CHAPTER 5: LABORATORY TESTING OF SLICKENSIDED SURFACES

The laboratory tests described in this chapter were conducted to measure drained residual strength, fast residual strength, and cyclic shear strength along pre-formed slickensided discontinuities in Rancho Solano Clay and San Francisco Bay Mud. Drained residual strengths were measured by performing strain-controlled direct shear tests and triaxial tests at slow rates of shear on specimens that contained pre-formed slickensided failure surfaces. Fast residual strengths were measured by performing strain-controlled direct shear tests at fast rates of shear on slickensided specimens. Cyclic shear strength was measured by performing stress-controlled cyclic direct shear tests on slickensided specimens.

The drained direct shear tests and triaxial tests are a valuable part of the laboratory test program because they provide a means of evaluating the effectiveness of the slickenside preparation and polishing process. The fast direct shear tests are useful because they provide improved understanding of the fast shear behavior along slickensided discontinuities. The cyclic direct shear tests provide an indication of how slickensided rupture surfaces behave under seismic loading conditions.

The direct shear tests described in this chapter were performed at Virginia Tech using two direct shear devices. Figure 5-1 shows the strain-controlled direct shear device used to perform the drained direct shear tests and fast direct shear tests. This device was built by Wykeham Farrance Engineering Ltd. Figure 5-2 shows the stress-controlled direct shear device that was used to perform the cyclic direct shear tests. This device was designed and constructed at Virginia Tech by modifying an existing simple shear device so that it could apply cyclic loading to a direct shear specimen. The triaxial tests described in this chapter were performed at Virginia Tech using automated triaxial test equipment manufactured by the GeoComp Corporation. The triaxial device that was used for testing is shown in Figure 5-3.

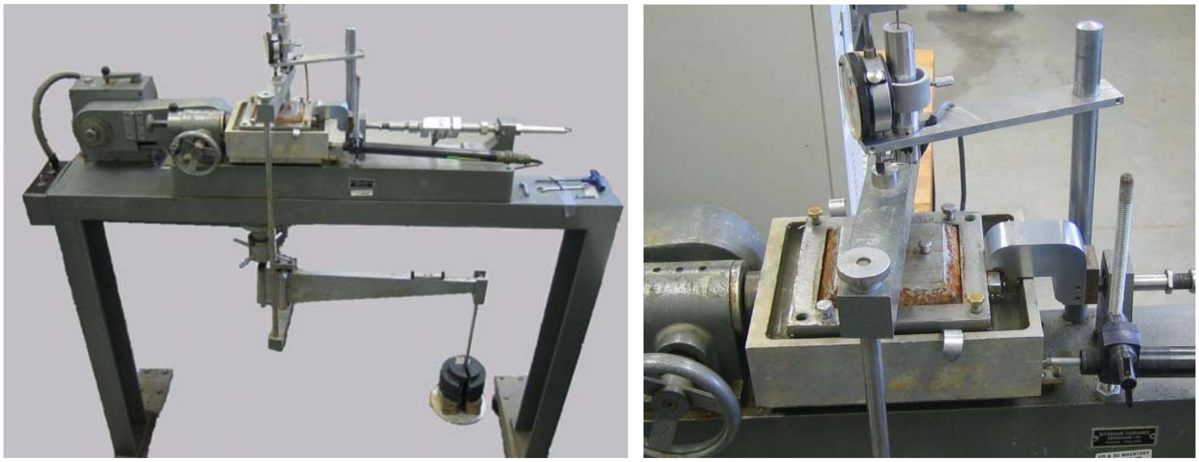

Figure 5-1. Wykeham Farrance direct shear apparatus.

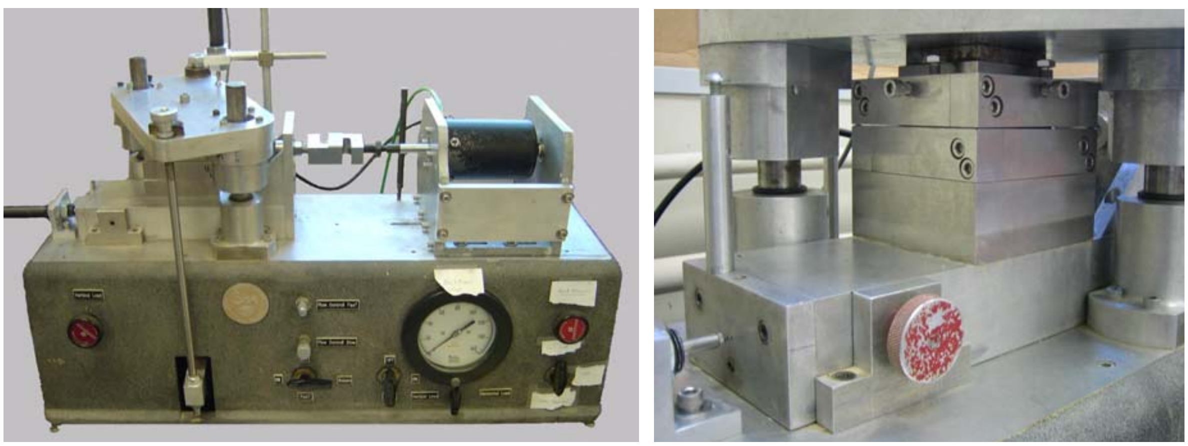

Figure 5-2. Virginia Tech cyclic direct shear device.

Figure 5-3. GeoComp automated triaxial test equipment.

Drained Direct Shear Testing of Rancho Solano Clay #1

In order to measure the drained residual shear strength along slickensided failure surfaces in Rancho Solano Clay #1, drained direct shear tests were conducted in general accord with the direct shear test method described in ASTM D 3080-98.

Direct shear tests can be used for measuring the shear strength along existing discontinuities in clayey soil (Skempton and Petley, 1967). Because remolded specimens were used in the testing program, it was necessary to develop a method for creating slickensided rupture surfaces in the laboratory. The effectiveness of the slickenside preparation process was evaluated by comparing the residual strengths measured along the prepared slickensided surfaces with those from the Bromhead ring shear testing program. This step was essential to ensure the validity of the slickenside preparation process.

As discussed in Chapter 3, the clay for the direct shear test specimens was prepared by first mixing it at a water content near its liquid limit. The clay was then pushed through the #40 sieve (opening size = 0.0165 inches) to remove larger soil particles that could interfere with the slickenside preparation process. The resulting clay slurry was then consolidated to 50 psi in a batch consolidometer to lower its water content.

Each of the direct shear test specimens was created by pressing the stiff clay from the batch consolidometer into the direct shear box and trimming it to the desired height. This formed test specimens that were 4″ x 4″ square, with heights of 0.5″. After trimming, the specimens were consolidated to 100 psi to stiffen the clay for easier slickenside formation.

After consolidation, the test specimen was repositioned so that its center coincided with the separation between the upper and lower shear boxes. The specimen was then wire cut to create a shear plane at the interface between the upper and lower shear boxes. The specimen could then separated into two pieces, an upper half and a lower half, which were polished to align clay particles in the direction of shear.

A specimen half was polished by shearing it along the entire length of a wet 12-inch frosted glass plate under moderate hand pressure. Four passes along the frosted glass plate were used for each half of the test specimen, taking care to remove the test specimen from the plate after each pass by shearing it off the edge of the glass, in order to not disturb the clay particles along the shearing plane. Care was taken to ensure that the direction of polishing coincided with the direction of shear that the specimen would experience in the direct shear device.

Once the two halves of the test specimen were polished, they were placed in the direct shear device, and the specimen was aligned such that the preformed shearing plane coincided with the shear plane between the two halves of the shear box. A bit of judgment was necessary at this stage, because the vertical position of the shear plane could change as a result of the specimen consolidation that occurred when the specimen was loaded to the desired testing normal stress. Achieving the appropriate vertical alignment of the shear plane took significant experience, and was critical for measuring the residual strength using this approach. Figure 5-4 shows the approach used to prepare the direct shear test specimens, and the final appearance of the failure plane after wet polishing.

Figure 5-4. Preparing a direct shear test specimen; (a) wire-cutting a direct shear specimen, (b) rubbing the cut plane on frosted glass to align clay particles, (c) the polished failure plane.

