Evaluation of horizontal permeability coefficient of saturated soil based on CPTU tests

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Abstract: The continuous data of piezocone test (CPTU) are usually used in soil classification and evaluating the design parameters of geotechnical engineering. One of the latest developments of CPTU testing technology in the world is that the permeability coefficient of saturated soil can be obtained rapidly and continuously by using the measured cone tip resistance, sleeve friction and pore water pressure to avoid the time-consuming shortcoming of pore pressure dissipation test. In this paper, the methods of determining saturated soil permeability coefficient based on CPTU test data are briefly reviewed and analyzed. CPTU tests were conducted on geological engineering sites. Samples were obtained using thin-walled soil samplers in clay sites and conducted laboratory horizontal permeability tests. Drilling and pumping tests were carried out in incohesive soil sites. Based on the results of laboratory permeability test and field pumping test, methods for continuous evaluation of saturated soil permeability coefficient based on CPTU are compared and analyzed. The results show that the dislocation theory is suitable for evaluating the in-situ permeability coefficient of saturated soils, but the accuracy is related to the flow model adopted and tends to underestimate the permeability of soils.

Keywords: Piezocone test; Horizontal permeability coefficient; Saturated soil; Dislocation theory

1. Introduction

The piezocone penetration testing (CPTU) is a fast, economical and effective in-situ testing technology, which is widely used in geotechnical engineering practice in the world. CPTU test provides nearly continuous geotechnical parameters such as the cone tip resistance q_t, the sleeve friction f_s and pore water pressure u_2, which can be used for soil classification, geotechnical characteristics evaluation and engineering design [1,2]. The pore pressure dissipation test in clay can be used to evaluate the in-situ consolidation and permeability characteristics of saturated soils. The consolidation theory was usually applied to interpret the pore pressure dissipation data [3,4].

The pore pressure dissipation test is time-consuming, especially for clay with high consolidation degree, it sometimes takes hours to determine t_{50}. Many scholars focused on developing a direct method using the high continuity of CPTU data to determine permeability coefficient of saturated soil. At present, there are mainly two categories for continuous interpretation of permeability coefficient: empirical and semi-empirical. Most of these methods are empirical, using CPTU data to determine the soil behavior type (SBT), and providing the proximate range of permeability coefficient [5]. Elsworth et al. [6,7] and Chai et al. [8] used dislocation theory combined with spherical or hemispherical flow model to derive the theoretical relationship between CPTU test index and permeability coefficient. Permeability coefficient is calculated based on these methods.

In this paper, methods for interpreting permeability coefficient of saturated soil based on CPTU dislocation theory was reviewed. CPTU tests was conducted on geological engineering sites to acquire continuous CPTU data. And these data were interpreted using different methods for permeability coefficient. Comparing with laboratory tests results, the accuracy of these methods in evaluating permeability coefficient is also analyzed and discussed.

2. *Interpretation methods based on dislocation theory*

The concept of dislocation theory was firstly proposed by Volterra [9], an Italian mathematician and physicist. It was originally used in material science to describe the internal micro-defects of crystalline materials and to explain the mechanical problems in deformation. Cleary [9] applied the dislocation theory to analyze the distribution of excess pore water pressure in saturated porous media due to the soil particle dislocated motion.

Elsworth [7,10] then used dislocation theory to explain the distribution of excess pore water pressure during CPTU probe penetration, pointing out that excess pore water pressure is related to penetration rate and soil consolidation coefficient. It can be concluded that the generation rate of excess pore water pressure increases with the increase of penetration rate and decreases with the increase of consolidation coefficient, assuming the soil is homogeneous. Elsworth [11] obtained the relationship between cone tip resistance and consolidation coefficient considering partial drainage conditions.

2.1 Elsworth and Lee's method

Elsworth and Lee [6] proposed the formula for calculating the permeability coefficient under partial drainage condition using CPTU test index to derive the equation of permeability coefficient as shown in table 1, including normalized cone tip resistance $Q_t = (q_t - \sigma_{v0})/\sigma'_{v0}$, pore pressure ratio $B_q = (u_2 - u_0/(q_t - \sigma_{v0})$ and effective angle of internal friction φ. In the equation, σ_{v0} is initial total vertical stress, σ'_{v0} is initial vertical effective stress, u_0 is the hydrostatic pressure. However, this method needs to rely on laboratory tests to obtain effective angle of internal friction φ in order to calculate the permeability coefficient. Therefore, Elsworth and Lee [7] put forward the method of determining in-situ permeability coefficient directly by$B_q Q_t$, and determined the range of partial drainage conditions according to $B_q Q_t$.

