SOILS AND FOUNDATIONS Vol. 35, No. 2, 37-47, June 1995
Japanese Society of Soil Mechanics and Foundation Engineering

DEVELOPMENT OF CENTRIFUGE CONE PENETRATION TEST TO EVALUATE THE UNDRAINED SHEAR STRENGTH PROFILE OF A MODEL CLAY BED

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ABSTRACT

Physical modeling utilizing a centrifuge is often attempted in order to investigate short-term stability problems of soft clay deposits whose undrained shear strength generally varies with depth. Since accurate evaluation of the strength profile in model beds is essential for such studies, a cone penetration test (CPT) technique in the centrifuge has been developed to obtain geotechnical information continuously with depth. A series of CPTs in homogeneous clay beds was conducted in order to establish the correlation between cone resistance q_c and undrained shear strength c_u. This empirical relationship can take account of the influences of penetration rate, stress level and the error associated with the stress acting on the rear of the cone tip. In the end, this CPT technique in the centrifuge has proved itself to be useful in evaluating the undrained shear strength profile in non-homogeneous clay beds.

Key words: centrifuge, clay, cone penetration test, model test, soft ground, undrained shear strength **(IGC:** D6/E14)

INTRODUCTION

Physical modeling utilizing a centrifuge is often attempted to investigate short-term stability problems of soft clay deposits (e.g. Davies and Parry, 1985). In order to interpret the test results, an accurate evaluation of the strength profile in the model bed is essential. As pointed out by Davies and Parry (1982), when relatively permeable soils are used, it is vital to measure the correct strengths of the clay beds during centrifuge flight. Moreover, since undrained shear strength of soft normally- or lightly over-consolidated clay generally varies with depth, complete strength profiles could preferably be obtained by continuous measurements with depth. With this in view, small cone penetrometer devices have been developed to evaluate strength profiles in non-homogeneous clay beds during centrifuge operation.

In the beginning, the penetrometer probes were calibrated not only under dead weight but also under all around water pressure applied to the cone tip. The latter calibration tests were carried out to examine the influence of the seal filling the opening behind the cone tip. The recorded apparent cone resistance q_c was observed to be smaller than the applied all around pressure p_o because of the stress acting at the back of the cone base. This stress, besides, was found to be less than p_o due to the compressibility of the sealing material.

A series of CPTs was conducted in homogeneous clay beds with the aim of establishing a correlation between cone resistance q_c and undrained shear strength c_u. In this experimental program, the effects of penetration rate and stress level were investigated, and an empirical relationship between q_c and c_u which can effectively take into account the error associated with the stress acting on the rear of the cone tip has been derived.

Cone Penetration Test (CPT)

The cone penetration test (CPT) has attracted increasing attention as a well-established site investigation technique especially offshore in accordance with recent developments in electronics (De Ruiter, 1982). The CPT is regarded as an in-situ strength test, which has several advantages over laboratory tests on undisturbed samples (Jamiolkowski et al., 1985) and is useful in centrifuge model work. Firstly, relatively simple operation of the CPT facilitates the introduction of this technique in the centrifuge. Secondly, extremely low shear strength ($c_u<20$ kPa) of soft clay prohibits sampling for alternative laboratory strength tests. Thirdly and above all, the continuous nature of CPT data is of great importance for model studies investigating the influence of variation of shear strength with depth on stability problems.

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Manuscript was received for review on May 24, 1994.
Written discussions on this paper should be submitted before January 1, 1996 to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

Comprehensive reviews of CPT interpretation methods may be found in Robertson and Campanella (1983), Wroth (1984) and Meigh (1987). Some of the important research results for CPT used in soft clays are discussed herein, focusing on the correlation between cone data and undrained shear strength.

Cone resistance q_c is usually related to undrained shear strength c_u of clay by the following equation similar to the bearing capacity formula;

$$q_c = c_u \cdot N_k + \sigma_{vo} \tag{1}$$

where σ_{vo} is the total overburden stress and N_k is the empirical cone factor, typical values of which are reported to vary between $10 \sim 20$ for normally-consolidated and $15 \sim 25$ for over-consolidated clays (Jamiolkowski et al., 1982; Konrad and Law, 1987).

Recent development of the piezocone test with pore pressure measurement (CPTU) has necessitated a re-examination of cone data. Correction of measured q_c to allow for pore pressure u acting on the exposed surface behind the cone tip was suggested (Fig. 1, Robertson and Campanella (1983));

$$q_c(\text{corrected}) = q_c(\text{measured}) + u \cdot (1-a) \tag{2}$$

where a is the net area ratio $(=A_R/A_c)$. The importance of this correction, especially for soft clays of low q_c and high u, was shown to reduce the systematic errors incorporated in the relationship of Eq. (1) (Lunne et al., 1986).

CPT in the Centrifuge

It should be noted that the CPT in the centrifuge will not strictly represent the CPT in the field because it is unrealistic to employ an extremely small scaled down cone in a high centrifuge acceleration.

For several years, miniature penetration probes used in the centrifuge have been investigated at Cambridge University including cone penetrometers and a piezocone (Almeida and Parry, 1985; Phillips and Valsangkar, 1987). They were developed in order to determine the soil parameters during centrifuge flight, because highly permeable clay such as kaolin gives different measured strengths during flight and after stopping the centrifuge (Davies and Parry, 1982). N_k values obtained at 100 g using c_u measured by the centrifuge vane test decreased with depth from 9.2 down to, surprisingly, negative values (Almeida and Parry, 1983). But with correction of Eq. (2) using an empirical relationship $u = u_o + 0.67 \cdot q_c(\text{corrected})$ (u_o: hydrostatic pressure), N_k values were found to lie between 8.3 and 17.5.

MINIATURE CONE PENETROMETER

The CPT under high acceleration field in a centrifuge requires special consideration with regard to the design of the cone penetrometer and its operational technique. Reliable measurement of cone resistance q_c continuously with depth is a paramount prerequisite, however, all elements of the equipment must be designed not only to be sturdy but as light as possible as well.

In non-homogeneous beds, the cone has to be sufficiently small to guarantee that the measured q_c at a certain depth will represent the shear strength of that particular point without being affected significantly by adjacent layers. At the same time, however, because of the very soft nature of the material, the cone area A_c must be large enough to ensure high sensitivity of measurement.

