The Vane Test—A Critical Appraisal

L'Essai au Scissomètre—Une Evaluation Critique

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SYNOPSIS Field and laboratory vane test results are presented for two highly plastic clays. Anisotropic strength analyses show certain anomalies, and tests and analyses are described for investigating the full torque-rotation relationship for the vane. It is concluded that the strength on vertical planes only can be measured accurately with current techniques, and a three-dimensional finite element analysis is used to provide a partial explanation of progressive failure and its effect on vane measured strength.

INTRODUCTION

Although the vane test would appear to be an ideal method for providing design parameters for problems of short term stability of soft clays, doubts have been expressed recently concerning its accuracy and relevance (e.g. Bjerrum 1973). This paper discusses three of the main sources of error - soil anisotropy, strain rate effects and progressive failure in brittle soils.

Field and laboratory data presented refer to two plastic clays, the properties of which are summarised in Table I.

	w_L	I_p		sensitivity	% < 2μ
Launceston	145	104	100-170	7 - 11	50-75
Yarra Delta	109	88	60-80	4 - 8	30-70

TABLE I. AVERAGE SOIL PROPERTIES FOR LAUNCESTON AND YARRA DELTA CLAYS.

METHODS OF ANALYSIS

1. Conventional Analysis

The undrained shear strength of a clay is usually calculated from

$$s_u = \frac{2M}{\pi D^2(L + \frac{1}{3}D)} \qquad \ldots(1)$$

where M = applied torque
L,D = vane length and diameter.

Equation (1) assumes isotropic properties and uniform shear stress around the sheared cylinder of soil.

Jackson (1969) modified the conventional analysis to give

$$s_u = \frac{2M}{\pi D^2(L + \frac{D}{N})} \qquad \ldots(2)$$

where N = 3.0 - uniform shear on cylinder ends,
= 3.5 - parabolic " " " "
= 4.0 - triangular " " "
= 3.7 - empirical correlation (Yarra Clay).

2. Aas Analysis

Aas (1967) showed that for anisotropic soils

$$[\frac{2}{\pi LD^2}]\ M = s_v + [\frac{D}{3L}]s_h \qquad \ldots(3)$$

where s_v = undrained shear strength on vertical surfaces
s_h = undrained shear strength on horiztonal surfaces.

Typical Aas plots for Yarra Delta Clay are shown in Fig. 1. The value of D/3L for M = 0 gives the anisotropy ratio = $\frac{s_v}{s_h}$. For Yarra Delta Clay Jackson found a range of s_h/s_v from 0.8 to 1.45. Jordan (1974) attempted to apply the Aas method to Launceston clay, but found that almost all of his graphs sloped the wrong way!

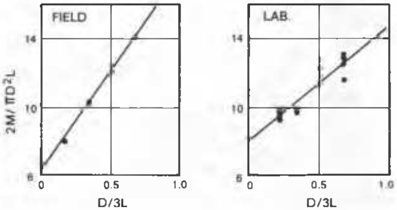


Fig. 1 AAS PLOTS FOR YARRA DELTA CLAY (AFTER JACKSON 1969).

3. Wiesel Analysis

Wiesel (1971) first discussed theoretically the problems arising from an Aas analysis if the shear stress peaks on the side and ends of the vane should occur at different rotations. Wiesel (1973) gave a simpler graphical method for the Aas analysis where by plotting M against L, for vanes with the same D

$$M = m_v \cdot L + 2M_h \qquad \ldots(4)$$

where m_v = torque on unit height of cylinder side.

If results are plotted at peak torque the Wiesel and Aas analyses are identical and will be referred to as the Wiesel-Aas analysis. A Wiesel plot for Launceston Clay is shown in Fig. 2.

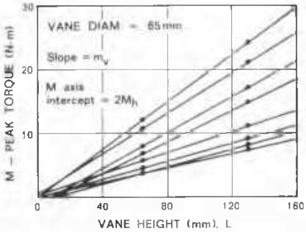


Fig. 2 WIESEL PLOT FOR LAUNCESTON CLAY (AFTER JORDAN 1974)

The average intercept on the M axis gives $2M_h = 0$, i.e. peak torque on the ends has occurred at smaller rotations than overall peak torque, and in a brittle soil the end shear stress rapidly falls to a low value. It was therefore decided to reconsider Wiesel's 1971 proposition and measure the full M-θ, torque-rotation curve for all vanes.