For partial drainage conditions, Elsworth and Lee [6,7] proposed that the change of pore water pressure induced by probe penetration can be approximately simulated by the displacement of the motion volume of a finite element in saturated porous media. The basic concept is shown in Fig. 1. The steady fluid stress distribution around the probe can be considered as equivalent to the stress generated by continuous injection of spherical holes fluid into porous media, and the volume of fluid injection is equal to the penetration volume. Elsworth and Lee [6,7] assumed that the flow q was approximately spherical dissipation, then the fluid radial flow rate around the probe along the spherical surface in unit time was as equation 1. The penetration volume of probe per unit time was as equation 2.

$$q = 4\pi a^2 i_a k \quad (1)$$

$$\Delta \mathrm{v} = \pi a^2 U \quad (2)$$

Where a is the piezocone radius, i_a is the hydraulic gradient at radius $\mathrm{r} = a$, k is the hydraulic conductivity, and U is the rate of cone penetration.

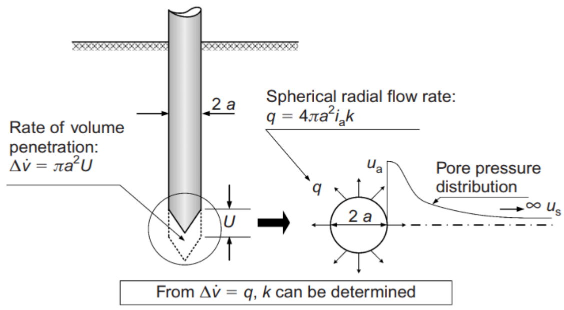

Figure 1. Basic concept of Elsworth and Lee's (2005) method

Elsworth and Lee [6,7] defined dimensionless permeability coefficient K_D as equation 3. Under the assumption that there is no residual fluid left after spherical dissipation, the relationship between K_D and $B_q Q_t$ can be deduced as equation 4. According to the results of linear fitting of engineering practice, equation 5 is obtained by modifying equation 4, where α and β are constants and recommend value as show in Table 1.

$$K_D = \frac{4k\sigma'_{v0}}{U\gamma_w a} \quad (3)$$

$$K_D = \frac{4k\sigma'_{v0}}{U\gamma_w a} = \frac{\sigma'_{v0}}{u_2 - u_0} = \frac{1}{B_q Q_t} \quad (4)$$

$$K_D = \frac{\alpha}{B_q {Q_t}^{\beta}} \quad (5)$$

2.2 Chai's method

On the basis of Elsworth and Lee's method, Chai et al. [8] improved their method and extended it to undrained clay, and put forward the assumption that hemispherical surface flow should be adopted. The improved equation for calculating dimensionless permeability coefficient (denoted as K_D') were as equation 6. Chai et al[8] pointed out that the form of relationship between K_D' and $B_q Q_t$, which directly calculated from CPTU test data, is the same as Elsworth and Lee's method [6,7]. However, the recommended value of α and β and the scope of their use were different from Elsworth and Lee's method, which was summarized in Table 1.

$$K_D' = \frac{2k\sigma_{v0}'}{U\gamma_w a} \quad (6)$$

Comparing equation 3 and equation 6,the form of K_D and K_D' are basically the same with slightly difference, which is due to the model used in Chai's method is the hemispherical flow model and in Elsworth and Lee's method is the spherical flow model. Therefor the conversion relationship between K_D and K_D' is that $K_D' = K_D/2$.

Elsworth and Lee's method and Chai's method based on dislocation theory are summarized in Table 1. It should be noticed that all these methods were established on the assumption that CPTU penetration induced positive excessive pore water pressure. However, following deficiencies still exist in these methods:

(1) For dense and clay layer with high consolidation degree, dilatancy effect often leads to negative excessive pore water pressure. These methods are no longer applicable.

(2) CPTU locates the pore water pressure sensor at different locations on the probe, i.e. at the cone surface (u_1), the cone shoulder (u_2) and behind the friction sleeve (u_3). However, Elsworth and Lee's method and Chai's method did not specify the measurement location of pore water pressure.

