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Experimental Study of Strength Recovery from Residual Strength on Kaolin Clay

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Abstract—Strength recovery effect from the residual-state of shear is not well address in scientific literature. Torsional ring shear strength recovery tests on kaolin clay using rest periods up to 30 days are performed at the effective normal stress 100kN/m^2. Test results shows that recovered strength measured in the laboratory is slightly noticeable after rest period of 3 days, but recovered strength lost after very small shear displacement. This paper mainly focused on the strength recovery phenomenon from the residual strength of kaolin clay based on torsional ring shear test results. Mechanisms of recovered strength are also discussed.

Keywords—Kaolin clay, Residual strength, Strength recovery, Torsional ring shear test.

I. INTRODUCTION

IN recent years, the torsional ring shear apparatus has been widely used to measure the residual shear strength of a soil. The main advantage of this apparatus is that it can shear a specimen continuously in one direction to obtain the large displacement that allows clay particles to be oriented parallel to the direction of shear, thus developing the true residual shear strength condition [10], [3], [4], [22]. Another advantage of the ring shear device is that no change occurs in the shear plane area during shearing. For precise measurement of residual strength, a large deformation is applied to a specimen so that platy clay minerals are oriented completely parallel to the shear plane [17]. The ring shear apparatus has frequently been used to achieve this objective.

Selection of shear strength parameters is a very important and difficult task in the design and repair of slopes containing a preexisting shear surface in reactive landslides. If a failure has already occurred in clay soils, any subsequent moment along the existing slope surface will be controlled by the drained residual strength [16]. Skempton [17] has mentioned that the field residual strength value of the slip surface soil should be the same as the strength calculated from the back analysis of the landslide in which movement has reactivated along a pre-existing slip surface. This means that the back analyzed and lab-determined strength parameters must be the same as those of lab tests carried out under precisely similar in-situ conditions. Bromhead and Curtis [5], Mesri and Feng [13], Stark and Eid [19], Tika [22], Tika and Hutchinson [23], Mesri and Shahien [12], Stark et al. [20], and Tiwari et al. [24] have concluded that the drained residual shear strength measured in a ring shear apparatus is in agreement with the back-calculated drained residual shear strength for a landslide slip surface.

Based on the back-analysis of an ancient landslide in cohesive colluvial soil in West Virginia, D'Appolonia et al. [8] have suggested that the mobilized shear strength is greater than the drained residual strength of the slip surface material. Direct shear tests on undisturbed specimens containing the preexisting shear surface, obtained from shallow portions of the slip surface, show peak strength greater than the drained residual strength. The researchers have suggested 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. [15] have investigated the strength gain in remolding and normally consolidated kaolinite and bentonite in reversal direct shear tests using rest periods of up to 4 days. Ramiah et al. [15] found that the strength gain for high plasticity soil (bentonite) is higher even with a short rest period. Anglei et al. [1] used direct shear tests whereas Angeli et al. [1] use Bromhead [4] ring shear tests to study the strength gain mechanism in different clays including London clay. Tests were performed on normally consolidated specimens. Angeli et al. [1], [2] have concluded that there is an increase in the recovered shear strength with time during these direct and ring shear tests. Gibo et al. [9] used a Bishop et al. [3] type ring shear device and concluded that the silt and sand dominated the sample recovered its strength, but the smectite dominated sample did not recover its strength. Stark et al. [20] have presented laboratory Bromhead [4] type ring shear test results on two soils of different plasticity for rest periods up to 230 days. Stark et al. [20] have observed that the magnitude of recovered shear strength increases with increasing soil plasticity, but the recovered strength was lost with small shear displacement. Carrubba and Del Fabbro [6] conducted Bromhead [4] ring shear tests similar to Stark et al. [20] in aging times of up to 30 days and found more strength gain in Montona flysch than Rosazzo flysch. If a preexisting shear surface soil exhibits strength recovery in a short period of time, it might be possible to design the remedial measure using shear strength greater than the drained residual strength for the problematic layer. This higher strength could reduce the cost of the remedial measures. So a study of strength recovery from the residual-state of shear is very important.

