

Bromhead Ring Shear Test Procedure

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ABSTRACT: Existing test procedures and a proposed modification for the Bromhead ring shear apparatus were found to yield drained residual strengths higher than values back-calculated from field case histories. A new test procedure is presented that yields drained residual strengths that are in excellent agreement with field case histories. The new test procedure utilizes the unmodified Bromhead ring shear apparatus and limits the settlement of the top porous stone, due to consolidation and/or soil extrusion during drained shear, to 0.75 mm. Since the specimen is confined radially by the specimen container, limiting the settlement of the top porous stone minimizes the wall friction that develops along the inner and outer circumferences of the specimen. The reduced wall friction results in the lowest measured residual strength and the best agreement with field case histories.

KEY WORDS: clays, clay shales, residual strength, slope stability, torsion shear tests

Skempton (1970, 1985) concluded that the drained postpeak drop in strength observed in overconsolidated clays is due to (1) an increase in water content due to dilation and (2) the orientation of clay particles parallel to the direction of shearing (Fig. 1). In normally consolidated clays the postpeak drop in strength is due entirely to the orientation of particles parallel to the direction of shearing. Particle reorientation will be significant in clays containing platy minerals and a clay fraction (percentage by weight of particles smaller than 0.002 mm) exceeding 25%. Large shear displacements in one direction are required to orient the clay particles parallel to the direction of shear and obtain a residual strength condition in both normally consolidated and overconsolidated clays.

At the present time, the reversal direct shear test is widely used to measure the drained residual strength of clays even though it has several limitations. The primary limitation is that the soil is sheared forward and then backward until a minimum or equilibrium shear resistance is measured. Each reversal of the shear box results in a horizontal displacement that is usually less than 1.3 cm. As a result, the specimen is not subjected to continuous shear deformation in one direction and thus only a partial reorientation of the clay particles is obtained. In addition, the cross-sectional area of the specimen is changing during shear and a substantial amount of soil is usually extruded out of the exposed shear plane during the test. These and other limitations usually

result in residual strengths that are higher than the residual values obtained from a torsional ring shear device (Stark and Eid 1992).

The main advantage of the torsional ring shear apparatus is that it shears the soil continuously in one direction for any magnitude of displacement. This allows full orientation of the clay particles parallel to the direction of shear and the development of a true residual strength condition. Other advantages of the ring shear apparatus include a constant cross-sectional area of the shear plane during shear, a thinner specimen which allows the use of a faster drained displacement rate, more reproducible results, and less laboratory supervision than the reversal direct shear test.

Skempton (1985), Bromhead and Curtis (1983), Bromhead and Dixon (1986), and Stark and Eid (1992) have shown that the drained residual strengths measured using a ring shear apparatus and remolded specimens are also in better agreement with back analyses of landslides than reversal direct shear tests. This is probably due to the partial reorientation of clay particles in the direct shear apparatus. It should be noted that Skempton (1985) stated that direct shear tests conducted on specimens with a fully developed slip surface located exactly at the shear plane of the direct shear box and arranged such that shearing follows the natural direction of movement will provide an accurate estimate of the field residual strength. These tests are referred to as slip surface tests and are significantly more difficult to perform than a ring shear test on remolded specimens.

A number of different forms of the ring shear apparatus have been developed, e.g., Hvorslev (1936 and 1939), La Gatta (1970), Bishop et al. (1971), and Bromhead (1979). However, the Bromhead (1979) ring shear apparatus is becoming more widely used because of cost, availability, and ease of operation. Bromhead and Curtis (1983) showed that this apparatus yields results that are in good agreement with those obtained using the more sophisticated apparatus developed by the Norwegian Geotechnical Institute and Imperial College (Bishop et al. 1971). Bromhead and Dixon (1986) and Stark and Eid (1992) also showed that the drained residual strength values measured with the Bromhead apparatus are in excellent agreement with the back-calculated values for landslides at Warden Point and Southern California, respectively. Newbery and Baker (1981) showed that the Bromhead ring shear test results are in good agreement with slip surface tests on shear zone material from the Wenallt slip. In summary, the Bromhead ring shear apparatus appears to provide reasonable estimates of the field residual strength.

Recently, a number of researchers, e.g., Anayi et al. (1988), Anayi et al. (1989), Anderson and Hammoud (1988), and Wykeham-Farrance (1988), have proposed different test pro-

¹Assistant professor of civil engineering, University of Illinois, Urbana, IL 61801.

²Geotechnical engineer, Moore and Taber, Inc., San Diego, CA 92127.

