Measurement of Drained Residual Strength of Overconsolidated Clays

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The drained residual shear strength of overconsolidated clays is an important parameter in assessing the stability of slopes that contain a preexisting shear surface. The main issue influencing a laboratory testing program to measure the drained residual strength is whether a natural or laboratory-formed shear surface will be used. A multistage test procedure using a modified Bromhead ring shear apparatus and an overconsolidated, precut, remolded specimen is described that provides a reliable and practical method for measuring the drained residual shear strength. Results of ring shear tests on 32 clays and clay shales reveal that the drained residual strength is controlled by clay mineralogy and the quantity of clay-size particles. The liquid limit is used as an indicator of clay mineralogy, and the clay-size fraction indicates the quantity of clay-size particles, which are particles smaller than 0.002 mm. Therefore, increasing the liquid limit and clay-size fraction decreases the drained residual strength. The ring shear tests also reveal that the drained residual failure envelope is significantly nonlinear for overconsolidated clays with a clay-size fraction greater than 50 percent and a liquid limit between 60 and 220. Analysis of several case histories shows that this nonlinearity should be incorporated into a slope stability analysis. Previous correlations do not provide an accurate estimate of the drained residual strength because they (*a*) are based on only one soil index property, for example, clay-size fraction or plasticity; and (*b*) do not provide an estimate of the stress-dependent nature of the residual failure envelope. A new correlation is presented that is a function of the liquid limit, clay-size fraction, and effective normal stress and can be used to estimate the entire nonlinear residual failure envelope.

The concept of residual strength has contributed greatly toward understanding the long-term shearing resistance that can be mobilized in overconsolidated clay slopes. The drained residual shearing resistance can be significantly lower than the peak strength (Figure 1) and is a crucial parameter in evaluating the long-term stability of new and existing slopes and the design of remedial measures. Skempton (*1*) concluded that the drained postpeak strength loss observed in overconsolidated clays is caused by (*a*) an increase in water content because of dilation and (*b*) the orientation of clay particles parallel to the direction of shearing (Figure 1). In normally consolidated clays the drained postpeak strength loss is caused entirely by the orientation of clay particles parallel to the direction of shear. Large continuous shear displacements in one direction are required to orient the clay particles parallel to the shearing direction and to achieve a drained residual strength condition.

Skempton (*2*) concluded that slopes that have undergone 1 or 2 m of displacement should be designed using a drained residual strength. Therefore, the drained residual strength pertains to slopes that contain preexisting shear surfaces, such as old landslides or soliflucted slopes, in shears in folded strata, and sheared joints or faults (*3*). The residual strength also is applicable to failed embankments and the occurrence of progressive failure in slopes. Slopes that have not undergone previous sliding can be designed using the fully softened strength (*2*), which corresponds to the peak strength of a remolded normally consolidated clay (Figure 1).

Stark and Duncan (*4*) and Chandler (*5*) have described several landslide case histories involving overconsolidated clays in which previous sliding had not occurred, and the back-calculated friction angle is less than the fully softened value. These case histories suggest that there may be circumstances in which slopes that have not undergone previous sliding may require design strengths that are less than the fully softened value. One such circumstance is the repeated loading caused by the annual draw-down cycle of a reservoir. Stark and Duncan (*4*) concluded that the slide in the upstream slope of San Luis Dam was caused by the accumulation of shear displacement and associated strength loss induced in the overconsolidated foundation clay during the 14-year reservoir draw-down history. The possibility of mobilizing a strength less than the fully softened value in natural or man-made slopes that have not undergone previous sliding is currently being studied by the author.

MEASUREMENT OF DRAINED RESIDUAL STRENGTH

Laboratory measurement of the drained residual strength requires the use of a specimen that (*a*) contains a natural shear surface or (*b*) can be precut or presheared to form a shear surface. As a result, the main issue to be decided in planning a residual strength test program is whether the shear surface will be formed naturally or in the laboratory. The resulting laboratory testing procedure will be significantly different depending on the technique used to form the shear surface. Other important issues in laboratory testing are whether a direct shear or torsional ring shear apparatus will be used, and the use of a single-stage or multistage test procedure. In a multistage test, after a residual strength condition has been established under the first effective normal stress, shearing is stopped, and the normal stress is doubled. The specimen is allowed to reconsolidate under a higher normal stress before shearing is recommenced. This procedure is repeated for a number of effective normal stresses to estimate the drained residual failure envelope. In summary, the laboratory test procedure recommended to measure the drained residual strength will depend primarily on the type of shear surface (field versus laboratory), test apparatus, and test procedure.

