DRAINED RESIDUAL STRENGTH FOR LANDSLIDES

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ABSTRACT

Drained residual shear strength is considered applicable for the analysis of slopes with a preexisting shear surface. Torsional ring and direct shear tests were performed to investigate the gain in strength, if any, along a preexisting shear surface with time. This study shows that after establishing the drained residual strength conditions, a measureable strength greater than the drained residual strength is obtained in both torsional ring and direct shear tests at effective normal stresses of 100 kPa or less. However, the recovered strength observed in the laboratory is lost after a small shear displacement which suggests that any strength gain may not be relied upon for stabilization purposes so the drained residual strength as measured using ASTM D6467 is recommended for landslide analysis and design.

INTRODUCTION

The selection of shear strength parameters for the analysis and repair of landslides is important. Based on Skempton (1964, and 1985), drained residual shear strength of clays and shales should be used in the analysis of slopes containing preexisting shear surfaces. However, D'Appolonia et al. (1967) suggest healing of a preexisting shear surface can occur because the back-calculated shear strength appeared to be greater than the laboratory determined residual strength for a West Virginia landslide. Subsequently, Ramiah et al. (1973), Angeli et al. (1996 and 2004), Gibo et al. (2002), Stark et al. (2005), and most recently Carrubba and Del Fabbro (2008) also suggest that the strength along a preexisting shear surface may increase with time if the sliding mass ceases movement and remains stable.

To investigate the possibility of strength gain, if any, along preexisting shear surfaces, torsional ring and direct shear tests were performed during this study. This study shows when a specimen that has achieved a residual condition is tested after a rest period, a strength greater than the drained residual value can be observed in both torsional ring and direct shear tests at effective normal stresses of 100 kPa or less which corresponds to shallow landslides or shallow portions of a slip surface (≤5 m). At effective normal stresses greater than 100 kPa, i.e., deep landslides or slip surfaces (>5 m deep), the strength gain observed in the laboratory testing is negligible. Furthermore, the recovered strength observed at effective normal stresses of 100 kPa or less is lost after a small shear displacement suggesting that the recovered strength may not be relied upon even for the design of shallow landslide remedial measures. Therefore, the drained residual strength measured in the laboratory using ASTM D6467 (2008a) should be used for the analysis of both shallow and deep-seated landslides and the design of remedial measures. However, the observed strength gain may be used to explain slope behavior, e.g., reduction in slope creep and stability before reactivation, and differences between measured and back-calculated strengths at low effective normal stresses.

SHEAR STRENGTH IN PREXISTING SHEAR SURFACES

Skempton (1964) suggests that the drained residual strength is mobilized along preexisting shear surfaces caused by prior landsliding, tectonic shearing, bedding shearing, and solifluction. Skempton (1985) concludes that strength of natural shear surfaces measured in the laboratory agree, within practical limits, with values derived from back-analysis of reactivated landslides.

Based on the back-analysis of an ancient landslide in cohesive colluvial soil in West Virginia, D'Appolonia et al. (1967) suggest that the mobilized shear strength is greater than the drained residual strength of the slip surface material. Direct shear tests on undisturbed specimens containing preexisting shear surfaces obtained from shallow portions of the slip surface, i.e., at the slope toe and top, show a peak strength greater than the drained residual strength at effective normal stresses of 100 kPa or less. The researchers postulate that the shear surface in the cohesive colluvial soil underwent "healing" which caused an increase in shear strength above the drained residual value.

Ramiah et al. (1973) present direct shear test results that show strength gain along the shear surface using remolded and normally consolidated clay minerals (kaolinite with LL=66% and bentonite with LL=400%) under three different effective normal stresses (σ'_n) i.e., 29.4, 58.8, and 98.1 kPa. Ramiah et al. (1973) show a strength gain for high plasticity soil (bentonite) even with rest periods up to 4 days whereas low plasticity soil (kaolinite) does not show a strength increase.

