SHEAR STRENGTH IN PREEXISTING LANDSLIDES

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ABSTRACT

Drained residual shear strength is used for the analysis of slopes containing preexisting shear surfaces. Some recent research suggests that preexisting shear surfaces in prior landslides, can gain strength with time. Torsional ring and direct shear tests performed during this study show that the recovered shear strength measured in the laboratory is only noticeably greater than the drained residual strength at effective normal stress of 100 kPa or less. The test results also show that the recovered strength even at effective normal stresses of 100 kPa or less is lost after a small shear displacement, i.e., slope movement. An effective normal stress of 100 kPa corresponds to a depth of about 5 m so the observed strength gain has little, if any, impact on the analysis of deep landslides. This paper describes the laboratory strength recovery testing and the results for soils with different plasticity at various rest periods and effective normal stresses.

Keywords: Soil mechanics, Landslides, Overconsolidated clays, Shear strength, Strength recovery, Slope stability, Ring shear test.

INTRODUCTION

The selection of shear strength parameters for the design and repair of slopes in landslide areas is important and difficult (Stark et al., 2005). Skempton (1964) concludes that if a failure has

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already occurred in clayey soils, any subsequent movement along the existing slip surface will be controlled by the drained residual strength. Skempton (1985) suggests that the strength of a clay will be at or close to the residual value on slip surfaces in old landslides, soliflucted slopes, bedding shears in folded strata, sheared joints or faults, and after an embankment failure. Therefore, the drained residual shear strength has been and is still being used for analysis of slopes that contain a preexisting shear surface.

D'Appolonia et al. (1967), Ramiah et al. (1973), Angeli et al. (1996 & 2004), Gibo et al. (2002), Stark et al. (2005), and Carrubba and Del Fabbro (2008) suggest that preexisting shear surfaces may exhibit a higher shear strength than the drained residual value after a period of time in which the slope remains stable, i.e., does not experience shear displacement. This assertion of strength recovery may impact landslide mitigation and remedial measures because the increased strength could result in savings to insurance companies and/or landslide mitigating agencies. Therefore, the objective of this study is to investigate the possibility of strength recovery along preexisting shear surfaces using a suitable laboratory shear device, test procedure that models field conditions, variety of natural soils with a range of plasticity from LL = 37-112%, a range of effective normal stresses from 100 to 600 kPa, and rest periods up to 300 days.

This paper describes the laboratory ring shear and direct shear strength recovery test procedures and the observed strength recovery behavior for a range of soil plasticity and effective normal stresses.

PREVIOUS STUDIES OF STRENGTH RECOVERY ALONG SHEAR SURFACES

D'Appolonia et al. (1967) conclude that the shear surface in a cohesive colluvial soil in an ancient landslide in West Virginia, underwent "healing" because the back-calculated shear

strength was found to be greater than the laboratory determined drained residual value. D'Appolonia et al. (1967) performed direct shear tests on undisturbed specimens containing the preexisting shear surface obtained from shallow portions of the slip surface, i.e., at the slope toe and top, and these tests show a peak strength greater than the laboratory drained residual strength at effective normal stresses of 100 kPa or less.

Ramiah et al. (1973) investigated the strength gain in remolded and normally consolidated clay minerals (kaolinite with LL=66% and bentonite with LL=400%) in reversal direct shear tests under three different effective normal stresses i.e., 29.4, 58.8, and 98.4 kPa. After reaching the residual condition, the specimens were resheared after rest periods of up to 4 days. Ramiah et al. (1973) show a strength gain for high plasticity soil (bentonite) even with a short rest period whereas low plasticity soil (kaolinite) does not show a strength increase.

Chandler (1984) presents a study of reactivated landslides which shows the back-calculated friction angles are greater than those measured using a ring shear device on slip surface specimens. Chandler (1984) did not discuss the possibility of strength recovery of the preexisting shear surfaces and attributed the difference in friction angle to the movement on a single shear plane in the ring shear device and possibly several different shear surfaces or a shear zone in the field.

Anglei et al. (1996) use direct shear tests whereas Angeli et al. (2004) use ring shear tests to study the strength gain mechanism in different clays including London clay. Tests were performed on normally consolidated specimens using rest periods of up to 5 days for direct shear and 9 days for ring shear for effective normal stresses ranging from 71 to 220 kPa but detailed results for only effective normal stress equal to or less than 100 kPa are presented. Angeli et al.

