A Study of the Effect of Vane Shape and Rate of Strain on the Measured Values of *In-Situ* Shear Strength of Clays

Une Etude des effets de la forme du moulinet et de la vitesse de déformation sur la résistance au cisaillement des argiles *in situ*

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SUMMARY

Comprehensive studies of the *in-situ* shear strength of clays have been made at four sites, using the vane test and vanes of various shapes. This paper describes the results of these tests and the method of interpreting the results. The primary purpose of the tests has been to investigate the possibility of measuring the anisotropy of the undrained shear strengths of normally consolidated clays.

In addition, the paper gives the results from two other types of field vane test, intended to investigate the effect of rate of strain on the shear strength. One type consists of slow tests with the time to failure being two to four days. The other type was the conventional rapid test performed one to three days after the vane was pressed into position.

SOMMAIRE

On a fait des essais élaborés sur quatre terrains avec des moulinets de formes différentes. L'article donne les résultats et décrit la méthode d'interprétation des essais. La raison principale de ces essais était de déterminer l'anisotropie dans la résistance au cisaillement à teneur en eau constante des argiles normalement consolidées.

De plus, on donne les résultats de deux autres types d'essais au moulinet, dans l'intention d'étudier l'effet de la vitesse de déformation sur la résistance au cisaillement. Un type d'essai était à petite vitesse (temps jusqu'à la rupture deux à quatre jours). L'autre type était l'essai conventionnel rapide effectué de un à trois jours après que le moulinet eût été enfoncé.

IT HAS FOR SOME TIME been apparent (Bjerrum, 1961), that, in Swedish and Norwegian sensitive and quick clays, the conventional laboratory shear tests give substantially higher values of the effective-stress shear-strength parameters than those calculated from *in-situ* undrained vane tests and from investigations of land slides. To study this problem the Norwegian Geotechnical Institute has carried out comprehensive research during the past three years, including field and laboratory tests, on sensitive clays. As a part of this programme, the *in-situ* shear strength was studied with the use of the vane test. To study the anisotropy of the shear strength properties, undrained vane tests have been performed with vanes of different shapes. The effect of the rate of strain was investigated by performing two additional types of vane tests, the consolidated-undrained and drained vane tests. The results of these three types of vane tests will be described in this paper.

The vane test series described below were performed at four different test sites around the Oslo fjord (Fig. 1). At each test site the subsoil is a soft, late glacial marine clay deposit. Average values of the geotechnical properties of the clay at the four sites are given in Table I.

UNDRAINED TESTS WITH VANES OF DIFFERENT SHAPE

A possible explanation of at least a part of the discrepancy between the results of laboratory tests and those from field measurements could be anisotropy of the shear strength of clay. It is possible that the undrained shear strength is dependent on the initial effective normal stress and the shear stress in the failure plane. *In situ*, these stresses might vary in different directions. In an attempt to determine the shear strength anisotropy of clay in its undisturbed state, *in-situ* undrained vane tests have been performed using vanes of various shapes.

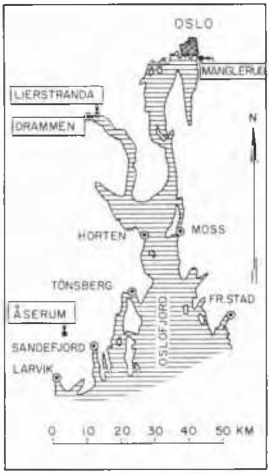

FIG. 1. Location of test sites.

Testing Procedure

The vane types used are shown in Fig. 2. Whereas the Norwegian Geotechnical Institute's standard vane has a ratio $H/D = 2$, the new vanes have H/D ratios ranging between 0.5 and 4. In addition, two vanes having a greater H/D ratio were used at Drammen and Lierstranda.

The tests were carried out in accordance with the standard procedure for vane tests (Andresen and Bjerrum, 1957). A

TABLE I. PROPERTIES OF THE CLAYS AT THE FOUR TEST SITES

	Test site			
	Åserum, slightly over-consolidated quick clay	Drammen, normally consolidated silty sensitive clay	Lierstranda, normally consolidated silty quick clay	Manglerud, normally consolidated silty quick clay
w (per cent)	67	34	35	36
w_L (per cent)	45	32	25	27
w_P (per cent)	26	18	19	19
I_P (per cent)	19	14	6	8
S_t	20–100	4–9	50–150	40–170
s_u/p	0.19	0.12	0.10	0.11

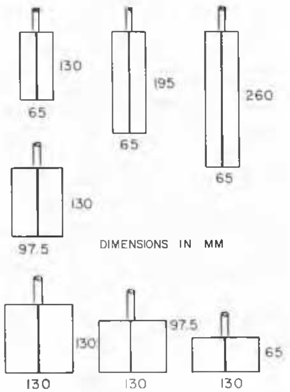

FIG. 2. Types of vanes used.

gradually increasing torsional moment was applied by rotating the top of the rod, at the lower end of which the vane is fixed, at an approximate constant rate of 1/10 degree per second. As the twist of the rod depends on its length and the magnitude of the torque, the use of the same rate of rotation will cause different rates of strain of the vane blades, depending on the size and the diameter of the vane. An initial series of tests, in which the rate of rotation was varied in the ratio 1 to 10, showed, however, that the rate of strain has no significant influence on the results, within the actual accuracy limits of the tests.

