Practice and development of the piezocone penetration test (CPTu) in geotechnical engineering of China

La pratique et le développement de l'essai de pénétration au piézocône (CPTu) en Chine

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ABSTRACT: The cone penetration test (CPT) technique is widely used in field site investigation due to its fast, repeatable, and cost-effective advantages. It can provide near-continuous information of soil properties and has a strong theoretical background. In this paper, the history and current development status of CPT, particular the cone penetration test with pore pressure measurement (CPTu) in China practice is systematically introduced. The relationship between international standardized CPTu and China CPT is proposed based on a great number of soils. The paper then presents the review and comparison of the soil characterization methods based on CPTu tests results in China, including stress history, deformation, consolidation and permeability characteristics.

RÉSUMÉ: L'essai de pénétration au cône (CPT) est largement utilisé dans les enquêtes de terrain pour ses avantages rapides, reproductibles et rentables. Il peut fournir des informations quasi continues des propriétés du sol et il a une solide théorie. Dans cet article, l'histoire et l'état et développement du CPT, notamment l'essai de pénétration au piézocône (CPTu) qui peut mesurer la pression d'eau interstitielle est systématiquement introduit en Chine. La relation entre les résultats normalisée interationale CPTu et des CPTs en Chine est proposée selon beaucoup des données. Par la suite, le document présente l'examen et la comparaison des méthodes de caractérisation des sols par les résultats des CPTUs en Chine, y compris l'historique des contraintes, des déformations, des caractéristiques de perméabilité et de consolidation.

KEYWORDS: Site investigation, CPT, CPTu, Engineering Characterization

1INTRODUCTION

The cone penetration test (CPT) has been used for decades to investigate the properties of soil in situ. Essentially, the test consists of pushing a penetrometer with a standard geometry (cylindrical with a diameter of 35.7 mm and a conical point with an apex angle of 60^o) into the soil at a rate of 20 mm/s, while measuring a number of parameters. The cone penetration test (CPT) is widely used in-situ testing method, especially in soft soil exploration. As a new kind of in-situ test technique, the piezocone penetration test (CPTu) has been attracting wide attention and widely used in the western developed country. It has been increasingly used because of its important advantages, such as simplicity, speed and continuous profiling. The piezocone, which provides near-continuous measurements of tip resistance, sleeve friction, and pore water pressure induced during the penetration, appears to be a powerful tool for determining the stress history of soft clay deposits.

The mechanical CPT like "Dutch" cone was developed by foreign engineers in Shanghai in the early 1930's (Liu and Wu, 2004). In 1954, the Holland mechanical CPT was first introduced into China. In 1964, the first electric single bridge CPT was independently produced in China with only one measurable parameter (e.g., total specific penetration resistance). Later, the double bridge CPT was developed to measure the tip resistance and sleeve friction independently in the 1970's, which is currently used in Chinese standards. The Holland CPTu was introduced into China in the early 1990's by Nanjing Hydraulic Research Institute, but its follow-up development is very slow. The multifunctional CPTu was introduced into China in 2005 by Southeast University researchers. In the following years, the related theory analysis and application practice of CPTu in China have been developed rapidly. In this paper, the relationship between international standardized CPTu and China CPT is proposed based on a great number of soils. The paper then presents the review and comparison of the soil characterization methods based on CPTu tests results in China, including determination of stress history, deformation, consolidation and permeability characteristics.

2 COMPARISON BETWEEN INTERNATIONAL STANDARDIZED CPTU AND CHINA CPT

Due to the inner geometry of a cone penetrometer, the ambient pore pressure will act on the shoulder area behind the cone. Therefore, the measured cone resistance should be corrected by the unequal area effect for the data presentation and interpretation. In literature works, most of the correlations were developed based on CPT with cone cross area of 10 cm^2 as per international standardized CPT and CPTu tests. However, in China, both 15 cm^2 and 20 cm^2 CPT devices are frequently used. Therefore, the internationalization of Chinese CPT is inevitable (Liu and Wu, 2004).