4. Proposed Method

The analysis, basically similar to Wiesel's, is shown in Fig. 3. Shear stresses may be calculated from any assumed distribution and the inferred torques. The calculations can be carried out at any rotation, θ, assuming that the mobilised shear stress patterns are similar for vanes of different lengths at the same rotation. Typical Launceston results are given in Fig. 4 and, in agreement with Fig. 2, the end torque is seen to peak early and drop to a low value before the side torque peaks.

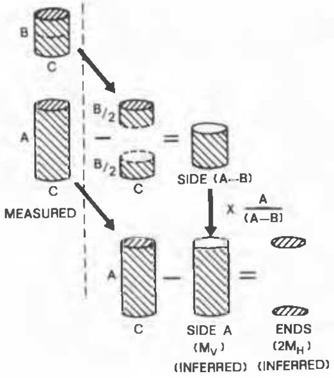


Fig. 3 ANISOTROPIC (M-θ) ANALYSIS

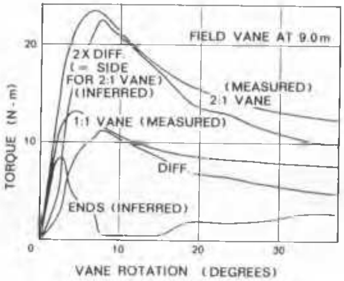


Fig. 4 TORQUE vs. ROTATION FOR LAUNCESTON CLAY UNDER EMBANKMENT

EXPERIMENTAL TECHNIQUES

1. Field Vane

A Geonor vane was used for all field testing, with 65 mm x 130 mm and 65 mm x 65 mm vanes. Failure occurred in 4-8 minutes, rotating the vane at 6° per minute. A large independently mounted protractor was used for rotation measurement.

2. Laboratory Vane

A modified Wykeham Farrance laboratory vane apparatus was used, fitted with a stiff but sensitive torque meter, so that work softening behaviour could be followed. The rotation rate was 24° per minute.

3. Strain Rate Corrections

Following Bjerrum (1973) the vane tests were corrected to the same strain rate as used in laboratory direct simple shear tests, *viz.* 0.08% per minute. The rate effects were found experimentally to be

Launceston – 9% strength change/log cycle of time
Yarra – 10% " " / " " " "

leading to the correction factors in Table II, which have been applied to all the vane results presented in this paper.

TEST	CORRECTION FACTOR	
	Launceston	Yarra
Simple shear	1.00	1.00
Field Vane	0.87	0.86
Lab. Vane	0.81	0.80

TABLE II. CORRECTION FACTORS FOR RATE OF TESTING

TESTS ON LAUNCESTON CLAY

1. Lab. vane tests

Results from Jordan (1974) and Parker (1976) are given in Fig. 5. The average shear strength, s_u from eqn. (1), is relatively independent of vane proportions but depends on the vane size. For anisotropic analyses s_v is significantly larger than s_u, and s_h varies unpredictably. The s_h/s_v ratio ranges from

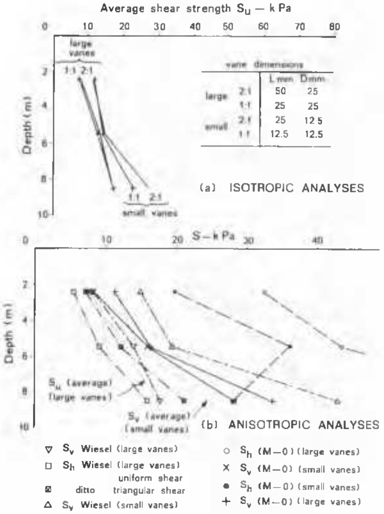


Fig. 5 LABORATORY VANE TESTS - LAUNCESTON CLAY (rate corrected).

