Residual Strength Determination in Direct Shear

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SUMMARY. - Current concepts on residual strength are outlined, and test results obtained from a large displacement fully automatic reversing direct shear apparatus are reported. The maximum travel between reversals and the rate of shearing were varied. Strength envelopes were obtained from sets of samples and from stage tests on single samples. The time-saving benefit of applying a large initial deformation at high speed was also investigated. Typical load displacement curves and strength envelopes are given. For some soils the travel available in the standard shear box is insufficient for an adequate determination of residual strength. A suggested procedure is given although the precise test technique is not important provided deformation rates are adequately low. In general, stage testing with fast initial shearing is recommended. Two common causes of abnormal load deflection curves are noted. Brittleness Indices up to 0.75 at 30 p.s.i. normal stress, and $\emptyset'_r$ values down to 10^o were obtained.

I INTRODUCTION

The concept of a residual shear strength has appeared in soil mechanics literature since 1937, but it was largely the work of Skempton (Ref. 1) which highlighted it as an important factor to be considered in long term stability analyses of natural slopes and cuts in certain soils, notably overconsolidated clays and clay shales.

Laboratory shear tests are frequently stopped once peak strength has been passed, but it is now accepted that, for soils with brittle strength characteristics, progressive failure in the field can lead to average mobilised shear strengths much lower than peak values and the complete stress-strain curve must then be taken into account.

A simplified picture of large strain behaviour of soils is given in Figure 1. The effective stress shear parameters c' and $\emptyset'$ are deduced from peak strength values, and the residual shear parameters c_r' and $\emptyset'_r$ from values of τ and σ at large strains, when the shear strength has reached a constant or near constant value. The difference between peak and residual strengths depends on soil type and stress history, and is most marked for heavily overconsolidated clay soils. This strength drop can be represented

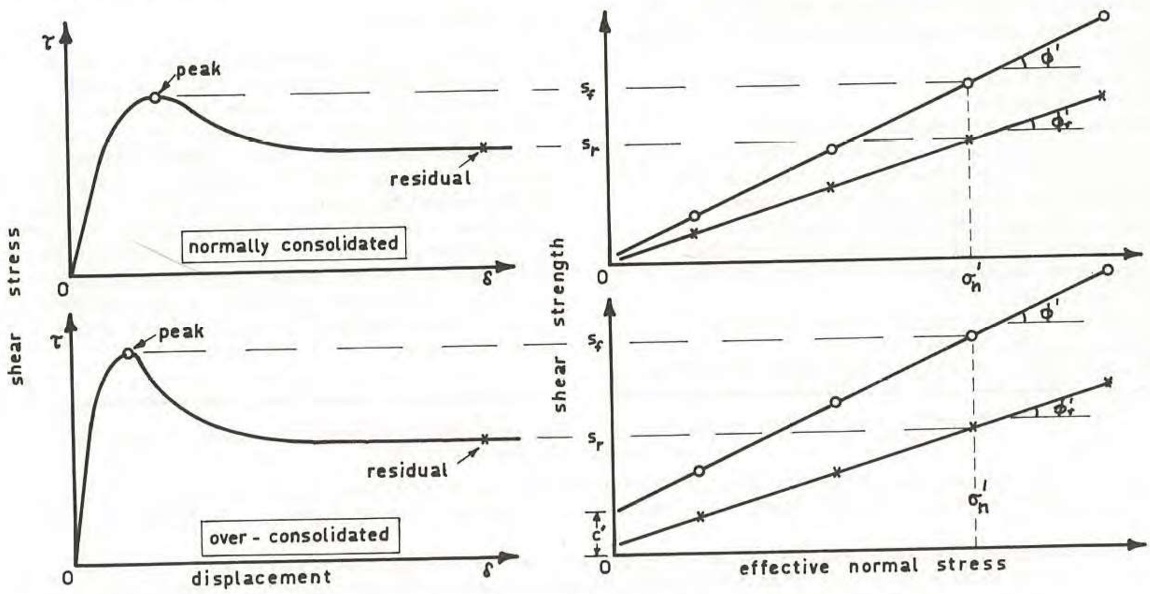

FIG. 1 Simplified Shear Strength Properties of Clay
(after Skempton and Hutchinson, Ref. 2)

by the Brittleness Index I_B[1], which is not a soil constant but decreases with increasing normal stress.

As the residual strength sets the lower limit of progressive strength reduction, to design for this value under all conditions would be unnecessarily conservative. However evidence shows that for brittle soils, under some circumstances, the field strength is likely to approach this minimum.

Skempton and Skempton & Petley (Refs. 1 and 4) have shown that the residual strength as determined in the reversing shear box correlates closely with the average mobilised strength calculated for a number of field failures in overconsolidated clays where movement has occurred along existing slip surfaces. Further, Bjerrum (Ref. 5) has concluded that for some overconsolidated plastic clays and clay shales the average shear strength along first time failure surfaces is likely to be close to residual. It also seems likely that for natural slopes in clay the ultimate or very long term stability is controlled by the residual strength. (Ref. 1)

Laboratory determination of residual shear strength is therefore necessary in relation to the analysis of long term stability of slopes, both natural and man-made. Residual strength is also of interest as a fundamental property of the soil, being largely related to the mineral composition of the clay on the failure surface (Kenney, Ref. 6) and more or less independent of the initial moisture content of the sample.