When different sizes of CPT and CPTU are employed, the question of scale effects inevitably arises. For piezocones ranging in area from 5 to 15 cm^2, the usual assumption, based on experience summarized by Lunne et al. (1997), is that scale effects are negligible in soil layers of sufficient thickness relative to the cone diameter: that is, quantities such as the cone resistance and excess pore pressure do not depend on the size of the piezocone. Powell and Lunne (2005) compared the results using the 10 cm^2 and 15 cm^2 piezocones in UK clays. The comparison of various cone sizes and configurations between China CPT and international standard CPTu device at 28 field testing sites is presented. To avoid the variability, all the tests were performed by the same operators. The elevations of the ground surface at different sites were measured and the difference of elevation may be considered.

To quantify the differences between CPT and CPTU measurements, the ratios of the CPTU to CPT cone resistance and sleeve friction measurements were calculated for each site. The reference line positioned at an average CPTU to CPT ratio equal to one in the plots of average ratios represents the theoretical value if soil variability was eliminated and if there was no effect of cone size. In general, the ratios of cone resistance and sleeve friction measurements fluctuate near one, and the measured values increase with depth. For the soft clay sites (Figure 1), the average fs ratio of the friction sleeve is always significantly greater than the average qc ratio. For the topsoil such as fill and silty clay, the ratios CPTU to CPT fluctuate drastically. The relationships of derived key parameters are developed between China CPT and international CPTu (Table 1). From the perspective of engineering practice, it is concluded that q_t = 1.03 q_c , f_s-$_{CPTu}$ = 1.05 f_s-$_{CPT}$. The empirical equation can be used as useful engineering tool to guide use of 10 cm^2 international CPTu in China.

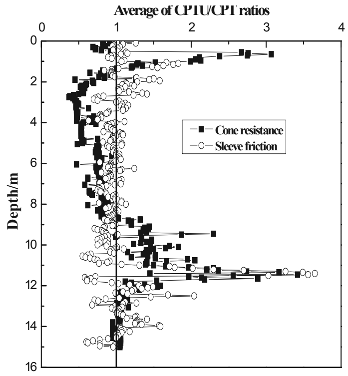

Figure 1. Statistical analysis of q_c and f_s ratios

Table 1. Conversion relationships between CPTu and CPT parameters.

Soil types	Regression equation	
	Cone resistance	Sleeve friction
Soft clay	$q_t = 1.04q_c$	$f_{s\text{-}CPTU} = 1.01 f_{s\text{-}CPT}$
Clay	$q_t = 1.02q_c$	$f_{s\text{-}CPTU} = 1.07 f_{s\text{-}CPT}$
Stiff clay	$q_t = 1.01q_c$	$f_{s\text{-}CPTU} = 1.06 f_{s\text{-}CPT}$
Silt	$q_t = 1.03q_c$	$f_{s\text{-}CPTU} = 1.06 f_{s\text{-}CPT}$
Silty sand	$q_t = 1.03q_c$	$f_{s\text{-}CPTU} = 1.03 f_{s\text{-}CPT}$

3 EVALUATION OF ENGINEERING CHARACTERISTICS BASED ON CPTU TESTS IN CHINA

3.1 Stress history

Since the advent of CPTU in geotechnics, nearly 20 different methods have been suggested for interpreting the preconsolidation pressure and the overconsolidation ratio of clays (Mayne 1991). In this study, the three sites with all sensitive clay deposits in Jiangsu province of eastern China are selected (Liu et al., 2007). These Quaternary clay deposits are located at Lianyungang, Changzhou and Nanjing respectively. Whenever possible, the OCR values interpreted from various in situ tests were compared with the oedometer values for Lianyungang marine clay. At the other test sites, in addition to oedometer results, some field OCR values were deduced from field performance observation of trial embankments. These field values provide a reliable basis for evaluating the validity of the various interpretation methods in Jiangsu clays. Table 2 presents a summary of the typical property values of the soil layers.

Table 2. Typical property values of the soils.