Figure 2 shows the structural cross-section of a cone penetrometer (cone diameter $D_c = 10$ mm) manufactured out of stainless steel. It comprises two load cells positioned on top, to be kept above the soil at all times, a shaft sleeve and an inner rod with a cone tip at the end. The opening of 1 mm between the cone shoulder and the

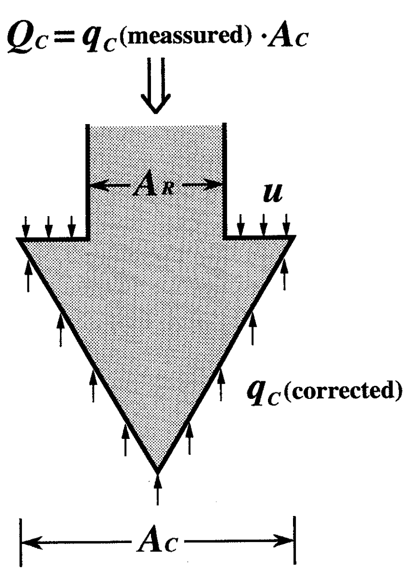


Fig. 1. Influence of pore water pressure behind the cone tip

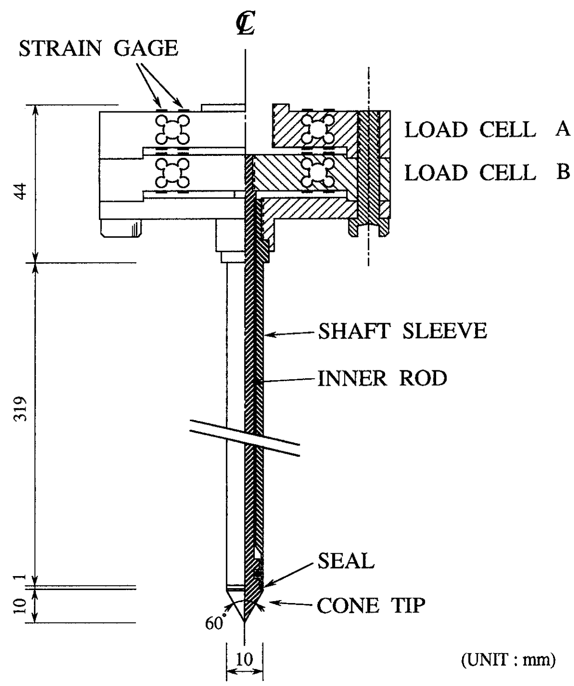


Fig. 2. Miniature cone penetrometer

end of the shaft sleeve is filled with silicone sealant to prevent the entry of soil particles and/or water into the penetrometer tip.

Load cell B measures total cone resistance force Q_c transmitted through the inner rod, while load cell A measures total cone penetration force Q_t including sleeve friction force Q_s. These load cells have sections of reduced rigidity where eight active strain gauges are attached to form a Wheatstone bridge.

CALIBRATION TEST

As suggested earlier by Eq. (2), careful consideration of the stresses acting on the rear of the cone tip is essential for accurate q_c measurement. Calibration tests were therefore conducted to investigate the influence of the seal filling the opening behind the cone tip.

As shown in Fig. 3, ambient pressure p_o was applied around the cone of two penetrometers (No. 1 and 2) of the same design in the chamber for both the cases with and without seal in the opening behind the cone tip. Figure 4 shows the test results demonstrating a completely linear response of measured cone resistance $q_c(=Q_c/A_c)$ to the applied water pressure p_o.

When there is no seal in the opening, provided that the greased O-ring does not transmit any significant amount of load to the shaft sleeve (Nyirenda and Sills, 1988), the condition of equilibrium is as follows (Fig. 5);

$$p_o \cdot A_c = Q_c + p_o \cdot (A_c - A_2) \tag{3}$$

considering $Q_c = q_c \cdot A_c$;

$$\frac{q_c}{p_o} = \frac{A_2}{A_c} = a_2 \tag{4}$$

Since the area ratio $a_2(=A_2/A_c)$ is 0.74 by geometry, almost identical values of q_c/p_o (=0.74 and 0.75) obtained from this calibration test confirm the validity of the above equilibrium consideration.

When there is a seal in the opening, similar consideration of equilibrium results in the following equation;