The Bishop et al. [3] type ring shear apparatus is best suited for investigation of the strength recovery in the laboratory

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because the shear is confined and occurs at a soil-to-soil interface, but in the Bromhead [4] ring shear apparatus, the shearing occurs at the top of the specimen between the soil to top bronze porous stone interface. Gibo et al. [9] used a Bishop et al. [3] type ring shear device for the first time to observe the strength recovery effect on the soil sample obtained from two different reactivated landslides. Gibo et al. [9] concluded that strength recovery effect should be considered in the stability analysis of a reactive landslide dominated by silt and sand particles at effective normal stress less than 100kN/m^2. However, the use of normally consolidated specimens and the short duration (i.e., 2 days) of the tests may not be sufficient to reach such a conclusion. Strength recovery observed for a normally consolidated Xuechengzhen specimen (i.e., silt and sand dominate) may be caused by some silt or sand particles being present along the shear surface which may have penetrated the shear surface or zone during secondary compression of the ring shear specimen and provided some additional shear resistance. However, Gibo et al. [9] concluded that the kamenose specimen (i.e., smectite dominated) did not show any strength recovery. This contradicts the finding of Ramiah et al. [15], which indicated bentonitic soil exhibit higher strength gain. The strength gain in case of Xuechengzhen specimen may have been more pronounced if Gibo et al. [9] had used a longer rest period. This follows because the residual shear strength in preexisting landslides is more common in over consolidated soil, and rest periods longer than two days are relevant to simulate the field condition.

In this study, commercial available kaolin clay is tested using the Bishop et al. [3] type ring shear apparatus for the rest periods 1, 3, 7, 15, and 30 days. This paper describes the laboratory ring shear strength recovery test procedure and observed the strength recovery behaviors of kaolin clay. The main objective of this study is to investigate the possibility of strength recovery along preexisting shear surface using a Bishop et al. [3] type torsional ring shear apparatus. Probable causes of strength recovery are also discussed.

II. MATERIALS AND METHOD

A. Structural Features of the Torsional Ring Shear Apparatus

The structural features of the torsional ring shear apparatus used for this study is shown in Fig. 1. It is based on the concept reported by Bishop et al. [3]. In this apparatus, the specimen container has inner and outer diameters of 8.0cm and 12.0cm respectively, and a depth of 3.2cm. The ratio of the outer to inner ring diameters is 1.5. A dial gauge is used on the upper plate to observe the change in the specimen volume during shear. The normal load is transmitted to the sample by the central shaft, which can be directly applied. The mechanisms are made in such a way that there is no eccentricity during the application of a normal load and shear strain.

The lower half of the apparatus below the plane of failure is made to rotate, while the upper part is not movable, as shown in Fig. 1. The load cell described by Bishop et al. [3] was fixed under the upper confining rings to measure the obstructed (tangential) load. The shear stress was calculated from the tangential load cell reading. A normal stress (i.e., σ_n) was applied directly above the apparatus to the annular specimen through the upper plate. Moreover, to observe the change in the specimen volume during shear, a dial gauge was used on the upper plate, as shown in Fig. 1, and arrangements were made to maintain the water heads at the top and bottom of the specimen to be the same so that the degree of saturation does not change during the shear. The gap between the upper and lower parts of the confining rings is usually opened to accurately measure the shear resistance of soils during shearing. This gap eliminates the contact friction between the upper and lower confining rings. The size of the gap can be controlled relative to a fixed datum by means of a differential screw. All of the test samples were placed in a remolded state because it has been demonstrated by Bishop et al. [3] that the residual friction angle is unaffected by the initial structure of the soil. In the standard testing procedure used in the tests, the sample were over consolidated and then sheared slowly until the residual shear zone is formed.

