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Timothy D. Stark[1] *and Hisham T. Eid*[1]

Modified Bromhead Ring Shear Apparatus

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ABSTRACT: The main factor affecting the drained residual strength measured in the Bromhead ring shear apparatus is the magnitude of wall friction developed along the inner and outer circumferences of the confined specimen. The magnitude of wall friction increases with the depth of the remolded 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, causing an increase in the measured residual strength.

A new specimen container is proposed for the Bromhead ring shear apparatus that allows a remolded specimen to be overconsolidated and precut prior to drained shearing. This minimizes settlement of the top platen and the horizontal displacement required to reach a residual strength condition. As a result, a multistage test can be conducted without excessive settlement and thus wall friction occurring in the new specimen container. The use of a multistage test significantly reduces the time required to establish a drained residual failure envelope. The use of an overconsolidated and precut specimen also provides a better simulation of the field conditions that lead to a large post-peak decrease in drained strength in clayshales, claystones, and mudstones, and residual strengths that are in excellent agreement with field case histories.

KEYWORDS: clays, shales, shear tests, clay shales, residual strength, slope stability, torsion shear tests, ring shear tests

The Bromhead ring shear apparatus (Bromhead 1979) has facilitated the use of torsional ring shear tests in engineering practice. The apparatus 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 mounted on the top loading platen and the bottom of the specimen container. The remolded specimen is confined radially by the specimen container, which is 5 mm 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 occurs at or near the soil/top porous stone interface. This results in the failure plane occurring at or near the soil/top porous stone interface.

The main factor affecting the drained residual strength measured in the Bromhead ring shear apparatus is the magnitude of wall friction developed on the failure plane (Stark and Vettel 1992). As the top porous stone settles into the specimen container, the wall friction influencing the shear plane increases and causes an increase in the measured residual strength.

Stark and Vettel (1992) proposed a new test procedure that minimizes the wall friction and yields residual strengths that are in excellent agreement with field case histories. This test procedure, termed the "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 (15% of the initial height). At settlements greater than 0.75 mm, the measured shear strength is significantly affected by wall friction. Settlement of the top porous stone is limited to 0.75 mm by adding soil and reconsolidating the specimen several times. Prior to drained shearing, the specimen surface should be approximately "flush" with the top of the specimen container after consolidation is completed at the desired normal stress. The specimen is sheared until a residual strength condition is obtained. Only one test is performed on each intact 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 affecting the measured residual strength. This study showed that limiting the total settlement due to consolidation and/or soil extrusion during shear to 0.75 mm yielded residual strengths in good agreement with field case histories. Since an intact remolded specimen, i.e., not precut or presheared, is used in the "flush" test procedure, large horizontal displacements are required to reach a residual condition. Sixteen to eighteen days are usually required to perform four tests and establish a drained residual failure envelope using intact remolded specimens and the "flush" test procedure for clays of moderate plasticity. The testing time was found to increase as the plasticity increased.

The main objective of this research was to develop a new specimen container for the Bromhead ring shear apparatus that allows the use of overconsolidated and precut, remolded specimens and the performance of multistage tests while limiting the settlement of the top platen to significantly less than 0.75 mm. In a multistage test, after a residual strength condition is established under the first normal stress, shearing is stopped and the normal stress is doubled. The specimen is allowed to reconsolidate under the higher normal stress before shearing is recommenced. After consolidation the specimen is sheared until a residual strength condition is obtained. This procedure is repeated for a number of stress levels.

Multistage tests significantly reduce the time required to establish a drained residual failure envelope because: (1) a new

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[1] Assistant professor and graduate research assistant of Civil Engineering, 2217 Newmark Civil Engineering Lab (MC-250), University of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801.

specimen does not have to be remolded and consolidated at each effective normal stress, and (2) the horizontal displacement required to reach a residual strength condition is significantly reduced because a residual condition was attained at the previous normal stress. Based on the results of multistage tests conducted during this study, only five to six days are usually required to measure the residual strength at four different effective normal stresses and establish a drained residual failure envelope for clays of moderate plasticity.

Modified Specimen Container and Multistage Test Procedure

The drained residual strength is most applicable to clayshales, claystones, and mudstones that exhibit a large post-peak drop in drained strength. The shear strength of these materials will be at or near the residual value on shear surfaces in old landslides or soliflucted slopes, in bedding shears in folded strata, in sheared joints or faults, and after embankment failures. To simulate the presheared condition of overconsolidated clays in the field, a procedure for testing overconsolidated and precut, remolded specimens in the Bromhead ring shear apparatus was sought.

The remolded shale and claystone specimens used during this study were obtained by air drying a representative sample of each material. The air-dried soil is ball milled until all of the representative sample passes the U.S. Standard sieve No. 200. 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 carefully place the soil paste into the annular specimen container 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-long surgical razor blade and/or a fine wire saw.

In the original Bromhead apparatus, remolded specimens were not overconsolidated because the settlement usually exceeded 0.75 mm. Excessive settlement leads to a substantial amount of wall friction influencing the failure plane unless soil is added and consolidated to reduce the vertical displacement. As a result, the specimen is normally consolidated and tested at effective normal stresses between 50 and 400 kPa in the original apparatus. The remolded specimens also cannot be precut because the specimen is confined radially by the original specimen container. Therefore, a new specimen container had to be designed such that a remolded specimen could be consolidated to 700 kPa, precut, and then sheared at effective normal stresses between 50 and 700 kPa with vertical displacements significantly less than 0.75 mm. A consolidation stress of 700 kPa was chosen to represent the maximum effective stress encountered in typical field case histories. Consolidation stresses greater than 700 kPa can be applied if required by the slope geometry.

