Application of piezocone to evaluate consolidation and permeability properties of Taihu lacustrine clay deposits

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ABSTRACT: Piezocone penetration tests (CPTU) were carried out at three expressway sites in Taihu lacustrine clay deposits. The coefficient of consolidation and coefficient of permeability of the Taihu lacustrine clay were studied by laboratory and piezocone dissipation tests in order to evaluate the consolidation and permeability characteristics. The in-situ horizontal coefficient of consolidation c_h value of the clay was also back analyzed from field settlement monitoring data. Comparisons of the results obtained by different methods indicate that the c_h values determined by CPTU are in the range of 0.77-3.34×10^{-3}cm^2/s and are typically 4-6 times higher than that of c_v. The coefficient of permeability is in the order of 10^{-6}-10^{-7}cm/s. The k_h value measured by falling-head permeability tests agrees well with that determined by CPTU tests. For soil improvement projects in the soft Taihu lacustrine clay, the coefficient of consolidation determined by CPTU dissipation tests is recommended in engineering practice.

1 INTRODUCTION

In traditional geotechnical applications, the parameters of consolidation and permeability are very important for estimating rates of settlement in foundation loading or embankment construction. Normally, they are obtained by laboratory tests on undisturbed soil samples. However, determination of these soil parameters is sensitive to inevitable sample disturbance. The traditional method will become very costly if high quality soil properties of a profile are required. As a result, it is often difficult to accurately define a complete profile for an entire deposit. The piezocone (CPTU) has developed into the most widely used test for ground investigation. Not only does it provide information about soil type and stratification details, but it can also be used to determine in situ soil properties (Lunne et al. 1997; Cai et al. 2007).

The purpose of this paper is to evaluate the capability of the current CPTU interpretation methods to predict the coefficient of consolidation of soft clay layers. Three expressway sites in Taihu lake soft clay deposits were selected in this study. At each site, CPTU dissipation tests were performed at different penetration depths where clayey soils were encountered. Laboratory oedometer tests were conducted on samples collected from these layers. The coefficient of consolidation from CPTU interpretation methods are then compared with laboratory test results. This paper presents a summary of these analyses results along with a few calculations based on field settlement observations.

2 LITERATURE REVIEW

Many theoretical and semi-empirical methods have been proposed for deriving the coefficient of consolidation from CPTU dissipation data. A comprehensive study on pore pressure dissipation was performed by Levadoux and Baligh (1986) and Baligh and Levadoux (1986) who proposed an interpretation method after evaluating dissipation tests in Boston Blue Clay. Houlsby and Teh (1988) proposed an interpretation based on the results of large strain finite element analysis of the penetration pore pressures and finite difference analysis of the dissipation pore pressure. They used an approach similar to the Levadoux-Baligh theory but including the effect of varying the rigidity index, I_r (= G/s_u). 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 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:

$$T^* = \frac{c_h t}{r^2 (I_r)^{0.5}} \tag{1}$$

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, as follows

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

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 above mentioned solution is applicable only for normally to lightly overconsolidated soils for the monotonic decay of pore pressure. However, for overconsolidated clays, many researchers have noticed a dilatory response where pore pressures initially increase during the dissipation test until a peak value was reached and thereafter a decrease with time was recorded until the total pressure reaches close to hydrostatic pressure corresponding to u_o (Chen and Mayne 1994; Lunne et al. 1997).

To account for the dilatory pore pressure dissipation response, Burns and Mayne (1998) proposed a method to evaluate the coefficients of consolidation from the field dissipation curves based on cavity expansion and critical state soil mechanics theories. Sully et al. (1999) proposed two methods to correct the dilatory dissipation curves and then to use these corrected curves with existing methods of interpretation such as Teh and Houlsby (1991) to evaluate c_h. For practical use, Mayne (2001) proposed a mathematical approach that instead of matching just a single point (usually 50%) of the recorded dissipation, the complete curve is adjusted to obtain the best global value of the horizontal coefficient of consolidation, c_h. The excess pore pressure Δu_t at any time t can be compared with the initial values during penetration (Δu_i) and measured initial excess pore pressure ($\Delta u_i = u_2 - u_0$). The excess pore water pressure is given by:

$$\Delta u_i = \left(\Delta u_{oct}\right)_i + \left(\Delta u_{shear}\right)_i \quad (3)$$

where $\left(\Delta u_{oct}\right)_i$ is the octahedral component during the cone penetration and $\left(\Delta u_{shear}\right)_i$ is the shear-induced component. The excess pore pressure at any time t can be obtained in terms of the modified time factor T^*:

$$\Delta u = \frac{\left(\Delta u_{oct}\right)}{1+50T^*} + \frac{\left(\Delta u_{shear}\right)}{1+5000T^*} \quad (4)$$

In above equation the modified time factor, T^*, is defined in equation (1). The method proposed by Mayne (2001) was followed for analyzing dilatory pore pressure dissipation curves in this research study.

