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Vane Shear Behavior of Soft Bangkok Clay

ABSTRACT: The field vane shear test is one of the most common in situ tests to obtain the undrained shear strength of soft clay. Uncoupling of the torque generated by the soil resistance along the vertical and horizontal planes of the vane has been done by conducting conventional direct shear test and newly developed vertical direct shear test on the soil. From the shear stress-displacement relationship of the direct shear tests, simple analysis is performed to simulate the field vane behavior at various depths. The results of the simulation agree well with those obtained from the field vane tests on soft Bangkok clay. The conventional method of computing the undrained shear strength of the field vane shear based on the maximum torque is close to the equivalent average value from the shear box tests. A special laboratory triaxial vane apparatus was also used to study the shearing behavior of the soft clay with the capability of K_o-consolidating the sample before conducting the vane shear test. The results of the triaxial vane tests were also compared with the predictions. The predicted torque values are lower than the experimental data for the same angle of rotation.

KEYWORDS: anisotropy, clays, in situ testing, laboratory tests, shear strength, torsion

Notation

A_h	Horizontal shearing area of vane
A_{total}	Total shearing area of vane
A_v	Vertical shearing area of vane
c_u	Undrained shear strength
$c_u(rem)$	Remolded undrained shear strength
D	Diameter of vane
e	Base of natural logarithm = 2.718
ε_v	Vertical strain
G_s	Specific gravity
H	Height of vane
I_p	Plasticity index
θ	Angle of rotation
r	Distance from center of vane
R	Radius of vane
S_t	Sensitivity of soil
σ'_v	Vertical effective stress
T	Torque
θ_f	Angle of rotation at maximum torque
T_h	Torque generated by shearing in horizontal plane of vane test
τ_{hh}	Shear stress developed in shearing along vertical plane
$T_{\max}$	Maximum torque generated in vane test
T_{total}	Total torque generated in vane test
T_v	Torque generated by shearing in vertical plane of vane test
τ_{vh}	Shear stress developed in shearing along horizontal plane
w_l	Liquid limit
w_n	Natural water content

Introduction

The field vane shear test is typically used for measuring the undrained shear strength of soft clay. The main problem associated with the vane testing is that the result obtained gives an "average" undrained shear strength, consisting of a combination of vertical and horizontal strength components. If the soil is anisotropic, then the conventional way of computing undrained shear strength in the vane test will be affected by its geometry. For instance, a height to diameter ratio of two is usually adopted in the shear vane, and any change in the ratio will give a different computed shear strength due to anisotropic nature of the soil. Thus, to better understand the vane shear behavior, it is essential to uncouple the soil resistance of the horizontal and vertical shearing surfaces. The shearing behavior of the horizontal plane at the top and bottom of the field vane can be related to the conventional direct shear box, as illustrated in Fig. 1. As for the vertical shearing surface, the behavior can only be represented by a different shearing device with the capability of K_o-consolidating the sample in vertical direction and shearing horizontally on a vertical plane, as shown in Fig. 1. These two types of shearing devices will provide the shear stress-displacement relationships in both shearing planes. Based on these relationships, it is possible to simulate the vane shear behavior by utilizing the results of shear box tests. Essentially, the vane shear test consists of inducing shear failure along a cylindrical surface by the application of a torque through a rod connected with a four-bladed vane. By using the stress-displacement relationship from the shear box tests, the torque versus rotation can be generated, which can be compared with the vane shear tests. A triaxial vane apparatus was also designed and fabricated for investigating the vane shearing behavior under controlled condition in the laboratory.

As described by Silvestri and Aubertin (1988), the soil along the horizontal shearing surface of the vane will fail progressively, starting from the outer edge towards the center during shearing. This

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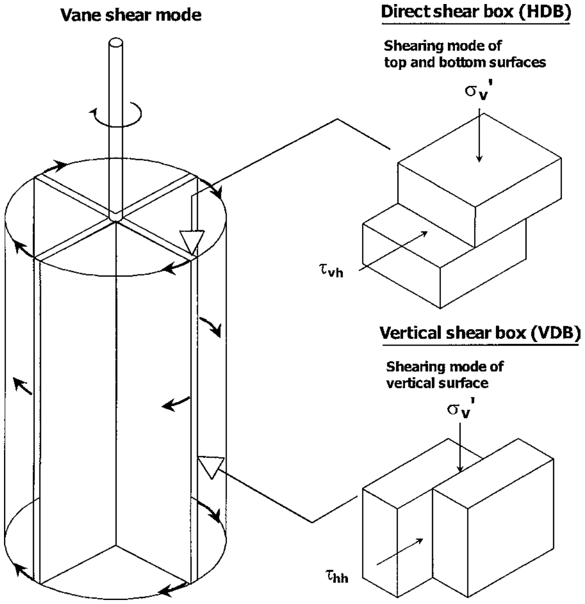

FIG. 1—*Simulation of vane shear mode.*

implies that the maximum possible shear stress in the horizontal plane will not occur at the same angle of rotation. Whereas for the vertical face, the shear stress is uniformly distributed along the vertical surface, the maximum shear stress will be reached at the same angle of rotation. Furthermore, most clays exhibit strain softening behavior, then the maximum torque in the vane test will not coincide with the peak strength on all shearing surfaces, hence the undrained shear strength computed from the vane shear test will not represent the true peak resistance of the soil. Alencar et al. (1988) suggested that soil with rapid post peak reduction of strength would greatly be affected by this progressive failure.

Testing Equipment and Procedure

Conventional Direct Shear Box

The equipment used for determining the shear stress-displacement relationship in the horizontal shearing plane is the conventional direct shear box (Type: HDB) as shown in Fig. 2. The shear box consists of two halves: the lower half of the box can slide freely relative to the upper half when pushing by a motorized drive unit. The size of the specimen is 6 cm in diameter and 2 cm in height. The tested sample is trimmed into cylindrical shape by the cutting shoes mounted on a trimming frame. For consolidation, the vertical load was applied incrementally until the overburden effective stress was reached. The preshear consolidation stress is maintained for 24 h to ensure that the end of primary consolidation is fully reached. The undrained shear condition is achieved by maintaining the height of the sample constant during shearing with adjustment on the vertical applied load. During the shearing process, the relative displacement of the two portions of the specimen and the applied shearing force are measured by a load cell and displacement transducer. The rate of shearing is 1 mm/min, and the test was terminated when the horizontal displacement reached 2 cm.