II CHOICE OF TEST TYPE

Residual strength is generally determined from one or more of three types of test:-
(a) Reversing direct shear
(b) Triaxial compression
(c) Ring shear

Most residual strength testing to date has been done in 6 cm. square direct shear boxes, modified to permit reversal of the direction of shear (Ref. 1). This test has many advantages for residual strength determination, viz:-
(i) Thin samples with reasonably rapid drainage times can be used;
(ii) Specimens can be readily oriented in the correct direction of sliding - this is valuable when testing defects such as faults, fissures and pre-existing slip planes;
(iii) Large deformations can be obtained by continuous reversing of shear direction;
(iv) Reasonably large areas of failure surface can be tested;
(v) Specimens can be readily wire cut after consolidation, if desired;
(vi) The apparatus is widely available and needs only minor modification.

The triaxial test has also been used by a number of investigators.[2] Published data shows that, in general, comparable values of ϕ'_r are obtained from direct shear and triaxial tests, whether on intact samples or preformed slip surfaces, and the simplicity of the shear box therefore makes if preferable.

The ring shear apparatus has also been used to investigate residual strength behaviour (de Beer, Ref. 9; Sembenelli and Ramirez, Ref. 10). This test, in which an annular[3] specimen is subjected to torsional shear, is the only test in which very large uniform deformations can be applied in the laboratory. Although Skempton and Hutchinson (Ref. 2) have recently claimed that such large deformations, of the order of one metre or more, could be required to reach the residual state for some clays, and that the values of ϕ'_r so obtained by ring shear are appreciably lower that those otherwise obtained, this contradicts the observations of de Beer (Ref.9) who found lower values of ϕ'_r from the direct shear test. The ring shear apparatus has a number of disadvantages, but the greatest one at this point in time seems to be that there is so far no direct field evidence to substantiate the applicability of residual strengths measured in this way.

Such direct evidence does exist for a number of soils tested in direct shear, as already mentioned. A further factor which tends to confirm the validity of direct shear testing for obtaining residual strengths is the observation of Skempton and Petley (Ref. 4) that in reversing shear tests performed on initially unsheared material the results were in good agreement with both shear box and triaxial tests on natural (i.e. existing) slip surfaces.

Because of the above considerations the reversing direct shear test seems to be preferable for current studies of residual shear strength.

III EXPERIMENTAL PROGRAMME

(a) Background

Despite the apparently wide use of direct shear testing for determining residual strength, little has been published on the exact techniques used or the effect of different techniques on the strength parameters obtained. For example there does not appear to be any information on:- the effect of distance travelled between reversals, and whether or not this has a minimum acceptable value; the possibility of obtaining multiple data from single specimens; or the possibility of using high strain rates to achieve large displacements quickly, with subsequent low strain rates for much shorter times while drained equilibrium is being established.

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1 $I_B = \frac{s_f - s_r}{s_f}$, Where s_f and s_r are, respectively, the peak and residual strengths in any one test (suggested by Bishop, Ref. 3)

2 Techniques and/or results obtained using normal triaxial equipment have been described by Chandler (Ref. 7) Webb (Ref. 8), and Skempton & Petley (Ref. 4). There are a number of difficulties of which the most important are:-
(i) That of obtaining accurate estimates of strength at low confining pressures (Webb, loc cit), and
(ii) The likelihood with many clays that sufficient movement cannot be obtained to achieve the residual stage on other than existing discontinuities or precut planes (cf. Webb, Fig. 12).

3 Or, rarely, disc shaped as in the work of Sembenelli and Ramirez; Ref. 10

Information such as this can be of great assistance to the investigator in increasing both the productivity of his testing programme and the confidence which he places in his results. The object of this experimental programme has been to provide such information, and subsequently to define as well as possible the simplest acceptable procedure for reversing-direct-shear determination of residual strength.

(b) Series A

Series A test results were obtained on a decomposed Silurian clay which outcrops extensively around Melbourne. It is normally a yellow-brown stiff fissured clay with a stress-strain behaviour indicating that it is quite highly overconsolidated. The clay is Kaolinitic, and for the samples tested the PI has been around 35%. The peak drained strength of samples tested has generally been between 20 and 30 lb/sq.in. and the ratio of peak to residual strength between 2 and 3, with a maximum of 4.

Thirty four test results are available for study. For simplicity in presentation the tests have been grouped in "sets" of results within the Series. All samples within each set were taken immediately adjacent to one another, and the whole series has been conducted on soil from one block sample. Twenty four test results have been obtained at the same normal stress (30 lb/sq.in.) in order to determine the effects of strain rate, length of travel, and different reversing techniques. Other samples have been used to investigate handwinding and stage testing effects.

(c) Series B and C

These results are selected from many obtained on samples made available in the course of commercial testing.

The Series B soil was a stiff grey over - consolidated silty clay. This material is from the clay layer underlying the coal seam presently being mined by the State Electricity Commission, Victoria, at Morwell. It is Kaolinitic, with a PI around 20-25%, varying somewhat with clay content.

The most important information presented from these tests relates to the validity of multiple normal stress stage testing of individual samples. Data was also obtained as to the effect of handwinding - the use of high speed (undrained) initial deformations (2 ins. per minute) - on the subsequent drained deformation required to define the residual strength.

Series C tests were conducted on remoulded samples of a fault zone infill - a white clay with high fines content, exceptionally talcy when dry, with a low mica content and a PI of 22%. The mineral composition of the sample is not known. These results are presented as an illustration of the low residual shear strength and the formation of well-developed slickensides which have been observed in remoulded soils.

(d) Series D

Remoulded Kaolin samples were used to determine whether the procedures of pre-cutting the failure plane or rapid initial shearing affected measured residual strength. These tests also provide a basis for comparison with the results of other investigators.

IV APPARATUS

(a) All the results reported in this paper have been obtained from direct shear tests. For one set of tests a standard Wykeham Farrance Reversing Shear Box Apparatus was used, but the remainder have been carried out on an extensively modified version of the same manufacturer's basic non-reversing machine.