An empirical correlation proposed by Parez and Fauriel (1988) was used to deduce the horizontal coefficient of permeability k_h. Only requiring the use of t_{50} values obtained from u_2 filters, the correlation exhibits monotonic dissipation according to the following equation:

$$k_h = (251 \times t_{50})^{-1.25} \quad (5)$$

3 GEOLOGICAL CONDITIONS AND BASIC SOIL PROPERTIES

The Taihu area of Jiangsu province (including Suzhou, Wuxi, Changzhou and Huzhou cities) is located in the Southern Yangtze Delta in the eastern part of China. The area is about 12,000 km^2 and 5,800 km^2 for the Su-Xi-Chang area and Huzhou City, respectively. The ancient Taihu lake is transgression and regression integrated barrier-lagoon sedimentary system, based on the previous achievement on lagoon and through detailed investigation of areal geology of Jiangsu. With the developments of the highway, the site investigation became very important. The piezocone test sites were selected in Husuzhe, Ningchang and Shenjiahu expressway in Taihu area. The Taihu area lacustrine clay deposits developed under such sedimentary environment and influenced by the alluvium of the Yangtze River, therefore there formed the typical lacustrine soft soil with high water content, high organic matter content, high compressibility and inferior engineering properties. Map location of Taihu lake area is shown in Figure 1.

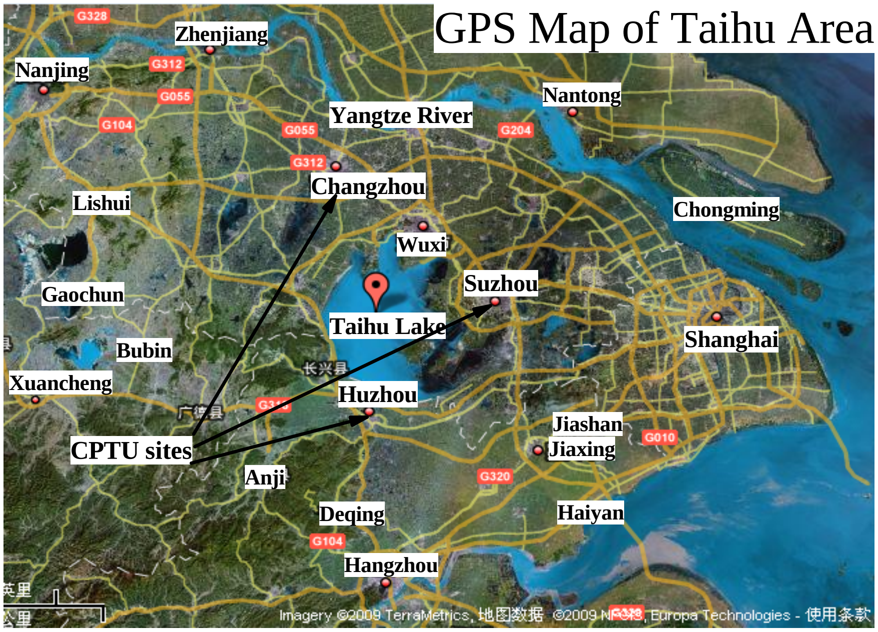

Figure 1. View of the Taihu lake area with the locations of the sites

In each of the investigated sites, the high quality piston samples were taken at different depths that corresponded to the depths of piezocone dissipation tests for comprehensive laboratory testing. Before the embankment construction, soil samples were collected by means of a stationary piston sampler 76 mm in diameter at 1.0 m interval below ground level. Once the stationary piston sampler was withdrawn from the borehole, the soil at the ends of the tube was excavated for wax sealing at both ends. The laboratory testing program includes basic soil characterization tests such as water content, unit weight, Atterberg limits and specific gravity. The oedometer consolidation tests were also conducted on recovered samples in order to evaluate the reference consolidation parameters of the soil. Table 1 summarizes the soil properties for the different investigated sites obtained from laboratory tests.

