

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.

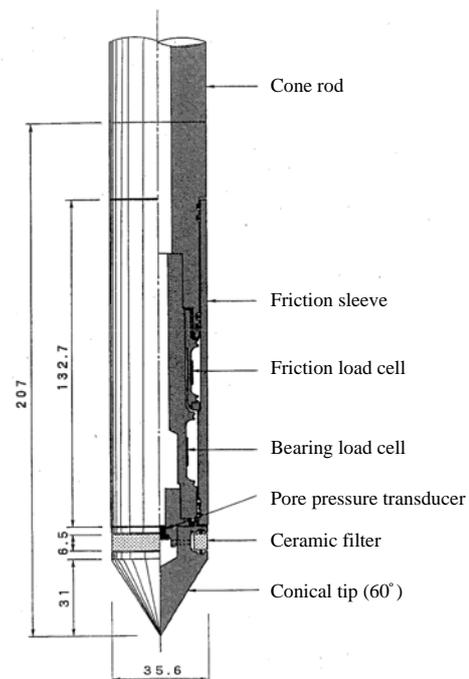
A simple equation based on ECPT data was derived to clean the samples from disturbed soils. This equation was proposed to make the device more effective when we determine s_u values based on ECPT data. The equation was derived using data from 11 Ariake sites clay, with depths ranging between 13 and 25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



(Dimension in mm)

Fig. 1 A section elevation of the electronic cone

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Note: Discussion on this paper is open until December 31, 2007

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 procedure 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_n), 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_t) 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 and u 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:

$$u_d = u - u_s \quad (1)$$

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:

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

where $a = 2 \sim 4$ and $b = 20 \sim 40$ i.e. b is equal $10a$.

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 replotting 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

