SOILS AND FOUNDATIONS Vol. 21, No. 4, Dec. 1981
Japanese Society of Soil Mechanics and Foundation Engineering

SHEAR MECHANISMS OF VANE TEST IN SOFT CLAYS

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ABSTRACT

Although the vane shear test has become a widely used site investigation method for saturated soft clays, its shear mechanism is very complicated and consequently the significance of the resulting vane strength is not necessarily clarified.

In this paper, the shear mechanism of vane test in soft clays is investigated, mainly focussing the stress states on the vertical shear plane. Two types of laboratory vane tests are carried out for the normally K_0-consolidated clays, involving total stress and pore water pressure measurements around shear plane. Also, finite element analysis of vane test is carried out, using a technique of multi-dimensional elasto-plastic consolidation analysis developed by the authors elsewhere.

Based on both the experimental and analytical results, some important implications for the vane shear mechanism are shown through considerations of stress distributions and stress path behaviors.

Key words: clay, effective stress, finite element method, pore pressure, shear mechanism, shear strength, stress distribution, stress path, vane shear test
IGC: D6

INTRODUCTION

The vane shear test was developed to measure the in-situ undrained strength of cohesive soils, and has become a widely used site investigation method for saturated soft clays. Generally, the vane shear is a cylindrical shear due to four vane blades, which is developed by inserting into the ground and rotating them. This process in the vane test produces such an advantage that the in-situ strength measurement become possible with less disturbance and smaller stress changes of soil than in the tests involving the soil sampling. However, the process conversely makes the vane test into a non-element test, involved by a non-uniform stress distribution on the shear plane. Thus, the vane test has a complicated shear mechanism, and consequently the significance of the resulting vane strength has not been necessarily clarified.

The difficulty in the vane test exist in the point whether the vane test which is basically considered as a non-element test can estimate the undrained strength of a soil element. It is no exaggeration to say that, to solve the difficult point described above, many

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Written discussions on this paper should be submitted before October 1, 1982.

researchers have investigated the vane shear mechanism for the effective practical use of the vane test. Recently, a symposium on the vane test was held in Japan, directing the search for a standard of its test procedure.

It may be generally considered that the investigations of the vane test should be developed by both the experimental and analytical methods as supplemented each other, as seen also in the study of Cadling and Odenstad (1950). As for the experimental investigation, the vane shear mechanism has been estimated, based on the in-situ vane test results under the various test conditions, and the factors influencing them have been discussed (Carlson, 1948; Aas, 1965, 1967; Flaate, 1966; Blight, 1968; La Rochelle et al., 1973; Wiesel, 1973; Arman et al., 1975; Torstensson, 1977), and also the results of various laboratory and field tests have been compared for the vane shear mechanism (Kenny and Landva, 1965; Shibata, 1967; Shibata and Tagawa, 1968; Donald et al., 1977; Eden and Law, 1980). Recently, shear stress distributions on both vertical and horizontal blade edges were measured by using a special instrumented vane blade (Menzies and Merrifield, 1980). To clarify the vane shear mechanism from the viewpoint of the effective stress, it is essential to know the stress states on the shear plane, especially the pore water pressure distribution (Shibata, 1967; Bjerrum, 1973; Schmertmann, 1975). It may be very difficult, however, to measure the pore water pressure on the shear plane (Wilson, 1963), because of the complicated vane shear mechanism. Consequently, the effective stress clarification of the mechanism is not sufficient up to date.

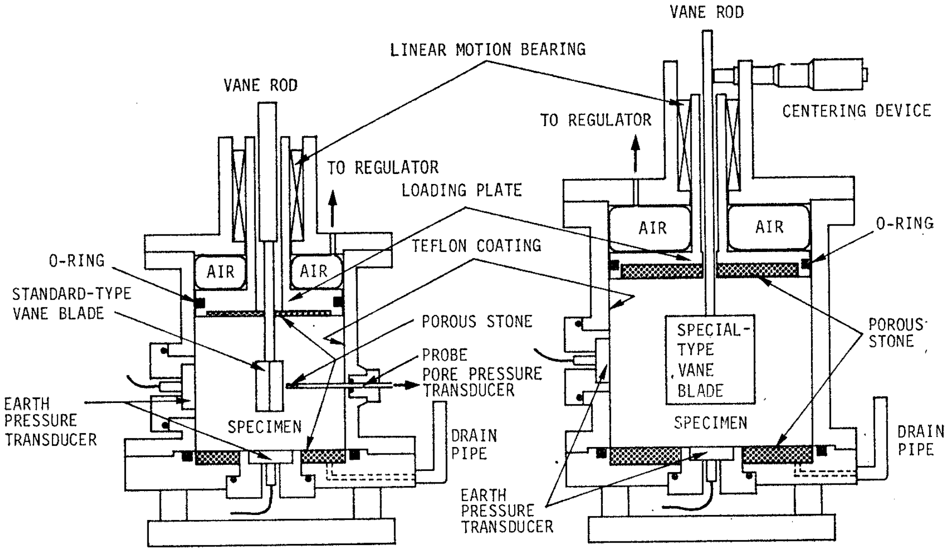
On the other hand, the analytical investigations of the vane test have been carried out far less than the experimental ones. One of the reasons may come from the difficulty of the mathematical treatment. However, the development of the numerical calculation techniques, especially the finite element method, makes comparatively easy the analysis of the vane test. Nevertheless, finite element analyses of the vane shear have been carried out, assuming that soils are linearly elastic (Donald et al., 1977) or non-linearly elastic, without considerations of the consolidation or the local water migration during shear. Therefore, it is necessary to analyze the vane shear based on a more realistic constitutive equation.