(b) The relevant modifications which have been adopted to produce the Monash automatic reversing, automatic recording, large displacement shear box are as follows:-

(i) Replacement of the standard upper and lower halves of the shear box which, because of partially relieved contact faces,[1] can only be used for shear in the forward direction.

(ii) Provision of a roller connexion between the shear box and the proving ring. This connexion is designed to transmit horizontal tension and compression loads with negligible end float, without restraining free vertical movement of the upper half of the shear box.

(iii) Provision of a screwed connexion between the motor drive and the reservoir to give push pull control, again with negligible end float.

(iv) Provision of a universal ball joint at the fixed end of the proving ring, and calibration of the ring in tension as well as compression.

(v) Accurate realignment of the whole apparatus to prevent extraneous forces from being developed as a result of the rigid and semi-rigid connexions.

(vi) Various minor modifications in order to increase the maximum possible box displacement to ±½ in. from the central position.

(vii) Control of the motor drive is achieved with a 12 volt relay switching system. Direction control utilizes one micro switch at each end of the travel range.

(viii) The recording of force and displacement was achieved initially by the use of two LVDT displacement transducers - one measuring deflection of the proving ring, and the other measuring the relative displacement of the two halves of the shear box. Output from the LVDT's was fed directly into an X-Y recorder giving a printout such as that in Figure 2.

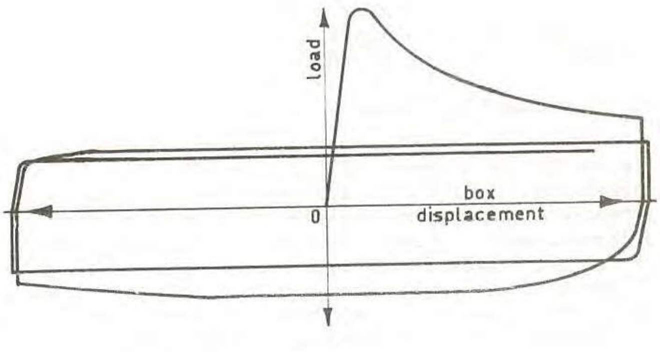

FIG. 2 X-Y Recorder Printout

1 This relief is presumably to reduce the area of metal to metal contact which occurs if the upper half of the box settles onto the lower half.

An alternative arrangement has employed an X-T recorder. Using this recorder the transducer measuring box displacement has been eliminated. If required, box displacement at any time can be calculated knowing the chart speed, the actual (not the nominal) machine speed, and the ring compression or extension. However, as the later results show, it is seldom necessary to know this value precisely.

V EXPERIMENTAL TECHNIQUES

(a) General

All tests have been on 6 cm. square by one inch thick samples which have been set up under the required normal stress and allowed to consolidate overnight. Deformation rates are discussed in Section VI. Testing has been conducted under controlled temperature and humidity conditions.

(b) Standard Technique

It seems likely that the test procedure outlined in the Wykeham Farrance Reversing Shear Box booklet is fairly widely used and it will therefore be described as standard. Other techniques investigated have been prompted by the economic desirability of:-

(i) Reducing machine time to a minimum consistent with obtaining genuine values for the residual shear strength, and

(ii) Obtaining as much information as possible from each sample.

In the standard technique, the initial shearing procedure is the same as for regular non-reversing tests. At the end of normal forward travel (presumably about 0.25-0.30 in.) the proving ring load is first released by adjusting the tail stock and the motor then manually reversed. The shear box is then driven back to a zero displacement position with the ring in tension, and the load in the ring is again released before the motor is reverted to forward travel. This procedure is repeated as often as required to obtain the residual shear strength.

(c) Automatic Reversing

In this variation, when the box reaches the limit of its forward travel the motor is automatically reversed and the stress release process occurs at a slow rate, controlled by the motor. This is repeated at each direction reversal, and eliminates the need for an operator. Periodic readings of the dial gauges are taken to provide a check of the values obtained from the record chart.

(d) Increased Box Travel

In nature, residual shear strength conditions are reached as a result of large uni-directional deformations. In the standard shear box large deformations can only be achieved by cumulative small deformations in opposite directions. In particular, use of the standard technique requires quite a number of reversals to achieve the required conditions, and it is not known what effect these reversals have on the ultimate strength behaviour of the sample.

To investigate this effect in the 6 cm. shear box, the box was modified to allow a maximum travel of 1 in. between reversals, and tests were conducted with maximum displacements of ± 1/8 in., ± ¼ in., and ± ½ in. from the central position.

When box displacements are large a problem arises as to the necessity of applying area corrections. An important advantage of the ± deflexion shear box is that the shear stress can be measured at the position of zero displacement both for the forward and reverse directions of travel, and consequently the question of area correction need not arise. Furthermore, study of the variation of shear load with box displacement makes possible some conclusions as to the necessity of these corrections.

(e) Stage Testing

Because of their potential for time saving, multiple normal stress stage tests have been investigated.

Once residual strength conditions have been established at the initial normal stress, the shearing is stopped and the normal stress increased. In some cases the sample has been left to consolidate overnight before shearing is recommenced. The residual strength envelopes obtained this way have been compared with the envelopes determined from individual samples.

(f) Speed Variations

The question of speed effects in relation to measured residual strength is a complex one, and a wide range of speeds and combinations of speeds has been investigated. Two concepts in particular have seemed important. Firstly, it appears that a significant factor in the drop-off of strength to the residual value is the orientation of domains of clay particles (Ref. 4). This orientation process might be independent of the speed of shearing, and if this were so a satisfactory technique would be to apply large deformations (with consequent substantial particle orientation) at high speed and to then slow down the test to let drained conditions establish before the residual strength is determined. A novel version of this technique which has been tried is that of applying the initial deformation by handwinding at about 2 ins. per minute, before completing the test at the normal slow rate.