Once the polishing process was completed for each half of the test specimen, the two halves were reassembled and the specimen was placed in the direct shear device. The direct shear test was then begun by consolidating the specimen to the desired testing normal stress. During consolidation, the normal force was applied by a dead-weight lever-arm system, and vertical displacements were recorded in order to ensure that pore pressures were completely dissipated before the commencement of shear.

Upon completion of consolidation, the specimen was sheared using slow, displacement-controlled loading. In order to minimize shear-induced pore water pressures so that the test could be considered “drained”, slow-shear displacement rates were selected using the following equation (from ASTM D 3080-98):

$$\text{Displacement Rate} = \frac{\text{Displacement at Failure}}{\text{Time to Failure}} = \frac{0.5''}{50 \times t_{50}} \qquad (5\text{-}1)$$

In the above equation, t_{50} is the time required for the specimen to achieve 50% consolidation under the applied normal stress. The value of t_{50} was determined using data from consolidation tests and early direct shear tests. A displacement rate of 0.000123 in/min was used for drained direct shear testing of Rancho Solano Clay #1. This value is believed to be a conservative displacement rate that would ensure full pore pressure dissipation during shear.

Test specimens were sheared until the stress-displacement curve showed that a constant minimum shear stress had been reached. In all cases, shearing was continued for at least 0.3 inches and for no more than 0.5 inches (the maximum permissible travel of the shear box).

A total of 13 drained direct shear tests were performed on Rancho Solano Clay #1. Specimens were tested at four initial normal stresses: 7.9 psi, 14.5 psi, 28.8 psi, and 50.4 psi. Data sheets for each direct shear test are given in Appendix B. A typical friction ratio vs. displacement curve for Rancho Solano Clay #1 is shown in Figure 5-5. Friction ratios in the strain-controlled direct shear device were calculated using the following equation:

$$\text{Friction Ratio} = \frac{\text{Corrected Shear Stress}}{\text{Corrected Normal Stress}} = \frac{\text{Shear Force}}{\text{Normal Force}} \qquad (5\text{-}2)$$

This soil typically exhibits a small peak in shear resistance, possibly due to a “healing” effect on the shear plane. The shear resistance then drops to a nearly constant value, which can be considered the residual strength for the soil. A gradual increase in shear strength is often observed as the specimen is sheared to larger displacements, as shown in Figure 5-5. This “saddle” shape has been observed by other researchers testing clays in the direct shear device (Bishop et al., 1971), and is thought to be caused by the combined effects of extrusion and machine friction.

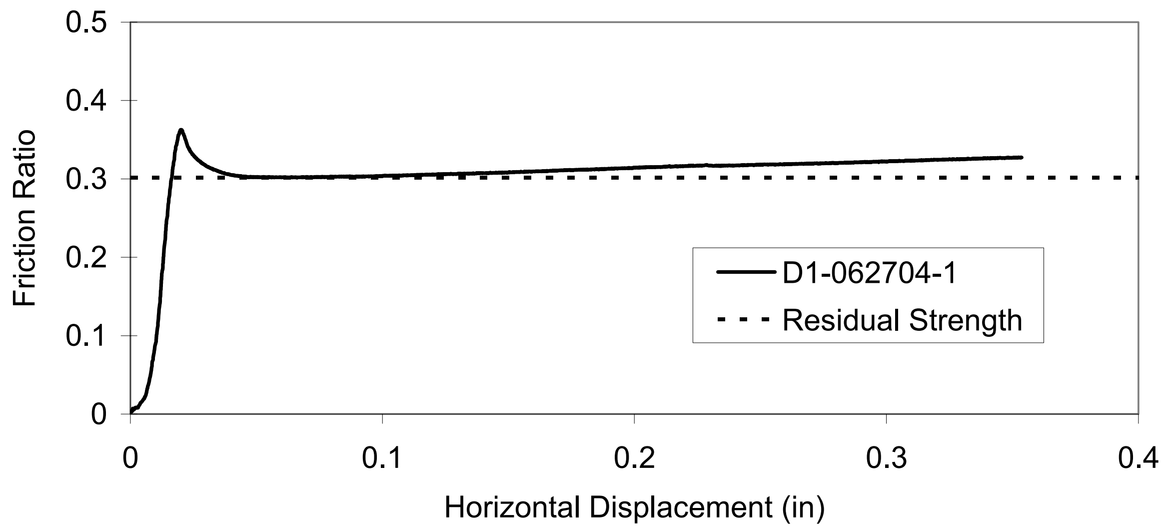

Figure 5-5. Friction ratio vs. displacement for direct shear test D1-062704-1.

Statistical analysis results of the measured residual shear stresses are given in Table 5-1. Statistical analysis results of the measured secant residual friction angles are given in Table 5-2. Secant residual friction angles were calculated using the following formula, which assumes that there is no residual cohesion:

$$\text{Secant Residual Friction Angle} = \tan^{-1}\left(\text{Residual Friction Ratio}\right) \qquad (5\text{-}3)$$

The standard deviations of the residual shear stresses and the secant residual friction angles were calculated using the nonbiased method, given by the following formula:

$$\text{Standard Deviation} = \sqrt{\frac{n\sum x^2 - (\sum x)^2}{n(n-1)}} \qquad (5\text{-}4)$$

where: x = sample value, and
n = total number of samples.

Comparisons between the average residual shear stresses and secant residual friction angles measured in the Bromhead ring shear device and the direct shear device are given in

Figure 5-6 and Figure 5-7. The bands surrounding each value of average secant friction angle in Figure 5-7 are the minimum and maximum secant residual friction angles measured at that normal stress.

Table 5-1: Residual Shear Stresses Measured in Direct Shear Tests on Rancho Solano Clay #1

Initial Normal Stress (psi)	Number of Tests Performed	Average Residual Normal Stress (psi)	Average Residual Shear Stress (psi)	Standard Deviation of Measured Residual Shear Stress (psi)	Minimum Measured Residual Shear Stress (psi)	Maximum Measured Residual Shear Stress (psi)
7.9	4	8.4	2.9	0.32	2.5	3.2
14.5	4	14.8	4.7	0.26	4.5	5.0
28.8	3	29.6	8.7	0.33	8.4	9.0
50.4	2	52.6	15.5	2.51	13.7	17.3

Table 5-2: Secant Residual Friction Angles Measured in Direct Shear Tests on Rancho Solano Clay #1

Initial Normal Stress (atm)	Number of Tests Performed	Normal Stress at Failure (atm)	Average Secant Residual Friction Angle (degrees)	Standard Deviation of Measured Secant Residual Friction Angle (degrees)	Minimum Measured Secant Residual Friction Angle (degrees)	Maximum Measured Secant Residual Friction Angle (degrees)
0.5	4	0.6	18.7	1.1	17.2	19.6
1.0	4	1.0	17.6	0.8	16.8	18.6
2.0	3	2.0	16.4	0.8	15.8	17.2
3.4	2	3.6	16.4	2.0	15.0	17.7

As shown in Figure 5-6 and Figure 5-7, good agreement was obtained between the residual strengths measured in the Bromhead ring shear device and the direct shear device. This provides experimental validation for use of the wet polishing method with Rancho Solano Clay #1.

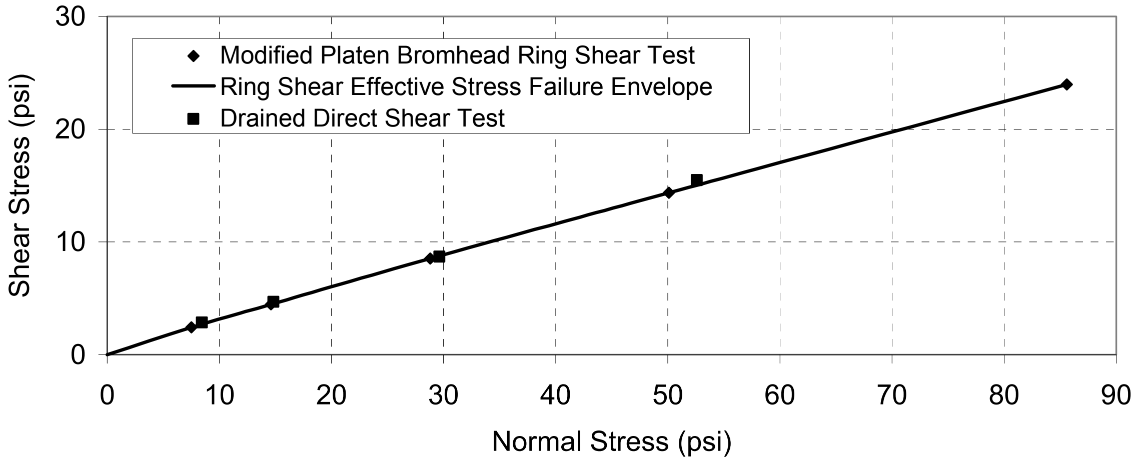

Figure 5-6. Comparison between Bromhead ring shear and direct shear test results for Rancho Solano Clay #1.