Thus, the direct approach to the clarification of stress distributions on the vane shear plane have not sufficiently been carried out, because of both the experimental and analytical difficulties. In view of such a situation as described above, this investigation was begun prior to 1973 and some results were reported (e. g. Matsui and Oritate, 1973; Ito et al., 1975). In this paper, first, the total stress and pore water pressure distributions on the vertical shear plane of laboratory vane are measured experimentally for the normally K_0-consolidated clays. Then, the experimental results are compared with the analytical ones due to finite element method using a technique of multi-dimensional elasto-plastic consolidation analysis developed by the authors (Matsui and Abe, 1981). Finally, based on those experimental and analytical results, the vane shear mechanism is discussed in detail, and some implications for the mechanism will be shown.

MEASUREMENT OF STRESS DISTRIBUTIONS ON VANE SHEAR PLANE

Outline of Laboratory Vane Test

To clarify the stress state around the shear plane of the vane test, two kinds of laboratory vane tests are carried out, involving measurements of the total normal stress and the pore pressure on the vertical shear plane. Test specimens are prepared by the normally K_0-consolidation within soil container cells, as shown in Fig. 1, to turn out a consolidation state as in the existing ground. In one of the vane tests, an ordinary four-blades vane is used and the pore pressure on the shear plane is measured through a probe in-



(a) (b)

Fig. 1. Consolidation cells (a) for standard type vane blade and (b) for special type vane blade

serted into the consolidation cell, as shown in Fig. 1(a). In another vane test, measurements of the total normal stress and the pore pressure around the vertical shear plane are attempted using a special cylindrical vane, in which small miniature transducers of pore water and earth pressures are mounted, as shown in Fig. 2. In the following chapter, the former vane test is called as "standard type", while the latter as "special type". Each test is carried out for almost identical several specimens, varying the relative position between vane blades and the measuring points of the pore pressure or the total normal stress. Checking the identity of those specimens, the distributions of excess pore pressure and total normal stress increment on the vertical shear plane at a certain angle of vane rotation can be obtained. Therefore, the authors paid special attentions to the accuracy of tests and the reproducibility of specimens, especially to the reduction of side friction of consolidation cell for a uniform specimen, the prevention of eccentric vane axis and the stability of measuring system.

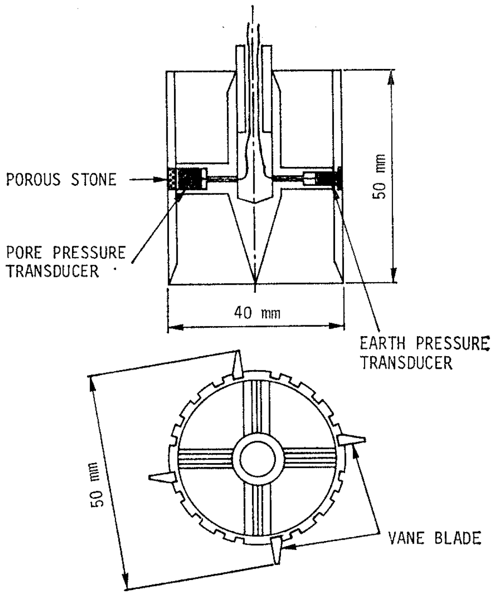


Fig. 2. Special type vane blade

Testing Apparatus and Clay Samples

The vane shear tests were carried out using a laboratory vane testing apparatus designed at the Osaka University. The apparatus is of the rotating type of the turntable on which the specimen is placed, and can give constant angular velocities between 0.002 deg/s and 5.0 deg/s to the specimens. The vane torque is measured by means of a small capacity load transducer of high accuracy through an arm fixed on the vane axis. The advantage of this type of torque measurement is almost negligible rotation of vane blades during shear, which leads to a uniformly constant angular velocity regardless of the magnitude

Table 1. Physical properties of clays

		Kaolin clay	Senri clay	Mixed clay
Liquid limit	w_L (%)	52.8	92.6	65.9
Plastic limit	w_P (%)	32.7	37.7	33.2
Plasticity index	I_p (%)	20.1	54.9	32.7
Specific gravity	G_s	2.69	2.68	2.69
Clay fraction ($<2\,\mu$m)	(%)	60.0	43.0	56.0
Coefficient of permeability	k (cm/min)	3.0×10^{-5}	2.5×10^{-6}	—

of torque. The vane axis is vertically supported by a ball bearing, and then its small rotation makes a little torque loss, which is corrected through the preliminary experiments.

