A NEW APPROACH TO DETERMINE SOIL PARAMETERS FREE FROM REGIONAL VARIATIONS IN SOIL BEHAVIOR AND TECHNICAL QUALITY

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ABSTRACT

In order to evaluate soil parameters free from regional variations both in soil behaviour and technical quality, a new procedure to determine the shear strength for design use, $\tau_{f(m)}$, as well as consolidation yielding stress, $\sigma'_y$ is proposed. Various methods to determine $\tau_{f(m)}$ in current practice are first reviewed and it is then revealed that regional difference in technical quality is significant. It is indicated that cone penetrometer, sheathed field vane and direct shear tests are recommended as the tests to minimize the effect of quality difference together with that the direct shear strength offsets the strength anisotropy and be uniquely related to $\tau_{f(m)}$.

Results of investigations with the proposed method consisting of three tests described above are presented for three marine clays. Point resistance, field vane, direct shear and unconfined compression strengths were investigated and the correction factor to determine $\tau_{f(m)}$ from these strengths are shown together with those proposed in various methods. It is demonstrated that $\sigma'_y$ can be obtained from the shear strengths both in the field and in the normally consolidated state, and $\tau_{f(m)}$ can uniquely be related to $\sigma'_y$ irrespective of clay properties. Further, it is also shown that $\tau_{f(m)}$ and $\sigma'_y$ can be predicted without undisturbed samples when vane shear and direct shear strengths in the normally consolidated state are obtained.

Key words: clay, cone penetrometer test, consolidation yielding stress, direct shear test, in-situ test, shear strength, vane shear test (IGC: D6)

INTRODUCTION

Factors of safety, $F. S.$ values obtained from unconfined compression strength, $q_u$ and field vane shear strength, $\tau_{f(v)}$ are presented in Table 1 for two harbour structures constructed on soft marine clays in the Arabian Gulf and Tokyo Bay together with their field behaviour. The value of $F. S.$ from $\tau_{f(v)}$ indicates good

<table>
<thead>
<tr>
<th>Structure</th>
<th>Area</th>
<th>$F. S.$</th>
<th>Behaviour</th>
<th>$q_u/2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fag Steel</td>
<td>Arabian</td>
<td>1.24</td>
<td>stable</td>
<td>0.68</td>
</tr>
<tr>
<td>Jetty</td>
<td>Gulf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Daikokuch</td>
<td>Tokyo</td>
<td>1.26</td>
<td>failed</td>
<td>1.07</td>
</tr>
<tr>
<td>Dike</td>
<td>Bay</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Factors of safety obtained from $\tau_{f(v)}$ and $q_u/2$ for 2 harbour structures

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Written discussions on this paper should be submitted before October 1, 1992, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.
agreement with the field behaviour of Fao Steel Jetty, while F.S. value for Daikokuchuo Dike can not explain the fact that the dike failed. On the other hand, F.S. value from $g_u/2$ indicates a reasonable value for Daikokuchuo Dike, while the value is too small for Fao Steel Jetty. Since sampling, field vane test, F. V. T. and $g_u$ test were carried out by highly skilled Japanese technitians, there could be no possibility that either lower $g_u$ for Fao steel Jetty or higher $\tau_{foc}$ for Daikokuchuo Dike happened to be obtained by mistake. It can be concluded that the stability of clay should fundamentally be evaluated by $\tau_{foc}$ for Arabian Gulf clay and by $g_u$ for Tokyo Bay clay.

From this point of view, clay in the world will be classified into two clays: one of which behaviour can better be evaluated by $\tau_{foc}$ and the other better evaluated by $g_u/2$. Actually, F. V. T. and $g_u$ test have commonly been used in Europe and Canada for the former and in Japan for the latter. This difference in determining the shear strength for design use, designated with the symbol of $\tau_{f(mob)}$ in this paper, is due to the regional variation in soil behaviour or locality of soil on which the simple total stress method is based.

In order to overcome experience dependency arising from the locality of soil, various methods to determine $\tau_{f(mob)}$ have been proposed and practised such as the correction for $\tau_{foc}$ (Bjerrum, 1972), for $g_u$ (Nakase et al., 1972; Ohta et al., 1989), the SHANSEP method (Ladd and Foftt, 1974), the Modified Bjerrum's method (Hanzawa, 1979), the USALS method (Trak et al., 1980) and the correction for triaxial compression strength (Tsuchida et al., 1989). It should be pointed out, however, that all the methods are based on a common requirement that sampling and F. V. T. as well as laboratory tests must be conducted with a reasonable standard of quality. It is strongly suggested that it is generally difficult to satisfy this requirement in routine soil investigation when regional difference in technical quality is considered as revealed later. Technical quality is also an important factor in determining proper $\tau_{f(mob)}$, and without understanding of this subject, the use of any method introduced above is meaningless. It is an important task to find out a procedure to minimize the effect of regional variations both in soil behaviour and technical quality.

