Measuring “Fast” Shear Strengths Along Slickensided Surfaces in the Bromhead Ring Shear

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Abstract: Fast and slow ring shear tests were performed in the Bromhead ring shear device to examine the effect of the displacement rate on the shear strength measured along slickensided discontinuities in Rancho Solano Fat Clay. For each test, initial drained shearing was performed at a displacement rate of 0.018 mm/min, fast shearing was performed at a rate of 44.5 mm/min, and drained shearing was recommenced at a displacement rate of 0.018 mm/min. Significant variations in measured post-peak shear strengths were observed, and problems with the pore pressure response in the soil surrounding the slickensided plane are discussed. As a result of these problems, it was concluded that fast Bromhead ring shear tests may not be suitable for evaluating the effects of fast shearing on the strengths of slickensided surfaces.

DOI: 10.1520/GTJ101325

Keywords: Ring shear tests; Clays; Residual strength; Slickensides; Fast shearing; Laboratory test.

Reference: Meehan, C. L., Brandon, T. L., and Duncan, J. M. (2008). “Measuring “Fast” Shear Strengths Along Slickensided Surfaces in the Bromhead Ring Shear.” *Geotechnical Testing Journal*, ASTM, 31(3), 239-242. (doi:10.1520/GTJ101325)

Note: The manuscript for this paper was submitted for review and possible publication on June 25, 2007; approved for publication on December 2, 2007; and published online in January of 2008.

1 Introduction

Slickensided shear surfaces are formed in clay soils as a result of shear on distinct planes of slip, which aligns the plate-like clay particles parallel to the plane of slip (Duncan and Wright 2005). For landslides in overconsolidated clay and clay shale slopes, the stability of the slope is often controlled by the shear resistance that can be mobilized along pre-existing slickensided shear surfaces (Skempton 1985). The *residual strength* is the drained shear resistance that can be mobilized along a slickensided surface during slow shearing (Skempton 1964).

Residual strengths are used to evaluate the stability of slickensided slopes under long-term static loading (Duncan and Wright 2005). However, more rapid dynamic loading of slickensided surfaces occurs when an existing landslide is subjected to cyclic loading during an earthquake (e.g., Skempton 1985; Yoshimine et al. 1999). Rapid loading along slickensided surfaces also occurs as slickensides are formed during pile driving in clays and clay shales (Tika et al. 1996). For these loading cases, a reliable method of measuring the shear strength along existing slickensided surfaces is needed.

A number of researchers (Skempton 1985; Lemos et al. 1985; Tika et al. 1996) have used rapid shear tests in an NGI-type ring shear device to measure the effect of displacement rate on the shear strength that can be mobilized along existing slickensided surfaces. The advantage of using a torsional ring shear device for this type of testing is that it can apply unlimited shear displacement without reversal of the direction of shear (Duncan and Wright 2005). Other researchers (Yoshimine et al. 1999) have used fast-shearing tests and cyclic loading tests in a custom-built ring shear device to more accurately simulate the load condition that occurs when slickensided slopes are subjected to cyclic loading during an earthquake.

This paper presents the results from a series of Bromhead ring shear tests that were conducted to measure the drained residual strength and the “fast” residual strength along slickensided discontinuities in Rancho Solano Fat Clay. These tests were conducted as part of a larger research project examining the static and dynamic shear behavior of slickensided surfaces using ring shear, direct

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shear, triaxial, and centrifuge model tests (Meehan et al. 2007; Meehan et al. 2008; Meehan et al. 2010; Meehan 2006). The potential advantage to using the Bromhead ring shear device for this type of testing is that it is already widely used in the United States for measuring the drained residual strength of clay soils, and consequently, is more readily available for use by geotechnical practitioners than the NGI-type ring shear device.

2 Torsional Shear Testing in the NGI-Type Ring Shear and the Bromhead Ring Shear

The "NGI-type" ring shear is a torsional ring shear device that was developed by researchers at Imperial College and the Norwegian Geotechnical Institute (Bishop et al. 1971). This ring shear device is widely used for measuring the drained residual strength of clays and clay shales. In the NGI-type ring shear, an annular, ring-shaped soil specimen is subjected to torsional, displacement-controlled shearing under a constant normal force. As shown in Fig. 1, failure occurs by rupture of the soil specimen at mid-height, at the interface between the upper and lower specimen confining rings. Continued shearing results in clay particles becoming oriented along the failure plane, and development of slickensides along which the residual strength is measured.