The inside size of the standard type consolidation cell is 120 mm high and 85 mm in diameter, and a hole, through which a probe to measure the pore pressure is inserted, is equipped at the side wall of the cell, while that of the special type is 150 mm high and 120 mm in diameter, as shown in Figs. 1(a) and (b), respectively. In each cell, a consolidation pressure is applied to a specimen through an air bag, in which the pressure is controlled by a regulator, and a rigid loading plate laterally supported by linear motion bearings. The drainage during consolidation is permitted through both ends of a specimen. To reduce the side friction of the cells, their insides are treated with teflon coating. Two earth pressure transducers in the side wall of each cell and one in the bottom plate of each cell are installed to measure the stress states of a specimen. In the special type is used a special device to support the vane axis at the center, because the consolidation is carried out with the special type vane blade buried in the specimen.

The standard type vane blade is of ordinary four blades and has the height of 30 mm, the width of 15 mm and the thickness of 1 mm. The special type vane blade is shown in Fig. 2, in which a cylinder of 50 mm high, 40 mm in diameter and 2.5 mm thick is fixed to the vane axis through a cross-shaped support. Four vane blades of 50 mm high and 5 mm wide are attached to the cylinder in the regular angular interval of 90°. To vary the relative position between vane blades and the measuring points, twenty cuts are made on the side wall of the cylinder. Those cuts also serve to prevent the slide between the cylinder surface and the soil.

The test samples used are Kaolin clay, Senri clay and Mixed clay (Kaolin clay and Senri clay, 4 : 1 in weight), of which the physical properties are shown in Table 1. Kaolin clay is used for both the standard and special type vane tests, while other two kinds of clays only for the former test.

Test Procedure

The standard type vane test is carried out by the following procedure. (1) A remolded column-shaped sample of clay is set within the consolidation cell. (2) A consolidation pressure larger than the preconsolidation one is applied through the loading plate. The consolidation period is five times primary consolidation period for Kaolin clay, while two times for the other clays. The vertical and horizontal earth pressures are measured by the installed transducers during consolidation. (3) A pore pressure measuring probe is inserted through the cell wall, so that the tip of the probe is located at 1 mm outside the potential shear plane. (4) The standard type vane blade is inserted so as to give a certain relative position between vane blades and the probe. (5) The stress changes due to the vane insertion are measured through the installed transducers. After the excess pore pressure due to the vane insertion was dissipated, the vane shear is started. The angular velocity of the vane is 1.0 deg/s or 0.1 deg/s.

On the other hand, the procedure in the special type vane test is almost the same as in the standard type, except methods of the vane insertion and stress measurements on the shear plane. That is, the special type vane blade is inserted before consolidation as follows: i. e. a hole of a certain diameter is bored at the center of clay sample to reduce the inserting resistance and the sample disturbance, followed by filling the water in it and inserting the special type vane blade. The total normal stress and pore pressure around the vertical shear plane are measured by the small miniature transducers installed on the cylindrical wall, and their relative positions to vane blades can be varied by changing the positions of vane blades. The vertical consolidation pressure was 0.20 kgf/cm^2 (19.6 kPa) and 0.18 kgf/cm^2 (17.6 kPa) for the standard and special type vane tests, respectively.

Experimental Results

Table 2 shows the vertical and horizontal normal stresses before and after the vane insertion, the coefficient of earth pressure at rest, the maximum shear resistance of soils and the water content of specimens in the standard type vane tests. The averaged value for seven or eight specimens is shown in each data, followed by the amount of scatter in the parentheses.

The distributions of excess pore pressure on the vertical shear plane, measured at the maximum shear resistance, are shown in Fig. 3 for three kinds of clays, in case of the angular velocity of 0.1 deg/s. It is seen from this figure that for Kaolin clay a positive pore pressure is almost uniformly distributed, while for the other clays non-uniform pore pressure distributions occur, showing positive ones in front of the vane blades to the direction of vane rotation (around $\theta = 0°$ in the figure) and negative ones behind the vane

Table 2. Test results for standard type vane test

		Kaolin clay	Senri clay	Mixed clay
Mean vertical normal stress $\bar{\sigma}_V$ (gf/cm^2)	Before vane insertion	193 (187-200)	192 (187-196)	193 (191-196)
	After vane insertion	194 (191-196)	193 (187-196)	195 (191-196)
Mean horizontal normal stress $\bar{\sigma}_H$(gf/cm^2)	Before vane insertion	91 (80- 94)	87 (82- 98)	88 (83- 98)
	After vane insertion	103 (102-111)	93 (86- 98)	95 (85-102)
Coefficient of earth pressure at rest K_0		0.472 (0.43-0.49)	0.453 (0.44-0.48)	0.456 (0.44-0.50)
Maximum shear resistance $\tau_{\max}$ (gf/cm^2)		97 (92-101)	81 (78- 85)	105 (100-109)
Water content w (%)		47.8 (47.4-48.2)	76.1 (75.7-76.9)	57.4 (57.1-57.9)