$$q_t \cdot u_d = a u_d^2 + b^2 \quad (3)$$

$$q_t \cdot u_d = a (u_d^2 + 100a) \quad (4)$$

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

$$y = ax^2 + (10a)^2 \quad (5)$$

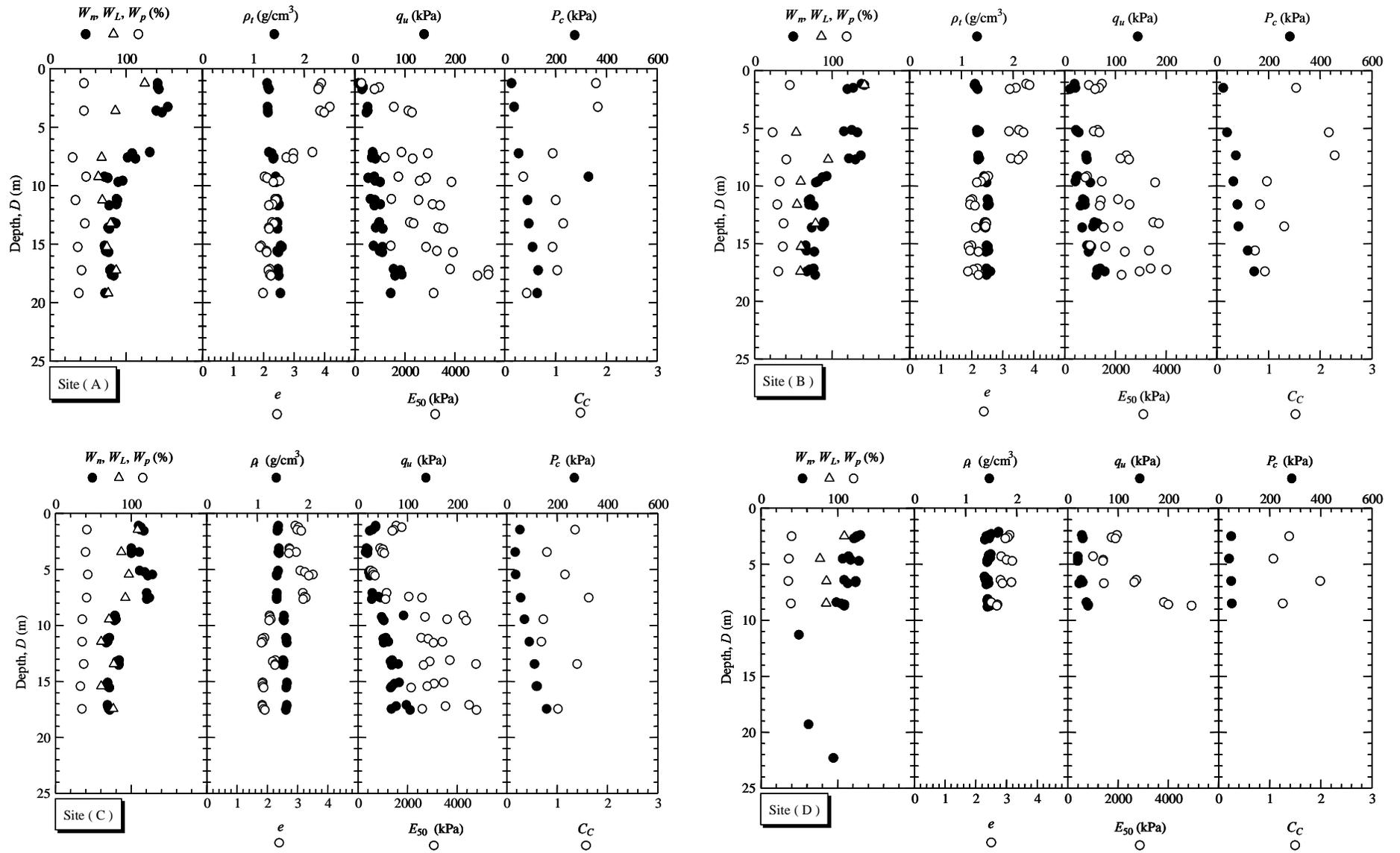