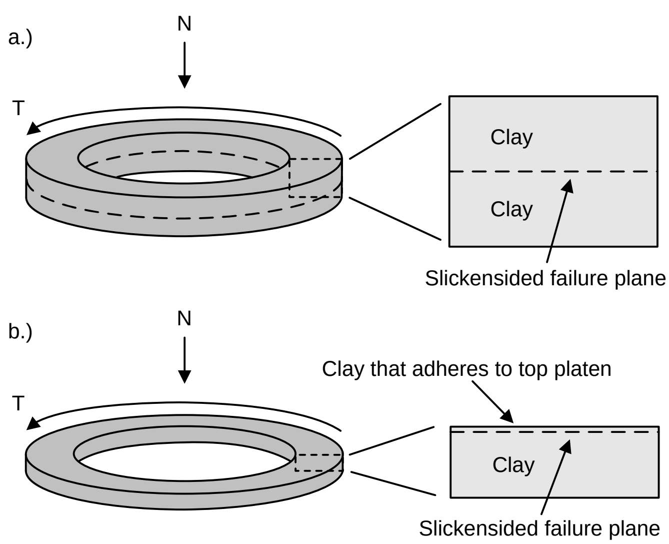

Fig. 1: Location of slickensided failure plane: (a) in the NGI-type ring shear, and (b) in the Bromhead ring shear.

In the United States, the Bromhead ring shear device (Bromhead 1979) is widely used for measuring the drained residual strength of clay soils. In the Bromhead ring shear, a thin annular soil specimen is subjected to torsional, displacement-controlled shearing under a constant normal force. As shown in Fig. 1, failure occurs by rupture of the soil specimen along its upper surface, where a thin layer of clay particles that adhere to the roughened upper platen are displaced relative to clay particles below. Continued shearing results in clay particles becoming oriented along the failure plane, and the development of slickensides along which the residual strength is measured. Because the failure plane is usually located at the top or close to the top of the specimen, the Bromhead ring shear is often categorized as a "smear-type" ring shear device.

During fast shearing along an existing slickensided surface in the field, pore pressures do not have time to dissipate, and the measured shear response along the slickensided surface can be considered *undrained*. Although it is not possible to control boundary drainage conditions directly in either the NGI-type ring shear device or the Bromhead ring shear device, the general assumption that is made by researchers using the "fast shear" test approach is that fast shearing provides a reasonably accurate means of measuring undrained strength along slickensided surfaces.

3 Soil Properties

The ring shear tests described in this paper were performed on "Rancho Solano Fat Clay" from the Rancho Solano residential development in Fairfield, CA. This soil was batch-mixed at water contents ranging from 1.0 to 1.2 times its liquid limit to ensure uniformity. The clay was then passed through a #40 sieve to remove larger soil particles that could interfere with operation of the Bromhead ring shear device.

Index tests on the resulting slurry yielded the following properties: Liquid Limit (LL) of 61, Plastic Limit (PL) of 25, Plasticity Index (PI) of 36, fines content (percent by dry weight passing the #200 sieve) of 93 %, clay size fraction (smaller than 2 micron) of 53 %, and a specific gravity of solids of 2.65. The USCS Classification for this soil is *fat clay (CH)*.

Prior to creation of ring shear specimens, the water content of the clay was reduced by bulk consolidation of large-batch soil samples in a "batch consolidometer." Using the batch consolidometer, the clay was consolidated from a slurry using a series of load steps (LIR=1), to a final consolidation pressure of 345 kPa. Sufficient time was allowed after application of each load for pore pressures to dissipate before the next load was applied. This batch consolidation reduced the subsequent compression that occurred during the ring shear tests, which reduced testing time and minimized intrusion of the top platen into the specimen container during each test.

