Landslides (2010) 7:157–167
DOI 10.1007/s10346-010-0199-7
Received: 10 September 2009
Accepted: 12 January 2010
Published online: 13 February 2010

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Direct shear testing of polished slickensided surfaces

Abstract A series of ring shear and direct shear tests were performed to measure the drained residual strength of three clay soils. For each of the soils, slickensided direct shear specimens were prepared by wire-cutting intact specimens, and polishing the resulting shear plane on a variety of surfaces to align the clay particles in the direction of shear. Drained direct shear tests were then conducted on each of the polished specimens. The resulting shear strengths were compared with the residual strengths measured in the ring shear device to evaluate the effectiveness of the different polishing techniques for creating slickensided surfaces. Test results indicated that the measurement of residual strengths along preformed slickensided surfaces is extremely sensitive to both the soil type and the slickenside preparation technique that is used. Consequently, this approach does not appear to be a viable alternative to conventional repeated direct shear or ring shear tests to measure residual shear strengths.

Keywords Direct shear tests · Torsion · Clay · Residual strength · Shear strength · Laboratory test

Introduction

Torsional ring shear tests have become the preferred method for measuring the residual shear strength of clayey soils (Duncan and Wright 2005). In the torsional ring shear test, a thin, annular soil specimen is subjected to slow, displacement-controlled shearing under a constant normal stress (Hvorslev 1939; La Gatta 1970; Bishop et al. 1971; Bromhead 1979). As shearing progresses, plate-like clay particles along the shear plane become oriented in the direction of shear, forming *slickensided* shear surfaces (e.g., Bishop et al. 1971; Duncan and Wright 2005).

The drained shear resistance that can be mobilized along a slickensided surface is the lowest strength that can be measured for a clay soil (Skempton 1964). The amount of shear resistance that can be developed is controlled by the mineralogical composition of the clay particles, the chemical state of the pore fluid, and the clay fraction that is present in the soil matrix (e.g., Kenney 1977; Lupini et al. 1981; Tiwari and Marui 2005). Additional research has shown that measurements of the residual friction angle are unaffected by the initial structure of the soil (Bishop et al. 1971). Consequently, residual strength values correlate well with intrinsic soil properties, such as clay fraction or Atterberg limits (e.g., Lupini et al. 1981; Stark and Eid 1994; Tiwari and Marui 2005). Residual strengths have been shown to be of great significance for landslide triggering and post-landslide stability in many clay slopes; the morphology of the shear surface along which the residual strength is mobilized has also been shown to play a significant role in landslide stability (e.g., Skempton and Petley 1967; Skempton 1985).

Currently, due to cost limitations and equipment availability, many testing laboratories use reversal direct shear tests (USACE 1986) in place of torsional ring shear tests to determine the residual strength of clayey soils. Residual strengths measured using the reversal direct shear test are usually higher than those measured in the ring shear device (e.g., Bishop et al. 1971; Stark and Eid 1992). The torsional ring shear test is preferred over the direct shear apparatus for measuring the residual shear strength of soils because the ring shear device can apply unlimited shear displacement without reversal in the direction of shear or change in the principal stress orientations (e.g., Duncan and Wright 2005).

Development of a simple method for artificially creating slickensided surfaces would be beneficial to geotechnical practitioners because it would allow residual strength testing to be performed using existing direct shear test equipment at little to no additional equipment cost.

Towards this goal, as part of a larger project examining the static and dynamic shear behavior of slickensided surfaces (Meehan 2006), a ring shear and direct shear testing program was undertaken to develop a method for artificially creating slickensided surfaces in the laboratory. A series of ring shear tests were performed on three clay soils to develop a baseline measurement of drained residual strength for each soil. For each of the soils, specimen cutting and polishing techniques were used to create slickensided failure surfaces in direct shear specimens. The residual strengths measured along the prepared slickensided surfaces were compared with the ring shear test results to evaluate the effectiveness of the slickenside preparation techniques.

Soil properties

The ring shear and direct shear tests described in this paper were performed on three different natural clay soils. Two of the soils were obtained from the Rancho Solano residential development in Fairfield, California. The third soil is San Francisco Bay Mud, which was obtained from Hamilton Air Force Base in California. The soils were batch-mixed at water contents ranging from 1.0 to 1.2 times their liquid limits to ensure uniformity. The clay slurries were then passed through a #40 sieve to remove larger soil particles that could interfere with operation of the Bromhead ring shear device (in accordance with ASTM D 6467-99 (1999)).

Index tests on the resulting slurries yielded the soil properties given in Table 1. Grain size curves for each of these soils are given in Fig. 1.

Drained ring shear testing

The ring shear tests described in this paper were performed using two Bromhead ring shear devices 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

Table 1 Rancho Solano Clay and San Francisco Bay Mud index properties

Clay	USCS classification	LL	PL	PI	Clay fraction[a]	Specific gravity
Rancho Solano Fat Clay	Fat Clay (CH)	61	25	36	53	2.65
Rancho Solano Lean Clay	Lean Clay (CL) with sand	41	19	22	27	2.79
San Francisco Bay Mud	Elastic Silt (MH)	85	38	47	47	2.70

[a] Clay fraction determined as the percentage of grains smaller than 0.002 mm

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, significant wall friction does not develop even if considerable top platen intrusion into the specimen container occurs during a test.

To further minimize the effect of wall friction, specimens were prepared and tested using a "single-stage" test procedure, which is described in more detail in the following paragraphs. Data supporting the effectiveness of the "single-stage, modified platen" test approach for reducing the effect of wall friction in the Bromhead ring shear device is provided in Meehan et al. (2007).

Prior to specimen placement in the ring shear device, the water content of test specimens was reduced by consolidating remolded test specimens in a batch consolidometer to a normal stress of 345 kPa. This decreased the total amount of specimen consolidation that occurred during the ring shear test, which reduced testing time and minimized intrusion of the top platen into the specimen container.