Fig. 2 A~D Physical and mechanical properties of Ariake clay with penetration depth

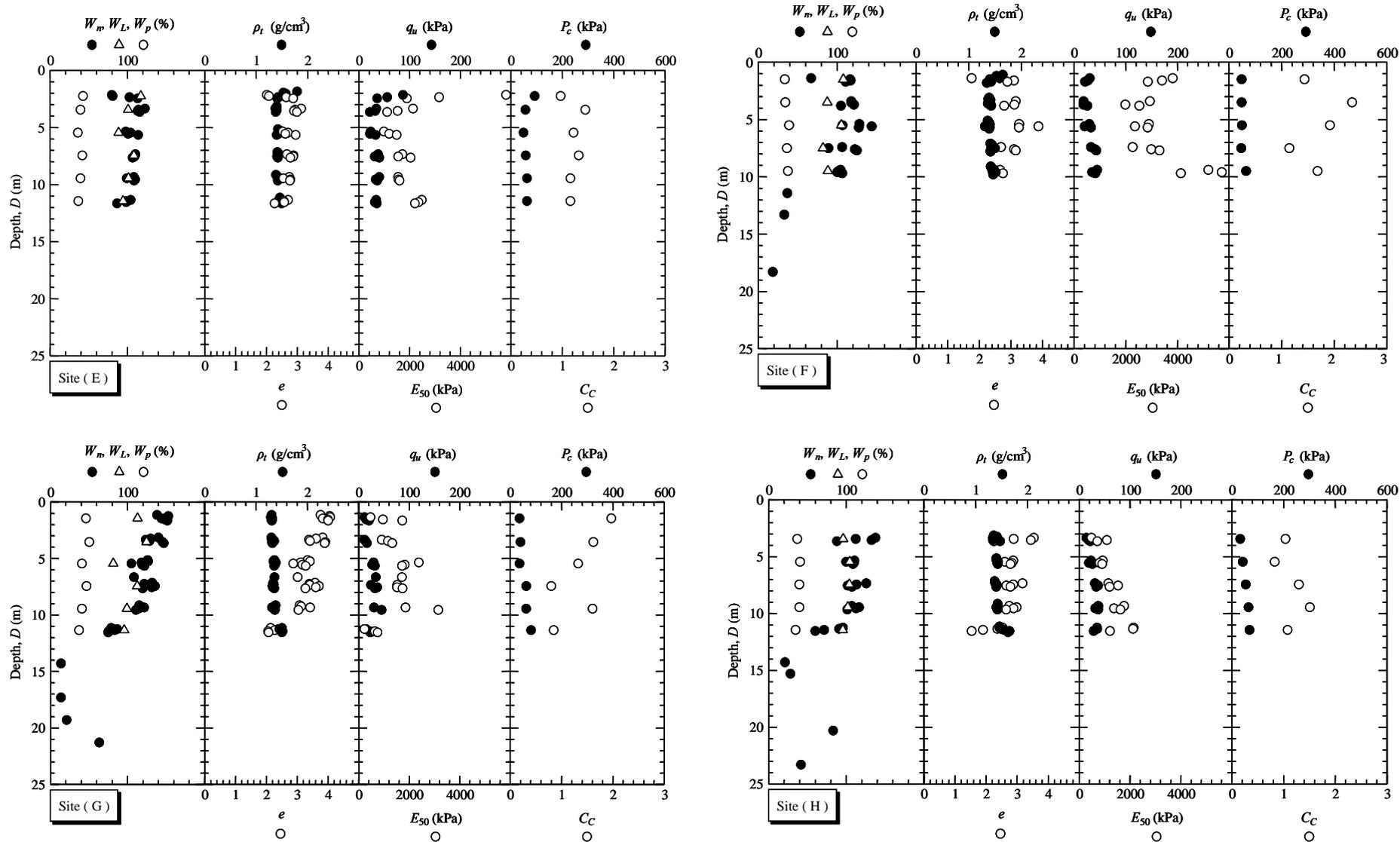


Fig. 2 E~H Physical and mechanical properties of Ariake clay with penetration depth