Natural Shear Surfaces

Samples containing natural shear surfaces can be obtained from pits, shafts, tunnels, open faces, and bore holes. However, bore hole samples are the least desirable because it is difficult to locate the slip

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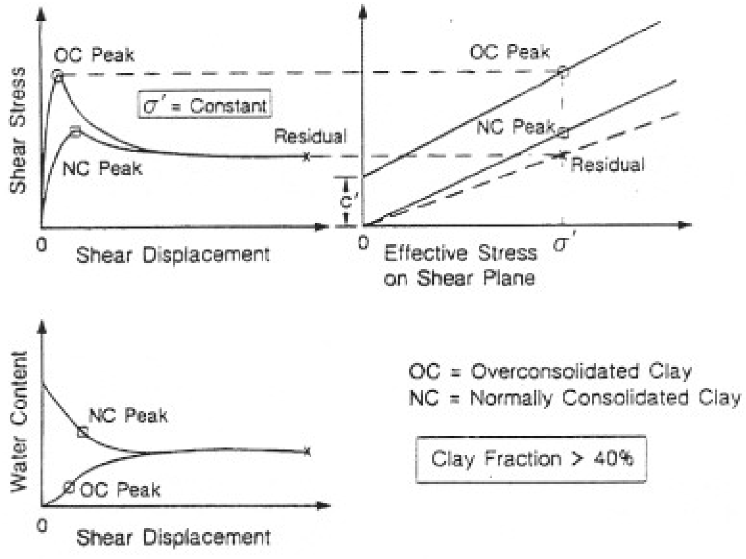

FIGURE 1 Drained shear characteristics of overconsolidated clays (*1*).

surface and to determine the natural direction of the shear in the recovered sample. The undisturbed specimen must be arranged in the direct shear apparatus such that the fully developed field slip surface is located at the gap between the upper and lower halves of the shear box. This is complicated by the fact that natural shear surfaces are usually nonhorizontal. The specimen then is sheared in the natural direction of movement. This test is referred to as a slip surface test and can provide an accurate estimate of the field residual strength (*3*). A similar process can be used to test natural shear surfaces in a torsional ring shear apparatus. However, it is difficult to obtain a natural slip surface sample, determine the direction of field shearing, and trim and properly align the usually nonhorizontal shear surface in the direct shear or ring shear apparatuses.

Laboratory-Formed Shear Surfaces

Because of the difficulties in obtaining and testing natural slip surfaces, the use of remolded specimens to measure the drained residual strength was investigated. Two types of remolded specimens, intact and precut, are used, and the relative merits of each will be discussed. In this study, a remolded specimen is obtained by air drying a representative sample of the overconsolidated clay or shale. The air-dried clay or shale is ball milled until all of the representative material passes U.S. Standard Sieve No. 200. Remolded silt and silty clay material (soil no. 1, 2, 3, 13, and 14 in Table 1) are obtained by using a mortar and pestle until all of the representative material passes U.S. Standard Sieve No. 40. Distilled water is added to the processed soil until a liquidity index of approximately 1.5 is obtained. The sample is then allowed to rehydrate for at least 1 week in a moist room. A spatula is used to place the remolded soil paste into the direct shear or ring shear specimen container to ensure that no air voids are present. The specimen is planed flush with the top of the specimen container using a razor blade, a fine wire saw, or both.

Normally Consolidated, Intact, Remolded Specimens

After consolidation, a normally consolidated, intact, remolded specimen is sheared until a drained residual strength is obtained. The main disadvantage of using an intact, remolded specimen is that a large continuous horizontal displacement, usually 250 to 400 mm, parallel to the direction of shear is required to form a shear surface and then to achieve a residual strength condition. Each reversal of a direct shear box is limited to a horizontal displacement that is usually less than 13 mm. Therefore, the use of a normally consolidated, intact, remolded specimen precludes the use of a reversal direct shear apparatus.

A torsional ring shear apparatus allows any magnitude of continuous shear displacement to be applied in one direction. This allows clay particles of an intact, remolded specimen to be oriented parallel to the direction of shear and the development of a residual strength condition. Other advantages of the ring shear apparatus include a constant cross-sectional area of the shear surface during the shear, a thinner specimen that allows the use of a faster drained displacement rate, minimal laboratory supervision during shear because there is no reversal of a shear box, and the use of data-acquisition techniques.

A number of different forms of the ring shear apparatus have been developed, for example, by Hvorslev (*6,7*), La Gatta (*8*), Bishop et al. (*9*), and Bromhead (*10*). However, the Bromhead ring shear apparatus is becoming widely used because of its cost, availability, and ease of operation. Bromhead and Curtis (*11*) showed that this ring shear apparatus yields results that are in good agreement with those obtained using the more sophisticated ring shear apparatus developed by the Norwegian Geotechnical Institute and Imperial College (*9*). Bromhead and Dixon (*12*) and Stark and Eid (*13,14*) also show that the drained residual strengths measured with the Bromhead apparatus are in excellent agreement with values back-calculated from landslide case histories.