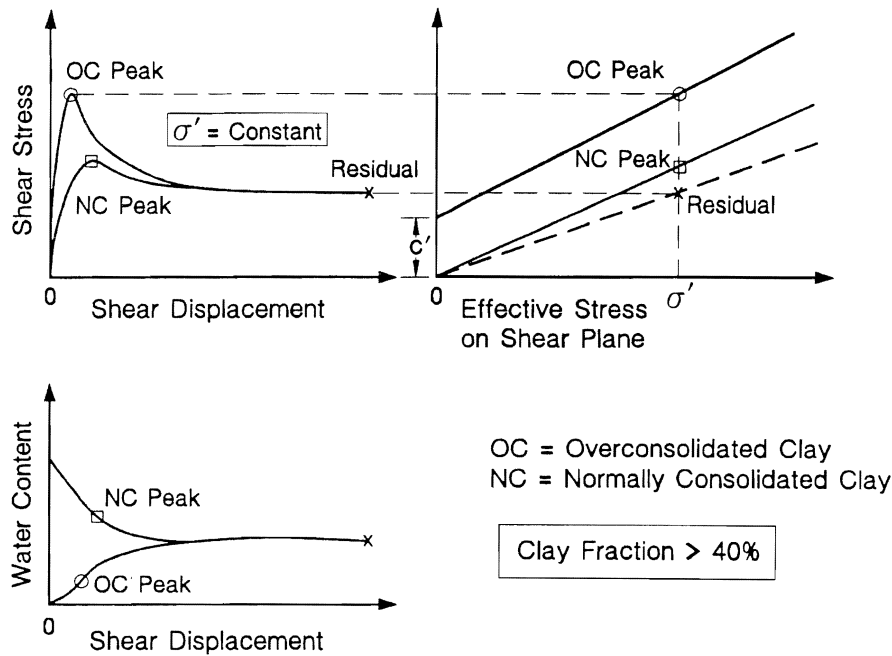


FIG. 1—Drained shear characteristics of clays (after Skempton, 1970).

cedures and/or modifications to the Bromhead ring shear apparatus. This paper presents test results which illustrate the effect of these different test procedures on the measured shear resistance and proposes a new test procedure that provides excellent agreement with field case histories. In addition, this paper illustrates the effect of inserting vanes into the top porous stone, as proposed by Anayi et al. (1989), on the measured shear resistance.

Bromhead Ring Shear Apparatus

The Bromhead ring shear apparatus is based on the original design developed by Bromhead (1979) and is manufactured by Wykeham-Farrance Engineering Limited. The ring shear specimen is annular with an inside diameter of 7 cm and an outside diameter of 10 cm. Drainage is provided by two bronze porous stones screwed to the bottom of the specimen container and to the top loading platen.

The specimen is confined radially by the specimen container, which is 0.5 cm deep. As a result of the confinement, wall friction is applied to the inner and outer circumferences of the specimen. The magnitude of wall friction increases with the depth of the specimen, and thus the plane of least wall friction, or shear resistance, occurs at or near the soil/top porous stone interface. This results in the failure plane occurring at or near the knurled surface of the top porous stone. This type of failure condition is often referred to as a "smear" condition (Bromhead 1986).

Effect of Ring Shear Test Procedure

At present there are four main test procedures for measuring the drained residual strength of cohesive soils in the Bromhead ring shear apparatus. These procedures are termed: (1) single stage, (2) preshearing, (3) multistage, and (4) the proposed "flush" procedure. The main factor affecting the residual strength measured in the Bromhead ring shear apparatus is the magnitude of wall friction that is developed along the inner and outer circum-

ferences of the specimen. The farther the top porous stone settles into the specimen container, the more wall friction that is developed on the shear plane and the higher the measured residual strength. In addition, during shear a small amount of soil is usually extruded between the top porous stone and the walls of the specimen container. As the top porous stone settles into the specimen container, the possibility of the extruded soil becoming trapped between the container and porous stone becomes greater. This may also lead to an increase in shearing resistance as the top platen settles.

Based on the test results obtained during this study, the amount of soil extrusion increases with displacement rate, effective normal stress, clay fraction, and swelling pressure of the specimen. A typical example of the effect of wall friction on the measured shear resistance is the result of two Bromhead ring shear tests on remolded Bearpaw shale from Fort Peck Dam. The liquid limit, plasticity index, and clay fraction of the Bearpaw shale are 288, 244, and 88%, respectively, and the remolded shale classifies as a clay of high plasticity, CH, according to the Unified Soil Classification System (USCS). The specimens had a thickness of 2 and 4 mm prior to shearing and resulted in drained residual shear strengths of 32 and 24 kPa, respectively, at a normal stress of 345 kPa. The difference in residual strength, i.e., 8 kPa or 25%, is attributed to the additional wall friction caused by the top porous stone settling an additional 2 mm into the specimen container prior to shear.

The test results presented herein will show that the lowest residual strength is measured when the top porous stone remains at or near the surface of the specimen container, i.e., little or no settlement occurs, and that this residual strength provides the best agreement with field case histories. It should be noted that the ring shear apparatuses developed by Bishop et al. (1971) and La Gatta (1970) allow the specimen container to be split into two parts so that the shear plane can be exposed, and thus wall friction does not develop on the shear plane. However, the equipment required to separate the annular specimen container and maintain the opening during shear is more complicated and more

expensive than the specimen container in the Bromhead apparatus. The objective of this paper is to recommend a test procedure that yields residual strengths that are in excellent agreement with field case histories and allows the use of the simpler and less expensive Bromhead ring shear apparatus.