Secondly, there is the question of pore pressure equilibrium in relatively fast tests. Since even for these tests the time to completion can be large, there is a possibility that the pore pressure equilibrium established during that time is an adequate one as far as the determination of residual shear strength is concerned. To investigate this possibility the effect of testing at rates above those normally accepted for drained testing has been examined.

VI EXPERIMENTAL RESULTS

(a) Typical Load-displacement Curves

Figure 3 shows two sections of a typical load-displacement curve for a soil with large reversal peaks. Each of the numbered shear stages represents a change of shear direction. The curve shows the brittle peak characteristic of overconsolidated soils. This is followed by the usual continuous drop in load after peak strength (usually for ½-1 in.), and a tendency for the load to drop a little *at each later reversal* until the residual state is reached. Note however that the load frequently remains approximately constant between direction changes.

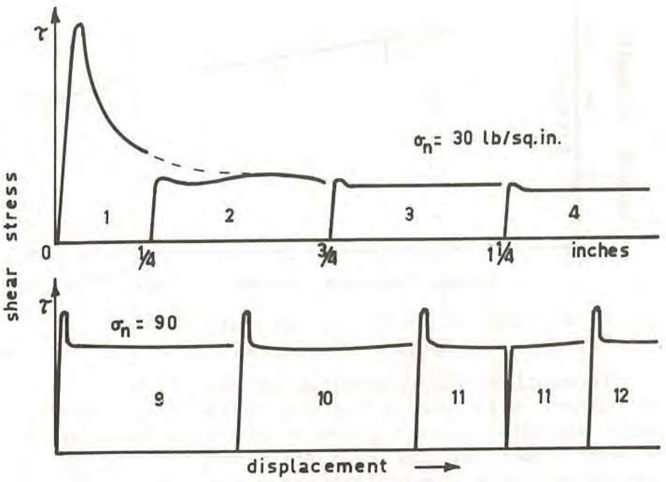

FIG. 3 Typical Load-displacement Curve

It follows that it is not necessarily sufficient to test the sample until a sensibly constant load value is obtained over a small displacement, but it is generally advisable to test until two consecutive reversals have the same failure loads. The practice of the authors has been to continue the test until two consecutive compression or tension runs are the same, because of the fact that tension and compression loads seldom correspond exactly. The variation is usually of the order of ± 5% at residual. It is possible that some of this difference is accumulation of apparatus errors despite the fact that great care has been taken with factors such as ring calibrations to reduce these errors as much as possible. That there are other factors involved is shown by the fact that in some tests consistent residual strength behaviour has varied by as much as 13% from the tension to the compression runs. In this case the lower value has always been accepted.

With some soils it has been found that the strength is consistently lower in the first forward direction (differences of the order of 10%), and this has occurred with many of the Series B samples. A similar effect is apparent in some of Kenney's results (Fig. 1, Ref. 6) and seems likely to be associated with a lack of perfect particle re-orientation on reversal.

The effects of reversal on the stress-strain curve vary significantly from sample to sample. Some samples show marked reversal peaks while other apparently identical samples show none at all.

Figure 3 shows the result (in reversal number 11) of reducing the shear load to zero and then re-commencing shear without reversing direction. In contrast to the sharp reversal peaks, the curve in this case does not peak at all. Kenney (loc cit) noted the same behaviour for shear tests on 1 mm. thick samples sheared between porous discs, and attributed the effect to a relocation of the shear plane at each reversal. In the direct shear box the zone within which the shear surface lies is usually much thicker than 1 mm., and quite large changes in the shear surface could occur between reversals. Some support for Kenney's explanation comes from the observation in some samples of dual failure surfaces separated by lenses of soil up to 3 mm. thick at the centre. It seems likely that the same phenomena could account for both the significant variation in reversal peaking between samples, and the apparently random variations between tension and compression strengths which so often occurs.

Although load curves frequently vary from the characteristic one shown, there are only two common significant variations which have evident causes. In tests which are conducted at speeds too great for drained conditions to be adequately established the load curve frequently rises over the full length of travel and never achieves a constant value: this behaviour no doubt arises as a result of the high strain rate giving inadequate time for pore pressure equilibrium in each cycle. In other tests it has sometimes been found that the load curve will behave as expected in one direction but each time rise gradually during at least part of the travel in the other direction. Figure 4 is a photograph of the shear plane in one such specimen and observation of test specimens indicates that inhomogeneities such as the one in this sample frequently contribute to this erratic type of load response.

(b) Typical Strength Envelopes

Figure 5 shows typical residual strength envelopes of three different soils. For the Series B samples the peak strength envelope is also shown.