1 gf/cm^2 = 98 Pa

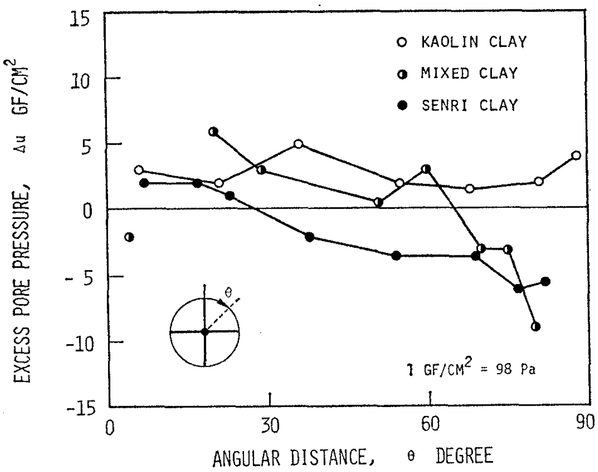


Fig. 3. Distributions of excess pore pressure for standard type vane test

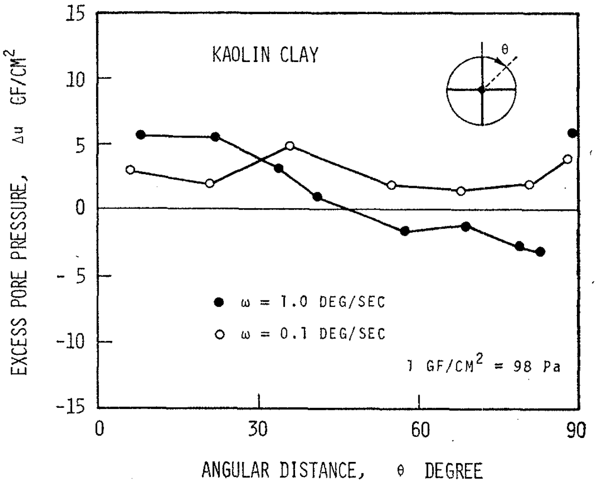
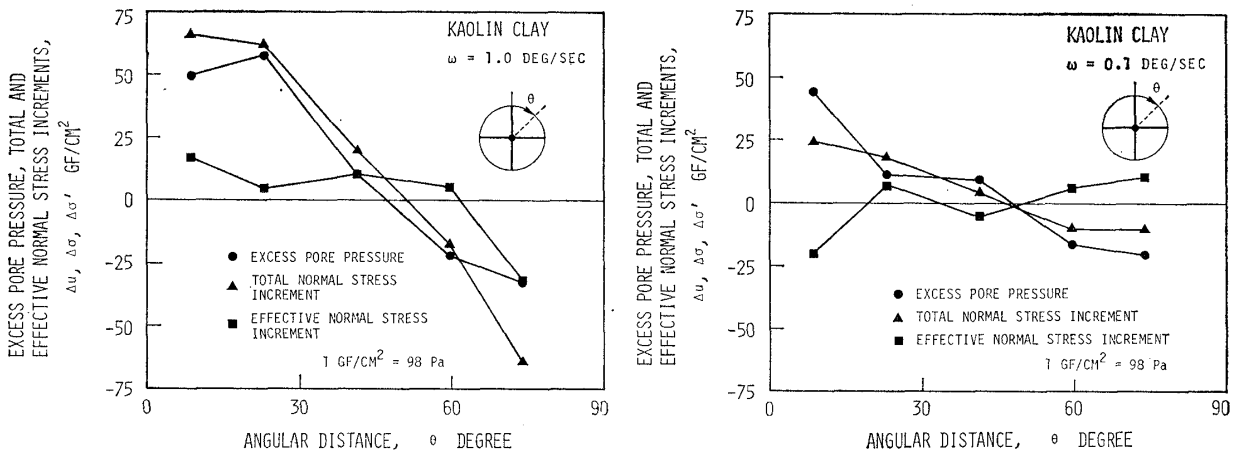


Fig. 4. Effect of angular velocity of vane rotation on excess pore pressure distribution for standard type vane test



(a) $\omega=1.0$ deg/s (b) $\omega=0.1$ deg/s

Fig. 5. Distributions of excess pore pressure, total and effective normal stress increments for special type vane test

blades (around $\theta=90°$ in the figure). For Mixed clay, the excess pore pressure on a large part of shear plane are positive, while for Senri clay negative. Fig. 4 shows the same distribution for Kaolin clay as in Fig. 3, comparing with the case of angular velocities of 1.0 deg/s. In case of the faster angular velocity, the negative pore pressure occurs behind the vane blades to the direction of vane rotation, and consequently the distribution becomes non-uniform.

Thus, it is substantiated from the results of the standard type vane tests that the pore pressure distribution around the shear plane significantly changes depending on both the permeability of clay and the angular velocity (the shearing period).

Figs. 5(a) and (b) show the results of the special type vane tests for Kaolin clay in cases of angular velocities of 1.0 deg/s and 0.1 deg/s, in which the distributions of the excess pore pressure, total and effective normal stress increments around the vertical shear plane are illustrated. It is clearly noticed from these figures that both the excess pore pressure and the total normal stress increment gradually decrease with increasing the angular distance from positive values in front of the vane blades to the direction of vane rotation ($\theta \simeq 0°$) until negative values behind the vane blades ($\theta \simeq 90°$), and that the resulting effective normal stress increments are distributed around zero, and then the effective normal stress itself does not change largely.