0.6 to 3.9! Anisotropy ratios from the various analyses are given in Table III.

Remoulded soil was also tested to remove the effects of any natural anisotropy the soil might have possessed. The results are summarised in Table IV. s_h/s_v seems to depend on vane proportions and is seldom even close to 1.0. It must be concluded that anisotropic (M-θ) analyses may not be reliable.

	2:1 and 1:1 vanes			1:1 and ½:1 vanes		
	s_v(kPa)	s_h(kPa)	s_h/s_v	s_v(kPa)	s_h(kPa)	s_h/s_v
Series 2	5.8	16.6	2.9	8.7	22.4	2.6
Series 3	5.8	22.4	3.9	8.7	7.2	0.8
Series 4	4.8	18.4	3.8	8.6	8.3	1.0

TABLE IV. LABORATORY TESTS ON REMOULDED LAUNCESTON CLAY

2. Field Vane - Virgin Soil

Jordan's (1974) tests performed without measurement of rotation, are plotted in Fig. 6, together with direct

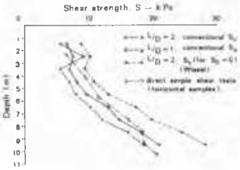


Fig. 6. FIELD VANE TESTS - LAUNCESTON (rate corrected)

TABLE III ANISOTROPY RATIOS

LAUNCESTON CLAY

Direct simple shear tests on vertical and horizontal samples $\frac{s_h}{s_v} = 0.89$

(a) Field Vane (Jordan) - no measurement of rotation.

$$\frac{s_h\ (\text{simple shear})}{s_v\ (\text{Wiesel-Aas})} = 0.85 \quad (s_h = 0,\ \text{Wiesel-Aas})$$

(b) Field Vane (Parker) - rotation measured.

Depth(m)	Anisotropic(M-θ) analysis 2:1 and 1:1				Wiesel-Aas analysis		
	▥ s_h/s_v	◢ s_h/s_v			▥ s_h/s_v	◢ s_h/s_v	◢ s_h/s_v
8.0 9.0 10.0 11.0	1.4 2.4 2.0 2.5	1.8 3.1 3.7 3.3			 0.8 0.6 1.1	 1.1 0.8 1.4	 1.4 1.0 1.8
Average →	2.1	3.7			0.8	1.1	1.4

0.95

(c) Lab. Vane (Parker) - rotation measured.

Depth(m)	Anisotropic(M-θ) analysis large vanes		small vanes		Wiesel-Aas analysis		(large vanes only - small vane s_h = 0)
	▥ s_h/s_v	◢ s_h/s_v	▥ s_h/s_v	◢ s_h/s_v	▥ s_h/s_v	◢ s_h/s_v	
2.4 5.5 8.5	2.9 2.1 2.0	3.9 2.7 2.7	1.3 1.7 0.6	1.8 2.2 0.8	0.9 0.65 0.7	1.2 0.9 0.9	
Average	2.3	3.1	1.2	1.6	0.7	1.0	

Av. 0.85

(d) Lab. Vane (Parker) - remoulded clay, rotation measured.

Test Series	Anisotropic(M-θ) analysis 2:1 and 1:1		1:1 and ½:1		Wiesel-Aas analysis		
	▥ s_h/s_v	◢ s_h/s_v	▥ s_h/s_v	◢ s_h/s_v	▥ s_h/s_v	◢ s_h/s_v	
1 2 3	2.1 2.9 2.9	2.9 3.9 3.8	1.9 0.8 0.7	2.6 0.8 1.0	0.5 0.8 1.0	0.7 1.1 1.3	
Average →	2.6	3.5	1.1	1.5	0.8	1.0	

YARRA DELTA CLAY

Direct shear tests on vertical and horizontal samples $\frac{s_h}{s_v} = 1.04$

(a) Field Vane (Jackson) - no measurement of rotation.

					Wiesel-Aas analysis	
					▥ s_h/s_v	◢ s_h/s_v
Average →					1.0	1.3

(b) Field Vane (Naismith) - rotation measured.