To begin each test, the processed clay 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 creating the test specimen, 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 dead-weight 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 was begun. In order to minimize shear-induced pore water pressures, slow-shear displacement rates were selected using the following equation (from ASTM D 6467-99 (1999)):

$$\text{Displacement rate} = \frac{\text{displacement at failure}}{\text{time to failure}} = \frac{2.5\,\text{mm (CL) or } 5\,\text{mm (MH or CH)}}{50 \times t_{50}} \qquad (1)$$

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 for each clay, a conservative displacement rate of 0.018 mm/min was used for testing. This displacement rate is the lowest displacement rate that

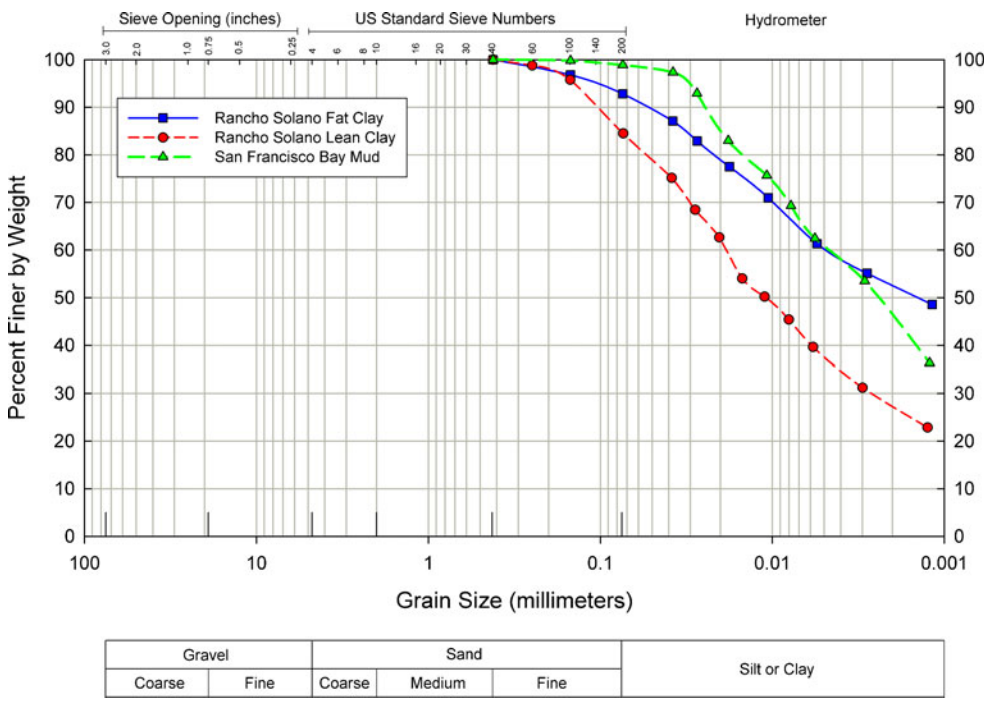

Fig. 1 Rancho Solano Clay and San Francisco Bay Mud grain size curves

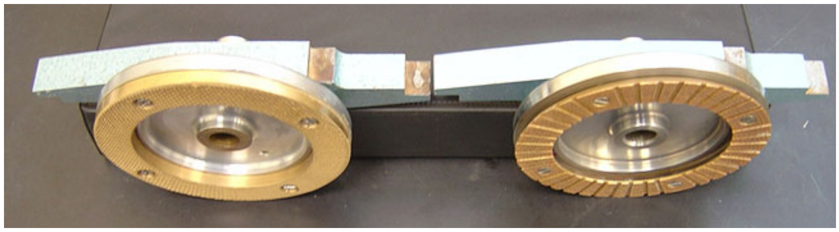

Fig. 2 Angle view that shows the difference between the original top platen (*on the left*) and the modified top platen (*on the right*)

can be applied by the Wykeham Farrance Bromhead ring shear device.

The measured residual strengths from a series of "single-stage, modified platen" ring shear tests on Rancho Solano Fat Clay, Rancho Solano Lean Clay, and San Francisco Bay Mud are shown in Tables 2, 3, and 4, respectively. As a number of tests were performed at each normal stress, it was useful (and more concise) to present the results after some statistical analysis. Multistage shearing of the specimens was not performed. By testing a new specimen at each normal stress, it was possible to avoid the effect of accumulated soil extrusion and top platen intrusion that occurs at the second and third normal stresses in a multistage test. A plot of average residual shear stress vs. normal stress and residual strength envelopes for the three soils is given in Fig. 3. The strength envelopes were developed by drawing smooth lines from the origin through the average residual shear stress values.

In Tables 2, 3, and 4, results from the Bromhead ring shear tests are also presented using the secant phi approach discussed by Skempton (1985). This approach assumes that there is no residual cohesion, which leads to the following formula for calculation of the secant residual friction angle:

$$\phi'_r = \tan^{-1}\left(\frac{\tau_r}{\sigma_N}\right) \quad (2)$$

A pot of average secant residual friction angle vs. normal stress for the three soils is given in Fig. 4. This data presentation approach is useful for illustrating the relative curvature of the residual strength failure envelope. For low normal stress tests, this data presentation approach is also useful for illustrating significant differences in residual friction angle that are often masked when data is presented using residual strength failure envelopes.

Previous research on preparation of direct shear and triaxial test specimens for measurement of residual strength

Preparation of direct shear and triaxial specimens for residual strength testing has been discussed by earlier researchers (e.g., Skempton 1964; Chandler 1966; Kenney 1967; Bromhead and Curtis 1983). These researchers recommend that overconsolidated clay specimens be wire cut to form a shear plane prior to the start of the test in order to concentrate shear displacement along a well-defined failure plane. This increases the likelihood that clay particles along the shear plane will become oriented in the direction of shear before the maximum permissible displacement is reached in the direct shear or triaxial device.

With this approach, in either test device, some shear displacement is still necessary to orient the clay particles in the direction of shear. To create a slickensided surface that is at its residual condition prior to the start of a test, Chandler (1966) recommended that pre-cut test specimens should be "polished" to orient the clay particles in the direction of shear, but the details of the polishing process were not specified.