Bromhead ring shear tests were performed on remolded Pierre shale from Reliance, South Dakota to illustrate the effect of the single stage, preshearing, multistage, and the proposed "flush" test procedures on the measured residual strength. The Pierre shale is classified as a clay of high plasticity according to the USCS. The liquid limit, plasticity index, and clay fraction are 184, 129, and 84%, respectively. The tests were conducted at a drained displacement rate of 0.018 mm/min. This displacement rate was calculated using the analytical procedure developed by Gibson and Henkel (1954) and values of coefficient of consolidation measured in consolidation tests and during the application of the normal stress. The value of coefficient of consolidation used in the calculation is 0.6 mm²/min.

The remolded specimens used during this study were obtained by air drying a representative sample. The air-dried soil is ball milled until all of the representative sample passes the No. 200 sieve. Distilled water is added to the pulverized soil until a liquidity index of about 1.5 is obtained. The sample is then allowed to rehydrate for at least one week. A spatula is used to place the soil paste into the annular specimen container. The paste is carefully placed to ensure no air voids are present. The top of the specimen is planed flush with the top of the specimen container using a 15.2-cm (6-in.)-long surgical razor blade and/or a fine wire saw. It should be noted that remolded specimens are not present prior to drained shear.

Single Stage Test Procedure

The single stage test procedure involves loading the remolded specimen to the desired effective normal stress and then shearing the specimen. After the test is completed, the specimen is removed from the apparatus and a new specimen is used for the next test. It can be seen from the test results on the Pierre shale, Fig. 2, that the single stage test procedure provided a good estimate of the residual strength at effective normal stresses less than approximately 200 kPa. At effective normal stresses greater

than approximately 200 kPa, consolidation of the specimen and soil extrusion during shear caused substantial settlement of the top porous stone into the specimen container. As a result, the measured residual strength is higher than the strength measured using the proposed "flush" test procedure. The "flush" test procedure, which will be described subsequently, yielded drained residual strengths that are in excellent agreement with field case histories and thus is assumed to be the "correct" test procedure.

Preshearing Test Procedure

The preshearing test procedure involves shearing the remolded specimen at a rapid displacement rate prior to drained shear. The rapid displacement rate can be applied by hand or using the gear box. The specimen is usually rotated approximately five revolutions. Before the drained displacement rate is applied, the specimen is allowed to dissipate any excess pore water pressures that were induced during rapid shearing. Only one test is performed on each specimen.

Wykeham-Farrance (1988) and Anayi et al. (1988) have reported that this preshearing technique facilitates the creation of a shear plane and reduces the amount of horizontal displacement required to reach a residual condition. The test results obtained during this study showed that this technique caused a substantial amount of soil to be extruded during the preshearing process. It can be seen from Fig. 2 that this extrusion resulted in residual strengths that are always higher than the proposed "flush" test procedure. This is due to the top porous stone settling into the specimen container due to consolidation of the specimen and soil extrusion during the preshearing process. It should be noted that the preshearing process did reduce the horizontal displacement required to obtain a constant shear stress by 30 to 40%. However, this test procedure is not recommended because it provides an unconservative estimate of the drained residual strength.

The preshearing process also removes the peak strength, which prevents an estimate of the drained postpeak behavior of the specimen. It should be noted that the shear displacement adjacent to the inner circumference is approximately 64% (Negussey et al. 1989) of the shear displacement adjacent to the outer circumference of the annular specimen. This leads to a slightly

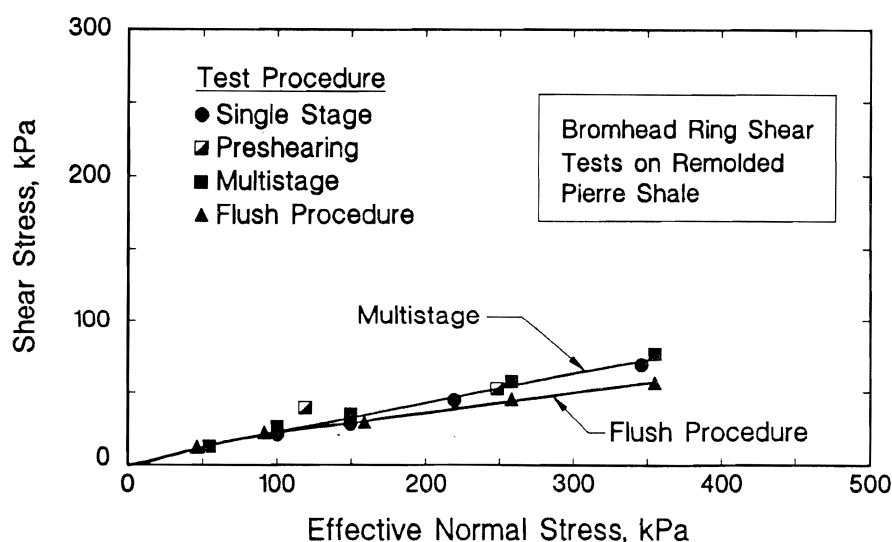


FIG. 2—Effect of test procedure on measured residual strength of Pierre shale.

lower peak strength value, especially in soils exhibiting a large postpeak strength loss. However, if a remolded specimen is used, the measured peak strengths have been found to be in good agreement with direct shear test results and can be used to estimate the postpeak behavior (Hvorslev 1936, 1939). The residual strength is not affected by differences in shear displacement because the same resistance is mobilized at the outer and inner circumferences of the specimen.