Comparing Fig. 5(b) with Fig. 4, in case of the angular velocity of 0.1 deg/s for Kaolin clay, the trends of excess pore pressure distributions in both the standard and special type vane tests are clearly different. This is so because the sizes and shapes of both type vane blades are different, which leads to the different conditions of the local pore water migration. Therefore, sufficient care for such different factors from in the standard type vane should be taken to explain test results.

ANALYSIS OF VANE TEST AND RESULTS

Analytical Model of Clay and Analytical Method of Vane Test

The special type vane test in the previous chapter is analyzed by finite element method using a technique of multi-dimensional elasto-plastic consolidation analysis developed by the authors (Matsui and Abe, 1981). The technique makes possible to consider the effect of the consolidation or the local pore water migration during vane shear. The stress-strain relation can be derived through a strain-hardening elasto-plastic model, which is derived

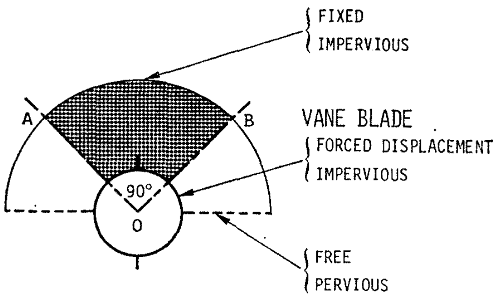


Fig. 6. Boundary and drainage conditions of analyzed semicircle region

Table 3. Basic mechanical constants of Kaolin clay

Compression index	λ	0.161
Swelling index	κ	0.031
Stress ratio at active critical state	M_a	1.42
Stress ratio at passive critical state	M_p	1.42
Void ratio at $p'=1\,\text{kgf/cm}^2$ (98 kPa)	e^*	1.104
Poisson's ratio	ν	0.3207
Coefficient of earth pressure at rest	K_0	0.472
Coefficient of permeability(cm/min)	k	3.0×10^{-5}

by referring to the concept of Cambridge theory.

The yield function F of the model is given by the following equation.

$$\left.\begin{aligned} &F=p'\left\{\frac{M_a+(\alpha_a-1)}{M_a+(\alpha_a-1)\eta_{k0}}\right\}^{\left(\frac{\alpha_a}{\alpha_a-1}\right)}-p_y'=0 && \text{for the active state}\\ &F=p'\left\{\frac{M_p+(1-\alpha_p)\eta_{k0}}{M_p+(1-\alpha_p)\eta}\right\}^{\left(\frac{\alpha_p}{1-\alpha_p}\right)}-p_y'=0 && \text{for the passive state}\end{aligned}\right\}\quad(1)$$

in which p' is the mean effective principal stress, η is the stress ratio ($=q/p'$, where q is the generalized shear stress), η_{k0} is the stress ratio on the K_0–line, M_a and M_p are stress ratios at the critical state in the active and passive stress states, respectively, α_a and α_p are parameters on the plastic strain increment ratio for the active and passive stress states, respectively, which are evaluated from the dilatancy behavior of shear test results of clays, and p_y' is the strain hardening parameter. The relation between the strain hardening parameter and the plastic volumetric strain v^p is shown by the following equation.

$$\frac{\delta p_y'}{p_y'}=\left(\frac{1+e}{\lambda-\kappa}\right)\delta v^p \qquad (2)$$

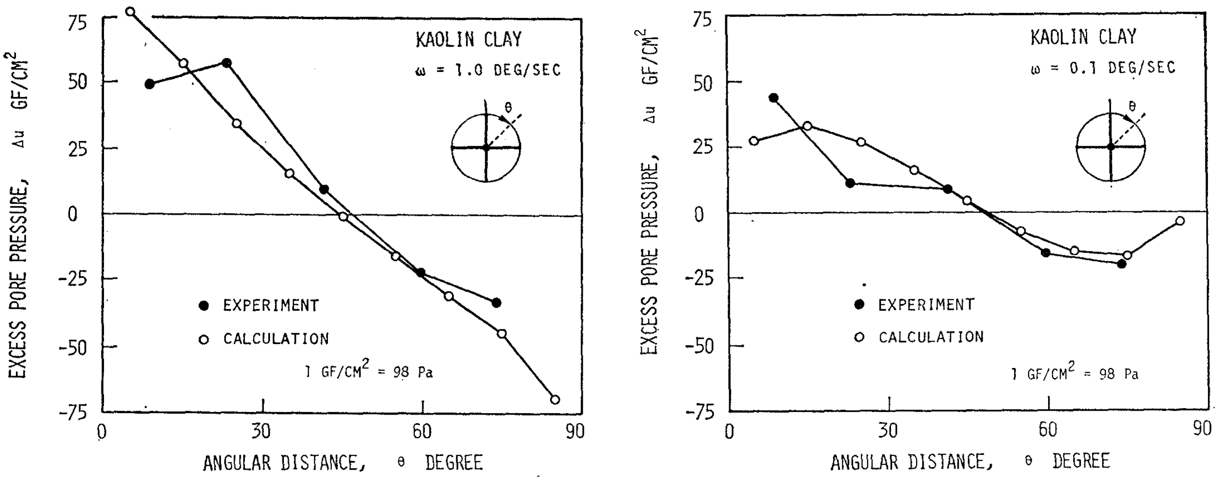
in which e is the void ratio, λ and κ are the compression and swelling indexes, respectively. The other detailed presentation of the analytical model can be found elsewhere (Matsui and Abe, 1981).