(1996 & 2004) report an increase in the recovered shear strength with time during these direct and ring shear tests.

Gibo et al. (2002) use ring shear tests to measure the strength recovery for two different reactivated landslides. Tests were performed on remolded, normally consolidated slip surface specimens at effective normal stresses ranging from 30 to 300 kPa using rest periods of two days. Gibo et al. (2002) conclude that it is reasonable to consider the recovered strength in the stability analysis of a reactivated landslide dominated by silt and sand particles and effective normal stress less than 100 kPa.

Stark et al. (2005) present laboratory ring shear test results on two soils of different plasticity, i.e. Duck Creek shale (LL=37%) and Otay Bentonitic shale (LL=112%), under a single effective normal stress of 100 kPa. This study was motivated by a 1991 landslide project near Seattle, Washington and suggests that a preexisting failure surface may undergo strength recovery and exhibit a shear strength that is greater than the residual value for rest periods up to 230 days at an effective normal stress of only 100 kPa. It was also observed that the magnitude of recovered shear strength increases with increasing soil plasticity but the recovered strength is lost with small shear displacement after the rest period.

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 effective normal stresses of 25, 50, and 100 kPa. Carrubba and Del Fabbro (2008) report more strength gain in Montona flysch than Rosazzo flysch but all of the testing occurred at an effective normal stress of 100 kPa or less.

Fig. 1 summarizes the test results presented by these prior studies using the ratio between the drained recovered shear strength (τ_{Rec}) and drained residual strength (τ_r) as a function of rest time. Even though these researchers used different devices and test procedures, all soils show a strength gain above the residual strength for a range of test procedures and shear devices at effective normal stresses of 100 kPa or less which corresponds to a landslide depth of 5 m or less.

LABORATORY STUDY OF SHEAR STRENGTH RECOVERY

General

All of the researchers discussed above used normally consolidated specimens except Stark et al. (2005) so some gain in strength may have resulted from secondary compression, i.e., decrease in void ratio, during the rest periods. Also the prior researchers used material passing #40 sieve (0.425 mm) whereas Stark et al. (2005) used material passing #200 sieve (0.002 mm). The peak strength observed after the rest period in the direct shear device also may have been caused by the shear surface moving below the gap between the top and bottom halves of the shear box due to secondary compression of a normally consolidated specimen. In the present study, laboratory testing was conducted to investigate the strength recovery of four natural clay soils with a range of plasticity (LL=37-112%), a test procedure that models field conditions, a range of effective normal stress from 100 to 600 kPa, and a rest period up to 90 days for all effective normal stresses and 300 days for an effective normal stress of 100 kPa. The laboratory tests were conducted at constant temperature of 70ºF and using distilled and deionized water to submerge the specimens for the entire duration of the tests.

The ring shear strength recovery tests performed herein utilize the following four soils: Duck Creek shale, Esperanza Dam silty clay, Madisette clay, and Otay bentonitic shale. The index properties of these soils are shown in Table 1 and were determined using the procedures presented in ASTM D4318 (2008a) and D422 (2008b). Duck Creek shale and Otay bentonitic shale were retested herein because a shear stress was not applied during the rest periods by Stark et al. (2005).

Strength Recovery Test Procedure

A torsional ring shear device was used to conduct strength recovery tests by Gibo et al. (2002), Angeli et al., (2004), Stark et al., (2005) and Carrubba and Del Fabbro, (2008) and was used herein. Although a direct shear device was also used to verify the ring shear results herein, this paper focuses on the ring shear test results because of space constraints.

Prior to strength recovery, the drained residual strength of the soil is measured using the equipment and procedure described in Stark and Eid (1993 and 1994) and ASTM D6467 (2008c). The strength recovery tests utilize remolded specimens from shear surface samples. The reconstituted specimen is consolidated in the ring shear device to an effective normal stress of 700 kPa. After consolidation at 700 kPa, the specimen is unloaded to the effective normal stress at which the strength recovery test will be conducted. After unloading to the desired effective normal stress, the specimen is pre-sheared to start formation of a shear surface using the procedure described in ASTM D 6467 (2008c). The pre-sheared specimen is allowed to dissipate excess pore-water pressures for 24-hours after pre-shearing before drained shearing is commenced. This 24-hour period is not a healing period but a pore pressure equilibration period. Afterwards, the pre-sheared specimen is sheared at a drained shear displacement rate of 0.018

mm/min until the drained residual shear strength is obtained. After achieving a drained residual strength, shearing is stopped and the specimen is allowed to rest in the ring shear device.