Table 1. Summary of laboratory soil properties for the investigated sites

Sites	γ (kN/m^3)	w (%)	w_L (%)	I_p	G_s	s_u (kPa)	OCR
Changzhou	19.4-19.9	23-25	38-39	18-19	2.74	44-52	1.0-5.8
Suzhou	16.4-16.7	64-69	55-57	17-20	2.73	32-34	1.1-4.6
Huzhou	17.5-18.2	41-76	36-65	15-28	2.72	38-40	1.3-3.6

Note: γ, unit weight; w, water content; w_L, liquid limit; I_p, Plasticity index, G_s, Specific gravity.

4 PIEZOCONE TESTS

The CPTU device used in this study was produced by Vertek- Hogentogler & Co. of USA. The equipment is a versatile piezocone system equipped with advanced digital cone penetrometers fabricated with 60° tapered, 10 cm^2 tip area cone which provided measurements of q_c, f_s, and u_2 with a 5-mm-thick porous filter located just behind the cone tip. The rate of penetration for all tests in this study was 20 mm/s. At this rate one set of readings could be obtained for every 50 mm of penetration. The shear wave velocities are measured at intervals of 1.0 m, corresponding to successive rod additions during advancement of the penetrometer. The typical profiles of q_t, f_s and u_2 with depth for the test are presented in Figure 2. The profiles confirm the high non-homogeneity of the Taihu area lacustrine soils to the depths investigated.

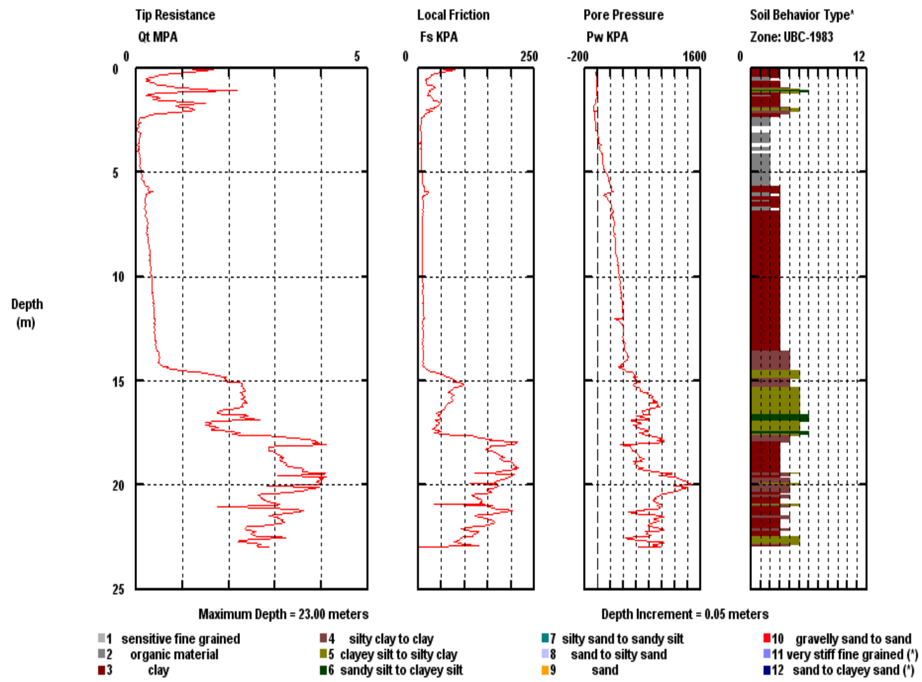

Figure 2. Typical CPTU profiles at Husuzhe expressway site in Taihu area

5 ANALYSIS OF TEST RESULTS AND DISCUSSION

A comparison of the coefficient of consolidation values determined from CPTU dissipation tests and laboratory oedometer tests is presented in Figure 3 in which the CPTU measures c_h values, whereas the conventional oedometer test measures c_v. It should be pointed out that all the laboratory and piezocone tests presented were conducted for intact soils. 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.

A comparison was made between the CPTU results and back analyses from settlement data of the embankment during construction for Shenjiahu expressway site. The back analyses method proposed by Asaoka (1978) was adopted to estimate the horizontal coefficients of consolidation from settlement data. The results from the CPTU interpretation analyses and back analyses of one site are plotted in Figure 4 as a function of depth, and it can be seen that there is generally a good agreement between the values from the CPTU interpretations and back analyses from monitored settlement data. The back calculated c_h value is slightly higher than that deduced from CPTU dissipation tests. This reconfirms that the CPT interpretations are close in agreements with the field observations and also potential sampling disturbances recorded in the field samples used for consolidation tests cannot be ignored.