Vertical Direct Shear Box

For shearing along the vertical surface of the consolidated soil sample, a vertical direct shear box (Type: VDB) is used as shown in Fig. 3, having the ability to K_o-consolidate the sample before applying the undrained shear by keeping the height constant. There are three main compartments of the vertical shear box with the middle compartment able to slide freely in the horizontal direction during shearing, creating two vertical shearing planes on each face of the compartment. All the compartments are resting on bearings to reduce friction, allowing them to move independently on the bearing base. It should be noted that K_o-consolidation could

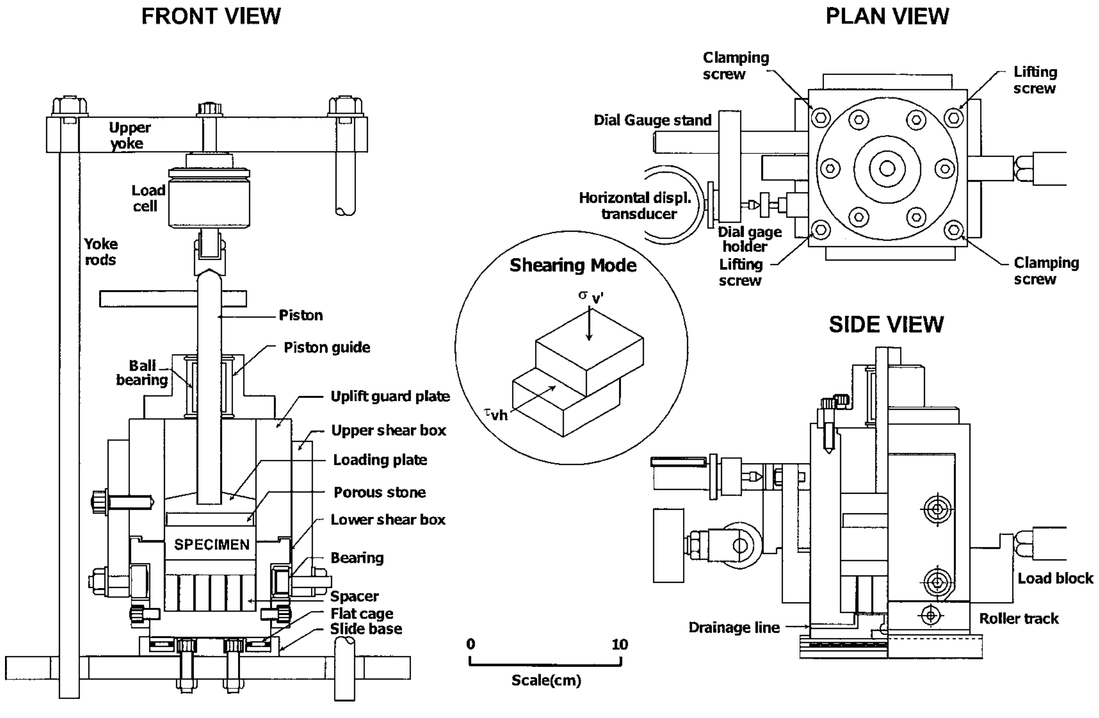

FIG. 2—*Direct shear box for shearing in horizontal plane.*

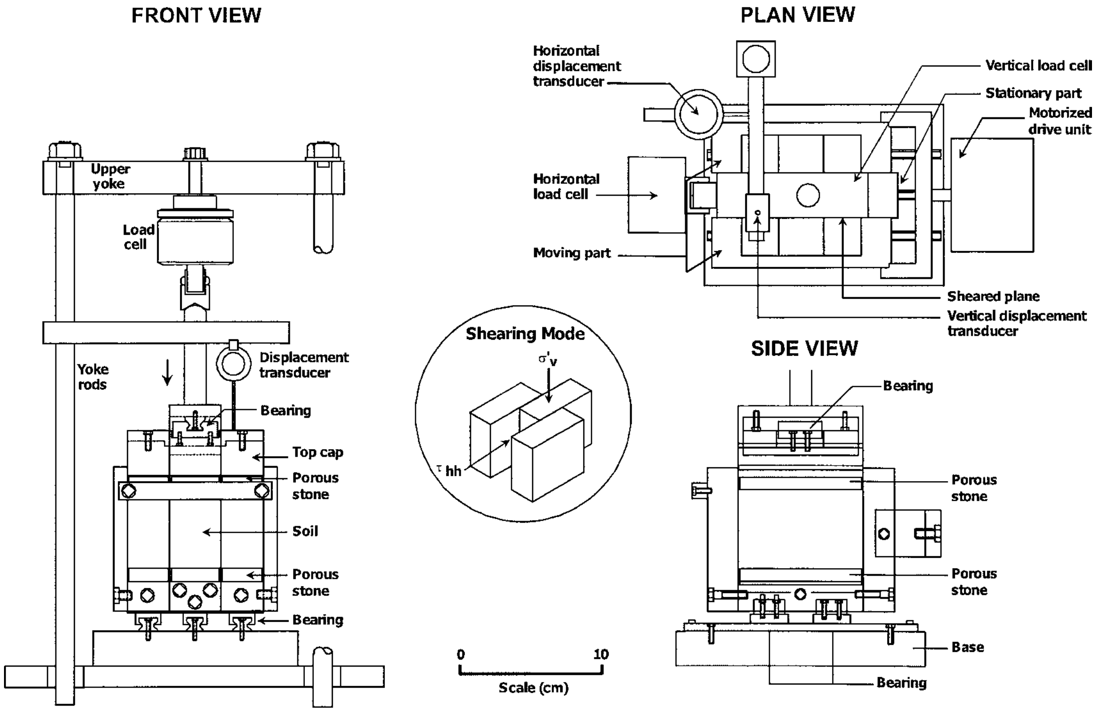

FIG. 3—*Direct shear box for shearing in vertical plane.*

be achieved easily, since the sample is restrained laterally by the compartments. A special top cap has been designed which can be divided into three segments to allow for sliding along with the middle compartment. The middle segment of the top cap is stationary, and the other two pieces are free to move horizontally. Six porous stones, three fixed to the top cap and the other flush with the base, facilitate drainage during consolidation. The undrained shear test is conducted by keeping the height of the sample constant during shearing, as in the horizontal shear box test.

The sample used in the vertical direct shear test is trimmed into rectangular shape by the special trimming frame, consisting of two vertical columns acting as a guide. The dimensions of the sample are 8 cm × 8 cm with height of 5.5 cm. After trimming, filter papers are placed around the sample to ease drainage during consolidation. The sample is transferred to the shear box with three compartments aligned by two restraint bars during consolidation. The top cap is lowered to the top of the soil, then the loading begins. Once the sample has consolidated to the required in situ vertical stress, the restraint bars are removed. The shearing begins by pushing the two moving compartments with the motor. Two load cells are used to measure the vertical and horizontal forces applied, and two displacement transducers are used to measure the vertical and horizontal displacements during shear.