Figure 2 illustrates the importance of continuous shear displacement in one direction on the measured residual strength of normally consolidated, intact, remolded specimens using the Santiago clay stone from San Diego, California (Table 1). It can be seen that direct shear tests using normally consolidated, intact, remolded specimens significantly overestimate the torsional ring shear test results because each reversal of the shear box is limited to a horizontal displacement of 5 mm and a limited amount of clay particles is oriented

TABLE 1 Clay and Shale Samples Used in Ring Shear Tests

Soil No.	Clay and Shale Samples	Clay and Shale Locations	Initial Water Content (%)	Specific Unit Weight (kN/m^3)	Liquid Limit	Plastic Limit	Clay Size Fraction (%)	Activity (PI/CF)
1	Glacial Till	Urbana, IL	8.4	16.1	24	16	18	0.44
2	Loess	Vicksburg, MS	14.0	16.5	28	18	10	1.00
3	Bootlegger Cove Clay	Anchorage, AL	34.8	18.6	35	18	44	0.39
4	*Duck Creek Shale	Fulton, IL	5.3	24.0	37	25	19	0.63
5	*Chinle (red) Shale	Holbrook, AZ	10.9	22.7	39	20	43	0.44
6	*Colorado Shale	Montana, MT	5.6	21.2	46	25	73	0.29
7	Panoche Mudstone	San Francisco, CA	14.2	19.6	47	27	41	0.49
8	*Four Fathom Shale	Durham, England	3.3	25.1	50	24	33	0.79
9	Mancos Shale	Price, UT	4.9	24.5	52	20	63	0.51
10	Panoche Shale	San Francisco, CA	12.0	20.2	53	29	50	0.48
11	*Comanche Shale	Proctor Dam, TX	11.5	23.1	62	32	68	0.44
12	*Bearpaw Shale	Billings, MT	15.7	21.8	68	24	51	0.86
13	Slide Debris	San Francisco, CA	18.1	19.6	69	22	56	0.84
14	Bay Mud	San Francisco, CA	73.0	15.0	76	41	16	2.19
15	*Patapsco Shale	Washington, D.C.	21.6	20.7	77	25	59	0.88
16	*Pierre Shale	Limon, CO	24.3	20.1	82	30	42	1.24
17	Santiago Claystone	San Diego, CA	20.7	19.6	89	44	57	0.79
18	Lower Pepper Shale	Waco Dam, TX	21.0	20.3	94	26	77	0.88
19	Altamira Bentonitic Tuff	Portuguese Bend, CA	62.0	17.5	98	37	68	0.90
20	Brown London Clay	Bradwell, England	33.0	18.9	101	35	66	1.02
21	*Cucaracha Shale	Panama Canal	18.4	20.7	111	42	63	1.10
22	Otay Bentonitic Shale	San Diego, CA	27.0	17.6	112	53	73	0.81
23	*Denver Shale	Denver, CO	30.5	18.7	121	37	67	1.25
24	*Bearpaw Shale	Saskatchewan, Canada	27.3	19.0	128	27	43	2.35
25	Oahe Firm Shale	Oahe Dam, SD	27.6	20.1	138	41	78	1.24
26	*Claggett Shale	Benton, MT	11.7	22.7	157	31	71	1.78
27	*Taylor Shale	San Antonio, TX	35.2	18.0	170	39	72	1.82
28	*Pierre Shale	Reliance, SD	42.8	17.7	184	55	84	1.54
29	Oahe Bentonitic Shale	Oahe Dam, SD	35.4	18.9	192	47	65	1.96
30	Panoche Clay Gouge	San Francisco, CA	34.8	21.8	219	56	72	2.26
31	Lea Park Bentonitic Shale	Saskatchewan, Canada	36.0	17.3	253	48	65	3.15
32	*Bearpaw Shale	Ft. Peck Dam, MT	15.8	21.8	288	44	88	2.77

* Index Properties from Mesri and Cepeda-Diaz (1986)

parallel to the shear. It should be noted that the direct shear tests reported here were conducted with a square specimen 60 × 60 mm in plan dimensions and 38 mm thick. Stark and Eid (*13*) used a landslide case history in the Santiago clay stone to show that the residual failure envelope measured using a ring shear apparatus and normally consolidated, intact, remolded specimens (Figure 2) is in good agreement with field observations.