4 Measuring the "Fast" Residual Shear Strength

The fast residual ring shear testing program was developed using the same rationale and test approach that was first proposed by Skempton (1985) for rapid shear testing in the NGI-type ring shear device. Using Skempton's (1985) approach, a clay specimen is first sheared slowly to create a slickensided failure surface, then sheared rapidly to measure the undrained shearing response along the slickensided shear surface, and then sheared slowly again to re-establish the drained residual condition. As noted earlier, this approach has been employed successfully by other researchers using the NGI-type ring shear device (Lemos et al. 1985; Tika et al. 1996; Tika and Hutchinson 1999). To the writers' knowledge, the usefulness of this test approach for measuring fast residual strengths in the Bromhead ring shear device has not been explored.

The ring shear tests described in this paper were performed using a Bromhead ring shear device built by Wykeham Farrance Engineering Ltd. (Bromhead 1979). The test specimens used in this apparatus had inside diameters of 70 mm, outside diameters of 100 mm, and initial thicknesses (prior to consolidation) of 5 mm. To minimize the effect of wall friction, each of the Bromhead ring shear devices was modified by machining the inside and outside edges of the porous bronze top platen back to a 45° bevel, as shown in Fig. 2. As a result of this modification, a significant reduction in wall friction is obtained even if considerable top platen intrusion into the specimen container occurs during a test. Data supporting the effectiveness of this device modification for reducing the effect of wall friction in the Bromhead ring shear device are provided in Meehan et al. (2007).

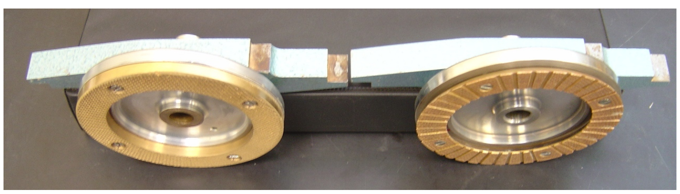

Fig. 2: Angle view that shows the difference between the original porous bronze platen (on the left) and the modified porous bronze platen (on the right).

To begin each test, the processed clay from the batch consolidometer was molded into the Bromhead ring shear specimen container by hand, and trimmed flush to the top of the specimen container using a long razor blade. Care was taken to ensure that all gaps were filled during this process. This specimen preparation test procedure is consistent with recommendations by Bromhead et al. (1999) and Harris and Watson (1997), who suggest that specimens be prepared at water contents closer to the plastic limit, because "shear surfaces form best at this level of moisture" (Bromhead et al. 1999).

After the test specimen had been created, the specimen container was placed in the ring shear loading device, and the specimen was consolidated using a series of load steps to the desired normal stress. During consolidation, the normal stress was applied by a deadweight lever-arm system, and vertical displacements were recorded to ensure that pore pressures for a given load step had dissipated before the next load was applied.

Once the pore pressures that were induced by consolidation had dissipated, slow shearing (Stage 1 shearing) was begun. In order to minimize shear-induced pore water pressures during this part of the test, slow-shear displacement rates were selected using the following equation (from ASTM D6467-99):

$$\text{Disp. Rate} = \frac{\text{Disp. at Failure}}{\text{Time to Failure}} = \frac{5\text{ mm}}{50 \times t_{50}} \tag{1}$$

In the above equation, t_{50} is the time required for the specimen to achieve 50 % consolidation under the applied normal stress. Based on the recorded consolidation data, a conservative displacement rate of 0.018 mm/min was chosen for drained shearing. This displacement rate is the lowest that can be applied by the Wykeham Farrance Bromhead ring shear device.

For each fast shear test, initial drained shearing was performed at a displacement rate of 0.018 mm/min (Stage 1 shearing), to create a slickensided failure surface within the ring shear test specimen.

After the residual condition had been reached, drained shearing was stopped, and fast shearing (Stage 2 shearing) was begun. Fast shearing was performed at a rate of 44.5 mm/min, which is the highest displacement rate that can be applied by the Wykeham Farrance Bromhead ring shear device. Specimens were sheared for two full revolutions in the ring shear device, which corresponds to a shear displacement of approximately 530 mm.

Fast shearing was then stopped, and sufficient time was allowed for pore pressures generated during shear to dissipate. Drained shearing was then resumed at a displacement rate of 0.018 mm/min (Stage 3 shearing). The third shearing stage was continued until the drained residual condition had once again been achieved. Figure 3 shows the fast shear response of three Rancho Solano Fat Clay specimens that were tested at normal stresses of 200, 345, and 590 kPa.