Triaxial Vane Apparatus

The triaxial vane test was first introduced by Kenney (1965) at the Norwegian Geotechnical Institute on Soft Clay Research. The triaxial vane shear apparatus (TX-V) developed in this research consists of a triaxial cell and a torque application machine, as shown in Fig. 4. The base of triaxial cell contains a vane housing and slotted porous stone to house the vane. Ball bearings are used to reduce friction between the vane shaft and the pedestal. A slotted porous stone is necessary to facilitate drainage and pore water pressure measurements during shearing. The vane in its retracted position is placed in the pedestal of the triaxial cell, and it can be inserted into the soil specimen by pushing the vane shaft upwards. The torque application machine is used to apply the torque to the vane during shearing. It can rotate the vane at a constant speed by means of a motor, and it can provide the angle of rotation as well as the applied torque by a calibrated spring. This machine is placed at the bottom of the triaxial cell with the vane shaft directly connected to the calibrated spring. The vane blade is made of four 0.33-mm-thick stainless steel plates with a width of 8.4 mm and a height of 16.8 mm, welded to a 2-mm-diameter stainless steel rod.

The soil sample is first trimmed into a cylindrical shape with diameter of 5 cm and a height of 10 cm. The sample together with the porous stones and top cap are placed in the triaxial cell. Vertical filter paper strips are used to accelerate consolidation. A back pressure is gradually applied to the specimen up to a value of 200 kPa, ensuring that full saturation is achieved. During the saturation process, the effective stress of 15 kPa is maintained. The sample is then K_0-consolidated to the in situ effective stress by applying incremental vertical and horizontal stresses, with the axial strain equal to volumetric strain during consolidation. The loading increment ratio used is kept at 20 % throughout the consolidation stage. After consolidation, the vane is pushed into the specimen with drainage valves open to ensure that the volume of the vane and the rod are compensated. When the vane has reached the testing position, the drainage valves are closed and the shearing begins one minute later. The rate of rotation is kept at 19°/min, and the generated torque is measured continuously until the rotation reaches 360°. Since the vane shaft is not perfectly rigid, corrections for twisting of the vane shaft must be made. Friction resistance of the O-rings and bearing is also measured. The torque experienced by soil would, therefore, be the measured total torque with the soil minus the torque due to friction.

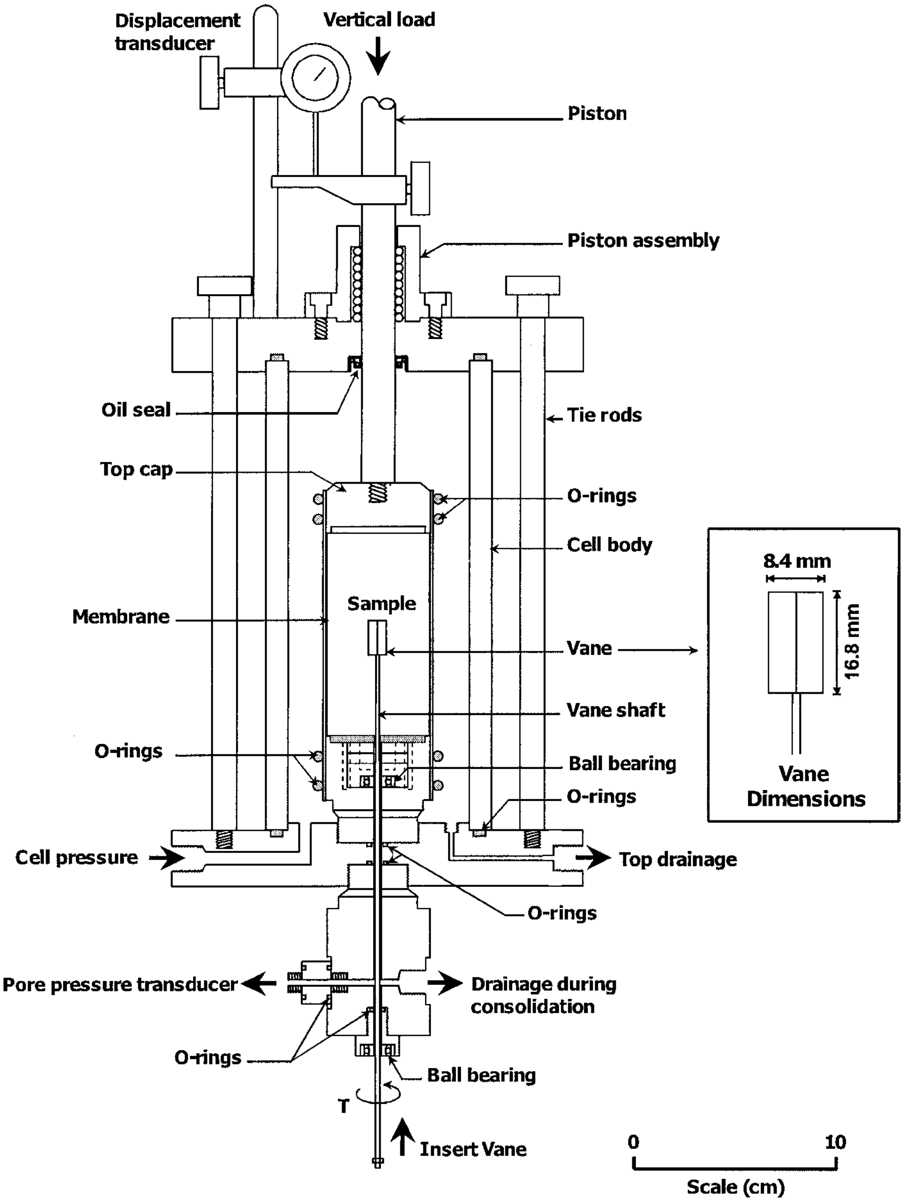

FIG. 4—*K_o consolidation triaxial vane apparatus.*

Geonor Field Vane Apparatus

The field vane tests were performed with the Geonor vane borer (Model No. H-10). The vane with four rectangular blades of equivalent diameter of 5.5 cm and a height of 11 cm was used in this research. The field vane test is conducted by pushing the vane together with its housing into the ground. The vane is stopped at a depth of 50 cm above the tested depth, then the vane is pushed out of the housing to the desired depth. A torque meter is locked in place and connected to the inner rods, which transfers the applied torque of the vane in the ground. The test is performed at a standard rate of 6°/min. The applied torque and rotation are recorded until rotation reaches about 30°. The measured rotations from the field vane tests have to be corrected, since the inner extension rods are twistable. Calibration was made by rotating the inner rods with the vane inside the housing, and corrections to the angle of rotation were done accordingly.

Testing Material and Testing Program

The soft clay used in this research work was collected from the campus of the Asian Institute of Technology (AIT) at a depth between 3.5 m and 5.5 m because of its uniformity. The thickness of the three uppermost layers in the AIT campus consists of 2-m-thick weathered clay crust, followed by a 6-m soft clay layer, and underlain by a layer of stiff clay of about 5–8 m thick. The water table varies from 1 to 2 m below ground surface, depending on the season.