Multistage Test Procedure

It has also been reported by Wykeham-Farrance (1988), Anderson and Hammoud (1988), and Anayi et al. (1988) that multistage tests can reduce test duration. In multistage tests, after a residual strength condition has been established under the first normal stress, shearing is stopped and the normal stress is doubled. The test specimen is allowed to reconsolidate under the higher normal stress before shearing is recommenced. This procedure is repeated for a number of stress levels. The test results on Pierre shale, Fig. 2, showed that multistage tests overestimated the residual strength at effective normal stresses greater than 100 kPa, i.e., Stages 2 through 5. The additional strength is probably due to wall friction developing as the top platen settles into the specimen container during the consolidation and shearing process in each stage of the test. Since the settlement of the top porous stone is small at effective normal stresses less than 100 kPa, the multistage test procedure yields a residual strength similar to the proposed "flush" test procedure. Therefore, the multistage test procedure may be acceptable if settlement of the top porous stone is limited to 0.75 mm (see proposed "flush" test procedure for details). This will only be achieved at low normal stresses and slow rates (0.018 mm/min) of displacement.

Proposed "Flush" Test Procedure

The proposed "flush" test procedure derived its name from the fact that the top porous stone is to remain at or near "flush" with the surface of the specimen container during shear. Increasing the thickness of the specimen prior to shear reduces the wall friction that is developed on the shear plane and thus reduces the measured residual strength. Conversely, decreasing the thickness of the specimen will increase the wall friction developed on the shear plane and thus increase the residual strength. The proposed "flush" test procedure involves the addition of remolded soil and reconsolidation of the specimen to increase the specimen thickness prior to drained shear. After consolidation is completed at the desired normal stress and the porous stone is approximately "flush" with the specimen container, the specimen is sheared using a drained displacement rate until a residual strength condition is obtained. Only one test is performed on each specimen.

The addition of soil and the reconsolidation of the specimen is time consuming. As a result, a sensitivity study was conducted to determine how far the top porous stone could settle into the specimen container without significantly effecting the measured residual strength. Based on this study it was determined that the specimen could undergo a total settlement, due to consolidation and/or soil extrusion during shear, of 0.75 mm (15% of the initial height) and still yield a residual strength in good agreement with field case histories. (One such case history is described subsequently.) It can be seen from Fig. 2 that the proposed "flush" test procedure results in the lowest residual strength, especially

at high normal stresses. As expected, at normal stresses less than 100 kPa the "flush," single stage, and multistage test procedures yield similar residual strengths because the settlement of the top porous stone is less than 0.75 mm in these tests.

To reduce consolidation settlement, it is suggested that the remolded soil be placed at a low water content, plastic limit or possibly lower, in the bottom half of the specimen container and at a higher water content, near the liquid limit, in the top half of the specimen container. At high normal stresses a water content near the plastic limit can be used for the entire specimen. It is important that enough water be added to the soil paste so that the specimen container can be filled evenly and without air voids, and that the specimen is saturated after consolidation. If settlement of the top platen exceeds 0.75 mm, soil should be added and the specimen reconsolidated to reduce the effects of malfunction.

Data Presentation

It is recommended that the shear stress and volume change data be plotted versus the logarithm of horizontal displacement as suggested by La Gatta (1970). This plotting technique accentuates the slope of the shear stress-displacement curve at large deformations, allowing the horizontal portion of the curve to be clearly defined. Figure 3 presents the results of a ring shear test

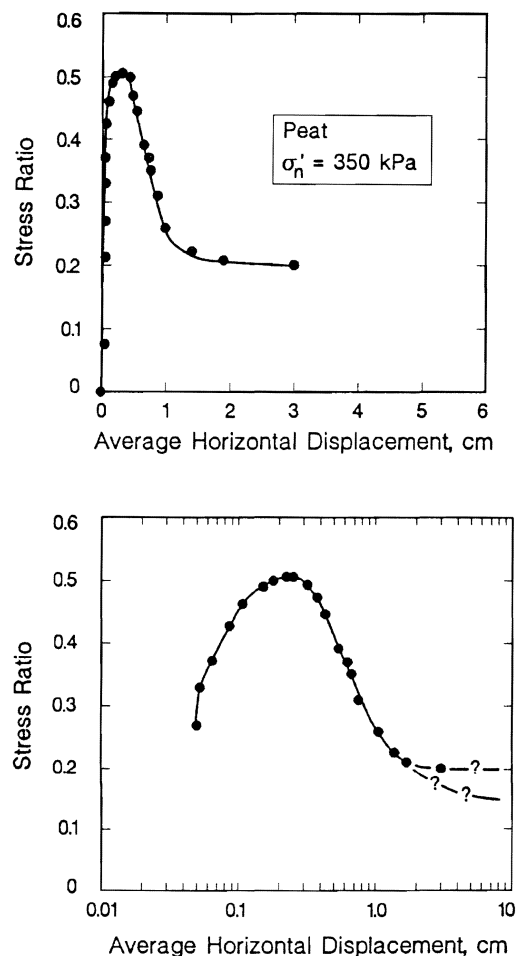


FIG. 3—Arithmetic and semilogarithmic presentation of drained ring shear test results.

on a specimen of San Francisco Bay mud that classifies as a peat (described subsequently). The stress ratio, i.e., the measured shear stress divided by the effective normal stress, was plotted using arithmetic and logarithmic scales. (The average horizontal displacement is calculated by multiplying the average circumference of the specimen by the ratio of the number of degrees traveled to 360° .) On an arithmetic scale, a residual strength condition appears to have been reached at a displacement of approximately 3 cm. However, on a logarithmic scale it is not clear whether the shear stress is still decreasing or it has reached a constant value. Therefore, to ensure that a residual strength condition is reached before the ring shear test is stopped, the shear stress or stress ratio should be plotted using the logarithm of horizontal displacement as the test progresses. Once the shear stress becomes essentially constant on a semilogarithmic plot, the test can be stopped.