Depth(m)	Anisotropic(M-θ) analysis 2:1 and 1:1		2:1 and 1½:1		Wiesel-Aas analysis	
	▥ s_h/s_v	◢ s_h/s_v	▥ s_h/s_v	◢ s_h/s_v	▥ s_h/s_v	◢ s_h/s_v
10 12 14 16 18	1.1 1.1 1.0 1.1	1.5 1.4 1.4 1.5	1.0 0.8 0.9	1.4 1.0 1.2	0.6 0.7 1.1 1.1 1.1	0.8 0.9 1.5 1.4 1.5
Average →	1.1	1.45	0.9	1.2	0.9	1.2

1.2 "1.05"

(c) Lab. Vane (Jackson) - no measurement of rotation.

Depth					Wiesel-Aas analysis	
					▥ s_h/s_v	◢ s_h/s_v
14.3 15.8 17.7					0.85 0.85 0.85	1.1 1.1 1.1
Average →					0.85	1.1

"1.0"

shear tests on horizontal samples. Again the 1:1 vane s_u strengths were lower than the 2:1 vane values, both being lower than s_v from a Wiesel analysis (with $s_h = 0$). Using the simple shear values as s_h, the average s_h/s_v was 0.85.

3. Field Vane - Under Levee Bank

Tests with rotation measurement by Parker (1976) on soil beneath the Launceston levee bank are presented in Fig. 7. The same general picture emerges as for virgin soil tests. Values of s_h from the anisotropic (M-θ) analysis are excessively high, the graph for a triangular stress distribution plotting well off the right hand side of the figure. Direct simple shear tests on vertical and horizontal samples gave $s_h/s_v = 0.89$. Other anisotropy ratios are listed in Table III. Values of s_h calculated from the Wiesel-Aas analysis appear reasonable, though sensitive to the assumed shear distribution.

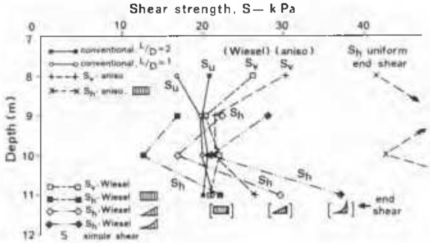


Fig. 7. FIELD VANE TESTS - LAUNCESTON (beneath levee bank). (Rate corrected)

4. Other Laboratory Tests

For comparative purposes test data obtained by Jordan (1974) are listed in Table V.

TEST TYPE	$\frac{s_u}{p_o}$ *
Triaxial Compression	0.92
Field Vane (s_v for $s_h = 0$)	0.58
Direct simple shear	0.57
Triaxial Extension	0.47
Field Vane (conventional s_u)	0.43

$^*\frac{\text{shear strength (undrained)}}{\text{effective overburden pressure}}$

TABLE V. UNDRAINED PROPERTIES OF LAUNCESTON CLAY

The soil is anisotropic in its strength behaviour, with conventional vane tests (rate corrected) giving the lowest normalised strength.

TESTS ON YARRA DELTA CLAY

Field vane tests, with rotation measurement, by Naismith are presented in Figs. 8 and 9. The soil is more brittle than Launceston clay and the (M-θ) analysis yields impossible negative values of end torque at intermediate rotations. This raises serious doubts about the applicability of the analysis to brittle soils.

Jackson's (1969) results from a Wiesel-Aas analysis of field tests are given in Fig. 10. Average values of s_h/s_v were 1.15 for field vanes and 1.04 for lab. vanes. Direct shear tests (not simple shear) gave $s_h/s_v = 1.04$. The agreement with laboratory vanes seems excellent, but is possibly fortuitous.