$$p_o \cdot A_c = Q_c + p_{rc} \cdot (A_c - A_1) \tag{5}$$

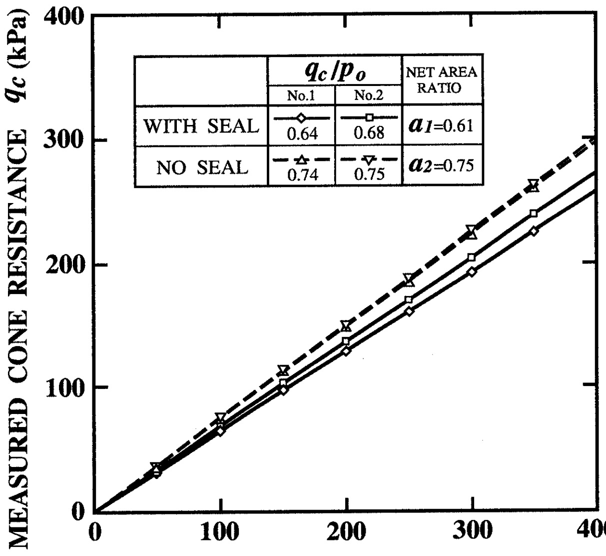


Fig. 4. Result of calibration test

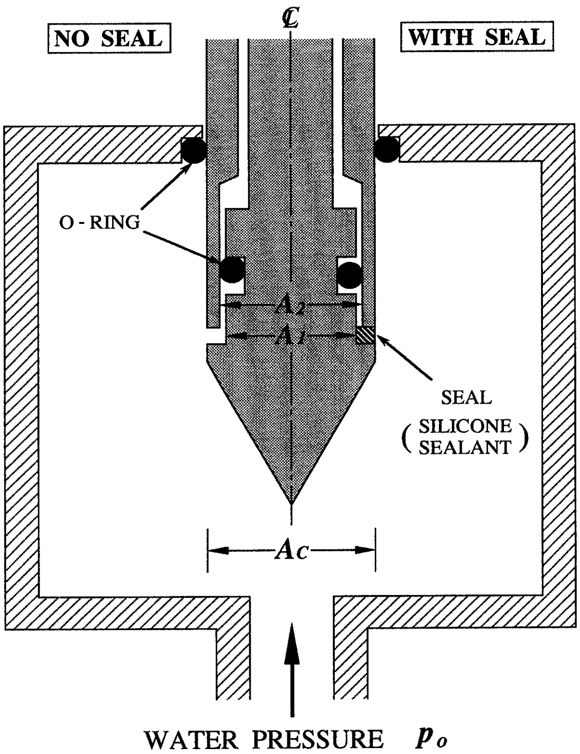


Fig. 3. Calibration test

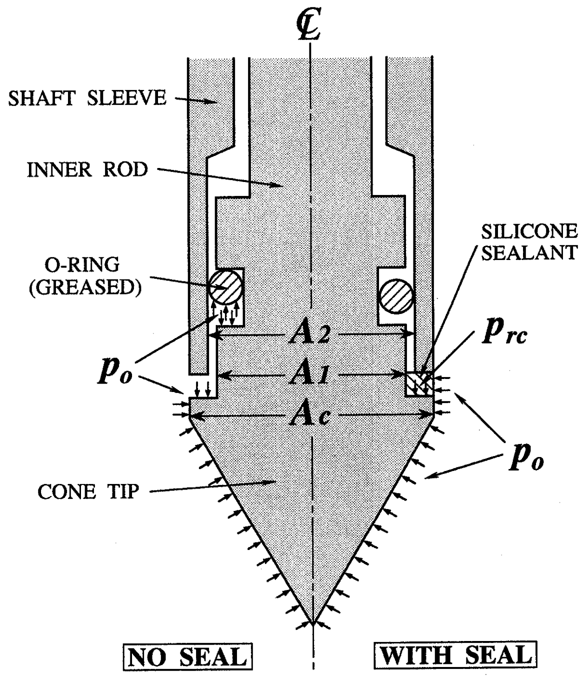


Fig. 5. Pressures around the cone tip

where p_{rc} denotes the average normal stress acting on the rear of the cone (Fig. 5). Considering $Q_c=q_c\cdot A_c$, Eq. (5) becomes;

$$\frac{p_{rc}}{p_o}=\left(1-\frac{q_c}{p_o}\right)\bigg/\left(1-\frac{A_1}{A_c}\right) \tag{6}$$

With the measured values of q_c/p_o (0.64 and 0.68) and the net area ratio $a_1(=A_1/A_c=0.61)$ by geometry, the ratio (p_{rc}/p_o) is calculated to be 0.92 and 0.82. This implies that the stress p_{rc} acting on the back of the cone tip is not identical to the applied water pressure p_o but to a reduced amount by some $8\sim18\%$.

According to simple elasticity theory assuming an axisymmetrical plane strain mode of deformation, this ratio (p_{rc}/p_o) is calculated to be;

$$\frac{p_{rc}}{p_o}=\frac{2\nu}{(1-2\nu)\cdot(A_l/A_c)^{1/2}+1} \tag{7}$$

where ν is the Poisson's ratio of the sealing material. The values of ν back calculated from the results of the calibration test using Eq. (7) are found to be 0.48 and 0.45, which is not very different from the expected range $0.46\sim0.49$ for elastic rubber. The discrepancy may be attributed to over-simplification of the plane strain assumption in this simple analysis. Nevertheless, Eq. (7) clearly demonstrates the effect of the compressibility of the sealing material on the stress p_{rc} acting behind the cone.

It should be noted that the stresses mobilized on the side of the seal can not be known exactly during actual CPTs; it is thereby impossible to evaluate the true cone resistance using a correction similar to Eq. (2). This rather pessimistic conclusion has never been pointed out before. The only exception is when just the cone tip has penetrated into clay while the rear of the cone is still above the surface, during which the stress on the side of the seal is definitely known to be either atmospheric pressure in the air or hydrostatic pressure in the water depending on the particular situation.

CONE PENETRATION TEST (CPT)

The clay used in this study was a remolded glacial clay till, with a plasticity index I_p of 23, taken from the Cowden site, North Humberside around the North Sea. Since the clay fraction F_c of 32% is characteristically high, consolidation takes place rather slowly; coefficient of consolidation c_v is typically found to be around 1 m^2/yr under a stress of 200 kPa.

Experimental Procedure

Four clay beds were prepared in circular Rowe cells with an internal diameter of 500 mm and 380 mm deep (Rowe and Barden, 1966). After several months of consolidation under specific consolidation pressures p_c in the laboratory, these clay beds were placed in the centrifuge strong box with a reaction frame and a loading bridge (Fig. 6).

The geotechnical centrifuge at the Univ. of Manchester with a radius of 3.2 m to a face plate is capable of accelerating a 3500 kg model package to about 130 g (Craig and Rowe, 1981). While 1 g tests were carried out in the horizontal position, as this centrifuge is not a swinging platform type, the strong box had to be rotated 90° into the vertical position for centrifuge tests conducted at vari-

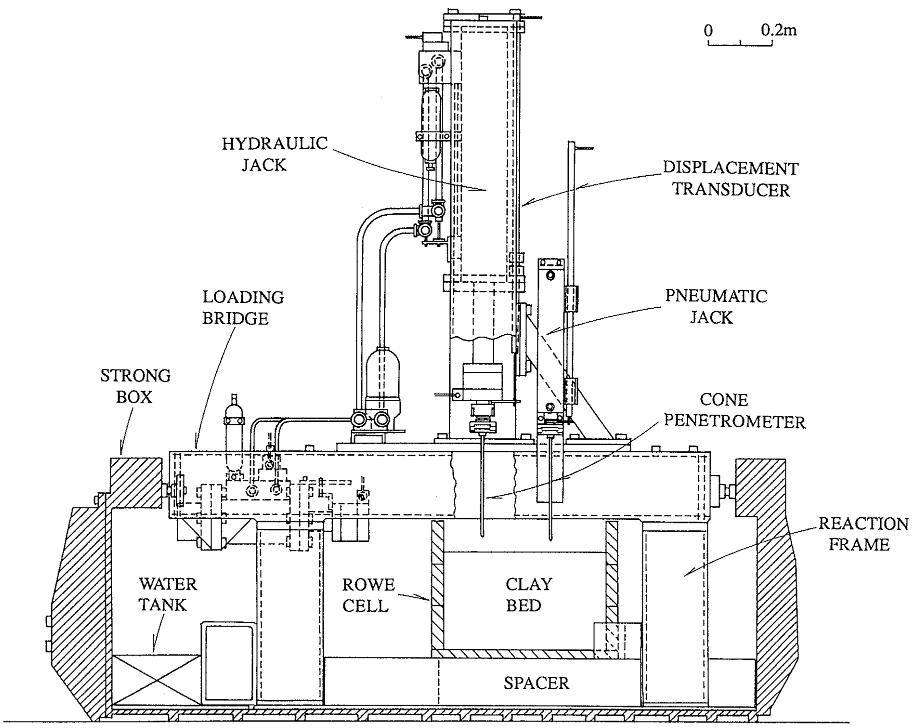


Fig. 6. Experimental setup in the centrifuge strong box

ous acceleration levels (45, 80 and 100 g). In order to cover the clay surface with water to prevent desiccation during a centrifuge run, water stored in the tank was pumped inside the cell at 30 g.

CPTs were operated by means of either a hydraulic or pneumatic system mounted on the loading bridge. When CPT was conducted using the servo-controlled hydraulic jack, a constant rate of penetration was maintained throughout the complete penetration depth. Whereas using the pneumatic jack, the cone penetrometer was held above the soil surface by compressed air until the desired acceleration level was reached. By reducing this air pressure slowly, the cone was subsequently allowed to fall into the clay bed due to its increased self-weight in the centrifuge test; thus the penetration rate could not be controlled and was found to be relatively fast (20 ~ 120 mm/sec) with moderate change during the course of penetration.