If a test is allowed to progress for an extended period of time after the residual strength condition has been reached, the shear stress may start to increase in the Bromhead apparatus. This has been observed in a few tests and is probably due to a slight increase in wall friction. The wall friction will increase as the test progresses because a small amount of soil is usually extruded during drained shear and the top porous stone will settle into the specimen container. If the total settlement of the top platen is less than 0.75 mm, the increase in shear stress with continued displacement should not be significant.

At the residual strength condition, the slope of the volume change curve should also be at or near zero. However, it may not reach exactly zero because of the inevitable soil extrusion that occurs during drained shearing. It should be noted that this extrusion is substantially less than that observed in reversal direct shear tests.

Field Case History

A field case history was used to verify the effect of the previously described ring shear test procedures on the measured residual strength. The case history involves a site in Southern California that is underlain by the Santiago formation. At this site the Santiago formation is composed of a claystone and a sandstone. The sandstone overlies the greenish- to bluish-gray claystone and is fine to medium grained. The remolded claystone classifies as a clay or silty clay of high plasticity, CH-MH, according to the USCS. The liquid limit, plasticity index, and clay fraction are 89, 45, and 57%. The coefficient of consolidation

used to estimate the drained displacement rate of 0.018 mm/min is 1.35 mm²/min.

The claystone is commonly fissured, displaying slickensided and shiny parting surfaces. A typical cross section through the slide is shown in Fig. 4. A more detailed description of the site and landslide is presented by Stark and Eid (1992). This case history was selected because the site has undergone at least three episodes of landsliding prior to the slide that was back-analyzed. Therefore, the claystone has undergone substantial shear displacement during geologic time and has probably developed a residual strength condition. In addition, the majority of the slide plane is approximately horizontal through the Santiago formation. This indicates that the slide occurred along a claystone layer, and thus the shear strength of this layer can be approximated by one set of shear strength parameters.

Bromhead ring shear tests, using the proposed "flush" test procedure and the multistage test procedure were performed on the claystone. The factors of safety computed using the cross section in Fig. 4, Spencer's (1967) stability method, and the two failure envelopes shown in Fig. 5 are presented in Table 1. It should be noted that the nonlinear failure envelopes were modeled using nineteen points and the nonlinear failure envelope option in the slope stability computer program UTEXAS2 (Wright, 1986) instead of values of c' and ϕ' . It can be seen from Table 1 that the "flush" test procedure results in the correct factor of safety, i.e., 1.00, for this landslide, while the multistage test procedure overestimated the factor of safety by 33%.

This case history illustrates the importance of test procedure and residual strength on the calculated factor of safety. If the slide plane was shallower, the effective normal stresses on the slide plane would be lower and the multistage and "flush" test procedures may have yielded similar factors of safety. However, the average effective normal stress acting on the slide plane through the Santiago formation is approximately 200 kPa, and thus the difference in the residual strength failure envelopes becomes apparent through the factor of safety. If the slide plane was deeper, the multistage test procedure would have predicted an even higher, i.e., more unconservative, factor of safety.

Recommended Ring Shear Test Procedure

Based on field case histories, it is recommended that the "flush" test procedure and remolded specimens be used to measure the drained residual strength in the Bromhead ring shear apparatus. This procedure limits the amount of settlement of the top porous

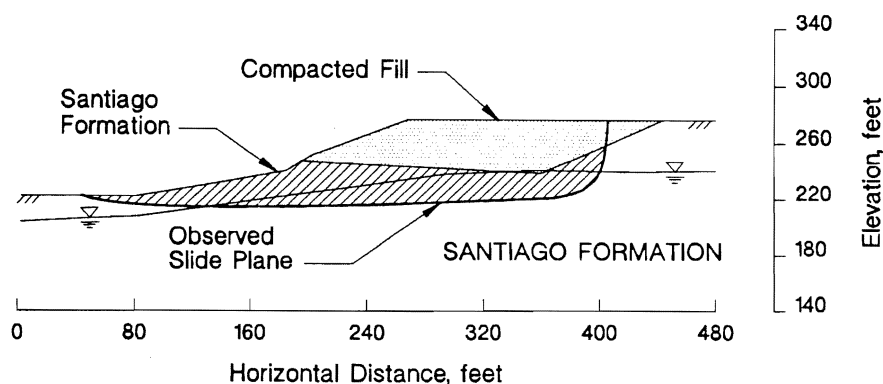


FIG. 4—Cross section through Southern California landslide.