Anglei et al. (1996) use direct shear tests whereas Angeli et al. (2004) use Bromhead ring shear tests to study the strength gain mechanism in different clays from northeastern Italy. Tests were performed on normally consolidated specimens using rest periods up to 5 days for direct shear and 9 days for ring shear tests and at σ'_n<100 kPa which correspond to the observed depth of the failure surfaces involved. Angeli et al. (1996 and 2004) report an increase in the recovered shear strength with time during direct and ring shear tests at σ'_n<100 kPa (landslide depth of < 5 m).

Gibo et al. (2002) use a Japanese torsional ring shear apparatus that is similar to the Bishop et al. (1971) ring shear device to investigate strength recovery in two specimens obtained from slip surfaces. Based on test results of remolded, normally consolidated specimens at σ'_n = 30, 60, 100, and 200 kPa, Gibo et al. (2002) conclude that it is reasonable to consider the recovered strength in a stability analysis of a reactivated landslide dominated by silt and sand particles and at low effective normal stresses.

Stark et al. (2005) present Bromhead ring shear test results on two soils of different plasticity, i.e. Duck Creek shale (LL=37%) and Otay Bentonitic shale

(LL=112%), for a single effective normal stress of 100 kPa. Stark et al. (2005) used reconstituted specimens overconsolidated to 700 kPa and then tested at an effective normal stress of only 100 kPa using ASTM D6467 (2008a). This study suggests that a failure surface which has achieved a drained residual strength condition may undergo "healing" and exhibit a strength that is greater than the residual value upon re-shearing for rest periods up to 230 days at σ'_n=100 kPa.

Carrubba and Del Fabbro (2008) conducted similar torsional ring shear tests as Stark et al. (2005) on Rosazzo (LL=45%) and Montona (LL=51%) flyschs from northern Italy, using normally consolidated specimens, aging times of up to 30 days, and at σ'_n = 25, 50, and 100 kPa. The researchers report strength gain in both the soils at $\sigma'_n \leq$100 kPa.

Test results presented by these prior researchers are summarized in Figure 1 which presents the ratio between the recovered shear strength (τ_{Rec}) and drained residual strength (τ_r) as a function of rest time. Even though these researchers used different devices, different soils, and different test procedures, all of the soils show a strength gain above the residual strength at $\sigma'_n \leq$100 kPa, i.e., a landslide depth of about 5 m or less. Ramiah et al. (1973) and Angeli et al. (1996) use direct shear whereas Gibo et al. (2002), Angeli et al. (2004), Stark et al. (2005), and Carrubba and Del Fabbro (2008) use various ring shear devices to investigate strength recovery in the laboratory.

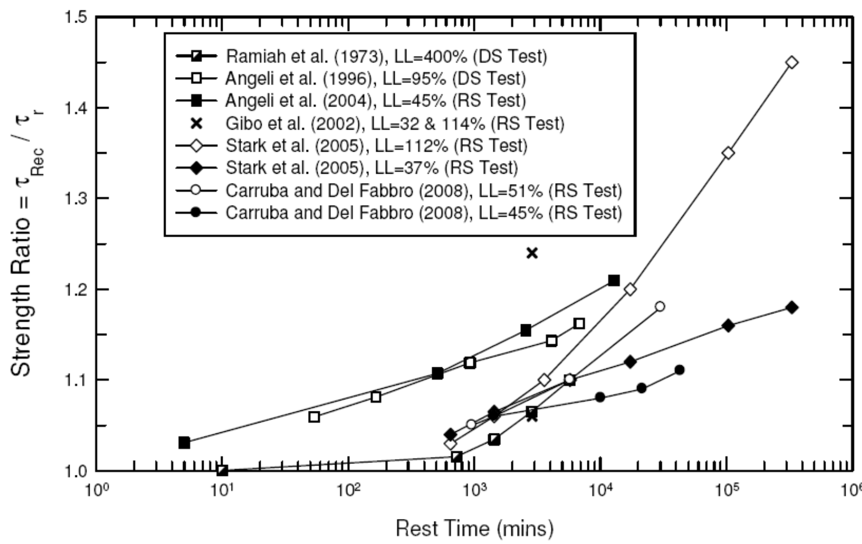


Figure 1. Summary of published strength recovery test results for effective normal stress of 100 kPa or less

