Theoretical and empirical investigations to evaluate in situ hydraulic conductivity using piezocone data

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Summary

The piezocone penetration test (CPTU) is an economic and efficient test to investigate the in situ hydraulic conductivity (*k*) of soils that is an essential parameter in geotechnical engineering. This article presents a modified theoretical method and an empirical curve to estimate *k* based on CPTU. The modified theoretical method is established on the cylindrical surface of pore water and the negative exponential distribution in dissipating pore pressure. Five indices are utilized to give a comparison between it and the proposed methods using data in the Yangtze Delta region, which reveals the accuracy of the proposed method. These approaches give the expression of a bi-linear relation defined by K_D-B_qQ_t, for undrained and drained soils, yet, from a pragmatic point of view, a simple ellipse curve may be suitable.

Introduction

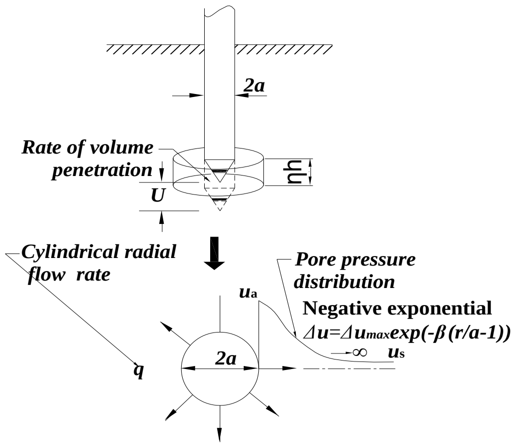
One of widely used, economic and efficient methods to determine in situ hydraulic conductivity is the piezocone penetration test (CPTU) (Campanella and Robertson 1988; Lunne et al. 1997; Mitchell and Brandon 1998). The utility of equations employed to describe the hydraulic conductivity of soils can be classified into three types. The first involves introducing a relation for the coefficient of consolidation of soils via the dissipation test, then indirectly deriving a further equation for hydraulic conductivity (Robertson et al. 1992; Danziger et al. 1997; Burns and Mayne 1998; Leroueil and Jamiolkowski 1991; Cai et al. 2007), a method that is both time consuming and labour intensive. A second possible approach is to apply the Soil Behaviour index proposed by Robertson (1990, 2009). This index, however, is empirical and may cause large errors in various parameters. The final method involves theoretical analysis based on a combination of dislocation analysis, Darcy's law and cavity expansion theory (Elsworth and lee 2005, 2007; Chai, et al. 2011; Wang, et al. 2013a, b; Zou, et al. 2014). Numerical simulations of piezocone dissipation tests (Yi et al. 2012a, b; Mahmoodzadeh et al. 2014, 2015; Ceccato and Simonini 2016) indicate that the distribution of excess pore pressures is more suitable for cylindrical flow in the horizontal direction, while the negative exponent distribution of initial excess pore water pressure satisfy the test results closely (Zhu and Tang 1986; Tang et al. 2002; Zhu et al. 2005; Ma et al. 2007). Classical approaches to evaluate hydraulic conductivity gave the expression of a bi-linear relation defined by KD-BqQt, for undrained and drained soils. Yet, it increase difficulties in distinguishing different soils. And the vast variability of the intersection point also hinders the accuracy, simplicity and operability of the piecewise functions. In addition, a dividing line may be selected with a certain degree of subjectivity, and the points in undrained and drained soils may be located in adverse zone (Zou, et al. 2014).

The object of this paper is to propose a theoretical and empirical approach to estimate the hydraulic conductivity. First, existing approaches are briefly reviewed and discussed. A new method is thereby presented in detail and compared with existing approaches using piezocone data from Yangtze Delta deposits through graphical and statistical methodology. And then, a simple ellipse is compared with a classical bi-linear line using graphical and statistical methodology.

Theory and/or Method

The direction and value assumptions of excess pore water pressure distribution are fundamental and substantial for a splendid method, yet, the previous methods emphasized pore water pressure distribution assumptions on finite local area, hence, the improved assumptions are as follows (shown in Fig. 1):

- A dynamic steady cylindrical flow of pore water will form around the tip of the cone
- The diameter of the cylindrical cavity is assumed to be the same as the diameter of the cone
- Excess pore water pressure in the soil around the cone has a negative exponential function distribution for radial distance, and there is no excess pore water pressure at an infinite distance



(b)

Fig. 1 Basic concept behind the method proposed in the present paper

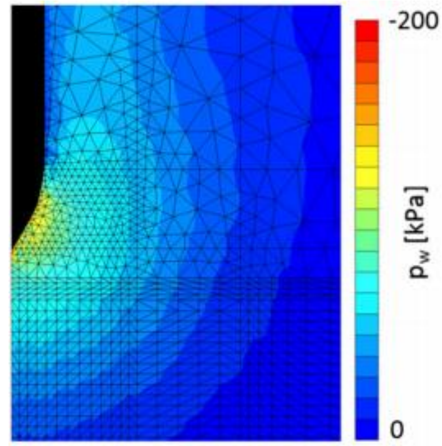


Fig. 2 Excess pore pressure distribution around the cone (Ceccato and Simonini 2016)