In the original Bromhead ring shear apparatus (*10*), settlement of the top platen into the specimen container caused by consolidation and shearing can induce significant wall friction along the inner and outer edges of the specimen. This wall friction can lead to an overestimation of the residual shear strength. Stark and Vettel (*15*)

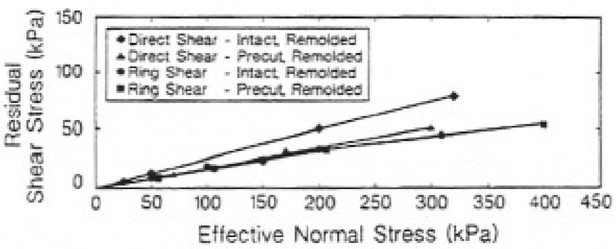

FIGURE 2 Drained residual failure envelopes for Santiago clay stone.

concluded that the wall friction will be significant if the vertical displacement caused by consolidation and shearing exceeds 0.75 mm. Soil can be added during the consolidation process such that the intact, remolded specimen is at or near the top of the specimen container before shearing. This is a time-consuming process, but it results in satisfactory test results (Figure 2).

The original specimen container of the Bromhead ring shear apparatus was modified by Stark and Eid (*14*); their device is described subsequently to (*a*) overcome the problem of wall friction; (*b*) allow the use of overconsolidated, precut, remolded specimens; and (*c*) permit the use of a multistage test procedure. It can be seen from Figure 2 that the ring shear tests on intact and precut, remolded specimens are in agreement. It should be noted that the normally consolidated, intact, remolded specimens in Figure 2 were obtained by adding a substantial amount of remolded soil paste during consolidation of the intact specimen, such that the specimen was flush with the top of the container before shearing.

Figure 3 illustrates the effect of wall friction on the measured residual strength of Pierre shale from Reliance, South Dakota (Table 1). It can be seen that using normally consolidated, intact, remolded specimens and a single-stage test procedure in the original Bromhead ring apparatus provides a good estimate of the residual strength at effective normal stress less than approximately 50 kPa. At effective normal stresses greater than 50 kPa, consolidation of the specimen and soil extrusion during shear cause the

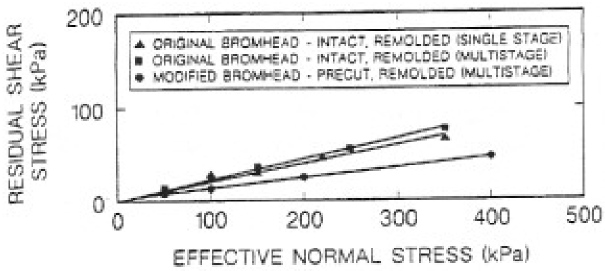

FIGURE 3 Effect of wall friction on measured residual strength of Pierre shale (Reliance).

vertical settlement to exceed 0.75 mm during a single-stage test, resulting in substantial wall friction and an overestimate of the residual strength. It should be noted that soil was not added during the consolidation phase in these tests.

It also can be seen that a multistage test procedure cannot be conducted in the original Bromhead apparatus with a normally consolidated, intact, remolded specimen. During the later stages of the multistage test, settlement of the top platen is significantly greater than 0.75 mm. This settlement and the resulting wall friction are greater than that observed in the single-stage test, which causes the multistage test to yield the highest drained residual failure envelope (Figure 3). It should be noted that additional remolded soil was not added during the consolidation phase in the multistage test.

The modified Bromhead ring shear apparatus allows a remolded specimen to be overconsolidated and precut, which minimizes settlement of the top platen during shear and reduces the horizontal displacement, and thus soil extrusion, required to achieve a residual strength condition. As a result, a multistage test procedure can be used with the modified apparatus and will yield a drained residual failure envelope (Figure 3) that is in excellent agreement with field case histories (*14,16*).

Overconsolidated, Precut, Remolded Specimens

A shear surface may be formed in a remolded specimen by overconsolidating and precutting or preshearing the specimen. The resulting specimen is termed an overconsolidated, precut, remolded specimen and can be used to reduce the horizontal displacement required to achieve a residual strength condition. In addition, it is anticipated that the use of an overconsolidated, precut specimen simulates the field conditions that lead to the development of a residual strength condition in overconsolidated clays. In this study, an overconsolidated, precut, remolded specimen is obtained by consolidating a specimen to a consolidation stress of 700 kPa. This consolidation stress was chosen to represent the maximum effective stress that typically is encountered in slope and embankment field case histories. After consolidation at 700 kPa, the specimen is unloaded and removed from the shear apparatus. The specimen is precut using a razor blade or presheared by subjecting the specimen to at least one revolution in the ring shear apparatus. The direct shear or ring shear specimen is precut in the direction of shear until a smooth and highly polished surface is obtained. After precutting, the specimen is loaded to the desired effective normal stress, which should be less than 700 kPa. This procedure results in a specimen that is overconsolidated before drained shear.