STRENGTH RECOVERY TESTS

A laboratory study was conducted herein to investigate the strength recovery using a natural cohesive soil, i.e., Madisette clay from Los Angeles, CA, with liquid and plastic limits of 83% and 29%, respectively, and a clay-size fraction, CF, (< 0.002 mm) of 52%, a similar consolidation and test procedure, two effective normal stresses of 100 and 300 kPa (5-15 m depth), and direct shear and Bromhead ring shear devices. The index properties were determined using ASTM D4318 (2008b) and D422 (2008c). The reconstituted specimen was prepared at an initial water content at or near the liquid limit and hydrated for one week under a moisture controlled environment. Water contents at the end of each ring and direct shear test were measured and these were almost equal to the plastic limit of the soil. The laboratory tests were conducted at constant temperature of 70ºF and using distilled and de-ionized water to submerge the specimens for the entire duration of both ring and direct shear tests.

In the field, after sliding occurs and the slide mass comes to rest, the slide mass remains subject to shear and normal stresses without undergoing any further shear displacement. Therefore, the application of a shear and normal stress during the rest period better simulates field landslide conditions than no shear stress being applied in the laboratory. Therefore, an effective normal and shear stress were applied in both ring and direct shear tests during the rest periods.

Ring Shear Test

The ring shear tests use an overconsolidated specimen up to 700 kPa, ASTM D6467 (2008a), and a drained rate of 0.018 mm/min to establish the drained residual strength condition at the desired effective normal stress before subjecting the specimen to a rest period. After achieving a drained residual strength condition, the specimen is subjected to a rest period under an applied effective normal and shear stress that corresponds to the residual shear stress of the soil. After the rest period, the test is restarted at a displacement rate of 0.018 mm/min and the maximum shear strength is observed. The maximum strength observed, if any, after the rest period is termed the recovered shear strength (τ_{Rec}). The specimen is sheared, usually a small displacement, until the strength returns to the drained residual value and then subjected to another rest period. Ring shear test results on Madisette clay for rest periods of 1, 10, 30, and 90 days at effective normal stresses of 100 and 300 kPa are presented herein for comparison with the direct shear test results. Stark and Hussain (2009) present ring shear results on four natural soils, including Madisette clay, at effective normal stresses ranging from 100 to 600 kPa and rest periods up to 300 days for σ'_n =100 kPa and 90 days for all other effective normal stresses.

Direct Shear Test

To verify the ring shear strength recovery test results, two direct shear tests were performed on Madisette clay using a reconstituted, precut specimen consolidated to 700 kPa. The specimen was consolidated to 700 kPa to simulate the ring shear test procedure so the test results could be compared. Also consolidating the specimen to 700 kPa reduced the potential of the shear surface moving below the gap between the top and bottom halves of the shear box during shearing or a rest period which may result in an increase in strength upon reshearing. The overconsolidation of the specimen also reduced the amount of extrusion during shearing.

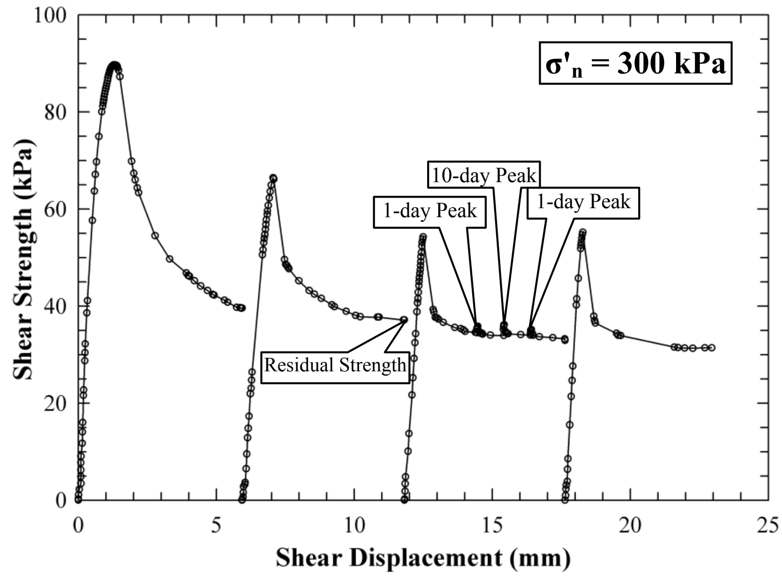
The two halves of the shear box case were consolidated in separate oedometer devices using the procedure described by Mesri and Cepeda-Diaz (1986). Consolidation was performed using incremental loading with a load increment ratio of unity (LIR=1.0) to prevent extrusion of soil during consolidation. Completion of primary compression was ensured under each load before adding the next load increment. After consolidating the specimen to an effective normal stress of 700 kPa, each half of the shear box was unloaded to 100 kPa in decrements to allow rebound and then reloaded to 300 kPa and allowed to recompress to minimize secondary compression during the direct shear test. At the end of consolidation, the thickness of the specimen left in the top and bottom halves of the shear box was 5.5 and 7.0 mm respectively.

