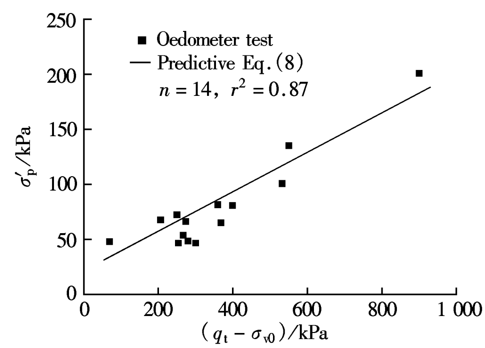

Fig. 2 Relationship between σ'_p and ($q_t - \sigma_{v0}$)

3 Results and Discussion

Three different empirical correlations between the consolidation yield stress or the OCR and the piezocone measurement data are considered below. The results are presented in the same order in which the methods are presented.

3. 1 Methods based on net tip resistance

Fig. 2 shows the relationship between the net tip resistance ($q_t - \sigma_{v0}$) and the consolidation yield stress measured in the laboratory oedometer tests on high-quality samples, and n is the number of data available. The correlation is excellent ($r^2 = 0.87$) for all of the data in which the consolidation yield stress varies between 46. 5 and 201. 4 kPa for Lixia River lagoonal deposit soil. The equation defining the result of the correlation is

$$\sigma'_p = \frac{q_t - \sigma_{v0}}{4.6} \tag{8}$$

Consequently, we can obtain the $N_{\sigma t}$ factor which is equal to 4. 6 in terms of the correlation relationship for Lixia River lightly overconsolidated clay. It should be noted that the correlation factor of 4. 6 is greater than that of Demers et al. for "Quebec" clays between 2. 9 and 4. 5 (3. 4 at average)[2]. Nearly 80% of the results obtained are within ±10% of the laboratory measurement of σ'_p.

Since the relationship between $(q_t - \sigma_{v0})$ and σ'_p is excellent, the correlation between the normalized net tip resistance Q_t and the overconsolidation ratio OCR is equally so. Fig. 3 shows the relationship between the OCR and Q_t. It remains approximately linear regardless of the value of the OCR, which varies between slightly below 0.8 and 3.0.

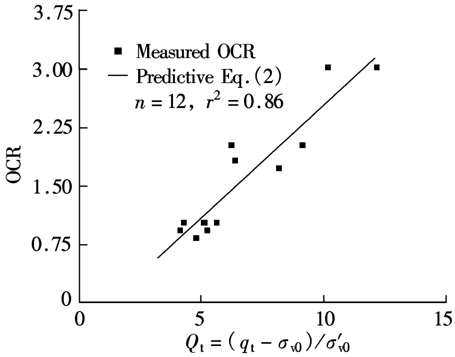

Fig. 3 Relationship between the OCR and Q_t

3.2 Methods based on excess pore pressure

Fig. 4 gives the relationship between the excess pore pressures $(E_{PP(2)} = u_2 - u_0)$ measured in the u_2 position and the consolidation yield stress measured in the laboratory oedometer tests at the site. It is shown that there is a well marked trend, but with a much lower coefficient of correlation $(r^2 = 0.73)$. With the K_{EPP2} ratio being a value of 0.22, the equation defining the results of the correlation is

$$\sigma'_p = 0.22(u_2 - u_0) \tag{9}$$

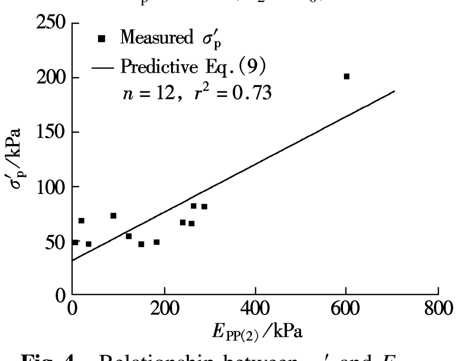

Fig. 4 Relationship between σ'_p and $E_{PP(2)}$

The correlation factor of 0.22 is much smaller than that obtained by Larsson et al. [10], between 0.3 and 0.4, and that of Mayne et al. [11] for "Champlain" clays (0.4), and that of Demers et al. for "Quebec" clays (0.49 on average) [2]. It is also much smaller than the value of 0.54 obtained from the data analysis of sites around the world by Kulhawy and Mayne[13]. There is greater scattering than that for the parameter $N_{\sigma t}$, and only 55% of the results are within an accuracy of ±10% of the laboratory measurement of σ'_p.