To achieve this objective the specimen container shown in Fig. 1 was fabricated. The new specimen container consists of the following four parts: (1) outer ring, (2) inner ring, (3) center core that is shown inside the outer ring (Fig. 2), and (4) a 3-mm-thick knurled porous stone. (The original thickness of the porous stone is 6.3 mm.) The outer ring is fixed to the inner ring using four set screws. The four shorter screws shown inside the porous stone (Fig. 2) are used to attach the bronze porous stone to the inner ring. The center core threads into the inner ring, creating the new specimen container (Fig. 3). The new specimen container has dimensions identical to that of the original container, including a specimen thickness of 5 mm. As a result, the new and original specimen containers are interchangeable. The main advantage of the new specimen container is that the annular specimen can be overconsolidated and precut prior to the shearing with little settlement of the top platen, and thus little or no wall friction.

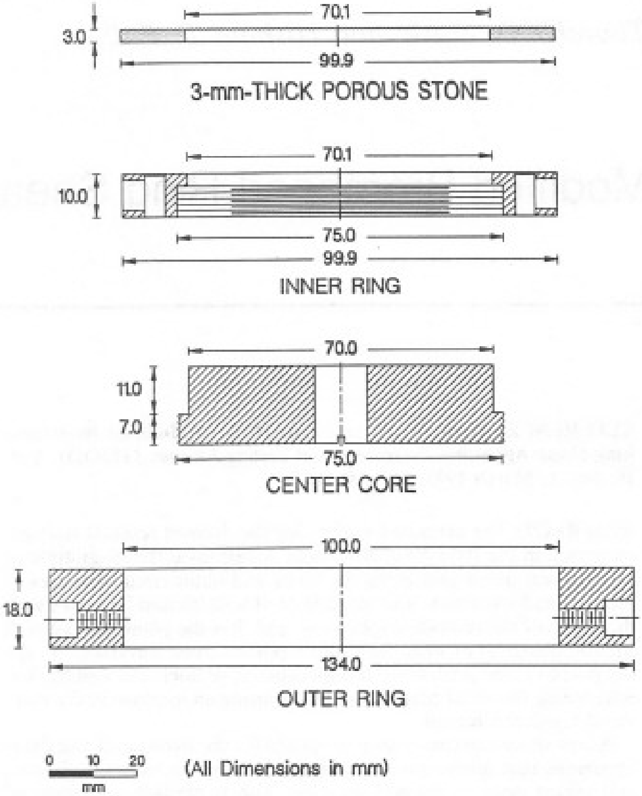

FIG. 1—*Schematic of new ring shear specimen container.*

Modified Ring Shear Test Procedure—After consolidation to 700 kPa, the specimen is presheared by slowly rotating the unloaded top platen in the direction of shearing for two or three revolutions (Fig. 4). Then, both the top platen and the specimen