Mesri and Cepeda-Diaz (*17*) used the reversal direct shear apparatus to test overconsolidated, precut, remolded specimens. Each half of the shear box is filled with the remolded soil paste described previously. The two halves of the shear box are consolidated to approximately 700 kPa in separate modified oedometers. Each face of the shear surface is consolidated against a Tetko polyester screen that is supported by a smooth, flat Teflon plate. After consolidation, the two smooth, flat surfaces are precut in the direction of shear with a razor blade. The two precut surfaces are assembled together and sheared under the desired normal stress. Shearing is continued until a constant minimum resistance is measured. Figure 2 shows that this procedure yields drained residual shear stresses that are in good agreement with torsional ring shear tests. However, the use of overconsolidated, precut, remolded specimens in a reversal direct shear apparatus requires substantially more equipment, time, and effort than the use of a ring shear apparatus.

A modified Bromhead ring shear apparatus (*14*) was used for testing the 32 clays and clay shales described in Table 1. The modified and original ring shear specimen containers use an annular specimen with an inside diameter of 70 mm and an outside diameter of 100 mm. Drainage is provided by annular bronze porous stones secured to the bottom of the specimen cavity and to the top loading platen. The specimen is confined radially by the specimen container, which is 5 mm deep.

After consolidation at a normal stress of 700 kPa, the modified specimen container is removed from the apparatus, and the specimen is raised so that it is slightly above the top of the specimen container. This allows the specimen to be precut and minimizes the magnitude of wall friction. The specimen is raised by lowering the inner and outer rings that surround the annular specimen (*14*). The inner and outer rings of the specimen container are lowered so that approximately 0.5 mm of the specimen is visible above the top of the container. A razor blade or the ring shear apparatus is used to precut or preshear, respectively, the exposed specimen. The razor blade is placed on the upper surface of the specimen container, and the specimen is precut in the direction of shear until a smooth and highly polished surface is obtained. This results in a precut surface flush with the top of the specimen container before shearing. The specimen also can be precut or presheared in the ring shear apparatus by shearing the specimen for at least one revolution in the apparatus. Before preshearing, the specimen is raised so that it is approximately flush with the top of the specimen container. It is anticipated that using the apparatus to preshear the specimen is more practical than removing the top platen and using a razor blade. It can be seen from Figure 2 that the precut and intact, remolded specimens yield similar residual shear stresses. However, the precut specimen does not require soil to be added during the consolidation phase and requires significantly less displacement to reach a residual strength condition.

Single-Stage Versus Multistage Test Procedure

The single-stage test procedure involves consolidating a specimen at the desired normal stress and then shearing the specimen. After the residual strength condition is reached, the specimen is removed from the apparatus, and a new specimen is used for the next test. In a multistage test, after a residual strength condition has been established under the first effective normal stresses, shearing is stopped, and the effective normal stress is doubled. This procedure is repeated for a number of effective normal stresses to estimate the drained residual failure envelope. A multistage test can significantly reduce the time required to establish a drained residual failure envelope because a new specimen does not have to be prepared, consolidated, and precut for each effective normal stress. In addition, the horizontal displacement required to reach a residual strength condition is significantly reduced because a residual strength condition was attained during the first stage of the test. A multistage test also ensures that the same material is tested at each normal stress, which results in a more reproducible residual failure envelope.

Figure 4 presents the shear stress–horizontal displacement relationships for a normally consolidated, intact, remolded specimen and the second stage of a multistage test on an overconsolidated, precut, remolded specimen. These tests were conducted on Santiago clay stone (Table 1) at an effective normal stress (σ'_n) of 100 kPa. The precut specimen exhibited a significantly lower peak strength because the specimen had already attained a residual strength condition during the first stage of shearing at an effective normal stress of 50 kPa. As a result, only approximately 10 mm of horizontal displacement is required to achieve a residual strength condition during the second stage of the test.

The intact, remolded specimen exhibited a significantly larger peak strength because a shear plane had not been previously formed and no reorientation of the clay particles occurred before drained shearing. As a result, a horizontal displacement of approximately 70 mm is required to obtain a residual strength condition. Because the shear displacement rate is 0.018 mm/min, it takes an additional 2.5 days to achieve a residual strength condition using an intact specimen compared with the precut specimen. It should be noted that the displacement rate of 0.018 mm/min used in the ring shear tests described here was estimated using the procedure described by Gibson and Henkel (*18*) and a degree of consolidation of 99.5 percent.

It also can be seen in Figure 4 that the precut and intact specimens yielded similar residual strengths. This was accomplished by adding soil and reconsolidating the intact, remolded specimen so that settlement of the top platen was negligible before shear. It should be noted that the vertical displacement of the precut, remolded specimen is only about 0.03 mm (Figure 4). This is less than the vertical displacement observed during the first stage of shearing (0.06 mm) and substantially less than the 0.35 mm measured with the intact specimen. The reduction in vertical displacement is attributable to the overconsolidated nature of the precut specimen and the smaller horizontal displacement required to reach a residual strength condition. This minimal vertical displacement ensures that a negligible amount of wall friction is applied to the shear plane during a multistage test.