After completion of six CPTs in each clay bed, laboratory vane tests using a Pilcon hand vane (19 mm dia., 28 mm high) were conducted. The measured undrained shear strength s_u was determined conforming to BS1377 (Serota and Jangle, 1972), and correlated empirically to the reference undrained shear strength c_u from a triaxial compression test using the following equation (Tani, 1990).

$$s_u = 1.07 \cdot c_u \tag{8}$$

In addition, water content measurements and unconsolidated undrained (UU) triaxial compression tests were also carried out; those test results are shown in Table 1.

Analysis of CPT Data

Figure 7 shows typical original time records from two load cells and a displacement transducer measured in centrifuge CPT. Since the load cells move during the test, careful consideration is required for the analysis. The measured load records are accordingly affected twofold, inertia effect and centrifugal acceleration field.

On the one hand, the influence of inertia is found to be of negligible amount 0.06N with respect to Q_c measurement, for an effective mass $m = 0.13$ kg and a maximum

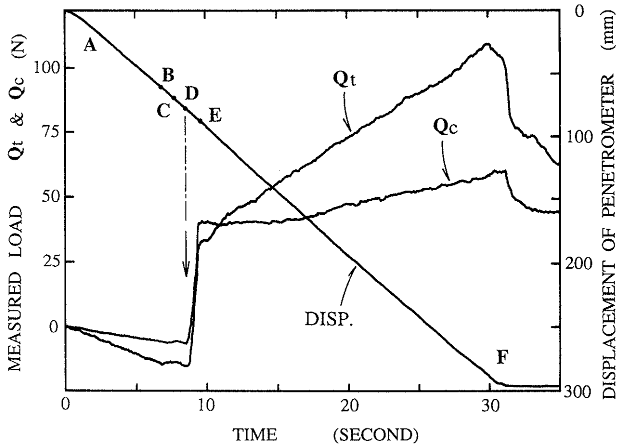


Fig. 7. Original time records of centrifuge CPT

acceleration of cone penetration not higher than 0.5 m/sec^2 (=50 (mm/sec)/0.1 (sec)) recorded in this study. On the other hand, the apparent change in Q_c during CPTs at 100 g (centrifuge angular velocity $\omega \fallingdotseq 19$ rad/sec) due to varying acceleration along the total penetration length of 0.25 m is calculated to be as large as 12N. This is a substantial amount compared to the measured net cone resistance force Q_c of the order of 20 ~ 100N, hence must be corrected properly.

Figure 8 illustrates schematically the relationships between displacement of the penetrometer (abscissae) and measured loads Q_t and Q_c (ordinates). The solid curve **ABCDEF** indicates a typical pattern of the original recorded data and the broken curve **CD′E′F′** for Q_c is ideal data where the assumption is made that no stress acts on the rear of the cone ($p_{rc} = 0$). As described above, any radial movement of the load cell itself with elements attached below affects its output as shown by the slope **AB** while the cone penetrometer travels through the air. **CJ**, **DI** (**D′I′**) and **GH** (**G′H′**) are drawn parallel to **ABK**. The buoyancies developed during penetration through the water, vertical distances between these lines, are calculated based on a knowledge of dynamics. As for the Q_c diagram, the vertical distances between **CJ** and **DI**, and **DI** and **GH** are evaluated on the basis of the results obtained from the calibration test taking into account the influence of the seal behind the cone tip.

It should be understood, that the true net loads of Q_t ($= Q_c + Q_s$) and Q_c of interest are the vertical distances between **DEF** and **DGH** and between **D′E′F′** and **D′G′H′** respectively. A serious problem arises here, concerning the analysis of Q_c, because it is anyhow impossible to make a correct measurement of Q_c (**ABCD′E′F′**) unless a jointless cone is used. Provided that the CPT is conducted in the water, the situation is exactly the same as the calibration test; thus the stress p_{rc} acting on the rear of the cone can be evaluated accurately. For CPT in the soil, however, it is no longer possible to estimate the extent of this influence. Consequently, the analysis of Q_c is obliged, in any case, to consider only the calculation for the vertical distance between **DEF** and **DGH** instead of

Table 1. Test case

Test bed No.	Consolidation pressure p_c (kPa)	Thickness H (mm)	Water content w (%)	Undrained shear strength		Parameters in Eq. (12)	
				c_u (kPa)[1]	s_u (kPa)[2]	N_k	α
1	150	210	24.0	23.2	24.3	13.5	0.637
2	300	261	22.1	39.0	40.5	11.8	0.724
3	400	260	20.6	52.1	56.0	13.1	0.739
4[3]	200 600	145 154	24.0 19.8	29.6 71.9	28.5 77.2	11.6	0.847