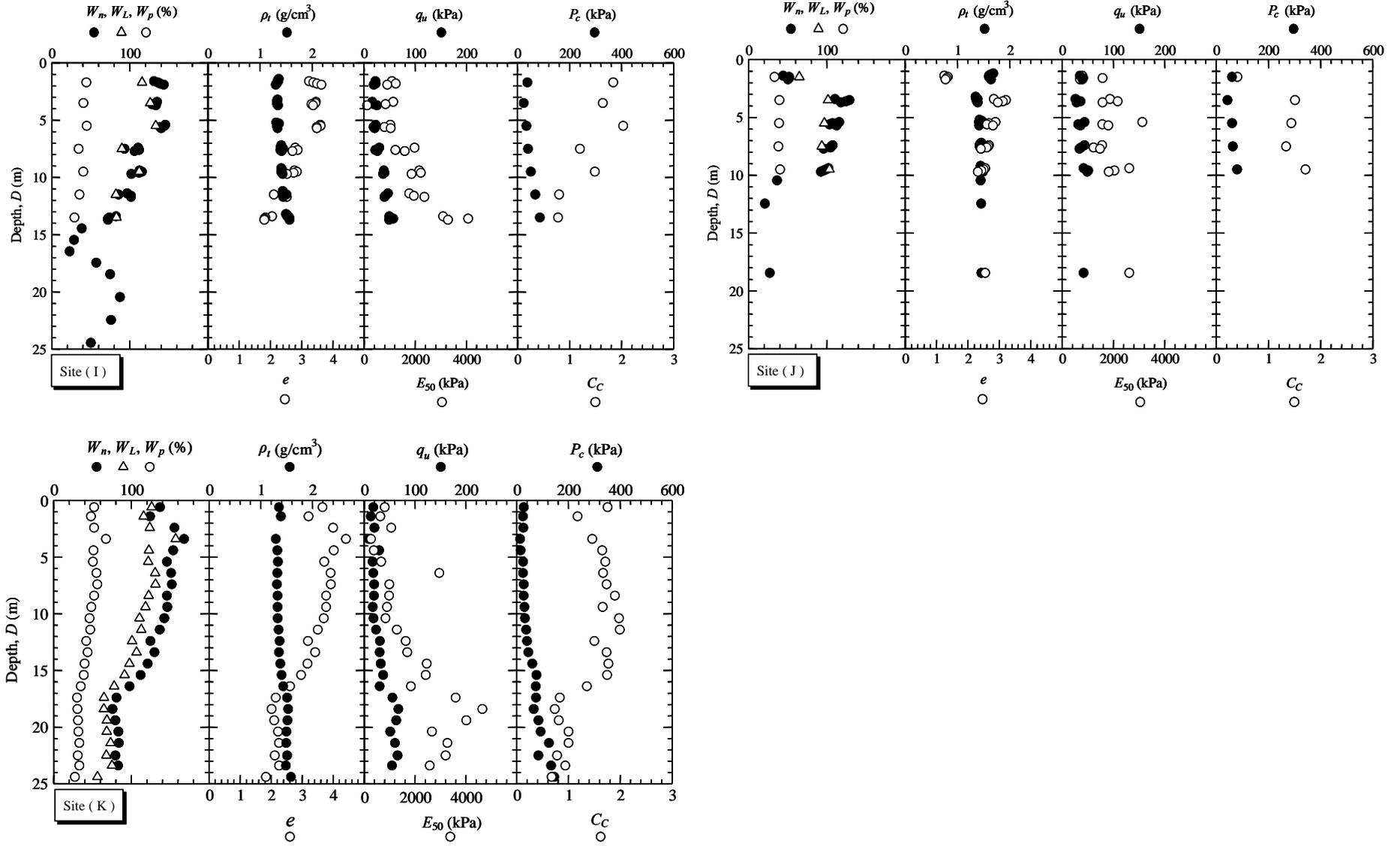


Fig. 2-I~K Physical and mechanical properties of Ariake clay with penetration depth