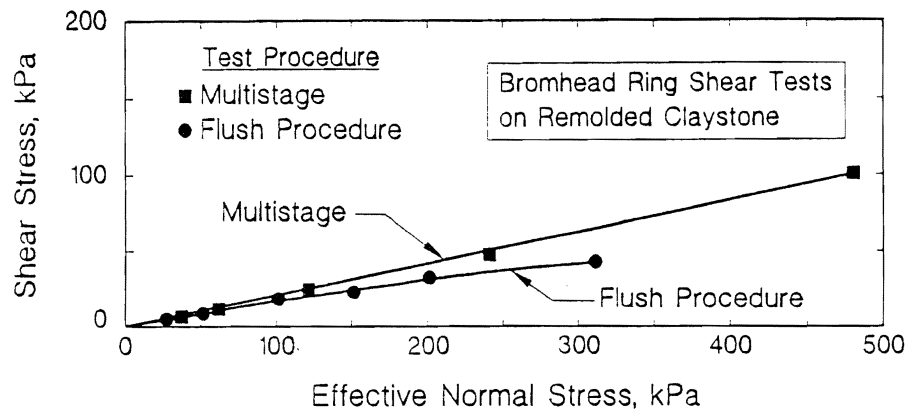


FIG. 5—Effect of test procedure on measured residual strength of claystone.

TABLE 1—Effect of test procedure on calculated factor of safety for Southern California landslide.

Test Type	Test Procedure	Specimen	Factor of Safety
Ring shear	Flush	Remolded	1.00
Ring shear	Multistage	Remolded	1.33

stone, due to consolidation and/or soil extrusion during drained shear, to 0.75 mm. At low effective normal stresses this settlement criterion may be satisfied without adding soil and reconsolidating the specimen. However, at medium to high normal stresses the "flush" test procedure will require the addition of soil and the reconsolidation of the specimen such that the top porous stone is within 0.75 mm of the surface of the specimen container throughout the test.

Effect of Vanes on Measured Residual Strength

As proposed by Anayi et al. (1989), small vanes were inserted into the top porous stone to force the shear plane to develop at or near the middle of the specimen instead of at the soil/top porous stone interface. The vanes are 0.6 cm long and extend 0.3 cm into the top porous stone and 0.3 cm into the specimen. Twenty-four vanes, spaced at approximately 15° or 11.25 mm apart, were inserted into the top porous stone. The vanes were fabricated such that the clearance with the walls of the specimen container was approximately 0.05 mm. To accommodate the vanes, a new specimen container that could utilize a 1.0-cm-thick specimen was also fabricated.

Two 5-in. (12-cm)-diameter shelly tube samples of San Francisco Bay mud were used to evaluate the effect of vanes on the measured residual strength. The samples were obtained from a depth of 8.9 and 15.9 m, and it can be seen from Table 2 that the index properties of these two samples differed significantly. The sample obtained from a depth of 15.9 m was classified as a clayey silt of high plasticity, MH, according to the USCS. Based on comparisons with other references, such as Bonaparte and Mitchell (1979), the index properties of this sample were found to be typical of the Bay mud found throughout the San Francisco Bay area. As a result, this sample will be referred to as Bay mud throughout the remainder of this paper. The sample obtained from a depth of 8.9 m was classified as a peat humus according to ASTM Classification of Peats, Mosses, Humus, and Related

TABLE 2—Index properties of San Francisco Bay mud samples.

Parameter	Peat	Bay Mud
Sample depth	8.9 m	15.9 m
Soil classification (USCS)	Peat humus	MH
% Clay (<0.002 mm)	38–42%	14–18%
% Organics	28–30%	1–2%
Natural water content	125–200%	74%
Liquid limit	359	56
Plasticity index	153	24
Coefficient of consolidation	0.08–0.94 m ² /year	0.84–1.21 m ² /year

NOTE: MH = clayey silt.

Products D 2607-69 (ASTM 1991). The structure of the peat was primarily amorphous; however, fibrous material was visible throughout the sample. As a result, this sample will be referred to as peat throughout the remainder of this paper.

A combination of undisturbed and remolded specimens of the Bay mud and peat were used during this study. An annular trimming ring was manufactured to aid the trimming of the undisturbed specimens. The undisturbed specimens were obtained by sawing off a small portion of the sample tube using a hack saw. The side of the tube was then sawn so that the tube could be pulled open and the sample exposed. The tube was carefully removed from around the sample and the trimming ring was placed on top of the sample. Surgical razor blades were used to excavate slowly around and in the middle of the trimming ring until 1.5 cm of soil had passed into the ring. The bottom of the specimen was then planed flush using a 15.2-cm-long razor blade and/or a fine wire saw. The undisturbed specimen was then carefully extruded into the ring shear apparatus. The portion of the specimen protruding from the specimen container was planed flush using the razor blade. The remolded specimens were obtained using the previously described procedure. The drained ring shear tests with and without vanes on the Bay mud and peat were performed at a displacement rate of 0.018 mm per minute.

