UNDRAINED SHEAR STRENGTH OF ARIAKE CLAY BY ELECTRONIC CONE PENETRATION TESTING

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ABSTRACT: Evaluation of undrained shear strength ($s_u$) of clay using laboratory tests usually faces serious problems due to large scatter caused by sample disturbance and different testing procedures. In this paper, the filtering equation which is expressed as function of the deformation modulus ($E_{50}$) and excess pore water pressure ($u_d$) is proposed as a simple equation and applied for 11 clay sites to drop the $s_u$ values those its soil are considered to be rather disturbed. The filtered selected $s_u$ values were compared to find fairly good agreement with the $s_u$ predicted by the electronic cone penetration testing data.

Keywords: Ariake clay, electronic cone factor, undrained shear strength, deformation modulus

INTRODUCTION

Electronic Cone Penetration Testing (ECPT) is an important ground investigation technique employed in many countries around the world for determining accurate stratigraphic profiles and providing a quantitative measure of soil properties.

The main purpose for pushing the electronic cone penetration into soft cohesive soils and silt deposits is to obtain data on the undrained shear strength ($s_u$).

The values of $s_u$, which are traditionally obtained from laboratory tests, usually include some erroneous values due to samples transportation, different testing procedure and the technique of determination of $s_u$ itself. In this research, filtering the samples from disturbed soil is needed.

A simple equation based on ECPT data was derived to clean the samples from disturbed soils. This equation was proposed to make the device more effective when we determine $s_u$ values based on ECPT data. The equation was derived using data from 11 Ariake sites clay, with depths ranging between 13 and 25 meters.

ELECTRONIC CONE PENETRATION TESTING RESULTS

Description of the Electronic Cone

The electronic cone (Fig. 1), used in this study, has an equal end area friction sleeve cone and an interchangeable tip to relocate the porous filter. The cone has a 60° apex angle, 10 cm² base area, 150 cm² friction sleeve $f_s$ and a conical tip with an end resistance $q_c$. A ceramic filter is located 0.2 cm above the conical tip. An electric cable usually connects the cone with the recording equipment at ground surface. The electronic

Fig. 1 A section elevation of the electronic cone

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cone offers obvious advantages such as rapid testing procedures, continuous recording, high accuracy and repeatability (Robertson et al., 1983). The device is pushed down into the ground at a rate of 1 cm/s, which is the rate used in standard procedures in Japan (JIS A 1220, 1976). This rate permits an averaging of 10 measurements for every 2 cm depth recorded in contrast to the rate of 2 cm/s specified in the European standard and also in the drafted international standard for cone penetration testing (De Beer et al. 1988). Konrad and Law (1987) indicated that tests, which were conducted at a standard rate of penetration, i.e., 2 cm/s, did not indicate any change in either cone resistance or pore water pressure profile when compared with the results obtained at a penetration of 1 cm/s.

Physical and Mechanical Properties of Ariake Clay Sites

Figures 2 (A–K) show some important physical and mechanical properties of Ariake clay sites. The tests are performed in Saga district (Saga sites from A to K).

The distribution of moisture content (w), liquid limit (w_l) and plastic limit (w_p) with penetration depth are almost similar in all clay sites. The change of wet density (ρ_w) is very small. Unconfined compressive strength (q_u) and preconsolidation pressure (P_c) increase proportional to the penetration depth while large scatter was noticed in the distribution of deformation modulus (E_{50}) especially at sites A, B and C.

A typical variation of compression index (Cc) with depth is noticed. It is ranging between 1 and 2 in most clay sites. Some values of Cc larger than 2 are noticed as shown in Figs2-B and F. Generally in this Figs., Cc decreases with depth.

Description of ECPT Profiles of Ariake Clay

The electronic cone penetration tests with controlled rate (1cm/s) of penetration have been carried out at 11 Ariake clay sites located in Saga district (Saga sites from A to K). The depths of these sites ranged from 13m at site G to about 25m at site K. The continuous electronic cone test profiles of Ariake clay are shown in Figs. 3-A–K, where they show the relationship between total cone tip resistance q_t, pore water pressure u and friction sleeve f_s with penetration depth D. The depth of the first three clay sites A, B and C ranged from 20 to about 21m, while the consequent seven clay sites from D to J had depths that ranged from 15 to about 17m. The depth of site K is about 25m.