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), Jamiolkowski 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 ($q_t - \sigma_{v0}$) by a cone factor (N_{kt}) using the following bearing capacity equation:

$$s_u = \frac{q_t - \sigma_{v0}}{N_{kt}} \quad (6)$$

where q_t is the total cone tip resistance and σ_{v0} 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:

$$s_u = \frac{q_t - \sigma_{v0}}{11} \quad (7)$$

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:

$$E_{50} = \frac{q_u}{\varepsilon_{50}} \quad (8)$$

where: q_u is the unconfined compressive strength and ε_{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:

$$n_0 = \exp(4.367 - 0.000732 u_d) \quad (9)$$

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

$$n_0 = \exp(4.360 - 0.0000488 E_{50}) \quad (10)$$

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:

$$E_{50} = 15.00 u_d - 143.44 \quad (11)$$

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:

$$E_{50} = 15 u_d \quad (12)$$

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

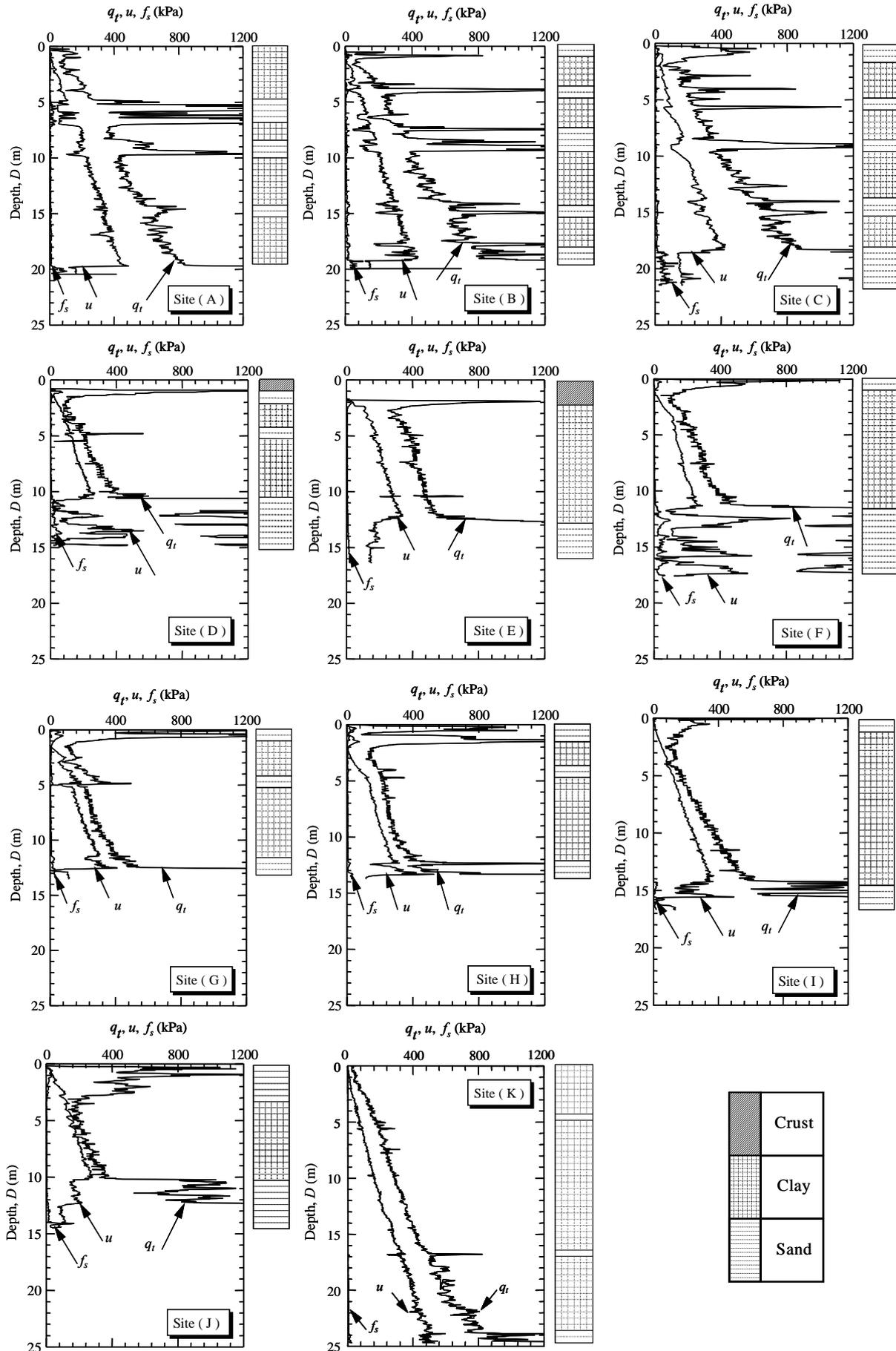


Fig. 3 A~K Electronic cone penetration test results in Ariake clay

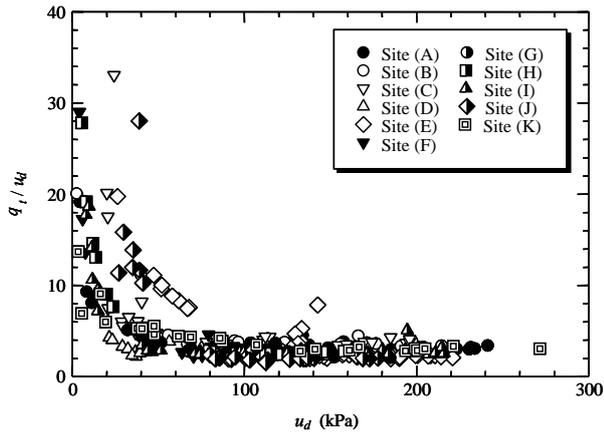


Fig. 4 The relationship between u_d and q_t / u_d before neglecting sandy soil

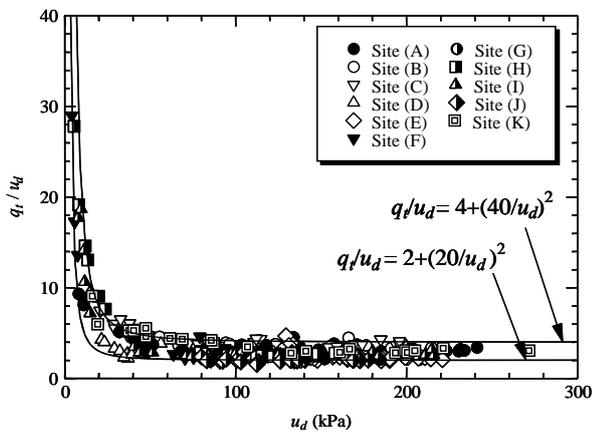


Fig. 5 The relationship between u_d and q_t / u_d after neglecting sandy soil

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 $\pm 20\%$. 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_{kt}) of 11 was used to predict the undrained shear strength

(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 $\pm 20\%$.