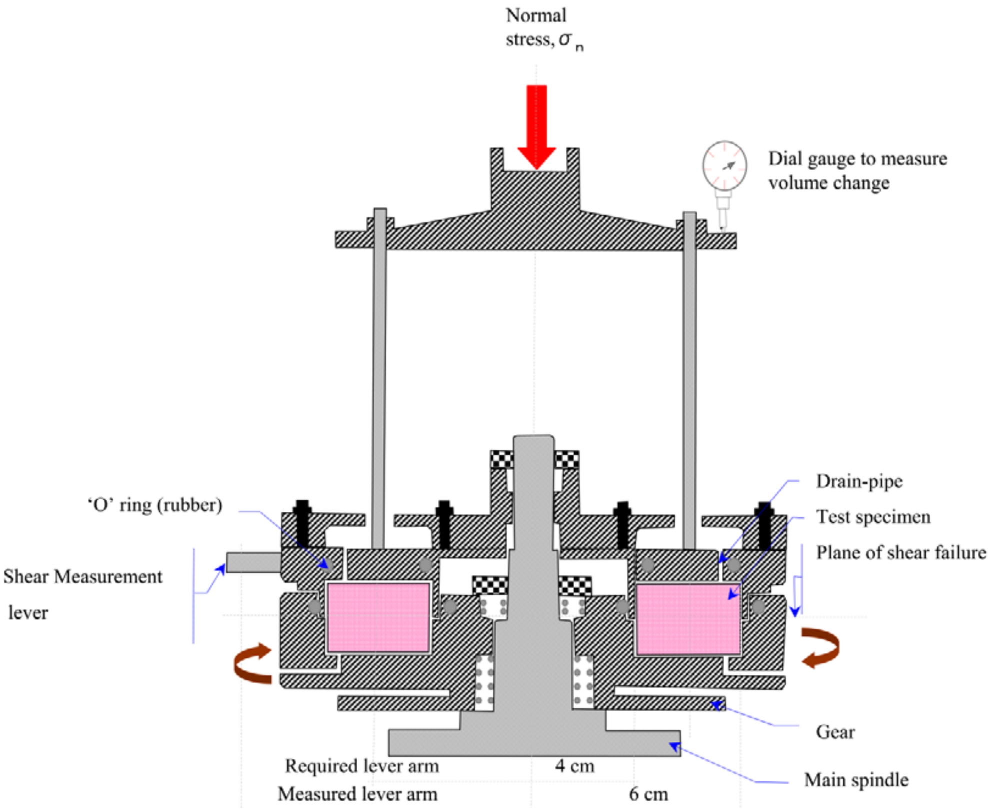

Fig. 1 Structural features of torsional ring shear apparatus

B. Test Sample

In this study, commercially available kaolin clay was taken. Before strength recovery test, physical tests such as water content, specific gravity, grain size analysis, and consistency limits (i.e., liquid limit, plastic limit, plasticity index) were carried out to evaluate the physical properties. Solid density of testing sample was measured 2.72g/cm^2 and liquid limit, plastic limit, and plasticity index was found 52.00%, 22.04%, and 29.96% respectively. Grain size analysis show that 74.00% of the particles was < 2µm, and reaming 26.00 % was 2µm -75µm.

C. Strength Recovery Creep Test Procedure

There are two main steps in the strength recovery test: (1) The ring shear test: This test is performed to obtain the residual-state of the shear of specimens in the fully saturated-state. This residual-state is confirmed when the shearing has reached value of minimum shear, indicating constant values for the both load-cell and dial gauge readings after a large displacement. The specimen is then ready for the strength recovery test. (2) The strength recovery test: when the specimen reaches the residual-state of shear, the strength recovery test will begin. In the strength recovery test, shearing is stopped after the residual-state of shear is achieved, 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. The shear force applied at the end of the residual strength test is maintained on the specimen throughout the rest period to simulate field conditions because the sliding mass in the field remains subject to a shear stress after movement. The motor used to rotate the lower part of the ring shear specimen container remains engaged and prevents any reduction in the shear force during the rest period. Therefore, the specimen remains subject to the residual shear and normal stress during the rest period. Here, the effective normal stress applied for the tests is 100kN/m^2.