(3) The permeability coefficients derived from Elsworth and Lee's method and Chai's method are horizontal, but the drainage path direction of spherical flow model and hemispherical flow model are vertical to the sphere surface rather than horizontal.

All of these may lead to deviation in the calculation of horizontal permeability coefficient.

Table 1. Evaluation of permeability coefficient based on dislocation theory

Equation	Recommend value of constant	Scope	
$K_D = \frac{\alpha}{B_q {Q_t}^{\beta}}$	$\alpha = \beta = 1$	$B_q Q_t < 1.2$	Theoretical results by Elsworth and Lee (2007)
	$\alpha = 0.62$ $\beta = 1.6$	$B_q Q_t < 1.2$	Engineering calibration results by Elsworth and Lee (2007)
$K_D' = \frac{\alpha}{B_q {Q_t}^{\beta}}$	$\alpha = \beta = 1$	$B_q Q_t < 0.45$	Theoretical results by Chai et al. (2011)
	$\alpha = 0.044$ $\beta = 4.91$	$B_q Q_t \geq 0.45$	Engineering calibration results by Chai et al. (2011)
$K_D = \frac{1}{Q_t\left[1 + \frac{1}{Q_t} - \frac{F_r}{tan\varphi}\right]}$	φ is the angle of soil internal friction	$10^{-7} < k < 10^{-4}$ (m/s)	Theoretical results by Elsworth and Lee (2005)
$K_D = \frac{1}{B_q}\left[\frac{F_r}{tan\varphi} - 1 + B_q\right]$			

3. Field tests

3.1 General situation of fields tests

cone penetration testing (CPT) was an effective technology in characterizing subsurface conditions. However, the use of the piezocone (CPTU) data for permeability coefficient calculation is relatively new in Jiangsu, as the accuracy of the CPTU-based permeability coefficient interpretation methods need to be evaluated. In this study, CPTU tests were carried out at three typical geological sites in Jiangsu Province, China. The groundwater level is located in the depth range of 0-5 m and the depth of CPTU tests range is 12-35m. Drill hole sampling and laboratory tests were carried out near each CPTU test hole. The distance between adjacent CPTU holes and drill holes is not more than 5 m. The correlation between CPTU data and permeability coefficient can be established and validated by comparing laboratory geotechnical test data and CPTU test data. General Soil description of test sites were shown in Table 2.

Table 2. Soil description of test sites

Projects	Soil layer	Depth (m)
Nanjing Financial center	Clay	0.9-5.5
	Silty clay	4.5-18.5
	Sandy silt	9.5-35
Zhangjiagang Power plant	Silty clay	0.7-14.2
Suqian-Suxin highway	Clay	1.8-6.0
	Silty sand	5.5~13.5
	Sand	12.5~26.5

3.2 In-situ CPTU tests

The cone used in the CPTU soundings were in complete conformity to ASTM D5778 [12] with a projected area of 10 cm^2, an apex angle of 60°, and a sleeve surface area of 150 cm2. The standard penetration rate during test is 2 cm/s. The tip resistance and sleeve friction are monitored by electric strain gauges, and the pore water pressure is measured by a pressure transducer that is connected to a porous filter element. The piezocone used in this study is also equipped with an inclinometer to monitor the verticality and a temperature sensor to record thermal variations. The pore pressure of CPTU in this research was measured behind the cone (u_2), and the cone area ratio was 0.80.

To ensure the accuracy of u_2 measurement, the pore pressure filter ring is vacuum-pumped 24 hours before the test, then immersed in degased glycerol and sealed. CPTU probe with pore pressure filter ring is pre-vacuumed before conducing tests to guarantee the probe fully saturated. Due to the sensitivity of pore pressure ratio (B_q) to groundwater level, the groundwater level in CPTU boreholes is measured after CPTU tests.

3.3 Determination of permeability coefficient

For low permeability clay, thin-walled soil sampler is used to obtain low disturbance soil samples, and variable head permeability test is used to determine the horizontal permeability coefficient of soil samples. For cohesionless soil, due to the difficulty of sampling, the in-situ horizontal permeability coefficient is measured by borehole pumping test.