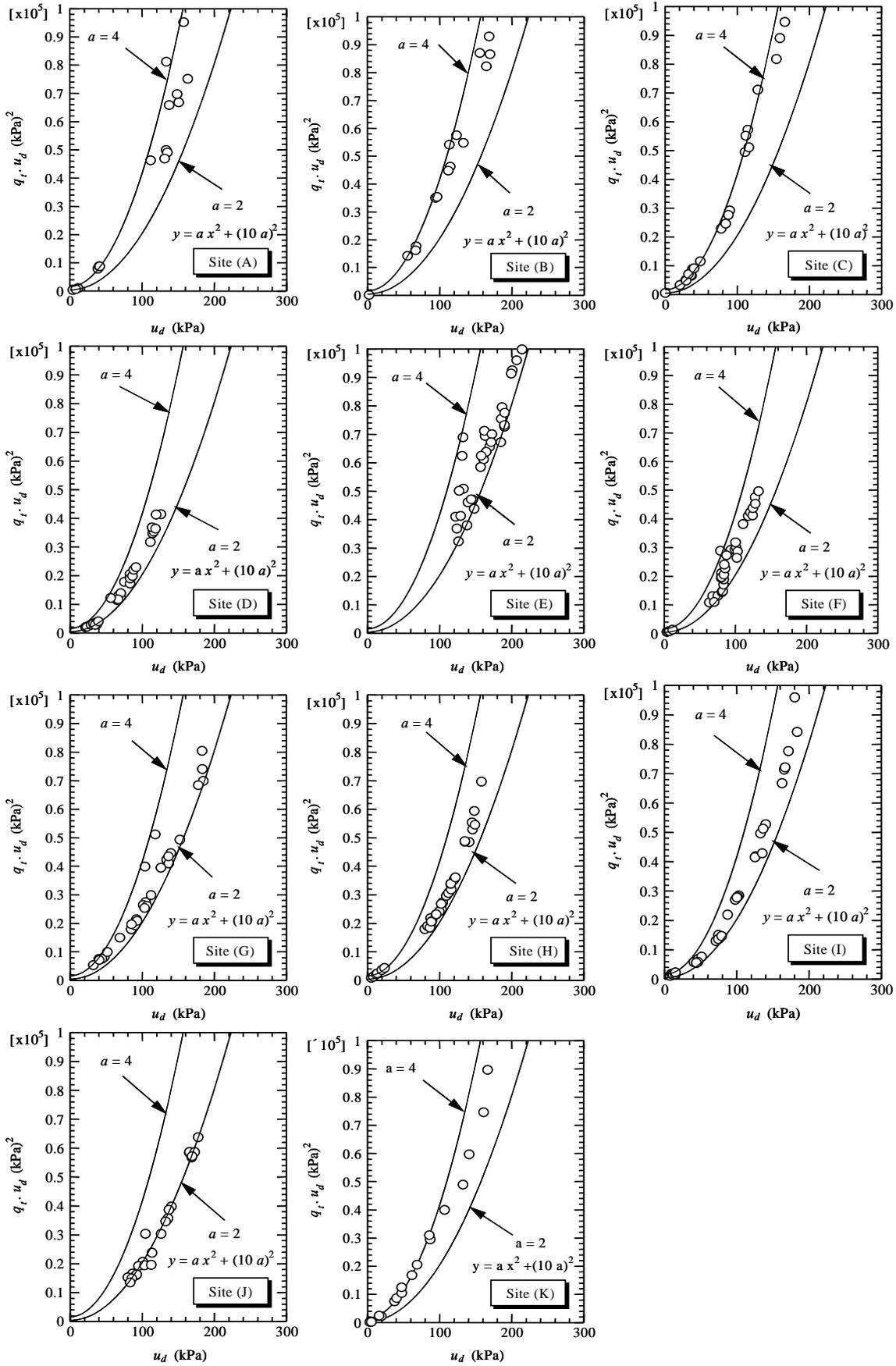


Fig. 6 A~K The relationship between effective pore water pressure and $(q_t \cdot u_d)$