In this paper, various existing methods having been proposed to determine $\tau_{f(mob)}$ are first reviewed and then regional difference in technical quality is discussed. Field and laboratory tests to minimize the difference in technical quality as well as the locality are examined, and a new procedure to determine $\tau_{f(mob)}$ and consolidation yielding stress, $\sigma'_v$ is proposed with support of field and laboratory tests results.

**REVIEW ON VARIOUS METHOD TO DETERMINE $\tau_{f(mob)}$**

It is well known that the shear strength of clay is highly anisotropic and strain rate dependent, and $\tau_{f(mob)}$ for short term stability analysis is given by Eq. (1) when the effect of progressive failure is not considered.

$$\tau_{f(mob)} = \tau_{fo} \times \mu_A \times \mu_R \tag{1}$$

where $\tau_{fo} = \text{in-situ shear strength}$, and $\mu_A$ and $\mu_R = \text{correction factors for strength anisotropy and strain rate effect}$.

The values of $\tau_{foc}$ and $g_u/2$ have been used for practice based on an assumption that these strengths will be approximately the same as $\tau_{f(mob)}$ when the effects of strength anisotropy, strain rate, and disturbance and stress release through sampling are appropriately balanced, which was called "lucky harmony" by Matsuo (1984). But as well be known, this assumption highly depends on locality of soil and technical quality.

In order to determine proper $\tau_{f(mob)}$ independent of experience dependency, many efforts have been devoted and various methods have been proposed and practised. Among these methods, direct determination of $\tau_{f(mob)}$ from $\tau_{foc}$, $g_u/2$ and the other strengths from conventional tests with the use of correction factor, $\mu$ is so called the simplified procedure in this paper. On the other hand, the SHANSEP and the modified Bjerrum's method, which are based on different concepts, are to determine
strain rate effect were investigated though the strain rate effect on $q_u$ was assumed to be the same as the one proposed by Bjerrum, and they proposed a method to determine $\tau_f(mo)$ from $q_u/2$ together with back-analysis on embankment failures on soft clay suggesting the validity of this method.

Tsuchida et al. (1989) conducted lots of triaxial compression, and $K_o$-consolidated triaxial compression and extension tests totaling more than 300 tests. In the CU triaxial compression test, undisturbed sample is isotropically consolidated at the mean effective stress in the field, $\sigma'_{mo}$, which is given by $(2/3)\sigma'_w$ assuming $K_o=0.5$ ($\sigma'_w$=effective overburden stress) for 2 hours, and then sheared by compression at a strain rate of 0.1%/min. The shear strength obtained from this test is approximately the same as the in-situ compression strength, $\tau_{f0(e)}$. They compared this strength with $\tau_f(mo)$ determined by $K_o$-consolidated triaxial compression and extension tests following the Modified Bjerrum’s method and found that there is an unique correlation between $\tau_{f0(e)}$ and $\tau_f(mo)$, which is given by $\tau_f(mo)=0.75\tau_{f0(e)}$ for alluvial and diluvial clays with $I_p=25$ to 90 found in Tokyo and Osaka Bays.

The USALS method which uses undrained strength at large strain in UU triaxial compression tests is suggested to be available only for some Canadian clays. Because of this reason, this method is excepted for more discussions in this paper.

The values of $\tau_{f0(mo)}$ in the methods described above are given by Eq. (2) and the values of $\mu$ are presented in Fig. 1.

$$\tau_f(mo) = \mu_1 \times \tau_{f0(e)} \quad \text{(Bjerrum)}$$

$$= \mu_2 \times q_u/2 \quad \text{(Nakase et al.)}$$

$$= \mu_3 \times q_u/2 \quad \text{(Ohta et al.)}$$

$$= \mu_4 \times \tau_{f0(c)} \quad : \mu_4 = 0.75\tau_{f0(e)} \quad \text{(Tsuchida et al.)} \quad \ldots \quad (2)$$

From the values of $\mu$ indicated in Fig. 1, the following questions rise.

(1) There is a big difference in $\mu_2$ and $\mu_3$ which are the correction factors for the same shear strength, $q_u/2$.

(2) $\mu_1$ for $\tau_{f0(e)}$ is greater than $\mu_3$ for $q_u/2$ when $I_p$ is equal to or less than 60% but $\tau_{f0(e)}$
of medium to low plastic clay is generally greater than $q_u/2$ as typically observed in F.S. for Fao Steel Jetty.

(3) In spite of that $\tau_{f_{o(c)}}$ should be greater than $q_u/2$, $\mu_4$ for $\tau_{f_{o(c)}}$ is greater than $\mu_6$ for $q_u/2$ when $I_p$ is in 35 to 60.