Each test series consisted of from 16 to 31 vane borings with the tests performed at 0.5-m intervals of depth through the selected stratum of the clay deposit. The borings were 1.5 to 2.0 m apart. At each site, 5 to 10 of the borings, distributed uniformly over the area, were performed with the standard vane to indicate natural variations of soil conditions. At least two borings were carried out with each of the different vanes used.

Interpretation

The interpretation is based on the usual assumption that the clay fails along the surface of a cylinder, the diameter and height of which are equal to those of the vane. Furthermore, the shear stresses are assumed to be fully mobilized and uniformly distributed across the entire failure surface, although not necessarily equal in magnitude for horizontal and vertical surfaces.

Denoting the undrained shear strength acting along horizontal and vertical planes, respectively, by s_H and s_V, the following expression for the failure torque measured in a vane test may be derived:

$$M = \pi DH(D/2)s_V + 2(\pi D^2/4)(D/3)s_H.$$

Hence

$$[2/(\pi D^2 H)]M = s_V + s_H(\tfrac{1}{3}\,D/H). \qquad (1)$$

This means that, in a graphical plot, with the vertical and horizontal axes representing $[2/(\pi D^2 H)]M$ and $(\tfrac{1}{3}\,D/H)$ respectively, equation (1) describes a straight line intersecting the vertical axis at a value equal to s_V and having an inclination equal to s_H. Hence, the intersection of this line with the negative $(\tfrac{1}{3}\,D/H)$ axis directly gives the value of s_V/s_H.

Test Results

The diagrams for determining the anisotropy ratio s_H/s_V at the four test sites are presented in Fig. 3. Each point represents the average value of $[2/(\pi D^2 H)]M$ from all borings with one type of vane. This involves from 75 to 290 readings with the standard vane, and from 30 to 116 readings with each of the other vanes used. The scattering of the average values of the failure torque for borings with the same type of vane is indicated by vertical lines through the points.

A detailed study of the diagrams in Fig. 3 gives the general impression that, in spite of inevitable natural scattering, the linear relationship described by equation (1) appears to be confirmed by the test results. These findings indicate that the assumptions on which the interpretation is based are approximately correct. The only exceptions are some of

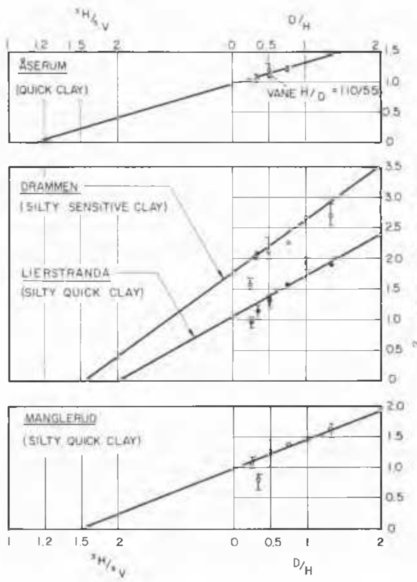

FIG. 3. Determination of the anisotropy ratio s_H/s_V from undrained tests with vanes of different shape at the four test sites.

the results obtained with the very long vanes with H/D ratios of three or more. This is very likely due to progressive failure, and the results of these vanes are, therefore, considered unreliable. This finding has been confirmed by a special test series using vanes with an H/D ratio of 6. These tests show that the failure torque does not increase with the height for vanes with the same diameter, when the H/D ratio exceeds a certain value. The straight lines in the diagrams, neglecting the questionable measurements, indicate values of the s_H/s_V ratios at the four test sites of 1.1, 1.5, 2.0, and 1.5, respectively (Table II).