Despite early research showing promise in this area, the use of pre-cut and polished direct shear or triaxial test specimens for measurement of residual strength never widely caught on. The reasons for this were unclear at the outset of this study. It was thought that adoption of reversal direct shear tests for measuring residual strength by the US Army Corps of Engineers (e.g., USACE 1986), and acceptance of the ring shear test as a superior residual strength test (e.g., Bishop et al. 1971; Stark and Eid 1992) caused this method to not be explored in further detail. However, this technique has the potential to produce better quality measurements of residual strength than the reversal direct shear test using commonly available test equipment, so the authors felt that it should be explored further. Additionally, these polishing techniques have the potential for use in broader research applications outside the realm of direct shear testing, such as undrained strength testing (Meehan 2006) or dynamic centrifuge testing (Meehan et al. 2008), which indicates that these techniques merit further study.

Drained direct shear testing of Rancho Solano Fat Clay

Direct shear tests can be used for measuring the shear strength along existing discontinuities in clayey soil (Skempton and Petley 1967). The direct shear device is well-suited to the measurement of shear strength along planar discontinuities because it forces shear to occur between the upper and lower shear boxes along a well-defined plane.

The goal of this research was to develop a method for creating slickensided surfaces in direct shear specimens in the laboratory,

Table 2 Residual shear strength data from "single-stage, modified platen" ring shear tests on Rancho Solano Fat Clay

σ_n (kPa)	No. tests performed	Avg. τ_r (kPa)	Stan. dev. τ_r (kPa)	Min. τ_r (kPa)	Max. τ_r (kPa)	Avg. ϕ'_r	Stan. dev. ϕ'_r	Min. ϕ'_r	Max. ϕ'_r
52	5	16.8	0.3	16.3	17.1	17.9°	0.3°	17.4°	18.2°
100	4	30.7	0.8	29.6	31.4	17.1°	0.4°	16.5°	17.4°
200	5	58.8	2.0	56.1	61.2	16.4°	0.5°	15.7°	17.0°
345	6	99.0	2.4	96.7	103.6	16.0°	0.4°	15.7°	16.7°
590	6	165.3	2.1	162.5	168.4	15.7°	0.2°	15.4°	15.9°

Table 3 Residual shear strength data from "single-stage, modified platen" ring shear tests on Rancho Solano Lean Clay

σ_n (kPa)	No. tests performed	Avg. τ_r (kPa)	Stan. dev. τ_r (kPa)	Min. τ_r (kPa)	Max. τ_r (kPa)	Avg. ϕ'_r	Stan. dev. ϕ'_r	Min. ϕ'_r	Max. ϕ'_r
52	9	22.8	2.0	19.5	24.9	23.6°	1.9°	20.6°	25.6°
100	3	40.1	1.7	38.7	42.1	21.8°	0.9°	21.0°	22.8°
200	1	73.2	N/A	N/A	N/A	20.1°	N/A	N/A	N/A
345	2	117.6	1.8	116.3	118.8	18.8°	0.3°	18.6°	19.0°

along which the residual strength of the soil can be measured. The measured residual strength can then be compared with the residual strength from the Bromhead ring shear tests, to evaluate the effectiveness of the slickenside preparation techniques.

Drained direct shear tests were performed using a displacement-controlled direct shear device built by Wykeham Farrance Engineering Ltd. This device tests square specimens, with side dimensions of 102 × 102 mm. Drained direct shear tests were conducted in general accord with the direct shear test method described in ASTM D 3080-98 (1999).

The three clays that were used in the direct shear testing program were first prepared as described in the "Soil Properties" section of this paper. The resulting clay slurries were consolidated to 345 kPa in a batch consolidometer to lower their water contents. Direct shear test specimens were created by pressing the clay from the batch consolidometer into the direct shear box and consolidating the clay to 690 kPa to stiffen it for easier slickenside formation. This second consolidation process ensured creation of more uniform direct shear test specimens, as reconsolidation in the direct shear box brought the clay specimens back to the virgin consolidation curve, forming test specimens that had similar void ratios.

The method of pre-consolidating large batches of the clay prior to individual specimen formation in the direct shear box was chosen because it significantly reduced the testing time for each direct shear test. As the purpose of the slickenside creation process was to form a failure plane along which particles are already oriented, the specimen preparation process effectively "wipes clean" the stress history for the clay along the failure plane. Because the shear resistance along the preformed failure plane dominates the shear behavior, minor variations in void ratio in the soil surrounding the failure plane are believed to have only a second-order effect on the measured shearing resistance. Direct shear tests conducted on a number of specimens consolidated directly to 690 kPa in the shear box (specimens prepared without using the batch consolidometer) confirmed that this assumption was correct.

After completion of consolidation, the direct shear specimens were unloaded and trimmed to a final height of 12.7 mm. This preparation method formed test specimens that were 102×102 mm square, with heights of 12.7 mm.

After consolidation, each test specimen was repositioned so that its vertical midpoint 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 be separated into two pieces, an upper half and a lower half, which were polished to align clay particles in the direction of shear.

Each specimen half was polished by sliding it a distance of 0.3 m along the surface of a wet 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 sliding it off the edge of the glass in order not to disturb the clay particles along the sliding 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. Some 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 shows the approach used to prepare the direct shear test specimens, and the final appearance of the failure plane after wet polishing.

The direct shear test was begun by consolidating the specimen to the desired 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. Drained direct shear testing of Rancho Solano Fat Clay was performed at a shear-displacement rate of 0.003 mm/min. This displacement rate was selected in a similar fashion as the displacement rate for the ring shear tests, and is believed to be slow enough to ensure full pore pressure dissipation during shear.