Bay Mud Test Results

Eight drained ring shear tests were performed, using the unmodified apparatus and the "flush" test procedure, on three undisturbed and five remolded Bay mud specimens. The peak and residual shear resistances from these eight ring shear tests were used to obtain the drained failure envelopes shown in Fig. 6. From Fig. 6 it can be seen that the residual failure envelope

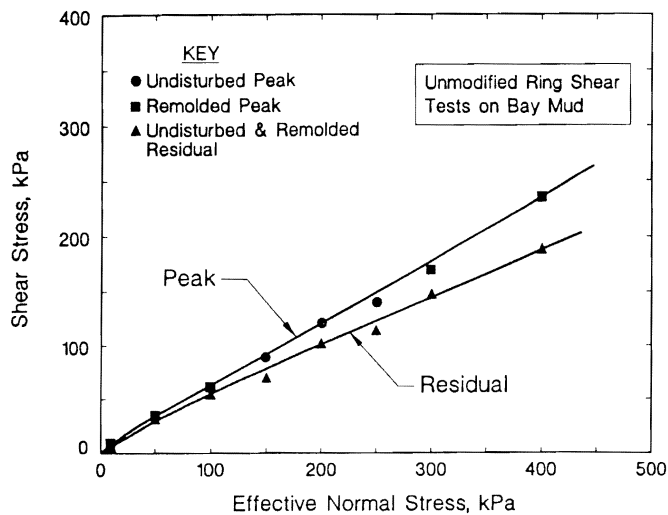


FIG. 6—Drained failure envelopes for Bay mud.

is only slightly, 10 to 20%, lower than the peak envelope. This is due to the low clay fraction present in the Bay mud sample, which results in a turbulent shear condition (Skempton 1985), and a residual strength only slightly less than the peak strength.

The drained peak and residual strengths from four ring shear tests with vanes inserted into the top porous stone are shown in Fig. 7. For comparison purposes the drained failure envelopes from the unmodified apparatus, i.e., Fig. 6, are also presented. It can be seen that the use of vanes resulted in peak strengths that were 15 to 20% greater than the peak values obtained from the ring shear tests without vanes. The use of vanes also resulted in residual strengths that were 10 to 15% greater than the residual values obtained from tests without vanes.

Peat Test Results

Eight ring shear tests without vanes incorporated into the top porous stone were performed using the "flush" test procedure on three undisturbed and five remolded specimens. The peak and residual shear resistances from these eight ring shear tests

were used to obtain the drained failure envelopes shown in Fig. 8. From Fig. 8 it can be seen that the residual failure envelope is 40 to 50% lower than the peak envelope. The drained postpeak behavior of the peat is illustrated in Fig. 3. This large strength loss is due to the high clay fraction (38 to 42%) and organic content (28 to 30%) present in the peat sample, which results in a sliding shear condition. This strength loss is significantly larger than the 10 to 20% measured for the Bay mud and illustrates the difference in the postpeak behavior associated with a turbulent and sliding shear condition.

The drained peak and residual resistances from five ring shear tests with vanes inserted into the top porous stone are shown in Fig. 9. Also, shown in Fig. 9 are the drained failure envelopes from the unmodified apparatus, i.e., Fig. 8. It can be seen that the use of vanes resulted in peak strengths that were 10 to 15% greater than the peak values obtained from tests without vanes in the top porous stone. The use of vanes also resulted in residual strengths that were 20 to 25% greater than the residual values obtained from tests without vanes in the top porous stone.

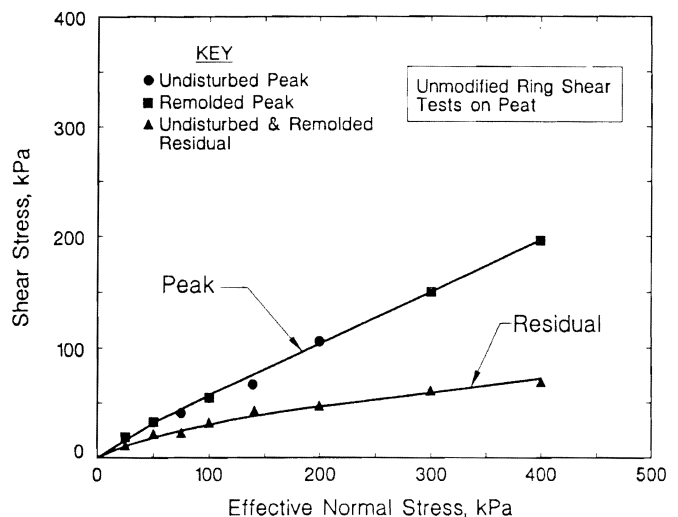


FIG. 8—Drained failure envelopes for peat.

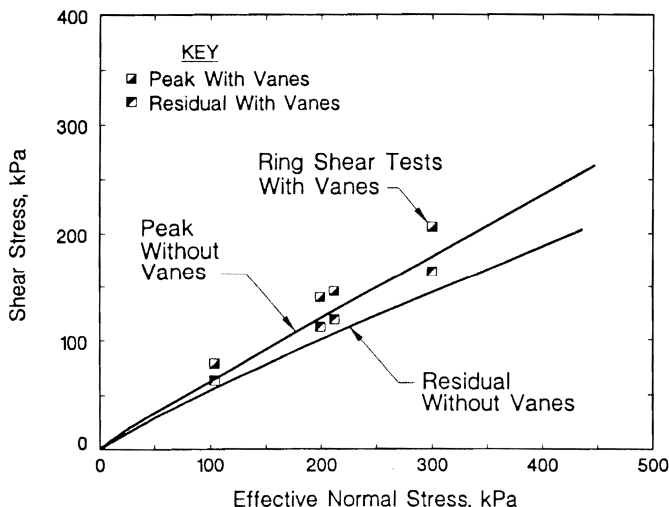


FIG. 7—Effect of vanes on drained failure envelopes for Bay mud.