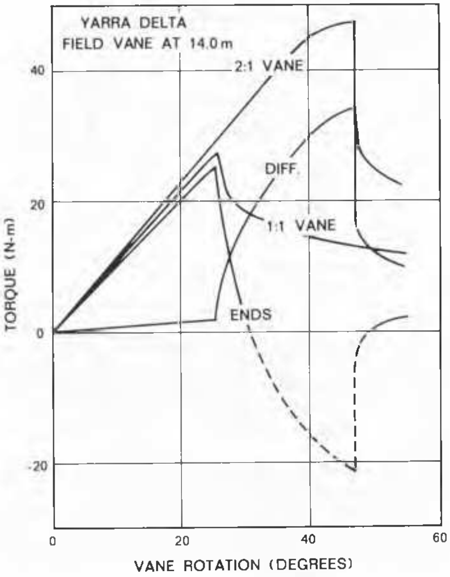


Fig. 8 TORQUE vs. ROTATION FOR YARRA DELTA CLAY

Fig. 9(a) shows s_v values calculated from various assumptions. Excellent agreement is obtained between the conventional average strength, s_u, [eqn. (1)], s_v from a Wiesel-Aas analysis assuming simultaneous peaks on side and ends, and direct shear tests on vertically oriented samples (points J). Values of s_v calculated from the full M-θ anisotropic analysis are high, and dependent on vane proportions.

Fig. 9(b) shows s_h values and a greater variation in strength. Below 14 m depth the agreement is again excellent and the s_h/s_v ratio averages 1.05. The anisotropic (M-θ) analysis gives very high s_h values, but the average anisotropy ratio for these analyses is only 1.3, a much more realistic value than the one obtained for Launceston clay. However this is a result of compensating errors, as both s_h and s_v are grossly overestimated. The points marked R represent rotational shear tests on cylindrical specimens by Naismith (1975). The low strength values (based on triangular shear distribution) are thought to be due to non-uniform stressing and progressive failure. The specimens

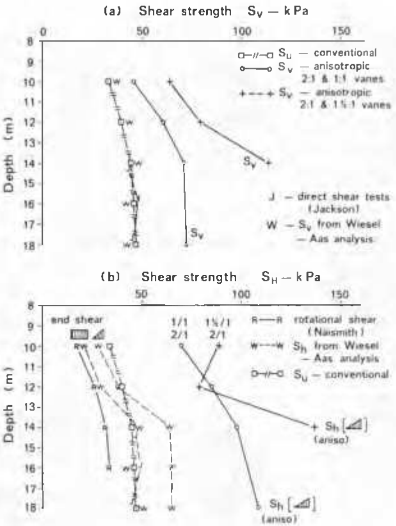


Fig. 9 UNDRAINED STRENGTH (FIELD VANES) ON (a) VERTICAL SURFACE AND (b) HORIZONTAL SURFACES FOR YARRA DELTA CLAY

deformed elastically prior to sudden failure in a stress controlled loading situation.

FINITE ELEMENT ANALYSIS

The inconsistencies in the results obtained demonstrated the need for a better understanding of the actual stress distribution around the sheared cylinder. This is an extremely complex problem but some preliminary analyses have been made using a three-dimensional finite element programme. The programme used was SOLID SAP with a 3-D solid brick element having three degrees of freedom at each node (Zienkiewicz - Irons brick ZIB 8).

The element mesh used is shown in Fig. 11. 1008 elements and 1280 nodes were used and the loading condition was a small imposed rotational displacement of the assumed rigid vane. Poissons ration was taken as 0.48 and a nominal modulus, E, was used in the calculations. The programme is a linear elastic one and only one calculation of stress versus rotation was made to give a picture of the relative proportions of shear stress acting on different sections of the surface which will become the failure cylinder.

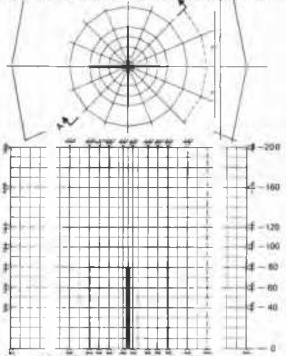


Fig. 11 FINITE ELEMENT MESH

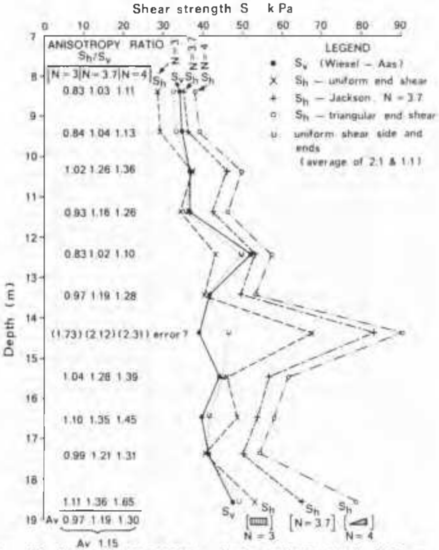


Fig. 10 FIELD VANE TESTS - YARRA DELTA CLAY (after Jackson) (Rate corrected) (Wiesel-Aas analysis)