The specimen is subjected to the applied effective normal stress and the measured residual shear stress for the entire duration of the rest period. Because the sliding mass in the field remains subjected to a shear stress after movement, the shear force applied at the end of residual strength test is maintained on the specimen throughout the rest period to simulate field conditions. The gears used to rotate the ring shear specimen container remain engaged and prevent any reduction in shear force during the rest period. Thus, the specimen remains subjected to the residual shear and normal stresses during the rest period. The rest periods used herein are 1, 10, 30, and 90 days for all applied effective normal stresses except 100 kPa which also used 300 days.

After a rest period of one day, shearing is restarted with the shear and effective normal stress corresponding to the drained residual condition. The specimen is sheared and the maximum strength after healing is measured, which may or may not be greater than the residual value. Shearing is continued until the initial drained residual strength is achieved again. After the drained residual strength is achieved again with additional shear displacement, shearing is stopped and the specimen is allowed to rest for the next rest period under the imposed shear and effective normal stress.

The recovered shear strength for the other rest periods, i.e., 10, 30, 90, and 300 days, are measured by repeating the procedure described above for the one day rest period (see Fig. 2). The drained residual strength at the end of shearing performed after each rest period is at or near the initially determined drained residual strength as shown in Fig. 2.

TEST RESULTS AND DISCUSSION

The fully softened shear strength (τ_{fs}) corresponds to the peak shear strength of a normally consolidated soil with random particle arrangement which is the upper bound strength used for the analysis of slopes that have not undergone previous sliding. Therefore, τ_{Rec} is not expected to exceed τ_{fs} in the laboratory or field because of the presence of a preexisting shear surface and alignment of the clay particles along the shear surface parallel to the direction of shear (see Fig. 2 where τ_{fs} is 42.0 kPa which is well above τ_{Rec}). Furthermore, τ_r is the minimum or lower bound strength which is used in the analysis of ancient and reactivated landslides and is also used as a reference strength for strength recovery because the recovered strength is the increase above the residual value. Thus, τ_{fs} and τ_r are considered upper and lower bound strengths, respectively, for the recovered strength and provide a means for evaluating the significance, if any, of the measured strength gain. The "*recovered strength ratio*" (RSR) is the difference between τ_{Rec} and τ_r divided by the difference between τ_{fs} and τ_r as shown in Eq. (1).

$$\text{Recovered Strength Ratio (RSR)} = \frac{\left(\tau_{\text{Rec}} - \tau_r\right)}{\left(\tau_{fs} - \tau_r\right)} \tag{1}$$

If no strength recovery occurs, τ_{Rec} equals τ_r and the RSR equals zero. If the soil gains strength to τ_{fs} (which is not likely/possible), τ_{Rec} equals τ_{fs} so the RSR equals unity. Thus, the range of values of the recovered strength ratio is zero to less than unity.

The data in Table 2 are used to calculate the RSR for each soil and each rest period at an effective normal stress (σ'_n) of 100 kPa. Table 2 also presents the values measured for drained fully softened friction angle (ϕ'_{fs}), drained residual friction angle (ϕ'_r), and drained recovered

friction angle (ϕ'_{Rec}) for each soil at σ'_n = 100 kPa. Corresponding RSR values calculated using Eq. 1 are plotted on Fig. 3. The plots show an increase in recovered strength ratio with increasing the rest periods for all four soils tested. Fig. 3 also shows that the RSR at an effective stress of 100 kPa is measurably greater than the drained residual strength but is negligible at effective normal stresses greater than 100 kPa. Furthermore, RSR increases for all of the soils tested with increasing rest time albeit at different magnitudes (see Fig. 3). These results are in agreement with prior testing, e.g., Ramiah et al. (1973), Angeli et al., (1996 and 2004), Gibo et al., (2002), Stark et al., (2005) and Carrubba and Del Fabbro, (2008) that show a strength gain at $\sigma'_n \leq$ 100 kPa (see Fig. 1). The main differences in the current study and other studies is the investigation of strength recovery at σ'_n > 100 kPa (up to σ'_n = 600 kPa) and rest periods up to 300 days or almost one year. Fig. 3 shows test results at σ'_n > 100 kPa are substantially lower than at σ'_n = 100 kPa with values of RSR less than 0.2 for Esperanza Dam and less than 0.1 for Madisette clay.