Undisturbed samples for conventional direct shear and triaxial vane tests were collected by using 1-m-long thin walled piston samplers of 7.5 cm diameter. For the vertical direct shear box test, soil samples were collected by using a 50-cm-long thin wall sampler, with diameter of 30 cm. General physical properties of the upper 8 m of soil are given in Table 1.

A total of eight conventional direct shear tests were conducted. All of the samples were K_o-consolidated to their in situ effective stress before subjected to the undrained shear. All tests were carried

TABLE 1—*General properties of Bangkok clay.*

					Gradation (%)		
Depth (m)	W_n (%)	W_l (%)	I_p (%)	G_s	Sand	Silt	Clay
2.5	85.8	95	67	2.70	4	28	68
3.5	93.3	117	77	2.69	2	29	69
4.5	92.1	109	74	2.66	2	23	75
5.5	86.9	92	63	2.67	13	20	67
6.5	68.5	72	49	2.68	2	24	74
7.5	59.9	76	51	2.70	7	29	64

out under the undrained shear condition by keeping the vertical displacement of the tested soil at zero during shearing. Vertical load was adjusted continuously during shearing to keep the volume constant. Six vertical direct shear tests were performed; all tested soil samples were K_o-consolidated to its in situ effective stress before shearing at a rate of 1 mm/min. Six triaxial vane tests were carried out on soil samples from depths of 3.5, 4.5, and 5.5 m. The samples were also K_o-consolidated to the in situ effective stress before inserting a vane into the samples for shearing. Twelve field vane shear tests were conducted in the field at depths of 3.5–5.5 m for comparison purposes.

Results and Discussion

K_o-Consolidation Behavior

All samples used in the laboratory shear tests were K_o-consolidated to the in situ effective stresses incrementally. The magnitudes of the preshear vertical strain are shown in Fig. 5, having values between 0.8 and 2 %. According to Berre (1986), the samples were considered to be of reasonable quality with a low degree of sample disturbance.

Shearing Behavior of Shear Box Tests

The results of the conventional direct shear and vertical direct shear tests, for samples collected from depths of 3.5–5.5 m, are shown in Figs. 6–8. For each test series, at least two samples

