Measurement and use of residual shear strength of cohesive soils

by A.B. HAWKINS* & K.D. PRIVETT$^5$

Careful testing has shown that similar results can be obtained using the Bromhead ring shear apparatus and the conventional reversal shear box.

Extended testing has confirmed that residual failure envelopes are curved and that the curvature is most pronounced below about 200kPa effective normal stress and in soils with a high clay fraction. Two new terms are introduced, Complete Failure Envelope and Lowest Residual Strength.

The importance of acquiring data relevant to the correct overburden pressures is emphasised; for a shallow slide of 1-2m the $\alpha'_{p}$ may be 70% higher than for a deep slide, with a high effective normal stress. Thus an appropriate figure should be read from the residual friction coefficient or from a straight line approximation over a selected normal stress range, preferably from the Complete Failure Envelope.

Correlation charts relating residual strength to clay fraction and/or plasticity index are only meaningful if the points have been established at the same effective normal stress, and also if this stress level is relevant to the problem being considered.

Introduction

THE RESIDUAL SHEAR STRENGTH of soils (Skempton, 1964) referred to as "ultimate strength" in the USA is widely used in slope stability analysis. The shear box, initially used to obtain peak shear strength parameters, was modified to measure the residual shear strength by continual forward and reverse shearing of the sample. A second type of apparatus, the ring shear, allows continuous shearing of a sample in one direction (Bishop et al., 1971).

A less sophisticated ring shear apparatus than that used by Bishop, known as the Bromhead ring shear (Bromhead, 1979) is now available. Because it is relatively cheap and easy to operate, its use is becoming widespread. Many practising engineers, however, still treat the results obtained with some reservation, claiming that the values of $\alpha'_{p}$ produced are underestimates of the "true" value. For instance, the 1981 Code of Practice for Site Investigation (British Standard 5930, Table 4) states "The residual shear strength of clay soil is increasingly used in slope stability problems. The multiple reversal shear box test is the one which is more commonly used, although the ring shear test would appear to be the more logical. This latter test tends to give lower parameters than the former."

There is very little practical advice in the literature for the non-specialist engineer wishing to use $\alpha'_{p}$ in his calculations. In this paper the two methods are discussed in the light of experience gained in testing dominantly cohesive soils. As the value of $\alpha'_{p}$ of many cohesive soils has been found to vary, to obtain the complete failure envelope testing must continue until the lowest value of $\alpha'_{p}$ is reached. Two concepts are introduced, Complete Failure Envelope and Lowest Residual Strength.

Remoulded samples have been tested in the 60mm and 100mm square shear box and in the Bromhead ring shear with a view to examining discrepancies between the two basic methods. During these series of tests two important effects were noted. First, the ease and speed with which residual conditions are reached in the ring shear test. Second, that many residual strength envelopes are curved slightly at effective normal stresses below approximately 200kPa; if this is not recognised there is a tendency to compare the "low" values of residual strength at high effective stress tested using the ring shear apparatus with shear box results obtained using low effective normal stress relevant to a shallow slide. This means that $\alpha'_{p}$ should not be considered as constant for a particular material, but a parameter which changes with the effective normal stress.

As $\alpha'_{p}$ varies with effective normal stress it is not possible to produce single diagrams for correlating the residual strength with other engineering parameters such as clay fraction and plasticity index. Such correlations should only be made if they include information relating to the effective normal stress involved during the testing to obtain the $\alpha'_{p}$ quoted.

Comparison between shear box and ring shear results

Hutchinson et al. (1980) show that there is a very good agreement between the results obtained using the Bromhead ring shear and the more sophisticated Geoconor apparatus. They conclude that the values of $\alpha'_{p}$ obtained for Gault Clay are in broad agreement with those determined by back analysis. Using the shear box however, the $\alpha'_{p}$ is up to 70% higher on samples tested at low effective normal stresses. Chandler et al. (1973) concluded that ring shear tests underestimated the field mobilised shear strength, whereas shear box tests were an over-estimation; while Townsend and Gilbert (1973) and Bromhead and Curtis (1983) report similar results from both types of test.