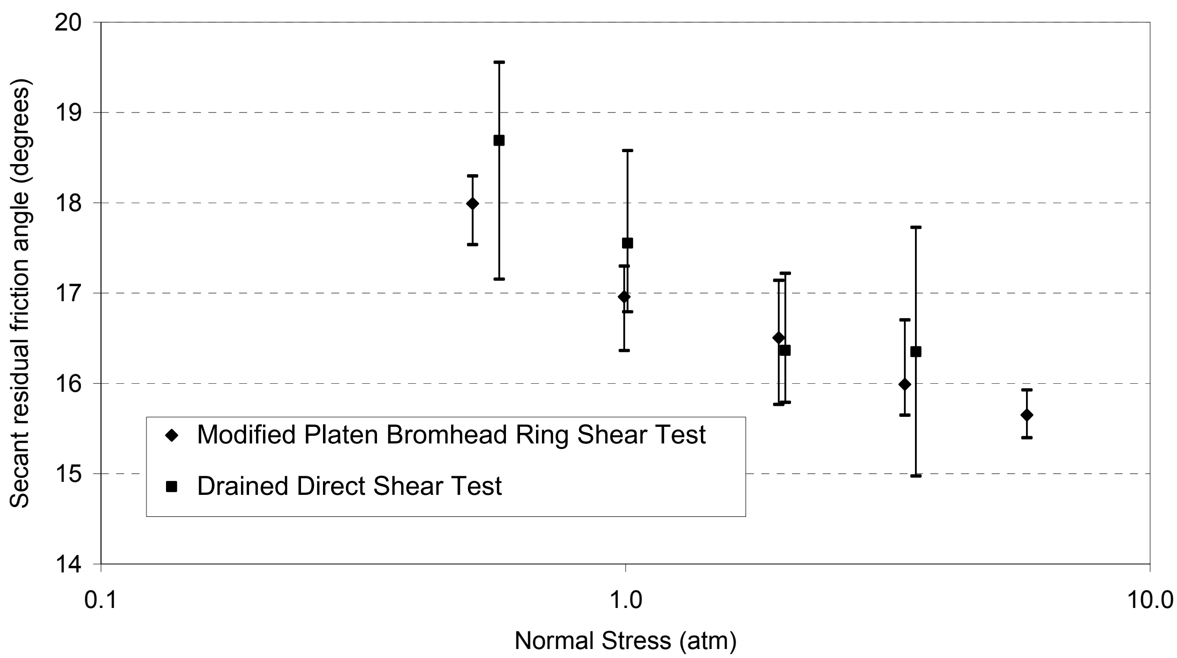

Figure 5-7. Comparison between Bromhead ring shear and direct shear test results for Rancho Solano Clay #1.

Drained Direct Shear Testing of Rancho Solano Clay #2

Direct shear tests were also used to measure the drained residual shear strength of Rancho Solano Clay #2. Specimens were prepared using the same “wet polish” method that had worked well for Rancho Solano Clay #1. The appearance of the Rancho Solano Clay #2 failure plane after wet polishing was indistinguishable from the Rancho Solano Clay #1 wet polished failure plane.

Two tests were performed, at an initial normal stress of 10.1 psi and a displacement rate of 0.000123 in/min. Data sheets for these direct shear tests are given in Appendix B. The friction ratio vs. displacement curves for these tests are shown in Figure 5-8. Figure 5-8 also shows the range of peak and residual friction ratios measured for Rancho Solano Clay #2 in the Bromhead ring shear device.

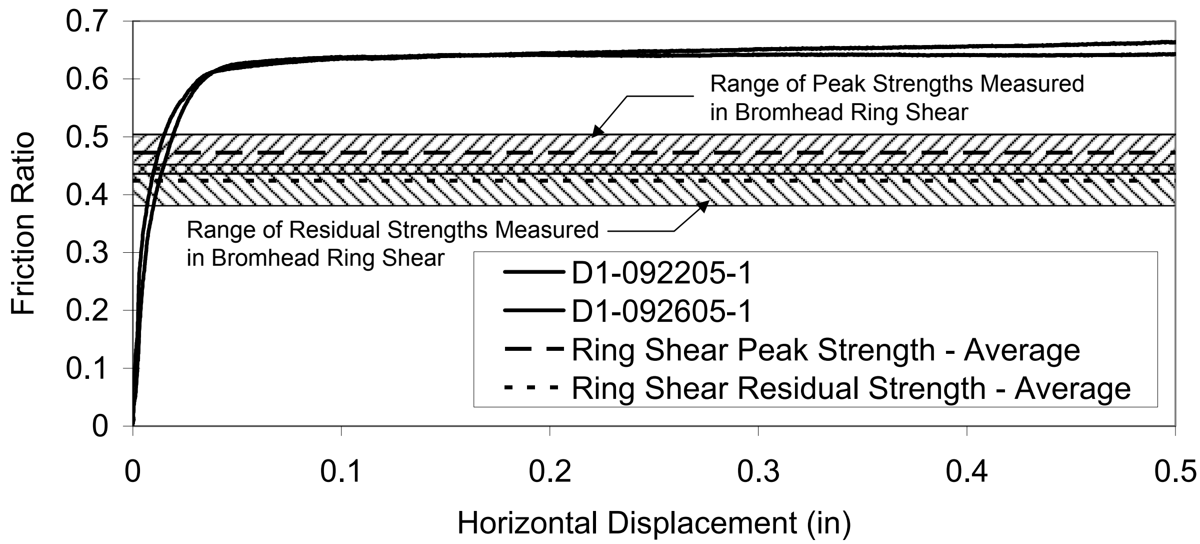

Figure 5-8. Comparison between Bromhead ring shear and "wet polish" direct shear test results for Rancho Solano Clay #2.

As shown in Figure 5-8, the shape of a typical friction ratio vs. displacement curve for Rancho Solano Clay #2 is significantly different than the curve for Rancho Solano Clay #1 (shown in Figure 5-5). Even more significant is the fact that the measured residual friction angle does not agree with the residual strength from the Bromhead ring shear device. The magnitude of this difference is quite large: 32.5° for the direct shear tests, as compared with 22.8° for the ring shear tests.

It was hypothesized that the use of a wet polishing method might have stripped fine particles from the pre-formed shearing plane in Rancho Solano Clay #2, effectively changing the grain size distribution at the shear interface. Such a change would alter the shear behavior of the soil, causing it to behave more like a silt or fine sand when sheared. This could explain why the residual friction angles are unusually high, and why the curve is shaped differently than what was observed for Rancho Solano Clay #1. It is not clear why wet polishing might have had this effect on Rancho Solano Clay #2, and why it did not have a similar effect on Rancho Solano Clay #1.

To explore this hypothesis, a series of direct shear tests were conducted on Rancho Solano Clay #2, using two different "dry" polishing methods. Using these methods, direct shear specimens were consolidated and wire-cut using the same approach that was used for the "wet" polish tests. The wire-cut test specimens were then polished on dry Teflon and dry glass surfaces, to orient the clay particles in the direction of shear.

For the dry Teflon polish method, a specimen half was polished by shearing it along the entire length of a dry 24-inch Teflon sheet under moderate hand pressure. A total of ten passes along the Teflon sheet were performed for each half of the test specimen. Figure 5-9 shows the dry Teflon polishing process, and the resulting slickensided failure plane.