Duck Creek shale with the lowest plasticity (LL=37%) and the smallest difference between τ_{fs} and τ_r exhibits the highest RSR at 100 kPa (see Fig. 3). Fig. 3 indicates that the rate of increase in RSR is decreasing after 300 days and σ'_n = 100 kPa so the RSR for Duck Creek shale probably will not reach unity. Otay bentonitic shale with the highest plasticity (LL=112%) and the largest difference between the τ_{fs} and τ_r exhibits the lowest RSR for the rest periods considered. Fig. 3 also shows that the increase in RSR for Otay bentonitic shale is starting to decrease with time and probably will not exceed an RSR of 0.4. Silty clay from Esperanza Dam and Madisette clay from Los Angeles exhibit RSRs in between Duck Creek and Otay bentonitic shales which is in agreement with the liquid limit/plasticity of these materials.

Fig. 4 presents the normalized strength ratio (NSR) given by Eq. (2) as a function of rest time on a semi-log scale.

$$\text{Normalized Strength Ratio (NSR)} = \frac{\left(\tan \phi'_{\text{Rec}} - \tan \phi'_{\text{r}}\right)}{\left(\tan \phi'_{\text{r}}\right)} \tag{2}$$

Fig. 4 shows the largest increase in NSR occurs for the highest plasticity soil and increases quicker than for lower plasticity soils at an effective normal stress of 100 kPa. The data in Fig. 4 may be important for landslides because many slides occur along high plasticity soil but a significant strength gain only occurred at an effective normal stress of 100 kPa.

In summary, higher plasticity soils exhibit a higher strength recovery at 100 kPa which may be caused by secondary compression, van der Waals attractions, thixotropic hardening and/or particle reorientation. The ring shear specimens tested herein were submerged in distilled and deionized water, and the tests were conducted at a constant temperature of 70ºF so desiccation, water chemistry, and temperature probably did not play a major role in the strength increase at $\sigma'_{\text{n}} = 100$ kPa. During the ring shear tests the water content of the specimens could not be determined because the specimens would have to be unloaded and new soil added to repair the ring shear specimen to measure water content. Water contents measured at the end of the test for each specimen were almost equal to the plastic limit of the soil. Some vertical settlement was observed during each rest period even though the applied normal stress remained constant during the rest period. This vertical settlement is probably due to secondary compression of the shear zone material during the rest period.

It is anticipated that at an effective normal stress of 100 kPa or less, the clay particles have a greater ability to rebound from being oriented parallel to the direction of shear causing a

small increase in strength than at high normal stresses. At higher effective normal stresses the clay particles cannot rebound or reorient because of the high applied normal stress, as a result, the clay particles remain essentially parallel to the direction of shear and thus the shear resistance after healing is at or near the previously attained residual strength.

USE OF RECOVERED SHEAR STRENGTH FOR DESIGN

The recovered strength may have an impact on the analysis and repair of shallow landslides (≤ 5 m depth) in high plasticity material because strength gain was observed at $\sigma'_n = 100$ kPa. τ_{Rec} appears to have little, to no, practical impact for deep landslides (see Fig. 4). Remediation of deep landslides is more of a concern because of the higher repair costs involved than shallow landslides. The recovered strength may be applicable to the shallow (≤ 5 m) portion of a deep landslide which is usually fairly small. Thus, it is anticipated that the recovered strength will not significantly impact the analysis or repair of deep landslides.

In addition, the test results herein show that even at low effective normal stress, most of the strength gain is lost if the specimen undergoes a small shear displacement. This indicates τ_{Rec} reflects a brittle and sensitive soil structure (see Fig. 2) and probably should not be relied upon in design even at effective normal stresses of 100 kPa or less. Thus, use of a recovered strength in the design of landslide remedial measures is not recommended at this time. However, the strength recovery may be useful in explaining the behavior of shallow landslides, such as explaining the amount and rate of slope creep or slope stability prior to reactivation as suggested by D'Appolonia et al. (1967). In summary, this study confirms Skempton's (1964 and 1985) suggestion of using the drained residual shear strength for remediation of reactivated landslides and for comparison with back-calculated shear strength values.