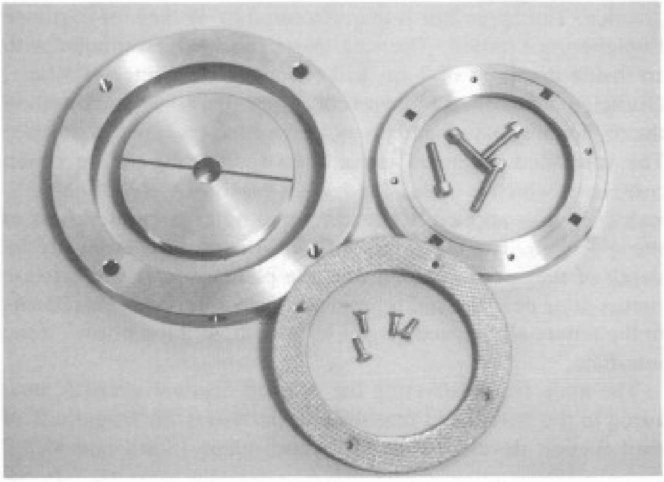

FIG. 2—*Components of new specimen container.*

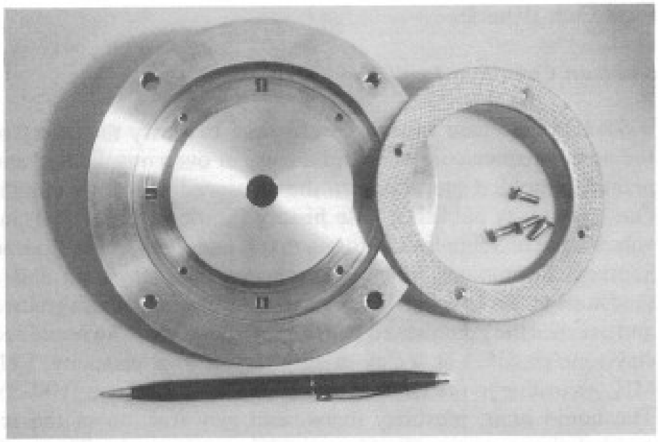

FIG. 3—*Assembled specimen container.*

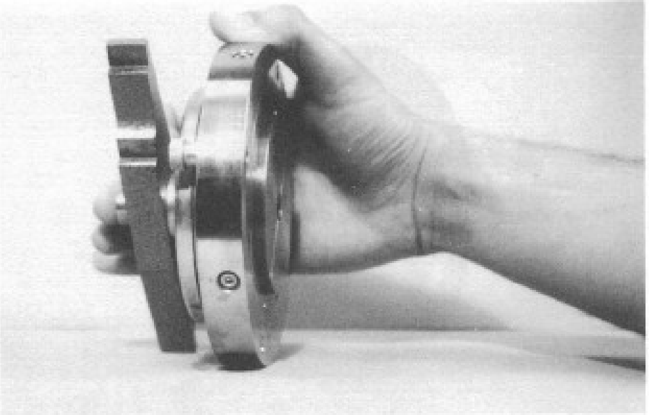

FIG. 5—*Center core threaded out of inner ring.*

container are removed from the apparatus. The center core of the modified container is threaded out of the inner ring (Fig. 5). After threading out the center core, the container is placed on a horizontal surface and the set screws that hold the inner ring in place are loosened. Two of the four loosened set screws can be seen in the outer ring in Fig. 6. The outer ring of the specimen container is lowered by pushing down on it until the outer ring becomes flush with the horizontal surface and center core that was initially threaded out (Figs. 6 and 7). The lowering of the outer ring exposes the specimen such that approximately 0.5 mm of the specimen is visible above the top of the specimen container.

After lowering the outer ring, the top platen is separated from the specimen container by slowly rotating the top platen in the direction of shear. After separation, a 15.2-cm-long surgical razor blade and/or wire saw is used to precut the specimen in the direction of shear. The razor blade or wire saw is placed on the upper surface of the specimen container, and the specimen is precut in the direction of shearing until a smooth and highly polished surface is obtained.

When the top platen separates from the specimen, approximately 0.1 to 0.3 mm of soil usually remains attached to the top porous stone. This soil was previously presheared and usually exhibits a polished surface. However, to increase the amount of particle orientation, the soil can be presheared again by moving a moistened finger over the soil in the direction of shear. This enhances the smooth and highly polished nature of the shear plane.

After precutting the specimen, the top platen and the specimen are assembled and loaded to an effective normal stress of 50 kPa. The specimen is sheared at a drained displacement rate based on values of coefficient of consolidation measured in oedometer tests and during consolidation of the ring shear specimen to 700 kPa and the procedure described by Gibson and Henkel (1954). After a residual strength condition is established at 50 kPa, shearing is stopped and the normal stress is doubled. After consolidation at 100 kPa, the specimen is sheared until a residual strength condition is obtained. This procedure is repeated for a number of stress levels and is called a multistage test procedure.

Overconsolidation and precutting of the remolded specimen significantly reduces the horizontal displacement required to reach a residual condition. The smaller horizontal displacement reduces the vertical displacement and thus wall friction that occurs during shear. The horizontal displacement is reduced by: (1) precutting that creates a shear plane and orients some of the clay particles parallel to the direction of shear, (2) overconsolidation which reduces soil extrusion during shear, and (3) concentration of the shear stresses and shear strains on the failure plane by the