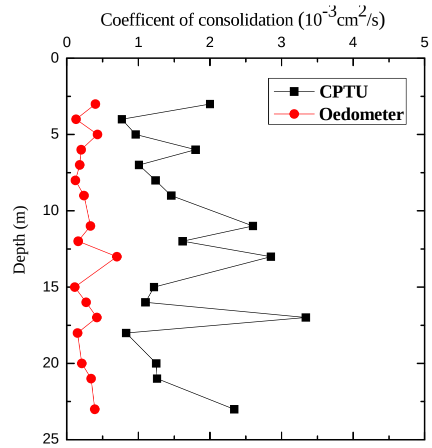

Figure 3. Comparison of c_v and c_h values measured from laboratory tests and CPTU, respectively

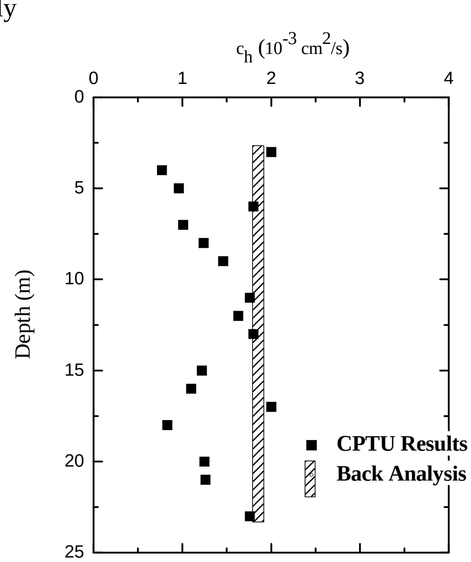

Figure 4. Comparison of c_h profiles from CPTU and back analyses

The k_v values measured by oedometer test and k_h values deduced from CPTU test are compared with each other in Figure 5. The values of coefficient of permeability from back-analyses and laboratory falling-head permeability tests are also presented in Figure 5. 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.

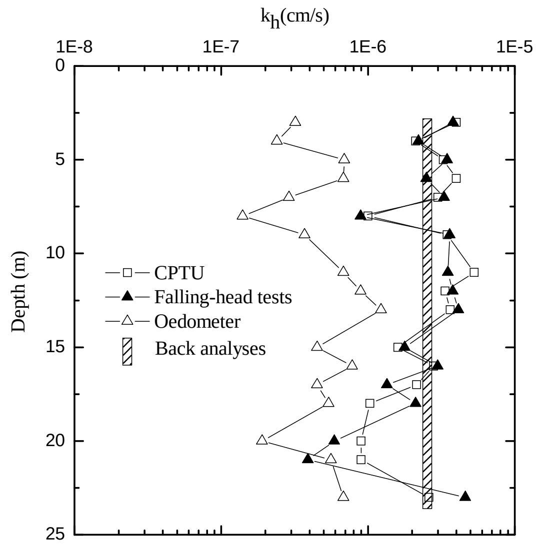

Figure 5. Comparison of permeability (k_h or k_v) profiles measured by different methods

6 SUMMARY AND CONCLUSIONS

Three expressway sites in Taihu lacustrine clayey deposits were used in this study. Undisturbed soil samples were extracted adjacent to the CPTU tests and used to calculate the laboratory reference values from the results of one-dimensional oedometer consolidation tests on vertically orientated samples. According to the field measured settlements data, the coefficient of consolidation and coefficient of permeability were back-calculated from Asaoka (1978) method. From the experimental investigation and the comparison between in situ and laboratory results, the following conclusions can be drawn:

(1) With the interpretation method of CPTU dissipation tests based on the cavity expansion theory and critical state soil mechanics concept proposed by Mayne (2001), it is possible to determine the coefficient of consolidation. The hydraulic conductivity of soils in the horizontal direction can be interpreted by Parez and Fauriel (1988) method.

(2) The c_h values of Taihu lacustrine clays measured through CPTU test are generally 4-6 times larger than the c_v values obtained through conventional oedometer test, while the k_h values measured by oedometer are lower than those obtained from CPTU test within 1-2 order of magnitude. These variations are attributed to potential sampling disturbances as well as a wide range of interpretation that are possible for analyzing time dependent dissipation data.

(3) It was also shown that the c_h values evaluated from the CPTU methods agree well with the back-analyzed field values base on monitored settlement profiles. This indicates the usefulness of the CPT dissipation test for quick and reliable estimation of horizontal and vertical coefficients of consolidation parameters. For soil improvement projects of the soft Taihu lacustrine clay, the coefficient of consolidation determined by CPTU dissipation tests is recommended in engineering practice.

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