SUMMARY AND CONCLUSIONS

This study expands on previous studies on strength gain along preexisting shear surfaces in terms of rest periods, range of effective normal stresses, particle size of the material tested, range of plasticity of soils, and stress condition during rest period. Based on the laboratory ring shear strength recovery test results for four natural soils that exhibit a range of plasticity described herein, the following conclusions are presented:

1. Strength recovery at low effective normal stresses of 100 kPa or less, which represents shallow landslides ($\leq$ 5 m depth) or shallow portions along a deep failure surface, is noticeable. Strength gain is essentially negligible at effective normal stresses greater than 100 kPa.

2. Strength gain at effective normal stresses of 100 kPa or less likely may result from rebounding/reorienting of clay particles previously oriented parallel to the direction of shear. At higher effective normal stresses, the particles are less able to rebound/reorient and therefore the strength gain is negligible.

3. High plasticity soils, with a large difference between the fully softened and residual strengths, exhibit a higher strength gain from the residual value than low plasticity soils at an effective normal stress of 100 kPa or less.

4. Even at low effective normal stress the recovered strength will not reach the fully softened strength for the soils tested because of the presence of a preexisting shear surface and clay particles oriented parallel to the direction of shear. The recovered shear strength for low plasticity soils (LL< 50%) is closer to the fully softened strength after

long recovery periods than high plasticity soils (liquid limit between 80% and 112%) at an effective normal stress of 100 kPa or less. This is caused by the smaller difference between the fully softened and residual strengths for low plasticity soils.

5. Use of the recovered strength for landslide remedial measures at effective normal stresses of 100 kPa or less is not recommended because the strength gain is lost with a small shear displacement. Therefore, Skempton's (1964 and 1985) suggestion of using the drained residual shear strength for remediation of reactivated landslides and for comparison with back-calculated shear strength parameters should still be followed. The recovered strength at $\sigma'_n \leq 100$ kPa may be useful in explaining the amount and rate of slope creep or slope stability prior to reactivation.