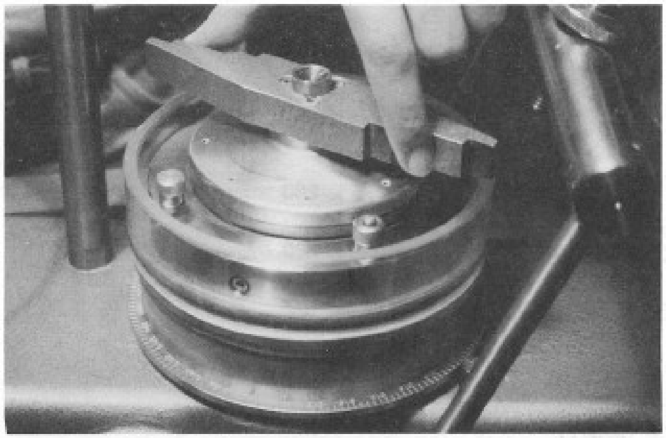

FIG. 4—*Preshearing overconsolidated soil.*

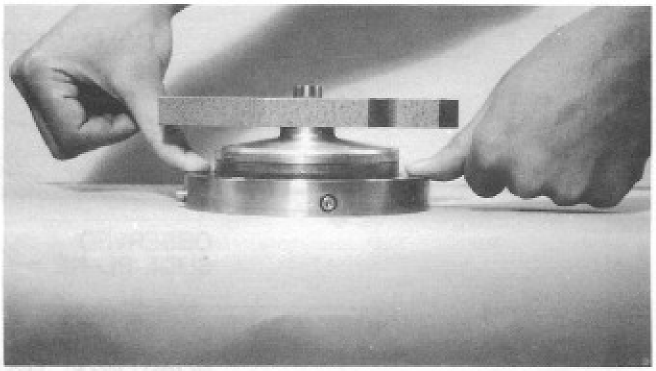

FIG. 6—*Exposing overconsolidated specimen by lowering outer ring.*

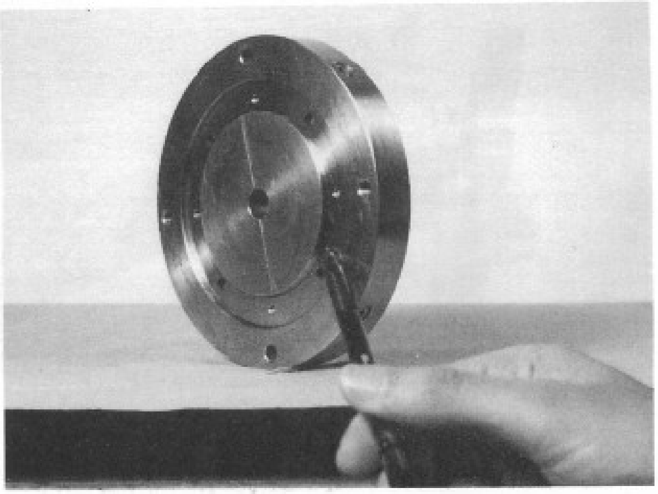

FIG. 7—*Specimen container after lowering outer ring.*

overconsolidated specimen and the rigid top porous stone. The precut failure plane occurs at or near the soil/top porous stone interface. Therefore, the rigid top porous stone and the underlying overconsolidated soil concentrate the shear stresses on the failure plane, which aids the reorientation of clay particles parallel to the direction of shear, reducing the horizontal displacement (Kanji and Wolle 1977).

In summary, the modified specimen container proposed for the Bromhead ring shear apparatus allows a remolded specimen to be overconsolidated and precut, which provides a better representation of the field conditions that lead to the development of a residual strength condition in clayshales, claystones, and mudstones. In addition, the use of an overconsolidated and precut specimen reduces the vertical displacement to significantly less than 0.75 mm, which minimizes the wall friction applied to the shear plane and allows a multistage test procedure to be utilized. Most importantly, the residual strengths measured with the new specimen container are in excellent agreement with field case histories. Two case histories that illustrate the accuracy of the measured residual strengths are described in the following section.

Field Case Histories

Southern California Landslide

Several field case histories were used to verify the effect of the new specimen container and the use of overconsolidated and precut, remolded specimens on the measured residual strength. One previously published case history (Stark and Eid 1992) involves a site in Southern California that is underlain by the Eocene Santiago Formation, which is composed of a claystone and a sandstone at this location. The sandstone is fine to medium grained and overlies the greenish- to bluish-gray claystone. The remolded claystone classifies as a clay or silty clay of high plasticity, CH-MH, according to the Unified Soil Classification System (USCS). The liquid limit, plasticity index, and clay fraction of the remolded claystone are 89, 45, and 57%, respectively. The coefficient of consolidation used to estimate the drained displacement rate of 0.018 mm/min is 1.35 mm^2/min.

The claystone is commonly fissured, displaying numerous slickensided and shiny parting surfaces. 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 reached a residual strength condition. In addition, the majority of the slide plane is approximately horizontal through the Santiago Formation, which indicates sliding occurred along a claystone seam or layer (Fig. 8).

Bromhead ring shear tests were performed on intact and precut remolded specimens of the Santiago claystone. Intact remolded specimens, i.e., not precut or presheared, were tested using the "flush" test procedure, whereas the precut specimens were overconsolidated to 700 kPa and precut using the modified ring shear test procedure described herein. Both specimens consist of remolded soil prepared using the previously described procedure. Figures 9 and 10 provide a comparison of the shear stress-horizontal displacement relations for the ring shear tests conducted using the intact and precut specimens at effective normal stresses of 50 and 100 kPa, respectively. It can be seen from Fig. 9 that the intact specimen exhibited a peak shear strength of approximately 23 kPa and the precut specimen exhibited a peak shear strength of only about 12 kPa. The precut specimen exhibited a lower peak strength because the precutting process created a shear plane and oriented some of the clay particles