Table 4 Residual shear strength data from "single-stage, modified platen" ring shear tests on San Francisco Bay Mud

σ_n (kPa)	No. tests performed	Avg. τ_r (kPa)	Stan. dev. τ_r (kPa)	Min. τ_r (kPa)	Max. τ_r (kPa)	Avg. ϕ'_r	Stan. dev. ϕ'_r	Min. ϕ'_r	Max. ϕ'_r
52	2	18.9	0.2	18.8	19.0	20.0°	0.2°	19.8°	20.1°
100	4	33.4	0.4	33.1	33.9	18.5°	0.2°	18.3°	18.7°
200	2	60.1	0.1	60.0	60.2	16.7°	0.04°	16.7°	16.7°
345	2	101.2	2.5	99.5	103.0	16.4°	0.4°	16.1°	16.6°
590	2	171.4	1.7	170.2	172.6	16.2°	0.2°	16.1°	16.3°

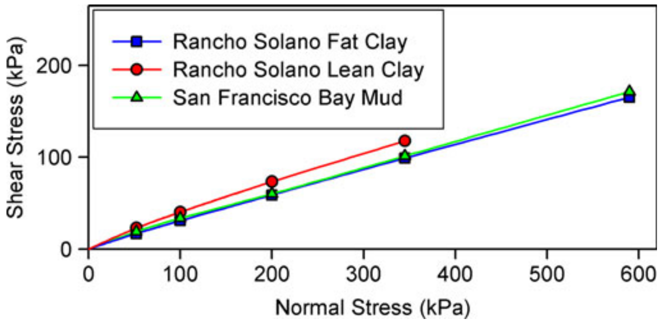

Fig. 3 Residual shear strength failure envelopes measured in ring shear tests

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 7.6 mm and for no more than 12.7 mm (the maximum permissible travel of the shear box).

Thirteen drained direct shear tests were performed on polished Rancho Solano Fat Clay specimens. Specimens were tested at four initial normal stresses: 54, 100, 198, and 347 kPa. A typical test result from the direct shear tests conducted on polished Rancho Solano Fat Clay specimens is shown in Fig. 6. Friction ratios were calculated using the following equation:

$$\text{Friction ratio} = \frac{\text{actual shear stress}}{\text{actual normal stress}} = \frac{\text{shear force}}{\text{normal force}} \qquad (3)$$

This soil typically exhibited a small peak in shear resistance, possibly due to a "healing" effect on the shear plane after consolidation and before shearing is begun. The shear resistance then dropped to a nearly constant value, which can be considered the residual strength for the soil. A gradual increase in shear strength was often observed as the specimen was sheared to larger displacements, as shown in Fig. 6. This "saddle" shape has been observed by other researchers testing clays in the direct shear device (e.g., Bishop et al. 1971), and is thought to be caused by the combined effects of extrusion and machine friction.

Statistical analysis results from the direct shear tests on wet-polished Rancho Solano Fat Clay specimens are given in Table 5. The corresponding secant residual friction angles, calculated using Eq. 2, are also given in Table 5.

As shown in Table 5, residual strengths measured for specimens formed using hand polishing techniques were repeatable from specimen to specimen, even when the specimens were prepared by different researchers. Moderate variations in the polishing procedure that was used (e.g., hand pressure applied, number of passes along the frosted glass plate) did not appear to have a significant effect on the measured test results. Consequently, it was concluded that for a given soil and a given polishing surface, moderate variations in the polishing procedure or applied polishing stress have only a second order effect. Polishing procedures that are different than the ones discussed in this paper might also work well for some soils.

Comparisons between the average residual shear strengths and secant residual friction angles measured in the Bromhead ring shear device and the direct shear device are given in Figs. 7 and 8. The bands surrounding each value of average secant friction angle in Fig. 8 are the minimum and maximum secant residual friction angles measured at that normal stress.

As shown in Figs. 7 and 8, good agreement was observed between the average 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 Fat Clay. More scatter was observed for residual strengths measured in the direct shear device, indicating the increased sensitivity of this test to factors such as shear plane alignment in the direct shear box, and variability in particle orientation as a result of soil polishing.

Drained direct shear testing of Rancho Solano Lean Clay

Direct shear tests were also used to measure the drained residual shear strength of Rancho Solano Lean Clay. Specimens were prepared using the same "wet polish" method that previously worked well for Rancho Solano Fat Clay. The appearance of the Rancho Solano Lean Clay failure planes after wet polishing was indistinguishable from that of the Rancho Solano Fat Clay.

Two tests were performed at an initial normal stress of 70 kPa and a displacement rate of 0.003 mm/min. The friction ratio vs. displacement curves for these tests are shown in Fig. 9, which also shows the average peak and residual friction ratios measured for Rancho Solano Lean Clay in the Bromhead ring shear device.

As shown in Fig. 9, the shape of a typical friction ratio vs. displacement curve for Rancho Solano Lean Clay is significantly different than the curve for Rancho Solano Fat Clay (shown in Fig. 6). Even more significant is the fact that the measured residual friction angle, as indicated by the friction ratio, is significantly different from 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 Lean Clay, effectively changing the grain size distribution at the shear interface so that it became primarily composed of more silt and fine sand grains (with fewer clay particles). Such a change would alter the shear behavior of the soil, causing it to behave more like a silt or fine sand when sheared, as shearing is forced to occur along a predetermined plane in the direct shear test. 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 Fat Clay. This hypothesis was supported by the observation that a significant amount of fine particles remained suspended in the water on the glass plate after polishing. It is not clear why wet polishing might have had this effect on Rancho Solano Lean Clay, and why it did not have a similar effect on Rancho Solano Fat Clay; it is suspected that differences in grain size distribution and clay mineralogy may play

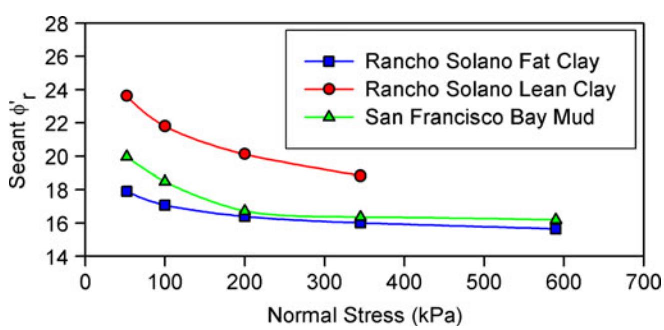

Fig. 4 Secant residual friction angles measured in ring shear tests

Fig. 5 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

a role (i.e., as shown in Fig. 1, Rancho Solano Fat Clay has a much larger proportion of both silt- and clay-sized particles).

To explore this hypothesis, a series of direct shear tests were conducted on Rancho Solano Lean Clay 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 for a distance of 0.6 m along the surface of a dry Teflon sheet under moderate hand pressure. Ten passes along the Teflon sheet were performed for each half of the test specimen. Figure 10 shows the dry Teflon polishing process, and the resulting slickensided failure plane.