The efforts to find out a simplified procedure to determine appropriate $\tau_{f_{o(mob)}}$ is very valuable but correction factors shown in Fig. 1. should cause some confusions to the engineer concerned with routine design work. In addition, it should be pointed out that each of the methods is based on a common requirement that undisturbed sampling, F.V.T. and laboratory tests are conducted with a reasonably high quality. This is a strict requirement when the regional difference in technical quality in the world is taken into account.

**REGIONAL DIFFERENCE IN TECHNICAL QUALITY**

A trimming method of undisturbed sample for $q_u$ and triaxial tests, which the author actually experienced in a country in 1989, is presented in Fig. 2. In spite of that the bottom plate of the trimmer has resistance for smooth rotation because of corrosion, the top plate was rotated during trimming and then the specimen was subjected to torsion. It was surprising that the diameter of the miter box ($D=33$ mm) was less than of the specimen ($D=35$ mm), which gives significant tension forces to the specimen at the final stage of trimming.
Table 2. Relative difficulty for various tests

<table>
<thead>
<tr>
<th>Tests</th>
<th>Relative difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.P.T.</td>
<td>D</td>
</tr>
<tr>
<td>Sampling</td>
<td>B</td>
</tr>
<tr>
<td>F.V.T.</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>D</td>
</tr>
<tr>
<td>q_n</td>
<td>A</td>
</tr>
<tr>
<td>Triaxial</td>
<td>A*</td>
</tr>
</tbody>
</table>

Actually, it was observed that some samples with thin sand seams failed in tension shear at this stage. Hanzawa (1987) reported a drastic change of $q_n$ values as shown in Fig. 3 where $q_n$ values measured by two contractors, A and B are compared, who used the same type stationary piston sampler.

The similar example for $\tau_{fo(\psi)}$ is presented in Fig. 4 where $\tau_{fo(\psi)}$ values measured by two contractors, A and B are also compared. Contractor A adopted a dry drilling method where continuous undisturbed sampling was conducted without the use of mud water, while contractor B used a penetration type sheathed field vane where drilling is not necessary. Dry drilling should cause significant tension forces to the clay when sampling tube is withdrawn, resulting in disturbance of the clay where F.V.T. is carried out. The great difference in $\tau_{fo(\psi)}$ values shown in Fig. 4 should be attributed to the disturbance caused by dry drilling. It should be pointed out that such a terrible operation like dry drilling to saturated clays is still widely used in the world. In addition, even drilling with the use of mud water is used in F.V.T., there is a possibility that irregular rotation of vane due to deflection of dril rods could take place, which gives higher $\tau_{fo(\psi)}$ values as shown in Fig. 5 which the author experienced in the Arabian Gulf.

**METHOD TO MINIMIZE THE EFFECT OF QUALITY DIFFERENCE**

As revealed in the previous section, it is suggested that execution of an investigation where sampling, F.V.T. and laboratory tests are carried out with a reasonable quality is a limited case in routine soil investigation in the world. There are two approaches to overcome this subject: 1) to improve the quality and 2) to use a method to minimize the effect of quality difference. Though the first method will be most desirable, the most practical method is the second one.

The test to be recommended from this point of view should be a simple one in operation. For example, $q_n$ test itself is a very simple test but it requires drilling, undisturbed sampling, sample transportation, extrusion of sample, trimming and finally $q_n$ test. When it is considered to be required a reasonably high quality at every stage, $q_n$ test is simple but complicated one. From this point of view, relative difficulty in various methods such as cone penetrometer test, C.P.T., F.V.T., undisturbed sampling, and $q_n$ and triaxial tests would be as summarized in Table 2. There could be no doubt that the relative difficulty is the lowest in C.P.T. and sheathed field vane test, S.F.V.T. is probably the second lowest one because drilling is not necessary in this test. When compared with these two tests, much more complicated operations are needed in undisturbed sampling, F.V.T. with a drilling method, and $q_n$ and triaxial tests.

In order to check that S.F.V.T. can minimize
the quality difference, S.F.V.T. was carried out by two contractors, A and B the same as shown in Fig. 4. The values of \( \tau_{f0(v)} \) measured by A and B are compared in Fig. 6, which demonstrates that there is no difference in \( \tau_{f0(v)} \) values. It can be said that S.F.V.T. as well as C.P.T., where drilling is not necessary but only penetration is needed, will be the best method to minimize the effect of quality difference. In addition, there are two advantages in these tests as summarized below.

(1) Since investigation speed is much faster than in other methods, point resistance, \( q_s \) and \( \tau_{f0(v)} \) as well as soil conditions can be obtained in shorter time.

(2) When pore water pressure and skin friction are measured in C.P.T., more information on soil properties can be obtained.