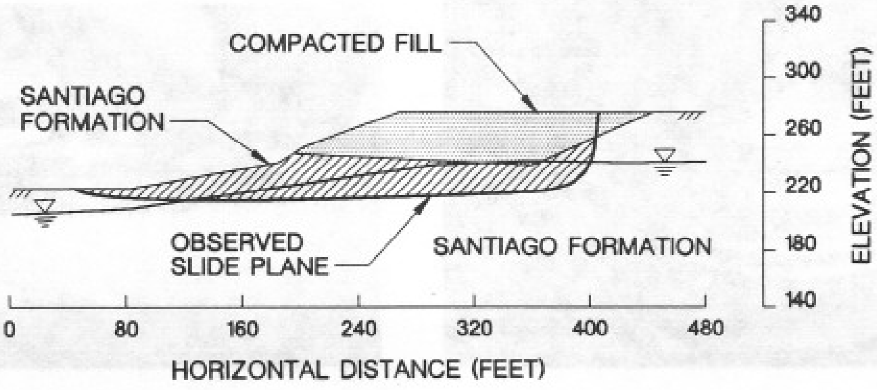

FIG. 8—*Cross section through Southern California Landslide.*

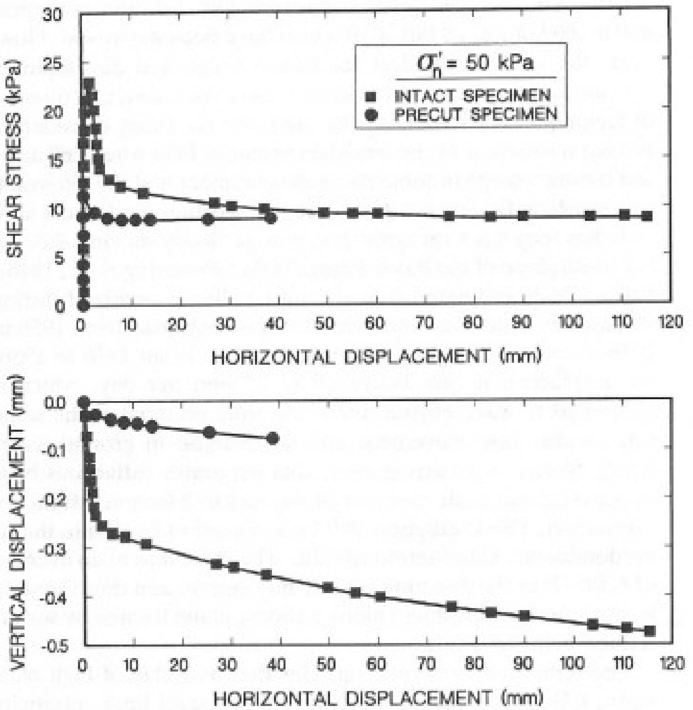

FIG. 9—*Drained ring shear test results for Santiago claystone at an effective normal stress of 50 kPa.*

parallel to the direction of shear prior to drained shearing. This resulted in a peak strength that is only slightly higher than the residual strength.

It can be seen from Fig. 9 that the intact and precut specimens yielded similar residual strengths. (It should be noted that soil was added and the intact specimen was reconsolidated such that settlement of the top porous stone was negligible prior to shear.) It can also be seen from Fig. 9 that the horizontal displacements required to reach the residual condition were significantly different. The precut specimen required about 15 mm of horizontal displacement, while the intact specimen required approximately 75 mm to obtain a residual condition. The reduced displacement can be attributed to the precutting process creating a shear plane and orienting some of the clay particles parallel to the direction of shear. In addition, the stiffness of the overconsolidated specimen probably facilitated the reorientation of clay particles during drained shear. It should be noted that the shear stress-horizontal displacement relations shown in Figs. 9 and 10 were also plotted using the logarithm of horizontal displacement, as suggested by La Gatta (1970), to verify that a residual strength condition was obtained. This plotting technique accentuates the slope of the shear stress-horizontal displacement relation at large displacements, allowing the horizontal portion of the curve to be clearly defined.

From Fig. 9 it can also be seen that the vertical displacement of the precut specimen is only 0.07 mm, whereas the intact specimen underwent a vertical displacement of about 0.5 mm. The difference in vertical displacement is due to the overconsolidated and precut specimen requiring less horizontal displacement to reach a residual condition. The reduced horizontal displacement and overconsolidated nature of the specimen decreases the amount of soil extrusion and thus vertical displacement. Since the total vertical displacement of the precut specimen during each stage is usually less than 0.1 mm, several tests can be performed on the same specimen without the total vertical displacement exceeding 0.75 mm and thus without significant wall friction developing. In summary, multistage tests can be continued until the vertical displacement exceeds 0.75 mm.

Figure 10 presents the shear stress-horizontal displacement relations for an intact specimen tested at an effective normal stress of 100 kPa and the second stage of the multistage test shown in Fig. 9. The precut specimen exhibited a significantly lower peak strength because the specimen has already attained a residual strength condition at an effective normal stress of 50 kPa. As a result, only approximately 10 mm of horizontal displacement is required to reach a residual condition at an effective normal stress of 100 kPa. The intact specimen exhibited a large peak strength because a shear plane had not been previously formed and no reorientation of the clay particles occurred prior to drained shearing. As a result, a horizontal displacement of approximately 70 mm is required to obtain a residual condition. This displacement is similar to that required for the intact specimen at an effective normal stress of 50 kPa. Since the shear displacement rate is 0.018 mm/min, it takes an additional 2.5 days to reach a residual strength condition using an intact specimen compared to the precut specimen.

It should be noted that the vertical displacement of the precut specimen is only about 0.03 mm (Fig. 10). This is less than the vertical displacement observed at an effective normal stress of 50 kPa and substantially less than the 0.35 mm measured for the intact specimen. The reduction in vertical displacement is due to the decrease in horizontal displacement required to reach a