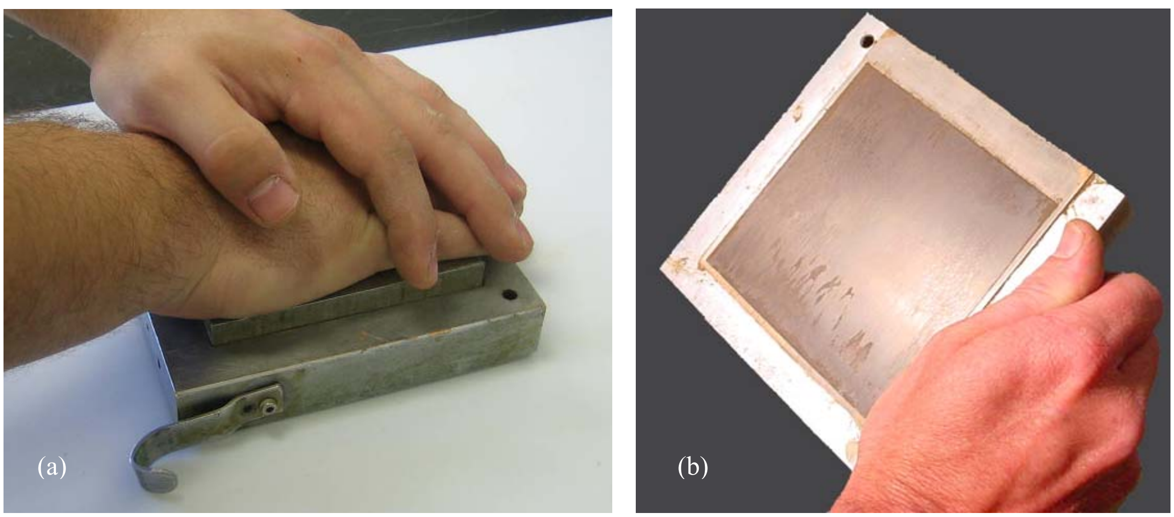

Figure 5-9. The dry Teflon polishing process; (a) rubbing the cut plane on dry Teflon to form slickensides, (b) the slickensided failure plane.

For the dry glass polish method, a specimen half was polished by shearing it along the entire length of a dry 12-inch frosted glass plate under moderate hand pressure. A total of ten passes along the glass were performed for each half of the test specimen. Figure 5-10 shows the dry glass polishing process, and the resulting slickensided failure plane. Note that the glass-polished specimen does not appear as slickensided as the specimen that was prepared using the dry Teflon polishing process.

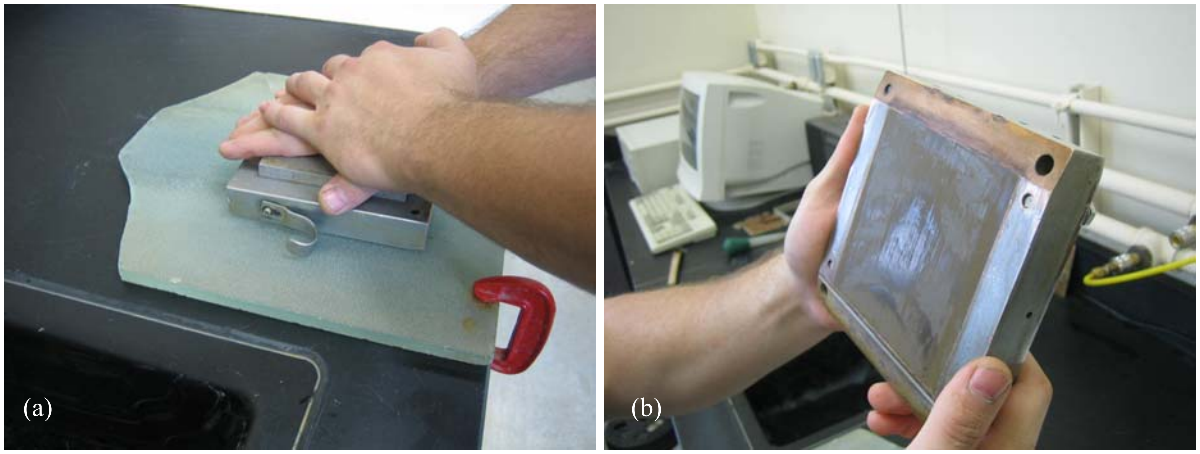

Figure 5-10. The dry glass polishing process; (a) rubbing the cut plane on dry glass to form slickensides, (b) the slickensided failure plane.

Dry polish direct shear tests were performed at an initial normal stress of 10.1 psi and a displacement rate of 0.000123 in/min. Data sheets for these direct shear tests are given in Appendix B. The friction ratio vs. displacement curves for these tests are shown in Figure 5-11. Figure 5-11 also shows the friction ratio that corresponds to the residual shear strength measured in the Bromhead ring shear device.

As shown in Figure 5-11, the dry polish method yields residual strengths for Rancho Solano Clay #2 that are <u>lower</u> than those measured in the Bromhead ring shear device – 11.8º to 12.3º for the direct shear tests, as compared with 22.8º for the ring shear tests. The shape of the friction ratio vs. displacement curves is more consistent with what was observed for Rancho Solano Clay #1 (shown in Figure 5-5). This supports the hypothesis that the wet polish method may have changed the grain size distribution on the shearing plane for Rancho Solano Clay #2. It is not clear why the residual strengths from dry polishing are so much lower than the ring shear residual strengths.

Additionally, as shown in Figure 5-11, the increase in strength that occurs as the specimen is sheared to large displacements is more pronounced for the specimen that was dry polished on Teflon than for the specimen that was dry polished on glass. This increase in strength is believed to be a testing artifact that was caused by slight misalignment of the preformed failure plane with the gap between the two halves of the direct shear box. The difficulty of aligning preformed shear planes in the direct shear device is consistent with what was observed by Skempton and Petley (1967). Good agreement was observed between the residual strengths measured in dry polish tests on Teflon and glass, despite the difference in behavior at large shear displacements.

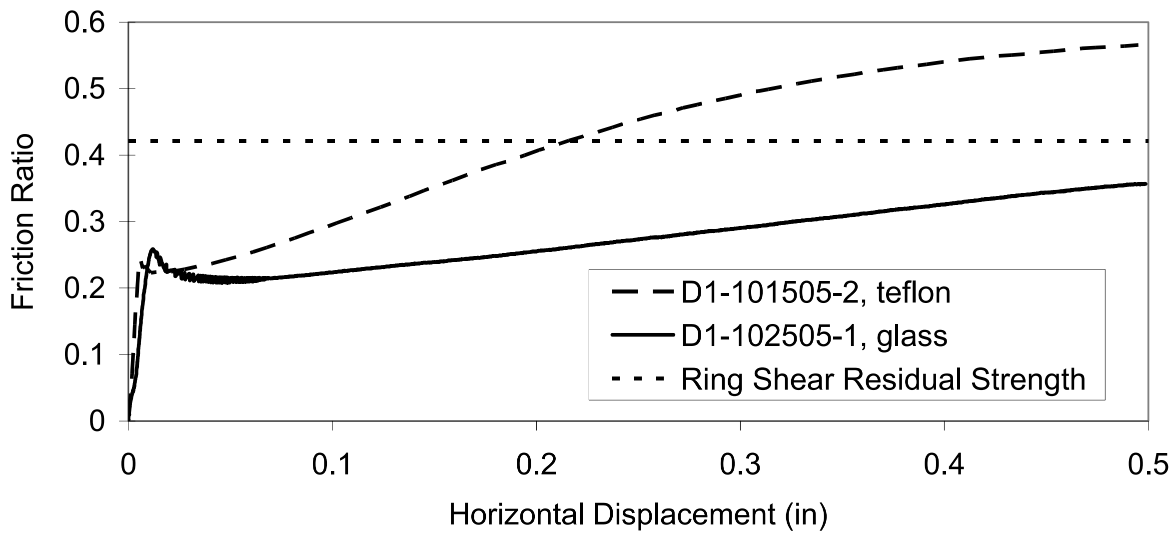

Figure 5-11. Comparison between Bromhead ring shear and "dry polish" direct shear test results for Rancho Solano Clay #2.

For Rancho Solano Clay #2, neither wet nor dry polishing techniques gave direct shear test results that agreed with the residual strengths measured in the Bromhead ring shear device. This result is unsatisfactory, and further research is necessary to identify why the direct shear test results deviated so significantly from the ring shear test results. Until the reason for this deviation is more clearly identified, the use of artificially prepared slickensides is not recommended for use in geotechnical engineering practice.

Drained Direct Shear Testing of San Francisco Bay Mud

Direct shear tests were also used to measure the drained residual shear strength of San Francisco Bay Mud. Specimens were prepared using the glass "wet polish" method and the Teflon and glass "dry polish" methods that were used to test Rancho Solano Clay #2. Figure 5-12 shows the appearance of the polished failure planes for three different test specimens.