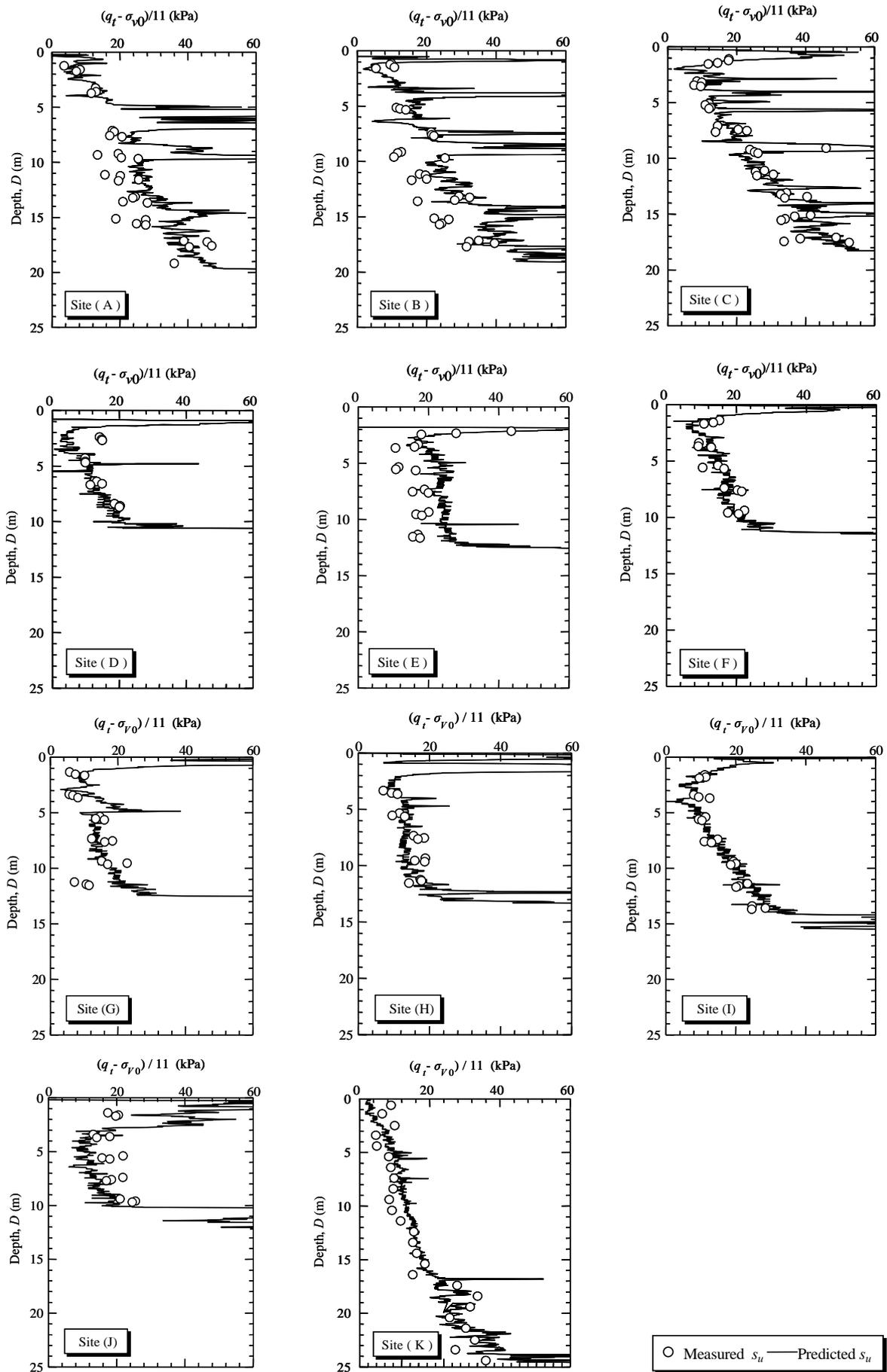


Fig. 7 A-K Predicted s_u from electronic cone results and measured s_u by unconfined compression test

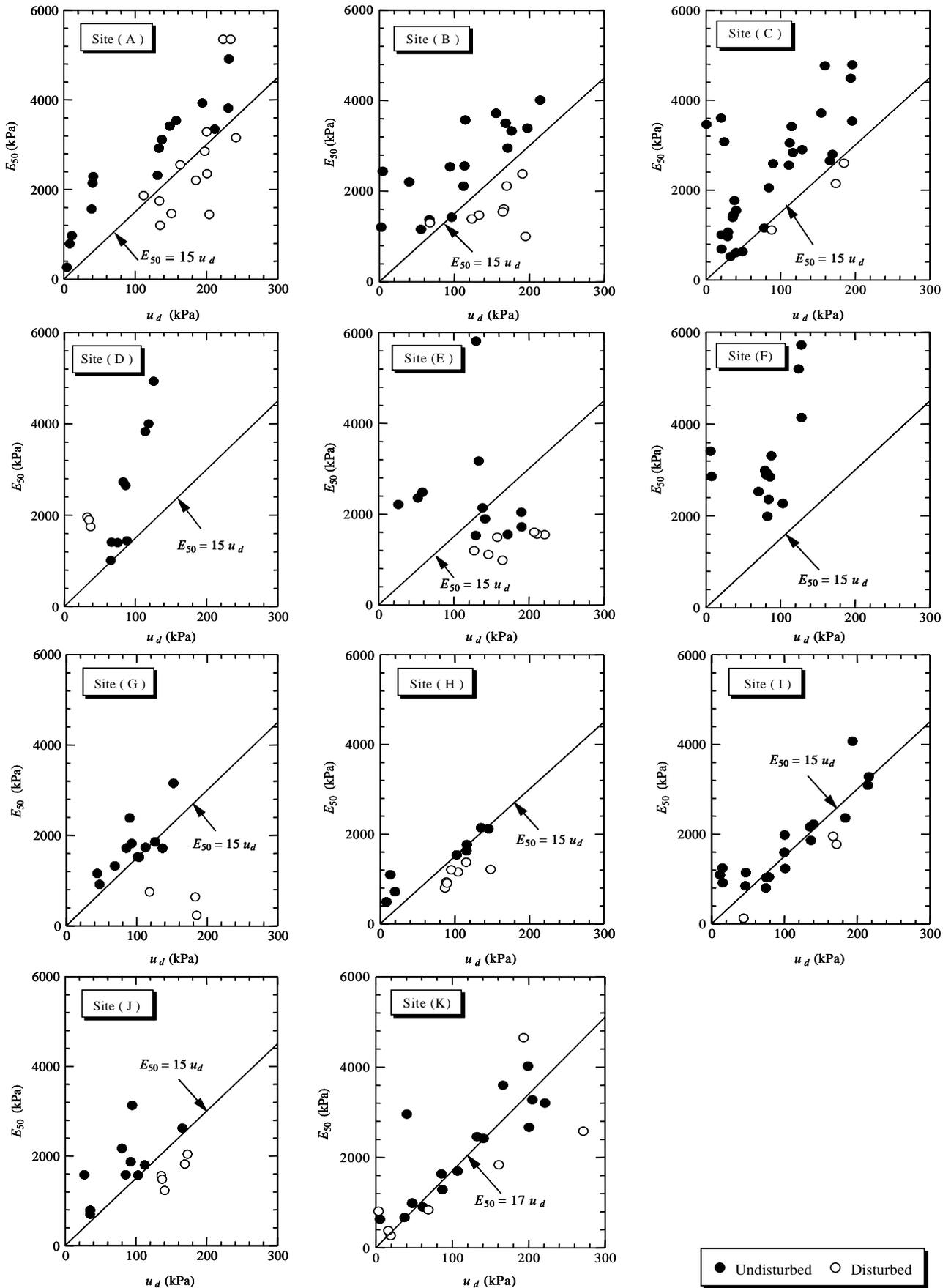


Fig. 8 A~K Relationship between pore water pressure and deformation modulus of Ariake clay