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Figure Caption List

List of Figs:
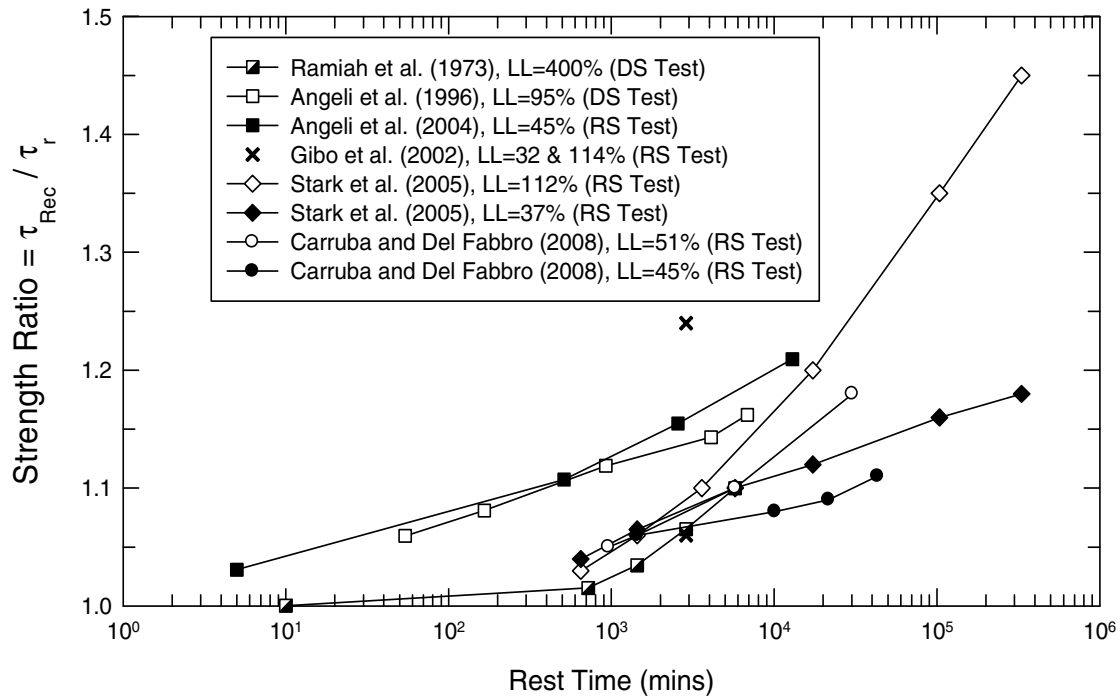
Fig. 1. Summary of published strength recovery test results
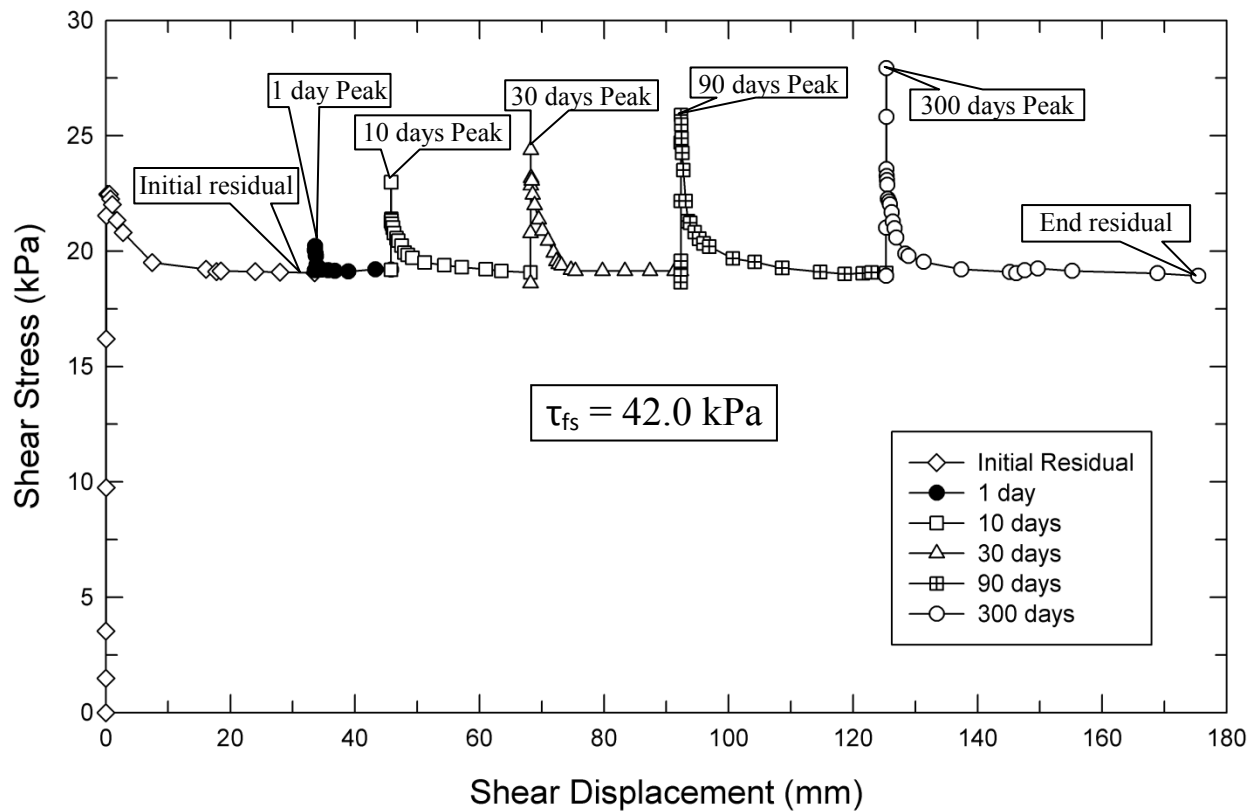
Fig. 2. Schematic diagram showing results of a strength recovery test on Madisette clay under an effective normal stress of 100 kPa

Fig. 3. Recovered strength ratio as function of rest time for various effective normal stresses

Fig. 4. Normalized strength ratio (NSR) versus rest time at various effective normal stresse