One major factor causing discrepancy between the results from the two methods is the difficulty with which residual conditions are reached in a reversal direct shear box, compared to the ease with which this is achieved in a ring shear device. Hawkins & Privett (1981) report comparative tests performed on a remoulded sample of the clay rich Cotham Member of the Rhaetic ($w_{c} = 96\%, w_{p} = 36\%, <0.002\text{mm} = 73\%$) using a Bromhead ring shear and 60mm and 100mm square reversal shear box. They conclude that the values of $\alpha'_{p}$ obtained are in broad agreement with those determined by back analysis. Using the shear box however, the $\alpha'_{p}$ is up to 70% higher on samples tested at low effective normal stresses. Chandler et al. (1973) concluded that ring shear tests underestimated the field mobilised shear strength, whereas shear box tests were an over-estimation; while Townsend and Gilbert (1973) and Bromhead and Curtis (1983) report similar results from both types of test.

One major factor causing discrepancy between the results from the two methods is the difficulty with which residual conditions are reached in a reversal direct shear box, compared to the ease with which this is achieved in a ring shear device. Hawkins & Privett (1981) report comparative tests performed on a remoulded sample of the clay rich Cotham Member of the Rhaetic ($w_{c} = 96\%, w_{p} = 36\%, <0.002\text{mm} = 73\%$) using a Bromhead ring shear and 60mm and 100mm square reversal shear box. They conclude that the values of $\alpha'_{p}$ obtained are in broad agreement with those determined by back analysis. Using the shear box however, the $\alpha'_{p}$ is up to 70% higher on samples tested at low effective normal stresses. Chandler et al. (1973) concluded that ring shear tests underestimated the field mobilised shear strength, whereas shear box tests were an over-estimation; while Townsend and Gilbert (1973) and Bromhead and Curtis (1983) report similar results from both types of test.

Fig. 1. Complete Failure Envelope showing the variation of residual friction coefficient (Lupini et al., 1981) with effective normal stress and the different appropriate values for shallow and deep slides.

*Department of Geology, University of Bristol, Bristol BS8 1TR

$^{5}$Now with Sir Robert McAlpine & Sons Ltd., Rigby Lane, Hayes, Middx.; formerly with the Department of Geology, University of Bristol

22 Ground Engineering
100mm square direct shear boxes. In the shear box samples a pre-cut plane was polished by several manual reversals in order to quicken the reaching of residual conditions before an automated reversing system, similar to that of Marsh (1972), was used for the tests. Even with a pre-cut polished plane, true residual conditions were not reached until the shear box had undergone many reversals. Although three or four reversals are often taken as being adequate, frequently at least ten reversals were necessary to ensure that minimum shear stress had been attained.

Despite care with sample preparation and testing, experience has shown that compared with the 100mm shear box, the smaller 60mm box is more prone to frictional and other intrinsic problems. In Fig. 2 one of the 60mm shear box envelopes crosses the other, one of the test plots showing a lower initial $\sigma'_n$ yet higher ultimate $\alpha'$ than the other run. There is, however, a good correlation between the 100mm shear box and the ring shear results. This is demonstrated in Table I where values of $\sigma'_n$ (assuming $c'_n = 0$) have been calculated for a number of effective normal stress levels.

In the case of the shear box a number of factors may combine to give high shear stress readings, some of which may not be appreciated by the operators of the machine and those using the results.

(a) The reversal of the shear box means a slightly oblique clay mineral alignment near the shear surface will suffer some particle readjustment with each change in direction (Skempton & Petley, 1967).

(b) The coalescence of opposing low-angled Riedel shears produces an undulating surface (Skempton, 1966; Early & Skempton, 1972).

(c) During testing material is squeezed out allowing the two halves of the apparatus to come together, resulting in metal to metal friction. The effects of the varying stresses around the edges of the sample during shearing are difficult to assess; this problem is not discussed further in this Paper.