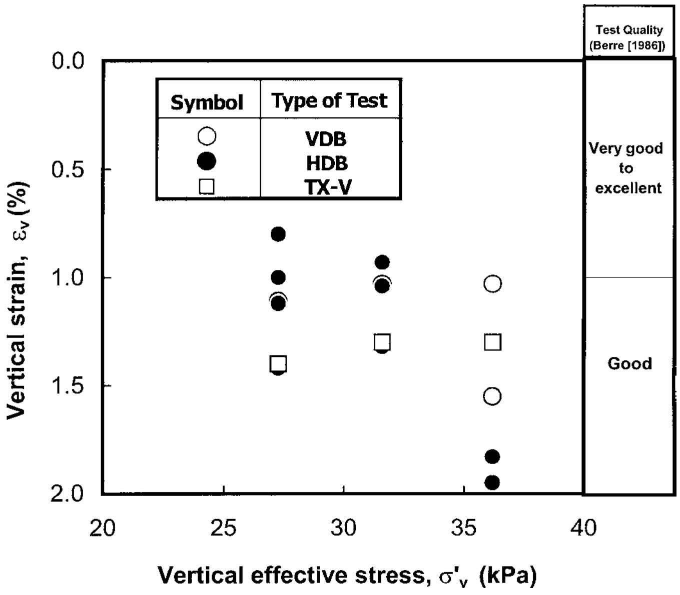

FIG. 5—*Vertical strain at in situ effective stress.*

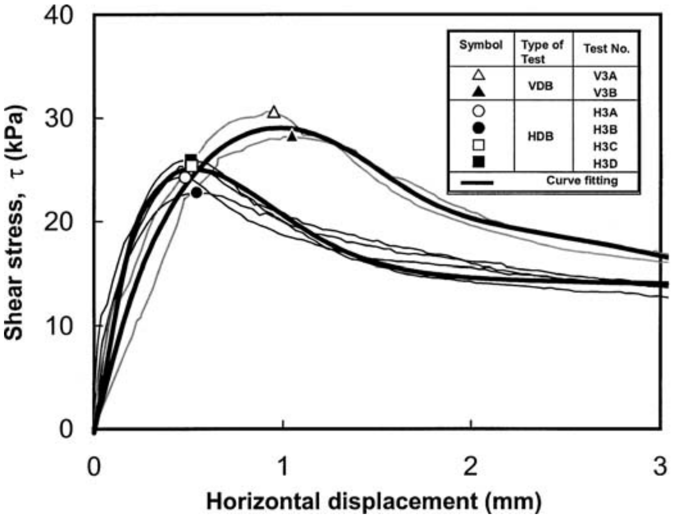

FIG. 6—*Relationship of shear stress and displacement at 3.5 m.*

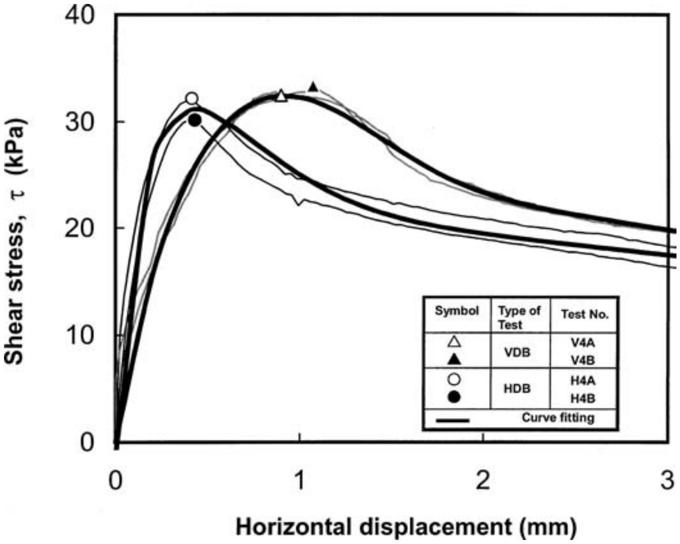

FIG. 7—*Relationship of shear stress and displacement at 4.5 m.*

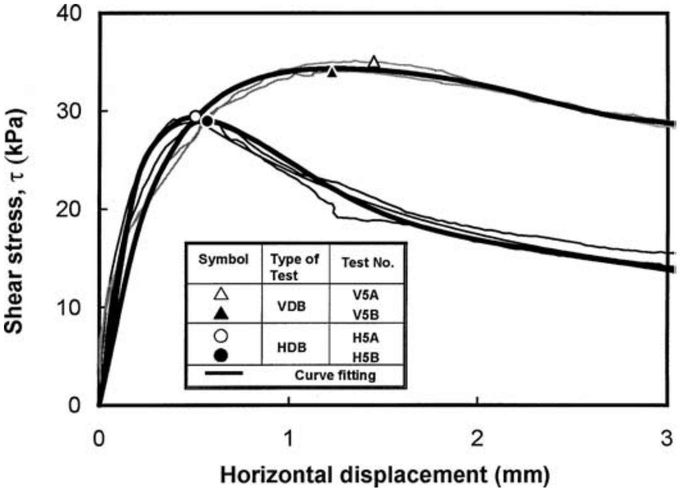

FIG. 8—*Relationship of shear stress and displacement at 5.5 m.*

TABLE 2—*Summary of undrained shear strength from various tests.*

Type of Equipment	Direct Shear		Field Vane				Triaxial Vane	
Depth (m)	Peak τ_{vh} (kPa)	Peak τ_{hh} (kPa)	c_u (kPa)	θ_f (°)	c_u (rem) (kPa)	Sensitivity S_t	c_u (kPa)	θ_f (°)
3.5	24.6 ±1.4	29.5 ±1.6	23.6 ±3.3	1.7 ±0.1	5.7 ±2.3	4.2 ±0.7	40.5 ±2.6	9.4 ±2.1
4.5	31.2 ±1.4	32.9 ±0.6	31.3 ±2.6	2.3 ±0.4	10.8 ±2.1	3.1 ±0.8	40.1 ±3.3	9.4 ±0.7
5.5	29.2 ±0.3	34.5 ±0.7	34.1 ±4.4	3.0 ±0.5	9.1 ±6.2	4.2 ±1.4	34.9 ±5.3	11.5 ±0.8

were tested under the same condition to check the consistency of the tests. In most cases, the results under the same testing condition are repeatable. Generally, all shear stress-displacement curves show strain softening response.

At all three depths, the results for shearing along the horizontal plane give lower maximum shear stress than those from shearing along the vertical plane, as tabulated in Table 2. The range of peak shear stress of horizontal shear tests is between 25 and 31 kPa, whereas the peak shear stress for shearing along the vertical plane varies from 30 to 35 kPa. The difference in the peak shear stress between the two shear surfaces ranges from 2 to 17 %. But the horizontal shear tests give stiffer response and lower displacement at peak than the vertical shear tests. The displacement at peak shear stress for the horizontal shear tests is about 0.5 mm, compared with a value of 1–1.3 mm for the vertical shear tests.

Simulation of Vane Shear Behavior

From the horizontal direct shear and the vertical direct shear test results, it is possible to simulate the torque versus rotation relationship of the vane shear. Since the simulation required integration, it is necessary to best fit the shear stress-displacement relationships of the direct shear box tests with mathematical equations. A simple form of the equation is as follows for both shearing planes:

For horizontal shearing plane:

$$\tau_{vh}(r,\theta) = A(e^{Br\theta}-1) - \frac{C\left(D\,10^{r\theta}\right)^{0.5}}{\left[1+\left(D\,10^{r\theta}\right)^{E}\right]^{F}} + G \qquad (1)$$

For vertical shearing plane:

$$\tau_{hh}(\theta) = H(e^{JR\theta}-1) - \frac{K\left(L\,10^{R\theta}\right)^{0.5}}{\left[1+\left(L\,10^{R\theta}\right)^{M}\right]^{N}} + P \qquad (2)$$

Where A through P are curve fitting constants.

The torque, generated by the shear stress along the horizontal shearing planes at the top and bottom of the vane, can be expressed by

$$T_h(\theta) = 2\int_0^R 2\pi r^2\,\tau_{vh}(r,\theta)\,dr \qquad (3)$$

The torque generated by the shear stress on the vertical shearing plane is given by:

$$T_v(\theta) = 2\pi R^2 H \tau_{hh}(\theta) \qquad (4)$$

Therefore, the total torque of the vane shear is

$$T_{total}(\theta) = T_h(\theta) + T_v(\theta) \qquad (5)$$

For each depth, the curve fitting constants in Eqs 1 and 2 were determined, and the torques generated by vane shearing were computed. A typical simulation result of a field vane test with diameter of 5.5 cm and a height of 11 cm is presented in Fig. 9, showing the torque versus rotation relationships of the vertical and horizontal shearing surfaces. The results clearly indicate that the torque generated along the vertical plane dominates the shear behavior.

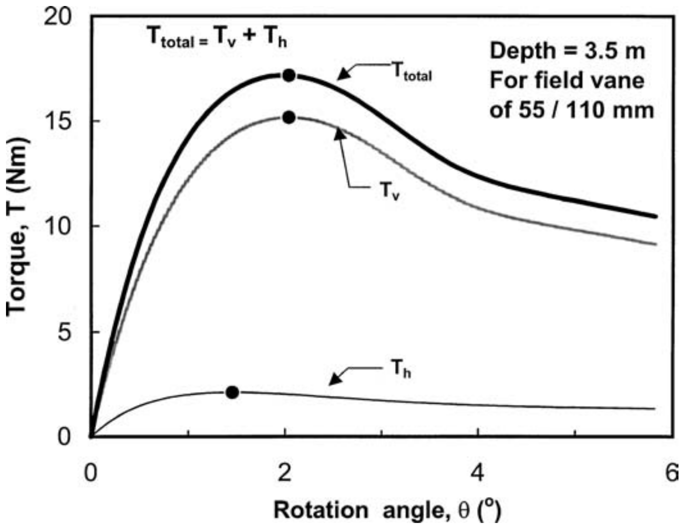

FIG. 9—*Components of torque.*

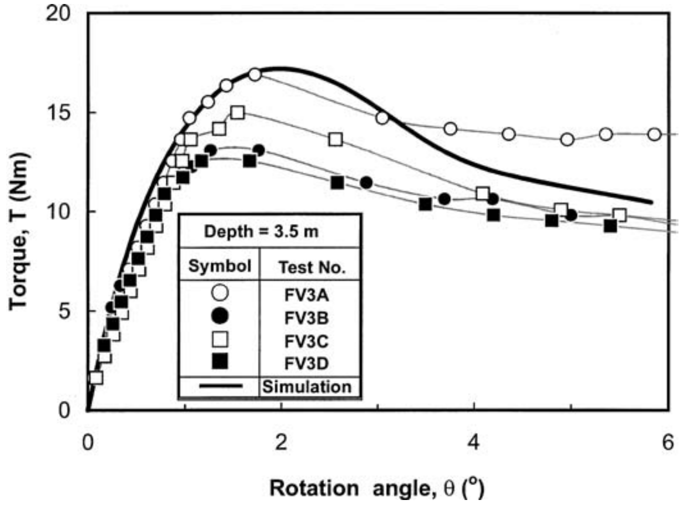

FIG. 10—*Torque versus rotation of field vane shear tests at 3.5 m.*

Prediction versus Measurement for Field Vane Tests

Predictions of the field vane at depths of 3.5, 4.5, and 5.5 m, based on Eqs 3–5, were made as shown in Figs. 10–12, along with field