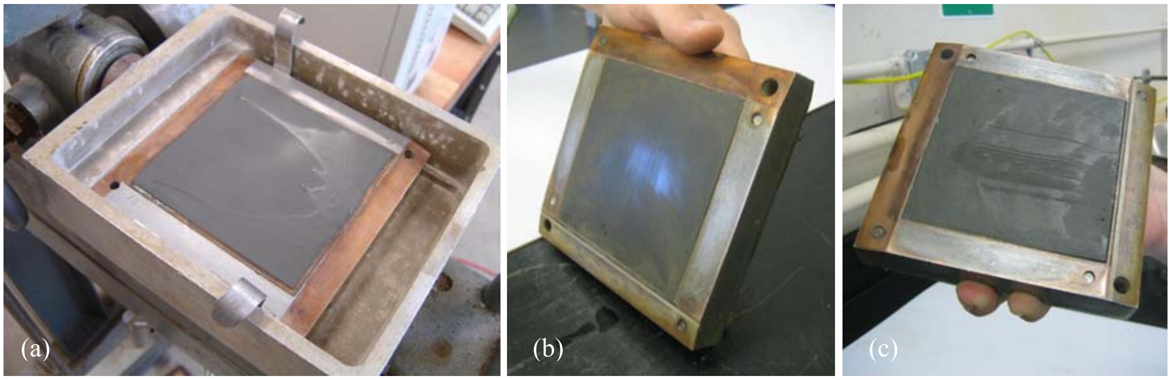

Figure 5-12. Appearance of slickensided failure planes in San Francisco Bay Mud after: (a) wet polishing on glass, (b) dry polishing on Teflon, and (c) dry polishing on glass.

Three direct shear tests were performed, at an initial normal stress of 14.9 psi and a displacement rate of 0.000123 in/min. Data sheets for these direct shear tests are given in Appendix B. The friction ratio vs. displacement curve for the "wet polish" test is shown in Figure 5-13. The friction ratio vs. displacement curves for the two "dry polish" tests are shown in Figure 5-14. Figures 5-13 and 5-14 also show the friction ratio that corresponds to the residual shear strength measured in the Bromhead ring shear device.

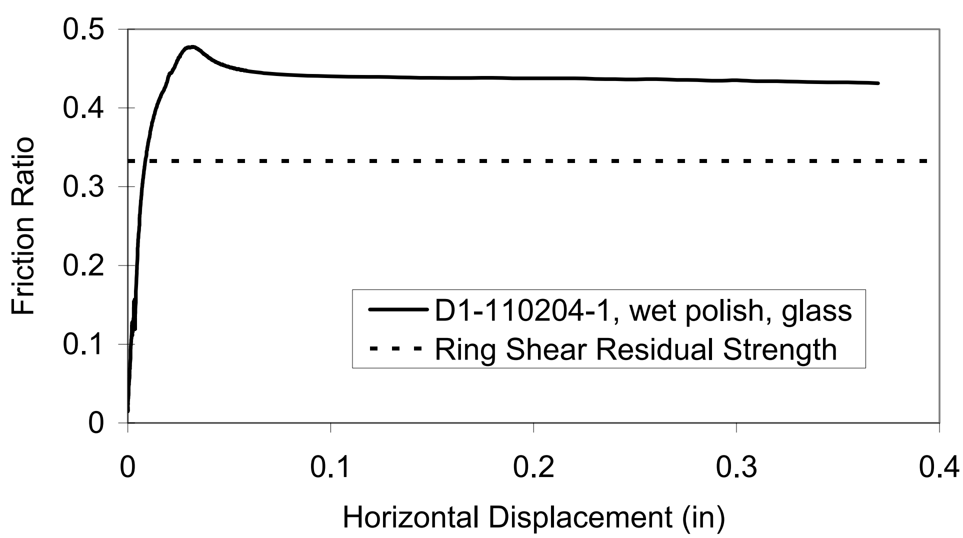

Figure 5-13. "Wet polish" direct shear testing on San Francisco Bay Mud.

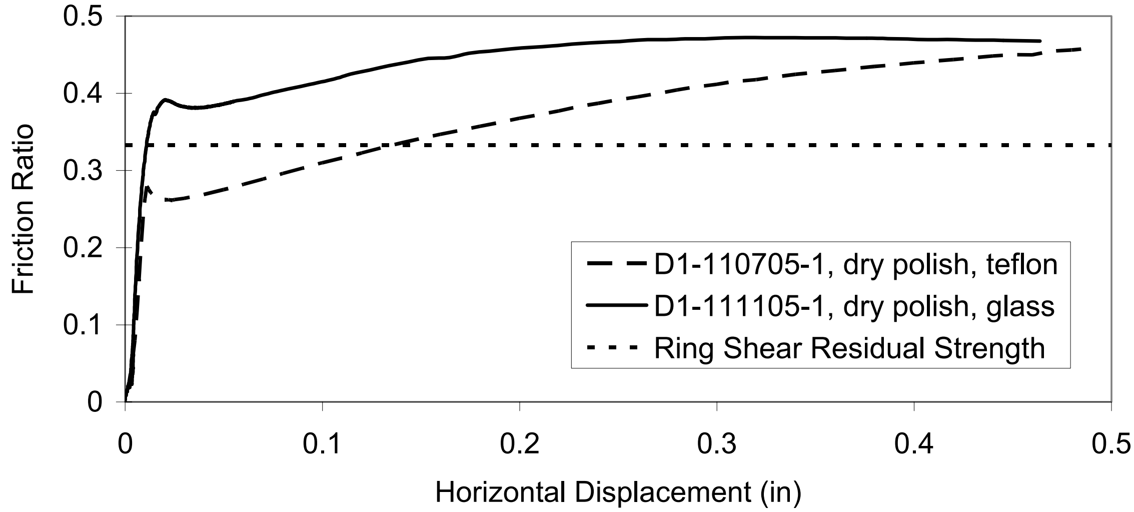

Figure 5-14. "Dry polish" direct shear testing on San Francisco Bay Mud.

As shown in Figure 5-13, the residual strength measured for the glass "wet polish" direct shear tests is higher than the residual strength measured in the Bromhead ring shear device – 23.3º for the direct shear tests, as compared with 18.4º for the ring shear tests. It is believed that this increased strength is due to a change in the grain size distribution of the soil along the shear interface, brought about by the use of a wet preparation process that strips clay fines from the shear interface during polishing. This mechanism is the same as the one used to explain the increased strengths measured for wet polished Rancho Solano Clay #2. The increase in strength of the wet polished San Francisco Bay Mud over the ring shear residual strengths is not as pronounced as what was observed for Rancho Solano Clay #2.

As shown in Figure 5-14, the Teflon dry polish method yields residual strengths for San Francisco Bay Mud that are lower than those measured in the Bromhead ring shear device – 14.7º for the direct shear tests, as compared with 18.4º for the ring shear tests. As was observed in Teflon dry polish tests on Rancho Solano Clay #2, the cause of this low strength value is unknown. It is believed that the Teflon dry polishing process somehow fundamentally alters the nature of the shear interface, either by causing changes in the physio-chemical interaction between clay particles or by increasing the amount of clay particles along the shearing interface.

The glass dry polish method yields residual strengths for San Francisco Bay Mud that are higher than those measured in the Bromhead ring shear device – 20.9º for the direct shear tests, as compared with 18.4º for the ring shear tests. This increased value of strength was likely caused by adhesion of the Bay Mud particles to the glass polishing plate, which resulted in an extremely poor quality polish along the prepared shearing plane. Visually, glass dry-polished San Francisco Bay Mud specimens appear the least slickensided of all the soil and polishing interface combinations that were tested.

<u>Triaxial Testing of Preformed Slickensided Surfaces</u>

In addition to the drained direct shear tests described in the previous sections, a series of triaxial tests were also performed to measure the drained residual shear strength along pre-formed slickensided failure surfaces. These tests were performed at Virginia Tech by Dr. Binod Tiwari, who has significant experience with soil laboratory testing. Dr. Tiwari has encountered significant obstacles during the triaxial testing program, including:

- Difficulties with the effect of end platen restraint on specimens that fail along a well-defined failure plane,
- Uncertainties involving the appropriate area correction and membrane correction to use when reducing the triaxial data, and
- Long test times for consolidated-drained triaxial tests, which has tied up equipment and made it difficult to run the desired number of triaxial tests in a timely fashion.