Based on the assumption $q = \dot{V} (= \pi a^2 U)$, the mathematical function adopted in this case is:

$$2\pi a \cdot \eta h \cdot k_h \cdot i_a = \pi a^2 U = \dot{V} \quad (1)$$

As shown in Fig. 2, based on the numerical simulation of piezocone dissipation tests (Ceccato and Simonini 2016), the scope of excess pore water pressure dissipation is not confined to the filter thickness h, but instead extends to a larger range ηh (where η is parameter calibrated with the experimental and simulation values). Yet, it could not be considered in previous methods.

It is essential to determine the distribution of initial excess pore water pressure during penetration, hence, a number of laboratory and field tests (**Error! Reference source not found.**) are carried out which revealed that the negative exponent distribution of initial excess pore water pressure near the tip fit the test results closely (Baligh and Levadoux 1980; Roy et al. 1981; Zhu and Tang 1986; Gupta and Davidson 1986; Tang et al. 2002; Zhu et al. 2005; Ma et al. 2007). Therefore, under the condition that excess pore water pressure is zero for radial distance $r \to \infty$, the distribution of pore water pressure u can be expressed as

$$u - u_s = (u_2 - u_s) e^{-\theta(r/a-1)} \quad (2)$$

where θ is a soil parameter: $0.35 < \theta \le 1.5$ for clay, $0.3 < \theta \le 0.35$ for silt and $0.1 < \theta \le 0.3$ for sand (Zhu and Tang 1986; Ma et al. 2007; Shen et al. 2015). According to Darcy's law, the hydraulic gradient on the surface of the cylinder i_a can be expressed by

$$i_a = \theta \frac{u_2 - u_s}{a\gamma_w} e^{-\theta(r/a-1)} \Big|_{r=a} = \theta B_q Q_t \frac{\sigma'_{v0}}{a\gamma_w} \quad (3)$$

Chai et al. (2011) considered that K_D values (and thus the value of k) deduced from CPTU tests mainly represent the hydraulic conductivity of a natural deposit in the horizontal direction. The results obtained from a series of classical numerical simulations of piezocone dissipation tests and in situ tests (see Fig. 2 and **Error! Reference source not found.**a, b for conventional CPTU), indicated the surface area for water flow could be cylindrical in shape around the cone at larger scales, even though this area seems spherical in shape only at finite local area. Whereas, the half-spherical surface area assuredly is more suitable for spudcans (**Error! Reference source not found.**c) and piezoballs (**Error! Reference source not found.**d). More conformity of the surface area and the distribution of initial excess pore water pressure with actual conditions increase the possibility of accuracy. Hence, the cylindrical surface is more suitable for conventional CPTU primarily.

Substituting Eq. (17) into Eq. (15), one can obtain

$$k_h = \frac{Ua}{2hh} \times \frac{1}{i_a} = \frac{a}{2hh} \times \frac{1}{B_q Q_t q} \times \frac{Uag_w}{s'_{v0}} \quad (4)$$

Defining $K_D''' = 1 / B_q Q_t$, kh is expressed as

$$k_h = \frac{a}{2hh} \times \frac{K_D'''}{q} \times \frac{Uag_w}{s'_{v0}} \quad (5)$$

Comparing with Elsworth’s method, the relationship is given by

$$K_D''' = qhhK_D / 2a \quad (6)$$

Based on previous methods (Elsworth and lee 2005; Chai, et al. 2011; Wang, et al. 2013 a, b; Zou, et al. 2014) it follows that

$$K_D''' = \begin{cases} 1 / B_q Q_t, B_q Q_t < e \\ a / (B_q Q_t)^b, B_q Q_t > e \end{cases} \quad (7)$$

where e is a constant parameter. According to international standards for CPTU cones, their height should be equal to 5 mm and their radius to 17.85 mm. Considering Ma et al. (2007) found the value of q equal to 0.3, the data provided by Elsworth and Lee (2005) (see **Error! Reference source not found.**) can be employed to obtain values of h =8 and e =0.98. Eq. (21) can then be expressed as follows:

$$K_D''' = \begin{cases} 1 / B_q Q_t, B_q Q_t < 0.98 \\ 0.87 / (B_q Q_t)^{7.81}, B_q Q_t > 0.98 \end{cases} \quad (8)$$

Examples

The area of Yangtze Delta (including Shanghai, Suzhou, Wuxi, Changzhou and so on) is located in the eastern part of China, where Seven sites (Yushan Park Station, Xinghui Road Station, Hongzhuang station, and Zhuhui Road station at Suzhou, Jiangbei work well and the fourth Yangtze River Bridge at Nanjing, the Yangtze Bridge at Taizhou) were selected for this study. In each of the investigated sites, high quality piston samples were taken at different depths that corresponded to the depths of piezocone dissipation tests for comprehensive laboratory testing.