It is assumed that the model clay is normally K_0–consolidated, and the basic mechanical constants for Kaolin clay are shown in Table 3. Furthermore, it is also assumed that the model clay is perfectly elasto-plastic after reaching failure, and is not time-dependent.

Outline of the numerical calculation and the necessary assumptions to analyze the stress states during vane shear are as follows: (1) The analysis is carried out on the vertical vane shear plane. The deformation condition is a plane strain one, restrained to the vertical direction. (2) The clay layer before vane shear is normally K_0–consolidated, of which the direction of the maximum principal stress is vertical. (3) The special type vane blade is used, and the vane blade itself is rigid. (4) There is no slip or separation between the vane blade and the clay. (5) The analyzed region is a semicircle of a diameter of 12 cm. The boundary and drainage conditions of the semicircle are shown in Fig. 6. The analytical results in the region of a sector OAB in Fig. 6 are always used in the following discussions. (6) Such three cases as a case of the undrained in each element (no local pore water migration) and two cases of the drained in angular velocities of 1.0 deg/s and 0.1 deg/s are analyzed.

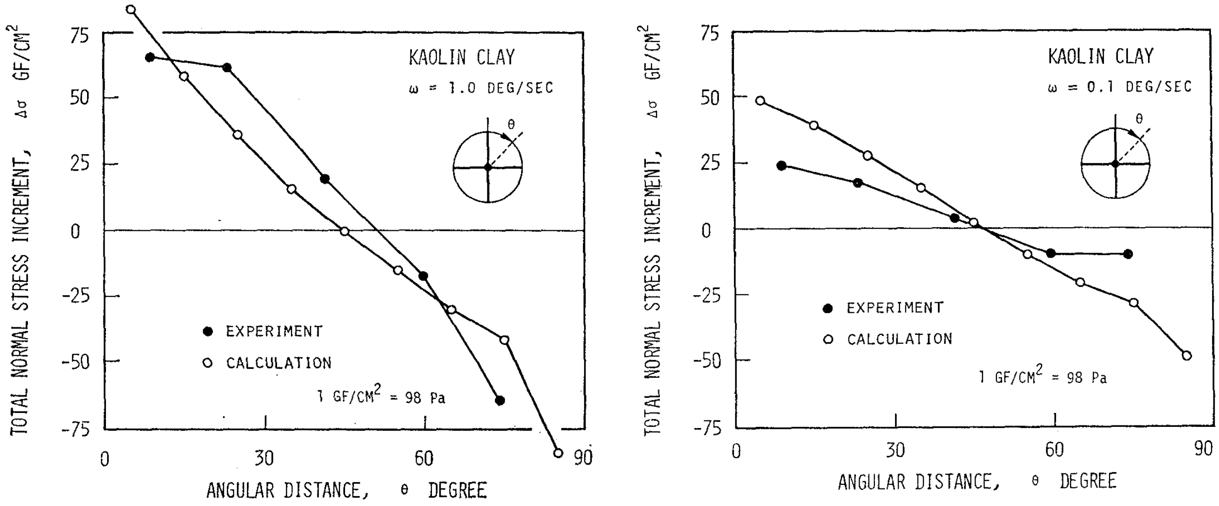
Comparison between Analytical and Experimental Results

Figs. 7, 8 and 9 show the distributions on the vertical shear plane of the excess pore



(a) $\omega=1.0$ deg/s (b) $\omega=0.1$ deg/s

Fig. 7. Comparison between analytical and experimental distributions of excess pore pressure



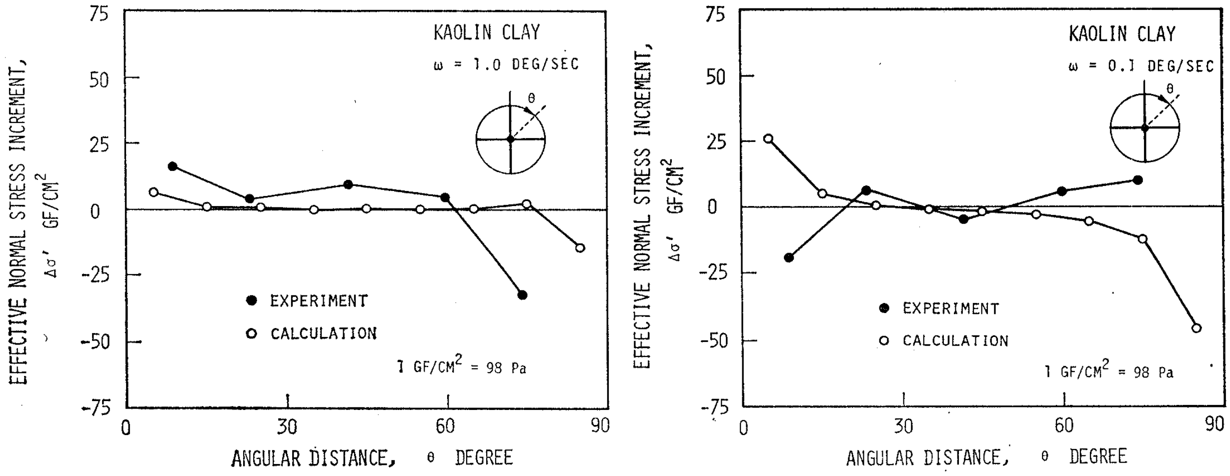
(a) $\omega=1.0$ deg/s (b) $\omega=0.1$ deg/s