**USE OF DIRECT SHEAR TEST**

Now let us assume that the effect of quality difference on \( q_s \) and \( \tau_{f0(v)} \) is negligible in C.P.T. and S.F.V.T. But the values of \( q_s \) and \( \tau_{f0(v)} \) are more than an index property of soil. It is necessary to find out a correlation between \( q_s \) or \( \tau_{f0(v)} \) and a clear shear strength, \( \tau_{f0} \) in Eq. (1). The laboratory test to determine the clear shear strength should at least satisfy the following conditions: 1) testing techniques including trimming and its mounting on device are easy, 2) \( K_0 \)-consolidation is easily achieved and 3) strength anisotropy can be evaluated.

The direct shear test, D.S.T. with the modified device developed by Mikase (1960), where constant volume shear test is possible, is recommended as the laboratory test to determine the clear shear strength, i.e., direct shear strength, \( \tau_{f0(d)} \). In the modified device of D.S.T., various improvements were also made such as to eliminate 1) friction between the inside of shear box and the plate to apply the vertical stress and 2) force acting to incline the shear box and the plate during shear. In addition, there are lots of advantages in the D.S.T. when compared with the triaxial test from the practical point of view as summarized in the followings:

(1) Testing technique is easier.

(2) Since the specimen is in a plate, 6 cm in diameter and 2 cm thick, a highly qualified sample with high uniformity could easily be selected when undisturbed samples are used.

(3) \( K_0 \)-consolidation is automatically achieved and strength anisotropy can be evaluated as revealed later.

(4) Deformation is in the plane condition which is in most cases similar to the ones in actual stability problems.

(5) Time required for consolidation and drained shear is much shorter.

(6) Cost is much cheaper.

A series of the consolidated constant volume D.S.T. with the modified device was carried out for various clays in the normally consolidated state, hereafter called N.C. state, at a deformation rate of 0.25 mm/min together with the \( K_0 \)-consolidated triaxial compression and extension tests at a strain rate of 0.1%/min in order to investigate the direct shear, compression and extension strengths in the N.C. state, \( \tau_{f0(d)} \), \( \tau_{f0(e)} \) and \( \tau_{f0(c)} \). The ratios of \( \tau_{f0(d)} \) to the average strength of \( \tau_{f0(c)} \) and \( \tau_{f0(e)} \) are presented in Table 3 together with the direct shear strength ratio in the N.C. state, \( \tau_{f0(d)}/\sigma'_{ve} \), ratio where \( \sigma'_{ve} \) is the vertical consolidation stress. It can clearly be seen that \( \tau_{f0(d)} \) is approximately equal to the average

<table>
<thead>
<tr>
<th>Clay</th>
<th>PI</th>
<th>( 2\tau_{f0(d)}/(\tau_{f0(c)}+\tau_{f0(e)}) )</th>
<th>( \tau_{f0(d)}/\sigma'_{ve} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surabaya</td>
<td>85</td>
<td>0.96</td>
<td>0.27</td>
</tr>
<tr>
<td>Natsushima</td>
<td>50</td>
<td>0.93</td>
<td>0.26</td>
</tr>
<tr>
<td>Ariake</td>
<td>upper</td>
<td>75</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>lower</td>
<td>50</td>
<td>1.04</td>
</tr>
<tr>
<td>Kuwana</td>
<td>upper</td>
<td>35</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>lower</td>
<td>52</td>
<td>0.96</td>
</tr>
<tr>
<td>Okinawa</td>
<td>15</td>
<td>1.02</td>
<td>0.295</td>
</tr>
<tr>
<td>Banjarmasin</td>
<td>upper</td>
<td>60</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>lower</td>
<td>70</td>
<td>1.02</td>
</tr>
</tbody>
</table>
strength of $\tau_{fa(c)}$ and $\tau_{fa(s)}$, and the value of $\mu_A$ is given by 1.0 for general case.

$$\mu_A = 1.0$$  (3)

Then $\tau_{f(mob)}$ can be related to $\tau_{fo(d)}$ as indicated below.

$$\tau_{f(mob)} = \tau_{fo(d)} \times \mu_R$$  (4)

Since the strain rate in the triaxial tests conducted in this study was 0.1%/min which is suggested to be faster than in the actual stability problem, correction for the strain rate is needed. Change of the shear strength with change of the strain rate obtained from the $K_0$-consolidated triaxial compression tests is presented for three marine clays in Tokyo Bay, Norway and Arabian Gulf with different $I_p$ ranging from 30 to 55 in Fig. 7 where $\tau_{fa(c)}$ ratios at a strain rate of 0.1%/min and at a given strain rate are plotted versus the strain rate. The strain rate in the actual stability problem is said to be $10^{-2}$ to $10^{-3}$%/min (Ladd and Foott, 1974; Larsson, 1980; and Kishida et al., 1983), and then the value of $\mu_R$ can be obtained as shown in Eq. (5).