TABLE II. AVERAGE TEST RESULTS

	Test site			
	Åserum	Drammen	Lierstranda	Manglerud
s_H/s_V	≈1.1	≈1.5	≈2.0	≈1.5
M_D/M_U				
Vane H/D = 260/65	0.91	1.21		
Vane H/D = 130/65	0.99	1.13	1.12	1.35
Vane H/D = 65/130		0.96	0.90	1.26
M_{CU}/M_U				
Vane H/D = 130/65			1.40	1.52
Vane H/D = 65/130			1.28	1.43

At the three test sites having normally consolidated clay (Drammen, Lierstranda, and Manglerud), the values of s_H/s_V vary from 1.5 to 2.0. It is of interest to observe that the measured value of s_H/s_V is comparable with the probable value of the ratio of vertical to horizontal effective stresses *in situ*, which can be expressed as $1/K_0$, where K_0 is the coefficient of earth pressure at rest. The lowest value of s_H/s_V is found at Åserum where the clay is overconsolidated, and the ratio between vertical and horizontal pressures *in situ* is believed, therefore, to be lower than at the other sites. Thus, the test results seem to show a reasonable dependence of the undrained shear strength on the normal effective stress acting on the failure plane.

In the above interpretation it was assumed that the shear stresses at failure are uniformly distributed over the end surfaces of the vane cylinder. If this assumption is not correct, the linearity of equation (1) will still be valid for vanes of varying diameter as long as the distribution is geometrically similar. A number of reasonable distributions have been investigated, all of them leading to higher values of s_H/s_V than found above. If, for instance, parabolic or triangular distributions are assumed, the s_H/s_V ratio would increase by 11 per cent and 33 per cent respectively.

DRAINED AND CONSOLIDATED-UNDRAINED VANE TESTS

The research programme also included a series of "drained" vane tests, in which an attempt was made to keep the rate of rotation so small that no excess pore pressure was set up during shear. Because the excess pore pressure set up in a vane test is partly due to shear and partly due to displacement caused by the penetration of the vane, the results of a drained test cannot be compared directly with a conventional undrained test. To study the effect of dissipation of pore pressures set up by the penetration, a series of "consolidated-undrained" vane tests was included in the programme.

Testing Procedure

The *drained vane tests* were carried out as controlled-stress tests. The load was applied in steps, the time interval between subsequent loadings being eight hours. The time to failure usually ranged from 2 to 4 days. The drained vane tests were carried out at the four test sites described above, and three of the vane types shown in Fig. 2 were used. Altogether 56 tests were carried out at depths varying from 4 to 18 m.

In the *consolidated-undrained vane tests* the vane was left, after penetration, for one to three days before the test was performed. There was no significant difference between the shear strengths observed in the tests where the vane was left for one day and in the tests where it was left for two or three days. The rate of rotation was equal to that used in the standard undrained vane tests. The consolidated undrained vane tests were carried out at two of the test sites, Lierstranda and Manglerud. Altogether 102 tests, involving 54 tests with the standard vane H/D = 130/65 mm, and 48 tests with the vane H/D = 65/130 mm, were performed.

Results

Typical results from a drained test (Lierstranda site) are shown in Fig. 4. It appears from the upper diagram that, for

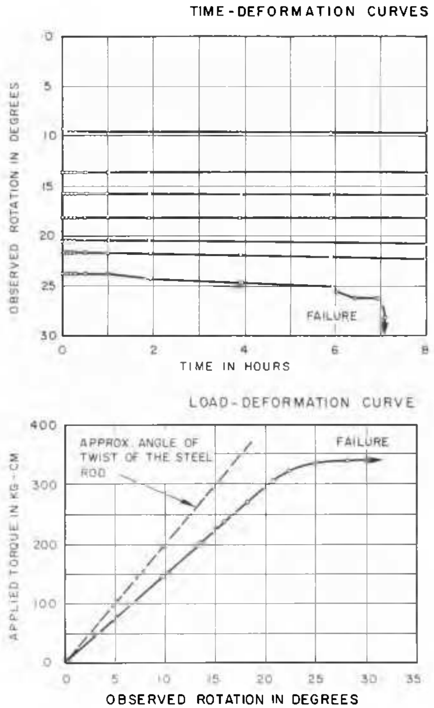

FIG. 4. Typical results from a drained vane test. Lierstranda test site, vane H/D = 65/130, depth 9.0 m.

an applied torque not exceeding 80 per cent of the failure value, the deformation of the clay is perfectly elastic. Further loading causes plastic deformation, the rate of which seems to be nearly constant. It is noteworthy that failure did not occur immediately after the last load was applied, but several hours later. The results seem to indicate that failure is dependent, not only on the magnitude of the applied stress, but also on the strain and possibly on the rate of strain.