To create a slickensided surface after consolidation, a surgical blade was used to pre-shear the lower face of the upper shear box and the upper face of the lower shear box. This pre-cutting resulted in orientation and alignment of clay particles along the face of each half in the direction of first movement of the shear box. This pre-shearing process reduced the shear displacement required to achieve the initial drained residual strength condition (see Figure 2 and 3) which reduced the amount of soil extrusion and potential for the shear surface to move below the gap between the top and bottom halves of the shear box.

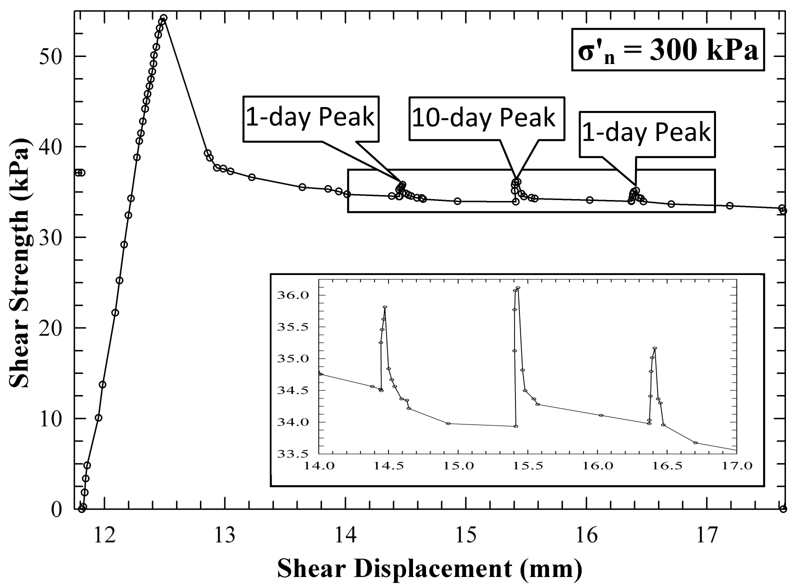
After completion of consolidation and preshearing, the two halves were placed on top of each other making a 12.5 mm thick specimen in the direct shear device. The assembled shear box was then placed in the direct shear apparatus and loaded to an effective normal stress of 300 kPa. Special care was taken to ensure that the shear surface remained within the gap between two halves of the shear box during re-loading to 300 kPa. After observing the compression/swelling behavior of the specimen in the assembled box, the specimen was sheared at a drained rate of 0.0034 mm/min based on ASTM D3080 (2008d) until the residual strength condition was established. The residual strength condition was obtained by reversing the shear box back and forth as shown in Figure 2.

After obtaining the drained residual strength condition, the test was continued until the shear stress-displacement relationship became constant while the shear box was moving in the forward direction (see third cycle of shear stress-displacement relationship in Figure 2). The test was stopped to observe the strength recovery, if any, when the shear box was moving in the forward. The forward direction was used because the proving ring would be in compression and not in tension during the rest periods to match the calibration process. When the shear stress-displacement relationship became constant, the test was stopped for a rest period of one day. During the rest period, the shear stress is not likely to drop because the soil is offering a shear resistance equal to its residual strength.