In the ring shear test, however, the continuous single direction of movement means that although there is some oblique alignment, there is no realignment once residual conditions have been reached. Some lateral squeezing occurs but it is proportionally less than with the shear box due to the low internal disturbance in the single directional movement; however care must still be taken, especially during tests of long duration and/or high loads. This has been discussed by Lawrence (1984).

Provided the ring shear apparatus can be proved to give meaningful results to be used intelligently by engineers, then the time element becomes important. To obtain a complete shear box envelope, using say six points, takes about two months. In the ring shear six points can be measured in less than a week. The other noticeable advantage is that the results are more reproducible than those obtained using the shear box.

The nature of the failure envelope

The majority of clay rich engineering soils tested by Privett (1980) were found to have curved residual failure envelopes, the maximum deflection occurring below 200kPa effective normal stress (see Fig. 1). This reinforces the view that the residual strength of a soil is not a unique parameter, but is dependent upon the normal stress acting on the soil (see Bishop, 1965).

There are many examples of curved residual failure envelopes in the literature. Garga (1970) cited Tiedemann (1937) who worked on the Weser-Elbe Canal clay. Skempton & Petley (1967) present curved failure envelopes for the Atherfield, Weald and London Clays. Hutchinson (1969, Fig. 19) shows points indicating a curved envelope in the lower stress range but decides to apply a straight line. Both Bishop and Chandler (in Parry, 1972) record the variation of $\sigma'_n$ with effective normal stress. Kenny (1967) states that the residual strength is dependent mainly on mineralogy and gives examples of curved failure envelopes. He notes that soils with a high proportion of expanding lattice clay minerals show the more pronounced curvature. Chandler (1976) obtained a good fit between back analysis and a laboratory determined curved failure envelope for the Upper Lias Clay. On the other hand, Bishop et al (1971) show the brown London Clay to have a curved envelope but the blue London Clay a straight envelope. Bromhead & Curtis (1983) have a straight envelope for brown London Clay and a curved one for the grey samples they tested. Townsend & Gilbert (1973) obtained straight line failure envelopes for their American "clay shales" while Lupini et al (1981) have chosen to express $c'_n$ as "linear to a good approximation".

Residual strength data can be replotted in terms of $\sigma'_n$ only by using $\sigma'_n$ and $\alpha'_n$ axes (the term $\sigma'_n$ has been called the residual friction coefficient by Lupini et al, 1981). By considering $\sigma'_n$ at a particular value of $\alpha'_n$, to be $\tan^{-1} \frac{\alpha'_n}{c'_n}$, then $c'_n$ is effectively reduced to zero and the variation of $\sigma'_n$ with effective normal stress can be appreciated.

Fig. 1 is a representative plot of typical residual strength data demonstrating how initially the residual friction coefficient falls rapidly as the effective normal stress increases before levelling out at a constant value. This value is defined as the tangent of the "Lowest Residual Strength" and the failure envelope is said to be "Complete" once this stage has been reached. The more conventional plot of shear stress versus normal stress is given beneath. As $\sigma'_n$ is not a constant, testing should begin at a low effective normal stress and continue until the complete failure envelope is obtained, i.e. the lowest residual strength has been established.

In practice it is essential to consider the entire failure diagram to be the residual strength and any numerical values of $\sigma'_n$ should be abstracted from the diagram at the effective normal stress appropriate to the particular slope stability problem (Fig. 1). Fig. 3 shows actual results from a Bromhead ring shear test carried out at a strain rate of

(continued on page 26)
0.0178mm/min on a sample from the Rhaetic Cotham Member plotted in the manner described above. It can be seen that $\sigma'_n$ drops rapidly from about 14° at an effective normal stress of 25kPa (equivalent to a 1.5m deep slide) to only 6°-7° at about 200kPa (equivalent to a 10+ m deep slide) where the curve flattens to a straight section.

It is still common practice to assume a straight line residual failure envelope which, with a best fit straight line, would give a small $c'$ in design. In this small $c'$ is often ignored. In the case of low effective normal stress this may be reasonable but with higher loads the calculations err on the side of safety, and with an erroneously low value of $\sigma'_n$ many existing slopes may even have had a calculated factor of safety of less than unity.