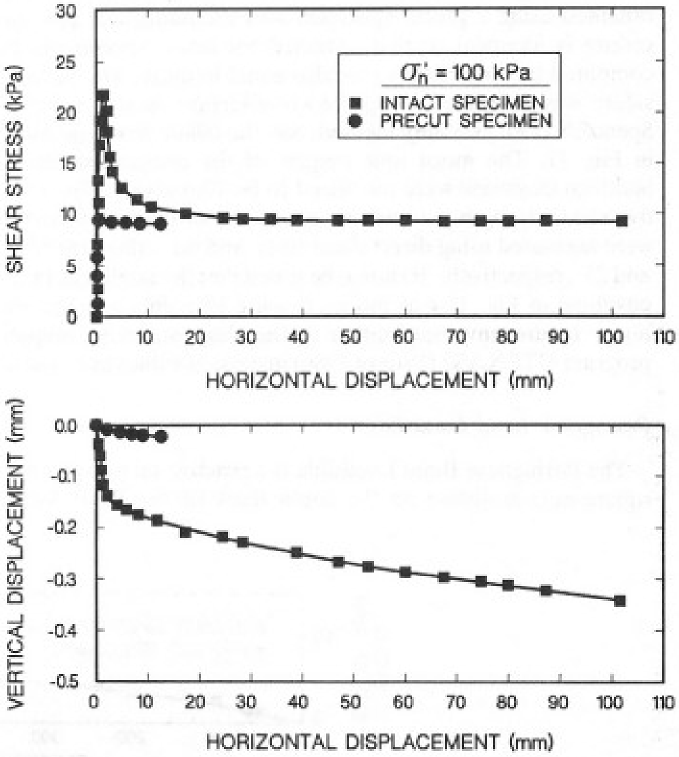

FIG. 10—*Drained ring shear test results for Santiago claystone at an effective normal stress of 100 kPa.*

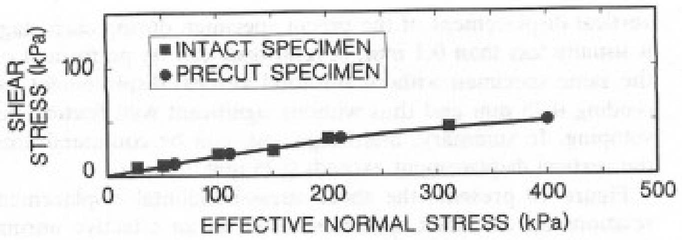

FIG. 11—*Effect of specimen and test procedure on measured residual strength of Santiago claystone.*

residual strength condition. This minimal vertical displacement ensures that a negligible amount of wall friction is applied to the shear plane.

Figure 11 shows the drained residual failure envelopes obtained for the intact and precut specimens. It can be seen that both specimens yielded drained residual strengths that are in excellent agreement and thus a similar residual failure envelope. The intact specimens yielded similar residual strengths because soil was added and consolidated several times such that the specimen surface was approximately "flush" with the top of the specimen container prior to drained shearing. However, approximately 17 days of testing were required to obtain the residual envelope using intact specimens, while only five days were required for the precut specimens. In general, one day is required to obtain a residual strength for each stage of the multistage test on a precut specimen.

Stark and Eid (1992) showed that the residual envelope obtained using intact specimens and the "flush" test procedure yielded a factor of safety equal to unity for the Southern California landslide case history. Since the residual failure envelope obtained using a precut specimen and the multistage test procedure is identical to that obtained for intact specimens, the computed factor of safety was also equal to unity. The factor of safety was computed using the cross-section shown in Fig. 8, Spencer's (1967) stability method, and the failure envelope shown in Fig. 11. The moist unit weights of the compacted fill and Santiago claystone were measured to be 19.6 kN/m^3. The effective shear strength parameters, c' and ϕ', of the compacted fill were measured using direct shear tests, and the values are 12kPa and 25°, respectively. It should be noted that the nonlinear failure envelope in Fig. 11 was modeled using 19 points and the nonlinear failure envelope option in the slope stability computer program UTEXAS2 (Wright 1986) instead of values of c' and ϕ'.

Portuguese Bend Landslide.

The Portuguese Bend Landslide is a reactivated part of a two-square-mile landslide on the south flank of the Palos Verdes Peninsula near Los Angeles, California. The slide area contained about 160 homes, all but 30 of which have been destroyed. However, the site is still ideal for future residential development because of the climate and ocean views. As a result, a number of techniques for stabilizing the landslide are being considered. Recent movement of the landslide began in 1956 when 260 acres slid during a surge in subdivision development and the extension of Crenshaw Boulevard. However, the Portuguese Bend Landslide has long been recognized as a large slowly moving slide on the south slope of the Palos Verdes Hills (Woodring et al., 1946). Ehlig (1992) estimated that the initial sliding occurred during Pleistocene time. Recent movement has continued from 1956 to 1976 at an average rate of 10 mm per day. From 1976 to 1986, the displacement rate increased to 25 mm per day, which is attributed to wave erosion removing slide material at the same rate as the slide movement and an increase in ground water levels. Sliding is occurring along thin bentonitic tuffaceous beds in the Altamira shale member of the middle Miocene Monterey Formation. The Portuguese tuff beds consist of bentonite that is predominantly Ca-montmorillonite. The shale dips at an average of 6.5 to 7° in the direction of slide movement, and thus the slide is attributed to movement along a sliding plane formed by water-soaked bentonitic tuff.

The remolded bentonitic tuff classifies as a clay of high plasticity, CH, according to the USCS. The liquid limit, plasticity index, and clay fraction of the remolded bentonitic tuff are 98, 61, and 68%, respectively. The coefficient of consolidation used to estimate the drained displacement rate of 0.018 mm/min is 0.2 mm^2/min.