1) by UU triaxial compression test
2) by laboratory vane test
3) two-layered bed

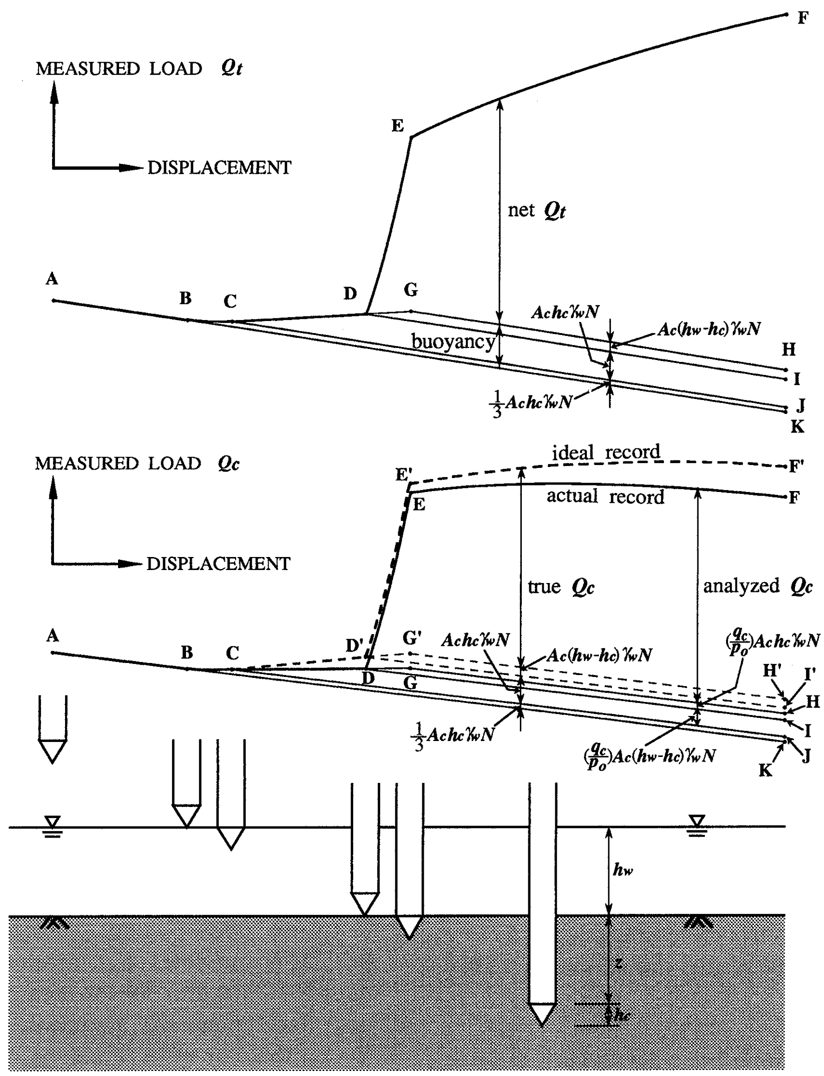


Fig. 8. Analysis of CPT data

between **D′E′F′** and **D′G′H′**. In other words, proper analysis of Q_c data can be made for the penetration of the cone tip only. The influence of the stress p_{rc} behind the cone, which is ignored throughout the rest of the penetration, will be taken into account afterwards when the analyzed Q_c data is correlated with undrained shear strength c_u.

Regarding the analysis of the measured cone data (Fig. 7), corrections for the acceleration and buoyancy effects were made as follows:

1) Find the sampling point where the cone tip strikes the clay surface as shown by the arrow in Fig. 7 which corresponds to **D** in Fig. 8. This point is regarded as the origin where Q_t and Q_c are taken as zero loads and the depth of penetration z is taken as $-h_c$ (height of cone tip, 10 mm);

2) Make correction for the acceleration effect by adding $m \cdot \omega^2 \cdot (z+h_c)$ to the measured Q_t and Q_c data, where $m \cdot \omega^2$ may be estimated from the observed slope of **AB** in Fig. 8. Hence Q_t and Q_c are computed to be the vertical distances between **DEF** and **DI**;

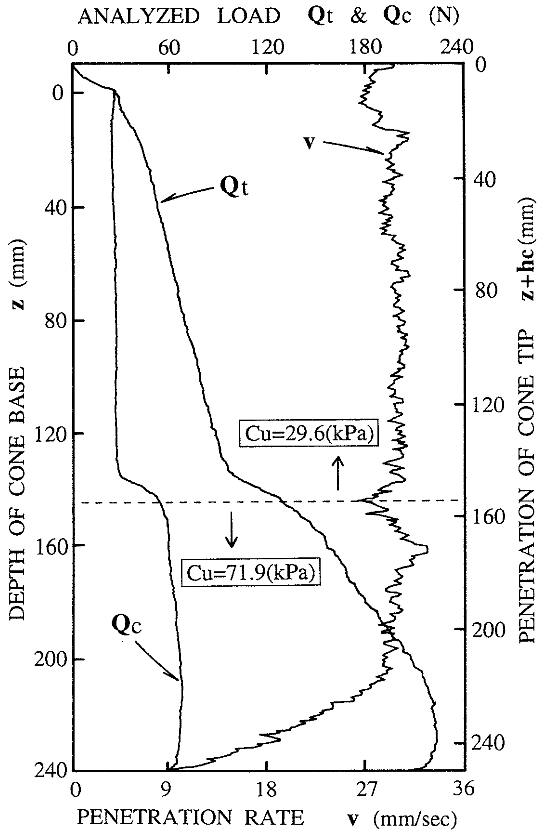
3) If there is any surface water, make correction for the buoyancy effect which is calculated as the distance between **DGH** and **DI** in Fig. 8. N denotes the ratio of centrifugal acceleration to gravitational and the value of (q_c/p_o) for Q_c correction is determined for each individual cone penetrometer by the calibration test. In reality, the amount of this correction was found to be relatively small (no more than 0.8 N for CPT at 100 g).

As a result, the analyzed Q_t and Q_c data finally become the vertical distances between curves **DEF** and **DGH.**

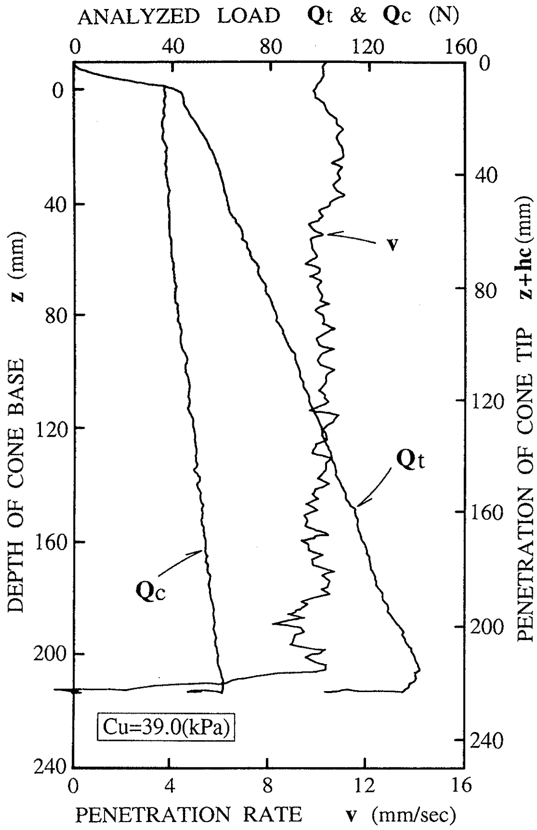
Interpretation of CPTs

Figures 9(a) to (c) show some examples of analyzed CPT results as changes of the adjusted values of Q_t, Q_c and penetration rate v with depth. The following conclusions may be drawn:

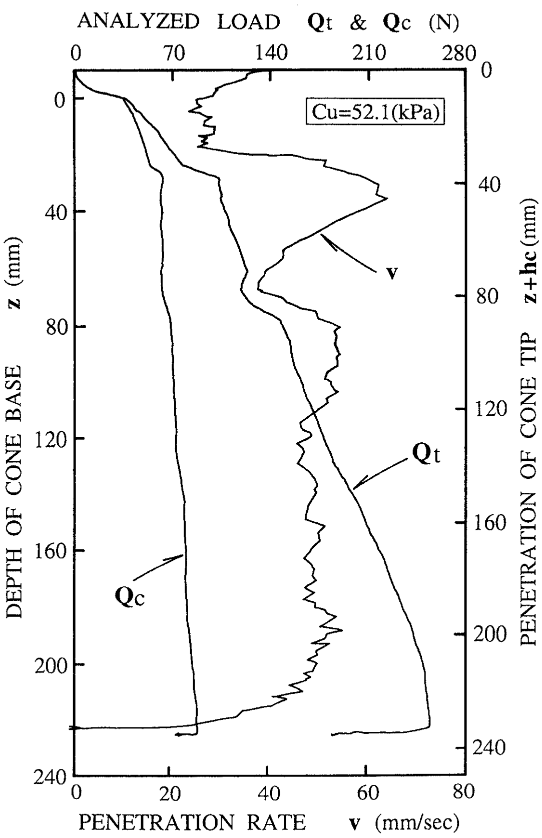
1) The cone data Q_t and Q_c are very consistent in providing excellent continuous information. This is believed to be due to the successful design of the load cells, simplicity of the test procedures, and the uniform nature of the shear process during penetration (Baligh et al., 1980);