4. Discussion

During the CPTU penetration process, when the probe encounters the soil layer interface, the test data tend to be affected and shown transition layer effect as stated by lunne et al. [5], which is that when probe located at the interface between clay layer and sand layer, the drainage condition of surrounding soil is difficult to define. In this paper, the CPTU data located in transition layer are eliminated to reduce the test error. Meanwhile, the average value of the CPTU test index (B_q, Q_t) profile is taken for analysis according to the borehole depth, so as to reduce the influence of spatial variability of soil layer. The horizontal permeability coefficient K_h was calculated by interpretation methods based on dislocation theory, and compared with the results of laboratory tests and field pumping tests, the total number of data points was 23.

Fig. 2 shows the relationship between CPTU index B_qQ_t and K_D, which is inversed from measured K_h based on Elsworth and Lee's method. For the data points of $B_qQ_t < 10^{-1}$, the curve of $K_D = 1/B_qQ_t$ fitting relatively poor than curve of $K_D = 0.62/(B_qQ_t)^{1.6}$. The data of $B_qQ_t < 10^{-1}$ distributed below the two curve, curve of $K_D = 0.62/(B_qQ_t)^{1.6}$ are closer to data points. For the data of $B_qQ_t > 10^{-1}$, the curve of $K_D = 1/B_qQ_t$ tend to underestimate K_D, however the curve of $K_D = 0.62/(B_qQ_t)^{1.6}$ fitting well in this range. Therefore, Elsworth and Lee's method tend to overestimate K_D for low permeability layer, and relatively accurate for high permeability soil using the curve of $K_D = 0.62/(B_qQ_t)^{1.6}$. This may be due to the B_qQ_t is not within the scope of its methods.

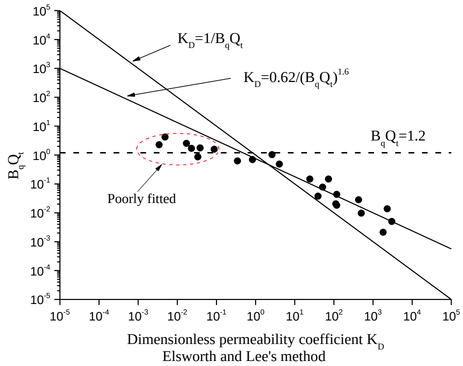

Figure 2 Relationship between inversed K_D and B_qQ_t

Fig. 3. shows more intuitively the comparison between the predicted K_h value based on Elsworth and Lee's method and the measured K_h value. The line of y=x in the double logarithmic coordinates means the predicted value equal to the measured value. The accuracy of the method can be described by the degree to which the data points are close to line y = x. Although in engineering practice, the error of permeability coefficient is acceptable when it is within an order of magnitude, it can be seen that the accuracy of the two methods is different. Large erro exists when the theoretical formula $K_D = 1/B_qQ_t$) is used to calculate the permeability coefficient. The predicted K_h is lower than the measured horizontal permeability coefficient and underestimated the permeability coefficient of soil layer. The theoretical formula $K_D = 0.62/(B_qQ_t)^{1.6}$ is more comforming to enginnering practice. About 13% of the data points are clearly above the line y = x and 56% of the data points are clearly below the line y = x. Therefore, the calibrated formula $K_D = 0.62/(B_qQ_t)^{1.6}$ is closer to the measured value.

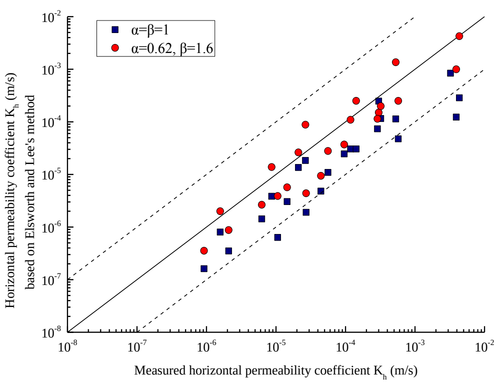

Figure 3 Comparison of measured K_h with calculated K_h based on Elsworth and Lee's method

Fig. 4 shows the relationship between CPTU index B_qQ_t and K_D', which is inversed from measured K_h based on Chai's method. All data points are discretely distributed near the curves proposed by Chai's method. Chai's method described the trend of data points better than Elsworth and Lee's method. No pooly fitted area exist in the range of $K_D' > 0.45$. However, in the $K_D' < 0.45$ interval, it deviates from the best fitting curve and tend to underestimate K_D'.