Site	Soil type	Water content/%	Liquid limit	Plasticity index
Lianyungang	muck	79.6	75.6	35.8
Changzhou	clay	23.5	41.8	19.0
Nanjing	mucky silty clay	41.4	36.4	13.3

Figure 2 shows the relationship between net tip resistance ($q_t - \sigma_{vo}$) and the preconsolidation pressure (σ'_p) measured in the laboratory oedometer test on high-quality samples. Here, n as shown in Fig. 1 is the number of data available. In Lianyungang marine clay deposits, the correlation is excellent (r^2 = 0.99) for all the data, and the preconsolidation pressure varies between 29 and 139 kPa. In Changzhou clay site, the correlation is good (r^2 = 0.95) for the data, and the preconsolidation pressure varies between 812 and 1789 kPa. It can be seen from Figure 5 that the relationship between net tip resistance and the preconsolidation pressure of Nanjing clay site is also pretty good (r^2 = 0.98). Consequently, we can obtain the value of Nσt factor, which is equal to 2.7 according to the correlation relationship for Lianyungang lightly overconsolidated clay. Similarly, for Changzhou lightly to moderately overconsolidated clay, the $N_{\sigma t}$ factor is 2.2. For Nanjing backswamp clay deposit, the $N_{\sigma t}$ factor is 2.5. Consequently, the equation defining the correlation of Lianyungang marine clay site can be expressed as follows:

$$\sigma'_p = \frac{q_t - \sigma_{v0}}{2.7} \tag{1}$$

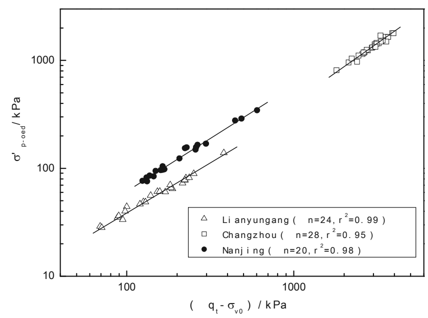

Figure 2. The relationship between preconsolidation pressure measured in oedometer test and net tip resistance

3.2 Deformation modulus

The one-dimensional constrained modulus, M, as measured in an oedometer test, has been expressed in terms of a coefficient, αm, and cone resistance:

$$M = \alpha_m q_c \tag{2}$$

where α_m is a correlation factor. In practice, it has been usual to correlate the modulus M to a penetration resistance. To estimate one-dimensional constrained modulus M, the correlation with net cone resistance (q_t -σ_{v0}) is used in the form (Kulhawy and Mayne, 1990):

$$M = 8.25 \times q_n = 8.25 \times (q_t - \sigma_{vo}) \tag{3}$$

Comparisons between M from CPTU with laboratory oedometric modulus for various types of soil proposed by Kulhawy and Mayne (1990) showed that the ratio M -$_{CPTU}$/ M -$_{lab}$ could equal to 2.21 for high-plasticity clays and silty soils. In Figure 3 the constrained modulus estimated with relationship (3) is plotted against that determined by laboratory oedometric tests, carried out on all the types of Jiangsu lagoonal soils. In our case, the ratio M-$_{CPTU}$/M-$_{lab}$ is always greater than the unity and is not influenced by the type of soil or by its cone resistance value (Cai et al. 2010).

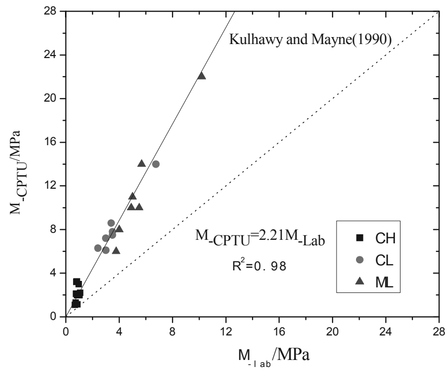

Figure 3. Measured versus predicted constrained modulus values

To examine the possibility for better correlations to estimate the constrained modulus from CPTu data, the corrected cone tip resistance (q_t) and the net cone resistance (q_t -σ_{vo}) were plotted against the laboratory measured constrained modulus as shown in Figures 4(a) and 4(b). A linear correlation was obtained between M and qt as follows:

M =3.36q_t $\qquad R^2$=0.78 (4)

And the following linear correlation was also obtained between M and (q_t -σ_{v0}) given as follows:

M =3.73(q_t -σ_{v0}) $\qquad R^2$=0.92 (5)

The arithmetic mean and standard deviation of (M_{-CPTU}/M_{-lab}) are 0.85 and 0.23 for the first correlation (M = 3.36q_t), whereas 1.02 and 0.29 for the second correlation [M=3.73(q_t - σ_{vo})].

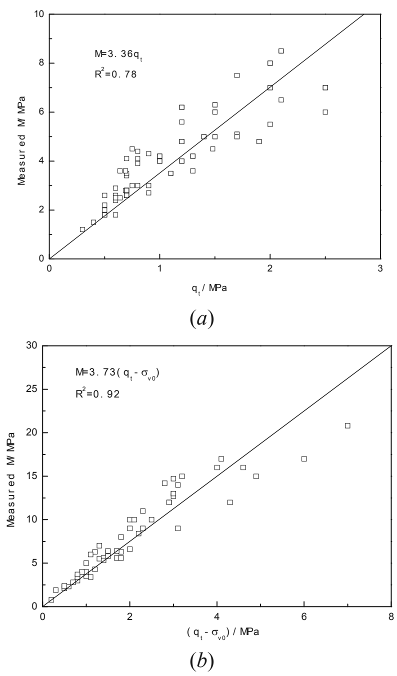

Figure 4. (a) q_t~Measured M ; (b) (q_t -σ_{v0}) ~Measured M

3.3 Consolidation and permeability properties

Many theoretical and semi-empirical methods have been proposed for deriving the coefficient of consolidation from CPTu dissipation data. Teh and Houlsby (1991) proposed a relationship between a dimensionless time factor and c_h value based on numerical analysis of dissipation pore pressure with the consideration of soil rigidity index parameter. Robertson et al. (1992) reviewed some dissipation data from piezocone tests, and concluded that the predicted coefficient of consolidation by Teh and Houlsby (1991) solution compared well with reference values from laboratory tests and field observations. Schnaid et al. (1996) and Danziger et al. (1997) showed that, when Teh and Houlsby's approach was employed to interpret various CPTU results, the calculated values of c_h were of the same order of magnitude as those measured independently in oedometer tests in the laboratory. Abu-Farsakh and Nazzal (2005) compared seven CPTU methods and showed that Teh and Houlsby (1991) and Teh (1987) methods can estimate c_h value better than the other prediction methods.

Teh and Houlsby (1991) proposed a relationship between a dimensionless time factor and c_h value. The dimensionless time factor, T^*, is defined as:

$$T^* = \frac{c_h t}{r^2 (I_r)^{0.5}} \tag{6}$$

where c_h = coefficient of consolidation in horizontal direction; r = radius of cone, typically 17.85 mm; I_r = rigidity index, G/S_u. Among the methods available for evaluating c_h from piezocone dissipation tests, the one proposed by Teh and Houlsby (1991) is probably most widely used (Robertson et al. 1992). Teh and Houlsby's (1991) equation is as follows:

$$c_h = \frac{T_{50}}{t_{50}} r^2 \tag{7}$$

where the time factor T_{50} is related to the location of the filter element and cone size. For a cone with a cross-sectional area of 10 cm^2 and with a shoulder filter element, T_{50} = 0.245 (Teh and Houlsby 1991). The t_{50} is the measured time for 50% dissipation. The method proposed by Teh and Houlsby (1991) was used here to interpret the coefficient of consolidation for the pore pressure dissipation curves in this study.