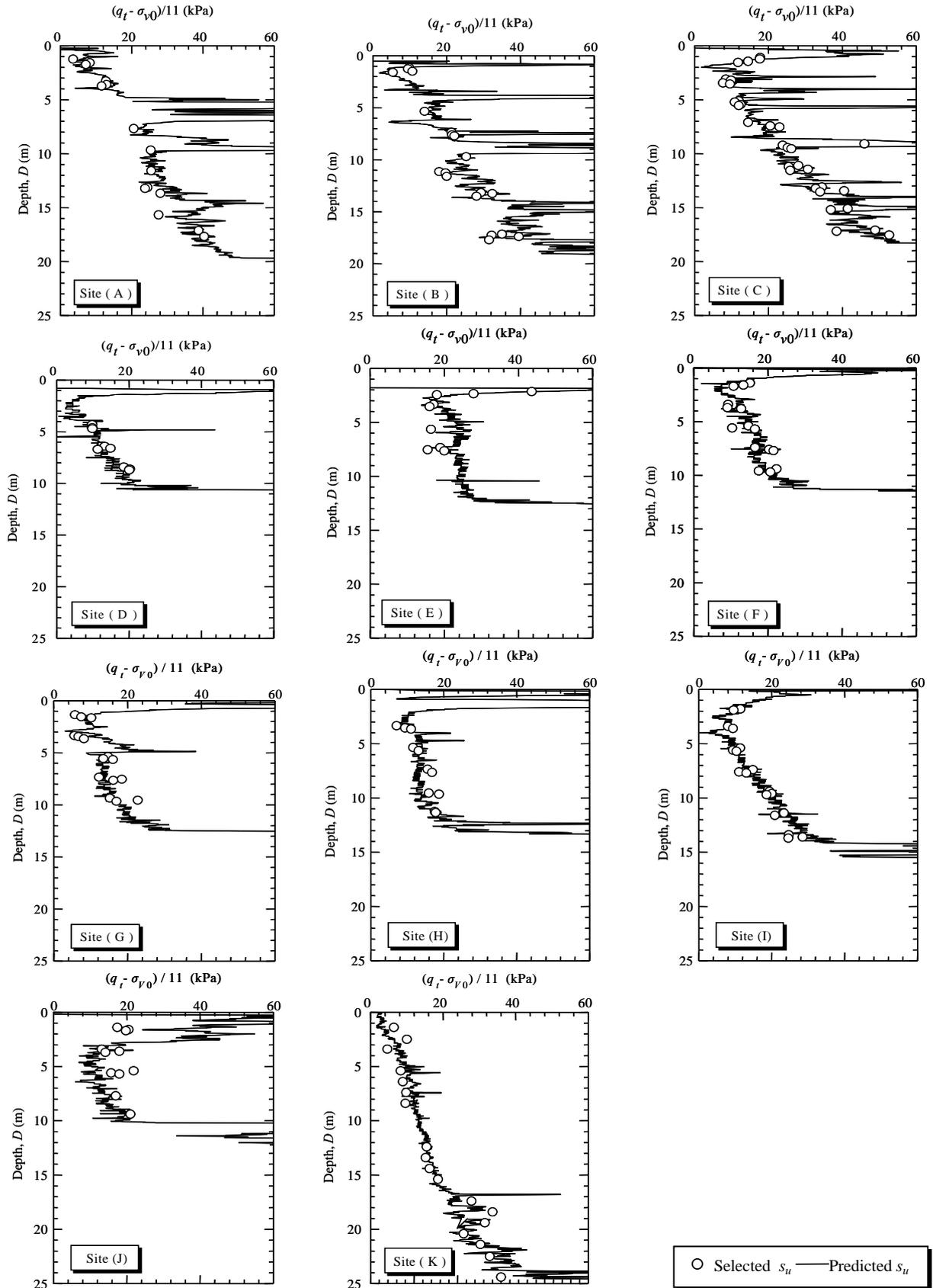


Fig. 9 A~K Comparison between predicted s_u from electronic cone results and selected s_u by unconfined compression test

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