For many of the soils tested the intercept c'_r for the stress range employed is non-zero. For other soils both zero intercept linear envelopes and curved

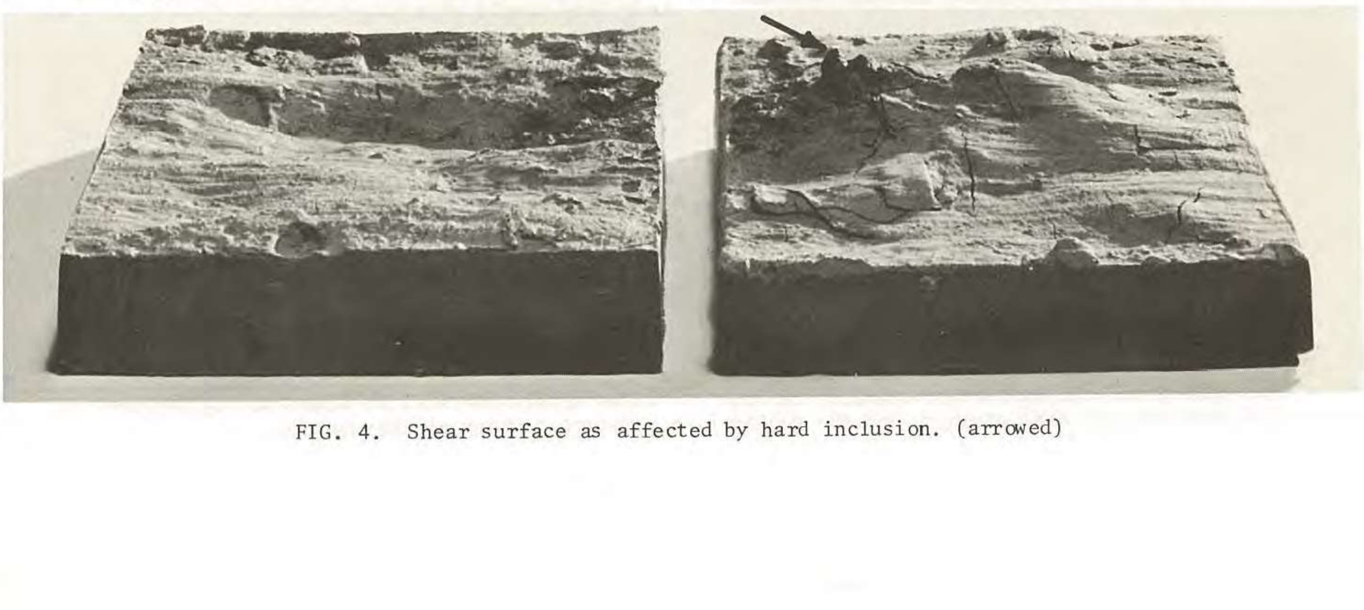

FIG. 4. Shear surface as affected by hard inclusion. (arrowed)

envelopes have been obtained, and the relatively high c'_r values which do occur are not considered to result from the test technique. Some investigators prefer to fit a curved envelope to test results in order to obtain $c'_r = 0$ (e.g. Skempton and Petley, Ref. 4). However, in cases where there is no evidence of envelope curvature over a wide stress range the authors consider that the use, in design, of c'_r values such as those given is reasonable.

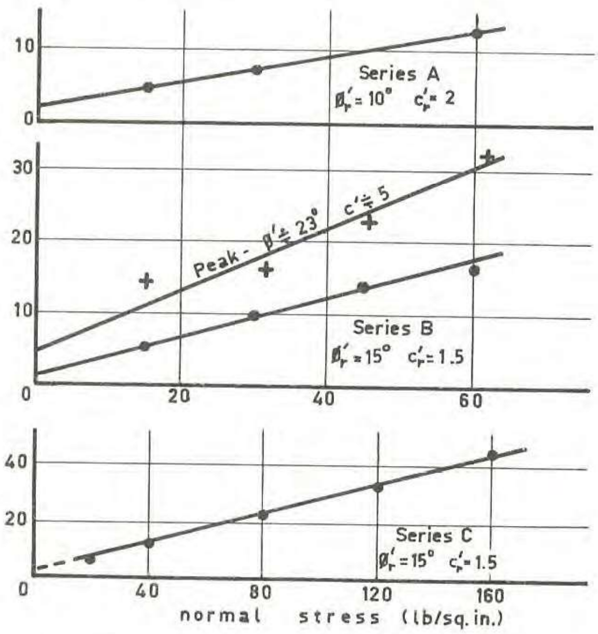

FIG. 5 Typical Strength Envelopes

(c) Effect of Moisture Content

Skempton (Ref. 1) demonstrated that the moisture content on the failure plane in a natural soil in the residual state can be significantly altered from the average moisture content of the adjacent soil. He suggests on the basis of this and other evidence (loc cit) that the stress history of a soil is not of any great significance in relation to the residual strength and that the angle ϕ'_r should therefore be a constant for any particular clay depending only on the nature of the particles. It follows that the moisture content on the failure plane and the residual shear strength should be much the same in all samples of a particular clay whatever the overall moisture content of the sample.

For the Series A tests which constitute the majority of the comparative testing the residual strengths at 30 lb/sq.in have been less consistent than might be expected from the above hypothesis. Figure 6 shows the residual shear strength plotted against sample moisture content at failure for 18 specimens all from the same block sample, and tested under the same conditions. There is clearly a variation of residual strength which correlates with sample moisture content although not necessarily arising from it. The significant factor in both variables could be the degree of weathering of the clay [1] although this has not as yet been investigated.

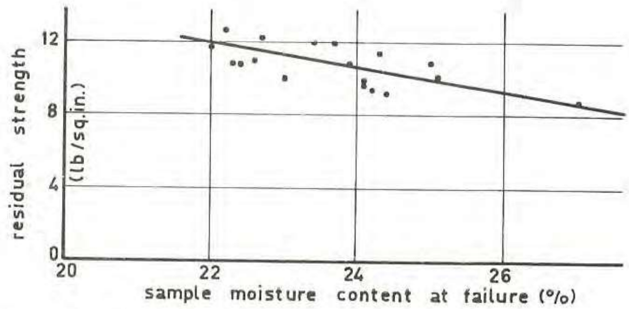

FIG. 6 Residual Strength vs. Moisture Content of Sample at Failure.