Fig. 8. Comparison between analytical and experimental distributions of total normal stress increment

pressure Δu, the total normal stress increment $\Delta\sigma$ and the effective normal stress increment $\Delta\sigma'$ at the maximum shear resistance, respectively, comparing with the experimental results. In these figures, (a) and (b) correspond to the cases of angular velocities of 1.0 deg/s and 0.1 deg/s, respectively. It is seen in these figures that both analytical and experimental results quantitatively agree well, including their distribution forms, although there may be slightly larger difference in both results near vane blades ($\theta\simeq0°$ or $90°$). Consequently, judging from the good agreement described above, it may be possible to estimate the stress states around the vertical shear plane of vane test, based on both results.

CONSIDERATIONS ON VANE SHEAR MECHANISM

Fig. 10 shows the analytical results of excess pore pressure distributions on the vertical shear plane at the maximum shear resistance for various conditions of the pore water migration. It is seen in this figure that the slower the angular velocity of vane, the smaller



(a) $\omega=1.0$ deg/s (b) $\omega=0.1$ deg/s

Fig. 9. Comparison between analytical and experimental distributions of effective normal stress increment

the changes in excess pore pressures, and that the result of drained case of $\omega=1.0$ deg/s is very close to that of the undrained case. Thus, synthetically judging from all results obtained before, the undrained condition for Kaolin clay may be approximately satisfied in cases of $\omega \geqq 1.0$ deg/s.

Based on the vane test results for silts (Blight, 1968), a practical criterion for the undrained condition (the degree of drainage is less than about ten percent) can be obtained as follows;

$$T=\frac{c_v t_f}{D^2} \leqq 0.02 \text{ to } 0.04 \qquad (3)$$

in which T is a time factor, c_v is the coefficient of consolidation, t_f is the test duration or time to failure and D is the width of the vane blades. The time factor for Kaolin clay at $\omega=1.0$ deg/s is calculated as $T \simeq 0.025$. Therefore, it is suggested that Eq. (3) can be also applied to cohesive soils.

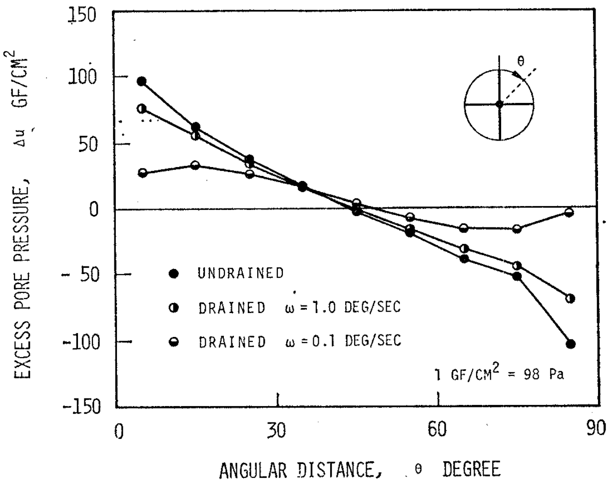
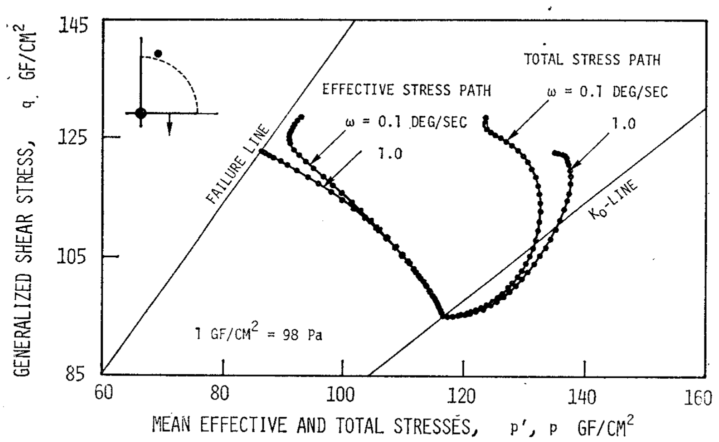