The time and cost factors involved in conventional shear box tests mean that they are usually only carried out over a restricted stress range; this should be relevant to the particular problem in question. Assuming true residual conditions have been reached in the laboratory test, then a straight line drawn between the (usually three) points will give the value of $\sigma'_n$ required. This is the long established method. The apparently very low results obtained with the ring shear are not in fact erroneous, they are merely a consequence of applying the established method of interpretation to the new machine (Hawkins & Privett, 1984). It has been shown that the two methods, if carried out correctly, can give very similar failure envelopes. The apparent difference arises because the failure envelope curves below about 200kPa effective normal stress.

The speed and ease of operation of the Bromhead ring shear means that it is tempting to establish more points; this is achieved by adding more weights on the lever loading device such that it is common to take the effective normal stress as high as 600kPa. If a straight line approximation is used the shear box appears to give a higher value of $\sigma'_n$ since only a portion of the complete failure envelope has been established, usually the steeper portion below 200kPa (a 10m deep slide). If the same straight-line method is applied to the entire failure envelope as established by the ring shear it is bound to produce a "lower $\sigma'_n$". This is shown in Table I where the envelopes from Fig. 2 have been used to calculate $\sigma'_n$ at various stress loads along with the best-fit regression straight-line. The 100mm shear box and the ring shear are very similar and it can be seen that the straight line value of $\sigma'_n$ is close to the lowest residual strength, because a greater proportion of the curve is above the 200kPa level.

**Correlations with other parameters**

An important consequence of the variation of $\sigma'_n$ with effective normal stress is the necessity to modify published correlations between $\sigma'_n$ and other parameters. For example the correlations with plasticity index discussed by Vaughan & Walbancke (1975) and Ingold (1975) give no indication of the effective normal stress to which the residual strengths refer. Thus Ingold's (1975, Fig. 1) value of 17° for the Upper Fuller's Earth from Swainswick, Bath, suggests there is a unique residual strength for that material. Ring shear tests carried out on this material (Privett, 1980) have shown however that $\sigma'_n$ varies by as much as 9° over the effective normal stress range of 27 to 615kPa. Such correlation diagrams are useless, therefore, unless all the values of $\sigma'_n$ have been calculated at the same effective normal stress and this value is quoted.

This approach has been adopted in Fig. 4, which shows the variation of $\sigma'_n$ with plasticity index at four effective normal stresses. Ingold's (1975) line is included for comparison. Most of the samples tested were rich in clay minerals, hence there are no points below 20% plasticity index. The data shows a big variation in $\sigma'_n$ for the samples with plasticity indices in the range 25-45%. Thus for typical soils ($\mu_1 = 25-45$) it is not possible to draw a line to represent the $\sigma'_n$ only a wide zone can be suggested.

This is shown in Fig. 5. The experimental determination of the clay fraction rarely measures the actual proportion of clay grade material in a sample. Most soil particles, especially the finer ones, are aggregated to varying extents; hence only the effectiveness of the dispersion technique is measured. Since it is extremely difficult to ensure that all the particles are separated yet none are cleaved, most workers adopt a standard dispersion technique for all soils (eg BS 1377). A rigorous adherence to the test procedure should allow comparison between samples; workers with differing dispersion techniques are likely to produce significantly different clay fractions for a given soil sample.

(a) Fine and possibly even medium silt grade particles are often sufficiently platy to behave as clay grade particles; thus while the 2µm value is convenient it may not be the most significant grade to establish; a separation at say 0.006mm may be more applicable when separating turbulent from sliding modes of failure.

(b) Since many fine soils are composed of clay grade aggregates, the effect of reducing such soils to their component parts and correlating this with strength parameters...
raises the question of validity. What importance does the percentage of particles less than 2 micrometres have on the in situ soil particles if the soil is composed of clay grade material held together to form larger aggregates?