(a)



(b)



(c)

Fig. 9. Analyzed CPT data.
(a) No. 4, 1 g, hydraulic jack.
(b) No. 2, 100 g, hydraulic jack.
(c) No. 3, 100 g, pneumatic jack

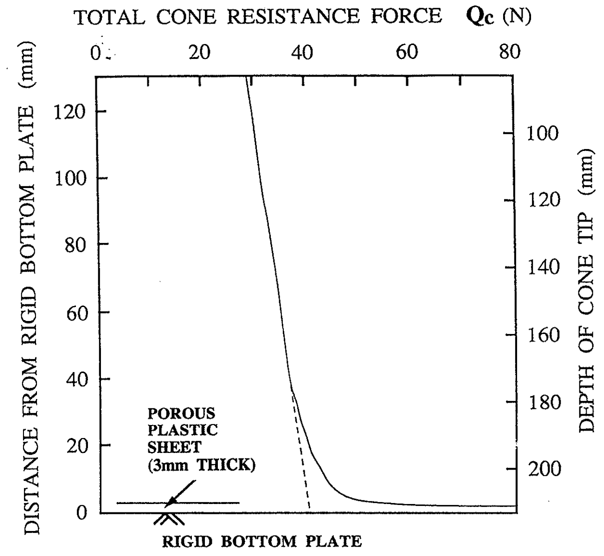


Fig. 10. Analyzed Q_c data of the test in which the cone tip struck the bottom (No. 1, 80 g, hydraulic jack)

2) During the penetration of just the cone tip, the analyzed Q_t and Q_c curves are proved to be perfectly matched. This confirms the successful measurement of even a very small load in the centrifuge as well as adequate analysis of the cone data;
3) At a constant rate of penetration using the hydraulic jack, Q_c seems to be relatively constant or to increase slightly with depth in 1 g CPTs (Fig. 9(a)). Whereas in centrifuge CPTs, Q_c apparently increases more or less linearly with depth (Fig. 9(b)). This is a clear evidence that cone resistance q_c $(=Q_c/A_c)$ is not only a function of undrained shear strength but also of stress level;
4) Test bed No. 4 is a two-layer bed in which the interface can be found at 145 mm depth and the strength ratio defined as c_u(lower layer)/c_u(upper layer) is 2.4 (Table 1). From Fig. 9(a), the cone resistance force Q_c appears to start picking up the presence of the lower stiffer layer ahead of the cone from the depth $z=125\sim135$ mm and to escape the influence of the upper softer layer behind the cone from the depth $z=145\sim150$ mm. In other words, the clay 20 mm $(=2\cdot D_c)$ ahead of and 5 mm $(=1/2\cdot D_c)$ behind the cone base may affect cone resistance q_c for the interface with this particular strength ratio. Although this seems smaller than the reported range $(2\sim4\cdot D_c)$ by Schmertmann (1978), it must be noted that this range is probably dependent on layer composition as well as stiffness of the clay. Figure 10 shows the result in which the cone tip was accidentally pushed too far until it struck the bottom. Despite an extreme type of interface with its strength ratio deemed to be almost infinity, the cone data did not pick up the presence of a rigid boundary until the cone base approached within $40\sim45$ mm $(4.0\sim4.5\cdot D_c)$ above the porous plastic sheet on the bottom. However, as far as normally- or lightly over-consolidated soft clay deposits are concerned, such non-homogeneous beds generally possess a considerably milder change of c_u with depth as compared to the cases discussed above with a sharp increase in c_u values at the interface. Hence by postulation, it may be justified to say that the cone resistance probably represents the shear strength of the immediate vicinity of the cone;
5) Cone resistance q_c is generally known to increase $5\sim30\%$ due to an order of magnitude increase in penetration rate (Meigh, 1987). This is believed to be an immediate consequence of rate dependent (viscous) behavior of clays (Acar and Tumay, 1986; Craig, 1983). On the other hand, in centrifuge CPTs using a 10 mm dia. cone, Almeida and Parry (1984) reported that variation of v between 2 and 20 mm/sec had little effect on q_c. But as can be seen in Fig. 9(c), the influence of penetration rate v on cone data in this soil is clear. Both Q_c and Q_t values increase with increasing penetration rate v but to a less pronounced extent for Q_c.

CORRELATION BETWEEN CONE RESISTANCE AND UNCONFINED COMPRESSION STRENGTH

Based on the above discussion, the following four main points must be examined in order to correlate cone resistance $q_c(=Q_c/A_c)$ and undrained shear strength c_u. They are:
1) influence of rate of penetration v on cone resistance;
2) influence of stress level on cone resistance;
3) error of Q_c measurement due to the stress p_{rc} acting on the rear of the cone;
4) representability of cone resistance in non-homogeneous beds.

For establishing the correlation, the reference c_u is taken as undrained shear strength obtained by UU triaxial compression tests in this study.

Influence of Rate of Penetration

Although the effect of penetration rate v on Q_c is observed to a lesser extent than that on Q_t, it is necessary to take the rate effect into account since the penetration rate v in the CPT using the pneumatic jack varies quite substantially (Fig. 9(c)). This dependence of q_c on v is believed to be a direct consequence of the strain rate effect on mechanical properties of clay, which is usually summarized as a linear variation with logarithm of strain rate. Hence by analogy, the proposed relationship between cone resistance q_c and penetration rate v may be expressed as:

$$q_c=q_c^*\left\{1.0+\beta\cdot\log\left(\frac{v}{v^*}\right)\right\} \tag{9}$$

where q_c^* is the cone resistance at a reference penetration rate v^* and the rate factor β is the slope of q_c against logarithm of v. This rate factor β, which may be defined as the increase in q_c for every log cycle of penetration rate, can be determined as follows:
1) A pair of CPTs is chosen so that both tests were conducted in the same homogeneous bed at the same acceleration level but at different penetration rates;
2) For a given depth of penetration z, two pairs of analyzed data (v_1, q_{c1}) and (v_2, q_{c2}) are computed. Since they are obtained under the same conditions (i.e. c_u, z, N, etc.) except for the rate of penetration v, the difference between q_{c1} and q_{c2} is attributed to the rate effect;
3) With the reference penetration rate v^* arbitrarily taken as 20 mm/sec, these data are substituted in Eq. (9); thereby q_c^*, the cone resistance at v^*, is calculated by eliminating the rate factor β:

$$q_c^*=\frac{q_{c1}\cdot\log(v_2/20)-q_{c2}\cdot\log(v_1/20)}{\log(v_2/v_1)} \tag{10}$$