To simplify the comparison of results an approximate relationship between residual strength and sample moisture content given by the line in Figure 6 has been drawn, and the measured strengths have been "corrected" to a standard moisture content of 22%. All Series A results at 30 lb/sq.in (as corrected) are plotted on Figure 7.

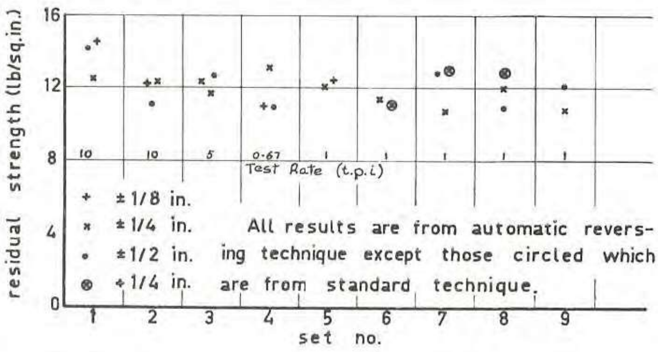

FIG. 7 Corrected Series A Results (30 lb/sq.in. tests)

(d) Area Corrections

Figure 2 is a reproduction of a typical load-displacement curve from an X-Y recorder (Load-vertical axis, relative box displacement-horizontal axis). After the first two reversals the load remains virtually constant over almost the entire 1 in. travel (-½ in. to + ½ in.) for each subsequent reversal. It would seem from this that it is not valid to apply area corrections even when the relative displacement of the box halves is of the order of 20% of the sample length. (i.e. if one assumes that the normal load is distributed over the full area of the sample, then the shear load should also be assumed to act over the full sample area.).

On physical considerations this is rather difficult to justify unless one assumes that the coefficient of friction - soil to soil - equals the coefficient of friction - soil to brass. However this behaviour has been regularly observed on soils having ϕ'_r values from 13° to 34°

In most tests it has been possible to obtain the load reading with the box at the central position, and the question of area corrections does not arise. Where this has not been possible, as for example in tests using the standard technique, no area corrections

[1] Since this determines the nature and quantity of clay particles within the soil it would be significantly reflected in both the residual strength and the equilibrium moisture content of the sample.

have been applied.

(e) Effects of Slow Stress Release at Reversal

In the standard technique the ring load is manually released at the end of each travel thus giving an immediate stress release to the sample. Using an automatic reversing machine the stress release occurs at motor drive speed and is quite slow.

In Figure 7 sets 6 to 8 have results from the standard technique circled, and these may be compared with all other results in sets 5 to 10 which were run at the same speed. No difference in measured strength seems to result from this change in procedure.

(f) Effect of Maximum Displacement

Figure 7 also shows that there is no consistent effect of different maximum displacements. However, on some occasions it has been found that ¼ in. travel between reversals is insufficient to obtain a steady load-displacement curve, a saw-toothed result (Figure 8) being obtained instead. For a reasonable estimate of residual shear strength ¼ in. travel tests are therefore likely to be unsatisfactory for some soils.

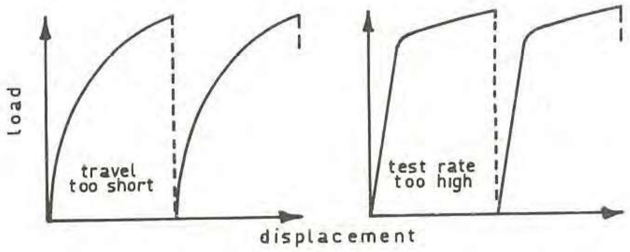

FIG. 8 Load-displacement Curve (Unsatisfactory test conditions)

This explains the difficulty noted by Skempton and Petley in interpreting stress-strain curves for some soils obtained from reversing shear tests in which the travel between reversals was only about 0.3 in. (Ref. 4).

Maximum displacement also affects the number of reversals necessary to reach the residual state. In the majority of tests on various soils, whatever the rate of testing (rapid handwinding excluded), the measured shear strength has become relatively steady after total shearing displacements of about 3 in. (extreme range 1¼-4 in.), and the number of reversals required to achieve the total displacement has not mattered.

(g) Effects of Handwinding, and Precutting Failure Planes

Handwinding at relatively high speed has been tried extensively, with the total travel before slow shear being varied from 3 in. to 10 in. Table I gives results from series B and D experiments.

Handwinding clearly does not produce the same extent of particle orientation as slow shearing, although the time to completion of the test using handwinding is generally somewhat reduced. A much more effective method of reducing the test time is that of pre-cutting a failure plane in the soil. This is not very feasible if the peak strength is required, but has been found satisfactory otherwise.

TABLE I

Series	Handwinding Travel (inches)	Further travel to residual after 16 hours consolidation (inches)
B	0	2 - 3
	3	1½
	7	2
	10	1½ - 2
D*	0	1
	5	3/4

* No time allowed for consolidation after handwinding

The (undrained) strength at the end of handwinding is frequently well below the residual strength. If handwound or pre-cut samples are sheared without further consolidation their strength tends to rise over the first reversal or two, presumably while drained equilibrium is being established.

The results on Kaolin showed the same residual strengths (within 1%) from tests using normal technique, handwinding, and pre-cut failure planes.

(h) Speed Effects

Investigations of residual shear strengths of a range of minerals and natural soils at speeds from very slow to creep rates (Kenney, Ref. 6) show insignificant speed effects in the range $70\text{-}10^6$ mins/mm. using 1 mm. thick samples. However it is noticable from Kenney's results that Kaolin, a relatively permeable clay, shows some increase in measured strength between 80 and 8 mins/mm., i.e. somewhere between ½ and 5 thousandths of an inch per minute (t.p.m.).