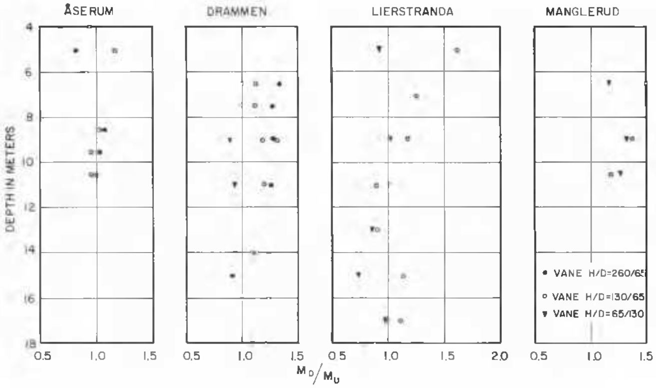

FIG. 5. Ratio between failure torque measured in drained and undrained vane tests.

A comparison of the failure torques observed in drained and undrained vane tests at the four test sites is shown in Fig. 5. The tests compared were performed with the same vane at a distance apart of 1.5 to 2.0 m (except at the Drammen site, vane 130 × 65, where the distance was 3.5 m). It is seen that the ratio M_D/M_U is of the order of 0.9 to 1.4. The average values of this ratio are summarized in Table II. At Åserum and Lierstranda the value is about 1.0, and at the other two sites it varies from 1.0 to 1.35. The results from all test sites show clearly that the ratio M_D/M_U depends on the type of vane used, the ratio increasing with increasing H/D ratio.

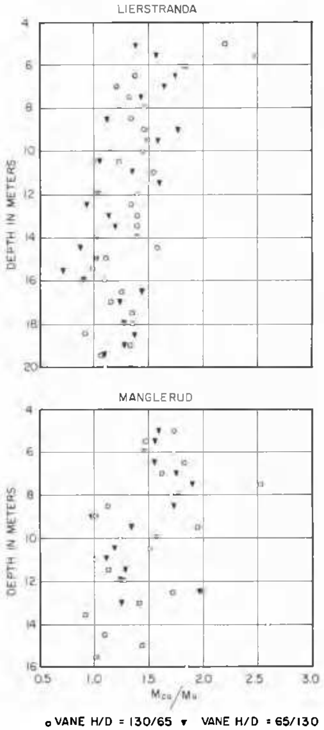

FIG. 6. Ratio between failure torque measured in consolidated-undrained and undrained vane tests.

A comparison between the consolidated-undrained and the undrained vane tests is shown in Fig. 6. The distance between the tests compared is 1.5 m. It is clear from the diagrams that the ratios M_{CU}/M_U at both test sites are substantially greater than one, being of the order of 1.3–1.5. Furthermore, the ratio again increases with the H/D ratio of the vane. This result has previously been confirmed by a series of tests carried out at the State Highway Laboratory, Oslo (Flaate, 1963).

Comparing the values of M_D/M_U and M_{CU}/M_U, it is clearly seen that the shear strengths observed in drained tests are smaller than the values observed in consolidated-undrained tests. The difference in per cent of the corresponding value from an undrained vane test amounts to 28 to 38 at the Lierstranda site and 17 at the Manglerud site. The results for the rates of strain used in these test series thus show a pronounced decrease in shear strength with decreasing rate of strain.

CONCLUSION

The paper describes an attempt to use the vane test to study the *in-situ* shear strength properties of sensitive clays. In spite of some uncertainties concerning the interpretation of vane test results, the following conclusions are drawn.

1. Undrained vane tests, involving the use of vanes with different shapes, have enabled an approximate determination to be made of the ratio between the undrained shear strengths acting along horizontal and vertical failure surfaces. This ratio, s_H/s_V, was found to be 1.1 at one test site where the clay is slightly overconsolidated, and varied between 1.5 and 2.0 at three other test sites where the soil consists of normally consolidated clay. The results seem to indicate a fairly reasonable relationship between undrained shear strength and the initial normal effective stress on the failure plane.

2. The results of consolidated-undrained vane tests have shown that, if the vane is left one day after penetration, a

substantial increase in shear strength occurs. The average ratio between failure torques observed in consolidated-undrained and undrained vane tests varies between 1.28 and 1.52, the greatest value being found for the vane having the greatest *H/D* ratio. This increase in shear strength is probably the result of dissipation of pore pressures set up by the penetration of the vane.

3. Drained vane tests have been carried out in which the time to failure varied between 2 and 4 days. Because the drained tests are influenced by the reconsolidation following the penetration of the vane, they should be compared with the consolidated-undrained tests to investigate the effect of rate of strain. Such a comparison shows that the shear strength observed in drained tests is 20 to 40 per cent smaller than the corresponding values observed in the consolidated-undrained tests. This finding indicates that the shear strength decreases with the rate of strain. However, due to insufficient knowledge of the change in effective stresses on the failure plane during a drained vane test, the effect of the rate of strain cannot be conclusively derived from the described tests. Drained tests carried out at different rates of strain are in progress to study this problem.

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