Some shear apparatuses may not be suited to a multistage test procedure. For example, in a direct shear apparatus a new shear surface may be created during subsequent shearing stages because of consolidation of the specimen under a successive normal stress. This consolidation may lead to a lowering of the previous shear surface below the gap between the upper and lower halves of the shear box, thus creating a new shear surface.

The original Bromhead ring shear apparatus can be used to measure the drained residual strength accurately if settlement of the top platen, caused by consolidation, soil extrusion during shear, or both, is limited to 0.75 mm (*15*). The modified Bromhead ring shear apparatus significantly reduces the time required to estimate a drained residual failure envelope by allowing the use of an overconsolidated, precut, remolded specimen and a multistage test procedure. An overconsolidated, precut, remolded specimen and a single-stage test procedure can be used in a reversal direct shear apparatus

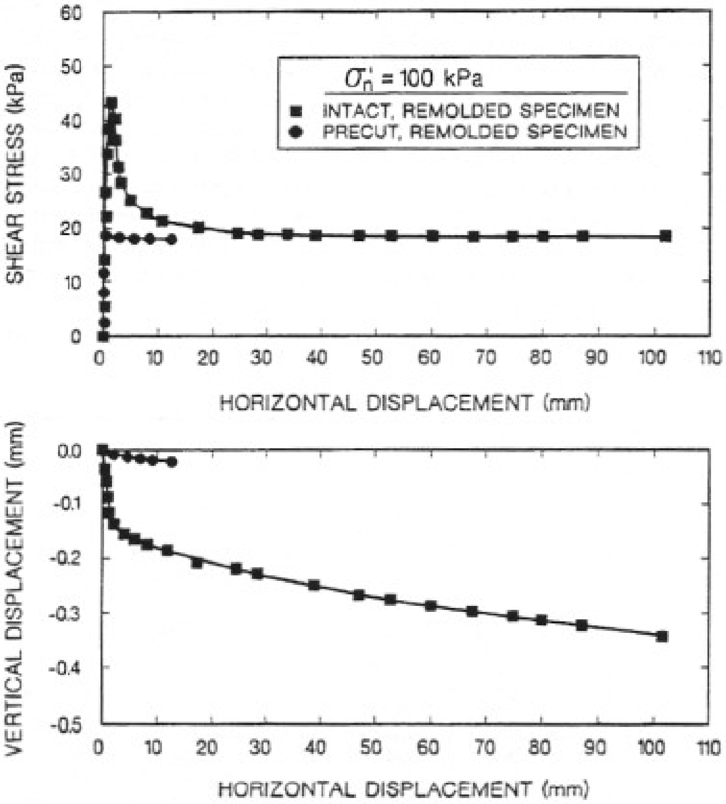

FIGURE 4 Drained ring shear test results for Santiago clay stone at effective normal stress of 100 kPa (*14*).

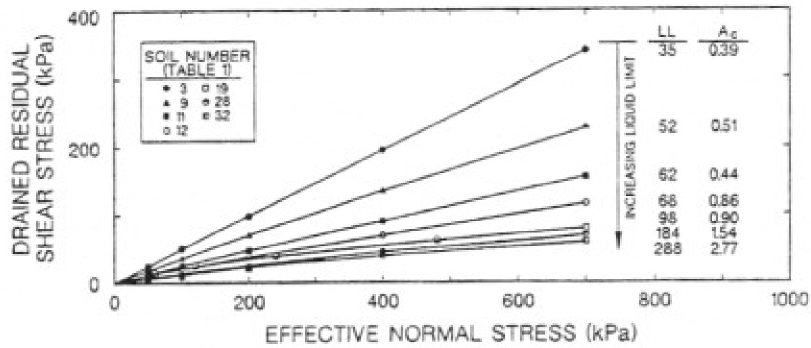

FIGURE 5 Effect of clay mineralogy on drained residual failure envelopes (*16*).

to obtain similar results as the modified Bromhead ring shear apparatus (Figure 2). However, this direct-shear procedure requires substantially more equipment (oedometers and a direct-shear apparatus) and time (*13*).

NONLINEARITY OF DRAINED RESIDUAL STRENGTH ENVELOPE

Stark and Eid (*16*) illustrate the effect of clay mineralogy and clay particle size on the drained residual strength using results of ring shear tests on 32 clays and clay shales (Table 1). The tests were performed using (*a*) the modified Bromhead ring shear apparatus; (*b*) overconsolidated, precut, remolded specimens; and (*c*) the multistage test procedure described previously. Figure 5 presents the drained residual failure envelopes for seven of the clays and clay shales listed in Table 1. It can be seen that the magnitude of the drained residual strength decreases with increasing liquid limit and activity. The activity (A_c) is defined as the plasticity index divided by the clay-size fraction. Both the liquid limit and activity provide an indication of clay mineralogy, and thus particle size and shape. In general, the plasticity increases as the platyness of the clay particles increases. Increasing the platyness of the particles results in a greater tendency for face-to-face interaction and thus a lower drained residual strength.