In the present test, sample thickness was approximately 25 mm. and the rates of testing were from 0.64 to 10 t.p.m. (60-4 mins/mm.) i.e., making allowance for drainage conditions, the speed range used here could be considered an extension of that investigated by Kenney in the direction of greater rates of deformation.

Test rates are shown on Figure 7, and there is no apparent effect of increasing the speed from 2/3 to 5 t.p.m. However the results from set 1 (10 t.p.m.) are noticably higher than average while those from set 2 (also 10 t.p.m.) are not. It seems then that for this soil 10 t.p.m. is possibly a little too fast and that undesirable pore pressures may exist at this speed.

To investigate this further, a number of samples have been deformed at low speed (1 t.p.m.) until residual strength is reached, and the test rate has then been increased to 10 t.p.m. In other tests the high speed "residual" has been obtained, and then the rate of deformation has been decreased to 1 t.p.m. and the changes in shear strength observed.

Where residual conditions have been reached at slow speeds initially, increase in test rate has in some cases had no effect on shear strength. In the majority of cases however it has altered both the shape of the load-displacement curve, and the estimated shear strength. At the higher speeds it is frequently found that the load curve is something like that represented in Figure 8 and a positive interpretation of the test results is very difficult.

For these tests the shear strength calculated from the load at the zero relative displacement condition has generally been found to be 10-15% higher than the slow speed residual value.

Where steady values of shear strength have first been obtained at 10 t.p.m. and the machine speed subsequently reduced to 1 t.p.m., the residual strength has been from 0 to 15% lower than the steady state high speed value. Subsequent return to high speed shearing resulted generally in a return to the higher strength values.

It seems fairly clear from the above results that significantly erroneous values will be obtained for the residual shear strength if test rates increase beyond a certain level. For the soil used in these tests - a relatively impermeable clay with PI ≐ 35% - that level would seem to be about 5 t.p.m.

Where it is necessary to select a suitable speed without any previous experience as a guide it would probably be advisable to run two tests at different speeds (say 10 t.p.m. and 1 t.p.m.) until steady state conditions are reached, and then reduce speed by a factor of 10 in each test and observe the changes in measured strength. When interpreting the results the variability of natural samples should be considered. For those who want a simple guide, results on the Series A soil used here show that if speed effects (as determined above) alter the measured strength by 10-20% the test rate in question should be considered 10 times too high. Other soils may, however, have more critical rate effects.

In the majority of tests or parts of tests which have been run at the higher speed (10 t.p.m.) the load deflection graph has been of the form shown in Figure 8. If this form of curve is obtained the shearing speed may well be too high, and this should be investigated.

(i) Stage Testing

Figure 9 shows the results of four Series B tests in which each sample has been failed at a different initial normal stress, with subsequent increases in normal stress in each test. τ vs. σ graphs are presented firstly for each sample showing all stages, then for the collected first stage results, and finally for all results obtained from the four samples. The four samples were taken from adjacent locations.

Figure 9 also shows results from one Series A test in which the load has been varied a number of times both up and down. It is evident that the strength is not affected by the stress history of the sample within the range tested, and that later stages give values the same as those obtained from the early stages.

All these results indicate that stage testing is a valid extension of the normal technique. At the test rate used for these samples the machine time required to obtain each initial point is usually about 2½ days, whereas that for further points is about 1 day only. (These are minimum times and both are significantly dependent on the constraints of normal working hours). Furthermore up to four points on the strength envelope can be obtained from one sample and from one setting up operation, although the brittleness is only obtained at one stress level.