After a rest period of 1 day, shearing is restarted with the shear and effective normal stress corresponding to the initial drained residual condition. The specimen is sheared at the same rate, i.e., 0.16mm/min, and the maximum strength after recovery/healing is measured, which may or may not be greater than the residual value. Shearing is continued until the residual-state of shear is achieved again. After the residual-state of shear is achieved again with additional shear displacement, shearing is stopped and the specimen allowed resting for the next period under the imposed shear and effective normal stress. The recovered shear strength for the other periods, i.e., 3, 7, 15, and 30 days, is measured by repeating the above procedure for the 1 day rest period (Fig. 2).

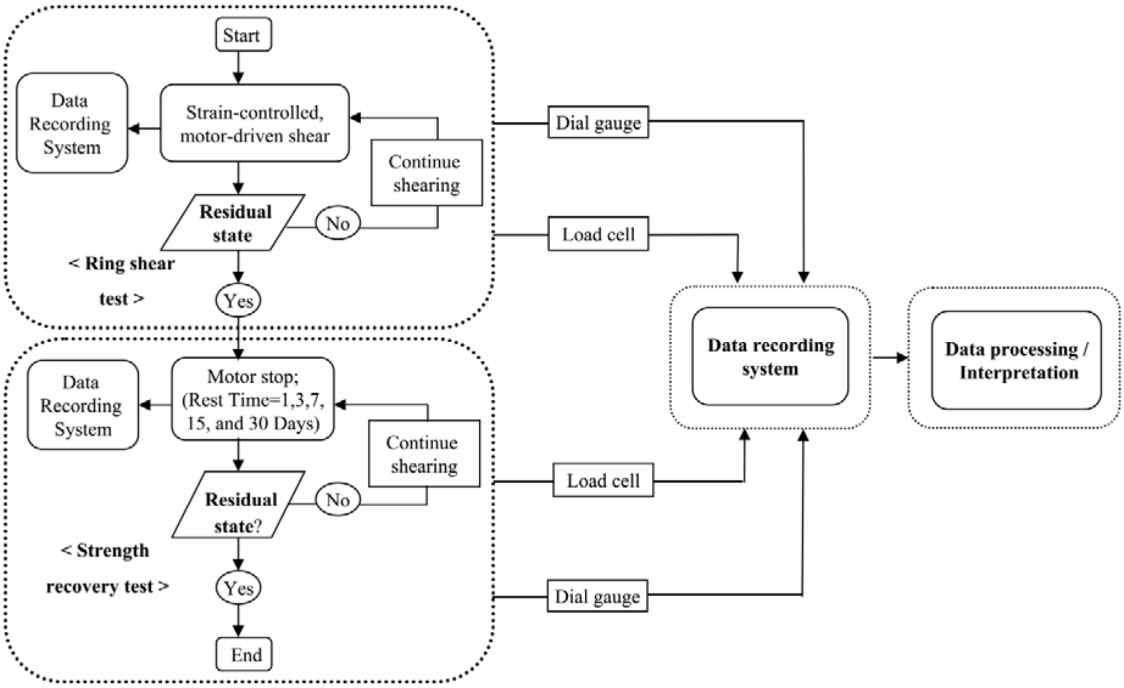

Fig. 2 Method of strength recovery test

III. RESULTS AND DISCUSSION

In strength recovery test, initially ring shear test was performed to obtain the residual-state of shear, and then strength recovery test was begun. Ring shear and strength recovery test results on kaolin clay are presented in terms of variation of shear stress and specimen depth with the shear displacement. Residual-state of shear obtained after 10.0cm of shear displacement in the initial condition. Fig. 3 shows the typical results of ring shear and strength recovery tests. Strength recovery test results in terms of frictional angles are summarized in Table I. The value of drained residual friction angle (ϕ_r) and the difference between drained recovered friction angle (ϕ_{Rec}) and residual friction angle ($\phi_{\text{Rec}} - \phi_r$) (i.e., increase in frictional angle, $\Delta\phi_r$) are presented in Table I. The recovered strength (τ_{Rec}) measured up to rest time of 3 days were negligible. After rest time of 3 days, slightly increase in the strength of the residual-state of shear is appeared with respect to increase in rest time. Summary of shear displacements during the strength recovery tests are presented in Table II. The results agree with some points of the ring shear strength recovery test results conducted by Angeli et al. [2], Stark et al. [21], and Carrubba and Del Fabbro [6] and also reversal direct shear test conducted by Rumiah et al. [15] and Angeli et al. [1]. Test results show that after the small shear displacement, the gained strength reached with residual-state of shear (Table II). That means the recovered strength lost after a small shear displacement. Hence recovered strength will not applicable for the analysis and repair of reactive landslides.