For the dry glass polish method, a specimen half was polished by shearing it for a distance of 0.3 m along the surface of a dry frosted glass plate under moderate hand pressure. Ten passes along the glass were performed for each half of the test specimen. Figure 11 shows the dry glass polishing process, and the resulting slickensided failure plane. Note that the glass-polished specimen does not appear as shiny as the specimen that was prepared using the dry Teflon polishing process.

It should be noted that selection of the cumulative displacements that were used for polishing was somewhat arbitrary, as little guidance exists in the technical literature about the best way to polish specimens. Most literature indicates that concentrated

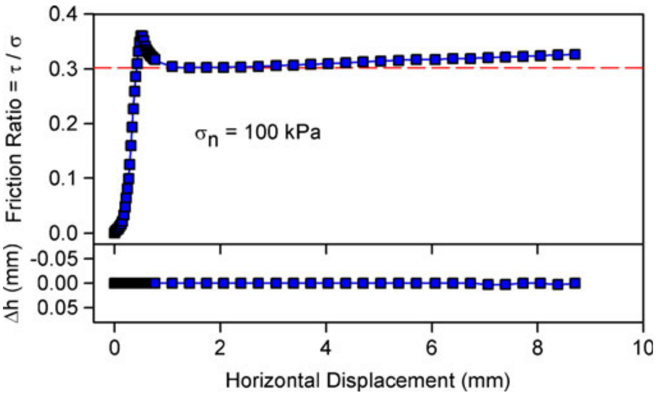

Fig. 6 A typical test result for direct shear tests conducted on polished Rancho Solano Fat Clay specimens

soil-on-soil shear in excess of somewhere between 5 to 25 cm is typically sufficient to form slickensides in the field (e.g., Skempton 1964; Skempton 1985). However, the amount of shear that needs to be applied along different polishing surfaces to sufficiently align clay particles is less clear. It is even more complicated to determine how much polishing is needed to completely orient the particles along a wire-cut surface that is initially slightly uneven.

The logic behind using different cumulative displacements for the glass and Teflon polishing surfaces is that clay particles tended to adhere better to the glass surface, so it was thought that better particle alignment along the shear plane could be achieved using smaller cumulative displacements against the glass. Additionally, since the particles adhered more to the glass surface, polishing the specimens to larger displacements resulted in excessive particle stripping, which was undesirable. Conversely, as the Teflon was so slippery, it was thought that more polishing would be required to achieve particle alignment along the shear plane.

After completion of polishing, the direct shear specimen halves were reassembled in the direct shear box, and reconsolidated to the desired testing normal stress. Vertical displacements were recorded to ensure that primary consolidation was completed prior to the commencement of shear.

Direct shear tests were performed on these polished specimens at an initial normal stress of 70 kPa and a displacement rate of 0.003 mm/min. The friction ratio vs. displacement curves for these tests are shown in Fig. 12, which also shows the friction ratio that corresponds to the residual shear strength measured in the Bromhead ring shear device.

As shown in Fig. 12, the dry polish method yields residual strengths for Rancho Solano Lean Clay that are lower than those measured in the Bromhead ring shear device (11.8° to 12.3° for the direct shear tests, as compared with 22.8° for the ring shear tests). However, it is interesting to note that the shape of the friction ratio vs. displacement curves for the dry polished specimens is more consistent with what was observed for tests conducted on wet polished Rancho Solano Fat Clay specimens (shown in Fig. 6). It is not clear why the residual strengths from dry polishing are so much lower than the ring shear residual strengths, while the qualitative shape of the friction ratio vs. displacement curves is in better agreement.

Similar to observations during wet polishing, a significant amount of soil particles remained on the polishing surfaces after

Table 5 Residual shear strengths measured in direct shear tests on wet-polished Rancho Solano Fat Clay specimens

Initial σ_n (kPa)	No. tests performed	Avg. σ_n at failure (kPa)	Avg. τ_r (kPa)	Stan. dev. τ_r (kPa)	Min. τ_r (kPa)	Max. τ_r (kPa)	Avg. ϕ'_r	Stan. dev. ϕ'_r	Min. ϕ'_r	Max. ϕ'_r
54	4	58.2	19.7	2.2	17.1	21.7	18.7°	1.1°	17.2°	19.6°
100	4	102.2	32.4	1.8	30.8	34.8	17.6°	0.8°	16.8°	18.6°
198	3	204.4	60.0	2.3	57.8	62.3	16.4°	0.8°	15.8°	17.2°
347	2	362.7	106.7	17.3	94.5	119.0	16.4°	1.9°	15.0°	17.7°

dry polishing. However, the key difference is that water was not used during the polishing process, and the grain size of the particles that were stripped may have been somewhat different. It is thought that perhaps some sort of selective stripping process was occurring, or possibly the larger particles stripped more easily than the fines during dry polishing. It seems possible that lower strengths could have been measured because the dry polishing process stripped out the coarser soil particles, leaving only finer particles along the shearing plane. However, this explanation is only postulated as a hypothesis, and as emphasized above, it is not clear why the residual strengths from dry polishing are so much lower than the ring shear residual strengths.

As shown in Fig. 12, 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. The reason for the observed increases in strength is not clear. Some of the possible increases in strength could have been 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, though no concrete experimental evidence exists to support this hypothesis. The challenges associated with aligning preformed shear planes in the direct shear device are described by Skempton and Petley (1967) and Bromhead and Curtis (1983). 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.

For Rancho Solano Lean Clay, 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 direct shear tests with artificially prepared slickensides is not recommended for geotechnical engineering practice.

Drained direct shear testing of San Francisco Bay Mud

Direct shear tests were also performed 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 Lean Clay. Figure 13 shows the appearance of the polished failure planes for three different test specimens.

Three direct shear tests were performed at an initial normal stress of 103 kPa and a displacement rate of 0.003 mm/min. The friction ratio vs. displacement curve for the "wet polish" test is shown in Fig. 14. The friction ratio vs. displacement curves for the two "dry polish" tests are shown in Fig. 15. Figures 14 and 15 also show the friction ratio that corresponds to the residual shear strength measured in the Bromhead ring shear device.