Figure 5 also shows that the drained residual failure envelope can be nonlinear. The nonlinearity appears to be significant for cohesive soils with moderate to high liquid limit and activity. Figure 6 presents the ratio of the secant residual friction angle at 50 kPa, $(\phi'_r)_{50}$, and 700 kPa, $(\phi'_r)_{700}$, for the 32 cohesive soils shown in Table 1. The secant residual friction angle corresponds to a linear failure envelope passing through the origin and the residual shear stress at a particular effective normal stress. It can be seen that the ratio of $(\phi'_r)_{50}$ to $(\phi'_r)_{700}$ is less than 1.3 for clay-size fractions less than 50 percent. For clay-size fractions greater than 50 percent, the ratio of $(\phi'_r)_{50}$ to $(\phi'_r)_{700}$ reaches a maximum of 1.85 to 1.9 at a liquid limit of approximately 100 and decreases to about 1.1 at a liquid limit of 288. Therefore, it may be concluded that the nonlinearity of the drained residual failure envelope is significant; that is $(\phi'_r)_{50}/(\phi'_r)_{700}$ is greater than 1.3 for overconsolidated clays with a liquid limit between 60 and 220 and a clay-size fraction greater than 50 percent. In this range of liquid limit and clay-size fraction, the residual friction angle undergoes a reduction of 25 to 45 percent for effective normal stresses ranging from 50 to 700 kPa.

The effect of a nonlinear residual failure envelope on a stability analysis was investigated using several case histories (*16*). It was found that a stability analysis is sensitive to the stress-dependent nature of the residual strength. As a result, it is concluded that it is more reliable to use the entire nonlinear residual envelope directly in a stability analysis. However, the case histories (*16*) also revealed that the use of a secant residual friction angle that corresponds to the average effective normal stress on the critical slip surface also will provide good agreement with field observations for long slablike failure surfaces that exhibit minor variations in effective normal stress. Thus, for practical purposes the nonlinear residual failure envelope can be estimated using a residual friction angle that

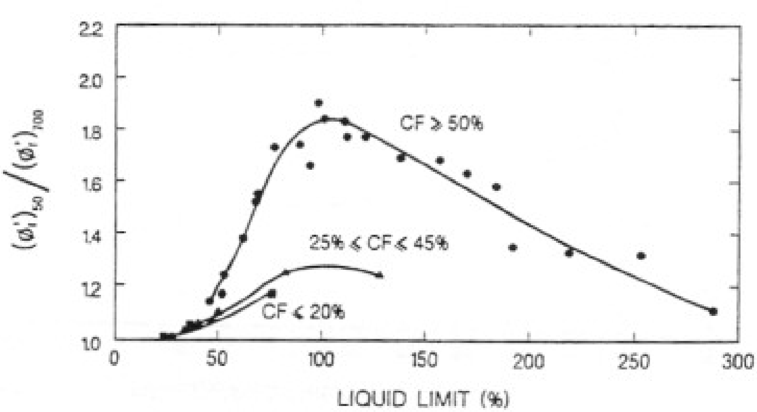

FIGURE 6 Reduction in residual friction angle from effective normal stresses of 50 to 700 kPa (*16*).

TABLE 2 Existing Drained Residual Friction Angle Correlations

Soil Index Property Used in Correlation	Drained Residual Strength Correlation Reference
Clay Size Fraction	Binnie, et al. (19) Blondeau & Josseaume (20) Borowicka (21) Collotta, et al. (22) Lupini, et al. (23) Skempton (3) Skempton (24)
Plasticity Index	Bucher (25) Clemente (26) Fleischer (27) Kanji (28) Lambe (29) Mitchell (30) Seycek (31) Vaughan, et al. (32) Voight (33)
Liquid Limit	Haefeli (34) Mesri and Cepeda (17) Mitchell (30)

corresponds to the average effective normal stress on the critical slip surface.

DRAINED RESIDUAL STRENGTH CORRELATIONS

Because of difficulties associated with obtaining natural slip surface specimens and the laboratory measurement of the drained residual strength, a number of correlations of drained residual friction angle have been proposed (Table 2). These correlations relate the drained residual friction angle to only one soil index property. Stark and Eid (*16*) showed that both the liquid limit and clay-size fraction are required to estimate the secant residual friction angle accurately. In addition, existing correlations ignore the stress-dependent behavior of the drained residual shear strength, which is significant for overconsolidated clays with a liquid limit between 60 and 220 and a clay-size fraction greater than 50 percent.