Figure 1

Fig. 1. Summary of published strength recovery test results

Figure 2

Fig. 2. Schematic diagram showing results of a strength recovery test on Madisette clay under an effective normal stress of 100 kPa
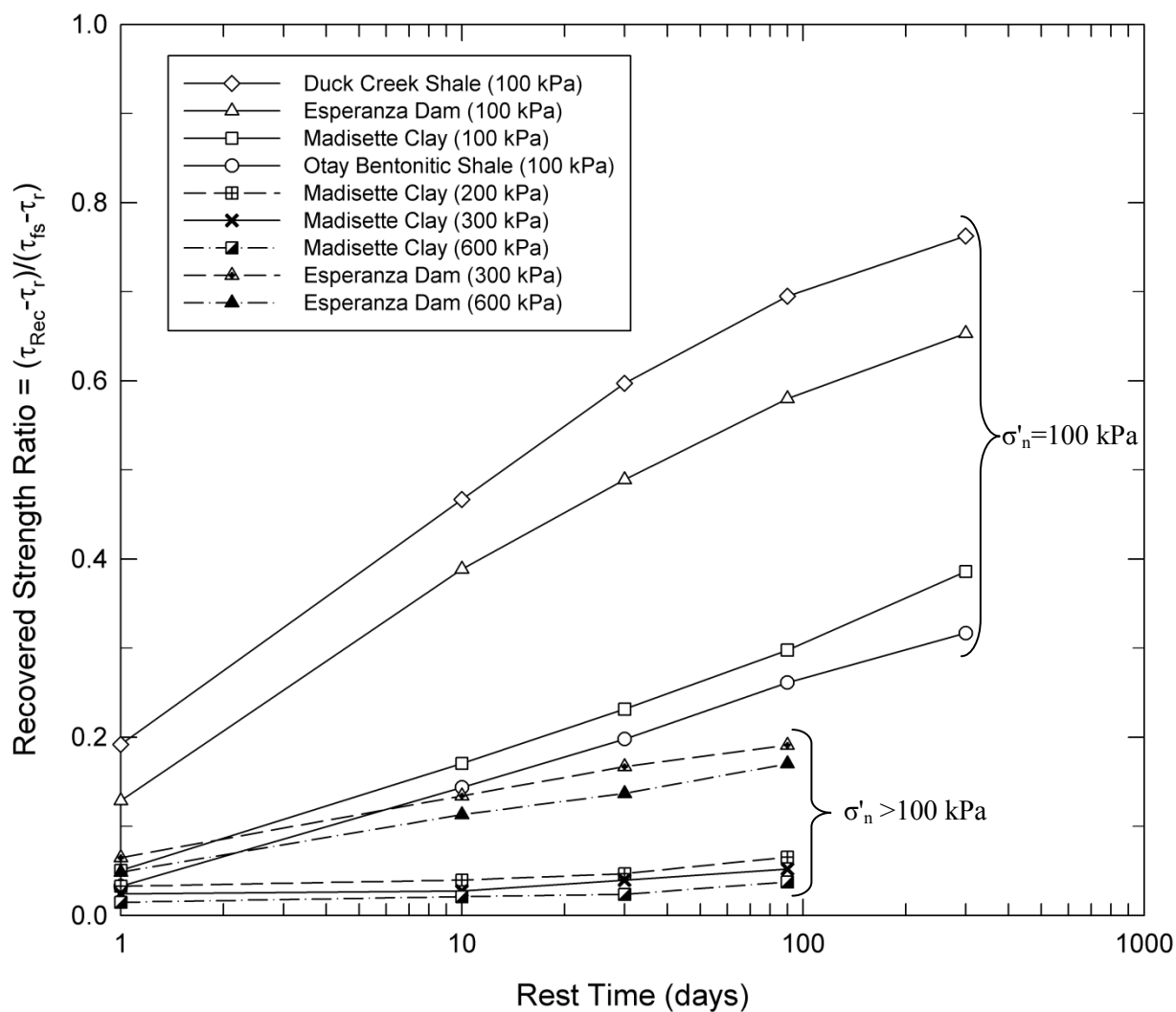
Figure 3

Fig. 3. Recovered strength ratio as function of rest time for various effective normal stresses