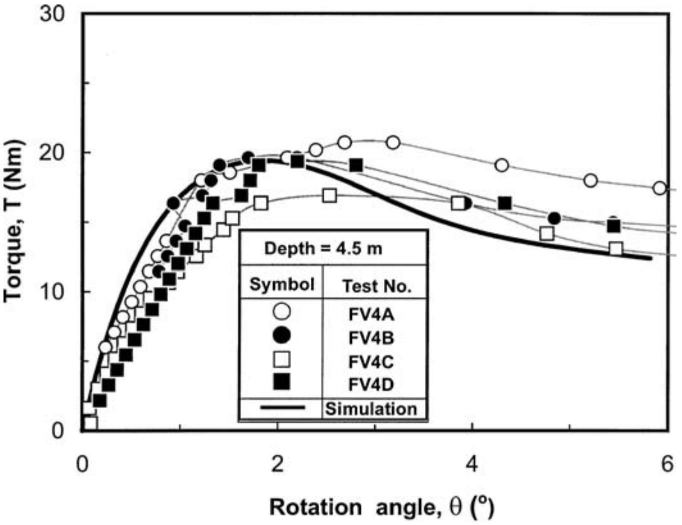

FIG. 11—*Torque versus rotation of field vane shear tests at 4.5 m.*

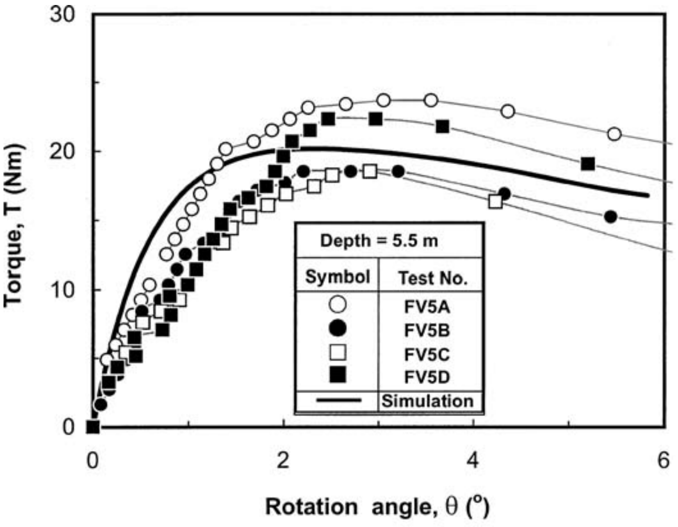

FIG. 12—*Torque versus rotation of field vane shear tests at 5.5 m.*

vane test results. For each depth, four field vane tests were carried out to provide the spatial variation of the tests. At a depth of 3.5 m, the predicted curve gives higher maximum torque than the field vane tests by about 19 %. The predicted rotation angle at maximum torque of 2° is fairly close to the average measured value of 1.7°. At depths of 4.5 and 5.5 m, the predicted maximum torque and corresponding rotation angle are in good agreement with measured values, but the predicted curves give higher stiffness. In summary, the predictions based on results of direct shear tests compare well with measured field vane data.

Prediction versus Measurement for Triaxial Vane Tests

Predictions of the triaxial vane shearing at all three depths were made as shown in Figs. 13–15. The experimental data of the triaxial vane are plotted along with the predicted curves. At a depth of 3.5 m, the predicted torque-rotation curve gives lower torque than the test data, underpredicting the maximum torque by about 30 %. But the rotation at maximum torque agrees well with the experimental data, having a value of about 10°. At a depth of 4.5 m, the predicted