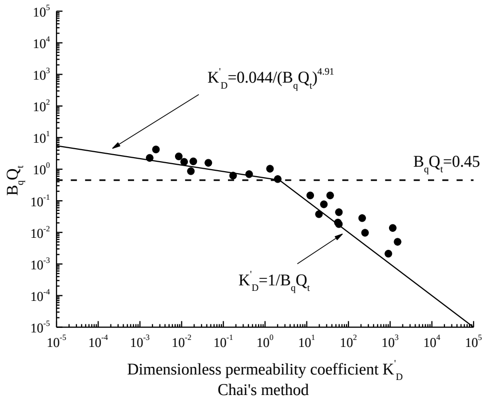

Figure 4 Relationship between inversed K_D' and B_qQ_t

Fig. 5. shows the comparison between the predicted K_h value based on Chai's method and the measured K_h value. All data points are located in the vicinity of line $\mathrm{y = x}$ in double logarithmic coordinates. The error of K_h prediction is no more than one order of magnitude. About 9% of the data are obviously above the line $\mathrm{y = x}$ and 30% are obviously below the line $\mathrm{y = x}$. Therefore, the K_h predicted by Chai's method is also tend to be underestimated than the actual value, i.e., tends to underestimate the permeability of saturated soil

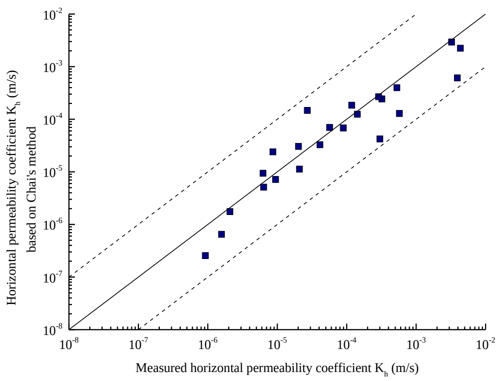

Figure 5 Comparison of measured K_h with calculated K_h based on Chai's method

Based on Elsworth and Lee's method and Chai's method, continuous horizontal permeability profile and laboratory tests horizontal permeability data is shown in Fig. 6. The calculation results and the laboratory permeability test results are basically in an order of magnitude range, which is within an acceptable range in engineering practice.

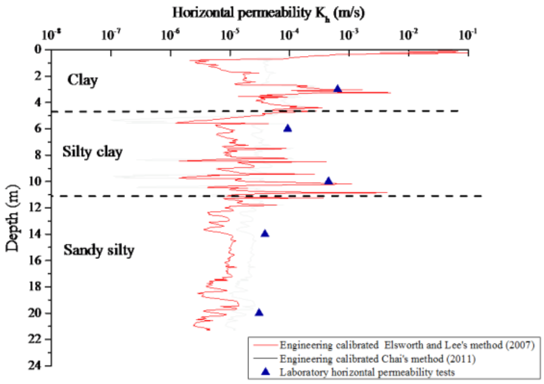

Figure 6 Comparison of continuous K_h profile and laboratory test results

The permeability coefficient of the same soil layer varies obviously, presumably because there are weak interbeds in the same soil layer, which results in the change of the permeability coefficient. However, the laboratory permeability test can not reflect the continuous change due to the limited amount of sampling location, leading to the incomplete reflection of fields permeability characteristic.

5. Conclusions

The following conclusions can be drawn from the study of CPTU index used to evaluate horizontal permeability of saturated soils:

(1) CPTU testing technology can provide continuous, high-resolution and high-precision pore pressure during penetration, which can be used to continuously and rapidly evaluate the in-situ horizontal permeability coefficient of saturated soil. Interpretation of continuous permeability coefficient based on dislocation theory avoided the time-consuming shortcomings of pore pressure dissipation test, which has broad engineering application prospects.

(2) Based on the dislocation theory, the dissipation of pore water around the probe is equivalent to the volume change caused by the probe penetration. Different flow models are used to describe the dissipation of pore water. Although some assumptions of these flow models can not correspond to the reality of pore water dissipation. It can roughly predict the in-situ permeability coefficient of soil layer within an acceptable range of engineering practice.

(3) Both Elsworth and Lee’s method and Chai’s method were calibrated based on engineering practice, which increased the prediction accuracy. But the predictions of K_h based on Elsworth and Lee’s method and Chai’s method are both underestimated permeability coefficient. Relatively, Chai's method is more accurate.

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