(d) The effect of mineralogy must be considered with the last two points, since the fine fraction of different soils may be composed of different clay minerals, each of which have particular physical and chemical properties.

**Conclusions and choice of residual strength parameters**

The following conclusions arise from this study:

1. The ring shear test is easy to perform, is reliable, relatively quick and hence cheaper than the shear box test.
2. As a result of the dual direction of movement the reversal shear box is likely to develop problems such as an undulose shear surface. This can lead to greater residual strengths being recorded than would be correct for the soil in a natural surrounding.
3. These problems can be reduced with care, although the tests performed at Bristol University favour the 100mm shear box as being more reliable than the 60mm device.
4. The shear box and ring shear both produce very similar failure envelopes.
5. The ring shear is less prone to errors and is considered the better tool to determine residual strength.
6. The Complete Failure Envelope of cohesive soils is typically curved. This curvature is most pronounced below about 200kPa effective stress. This gives a steeper slope, and hence a higher value of $\phi_r$ at lower normal stresses.
7. The difference observed between shear box and ring shear results (providing the shear box reached true residual conditions) is only apparent. With the ring shear test it is common to produce complete failure envelopes but most shear box tests are carried out at the lower end of the effective stress range. The assumption of straight-line failure envelopes will consequently suggest a discrepancy between the two methods.
8. As effective normal stress increases the failure envelope becomes straighter and the residual friction coefficient

---

**Fig. 4.** The relationship between plasticity index and $\phi_r$ for a number of soil samples shown at different effective normal stresses. The line suggested by Ingold (1975) has been inserted for comparison

**Fig. 5.** The relationship between $\% < 2\mu m$ and $\phi_r$ for the same soil samples as Fig. 4. Skempton's (1964) lines are inserted for comparison
approaches a constant value. This is termed the Lowest Residual Strength, \( \sigma'^* \), the residual angle of internal shearing resistance, \( \phi'^* \), is not a constant for many cohesive soils. In a clay rich material it has been shown to vary, with effective normal stress, from \( 0^\circ \) to \( 18^\circ \). In order to establish the value relevant to a particular problem, two of the methods is suggested:

(a) A straight-line approximation over the appropriate small stress range.

(b) The use of the \( \phi'^* \) against \( \sigma'^* \) plot to give a value of \( \phi'^* \) for a particular stress.

20. There is advantage to the Engineer in having a Complete Failure Envelope. In this way he can establish \( \phi'^* \) at any effective stress level, this may be important, for example, during changes in a design or new field appreciation.

11. Correlations between \( \phi'^* \) and other geotechnical parameters can only be used with confidence if the values of \( \phi'^* \) all relate to a specific stress level.

20. Soils with > 60% clay fraction and/or a plasticity index of > 45% have low residual strengths, generally with little scatter. Many soils encountered in engineering practice have clay fractions between 35-60% and plasticities of 25-45%. These soils show a wide scatter of residual strengths and it is considered inappropriate to use correlations in the analysis of such soils. It is in these soils that the mode of shear is likely to be partially turbulent and partially sliding as defined by Lupini et al. (1981).

12. Record should be noted that different groups of soil may behave very differently, for example the volcanic soils of Wesley (1977) do not fit these published correlations.

14. The actual cause of the curvature of the residual failure envelope remains obscure. It is clear that clay grade powdered glass gives an almost flat envelope while a greater percentage of fine clay minerals such as the smectite group (including montmorillonite) give a more pronounced curvature. Thus the clay mineral chemistry affects the continual breaking and reforming of electro-chemical bonds across a moving shear surface. It is also logical that a smoother, flatter, shear surface in which the particles are better aligned is likely to develop as higher normal stresses are applied.

15. Although material with less than about 35% clay grade has a higher shear strength, it is important for engineers/ geologists to remember that in the field it is frequently more difficult to determine the actual shear zone in these less clay dominant soils.

References


March, A.D. (1972): "Determination of residual shear strength of clay by a modified shear box method." TRRL Report LR 615, Department of the Environment, Department of Transport, Crowthorne, Berks.