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References

Burns SE, Mayne PW (1998) Monotonic and dilatory pore pressure decay during piezocone tests in clay. Can Geotech J 35 (6):

1063–1073.

Cai GJ, Liu SY, Tong LY, et al. (2007) Study on consolidation and permeability properties of Lianyungang marine clay based on piezocone penetration test. Chinese Journal of Rock Mechanics and Engineering 26(4): 846–857 (in Chinese).

Campanella RG, Robertson PK (1988) Current status of the piezocone test. In: Proc. 1st Int. Symp. on Penetration Testing, ISOPT, pp. 93–116.

Ceccato F, Simonini P (2016) Numerical study of partially drained penetration and pore pressure dissipation in piezocone test. Acta Geotechnica : 1-15.

Chai JC, Agung PMA, Hino T, et al. (2011) Estimating hydraulic conductivity from piezocone soundings. Géotechnique 61(8): 699-708.

Danziger FAB, Almeida MSS, Sills GC (1997) The significance of the strain path analysis in the interpretation of piezocone dissipation data. Géotechnique 47 (5): 901–914.

Elsworth D, Lee DS (2005) Permeability determination from on-the-fly piezocone sounding. J Geotech Geoenviron Eng 131(5): 643－653.

Elsworth D, lee DS (2007) Limits in determining permeability from on-the-fly uCPT sounding. Géotechnique 57(8): 769－685.

Leroueil S, Jamiolkowski M. (1991) Exploration of soft soil and determination of design parameters. In Proc. Geo-Coast'91, Orlando, Vol. 2, pp 969-998

Lunne T, Robertson PK, Powell JJM (1997) Cone penetration testing in geotechnical practice. London: Chapman and Hall.

Ma SZ, Tang YC, Meng GT, et al. (2007) Piezocone penetration test mechanism, methods and its engineering application. The China University of Geosciences Press, Wuhan, China.

Mahmoodzadeh H, Randolph MF, and Wang D (2014) Numerical simulation of piezocone dissipation test in clays. Géotechnique 64(8): 657-666.

Mahmoodzadeh H, Wang D, Randolph MF (2015) Interpretation of piezoball dissipation testing in clay. Géotechnique 65(10): 831-842.

Mitchell JK, Brandon TL (1998) Analysis and use of CPT in earthquake and environmental engineering. In Geotechnical site characterization, Rotterdam: Balkema, Vol. 1, pp. 69–96.

Robertson PK (1990) Soil classification using the cone penetration test. Can Geotech J 27(1): 151–158.

Robertson PK (2009) Estimating in-situ soil permeability from CPT and CPTU. Can Geotech J 46 (1): 442-447.

Robertson PK, Sully JP, Woeller DJ, et al. (1992) Estimating coefficient of consolidation from piezocone test. Can Geotech J 29(4): 539–550.

Tang SD, He LS, Fu Z (2002) Excess pore water pressure caused by an installing pile in soft foundation. Rock and Soil Mechanics, 23 (6): 725–732.

Wang JP, Shen SL (2013b) Determination of permeability coefficient of soil based on CPTU. Rock and Soil Mechanics (11): 3335-3339 (in Chinses)

Wang JP, Xu YS, Ma L, Shen SL, (2013a) An approach to evaluate hydraulic conductivity of soil based on CPTU test. Mar Georesour Geotech 31(3): 242–253.

Yi JT, Goh SH, Lee FH, Randolph MF (2012a) A numerical study of cone penetration in fine-grained soils allowing for consolidation effects. Géotechnique 62(8): 707-719.

Yi JT, Lee FH, Goh SH, Zhang XY, Wu JF (2012b) Eulerian finite element analysis of excess pore pressure generated by spudcan installation into soft clay. Comput Geotech 42(2012): 157-170.

Zhu XL, Tang SD (1986) Theoretical analysis of the coefficient of consolidation in soft clay estimated by pore water pressure-cone of cone penetration test. Geotechnical Investigation and Surveying 6: 8–12

Zhu XR, He YH, Xu CF, Wang ZL (2005) Excess pore water pressure caused by single pile driving in saturated soft soil. Chinese Journal of Rock Mechanics and Engineering 24(2): 725–732 (in Chinese)

Zou HF, Cai GJ, LIU SY et al. (2014) Evaluation of coefficient of permeability of saturated soils based on CPTU dislocation theory. Chinese Journal of Geotechnical Engineering 36(3): 519–528 (in Chinese)