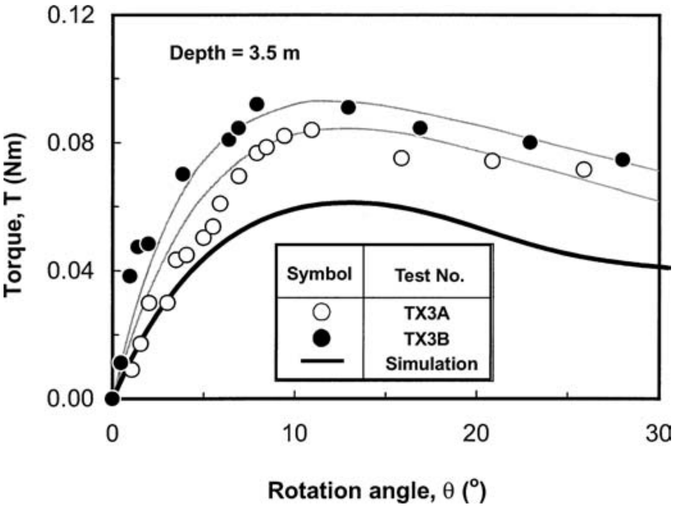

FIG. 13—*Torque versus rotation of triaxial vane shear tests at 3.5 m.*

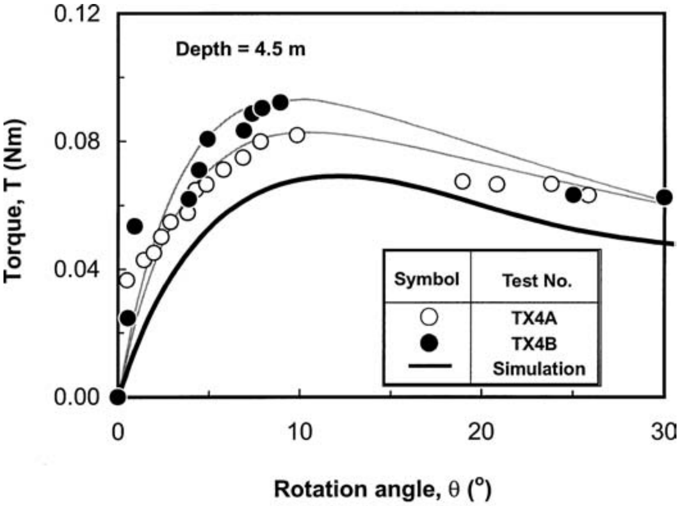

FIG. 14—*Torque versus rotation of triaxial vane shear tests at 4.5 m.*

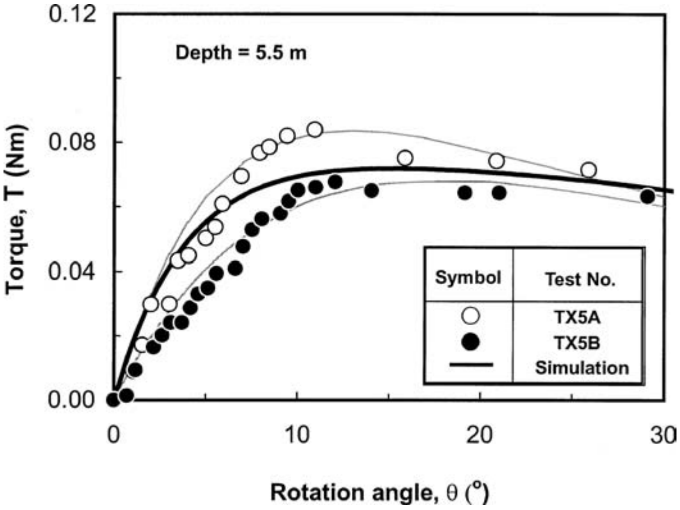

FIG. 15—*Torque versus rotation of triaxial vane shear tests at 5.5 m.*

curve shows very similar shape as the experimental results, but it underpredicts the maximum torque by about 21 %. The predicted rotation angle at maximum torque is reasonably similar to the test data. The predicted curve for a depth of 5.5 m agrees reasonably well with the experimental test result, indicating good agreement in both maximum torque and corresponding rotation angle. Generally, the prediction gives lower torque than the triaxial vane, but the shape of torque versus rotation is quite similar.

Discussion

The results of maximum torque and corresponding rotation angle for both the field vane and triaxial tests at different depths are summarized in Figs. 16–18. The predicted maximum torque and corresponding rotation angle are computed for different vane sizes, having relationships given below:

$$\text{Predicted maximum torque, } T_{\max} \propto D^3 \tag{6}$$

$$\text{Predicted corresponding rotation angle, } \theta_f \propto \frac{1}{D^3} \tag{7}$$

or

$$T_{\max} \propto \frac{1}{\theta_f} \tag{8}$$

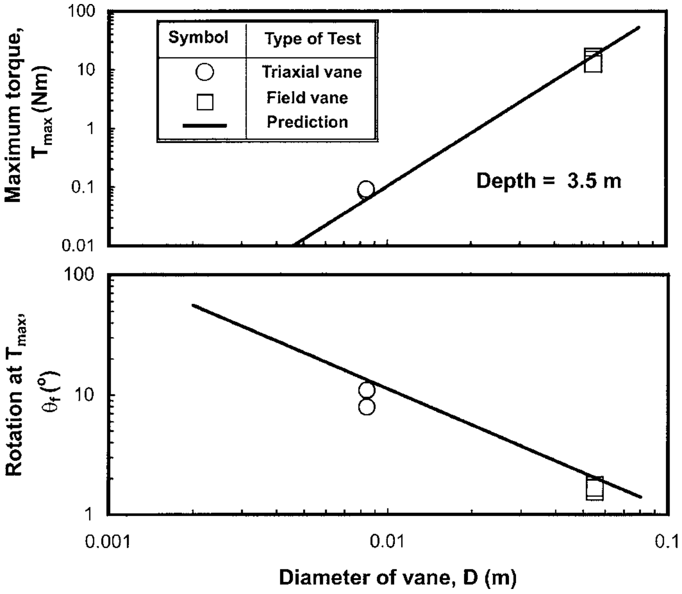

FIG. 16—*Relationship among maximum torque, corresponding rotation and vane size at depth of 3.5 m.*

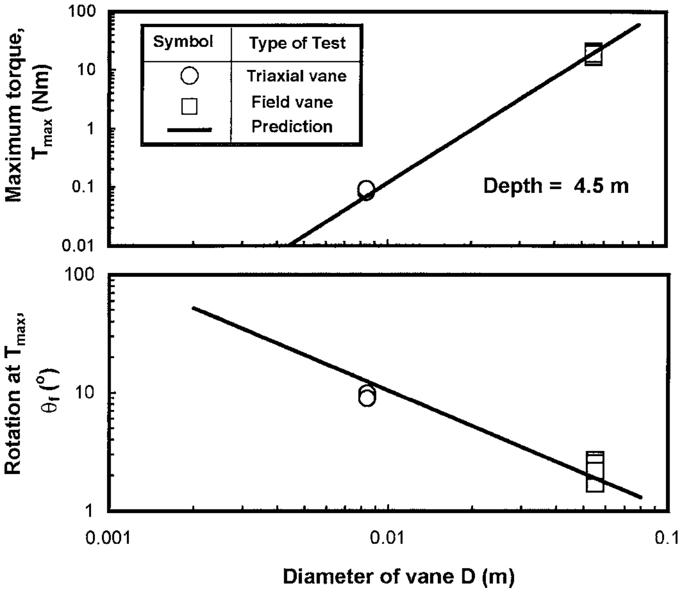

FIG. 17—*Relationship among maximum torque, corresponding rotation, and vane size at depth of 4.5 m.*

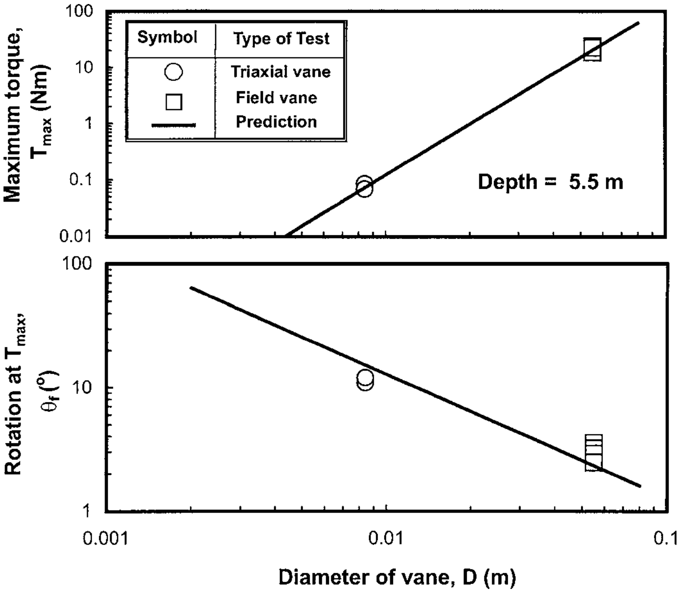

FIG. 18—*Relationship among maximum torque, corresponding rotation, and vane size at depth of 5.5 m.*

In the conventional method of computing the undrained shear strength of the field vane test, the torques of the horizontal and vertical planes are:

$$\text{Along horizontal planes:}\quad T_h = \frac{\pi D^3}{6}\tau_{vh} \tag{9}$$

$$\text{Along vertical plane:}\quad T_v = \frac{\pi D^2 H}{2}\tau_{hh} \tag{10}$$