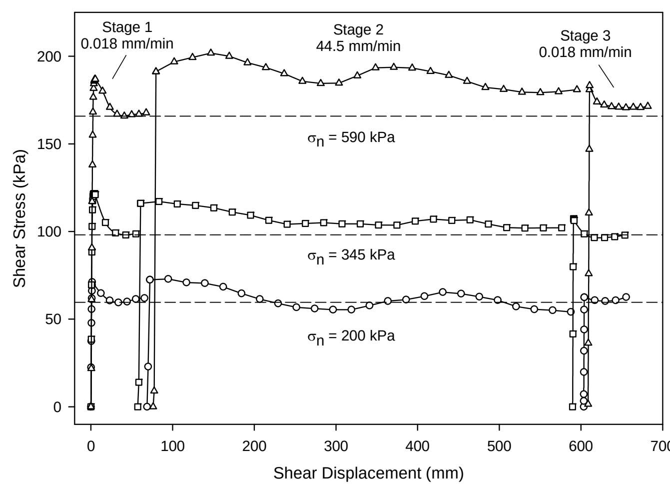

Fig. 3: The fast shear response of Rancho Solano Fat Clay.

The shear stress plots shown in Fig. 3 are representative curves selected from the results of eleven tests. The fast shear tests indicated that there is an increased "threshold strength" at the beginning of fast shearing. As fast shearing is continued, there is an additional increase in strength, to the "fast maximum" strength. As fast shearing continues past the fast maximum strength, the strength drops to a "fast minimum" strength. As shown in Fig. 3, the fast minimum strength was sometimes higher than the drained residual strength and sometimes lower than the drained residual strength. At the end of fast shearing, once drained shearing is resumed, a new slow peak strength is observed, which is higher than the drained residual strength. The strength then drops again to the drained residual strength, which coincides with the initial drained residual strength.

5 Discussion of Test Results

The measured Bromhead ring shear test results agree in most respects with what has been observed for clayey soils in the NGI-type ring shear apparatus (e.g., Skempton 1985; Lemos et al. 1985; Tika et al. 1996). However, there is one significant difference between the fast minimum shear behavior in the Bromhead ring shear device and what has been observed in the NGI-type ring shear device. This difference is the cyclic up-and-down nature of the stress-displacement curve, which is clearly evident in Fig. 3. This cyclic increase and decrease in shear resistance is probably not a true soil behavior phenomenon, and could be caused by either of the following mechanisms described below.

One possibility is the replacement of soil particles along the shearing plane, which might occur as follows: As soil is extruded from the shearing plane, "disturbed" (partially-oriented or fully-oriented) clay particles are replaced by clay particles from a previously undisturbed part of the overconsolidated clay surrounding the shear plane. The strength in the region of these undisturbed, nonoriented particles would be higher (it would be the "peak" strength), and additional shearing would be necessary to disturb these particles to bring them to a fully-softened or residual condition. Complete orientation of these particles along the shear plane is unlikely at higher displacement rates, due to the development of a more turbulent shear mechanism, as postulated by Skempton (1985). The "steady-state" shear condition that would be achieved at the higher displacement rate would likely consist of a combination of turbulent and sliding shear mechanisms along the shear plane. Cycles of clay particle extrusion and replacement by undisturbed particles along the shearing plane might cause variations in the measured shear strength. Unfortunately, the top platen modifications that are necessary to reduce wall friction in the Bromhead ring shear device also allow soil extrusion at a more rapid rate than usual, which would exacerbate this behavior, if it does occur.

A second possible mechanism for the observed "pumping" behavior is a machine effect that may be caused by subtle shifting of the top platen during shear. Figure 4 shows the fast shear response of a Rancho Solano Fat Clay specimen that was sheared to large displacements in the Bromhead ring shear device. The observed peaks and troughs in the stress-displacement curve occur on a cyclic basis, with approximately one full revolution (360°) of the specimen between successive peaks in the measured shear stress. This strongly suggests that the cyclic increase and decrease in measured shear resistance is a machine effect, probably wobbling of the top platen caused by load redistribution between the two proving rings and the center axle, and does not represent real soil behavior.