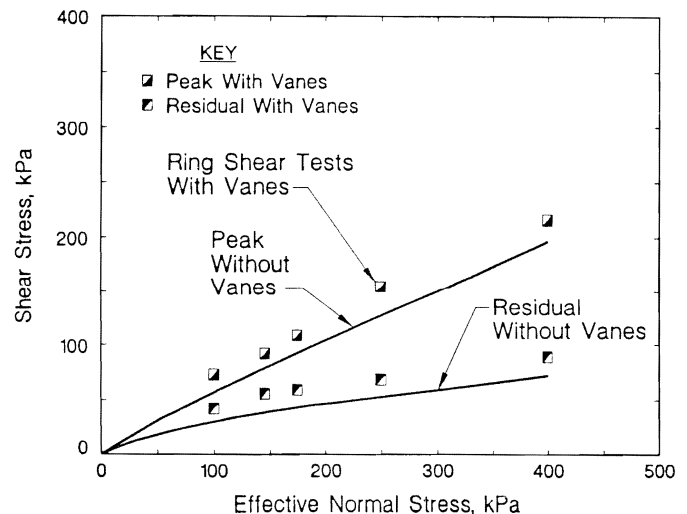


FIG. 9—Effect of vanes on drained failure envelopes for peat.

Discussion of Vanes in Bromhead Ring Shear Apparatus

Since the "flush" test procedure has been proven to yield residual strengths that are in excellent agreement with field case histories, it is anticipated that the use of vanes will overestimate the field residual strength. Three possible sources of the additional shearing resistance measured using vanes are: (1) soil being sheared between the side of the vanes and the walls of the specimen container; (2) the additional wall friction developed due to the failure plane occurring at the bottom of the vanes instead of the soil/top porous stone interface; and (3) the difference between a soil-to-soil shear interface and a soil/top porous stone interface.

Initially it was thought that a small amount of soil was being sheared between the vanes and the walls of the specimen container. Examination of the failed specimens revealed that soil was remaining between the vanes, creating soil wedges, and not being sheared between the vanes and the walls of the specimen container. Therefore, it was concluded that the increased shear resistance is probably due to the additional wall friction developed by the shear plane occurring at the bottom of the vanes instead of the soil/top porous stone interface.

The difference between a soil-to-soil shear interface and a soil/top porous stone interface was also investigated. Examination of the failed peat specimens using a scanning electron microscope and the naked eye revealed that a smoother and more polished shear plane developed in the tests with vanes than in similar tests without vanes. In addition, a better-defined shear zone developed in the Bay mud specimens when vanes were used. Therefore, the use of vanes appears to aid the development of a shear plane and the reorientation of the clay particles in both the peat and Bay mud specimens. This was also observed in Lias Clay by Anayi et al. (1989). However, the additional wall friction yields unconservative residual strength values.

In summary, the use of vanes in the Bromhead ring shear apparatus appears to result in a more desirable failure condition than the soil/top porous stone interface in the original apparatus. However, the vanes also result in residual shear strengths that are higher than back-calculated values, i.e., unconservative, due to the additional wall friction generated by the shear plane developing at the bottom of the vanes. If the additional wall friction can be reduced, the use of vanes in the Bromhead ring shear apparatus may provide a better estimation of the field shear conditions. In the interim, it is recommended that the proposed "flush" test procedure and the unmodified Bromhead ring shear apparatus be used to measure the residual strength.

Conclusions

The Bromhead ring shear apparatus has facilitated the use of torsional ring shear tests in engineering practice. However, a number of test procedures and a modification have been proposed for this apparatus. The main objective of this paper was to investigate the effect of these test procedures and the proposed modification on the drained residual strength.

The main factor affecting the measured residual strength is the magnitude of the wall friction that is developed along the inner and outer circumferences of the confined specimen. The magnitude of wall friction increases with the depth of the specimen, and thus the plane of least wall friction occurs at or near the soil/top porous stone interface. As the top porous stone settles into the specimen container, the wall friction influencing the shear

plane increases, which causes an increase in the measured residual strength.

The proposed "flush" test procedure limits the total settlement of the top porous stone, due to consolidation and/or soil extrusion during drained shear, to 0.75 mm. In addition, only one test is performed per specimen. The results of this study show that the proposed "flush" test procedure yields the lowest residual strength of the existing test procedures and provides the best agreement with field case histories.

The installation of vanes into the top porous stone, as proposed by Anayi et al. (1989), results in drained residual strengths that are substantially higher than the "flush" test procedure. It is anticipated that the higher strengths are due to the additional wall friction developed by the shear plane forming at the bottom of the vanes instead of the soil/top porous stone interface. Unless the additional wall friction can be reduced, the proposed "flush" test procedure and the unmodified Bromhead ring shear apparatus should be used to measure the drained residual strength.

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