TABLE I
SUMMARY OF STRENGTH RECOVERY IN TERMS OF FRICTIONAL ANGLES

Residual Frictional	Increase in Frictional Angles (deg) ($\Delta\phi_r = \phi_{\text{Rec}} - \phi_r$)				
Angles (ϕ_r, deg)	1 Day	3 days	7 days	15 days	30 days
25.85	0.00	0.10	0.29	0.84	1.07

TABLE II
SUMMARY OF SHEAR DISPLACEMENTS DURING STRENGTH RECOVERY TESTS

Shear displacement upon recovered strength (mm)					
Initial	1 Day	3 days	7 days	15 days	30 days
7.29	0.00	0.48	0.73	0.97	1.97

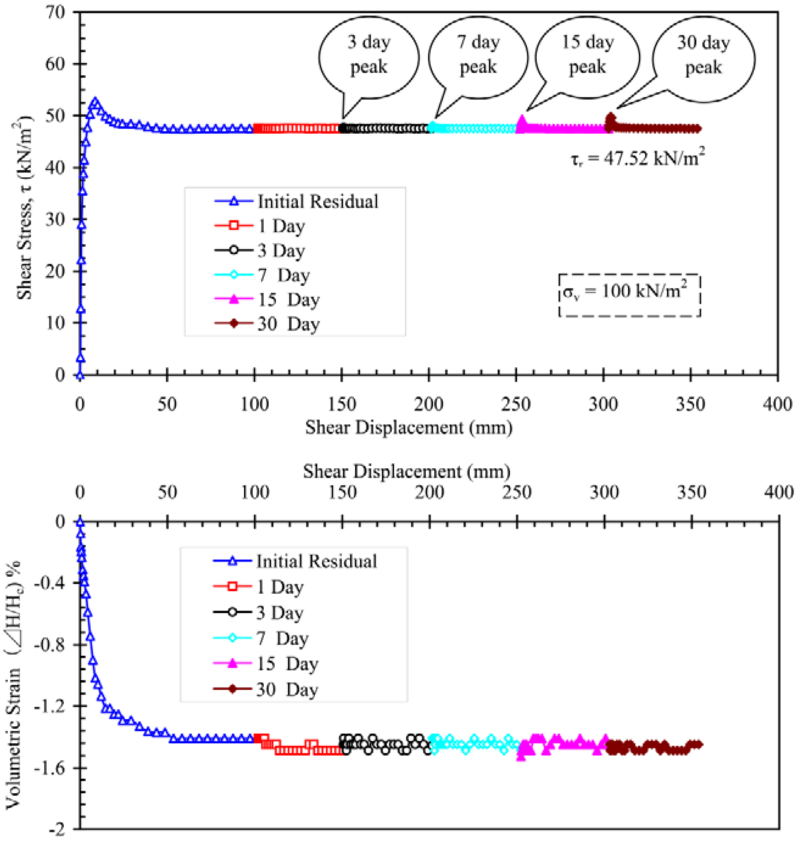

Fig. 3 Typical results of ring shear tests and strength recovery tests

IV. Probable Cause of Strength Recovery

Although some researchers have recognized that strength recovery above the residual value takes place over time [8], [15], [1], [2], [9], [21], [6], the actual mechanisms that cause this phenomenon remain unknown. However, a few hypotheses are proposed to discuss the mechanisms of strength recovery. A new hypothesis is also purposed in this study.