As shown in Fig. 14, 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—23.3° for the direct shear tests, as compared with 18.4° 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, caused by stripping clay particles from the shear interface during wet polishing, as was suspected for the wet polished Rancho Solano Lean Clay. 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 Lean Clay.

As shown in Fig. 15, 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 (14.7° for the direct shear tests, as compared with 18.4° for the ring shear tests). As was observed in the Teflon dry polish tests on Rancho Solano Lean Clay, the cause of this low strength value is unknown. The Teflon dry polishing process may alter the nature of the shear plane, either by causing changes in the physio-chemical interaction between clay particles or by increasing the amount of clay particles along the shearing interface.

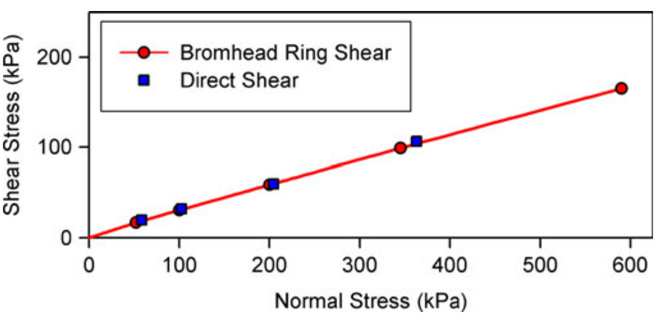

Fig. 7 Comparison between Bromhead ring shear and direct shear residual strengths measured for Rancho Solano Fat Clay

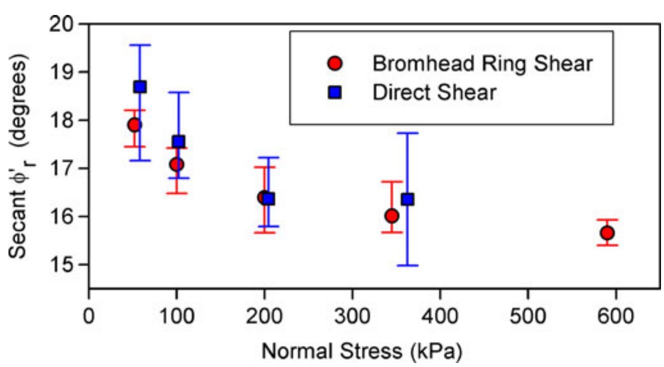

Fig. 8 Secant residual friction angles measured in Bromhead ring shear and direct shear tests on Rancho Solano Fat Clay

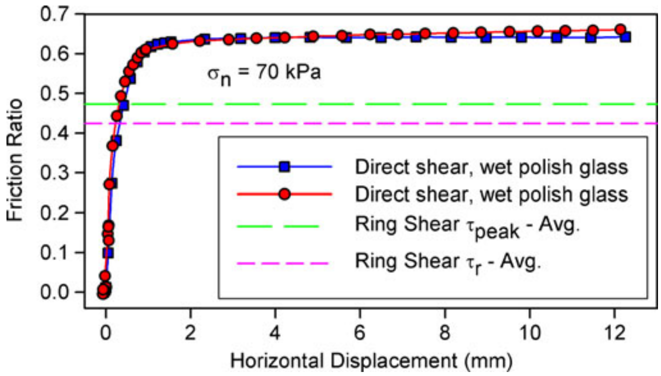

Fig. 9 Comparison between Bromhead ring shear and "wet polish" direct shear test results for Rancho Solano Lean Clay

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—20.9° for the direct shear tests, as compared with 18.4° for the ring shear tests. This increased value of strength was likely caused by the fact that the Bay Mud tended to adhere to the glass plate, resulting in a rougher and less polished surface. Visually, glass dry-polished San Francisco Bay Mud specimens appeared the least slickensided of any of the specimens that were prepared.

Summary and conclusions

Drained Bromhead ring shear tests were performed on Rancho Solano Fat Clay specimens, yielding average secant residual friction angles that decreased from 17.9° to 15.7° as the normal stress increased from 52 to 590 kPa. Tests performed on Rancho Solano Lean Clay specimens yielded average secant residual friction angles that decreased from 23.6° to 18.8° as the normal stress increased from 52 to 345 kPa. Tests performed on San Francisco Bay Mud specimens yielded average secant residual friction angles that decreased from 20.0° to 16.2° as the normal stress increased from 52 to 590 kPa. The decrease in measured secant residual friction angles with increasing normal stress shows the curvature of the residual strength failure envelopes.

Slickensided direct shear specimens were prepared by wire-cutting intact direct shear specimens, and polishing the wire-cut planes to align the clay particles in the direction of shear.

The potential payoff to this approach is that it would allow measurement of residual strengths for clay soils using direct shear equipment. Additionally, the same method for preparing slickensided surfaces could also be used to prepare triaxial specimens for undrained strength testing of slickensided surfaces, an approach that is beneficial for studying the seismic behavior of slickensided soil slopes (Meehan 2006).

In the testing program described here, specimens were polished by sliding pre-cut specimens over wet frosted glass, dry frosted glass, and dry Teflon. Drained direct shear tests were conducted on the polished specimens, to explore the effectiveness of different polishing techniques for preparing slickensided surfaces.

Table 6 shows how the results from the drained direct shear testing program compared with the residual strength values measured in the Bromhead ring shear device.

Based on a review of studies performed by previous researchers (e.g., Skempton 1964; Chandler 1966; Skempton and Petley 1967), it was envisioned that it would be a straightforward process to measure the residual strengths along preformed slickensided surfaces using traditional direct shear testing equipment. 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.

As shown in Table 6, 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 Fat Clay (wet polishing) did not work well for Rancho Solano Lean Clay or San Francisco Bay Mud. 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 Fat Clay test results). These polishing techniques have the potential for use in broader research applications outside the realm of direct shear testing, as discussed in Meehan et al. (2008). When a polishing process is used to prepare slickensides, the effectiveness of the preparation method should be confirmed by comparison with ring shear 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.