$$\mu_R = \frac{\tau_f(10^{-2} \text{ to } 10^{-3} \text{%/min})}{\tau_f(10^{-1} \text{%/min})}$$

$$= 0.82 \text{ to } 0.90 = 0.85$$  (5)

Then $\tau_{f(mob)}$ can finally be related to $\tau_{fo(d)}$ as expressed by Eq. (6).

$$\tau_{f(mob)} = 0.85 \tau_{fo(d)}$$  (6)

Direct shear strength ratios in the N.C. state, $\tau_{fa(d)}/\sigma'_{ve}$ shown in Table 3 are plotted versus $I_p$ in Fig. 8. The ratios $\tau_{fa(d)}/\sigma'_{ve}$ indicate a constant value irrespective of $I_p$, whereas the $\tau_{fa(c)}/\sigma'_{ve}$ ratios increase with increasing $I_p$. Since the shear mechanism in D.S.T. and F.V.T. is similar, these two ratios should indicate the same trend. On the other hand, it should also be pointed out that there is no significant difference in the strength change with the change of the strain rate for three clays as shown in Fig. 7 though the values of $I_p$ ranged from 30 to 55, which disagrees with Bjerrum's conclusion that the strain rate effect is greater the higher the $I_p$. Since these two subjects, 1) $\tau_{fa}/\sigma'_{ve}$ or $\tau_{fa(c)}/\sigma'_{ve}$ ratio and 2) the strain rate effect are very important in evaluating various soil parameters, it is desirable to do more detailed studies such as internationally cooperated simultaneous tests on various clays in the world.

**PROPOSED METHOD AND ITS PRACTICAL APPLICATION**

The proposed method consists of C.P.T., S.F.V.T. and D.S.T., and its sequences are as follows:

1. The C.P.T. and S.F.V.T. are first carried out for all over the project site in order to obtain $q_c$ and $\tau_{fa(c)}$ as well as for understanding of soil conditions.

2. Undisturbed sampling is then conducted...
at the representative points which are selected according to soil conditions.

(3) The D.S.T. is carried out in order to obtain \( \tau_{fo(d)} \), where the specimen from undisturbed sample is first consolidated at a stress being equal to the \( \sigma'_{vo} \) and then sheared at the constant volume condition.

(4) Correlations among \( q_e \), \( \tau_{fo(v)} \) and \( f_0(d) \) are first determined and then it is possible to relate \( q_e \) and \( \tau_{fo(v)} \) to \( \tau_{f(mo)} \) which is given by 0.85 \( \tau_{fo(d)} \).

A series of investigations with the proposed method was carried out on three clays:—
1) Surabaya clay in Indonesia, 2) Ariake clay in Saga prefecture, Japan and 3) Kuwana clay in Mie prefecture, Japan. Point resistance, skin friction and pore water pressure were electrically measured in C.P.T. with a penetration rate of 1 cm/sec. Diameter and height of the vane used in S.F.V.T. with a rotating arte of 0.1 sec were 5 cm and 10 cm, respectively for Surabaya clay, and 4 cm and 8 cm for Ariake and Kuwana clays. The devices for S.F.V.T. and C.P.T. are as shown in Fig. 9. The specimen for D.S.T., 6 cm in D and 2 cm thick, was first consolidated at \( \sigma'_{vo} \) until primary consolidation has been achieved and then sheared under the constant volume condition at a deformation rate of 0.25 mm/min. This test was conducted for all the undisturbed samples. The D.S.T. was also carried out on the representative samples from each clay in order to determine \( \tau_{fo(d)} \) in the N.C. state. In addition, \( q_u \) tests were conducted on all the undisturbed samples at a strain rate of 1%/min.

The values of natural water content, \( w_n \), liquid limit, \( w_L \) and plastic limit, \( w_p \) of the clays are presented in Fig. 10 together with soil conditions. Surabaya clay, which is covered with an alternative layer of loose sand and clay of 6 cm thick, is a highly plastic marine clay with \( I_p \) mostly ranging from 70 to 100. Ariake clay is divided into the upper and the lower clays at a depth of 11 m from the difference in \( w_n \) and \( I_p \). The values of \( I_p \) decrease with depth from 90 to 55 for the upper clay, while it is ranged from 45 to 60 averaging 52 for the lower clay. It is noted that \( w_n \) of Ariake clay is greater than \( w_L \) throughout the depth. Kuwana clay, covered with a sand layer of 10 m thick, is also divided into the upper and the lower clays at a depth of 17 m from the difference in \( w_n \) and \( I_p \) which are 35 for the upper clay and 50 for the lower clay on the average. Thin sand seams were quite often observed in the upper clay, particularly from 10 m to 14 m.