After one day of rest, the test was restarted at a rate of 0.0034 mm/min and the change in shear stress, if any, was noted. Any increase in shear stress above the residual value observed after restarting the test is the recovered strength after a rest period of one day. Specimen shearing was continued until the strength returned to the residual value and then the test was stopped for a rest period of 10 days. After 10 days, the test was restarted and changes in shear stress were measured. The maximum strength observed after a rest period of 10 days is the recovered strength at 10 days (see Figure 2). The one day test result was confirmed by repeating a one day rest period for the second time after obtaining the residual strength conditions after 10 days test (see Figure 2). To avoid excessive settlements at effective normal stress of 300 kPa, the specimen was not subjected to any other rest period.



(a)



(b)

Figure 2. (a) Complete test result of reversal direct shear strength recovery test at an effective normal stress of 300 kPa and (b) only third cycle during which specimen subjected to various rest periods.

After completion of the second one day rest period test (see Figure 2(b)), the specimen was sheared until it reached the original position by reversing the direction of shear until both halves of the shear box were aligned on top of each other. Both top and bottom halves were connected together with the locking box screws and the specimen was unloaded to an effective normal stress (σ'_n) of 100 kPa. The specimen was allowed to swell at this effective normal stress until no change in vertical dial gauge reading was observed. After the specimen completed swelling, the screws connecting the top and bottom halves of the shear box were removed to start shearing.