A. Primary and/ or Secondary Compression

Under the application of normal stress, secondary compression will occur even if no significant primary consolidation occurs [11]. In secondary compression, the strength will increase due to decrease in void ratio [11], micro interlocking, and inter particle constant [18]. If so, at a higher effective normal stresses, the amount of secondary compression should be greater than at lower effective normal stress and the strength recovery should be higher at a higher effective normal stresses. But Strack and Hussain [21] reported that the strength recovery was slightly noticeable at low effective stress of less than 100kN/m^2 and the strength recovery effect was negligible at the effective stress greater than 100kN/m^2. This suggests that the effect on the strength recovery due to the primary and secondary compression of the slip surface material may not have considerable. On the other side, over consolidated specimen reduce the magnitude of secondary compression during the rest period, so strength recovery may not cause of primary and/or secondary compression.

B. Van der Waals Attraction

The roughness of particle surface markedly decrease the Van der Waals attraction energy in a particle-semi-infinite medium therefore a smooth shiny slickensided surface is likely to exhibit more Van der Waals force of attraction [7]. It is assumed that oriented clay particles along a shear surface with smooth platy and shiny surfaces are likely to have greater Van der Waals attraction than randomly arranged clay particles. However, the test conditions were kept constant during test, which may not favor for the vender wall attraction between soil particles.

C. Cementation

Most of the soils contain free carbonates, ion oxides, alumina, and organic matter that may precipitate at inter particle contains and act as cementing agent [14]. D'Appolonia et al. [8] suggested that cementation may be a mechanism that contributes to the strength gain (healing) in an ancient landslide. In the cementation process, sufficient time should be needed. Hence, remolded specimen in the laboratory may not be assumed cementation because of insufficient time. The bond formed by cementation tends to be brittle and can be destroyed by small shear displacement. On the other hand, some external agents should be added for cementing process. But any other cementing agents (i.e., admixture) were not added during the test. Cementation may not have any role in the strength recovery phenomenon in this study.

D. Cation Exchange

Clay adsorbs cations of specific type and amounts under a given set of environmental conditions such as temperature, pressure, pH, and chemical and biological composition of water [14]. Cations that neutralize the net negative charge on the surface of soil particle in water are readily exchangeable with other cations [13]. The exchange reaction depends upon the relative concentration of cation in the water and electrovalence of the cations. The exchange reaction may change in the physical and physicochemical properties of the soil but do not affect the structure of clay particles [14]. In this study, all test conditions, e.g., application of effective normal stress, room temperature, etc. were kept constant during the test. Hence, the soil particles on the slip surface, which is already reached in a residual-state of shear, may not have the effect of cation exchange between soil particles.

E. Coefficient of Static Friction (μ_s) and Dynamic Friction (μ_k)

The shearing force required to initiate sliding between two surfaces is often greater than the force required to maintain motion because static friction is greater than kinetic sliding friction (i.e., $\mu_s > \mu_k$). During the rest condition, the coefficient of static friction (μ_s) is working and the coefficient of dynamic friction (μ_k) acts during shearing. Hence, the role of the coefficient of static friction (μ_s) and the coefficient of dynamic friction (μ_k) may be a mechanism leading to the strength recovery from residual-state of shear on a soil. However, the reason why the coefficient of static friction (μ_s) increases with the increase in duration of discontinued shear needs further investigation.

V. CONCLUSIONS

In this study, kaolin clay was tested using the Bishop et al. [3] type ring shear apparatus. The rest periods were kept 1, 3, 7, 15, and 30 days. The test results show that the recovered strength above the residual-state of shear is hardly noticeable with an increase in rest time, but an observed recovered strength in ring shear tests at an effective normal stress of 100kN/m^2 lost with a small shear displacement. However, the main findings of this study are summarized below:

1. Strength recovery on kaolin clay at an effective normal stress of 100kN/m^2 was hardly noticeable after a rest period of 3 days in a torsional ring shear test.
2. The mechanism involved in strength recovery/healing may be the role of the coefficient of static friction (μ_s) and the coefficient of dynamic friction (μ_K).
3. Strength recovery from the residual-state of shear was lost after a very small shear displacement. Hence, recovered strength could be neglected in the design and repair works of reactive landslides.

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