The mesh was not fine enough to give an accurate picture of stresses close to the vane blades, so the curves in Fig. 12 are plotted on the plane midway between the blades. These distributions must not be regarded as cross-sections of a solid of revolution about the longitudinal axis, as the distributions will undoubtedly vary with orientation. However, two main features emerge - the end distribution is roughly parabolic and the side shears are significantly higher at the ends than in the centre. Work is continuing on this analysis and the results will be published elsewhere.

DISCUSSION

The shear strength data presented in the Figures and Tables covers a wide range, the actual values being dependent on the method of analysis used and the size and proportions of the vanes.

Conventional Analysis

For the conventional analysis, assuming uniform shear all around the vane cylinder, the following conclusions can be drawn:

LAUNCESTON CLAY

(i) Small vanes give higher strengths than large vanes;

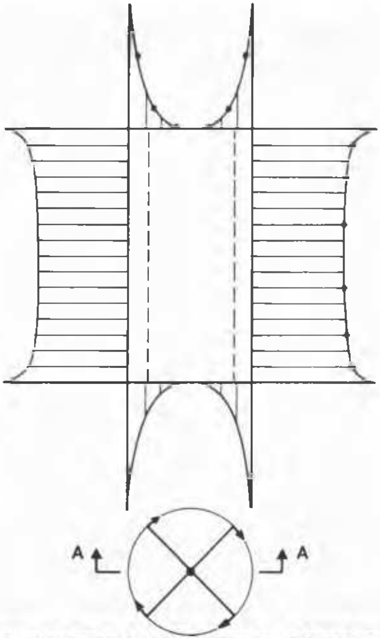


Fig. 12 SHEAR STRESS DISTRIBUTION ON CYLINDER WHICH WILL BECOME THE FAILURE SURFACE
- elastic range only.
- 3D F.E. analysis

(ii) 2:1 vanes give higher strengths than 1:1 vanes;

(iii) the average strength, s_u, is significantly smaller than the correct strength on vertical planes - as estimated from anisotropic analyses or direct simple shear tests (reasonable agreement was however obtained for laboratory tests with "large" vanes);

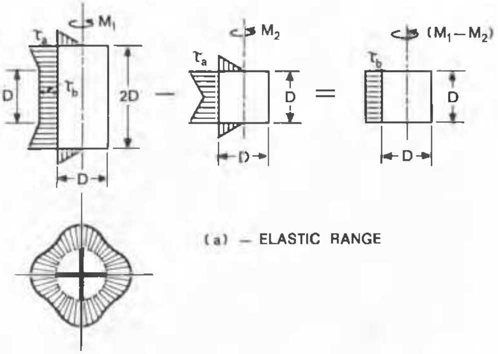
(iv) for remoulded Launceston clay the 1:1 lab. vanes were found to give 1.05 times the average strength derived from the 2:1 vanes. Any effects of soil structure should have been absent from these tests.

YARRA DELTA CLAY

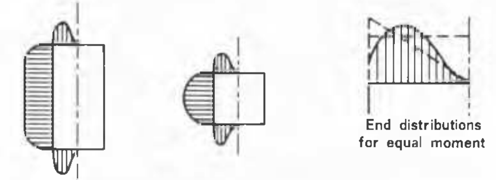
(i) 1:1 vanes give a slightly higher s_u than 2:1 vanes. (Average values were plotted in Fig. 10 - the ratio was very consistent at s1:1/s2:1 = 1.1 (Jackson); Naismith's tests gave a ratio of 1.02);

(ii) s_u in general agrees well with the correct strength on vertical planes estimated from direct shear tests or Wiesel-Aas anisotropic analyses.