Contrary to what one might have expected given the accuracy of each of the measured parameters, the correlation with the $E_{PP(2)}$ parameter is much more scattered than that obtained with the net tip resistance $(q_t - \sigma_{v0})$. It can be concluded from this that the use of a reliable penetrometer and a good method of calibration makes it possible to obtain excellent data for tip resistance[2].

It can be seen from Fig. 5 that the correlation with the N_{EPP} parameter is much more scattered than that obtained by the normalized net tip resistance Q_t.

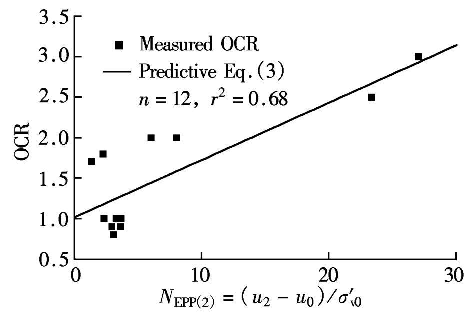

Fig. 5 Relationship between the OCR and $N_{EPP(2)}$

3.3 Methods based on effective tip resistance

It can be seen from Fig. 6 that there is a scattered correlation $(r^2 = 0.68)$ between the consolidation yield stress measured in the laboratory and $(q_t - u_2)$. The equation defining this relationship is

$$\sigma'_p = \frac{q_t - u_2}{5.88} \tag{10}$$

The factor $N_{\sigma e}$ with the value of 5.88 is much higher than the value of 0.50 obtained by Chen et al. [8] according to the compilation of 84 worldwide sites, and the value of 1.0 obtained by Larsson et al. [10] and that of Demers et al. for "Quebec" clays (1.83) [2].

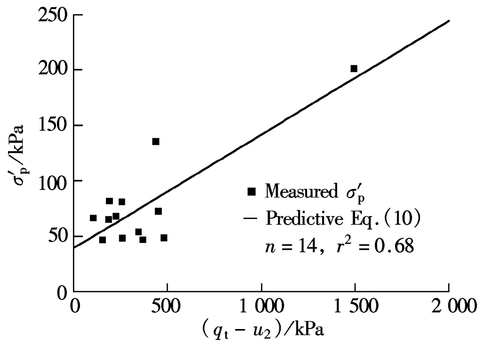

Fig. 6 Relationship between σ'_p and $(q_t - u_2)$

4 Conclusion

In this paper, some of the existing empirical methods for interpreting stress history in clays from piezocone tests are briefly reviewed. It can be seen from this review that no universal correlation exists for all worldwide sites. However, for a given clay deposit, there do exist a most appropriate method to reflect the overconsolidation ratio based on piezocone test data.

Three empirical methods for correlating piezocone measurements with the consolidation yield stress and overconsolidation ratio were examined for lagoonal clay deposits of Lixia River. In the examined case, it can be seen that there are different scatters of predicted consolidation yield stress values from the three empirical correlations as compared against those inferred from oedometer tests. The excellent relationship ($r^2 = 0.87$) was obtained based on the net tip resistance ($q_t - \sigma_{v0}$) to relate the consolidation yield stress. A scattered correlation ($r^2 = 0.73$) was obtained with the excess pore pressures measured at the shoulder (position u_2). Finally, the difference between the tip resistance and the pore pressure, called the effective tip resistance, gives a more scattered correlation ($r^2 = 0.68$). Consequently, among the three empirical correlations, the most reliable and effective relationship is the one directly relating the consolidation yield stress to the net tip resistance with the factor $N_{\sigma t}$ and, accordingly, the one relating the OCR to the normalized net tip resistance Q_t in the lagoonal clay deposits of Lixia River.

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基于 CPTU 测试的泻湖相沉积土固结屈服应力和 OCR 确定方法

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摘要:回顾了基于 CPTU 测试成果确定粘土固结屈服应力和超固结比的方法,表明土的固结屈服应力和超固结比与 CPTU 测试参数之间不存在惟一的相关关系,仅仅针对某一地区的相关关系才是有效的. 根据苏北里下河地区泻湖相沉积土的 CPTU 测试资料,对 3 种经验方法进行了比较. 评价了固结屈服应力与 CPTU 测试参数现有经验关系的有效性,并且确定出适宜于里下河地区泻湖相沉积土的预测方法. 结果表明:基于净锥尖阻力的相关关系比其他经验方法具有较高的精度,可以有效地预测该地区泻湖相沉积土的固结屈服应力和超固结比.

关键词:孔压静力触探;固结屈服应力;超固结比;泻湖沉积;相关关系

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