As a result of these challenges and uncertainties, it has proven far more difficult to use triaxial tests than direct shear tests to measure the shear strength along pre-formed slickensided discontinuities. Because of the difficulties encountered, the triaxial test is not recommended for future testing of this type.

Because of the uncertainty surrounding the triaxial test results at this time, useful conclusions cannot be drawn from the triaxial test data regarding the residual strength behavior of pre-formed slickensided surfaces. Consequently, the results from Dr. Tiwari's triaxial testing program are not included in this dissertation. Dr. Tiwari plans to continue triaxial testing.

<u>Discussion of Experience with Laboratory Testing of Preformed Slickensided Surfaces</u>

At the beginning of this research project, it was envisioned that is would be a straightforward process to measure the residual strengths along preformed slickensided surfaces using traditional direct shear and triaxial testing equipment. This assumption was based on previous research performed by Skempton (1964), Chandler (1966), and Skempton and Petley (1967). The potential payoff to this approach was that it would allow geotechnical practitioners to simulate earthquake loading along slickensided surfaces using simple test equipment available in most geotechnical laboratories. However, in order to measure accurate dynamic strengths along preformed slickensided surfaces, it is essential to first establish a laboratory method for preparing slickensided surfaces that behave like those formed in the field.

As is evident from the discussion in the previous sections, it was found to be significantly more difficult than anticipated to prepare slickensided surfaces that exhibited the expected drained residual strength behavior. Table 5-3 shows how the results from the drained direct shear testing program compare with the residual strength values measured in the Bromhead ring shear device.

Table 5-3: Comparison of Drained Direct Shear Test Results with Bromhead Ring Shear Test Results for Different Polishing Methods

Soil	Wet polishing on glass	Dry polishing on Teflon	Dry polishing on glass
Rancho Solano Clay #1	Excellent agreement between Direct Shear and Bromhead Ring Shear	Not performed	Not performed
Rancho Solano Clay #2	Direct Shear 43% Higher than Bromhead Ring Shear	Direct Shear 46% Lower than Bromhead Ring Shear	Direct Shear 48% Lower than Bromhead Ring Shear
San Francisco Bay Mud	Direct Shear 27% Higher than Bromhead Ring Shear	Direct Shear 20% Lower than Bromhead Ring Shear	Direct Shear 14% Higher than Bromhead Ring Shear

As shown in Table 5-3, the effectiveness of a given polishing technique varied greatly for the three soils tested. Consistency was not obtained between different soils for any of the polishing methods explored in this study. The polishing approach that worked well for Rancho Solano Clay #1 did not work at all for Rancho Solano Clay #2, despite the fact that the soils are from the same area and are quite similar. Because the test results were so sensitive to soil type and to the polishing process used, a single method for preparing slickensided surfaces in the laboratory could not be identified. Consequently, the use of artificially prepared slickensides is not recommended for use in geotechnical engineering practice.

For research purposes, it is possible to form slickensided surfaces in the laboratory that behave similarly to those created by soil-on-soil shearing processes (as illustrated by the Rancho Solano Clay #1 test results). When a polishing process is used to prepare slickensides, the effectiveness of the preparation method should be confirmed by comparison with Bromhead ring shear strength test results. It is recommended that a number of tests be performed for this purpose, to explore the sensitivity of the measured strengths to the preparation method for the soil being studied.

As shown in Table 5-3, Rancho Solano Clay #1 was the only soil that gave drained strengths that compared consistently well with those measured in the Bromhead ring shear device. As a result, fast direct shear and cyclic direct shear tests were only performed on wet polished Rancho Solano Clay #1 specimens.

Fast Direct Shear Testing of Rancho Solano Clay #1

Fast direct shear tests were performed on Rancho Solano Clay #1 test specimens to explore the effect of loading rate on the shear behavior along slickensided discontinuities. Test specimens were prepared using the "wet polish" preparation method, which forms slickensides that behave similarly to those formed by soil-on-soil shear.

Four strain-controlled direct shear tests were performed at a displacement rate of 0.048 in/min, which is the maximum loading rate that can be applied in the Wykeham-Farrance direct shear device. Two test specimens were tested at a normal stress of 14.5 psi and two were tested at 28.8 psi. Data sheets for these direct shear tests are given in Appendix

B. The friction ratio vs. displacement curves for the 14.5 psi normal stress tests are shown in Figure 5-15. The friction ratio vs. displacement curves for the 28.8 psi normal stress tests are shown in Figure 5-16. For comparison purposes, Figures 5-15 and 5-16 also show friction ratio curves measured in slow direct shear tests.

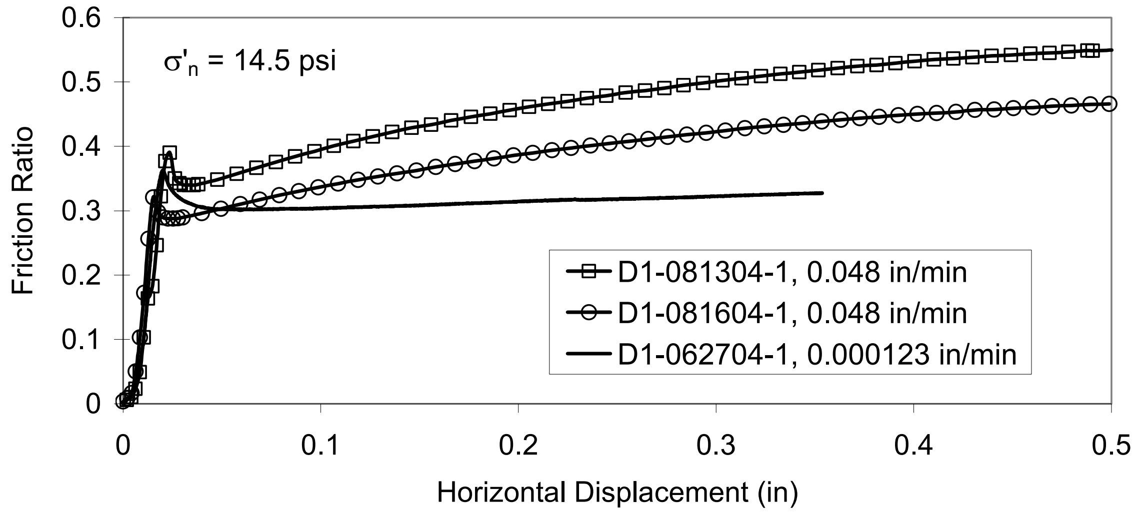

Figure 5-15. Comparison between fast and slow direct shear tests conducted on Rancho Solano Clay #1 at a normal stress of 14.5 psi.

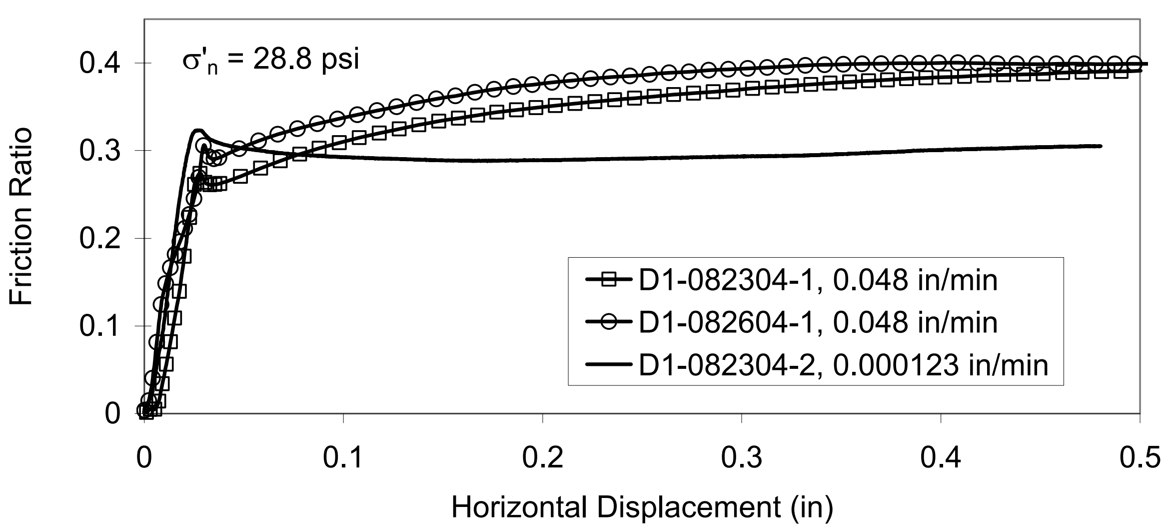

Figure 5-16. Comparison between fast and slow direct shear tests conducted on Rancho Solano Clay #1 at a normal stress of 28.8 psi.