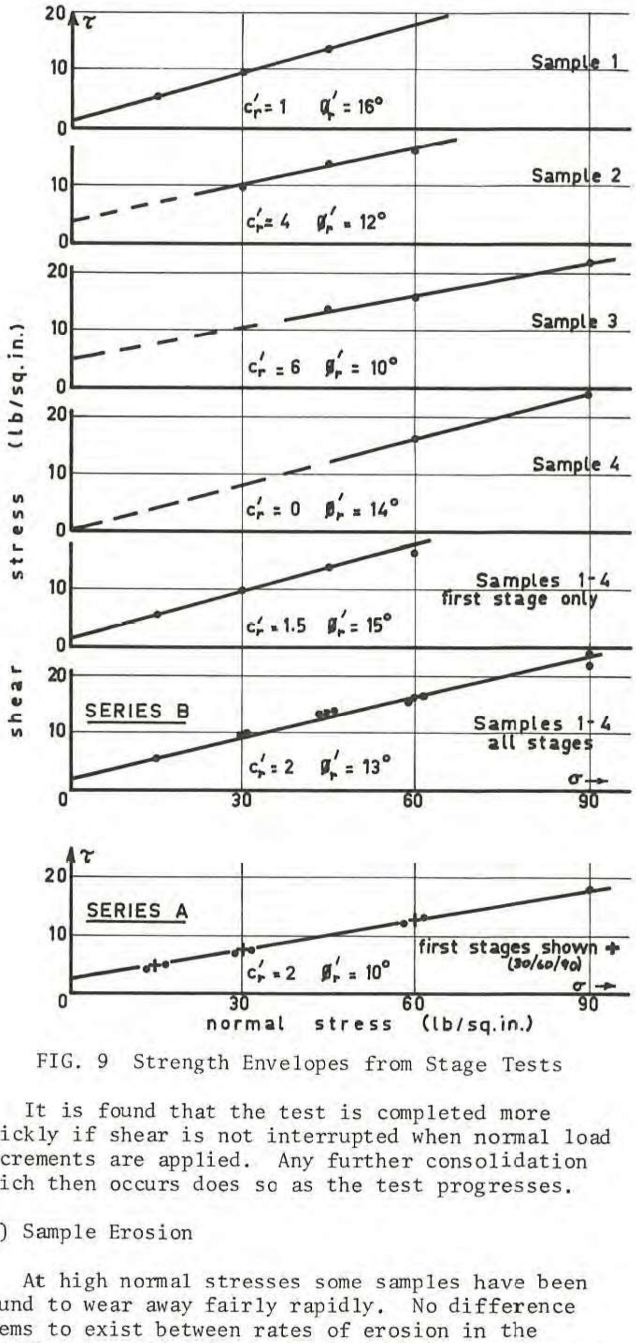

FIG. 9 Strength Envelopes from Stage Tests

It is found that the test is completed more quickly if shear is not interrupted when normal load increments are applied. Any further consolidation which then occurs does so as the test progresses.

(j) Sample Erosion

At high normal stresses some samples have been found to wear away fairly rapidly. No difference seems to exist between rates of erosion in the standard box using the standard technique and rates in the modified box using larger maximum displacements. Where stage testing is employed the sample will generally be subjected to very substantial cumulative shear displacements and it is advisable to have ½ in. thickness of sample above the shear plane for such tests. Thickness of all samples in the tests reported herein have been 1 in. with the failure plane approximately at midsample height at setup.

It should be recognized that the material being sheared at one reversal is not precisely the same as that sheared at the next and in stage tests the results should be expected to reflect to some extent the small-scale variability of the natural materials.

(k) Remoulded Samples

Tests on remoulded samples in Series C and D were generally found to reach residual strengths more quickly than was the case for natural samples. Slickensides are formed in remoulded material as in natural samples, and a photograph of one such case is shown in Figure 10. (The sample separated readily). Total travel for this sample was 2 inches at 1 t.p.m. (40 min/mm) and normal stress was 20 lb/sq.in. The residual strength envelope for this material is shown in Figure 5. (four different samples.)

FIG. 10 Slickenside Formed in Remoulded Sample

(*l*) Kaolin

Results for the Kaolin were as follows:- for $c'_r = 0$, $\tan \phi'_r = 0.18$ ($\phi'_r = 10^{\circ}$), at normal stresses of both 30 and 60 lb/sq.in. This is somewhat lower than the value obtained by Kenney (Ref. 6) in his apparatus.

(m) Machine Modifications

The circled results on Figure 7 were obtained using not only the standard technique, but the standard Wykeham Farrance Reversing shear machine. As previously noted these results are not significantly different from those obtained on the extensively modified shear box. It follows that the results from the standard machine have not been affected noticably by the relatively large amounts of end play in the drive system, or the considerable amount of vertical restraint which can be afforded the top half of the shear box by its yoke system. Modifications (ii), (iii), and (v) (Section IV) can therefore be considered unnecessary.

VII CONCLUSIONS

(a) The reversing shear box is a convenient apparatus for measuring both peak and residual strengths of soils. The laboratory conditions under which these tests are made are quite different from those which exist in the field. It does not follow, however, that these differences necessarily lead to significant errors in the laboratory estimation of field residual strengths. A number of variables and variations of test technique have been isolated and examined to determine their effects on measured residual strength. In general the test results are insensitive to significant changes in the test procedure, deformation rate being the one exception.

On the basis of the tests analysed so far the following procedure would be recommended for a machine with minimum modification.[1]

(i) For a 6 cm. square box a 1 in. thick sample should be used.

(ii) Using unmodified shear box halves the travel limits should be set at about plus 0.4 ins., and minus nothing. (Unmodified boxes might not always allow sufficient travel for correct determination of residual strength.)

(iii) A deformation rate suitable for determining the drained strength parameters for the soil in question should be selected. A speed of 0.001 inches/min. is likely to be suitable for fissured overconsolidated clays.

(iv) The normal stress should be selected on the basis of the number of samples available. Both "positive" and "negative" staging give satisfactory results.

(v) Consolidation of the sample under the applied normal stress is only necessary where peak drained strengths are desired from the sample.

(vi) After the peak strength has been passed, rapid handwinding for 2-3 ins. travel can be used to hasten particle orientation.

(vii) The test should be continued until closely similar results are obtained on consecutive forward or consecutive reverse movements, and not stopped when the load appears to be steady within one movement. It will generally be found that about 2-2½ ins. total deformation is necessary, irrespective of the number of reversals involved.

(viii) When the residual state has been reached the normal stress may be varied in whatever stages are required by the investigation programme, a check being kept on sample erosion particularly when the normal stresses are high.

(b) Load-deformation curves which are difficult to interpret will often be found to result from heterogeneous specimens, or from too high deformation rates.

(c) With some soils uni-directional movements greater than 0.4 ins. might be necessary for correct determination of the residual strength. The standard 6 cm. square shear box would not give adequate travel for these soils.

[1] For a basic non-reversing shear box the minimum modification is:-
(i) Provision of push-pull connexions at motor drive and proving ring.
Desirable modifications are considered to include:-
(ii) Automatic reversing control.
(iii) Automatic load recording.
(iv) Modification of upper and lower box halves to give unrelieved faces allowing displacement in both directions.

(d) The value of c'_r is not necessarily zero even for relatively low stress ranges.

(e) The results for the Kaolin indicate that the method of conducting residual shear tests does affect the laboratory estimate of ϕ'_r.

(f) Some Australian soils show very high brittleness indices (up to 0.75 at 30 lbs/sq.in) and it is worth noting that it is for soils such as these that residual strengths are most likely to be of relevance.

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