Figure 4
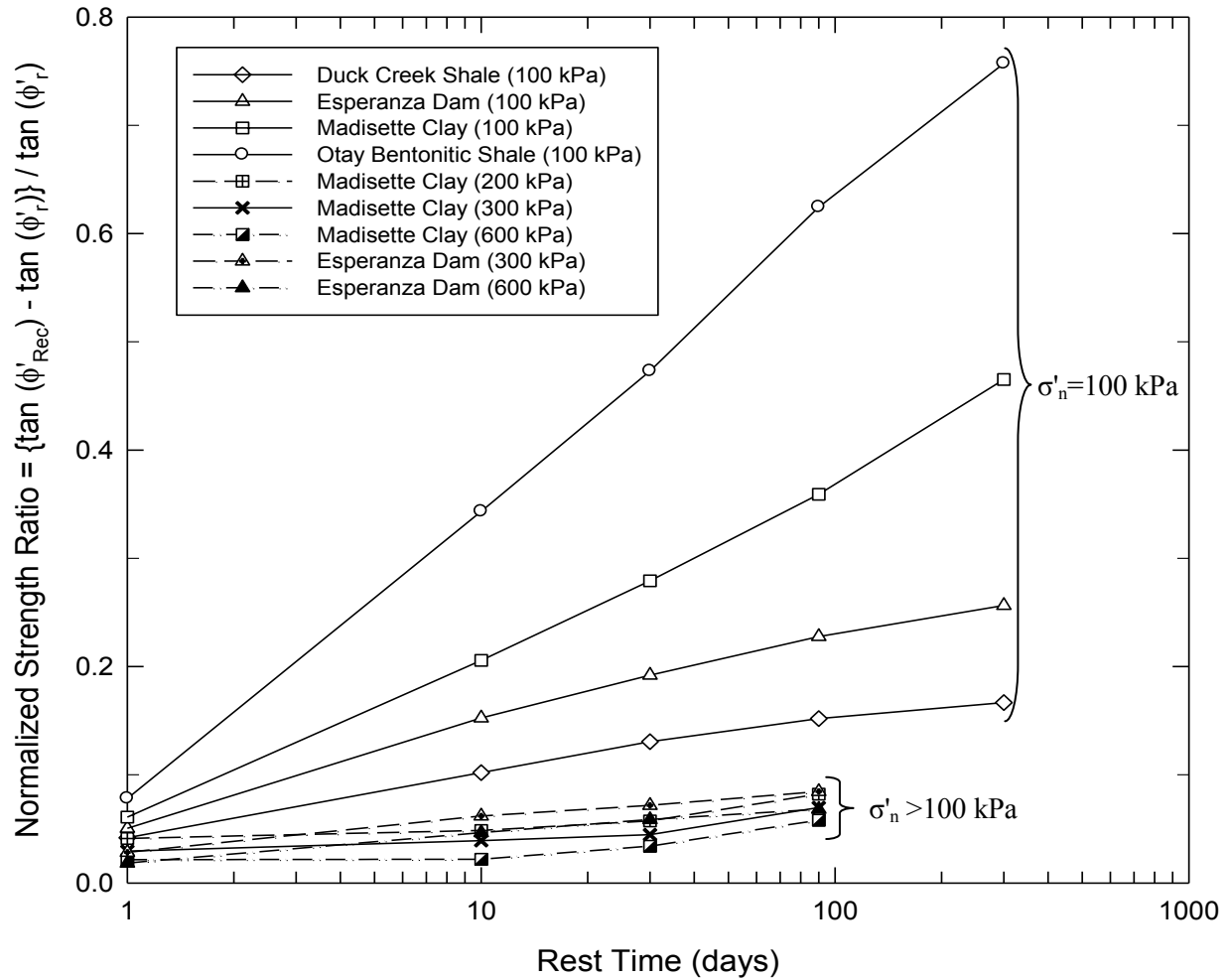
Fig. 4. Normalized strength ratio (NSR) versus rest time at various effective normal stresses

Table 1 & 2

Table 1. Index properties of soils selected for strength recovery tests

Soil Type	Soil Locations	Liquid Limit (%)	Plastic Limit (%)	Clay size fraction (CF) (<0.002mm, %)	Plasticity Index (PI)	Activity (A_c)
Duck Creek Shale	Fulton, IL	37	25	19	12	0.63
Silty Clay	Esperanza Dam, Ecuador	55	40	28	15	0.54
Madisette Clay	Los Angeles, CA	83	29	52	54	1.04
Otay Bentonitic Shale	San Diego, CA	112	53	73	59	0.81

Table 2. Increase in friction angles measured during strength recovery tests at effective normal stress of 100 kPa

Soil Type	Secant Friction Angles		Increase in Friction Angles ($\Delta\phi' = \phi'_{Rec} - \phi'_r$)				
	(ϕ'_{fs}, deg)	(ϕ'_r, deg)	1 day	10 day	30 day	90 day	300 day
Duck Creek Shale	33.6	28.6	1.00	2.40	3.05	3.53	3.86
Silty Clay	30.1	22.6	1.02	3.03	3.79	4.47	5.01
Madisette Clay	22.8	10.8	0.63	2.14	2.9	3.72	4.92
Otay Bentonitic Shale	19.0	5.8	0.45	1.97	2.71	3.57	4.32