As shown in Figures 5-15 and 5-16, fast direct shear tests exhibit different behavior than drained direct shear tests. Initially, there is an increase in shear resistance, possibly due to a "healing" effect on the shear plane. The shear resistance then drops to a post-peak minimum value, which can be considered the "fast residual strength" for the soil. Upon additional shearing, there is a significant increase in shear resistance that continues throughout the remainder of the test.

The initial peak shearing resistances from the fast direct shear tests were equal to or slightly lower than the peak shear resistances observed in the drained direct shear tests. The fast residual strengths varied significantly, coming in both lower and higher than the residual strengths measured in the drained direct shear tests. Consequently, the results do not show conclusively how the residual strength changed as the loading rate was increased from 0.000123 in/min to 0.048 in/min.

The increase in mobilized shear resistance that occurred after the fast residual strength is likely due to a combination of soil strengthening and machine effects in the direct shear device. Skempton (1985) reported an increase in residual strength of 2.5% per log cycle increase in strain rate, so it is reasonable to expect an approximately 6% increase in shear resistance as the displacement rate is increased from 0.000123 in/min to 0.048 in/min. Additionally, it is possible that the increased loading rate led to disturbance of the smoothly polished failure plane, which caused a corresponding increase in measured shear resistance that became more pronounced with increased displacement (Lemos et al., 1985; Skempton, 1985; Tika et al., 1996). This effect is likely minimal however, as the aforementioned researchers have reported that this increase typically does not become pronounced until displacement rates on the order of 0.4 in/min to 4 in/min.

It is likely that a large portion of the increased shearing resistance that occurs past the fast residual strength is due to machine effects in the direct shear device. Frictional forces between the shear boxes and soil extrusion caused saddle-shaped curves in the slow direct shear tests, and it is likely that their effect was more pronounced during the fast shear tests. Additionally, as shown in Figure 5-11, slight misalignments of the preformed shearing plane in the direct shear box can cause a significant increase in the mobilized shear resistance at large displacements.

Cyclic Direct Shear Testing of Rancho Solano Clay #1

Cyclic direct shear tests were performed on Rancho Solano Clay #1 test specimens to examine the behavior of slickensided rupture surfaces under cyclic loading conditions. Test specimens were prepared using the "wet polish" preparation method, which forms slickensides that behave similarly to those formed by soil-on-soil shear.

Eight stress-controlled cyclic loading direct shear tests were performed in the cyclic direct shear device at Virginia Tech. Specimens were tested at a normal stress of 14.9 psi and a cyclic load frequency of 0.5 Hz. Data sheets for the cyclic direct shear tests are given in Appendix B.

Prior to application of the cyclic loading, specimens were subjected to a static shear stress in the direct shear device. This allowed cyclic loading to be applied around a sustained static stress, which mimics the state of stress mobilization that exists in a slope in the field. A target static shear stress ratio of 0.2 was used for these tests, which corresponds to approximately 60% of the drained residual shear strength. Table 5-4 lists the applied static load for each test and the resulting displacement.

Table 5-4: Applied Static Load and Resulting Displacement for the Cyclic Direct Shear Tests

Test Number	$\tau_{static}/\sigma'_{fc}$	Displacement Upon Load Application
D2-040805-1	0.21	0.0015
D2-042905-1	0.22	0.001
D2-062105-1	0.19	0.0017
D2-062705-1	0.20	0.0018
D2-062805-1	0.21	0.001
D2-090105-1	0.19	0.001
D2-092705-1	0.24	0.0026
D2-092905-1	0.17	0.0011

As shown in Table 5-4, only a very small amount of displacement occurred upon application of the static load.

After each specimen had come to equilibrium under the applied static load, cyclic loading was applied. Each specimen was subjected to 500 constant-amplitude sinusoidal stress pulses, with a cyclic load frequency of 0.5 Hz. A plot of applied shear stress vs. time for cyclic direct shear test D2-090105-1 is shown in Figure 5-17. A close-up view of the applied shear stress pulses for test D2-090105-1 is shown in Figure 5-18. The resulting horizontal and vertical displacements for test D2-090105-1 are shown in Figure 5-19.

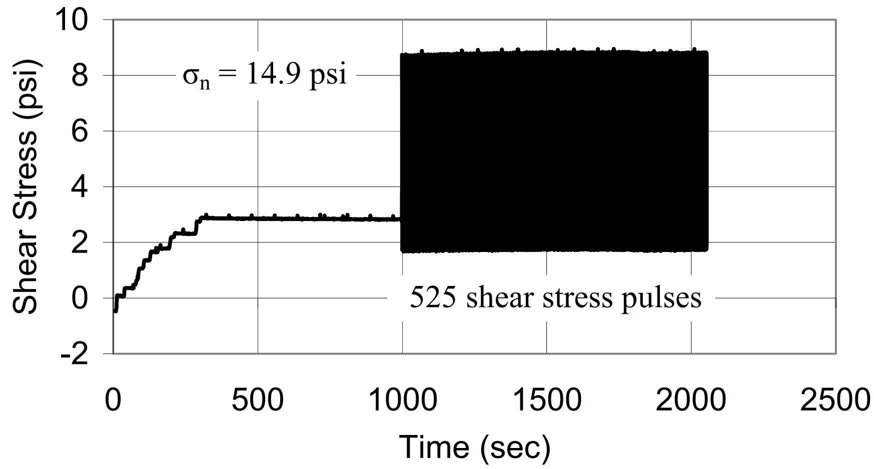

Figure 5-17. Applied shear stress vs. time for cyclic direct shear test D2-090105-1.

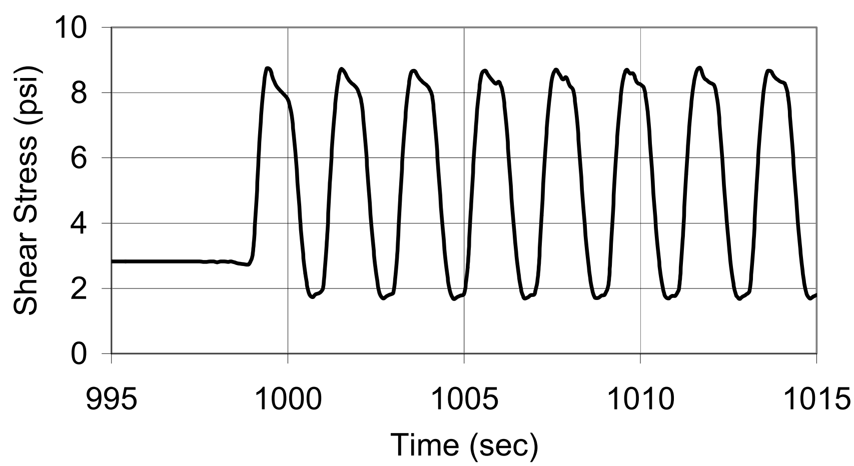

Figure 5-18. Shape of shear stress load pulses for test D2-090105-1.

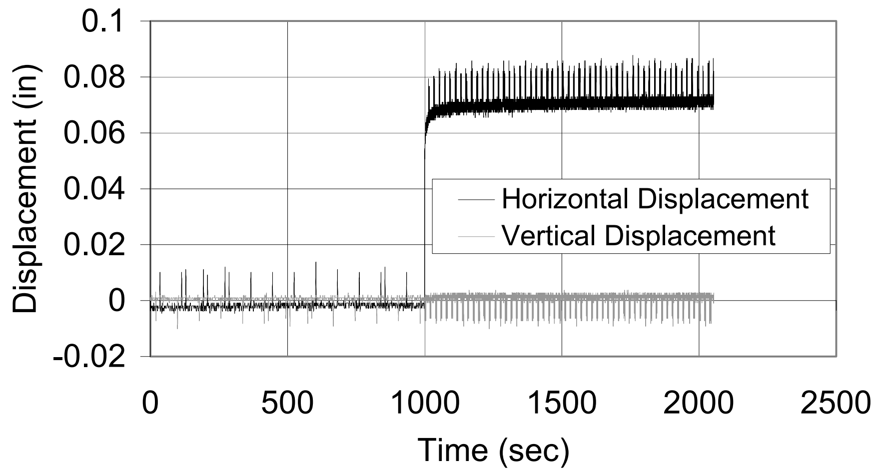

Figure 5-19. Measured horizontal and vertical displacement for test D2-090105-1.