The values of \( \tau_{fo(v)} \), \( q_e \), and \( q_u/2 \) measured are plotted versus \( \tau_{fo(d)} \) in Fig. 11. Then correlations between these strengths and \( \tau_{fo(d)} \) can easily be obtained as given by Eq. (7).

In determining correlations, \( \tau_{fo(v)} \) of the upper Kuwana clay with sand seams, which are indicated by black circles in Fig. 11, were excepted because there is a trend that \( \tau_{fo(v)} \) of such a clay show the higher value than the actual shear strength.

\[
\begin{align*}
(1) & \quad \text{Surabaya clay} \\
\tau_{fo(v)} &= 0.8 \tau_{fo(d)} \\
q_e &= 14 \tau_{fo(d)} \\
q_u/2 &= 0.85 \tau_{fo(d)} \\
\end{align*}
\]

\[
\begin{align*}
(2) & \quad \text{Ariake clay} \\
\tau_{fo(v)} &= 0.8 \tau_{fo(d)} \\
q_e &= 14 \tau_{fo(d)} \\
q_u/2 &= 0.85 \tau_{fo(d)} \\
\end{align*}
\]

\[
\begin{align*}
(3) & \quad \text{Kuwana clay} \\
\text{not applicable} \\
\end{align*}
\]
Fig. 10. Values of $w_s$, $w_L$ and $w_p$ of the clays plotted against depth.

Fig. 11. The values of $t_{fo(d)}$, $q_c$ and $q_u/2$ plotted against $t_{fo(d)}$ for a) Surabaya clay, b) Ariake clay and c) Kuwana clay.
Fig. 12. Correction factor, \( \mu \) for \( \tau_{fo(v)} \) and \( q_u/2 \) obtained from this study and proposed in various methods

\[
\begin{align*}
\tau_{fo(v)} &= \tau_{fo(d)} \\
q_v &= 16 \tau_{fo(d)} \\
q_u/2 &= 0.9 \tau_{fo(d)}
\end{align*}
\]

Using \( \tau_{f(mob)} = 0.85 \tau_{fo(d)} \), correlations for \( \tau_{fo(v)} \), \( q_v \) and \( q_u/2 \) to \( \tau_{f(mob)} \) are obtained as indicated in Eq. (8).

1. Surabaya clay

\[
\begin{align*}
\tau_{f(mob)} &= 1.05 \tau_{fo(v)} \\
q_v &= q_u/16.5 \\
q_u/2 &= q_u/2
\end{align*}
\]

2. Ariake clay

\[
\begin{align*}
\tau_{f(mob)} &= 1.05 \tau_{fo(v)} \\
q_v &= q_u/16.5 \\
q_u/2 &= q_u/2
\end{align*}
\]

3. Kuwana clay

\[
\begin{align*}
\tau_{f(mob)} &= 0.85 \tau_{fo(v)} \\
q_v &= q_u/19 \\
q_u/2 &= 0.95 q_u/2
\end{align*}
\]

The correction factors, \( \mu \) for \( \tau_{fo(v)} \) and \( q_u/2 \) given by Eq. (8) are presented in Fig. 12 together with those proposed by Bjerrum (1972), Nakase et al. (1972) and Ohta et al. (1989). The following comments can be made:

1. The values of \( \mu \) for \( \tau_{fo(v)} \) and \( q_u/2 \) obtained from this study strongly suggest that there is no unique correlation between \( \mu \) and \( I_p \), which is consistent with the author’s long time opinion (Hanzawa, 1983a).

2. Direct use of \( \tau_{fo(v)} \) as \( \tau_{f(mob)} \) is possible for Surabaya and Ariake clays (\( \mu = 1.05 \)) but unconservative for Kuwana clay (\( \mu = 0.85 \)).

3. The values of \( \mu \) for \( q_u/2 \) are 0.95 to 1.0 and then \( q_u/2 \) can directly be used as \( \tau_{f(mob)} \) for three clays when appropriate sampling and \( q_u \) test are executed.

4. There is a great difference in \( \mu \) values between those obtained from this study and proposed by Bjerrum for \( \tau_{fo(v)} \) and Ohta et al. for \( q_u/2 \). The main reason for this difference is probably due to a different conclusion to the strain rate effect.

5. It will be a rare case to do a detailed stability analysis using \( q_e \) but when \( \mu \) values ranging from 1/16.5 to 1/19 are considered, it is probably one of the practical methods to do a preliminary analysis with the use of \( \mu = 1/20 \).