Site D has a crust layer at the first 0.82m depth while site E has a crust layer at first 1.83m depth. These crust layers were considered when we calculated the overburden pressure (σ_v0) of the soil.

The profiles of the pore water pressure u of all sites are almost similar. In all clay sites, there is a general increase in q_t along with depth. There are sudden decreases in u in all sites especially in sites A, B and C, that suggests the presence of some thin sandy layers (the figures show a significant increase in q_t at these locations). Thus, the piezometer probe is considered an excellent device for detecting the thin sandy layers within clay deposit (Baligh et al., 1980).

Compared with sandy soils, clayey soils generally have low cone bearing and high friction ratios. However, the measurement of the friction sleeve is sometimes less accurate and less reliable than that cone of the resistance (Lunne et al., 1986). Thus, f_s values were too small to be compared with u and q_t so, the data of f_s did not use in this paper.

In this research, using of the excess pore water pressure u_d gave good results better than using the recorded pore water pressure u where u_d is determined by the following equation:

\[ u_d = u - u_s \]  

where u_s is the static water pressure.

The relationship between (q_t / u_d) and u_d for all data (clay and sand) is shown in Fig. 4 and represented by the following equation:

\[ \frac{q_t}{u_d} = a + \left( \frac{b}{u_d} \right)^2 \]  

where \( a = 2.4 \) and \( b = 20-40 \) i.e. b is equal 10 a.

In this figure, all data are checked, we found that the clay soil gathered as a curve and the scatter data around this curve represent sandy soils. Deleting the sandy data and reploting the figure again as shown in Fig. 5 where the clayey soil are bounded by Eq. (2) where the constant a is equal 2 and 4.

Multiplying Eq. (2) by \( u_d^2 \), we obtain

\[ q_t \cdot u_d = a u_d^2 + b^2 \]  

\[ q_t \cdot u_d = a \left( u_d^2 + 100a \right) \]  

To make Eq. (4) simpler it is rewritten in the form of:

\[ y = ax^2 + \left( 10a \right)^2 \]
Fig. 2A-D Physical and mechanical properties of Ariake clay with penetration depth.
Fig. 2 E–H  Physical and mechanical properties of Ariake clay with penetration depth
Fig. 2-I-K  Physical and mechanical properties of Ariake clay with penetration depth
where the constant \( a = 2 \) for the lowest case and 4 for the highest case (Figs. 6 A–K).

As we notice in these figures most data are located in the area, delimited by the curves of Eq. (5).

**DISCUSSION OF THE RESULTS**

**Prediction of the Undrained Shear Strength**

Interpretation of soil strength from ECPT is dependent on drainage conditions. Generally undrained shear strength \( s_u \) is determined from undrained penetration.

Comprehensive reviews of \( s_u \) evaluation from cone penetration testing data have been presented by Baligh et al. (1980), Lunne and Kleven (1981), Jamiołkowski et al., (1980) and Robertson et al., (1986). Unfortunately the evaluation is complicated by the fact that \( s_u \) is not a unique parameter and depends on type of test, rate of strain and orientation of the failure planes (Worth, 1984). As a result, CPT data is generally interpreted based on empirical or approximate theoretical solutions (Campanella and Robertson 1988).

The undrained shear strength is derived by dividing the net cone resistance \( (q_t - \sigma_{vo}) \) by a cone factor \( (N_{kt}) \) using the following bearing capacity equation:

\[
s_u = \frac{q_t - \sigma_{vo}}{N_{kt}}
\]  

(6)

where \( q_t \) is the total cone tip resistance and \( \sigma_{vo} \) is the overburden pressure.