Figure 12 shows the residual failure envelopes for the bentonitic tuff obtained using: (1) intact remolded specimens and the "flush" test procedure; and (2) a precut remolded specimen and the multistage test procedure. The bentonitic tuff sample was obtained from the slide plane at the toe of the landslide approximately 150 m east of Inspiration Point. It can be seen that the intact and precut remolded specimens yielded residual strengths that are in good agreement at effective normal stresses less than approximately 400 kPa. However, at effective normal stresses greater than 400 kPa, the precut specimen yields a lower residual failure envelope. This is due to the difficulty in limiting the vertical displacement of the intact specimen to 0.75 mm at effective normal stresses greater than 400 kPa. If the vertical displacement is at or near 0.75 mm, a substantial amount of wall friction is developed on the shear plane, and thus a higher residual strength is measured.

The difference in the residual failure envelopes measured using intact and precut specimens increases with soil plasticity and clay fraction. The increased plasticity causes larger vertical displacements during consolidation and drained shear and thus higher wall friction. As a result, the effective normal stress at which the

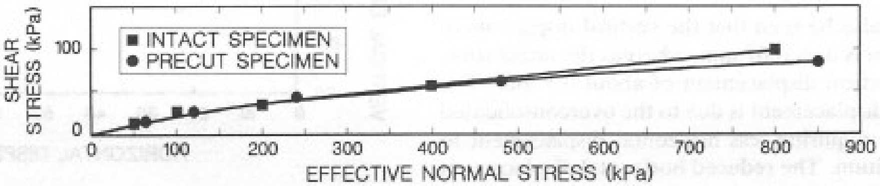

FIG. 12—*Effect of specimen and test procedure on measured residual strength of Portuguese Bend bentonitic tuff.*

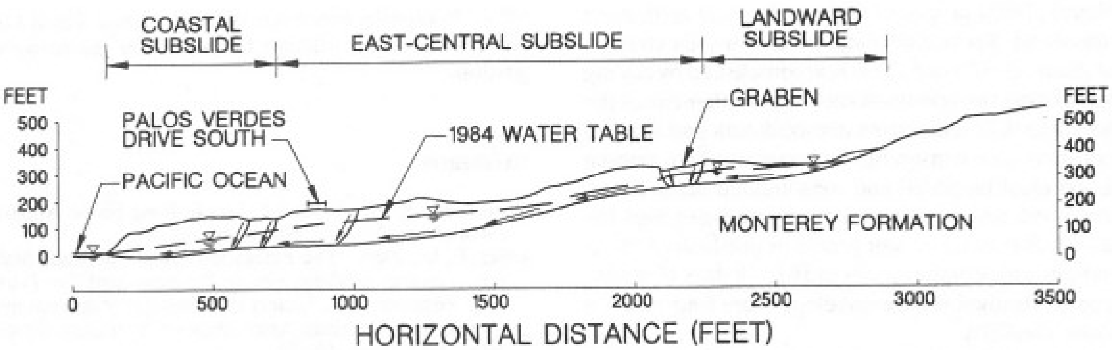

FIG. 13—*Typical cross section through Portuguese Bend Landslide (after Ehlig 1987).*

residual envelopes for the intact and precut specimens diverge decreases as the plasticity and clay fraction increases.

Factors of safety were calculated using the cross section shown in Fig. 13 (Ehlig 1987), Spencer's (1967) stability method, and the two failure envelopes in Fig. 12. The nonlinear failure envelopes were modeled using 19 data points in UTEXAS2 (Wright 1986). Figure 14 presents the bentonitic tuff failure envelopes in terms of the normalized shear stress, which is defined as the shear stress (τ) divided by the effective normal stress (σ'_n). It can be seen that normalizing the shear stress accentuates the curvature of the failure envelope of the bentonitic tuff. This nonlinearity should be modeled in stability analyses. The average moist unit weight of the slide mass was measured to be 17.5 kN/m^3. The effective shear strength parameters, c' and ϕ', for the nonhorizontal slide surface, i.e., inclined at 15° or greater, were estimated to be 0.0 kPa and 20°, respectively. The slide movement appears to be controlled by the coastal subslides (Fig. 13), and field observations show that if the coastal subslide moves, the remainder of the slide will move also (Ehlig 1992). The coastal subslides have been moving since the initial Pleistocene landslide, and, as a result, the strength of the bentonitic tuff in this area has probably reached a residual value.

The residual failure envelope obtained using a precut specimen and the multistage test procedure yielded a factor of safety of 1.02 for the coastal subslides, which is in good agreement with field observations. The residual envelope obtained using intact specimens and the "flush" test procedure yielded a factor of safety of 1.13 for the coastal subslides. Since the average effective normal stress along the slide plane in the coastal subslides is approximately 500 kPa, the difference in the residual failure envelopes is reflected in the computed factors of safety.

In summary, it is recommended that an overconsolidated and precut remolded specimen and the multistage test procedure be used to estimate the field residual strength. This provides a better simulation of field conditions that lead to a residual strength condition and significantly reduces test duration. Therefore, the new specimen container described herein is recommended for engineering practice because it allows a remolded specimen to be overconsolidated and precut and reduces the time required to obtain a residual failure envelope to about five days. However, intact remolded specimens and the original specimen container can be used to obtain accurate measurements of the field residual strength if enough soil is added and consolidated prior to shear such that the total vertical displacement during consolidation and shear is less than 0.75 mm.

Conclusions

The main factor affecting the drained residual strength measured in the Bromhead ring shear apparatus is the magnitude of wall friction developed along the inner and outer circumferences of the confined specimen. The magnitude of wall friction increases with the depth of the remolded 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.