As shown in Figures 5-17 and 5-18, the applied cyclic load was not always symmetric about the static load. This was due to limitations of the stress application system, which made it difficult to apply the desired loading to the specimen consistently. These device stress-control problems were not addressed because the solution was costly, and because the effect of the unsymmetric loading on the test results was believed to be second-order.

As shown in Figure 5-19, there was significant electrical noise in the recorded horizontal and vertical LVDT data. This noise was introduced by the data acquisition system, appearing as periodic spikes in the recorded displacement values. Because caution was taken when analyzing and interpreting test results, this electrical noise is believed to have no effect on the interpreted test results. The electrical noise problems with the data acquisition system were not addressed because the solution was costly and because it was still possible to interpret the tests results with good accuracy.

Data from the cyclic direct shear tests were analyzed by plotting the applied shear stress ratio vs. displacement. A plot of shear stress ratio vs. displacement for test D2-090105-1 is shown in Figure 5-20. Shear stress ratios in the cyclic direct shear device were calculated using the following equation:

$$\text{Shear Stress Ratio} = \frac{\text{Shear Stress on the Slip Plane}}{\text{Initial Effective Normal Stress on the Slip Plane}} \qquad (5\text{-}5)$$

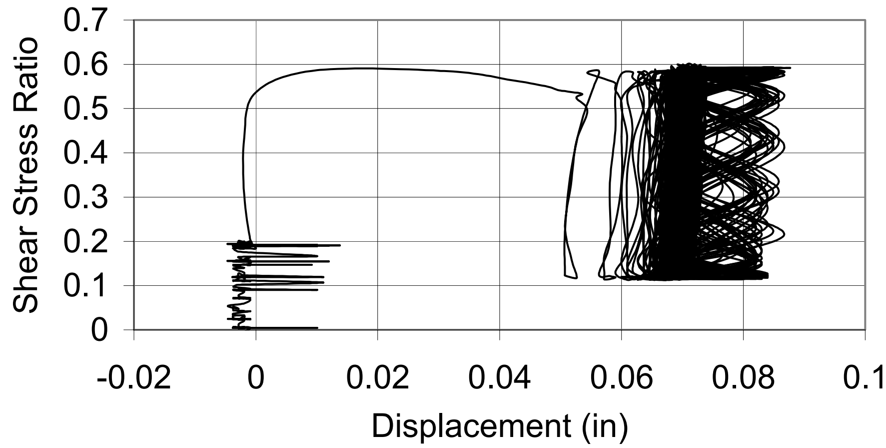

Figure 5-20. Shear stress ratio vs. displacement for test D2-090105-1.

As shown in Figure 5-20, most of the displacement that occurred during test D2-090105-1 happened in the first few pulses. As shear displacement occurred on the slickensided plane, the specimen exhibited displacement hardening, with smaller and smaller amounts of displacement observed for each consecutive pulse. (The apparent increases in horizontal displacement of approximately 0.012 inches during the first cycle and any pulses observed beyond 0.073 inches are due to electrical noise.) Table 5-5 lists the cyclic shear stress ratio and the cumulative displacements recorded as a function of the number of applied stress cycles for each test. Figure 5-21 is a plot of the values listed in Table 5-5, with a hatched zone drawn between the upper and lower bounds of the measured data. Figure 5-21 also plots the stress ratio vs. displacement from test D1-062704-1, a drained direct shear test.

Table 5-5: Applied Shear Stress Ratio and Resulting Displacement During Cyclic Loading

Test Number	τ_{peak}/σ'_{fc}	1 Cycle	2 Cycles	3 Cycles	5 Cycles	10 Cycles	100 Cycles	500 Cycles
D2-040805-1	0.52	0.0443	0.0489	0.0508	0.0526	0.0563	0.0646	0.0655
D2-042905-1	0.64	0.0378	0.0425	0.0452	0.0471	0.0489	0.0563	0.0591
D2-062105-1	0.30	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017	0.0017
D2-062705-1	0.31	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018	0.0018
D2-062805-1	0.38	0.001	0.001	0.001	0.001	0.001	0.002	0.003
D2-090105-1	0.58	0.0507	0.0572	0.0609	0.0618	0.0655	0.0683	0.0701
D2-092705-1	0.63	0.0839	0.095	0.0996	0.1061	0.1116	0.1292	0.1347
D2-092905-1	0.66	0.1375	0.1625	0.1726	0.1818	0.1911	0.216	0.2243

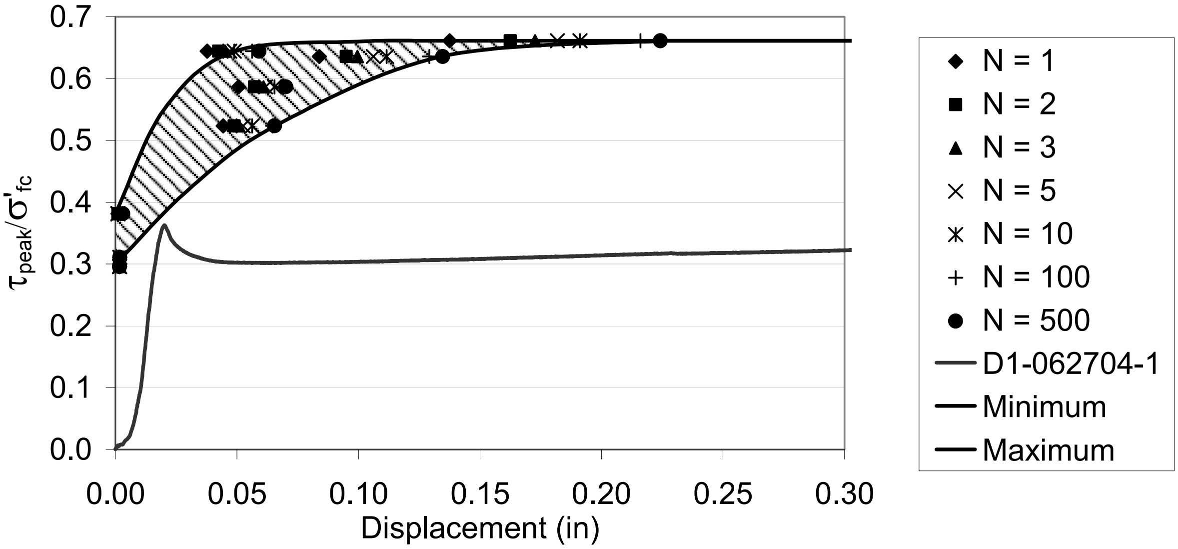

Figure 5-21. Approximate relationship between peak shear stress ratio and displacement for cyclic direct shear tests on Rancho Solano Clay #1.

From this data, it is clear that there is a relationship between the applied cyclic shear stress ratio and the resulting displacement during the test. When cyclic loads with a peak shear stress ratio less than 0.4 are applied, no displacement occurs. Some displacement occurs when cyclic loads with a peak shear stress ratio greater than 0.5 are applied and more significant displacements are observed at cyclic stress ratios above 0.6.

As shown in Figure 5-21, the relationship between peak shear stress ratio and displacement becomes asymptotic at a shear stress ratio of 0.66. At this value, large displacements are observed in the first few pulses, and displacement hardening is not effective at slowing the accumulation of displacement. From this data, a shear strength ratio of 0.66 was chosen as the cyclic strength for Rancho Solano Clay #1. This strength ratio corresponds to sinusoidal cyclic loading conditions imposed at a frequency of 0.5 Hz. This cyclic strength is 2.2 times higher than the drained shear strength mobilized along slickensided surfaces in Rancho Solano Clay #1 during slow loading. Consequently, it would be excessively conservative to use drained residual strengths for dynamic analyses of slickensided slopes in Rancho Solano Clay #1.