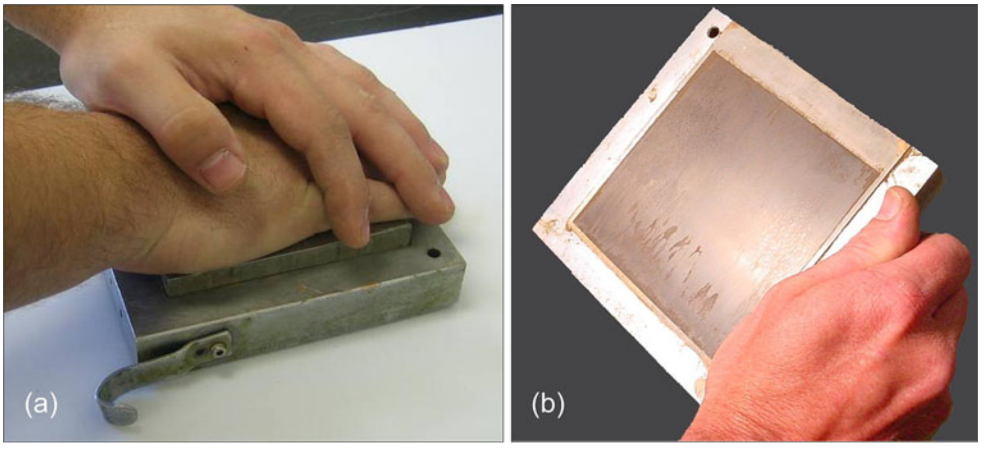

Fig. 10 The dry Teflon polishing process; **a** rubbing the cut plane on dry Teflon to form slickensides, **b** the slickensided failure plane

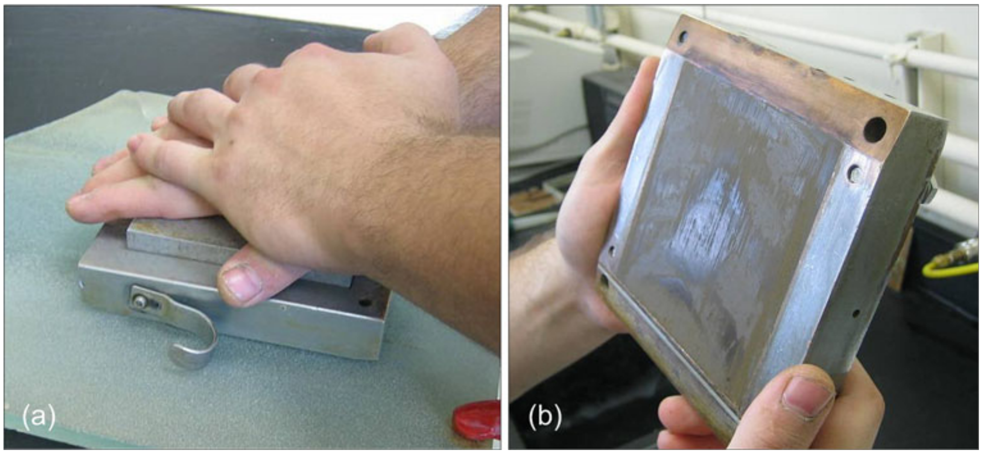

Fig. 11 The dry glass polishing process; **a** rubbing the cut plane on dry glass to form slickensides, **b** the slickensided failure plane

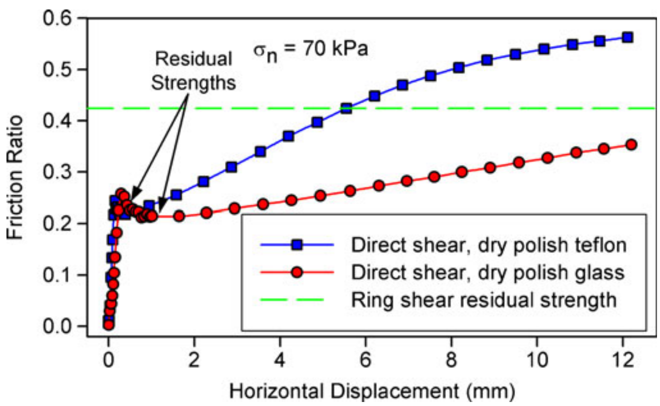

Fig. 12 Comparison between Bromhead ring shear and "dry polish" direct shear test results for Rancho Solano Lean Clay

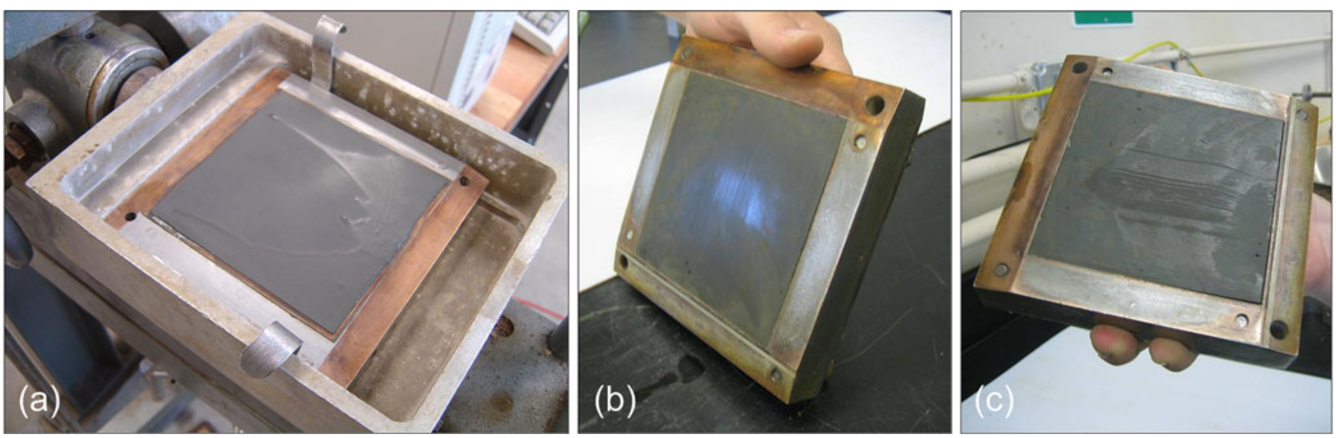

Fig. 13 Appearance of slickensided failure planes in San Francisco Bay Mud after: **a** wet polishing on glass, **b** dry polishing on Teflon, and **c** dry polishing on glass