The differences between small and large vanes can be attributed to scale effects. Both clays have a mildly fissured structure which would favour higher strengths with smaller vanes. However, a compensating effect exists when comparing vanes of the same D but different L. Fig. 13(a) shows a simplified possible stress distribution around a vane, based on the results in Fig. 12. The distribution is valid for the elastic range only, but for the soils investigated pre-peak behaviour was predominantly elastic.



(a) — ELASTIC RANGE



(b) — PLASTIC RANGE

Fig. 13 POSSIBLE SHEAR STRESS DISTRIBUTIONS

For an isotropic work-softening soil the peak strength would be reached first at the vane corner, and by the time peak torque had been reached the stress distribution would be similar to that in Fig. 13(b). A method of analysis based on uniform stress distribution should give appreciable underestimates of both s_h and s_v (which might still appear to be equal, as they should for isotropic soils). The corner effect would be more significant for the 1:1 vane than for the 2:1 vane. The Launceston vane tests on undisturbed clay (Figs. 5,6) verify these conclusions. For remoulded Launceston clay the scale effect was almost absent and as the samples were only slightly work-softening the progressive failure concepts of Fig. 13(b) were not relevant. For such conditions the conventional uniform shear stress analysis can be used confidently.

The results for Yarra Delta clay are a little more difficult to interpret. The soil exhibits a more brittle failure than the Launceston clay and the effects of progressive failure would be expected to be more significant. However, the 1:1 vanes gave consistently s_u equal to 1.1 times the value for 2:1 vanes, and it is possible that the scale effect for the smaller 1:1 vane outweighed the reduction due to progressive failure. The average value of s_u also agreed well with all other tests (Fig. 9) - again a surprising result, but it is possible that all the tests represented were affected to approximately the same degree by progressive failure. The shear box tests carried out by Jackson were typical 60 mm square direct shear box tests, which involve appreciable edge effects, and not direct simple shear tests as performed on the Launceston clay (in an N.G.I. type machine, Geonor model.

Anisotropic Analyses

Two methods of anisotropic strength analysis have been used in these investigations. The one referred to as the anisotropic (M-θ) analysis was an attempt to allow for side and end torques peaking at different rotations. The other was the Wiesel analysis for the special case of torques peaking at the same rotation, which has been referred to as the Wiesel-Aas analysis, as it should give the same results as Aas' original procedures.

The full range of anisotropy ratios, s_h/s_v, obtained has been given in Table III. The most striking features of this table are that the anisotropic (M-θ) analysis frequently leads to excessive estimates of the ratio, regardless of the distribution of end shear assumed, and that the Wiesel-Aas analysis either works very well, for at least one plausible end shear distribution, or not at all - giving $s_h \simeq 0$! From the other laboratory tests performed on oriented samples it seems reasonable to assume that realistic values of the anisotropy ratios are

Launceston $s_h/s_v \simeq 0.9$
Yarra Delta $s_h/s_v \simeq 1.05$

It should also be noted that although the average values of s_h/s_v show some consistency, the variations within each column can be large. Bjerrum (1973) presented direct simple shear tests results for samples cut with a wide range of orientations, and even for soils which showed a large difference between the absolute maximum and minimum strengths the ratio of s_h to s_v did not depart greatly from 1, i.e. any method of vane test interpretation which leads to very high or very low values of anisotropy ratio must be suspect.

For Launceston clay the Wiesel-Aas method appears to give reasonable anisotropy ratios for an end shear distribution between uniform and triangular. This is in agreement with the concepts of Fig. 13(b). However, in two cases - the small laboratory vanes in undisturbed samples and Jordan's field vanes in undisturbed soil - ratios close to zero were obtained. For the only one of these cases which could be checked by the (M-θ) analysis - the small laboratory vanes in undisturbed samples - a reasonable, though slightly high value of 1.2 was obtained for a uniform end shear. At present it is impossible to say why only some series of tests show $s_h \simeq 0$ when s_v reaches its maximum, but for those tests that do, both methods of analysis indicate that peak moment occurs on the ends at lower rotations than on the side, and that the end moment then rapidly decays to small values. Unfortunately the value of s_h calculated from the (M-θ) analyses is usually excessively large (Figs. 5 and 7) and even when s_h/s_v seems to be reasonable it is only because both strengths are over estimated.