4) These two pairs of data (q_c, v) are normalized in terms of q_c^* and v^* (=20 mm/sec) respectively;
5) The calculations of items 2 to 4 are made for depths at 20 mm intervals and the results have been plotted in Fig. 11 as relationship between q_c/q_c^* in linear scale and v/v^* in logarithmic scale. Since q_c^* values become erratic if the difference of v is too small $(|\log(v_1/v_2)|<0.05$ in Eq. (10)), these data are excluded from the figure;
6) The rate factor β is computed by least square analysis and is determined to be 0.10 shown as the slope of the regression line in Fig. 11. Therefore Eq. (9) becomes:

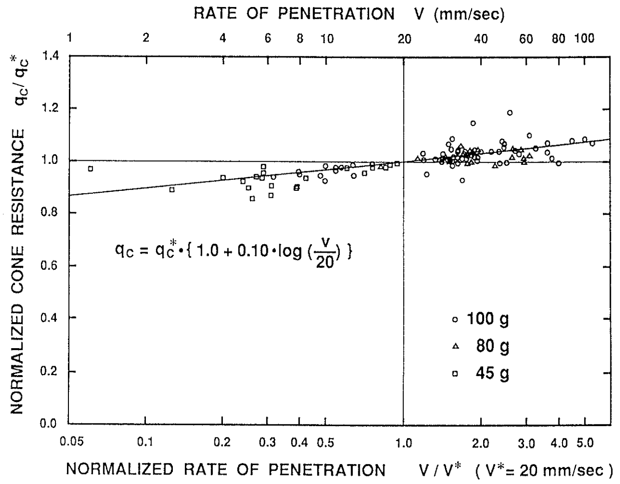


Fig. 11. Rate effect observed in CPT

$$q_c = q_c^* \cdot \left\{1.0 + 0.10 \cdot \log\left(\frac{v}{20}\right)\right\} \tag{11}$$

This equation indicates that cone resistance q_c increases 10% for every ten-fold increase in penetration rate v, which is consistent with most of the reported values of $\beta = 0.05 \sim 0.30$ for CPT (Meigh, 1987).

Influence of Stress Level and Seal in the Gap

The linear increase of cone resistance q_c $(=Q_c/A_c)$ with depth in homogeneous beds, which is more rapid in centrifuge CPTs (Fig. 9), appears to support the type of Eq. (1) correlating q_c and c_u; with q_c expressed as a function of total overburden stress σ_{vo}. In addition, judging from the results of the calibration test (Fig. 4), the stress p_{rc} acting on the back of the cone tip, which causes erroneous q_c measurement, is reasonably thought to be proportional to the stresses acting on the side of the seal. These stresses, in turn, may be assumed to be proportional to the stress level at the depth of the seal z. As a consequence, it is hypothesized that the error of measured q_c caused by the stress p_{rc} is proportional to σ_{vo}. Thus a modified Eq. (1) is proposed as:

$$q_c^* = c_u \cdot N_k + \alpha \cdot \sigma_{vo} \tag{12}$$

where the coefficient α represents the influence of stress level as well as the amount of error caused by the stress p_{rc} acting on the back of the cone tip. In order to determine the values of N_k and α, Eq. (12) may be written as:

$$\frac{q_c^*}{c_u} = N_k + \alpha \cdot \left(\frac{\sigma_{vo}}{c_u}\right) \tag{13}$$

where N_k and α are expressed as the intercept and slope of a straight line of the $(q_c^*/c_u) \sim (\sigma_{vo}/c_u)$ relationship.

Figure 12 shows an example of the plot for CPTs conducted in bed No. 2, wherein values of q_c^*/c_u and σ_{vo}/c_u are computed for penetration depths at 20 mm intervals. As far as the calculation of total overburden pressure σ_{vo} is concerned, it should be noted that in Q_c $(=q_c \cdot A_c)$ analysis, Q_c value is zero for $z = -h_c$ and the subsequent effect of buoyancy due to the penetration of the cone tip is properly taken into account. It does not need, therefore, to account for water pressure at the soil surface $h_w \cdot \gamma_w \cdot N$ (γ_w: unit weight of water) in the calculation; thus $\sigma_{vo} = z \cdot \gamma_t \cdot N$ (γ_t: total unit weight of the soil) even for the CPTs with surface water (Fig. 8).

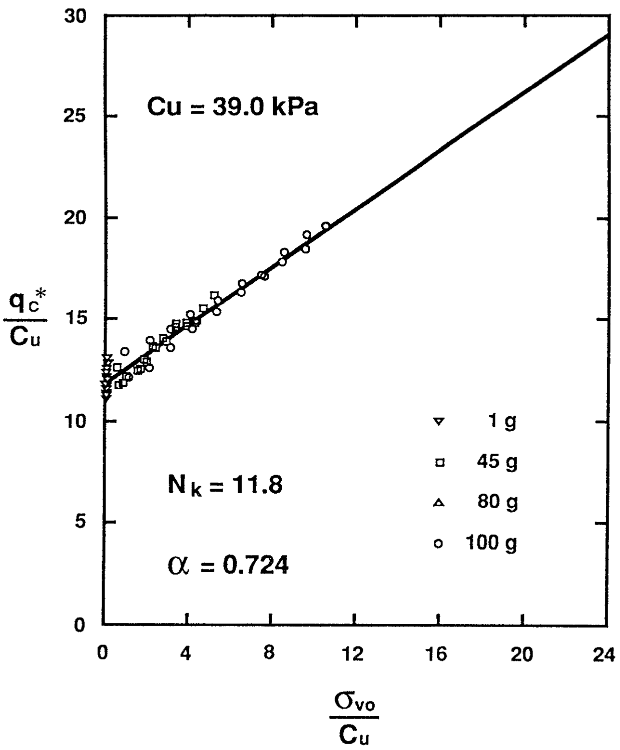


Fig. 12. Typical example of $(q_c^*/c_u) \sim (\sigma_{vo}/c_u)$ relation (No. 2)

As shown in Fig. 12, a linear distribution of data points with modest scatter effectively justifies the proposed expression of Eq. (12). N_k and α values are determined by the use of regression analysis and the results for each bed are shown in Table 1. The computed cone factors N_k are close to each other and fall within the range of values found in the literature, though strictly speaking, direct comparison is impossible due to the introduction of the coefficient α. The average values of $N_k = 12.5$ and $\alpha = 0.737$ are used for the correlation between q_c^* and c_u:

$$c_u = \frac{q_c^* - 0.737 \cdot \sigma_{vo}}{12.5} \tag{14}$$

It is interesting to note that under an extreme condition where CPT is conducted in clay of $c_u = 0$ kPa, namely in water as the calibration test, Eq. (14) implies $q_c^*/\sigma_{vo} = 0.737$ which might be comparable to the test results of $q_c/p_o = 0.64$ and 0.68 (Fig. 4).