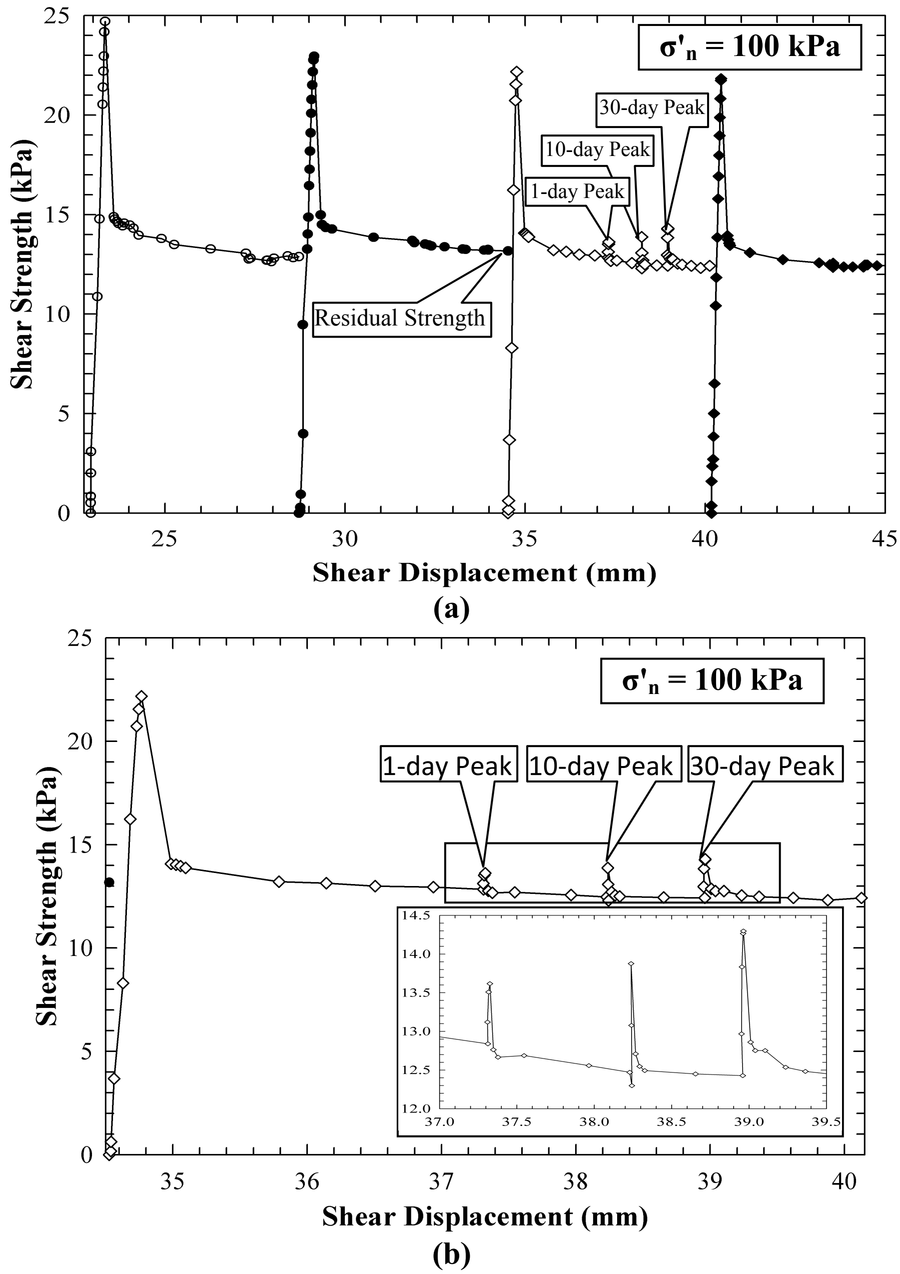


Figure 3. (a) Complete test results for direct shear strength recovery test at an effective normal stress of 100 kPa and (b) third cycle during which specimen subjected to various rest periods.

The specimen was sheared at the same drained rate, i.e., 0.0034 mm/min and a residual strength condition at effective normal stress of 100 kPa was established. The test was stopped following the same procedure described for an effective normal stress of 300 kPa and subjected to rest periods of 1, 10, and 30 days (see Figure 3). The maximum shear resistance observed after each rest period is the recovered strength for that particular rest period. Shorter rest periods were selected for the direct shear tests to reduce the potential for the shear surface to move below or above the gap between the two halves of the shear box and causing a strength increase. Vertical displacement versus shear displacement behavior during shearing at σ'_n of 300 and 100 kPa are shown in Figure 4.

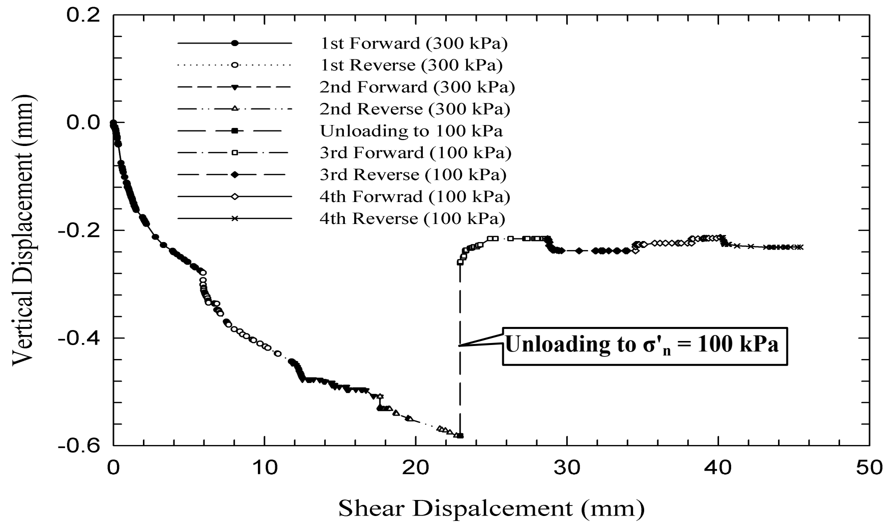


Figure 4. Vertical settlement versus shear displacement during reversal direct shear strength recovery test at effective normal stresses of 300 and 100 kPa for specimen consolidated to 700 kPa.

TEST RESULTS AND DISCUSSION

Figure 5 shows the ratio between the recovered and residual shear strengths (τ_{Rec}/τ_r) as a function of rest time from ring and direct shear test results at 100 and 300 kPa on Madisette clay. The ring shear (RS) and direct shear (DS) test results at an effective normal stress of 100 kPa differ but are in agreement at 300 kPa. The difference between the RS and DS test results at an effective normal stress of 100 kPa may be due to differences in measured drained residual shear strength in each device, difference in test procedures, and state of applied stresses during the rest periods in both devices. The drained residual strengths measured in the RS tests are in agreement with Stark et al. (2005) but the DS residual strengths are lower.