The coefficient of permeability in the horizontal direction can be estimated from a CPTU dissipation test and by means of the correlation factor (k_h/k_v) proposed by Jamiolkowski et al. (1985). Baligh and Levadoux (1980) recommended that the horizontal coefficient of permeability could be estimated from the expression:

$$k_h = \frac{\gamma_w}{2.3\sigma'_{v0}} RRc_h \tag{8}$$

where RR = compression ratio in the overconsolidated range, and can be obtained from the consolidation tests at the corresponding stress level.

A comparison of the consolidation coefficient values measured by CPTu dissipation test and laboratory oedometer test is presented in Figure 5 in which the CPTU test measures c_h values, whereas the conventional oedometer test measures c_v. It can be seen that the c_v values measured by oedometer test are lower than the c_h values measured by CPTu tests. The c_h values of the lacustrine clay measured by the CPTu tests are generally 4-6 times larger than the c_v values measured by the conventional oedometer test, indicating anisotropic characteristic of the soil.

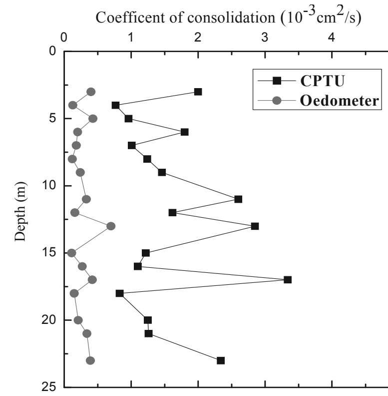

Figure 5. Comparison of cv and ch profiles measured from CPTu and laboratory tests

The k_v values measured by oedometer test and k_h values deduced from CPTu test are compared with each other in Figure 6. The values of coefficient of permeability from back-analysis and falling-head permeability tests are also presented in Figure 6. The comparison shows that the k_h values measured by oedometer are lower than those obtained from CPTu test within 1-2 order of magnitude. The coefficient of permeability of Taihu lacustrine clay is in the order of 10^{-5}-10^{-7}cm/s. The k_h value measured by falling-head permeability tests agrees well with that determined by CPTu tests.

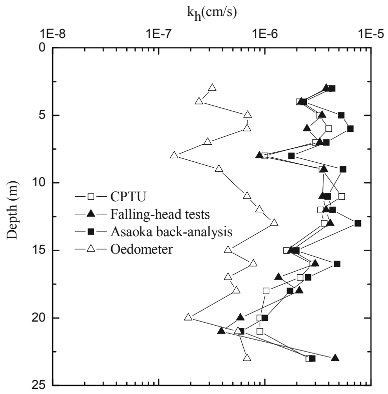

Figure 6. Comparison of k_h profiles measured by different methods

4 CONCLUSIONS

The comparison of various cone sizes and configurations between China CPT and international standard CPTu device at 28 field testing sites is presented. The relationships of derived key parameters are developed between China CPT and international CPTu. From the perspective of engineering practice, it is concluded that $q_t = 1.03\ q_c$, $f_{s\text{-CPTU}} = 1.05\ f_{s\text{-CPT}}$. The empirical equation can be used as useful engineering tool to guide use of 10 cm^2 international CPTu in China. The field CPTu tests were carried out in Jiangsu sites to evaluate the stress history. Consequently, we obtained the value of $N_{\sigma t}$ factor, which is equal to 2.7 according to the correlation relationship for Lianyungang lightly overconsolidated clay. The results show that ratio of M derived from Kulhawy and Mayne 1990's method to that determined from laboratory oedometric tests, $M_{\text{-CPTU}}/M_{\text{-lab}}$, practically equals to 2.21 for high plasticity clays. A quick estimation of the magnitude of coefficient of consolidation c_h is proposed by pore pressure dissipation (type u_2) tests from the CPTu database. Comparisons of the results obtained by different methods indicate that the values of horizontal coefficient of consolidation determined by CPTu are typically 4 to 6 times those of laboratory tests. The coefficient of permeability values measured by laboratory tests are less than by almost 1-2 orders of magnitude with that determined by CPTu tests in Jiangsu soft clays.

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