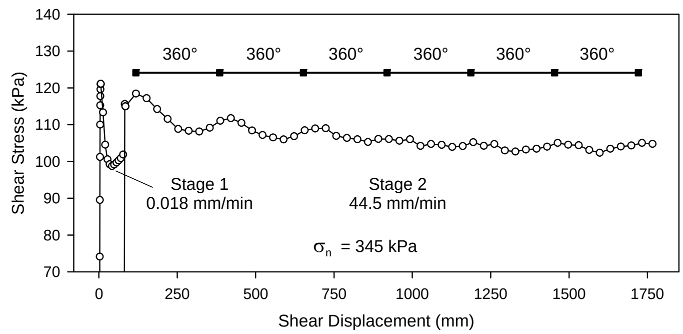

Fig. 4: The fast shear response of Rancho Solano Fat Clay sheared to large displacements in the Bromhead ring shear device.

This phenomenon makes it impossible to quantify the value of the fast minimum residual strength. Even from a qualitative standpoint, in some cases, it is not clear whether the fast minimum strength is higher than or lower than the drained residual strength (as shown by the $\sigma_n = 200$ kPa test in Fig. 3).

In addition to the physical problems of extrusion and top platen shifting during fast shear tests, there also exists some uncertainty regarding the pore pressure development surrounding the slickensided failure plane. Skempton (1985) has shown that rapid shearing along pre-existing slickensided discontinuities can lead to significant gains in strength above the drained residual strength condition. Skempton (1985) hypothesized that this strength gain is due to disturbance of the originally ordered clay particles, which causes a transition from the sliding mode to the turbulent mode of failure. As the clay particles along the shearing plane are disturbed, negative pore pressures are developed along the shearing plane, resulting in a pore pressure gradient into the surrounding soil. These negative pore pressures are dissipated as shear continuous, which is what causes a decrease in strength from the "fast maximum" condition to the "fast minimum" condition.

With the NGI-type ring shear device, there is a significant amount of clay above and below the failure plane, giving a relatively long drainage path for pore pressure dissipation. However, in the Bromhead ring shear device, shearing takes place at or very close to the top platen. Therefore, the drainage path length from the shearing plane to the closest free-draining boundary is very short, and any negative pore pressures developed are dissipated relatively quickly. This leads to a pore pressure response that is different than what would occur in the field, or in the NGI-type ring shear device. Consequently, the Bromhead ring shear device may not provide a reliable means of evaluating fast shear strengths in the field.

6 Conclusions

A series of "fast" ring shear tests were performed in the Bromhead ring shear device to examine the effect of loading rate on the strength measured along existing slickensided discontinuities in Rancho Solano Fat Clay. For each test, initial drained shearing was performed at a displacement rate of 0.018 mm/min, fast shearing was performed at a rate of 44.5 mm/min, and drained shearing was recommenced at a displacement rate of 0.018 mm/min. This test approach is consistent with what has been performed by others (e.g., Skempton 1985) in the NGI-type ring shear device.

The measured fast shear strengths exhibited a cyclically varying post-peak strength response that made it impossible to accurately quantify the shear resistance that was mobilized along the slickensided surface. This cyclic increase and decrease in shear strength was likely caused by shifting of the top platen during fast shear, possibly coupled with extrusion and replacement of soil particles along the slickensided shear plane. Physical problems with the measured fast shear test results were further complicated by the fact that the pore pressure response along the slickensided plane in the Bromhead ring shear device is not the same as the pore pressure response that would be observed in the field during fast loading along a slickensided surface. As a result of these problems, the fast ring shear test results for Rancho Solano Fat Clay could not be used to accurately quantify the effect of loading rate on the shear strength measured along slickensided surfaces.

It should be noted that the conclusions drawn in this paper are limited to the soil that was tested during the research program. Additional testing of other clay soils is needed to further substantiate these observations.

Acknowledgments

Funding for this research was provided by the National Science Foundation under Award Nos. CMS-0321789 and CMS-0324499 and by Virginia Tech, through the Instructorship Position. The authors would like to acknowledge the suggestions and assistance of Binod Tiwari, Derek Martowska, and Michael Wanger.

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