Figure 7 presents a new correlation of drained residual friction angle. It can be seen that there is a relationship between the secant residual friction angle at effective normal stresses of 100, 400, and 700 kPa and both the liquid limit and clay-size fraction. The higher the liquid limit and clay-size fraction, the lower the secant residual friction angle. The liquid limit appears to be a suitable indicator of clay mineralogy, and thus drained residual strength. However, the clay-size fraction remains an important predictive parameter because it indicates the quantity of clay-size particles, which are particles smaller than 0.002 mm. The proposed correlation differs from existing correlations because the drained residual friction angle is a function of the liquid limit, clay-size fraction, and effective normal stress. Stark and Eid (*16*) compare the proposed and existing correlations using field case histories. It was found that the proposed correlation provided the best agreement with the back-calculated values of the residual friction angle for the field case histories considered, because it incorporates clay mineralogy, the clay-size fraction, and effective normal stress.

The nonlinearity of the drained residual failure envelope is evident by the decrease in the secant residual friction angle with increasing effective normal stress. Figure 7 also confirms that the nonlinearity is significant for cohesive soils with a clay-size fraction greater than 50 percent and a liquid limit between 60 and 220. For example, at a liquid limit of 100 and a clay-size fraction greater than 50 percent, the secant residual friction angle decreases from 9.5 degrees at an effective normal stress of 100 kPa to 6.0 degrees (or 36 percent) at an effective normal stress of 700 kPa. For clay-size fractions less than 50 percent and liquid limits less than 120, the reduction in residual friction angle from 100 to 700 kPa is less than approximately 1.5 degrees.

The secant residual friction angle for a cohesive soil can be estimated for a particular effective normal stress using the liquid limit and clay-size fraction and linearly interpolating between the curves presented in Figure 7. In addition, Figure 7 can be used to estimate the nonlinear residual failure envelope by plotting the shear stress corresponding to the drained residual friction angle at effective nor-

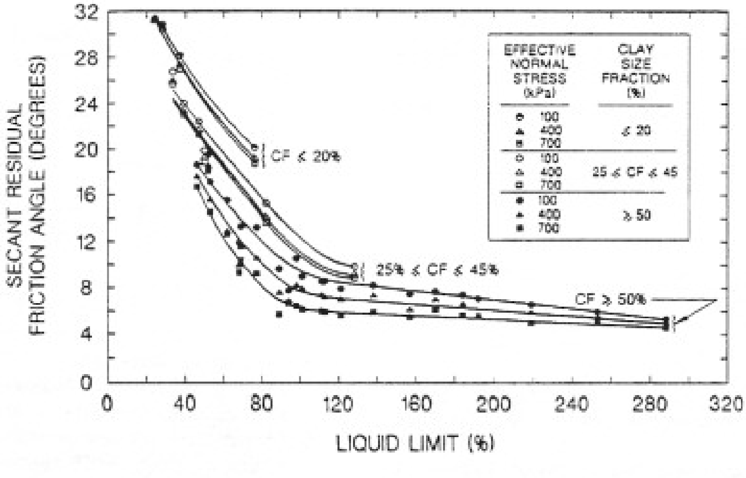

FIGURE 7 Relationship between drained residual friction angle and liquid limit (*16*).

mal stresses of 100, 400, and 700 kPa. A smooth curve can be drawn through these three points and the origin to estimate the nonlinear residual failure envelope.

CONCLUSIONS

The drained residual shear strength of overconsolidated clays is an important parameter in assessing the stability of slopes that contain a preexisting shear surface, such as old landslides or soliflucted slopes, bedding shears in folded strata, sheared joints or faults, or a failed embankment (*3*). Therefore, laboratory measurement of the drained residual strength requires a specimen that contains a shear surface. Because of difficulties in obtaining and testing natural slip surface specimens, a laboratory technique that uses overconsolidated, precut, remolded specimens was developed. A Bromhead ring shear apparatus was modified to permit the use of overconsolidated, precut, remolded specimens and a multistage test procedure. The drained residual strengths measured using this apparatus and test procedure are in excellent agreement with field case histories (*16*).

The magnitude of the drained residual strength is controlled by the type of clay mineral and the quantity of clay-size particles. The liquid limit provides an indication of clay mineralogy, and the clay-size fraction indicates the quantity of clay-size particles, which are particles smaller than 0.002 mm. Therefore, both the liquid limit and clay-size fraction should be used in correlations to estimate the drained residual strength. The results of ring shear tests on 32 clay and clay shales reveal that the drained residual failure envelope can be nonlinear. The nonlinearity is significant for cohesive soils with a clay-size fraction greater than 50 percent and a liquid limit between 60 and 220. This nonlinearity should be incorporated into stability analyses by modeling the entire residual failure envelope or using a secant residual friction angle that corresponds to the average effective normal stress on the slip surface. A new drained residual friction angle correlation is presented that is a function of the liquid limit, clay-size fraction, and effective normal stress. This correlation can be used to estimate the entire nonlinear residual failure envelope or a secant residual friction angle for the average effective normal stress on the slip surface.

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