Representability of Cone Resistance in Non-homogeneous Beds

The above-mentioned correlation to calculate c_u value from Eqs. (11) and (14) with the known values of q_c, v, z,

γ_t and N is established based on the data obtained from CPTs in homogeneous beds. However, the question "what depth does the estimated strength stand for?" may arise on application of this correlation to the cases for non-homogeneous beds. As discussed earlier, owing to the soft nature of the clay ($c_u \leqq 72$ kPa) used in this project, it is anticipated that only soil in the immediate vicinity of the cone tip will be involved in the shear process determining the cone resistance. Therefore, for convenience, it was decided that the c_u value evaluated from cone data will represent that at the depth of the cone base z. Through monotonically increasing shear strength with depth for the case of a normally-consolidated clay, the softer layer behind the cone base and stiffer one ahead of the cone may probably offset their opposite influence to some extent.

Comments

It should be borne in mind, that the correlation of q_c and c_u, summarized as Eqs. (11) and (14), is established specifically for this study. For application of this result to other situations, special attention must be given to examining any deviation from this particular CPT practice and interpretation described herein.

In addition, some comment is made concerning the so-called "scale effect" for CPT in the centrifuge (Phillips and Valsangkar, 1987). "Scale effect" in soil mechanics is understood to be composed of "size effect" and "stress level effect" (Tatsuoka et al., 1990). Since the same size penetrometer ($D_c = 10$ mm) has been used throughout this work, the former should not have any influence on the results (Carpenter, 1982). As far as the cone resistance q_c is concerned, the latter "stress level effect" is thought to be taken into account in the expression given by Eqs. (12) to (14). Suspicion, however, may arise about possible "depth effect" which is the influence of depth ratio z/D_c on q_c. Nevertheless, there seems to be no definite evidence that the relation $q_c^*/c_u \sim \sigma_{vo}/c_u$ in Fig. 12 is dependent on the acceleration level. This implies that there is no influence of the depth ratio z/D_c on q_c^* for a given σ_{vo}. The depth effect, therefore, is ignored in establishing the correlation between q_c and c_u, as CPT is regarded as one of the typical deep geotechnical problems.

EXAMPLE

Non-homogeneous clay beds modeling a soft normally-consolidated clay deposit were prepared by the hydraulic gradient similarity method (Zelikson, 1969) in Rowe cells to study a foundation stability problem in the centrifuge (Tani, 1990). This seepage-induced consolidation technique has been proved successful in providing model clay beds with a more or less linearly increasing strength profile comparable to that of soft normally-consolidated clay in the field.

Two CPTs were carried out in each bed at 100 g to evaluate the undrained shear strength profile of the model bed immediately before the foundation loading test. Furthermore, after stopping the centrifuge, laboratory vane tests and water content measurements were also made at several depths. It should be noted that the softening effect or loss of strength of the beds during the course of tests are expected to be insignificant due to the rather impermeable nature of the clay material, Cowden clay, selected for this project.

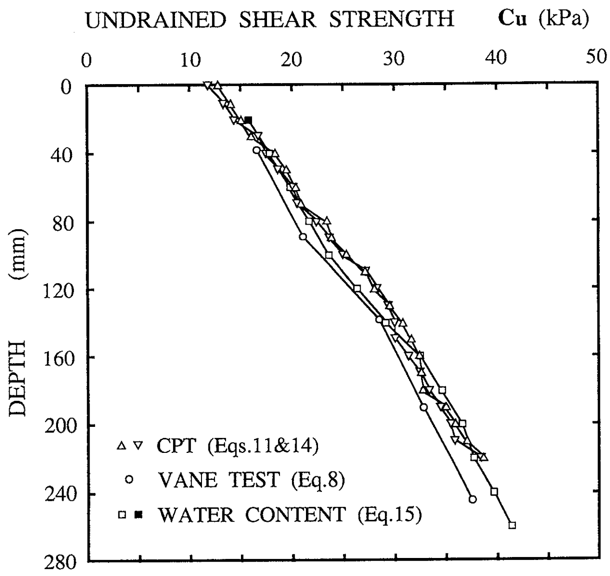


Fig. 13. Estimated undrained shear strength profile

Figure 13 shows a typical result of estimated undrained shear strength profile determined by various methods including two centrifuge CPTs at 100 g. Note that c_u herein refers to the undrained shear strength obtained by UU triaxial compression tests; thereby the empirical relation of Eq. (8) is used to convert measured s_u into c_u. Furthermore, from the average profile of water content w (%), c_u (kPa) may be estimated using the empirical relation proposed for Cowden clay (Craig and Chua, 1987):

$$\log_{10}(c_u) = 3.804 - 0.101 \cdot w \quad (15)$$

Nevertheless, since the triaxial test becomes extremely difficult to perform on very soft samples, extrapolation of Eq. (15) towards $w > 25.5\%$ ($c_u < 17$ kPa) may not be justified; thus the estimated results are shown as solid squares.

Excellent agreement among various evaluation methods illustrates more or less linearly increasing undrained shear strength c_u with depth with very low values at the surface. Almost identical c_u profiles were estimated from two CPTs with different penetration rate histories; both CPTs were conducted using pneumatic jacks. This emphasizes the great consistency of the CPT technique in obtaining data continuously with depth as well as the adequacy of the CPT analysis in taking into account the rate effect.

CONCLUSION

This report describes the development of CPT technique in the centrifuge in order to evaluate shear strength profiles of clay beds for use in physical modeling to study short-term stability problems. The evaluation method presented herein is the correlation between cone resistance q_c and undrained shear strength c_u which is specific for a particular CPT practice adopted for this study. Some of the conclusions which are drawn in this study, however, may also provide valuable information for CPTs conducted in the field for practical purpose:

1) Whether the filling material in the gap behind the cone is permeable or not, complete correction of measured cone resistance q_c for the stress p_{rc} by Eq. (2) is impossible. This rather pessimistic conclusion has never been pointed out before, because the exact value of p_{rc} is not identical to pore pressure u but effective stress components acting on the side of the filling would contribute to p_{rc}. However, this influence may be accounted for in the relation of q_c and c_u as proposed by Eq. (12) which modifies the conventional relation of Eq. (1). A newly introduced parameter α may be evaluated as (q_c/p_o) obtained by the calibration test as a first approximation;

2) The influence of penetration rate v on cone resistance q_c can be properly evaluated by Eq. (9), which is an analogical expression of the strain rate effect on mechanical properties of clay.

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