According to Rashwan et al. (2005), the value of electronic cone factor \( N_{kt} \) was theoretically proposed as 11 depending on a semi-empirical analysis. The value of 11 is used to predict safely the values of \( s_u \) in Ariake clay so that:

\[
s_u = \frac{q_t - \sigma_{so}}{11}
\]  

(7)

In order to check the applicability of \( N_{kt} \) value of 11, the predicted \( s_u \) profiles, which were obtained from the electronic cone penetration testing results using \( N_{kt} \) value of 11 and \( s_u \) values which were measured by unconfined compression test \( (s_u \) is the half value of the unconfined compressive strength \( q_u \) at failure), are shown in Figs. 7-A–K. These figures show the measured values of \( s_u \) which are represented by the open circles, while the predicted \( s_u \) values are represented by the continuous solid line. The values of \( s_u \) which are far from the continuous line suppose to be erroneous values of \( s_u \), while the values, which lay on’or very near from the line, are considered right \( s_u \). There are some scattering values especially at sites A, B, E, and J due to different procedures, various types of laboratory tests and samples disturbance.

**Filtering of Undisturbance Clay**

The deformation modulus \( (E_{50}) \) is the slope of the initial part of the unconfined compression-shear strain curve. It is defined by the following equation:

\[
E_{50} = \frac{q_u}{2 \epsilon_{50}}
\]  

(8)

where: \( q_u \) is the unconfined compressive strength and \( \epsilon_{50} \) is the vertical shear strain defined at \( q_u / 2 \).

Basically \( E_{50} \) can be used to check the disturbance of strength of clay, the excess pore water pressure as it is considered as a reflector of the structure of the clay. In this paper, \( E_{50} \) was used with \( u_d \) to check the disturbance of strength of clay.

The excess pore water pressure is proportional to porosity \( (n_0) \) (Rashwan et al., 2005) so that:

\[
n_0 = \exp(4.367 - 0.000732 u_d)
\]  

(9)

Also \( E_{50} \) is proportional to \( n_0 \) (Rashwan and Konmoto, 2005) so that:

\[
n_0 = 4.360 - 0.0000488 E_{50}
\]  

(10)

Equations 9 and 10 were obtained by least square method using cone penetration and laboratory data. By solving Eqs. (9) and (10) simultaneously, the following equation can be obtained:

\[
E_{50} = 15.00 u_d - 143.44
\]  

(11)

The constant in Eq. (11) is too small compared with \( E_{50} \) values. In order to make this equation more simple we neglected the constant so that:

\[
E_{50} = 15 u_d
\]  

(12)

Equation (12) is represented by a straight line in Figs. 8-A–K. In these figures, most of erroneous soil values are located under the straight line (are shown by opened circles), while most of undisturbed soil values are
Fig. 3 A–K  Electronic cone penetration test results in Ariake clay
(s_u) of Ariake clay by using electronic cone penetration testing data.

Filtering equation (Eq. 12) is a simple equation which was derived to classify disturbed and undisturbed soils and to remove the disturbed soil when evaluating the values of s_u. Selected s_u were compared to find fairly good agreement with the s_u values predicted by the electronic cone penetration testing data with an error of about ±20%.

Fig. 4 The relationship between u_d and q_i / u_d before neglecting sandy soil

Fig. 5 The relationship between u_d and q_i / u_d after neglecting sandy soil

located above the straight line. Thus, equation (12) can be used to filtrate the samples from disturbed soil.

By selecting the undisturbed points (the points which touch or are very close to the continuous line in Figs. 7-A–K) and redrawing the figures again, as shown in Figs. 9-A–K. The selected s_u in Figs. 9-A–K were compared with predicted s_u obtained from ECPT data by using equation (2), the error was about ±20%. The error was calculated depending on the total number of points before selecting the undisturbed s_u and the number of points remaining after selecting the undisturbed s_u.

CONCLUSIONS

In this paper, a value of electronic cone factor (N_C) of 11 was used to predict the undrained shear strength
Fig. 6 A–K The relationship between effective pore water pressure and \( q_r - u_d \)
Fig. 7  A–K  Predicted $s_u$ from electronic cone results and measured $s_u$ by unconfined compression test
Fig. 8 A–K Relationship between pore water pressure and deformation modulus of Ariake clay
Fig. 9 A–K  Comparison between predicted $s_u$ from electronic cone results and selected $s_u$ by unconfined compression test.
REFERENCES