For height to diameter ratio of 2 (H = 2 D) and assuming that $\tau_{vh} = \tau_{hh}$ at peak, then the ratio of T_h to T_v is:

$$\frac{T_h}{T_v} = \frac{1}{6} = 0.167 \tag{11}$$

At peak torque, the undrained shear strength from conventional method gives

$$c_u(T_{\max}) = \frac{6}{7\pi D^3}T_{\max} \tag{12}$$

Based on the direct shear test results, the peak τ_{vh} is less than the peak τ_{hh}. In the vane shearing, the shear stress of the top and bottom shearing planes will reach the peak at the outer edge of the vane and move towards the center of the vane. Whereas the shearing resistance along the vertical plane will be constant at the same rotation, due to the anisotropic nature and strain softening behavior of the clay as well as the progressive failure on the horizontal planes in the vane shear test, the ratio of T_h:T_v at maximum torque is less than 1/6, as indicated in Fig. 19. At maximum torque, the predicted rotation angle is about 1.9–2.1°, with maximum torque ratio of

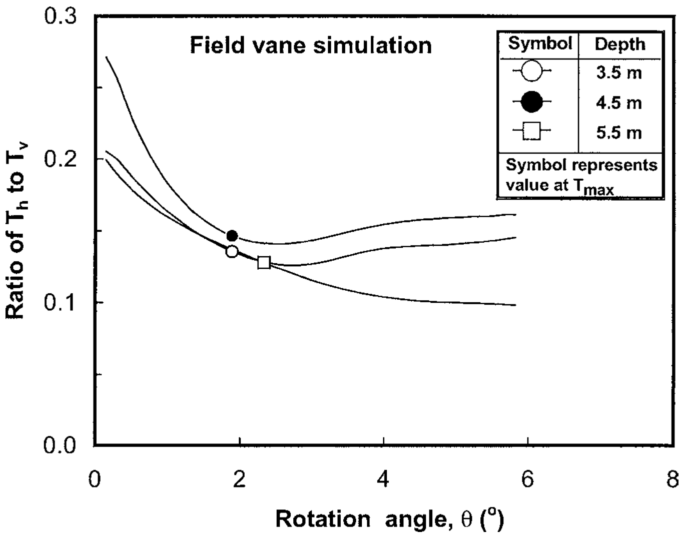

FIG. 19—*Ratio of T_h to T_v versus rotation.*

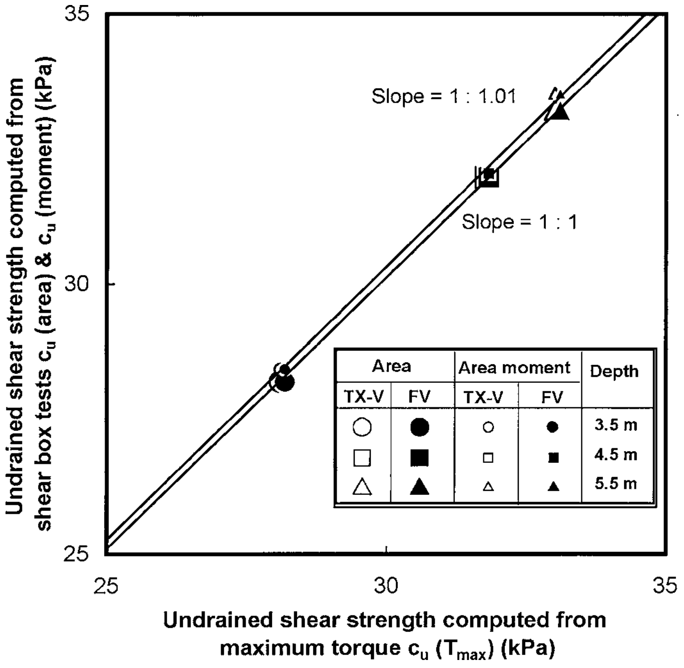

FIG. 20—*Relationship of undrained shear strengths computed from direct shear box and predicted maximum torque results.*

0.13 to 0.15, indicating that the torque component in the horizontal plane has slightly less influence on the total torque than assumed in conventional method.

From the area ratio of the horizontal and vertical shearing planes of the vane, which is 1:4, an average undrained shear strength of the vane can be represented by the following equation:

$$c_u(average) = \frac{A_h \tau_{vh}(peak) + A_v \tau_{hh}(peak)}{A_{total}}$$

Since the area ratio of A_h:A_v is 1:4, then the above equation becomes:

$$c_u(average) = \frac{\tau_{vh}(peak) + 4\,\tau_{hh}(peak)}{5} \tag{13}$$

The undrained shear strength of the clay was computed, based on Eqs 12 and 13, and comparison was made as presented in Fig. 20. The results indicate that the undrained shear strength computed by the conventional method gives almost the same value as the average strength of the direct shear tests, indicating that field vane tests will provide strength comparable to strength from direct shear tests. It should be noted that the difference in strength between the two methods would increase with increasing post peak reduction of strength.

If area moment ratio (which is 1:6) is taken into consideration instead of area ratio, then the average undrained shear strength can be expressed as

$$c_u(average) = \frac{\tau_{vh}(peak) + 6\,\tau_{hh}(peak)}{7} \tag{14}$$

The results from the above equation are compared with results from Eq 12, indicating a difference of only 1 % as shown in Fig. 20. For a perfectly plastic material, the undrained shear strength computed from Eqs 12 and 14 will yield the same value. For Bangkok clay, the strength behavior from recompression triaxial tests in extension and compression modes at in situ stresses is almost isotropic with anisotropy ratio of about 1 (Lai 1993) and a low sensitivity of 3 to 4; therefore, the strength difference is less significant.

Conclusions

Vertical and horizontal direct shear tests have been performed on soft Bangkok clay at depths of 3.5, 4.5, and 5.5 m to understand better the anisotropic behavior of the clay. The results of vertical direct shear tests were used to simulate the torque generated by shearing along the vertical face of the vane shear, whereas the horizontal direct shear test results are used for simulating the torque generated along the top and bottom shearing planes of the vane. Predictions based on the direct shear tests are made and compared with the measured field vane data, as well as laboratory triaxial vane data.

Based on the experimental and predicted results, the following conclusions can be drawn:

- The results of direct shear tests on vertical and horizontal planes indicate that Bangkok clay is slightly anisotropic. The peak shear stress occurs at a displacement of 0.5 and 1.1 mm for shearing in the horizontal and vertical planes.
- The simulations of field vane behavior based on direct shear tests agree relatively well with measured field vane tests in both torque and rotation.
- The predictions of the triaxial vane behavior are less reasonable, but the predicted torque-rotation curves have similar shape as the measurement. The difference in the maximum torque ranges from 0 to 30 %.
- The predicted ratio of T_h to T_v at maximum torque ranges from 0.13 to 0.15, which is less than the value of 0.167 used in the conventional method.
- An average undrained shear strength, based on the results of direct shear tests and area ratio or area moment ratio, gives almost the same value as from the conventional method.

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