DETERMINATION OF CONSOLIDATION YIELDING STRESS

Three clays investigated in this study are classified into the normally consolidated aged clay (Bjerrum, 1973). Characteristics of this type of clay were studied by Hanzawa (1983b, 1989) and one of the important features is that its consolidation yielding stress, \( \sigma'_y \), is given by Eq. (9).

\[
\sigma'_y = \tau_{fo}/\tau_{fu}/\sigma'_w
\]

The values of \( \sigma'_y \) of three clays obtained using \( \tau_{f(n(d)} \)/\( \sigma'_w \) shown in Table 3 and \( \tau_{fo(v)} \) values are presented and compared with \( \sigma'_y \) obtained from the standard and strain controlled oedometer tests in Fig. 13 though the strain controlled oedometer tests were not carried out on Surabaya clay. The strain rate in the strain controlled tests was 0.02%/min at which excess pore water pressure during loading was zero until \( \sigma'_y \) is obtained (Hanzawa, 1989). The values of \( \sigma'_y \) determined by Eq. (9) show good agreement with \( \sigma'_y \) values from the strain controlled oedometer tests and greater than those from the standard oedometer tests. Hanzawa (1989) reported that \( \sigma'_y \) of Surabaya clay from Eq. (9) showed good agreement with \( \sigma'_y \) determined by in-
Fig. 13. Values of $\sigma'_y$ obtained from Eq. (9) and from standard and strain controlled oedometer tests

situ $\epsilon$-$\sigma'_y$ curve made by settlement and excess pore water pressure measurements under the reclaimed fill. Hanzawa (1989) also pointed out that $\sigma'_y$ of Ariake clay should be determined by the strain controlled oedometer tests because $\sigma'_y$ from this test can well explain the in-situ shear strength characteristics of this clay.

With the use of Eq. (9) and the relation, $\tau_{f(mob)}=0.85\tau_{f(oc)}$, on the other hand, $\tau_{f(mob)}$ is also given by a function of $\sigma'_y$ as shown by Eq. (10).

$$\tau_{f(mob)} = 0.85 \times \tau_{f(oc)}$$

$$= 0.85 \times \tau_{f(oc)} / \sigma'_{vo} \times \sigma'_y$$

(10)

The correlations between $\tau_{f(mob)}$ and $\sigma'_y$ for each clay are then given by Eq. (11).

$$\tau_{f(mob)} = 0.85 \times 0.27 \sigma'_y = 0.23 \sigma'_y$$

(Surabaya clay)

$$= 0.85 (0.27 \sim 0.28) \sigma'_y = 0.235 \sigma'_y$$

(Ariake clay)

$$= 0.85 \times 0.27 \sigma'_y = 0.23 \sigma'_y$$

(Kuwana clay)

As indicated in Eq. (11), $\tau_{f(mob)}$ is uniquely related to $\sigma'_y$ irrespective of overconsolidation ratio, OCR and $I_p$. Mesri (1975) also pointed out that $\tau_{f(mob)}$ could be given by 0.22 $\sigma'_y$ irrespective of $I_p$ when the typical values of $\tau_{f(oc)} / \sigma'_{vo}$, OCR and $\mu$ reported and proposed by Bjerrum (1973) are combined. It is also possible to correlate $\tau_{f(oc)}$ and $q_e$ to $\sigma'_y$ using Eq. (8) and (11) as shown below.

$$\sigma'_y = 4.5 \tau_{f(oc)}$$

(Surabaya clay)

= 4.5 $\tau_{f(oc)}$ (Ariake clay) \hspace{1cm} (12a)

= 3.7 $\tau_{f(oc)}$ (Kuwana clay)

$$\sigma'_y = q_e / 3.8$$

(Surabaya clay)

= $q_e / 3.8$ (Ariake clay) \hspace{1cm} (12b)

= $q_e / 4.4$ (Kuwana clay)

The correlations given by Eqs. (8) and (12) can effectively be used not only for design but also for quality control where proper evaluation of $\tau_{f(mob)}$ and $\sigma'_y$ during construction is very important.
USE OF THE PROPOSED METHOD WITHOUT UNDISTURBED SAMPLE

When strength ratio between $\tau_{fn(v)}$ and $\tau_{fn(d)}$ in the N.C. state is known, it is possible to determine $\tau_{f(mob)}$ and $\sigma'_y$ using $\tau_{fo(v)}$ from S.F.V.T. and the $\tau_{fn(v)}/\tau_{fn(d)}$ ratio without undisturbed samples as given by Eq. (13) when characteristics of the normally consolidated aged clay are taken into account as ideally shown in Fig. 14.

$$\tau_{f(mob)} = 0.85 \tau_{fo(d)}$$
$$\tau_{fo(v)} = 0.85 \tau_{fo(v)} \times \tau_{fn(d)}/\tau_{fn(v)}$$
$$\sigma'_y = \tau_{fo(v)} \div \tau_{fn(v)}/\sigma'_{ce}$$