The RS and DS data in Figure 5 shows that the recovered strength is greater than the drained residual strength at an effective normal stress of 100 kPa and is essentially negligible at an effective normal stress of 300 kPa. An effective normal stress of 100 kPa corresponds to shallow landslides ($\leq$ 5 m deep) which suggest that the strength recovery is possible only in shallow landslides or at shallow depths of deep-seated landslides. These findings are in agreement with the conclusions presented by D'Appolonia et al. (1967), Ramiah et al. (1973), Angeli et al. (1996 and 2004), Gibo et al. (2002), Stark et al. (2005), and Carrubba and Del Fabbro (2008). At shallower depths this gain may be caused by the rebound or unbending of the oriented clay particles along the shear surface at the lower effective normal stress which may not be possible at greater depths due to higher effective normal stresses. It is also observed during the tests that the recovered strength is lost after a small shear displacement so the recovered strength may not be useful for practice. Furthermore, the strength gain at 100 kPa or less may not be economically significant for the repair of shallow landslides or shallower portion of a deep-seated landslide. Instead this strength gain may be useful in explaining the behavior of shallow landslides investigated by researchers such as D'Appolonia et al. (1967), Angeli et al. (1996 and 2004) and Gibo et al. (2002). For example, the observed strength gain may be used to explain slope behavior, such as reduction in slope creep, cessation of slope movement, and stability before reactivation. The possibility of strength gain should also considered in back-analyses of landslides especially when the measured drained residual strength appears to be lower than the back-calculated value at low effective normal stresses. In summary, it is recommended that the drained residual shear strength measured using ASTM D6467 (2008c) be used for the analysis and design of remedial measures for shallow and deep-seated landslides.

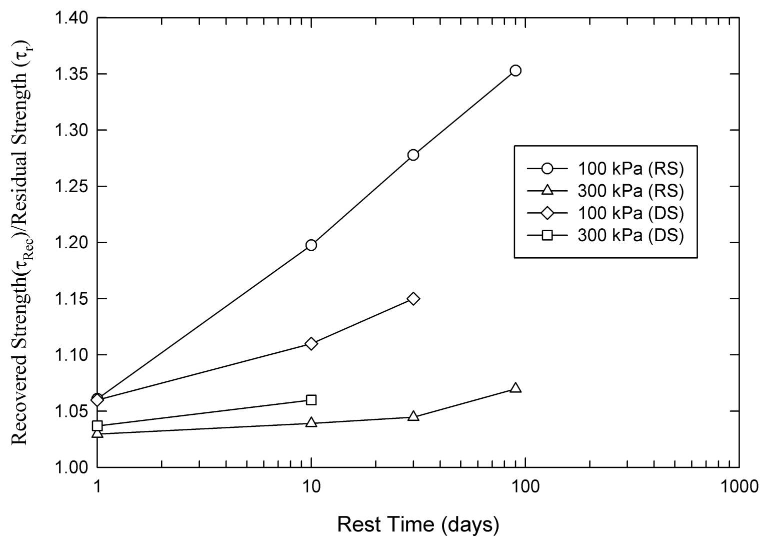


Figure 5. Ratio between recovered and residual strength as function of time observed during ring shear (RS) and direct shear (DS) tests at effective normal stresses of 100 and 300 kPa.

CONCLUSIONS

Based on the test results presented herein, a strength gain above drained residual strength is possible in shallow landslides or at shallower depths of a deep-seated landslide (depth of 5 m or less) and is negligible in deep-seated landslides with depths greater than 5 m. The observed recovered strength in ring and direct shear tests even at an effective normal stress of 100 kPa is lost with a small shear displacement and the benefit of this strength for the repair of shallow landslides or the shallower portion of a deep-seated landslide may not be economically significant. This leads to the conclusion that the observed strength gain has limited practical significance in the analysis and repair of landslides. However, the strength gain may be useful in explaining the behavior of shallow landslides, such as amount and rate of slope creep and stability prior to reactivation. It is also concluded that the analysis and design of both shallow and deep-seated landslides should use the drained shear strength measured using ASTM D6467 (2008c).

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