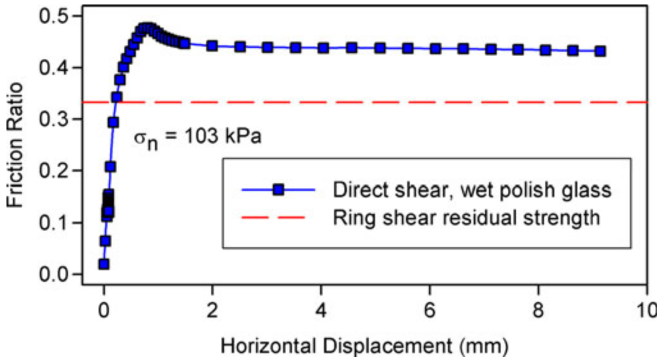

Fig. 14 "Wet polish" direct shear test results for San Francisco Bay Mud

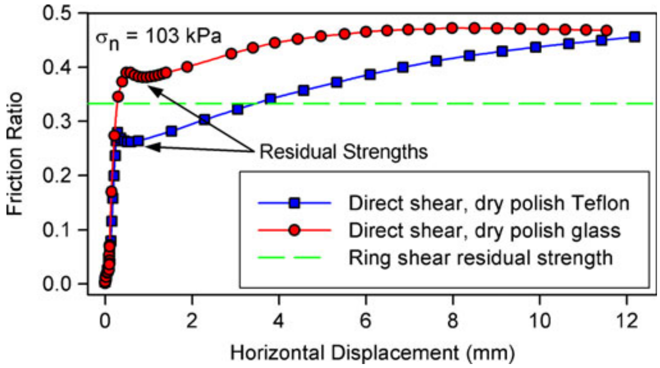

Fig. 15 "Dry polish" direct shear test results for San Francisco Bay Mud

Table 6 Comparison of drained direct shear test results with Bromhead ring shear test results for different polishing methods

	Direct shear strengths vs. ring shear strengths		
Soil	Wet polishing on glass	Dry polishing on Teflon	Dry polishing on glass
Rancho Solano Fat Clay	Excellent agreement	Not performed	Not performed
Rancho Solano Lean Clay	DS 43% higher	DS 46% lower	DS 48% lower
San Francisco Bay Mud	DS 27% higher	DS 20% lower	DS 14% higher

Acknowledgements

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 Derek Martowska and Michael Wanger.

References

ASTM Standard D 6467–99 (1999) Standard Test Method for Torsional Ring Shear Test to Determine Drained Residual Shear Strength of Cohesive Soils, *Annual Book of Standards*, Vol. 4. ASTM International, West Conshohocken

ASTM Standard D 3080–98 (1999) Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, *Annual Book of Standards,* Vol. 4. ASTM International, West Conshohocken

Bishop AW, Green GE, Garga VK, Andresen A, Brown JD (1971) A new ring shear apparatus and its application to the measurement of residual strength. Geotechnique 21(4):273–328

Bromhead EN (1979) A simple ring shear apparatus. Ground Eng 12(5):40–44

Bromhead EN, Curtis RD (1983) A comparison of alternative methods of measuring the residual strength of London clay. Ground Eng 16(4):39–40

Bromhead EN, Harris AJ, Ibsen M-L (1999) Statistical variability of ring shear test results on a shear zone in London Clay. Slope Stability Engineering, Vol. 2, Japan, pp. 1109–1114

Chandler RJ (1966) The measurement of residual strength in triaxial compression. Geotechnique 16(3):181–186

Duncan JM, Wright SG (2005) Soil strength and slope stability. Wiley, Hoboken

Harris AJ, Watson PDJ (1997) Optimal procedure for the ring shear test. Ground Eng 30 (6):26–28

Hvorslev MJ (1939) Torsion shear tests and their place in the determination of the shearing resistance of soils. Proc. of ASTM Symposium on Shear Testing of Soils 39:999–1022

Kenney TC (1967) The influence of mineral composition on the residual shear strength of natural soils. Proc. Geotechnical conference, Vol. 1, Oslo, Norway, pp. 123–129

Kenney TC (1977) Residual Strengths of Mineral Mixtures. Ninth International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, Japan, pp. 155–160

La Gatta DP (1970) Residual Strength of Clays and Clay-Shales by Rotation Shear Tests. *Harvard Soil Mechanics Series No. 86*. Harvard University, Cambridge

Lupini JF, Skinner AE, Vaughan PR (1981) The drained residual strength of cohesive soils. Geotechnique 31(2):181–213

Meehan CL (2006) An Experimental Study of the Dynamic Behavior of Slickensided Slip Surfaces," Ph.D. thesis, Virginia Tech

Meehan CL, Brandon TL, Duncan JM (2007) Measuring drained residual strengths in the Bromhead ring shear. Geotechnical Testing Journal ASTM 30(6):466–473

Meehan CL, Boulanger RW, Duncan JM (2008) Dynamic centrifuge testing of slickensided shear surfaces. J Geotech Geoenviron Eng ASCE 134(8):1086–1096

Skempton AW (1964) Long-term stability of clay slopes. Geotechnique 14(2):75–102

Skempton AW (1985) Residual strength of clays in landslides, folded strata, and the laboratory. Geotechnique 35(1):3–18

Skempton AW, Petley DJ (1967) The Strength Along Structural Discontinuities in Stiff Clays. Proc. Geotechnical Conference, Vol. 2, Oslo, Norway, pp. 29–46

Stark TD, Eid HT (1992) Comparison of Field and Laboratory Residual Strengths," *Stability and Performance of Slopes and Embankments II*, ASCE, Vol. 1, Berkeley, CA, pp. 876–889

Stark TD, Eid HT (1994) Drained residual strength of cohesive soils. J Geotech Eng ASCE 120(5):856–871

Tiwari B, Marui H (2005) A new method for the correlation of residual shear strength of the soil with mineralogical composition. J Geotech Geoenviron Eng ASCE 131 (9):1139–1150

USACE (1986) Laboratory Soils Testing—Engineer Manual 1110-2-1906. United States Army Corps of Engineers, Washington

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