In order to investigate $\tau_{fn(v)}$ values in the N.C. state, a series of the laboratory vane shear tests was carried out for Ariake and Kuwana clays. In this test, a slurried clay was first preliminarily consolidated at $\sigma'_{ce}=20$ kPa in a cylindrical device as shown in Fig. 15 and then again consolidated at different $\sigma'_{ce}$ ranging from 50 to 100 kPa until primary consolidation has been achieved, which was determined by the Taylor's $\sqrt{t}$ fitting method. After that, the consolidation load was released and the vane shear test with $D=1.5$ cm and $H=3$ cm was carried out at a rotating rate of $0.1^\circ$/sec. The values of $\tau_{fn(v)}$ obtained from the laboratory vane shear tests are plotted versus $\sigma'_{ce}$ in Fig. 16 together with $\tau_{fn(d)}$ values from the D.S.T. The values of $\tau_{fn(v)}/\tau_{fn(d)}$ of the upper Ariake and the lower Kuwana clays were as follows:

$$\tau_{fn(v)}/\tau_{fn(d)} = 0.23/0.28 = 0.82$$
(upper Ariake clay)

$$= 0.27/0.27 = 1.0$$
(lower Kuwana clay)

These ratios indicate quite good agreement with the $\tau_{fo(v)}/\tau_{fo(d)}$ ratios as shown in Fig. 11 and Eq. (7). It is then possible to obtain $\tau_{f(mob)}$ and $\sigma'_y$ without undisturbed samples with the use of Eq. (13).

Finally, the flow chart for the proposed method is presented in Fig. 17 for both cases with and without undisturbed samples.
CONCLUSIONS

In order to overcome regional variations both in soil behaviour and technical quality, a new procedure consisting of C.P.T., S.F.V.T. and D.S.T. was proposed to determine $\tau_{f_{\text{mob}}}$ and $\sigma'_y$ of soft clay deposits. From the discussions and test results presented in this study, the following conclusions and suggestions can be made,

(1) A review on procedures currently proposed to determine $\tau_{f_{\text{mob}}}$ suggests that there is a contradiction in correction factor, $\mu$ proposed in each of the methods.

(2) C.P.T., S.F.V.T. and D.S.T. will be recommended as the tests to minimize the effect of difference in technical quality.

(3) Direct shear strength offsets the strength anisotropy and then uniquely be related to $\tau_{f_{\text{mob}}}$ which is given by $0.85 \tau_{f_{\text{o(d)}}}$.

(4) An unique correlation was obtained among $\tau_{f_{\text{o(v)}}}$, $q_c$, $q_u/2$ and $\tau_{f_{\text{o(d)}}}$ of three clays investigated in this study, and then $\tau_{f_{\text{mob}}}$ can be related to these strength as shown by Eq. (8).

(5) The correction factor, $\mu$ for $\tau_{f_{\text{o(v)}}}$ and $\mu_{u/2}$ obtained from this study strongly suggests there is no unique relationship between $\mu$ and $I_p$.

(6) The value of $\sigma'_y$ can be obtained from $\tau_{f_{o}}$ and $\tau_{f_{n/\alpha_{vc}}}$, and then $\tau_{f_{\text{mob}}}$ is also related to $\sigma'_y$, which is given by $0.23 \sigma'_y$ irrespective of overconsolidation ratio and $I_p$.

(7) Then both $\tau_{f_{\text{mob}}}$ and $\sigma'_y$ can be related to $q_c$ and $\tau_{f_{\text{o(v)}}}$ as indicated in Eqs. (8) and (12) which are very useful for design and quality control.

(8) It is also possible to determine $\tau_{f_{\text{mob}}}$ and $\sigma'_y$ without undisturbed sample when $\tau_{f_{\text{n(e)}}}$ and $\tau_{f_{\text{n(d)}}}$ values in the N.C. state are obtained.

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**Fig. 17. Flow chart for the proposed method**
NOTATION

F. S. = factor of safety

\( q_r \) = cone resistance in C. P. T.

OCR = overconsolidation ratio

\( \tau_{fmob} \) = shear strength for design use

\( \tau_{fs} \) = shear strength in the normally consolidated state

\( \tau_{fns} \) = compression strength

\( \tau_{ffe} \) = direct shear strength

\( \tau_{fne} \) = extension strength

\( \tau_{fve} \) = vane shear strength

\( \tau_{fe} \) = in-situ shear strength

\( \tau_{fsc} \) = in-situ compression strength

\( \tau_{fse} \) = in-situ direct shear strength

\( \tau_{fsr} \) = in-situ vane shear strength

\( \sigma' \) = effective stress

\( \sigma'_{mo} \) = in-situ mean effective stress

\( \sigma'_{vc} \) = vertical consolidation stress

\( \sigma'_{mo} \) = effective overburden stress

\( \sigma'_{y} \) = consolidation yielding stress

\( \mu \) = correction factor to determine \( \tau_{f(mob)} \)

\( \mu_a \) = correction factor for strength anisotropy

\( \mu_s \) = correction factor for strain rate effect

REFERENCES