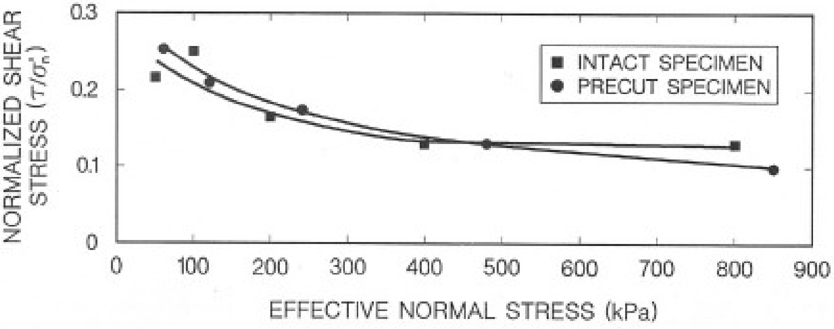

FIG. 14—*Relationship between normalized shear stress and effective normal stress for Portuguese Bend bentonitic tuff.*

Stark and Vettel (1992) proposed limiting the total settlement of the top porous stone, due to consolidation and/or soil extrusion during drained shear, to 0.75 mm. This is accomplished by adding soil and reconsolidating the specimen such that settlement of the top platen is less than 0.75 mm during consolidation and drained shear. This process is time consuming, especially at high normal stresses where soil must be added and consolidated many times. In addition, only one test is performed per specimen and the remolded specimen is intact, i.e., not precut or presheared, prior to drained shearing. This usually results in 16 to 18 days of testing to obtain a drained residual failure envelope from four tests on clays of moderate plasticity.

A new specimen container is proposed for the Bromhead ring shear apparatus that allows a remolded specimen to be overconsolidated and precut prior to shearing. The new specimen container is interchangeable with the original specimen container and limits the amount of settlement to significantly less than 0.75 mm. The settlement is reduced because the specimen is overconsolidated and precut prior to shearing, which leaves the specimen flush with the top of the specimen container prior to shear. In addition, the precutting process orients particles parallel to the direction of shear, which reduces the horizontal displacement, and thus settlement of the top platen, required to reach a residual strength condition. The significant reduction of settlement allows the performance of multistage tests that reduce the time required to measure a drained residual failure envelope to five or six days. The use of an overconsolidated and precut specimen also provides a better representation of field conditions that lead to a large post-peak decrease in drained strength and, most importantly, residual strengths that are in excellent agreement with field case histories.

Acknowledgment

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References

Bromhead, E. N., 1979, "A Simple Ring Shear Apparatus," *Ground Engineering*, Vol. 12, No. 5, pp. 40–44.

Ehlig, P. L., 1987, "The Portuguese Bend Landslide Stabilization Project," *Geology of Palos Verdes Peninsula and San Pedro Bay*, Part 2, P. J. Fishcher, Ed., Society of Economic Paleontologists and Mineralogists and American Association of Petroleum Geologists, Los Angeles, June 7, pp. 17–24.

Ehlig, P. L., 1992, "Evolution, Mechanics and Mitigation of the Portuguese Bend Landslide, Palos Verdes Peninsula, California," *Engineering Geology in Southern California*, B. W. Pipkin and R. Proctor, Eds., Stark Publishing Co., Los Angeles, CA, pp. 1–69.

Gibson, R. E. and Henkel, D. J., 1954, "Influence of Duration Tests at Constant Rate of Strain on Measured 'Drained' Strength," *Geotechnique*, Vol. 4, No. 1, pp. 6–15.

Kanji, M. A. and Wolle, C. M., 1977, "Residual Strength—New Testing and Microstructure," Vol. 1, *Proceedings*, Ninth International Conference on Soil Mechanics and Foundation Engineering, Tokyo, Japanese Society of Soil Mechanics and Foundation Engineering, Tokyo, pp. 153–154.

La Gatta, D. P., 1970, "Residual Strength of Clays and Clay-Shales by Rotation Shear Tests," Ph.D. thesis reprinted as *Harvard Soil Mechanics Series*, No. 86, Harvard University, Cambridge, MA, pp. 204.

Spencer, E., 1967, "A Method of Analysis of the Stability of Embankments Assuming Parallel Inter-Slice Forces," *Geotechnique*, Vol. 17, No. 1, pp. 11–26.

Stark, T. D. and Eid, H. T., 1992, "Comparison of Field and Laboratory Residual Strengths," *Proceedings*, ASCE Specialty Conference on Stability and Performance of Slopes and Embankments—II, Vol. 1, University of California, Berkeley, CA, ASCE, New York, pp. 876–889.

Stark, T. D. and Vettel, J. J., 1992, "Bromhead Ring Shear Test Procedure," *ASTM Geotechnical Testing Journal*, Vol. 15, No. 1, March 1992, pp. 24–32.

Wright, S. G., 1986, "UTEXAS2: A Computer Program for Slope Stability Calculations," Geotechnical Engineering Software GS86-1, Department of Civil Engineering, University of Texas, Austin, p. 109.

Woodring, W. P., Bramlette, M. N., and Kew, W. S. W., 1946, "Geology and Paleontology of Palos Verdes Hills, California," U.S. Geological Survey Paper No. 207, U.S. Department of the Interior, Denver.