For the remoulded samples the Wiesel-Aas analysis surprisingly gives slightly low values of anisotropy ratio on the average, unless a triangular end distribution is assumed, but the scatter of results is excessive and further tests would be required. The (M-θ) analysis again gives high results except for one or two specific tests.

For Yarra Delta clay the Wiesel-Aas analysis in all cases seems to give an excellent estimate of the anisotropy ratio with an end shear distribution somewhere between uniform and triangular, the latter generally giving the higher results. For the field vanes and the (M-θ) analysis reasonable values are obtained from the uniform end shear assumption, in spite of the brittle nature of the soil. However, reference to Fig. 9 shows that both s_h and s_v are overestimated and the reasonable anisotropy ratios are quite fortuitous.

A partial explanation for these phenomena can be made with reference to Fig. 13(b). As discussed earlier progressive failure would lead to underestimates of s_h and s_v, even when they peaked simultaneously. If the corner and end effects were of the same magnitude for 2:1 and 1:1 vanes then subtraction of torques at failure would still yield reasonably accurate values for peak shear strength on the side of the vane. This is borne out by the evidence presented. However subtraction of twice the torque difference to give the end torques would lead to an underestimate of s_h, particularly using the uniform stress distribution, and this was found to occur frequently with the Wiesel-Aas analysis. (Both analyses should give identical results if the torques peak simultaneously.)

For the (M-θ) analysis the assumption that the form of the stress distribution over the whole failure surface is identical for vanes of different proportions, at the same rotation θ, needs closer investigation. The curves for Yarra Delta clay show that the initial sections of the M-θ curves are almost identical and the soil is obviously reacting elastically in this region. The stress distributions of Fig. 13(a) would then apply, and a too small proportion of the total torque would be assigned to the side shear, leading to excessive values of s_h. The same remarks apply to a slightly lesser degree, to Launceston clay.

Reference to Fig. 8 shows that the difference curve, which purports to represent the torque due to side shear, rises to too large a value giving the impossible situation where twice the torque difference is much greater than the full torque on the 2:1 vane. This is because the 2:1 vane still has essentially an elastic stress distribution while the 1:1 vane has a plastic distribution with the strength on ends and side well below peak. Subtraction will inevitably lead to an overestimate of s_v, particularly for brittle soils. This effect also exists to a lesser extent in the Launceston clay tests.

The apparent independence of the initial sections of the M-θ curves on vane size or geometry can be explained by St. Venant's principle, as an appreciable volume of soil is being distorted by the vane and the overall deformations will be relatively independent of the detailed manner in which the stresses are being transferred from vane to soil. The M-θ relationships for the side and end surfaces cannot be treated independently, as they are in current methods of vane analysis, as the strains prior to failure are predominantly elastic rather than plastic. For example, for Yarra Delta clay overall failure required rotations of 30° to 60°, but with the torsional shear samples, where strains were confined to a thin layer, failure occurred after 1° to 3° rotation.

CONCLUSIONS

A universally correct method for analysing the vane test has yet to be developed. The strength on vertical surfaces, s_v, is best estimated from tests on two different proportions of vane, analysed by the Wiesel-Aas method. The strength on horizontal surfaces s_h, cannot be estimated reliably by any current method, unless the soil is isotropic and non work-softening. The anisotropy ratio, s_h/s_v, may be estimated for some soils by the Wiesel-Aas approach, but anisotropy is better investigated using other tests.

A partial explanation of vane behaviour may be derived from a three-dimensional stress analysis. This analysis needs to be extended to cover different vane proportions and, if possible, elastic-plastic behaviour. It should also investigate stress variations around the circumference of the sheared cylinder but it is doubtful whether the complications involved will be justified by any increased usefulness of the vane results.

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