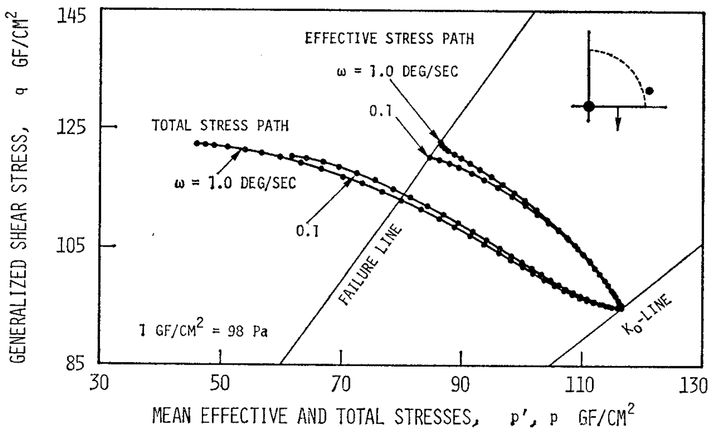
Fig. 10. Effect of local pore water migration on excess pore pressure distribution

In the vane tests of normally consolidated clays, the contractive and dilative zones may occur in front of and behind the vane blades to the direction of vane rotation, respectively. Approximately holding the undrained condition, in front of the vane blades, both the excess pore pressure and the total normal stress increase, while behind the vane blades, both of those decrease. The resulting effective normal stress, however, does not change significantly. Such the vane shear mechanism as described above, substantiated through both experimental and analytical results, may imply that the vane test for normally consolidated clays can be assumed an element test.

Because the distribution gradient of excess pore pressure around the shear plane, especially around the vane blades, is large, the smoothing of the excess pore pressure will rapidly occur. As the results, the clays in front of the vane blades may become contractive (consolidated), followed by the increase of the effective normal stress, and the clays



(a) Element in front of vane blade



(b) Element behind vane blade

Fig. 11. Analytical stress path behaviors

behind the vane blades may become dilative (swelled), followed by the decrease of it. Figs. 11 (a) and (b) show the analytical stress paths for Kaolin clay. It is seen in this figure that, in case of the slower angular velocity, an element in front of the vane blade does not reach failure because of the consolidation effect, while that behind the vane blade reaches failure at a lower shear stress because of the swelling dilation. These results give a support to the vane shear mechanism described above.

CONCLUSIONS

In this paper, the shear mechanism of vane test has been clarified, based on both the experimental and analytical results. The main conclusions obtained are summarized as follows:

(1) The analytical results of the stress states around the vertical shear plane of vane test, which are obtained by finite element method using a technique of multi-dimensional elasto-plastic consolidation analysis developed by the authors, quantitatively agree well with the experimental ones. Consequently, it may be possible to estimate the vane shear mechanism, based on both results.

(2) The excess pore pressure distribution around the vertical shear plane of vane test significantly changes depending on both the permeability of soils and the angular velocity of vane (the shearing period).

(3) For Kaolin clay used, the undrained condition (no pore water migration) is

approximately satisfied in cases of $\omega \geqq 1.0$ deg/s. A practical criterion of Eq. (3) for the undrained condition may be also valid for clays.

(4) As far as the undrained condition approximately holds, in front of the vane blades to the direction of vane rotation, both the excess pore pressure and the total normal stress on the vertical shear plane increase, while behind the vane blades both of those decrease. The effective normal stress on it, however, does not change significantly. Such a vane shear mechanism is given a support by the stress path considerations.

(5) The vane shear mechanism described above may imply that the vane test for normally consolidated clays approximately under the undrained condition (no pore water migration) can be assumed an element test.

In this paper, the vane shear mechanism for soft clays has been discussed, mainly focussing the stress states on the vertical shear plane. Studies on the disturbance and consolidation of clays due to the vane insertion, the adhesion characteristics between the vane blade and the clays, and the rotation of the principal stress on the shear plane are left out. To clarify the vane shear mechanism for various types of soils, further investigations are also necessary especially on the effects of the loading rate, the anisotropy and the progressive failure.

ACKNOWLEDGEMENTS

The authors are indebted to Professor T. Ito, at the Osaka University, for his kind support and encouragement. They wish also to express their gratitude to Messrs. K. Oritate and Y. Ohkita for their experimental works. This study was performed with the financial support of Grant-in-Aid for Scientific Research, the Ministry of Education. This support is gratefully acknowledged.

NOTATION

c_v = coefficient of consolidation
D = width of vane blade
e = void ratio
F = yield function
p' = mean effective principal stress
p_y' = strain hardening parameter
q = generalized shear stress
T = time factor
t_f = test duration or time to failure
$\varDelta u$ = excess pore pressure
v^p = plastic volumetric strain
α_a, α_p = parameters on plastic strain increment ratio for active and passive stress states, respectively
η = stress ratio
η_{k0} = stress ratio on K_0-line
θ = angular distance
κ = swelling index
λ = compression index
M_a, M_p = stress ratios at the critical states in active and passive stress states, respectively
$\varDelta\sigma$ = total normal stress increment
$\varDelta\sigma'$ = effective normal stress increment
ω = angular velocity

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(Received February 2, 1981)