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Strength Recovery of Landslide Soils from the Residual State of Shear

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ABSTRACT: A preexisting shear surface of a reactivated landslide has been subjected to repeated sliding and recession. During the sliding, the shear strength of shear zone has been reduced to the residual state, but the strength may be recovered from the residual state to some extent during a rest period. In this study, three landslide soils collected from the different large-scale landslide sites in Nepal and Japan are tested in a ring shear apparatus for the discontinued shear rest periods of 1, 3, 7, 15, and 30 days. Test results show that recovered strength measured in the laboratory is slightly noticeable after a rest period of 3 days, but recovered strength is lost after a very small shear displacement. This paper mainly focuses on the strength recovery behavior in highly plastic and less plastic soils from the residual-state of shear. The probable causes of the strength recovery are also discussed.

INTRODUCTION

When a soil material is sheared, a minimum constant strength value is attained after a large displacement which is called residual stae of shear. In the laboratory, the ring shear apparatus is widely used to measure the residual shear strength of a soil because of its two major advantages. The first advantage of the ring shear apparatus is that it can shear the specimen continuously in one direction to obtain a large displacement; where the clay particles to be oriented parallel to the direction of shear to develop the true residual shear strength condition. Another advantage of the ring shear apparatus is that no change occurs in the shear plane area during shearing (Skempton, 1985; Bhat et al., 2011a, b, 2012a, b, 2013e, f, g).

D'Appolonia et al. (1967) reported that the mobilized shear strength is greater than the drained residual strength of the slip surface material. Ramiah et al. (1973) investigated the strength gain in remolded and normally consolidated kaolinite and bentonite in reversal direct shear tests, using rest periods of up to 4 days. Ramiah et al. (1973) found that the strength gain for high plasticity soil (bentonite) is higher even with a short rest period. Angeli et al. (1996) concluded that there is an increase in the recovered shear strength with time during these direct and Bromhead (1979) type ring shear tests. Stark et al. (2005) 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 (2008) conducted Bromhead (1979) ring shear tests, similar to those performed by Stark et al. (2005), for aging times of up to 30 days and found more strength gain in Montona flysch than in Rosazzo flysch. Strength recovery is negligible in clayey soils after a 3 day rest period, but it is lost after a small shear displacement (Bhat et al., 2013b, c, d). Nakamura et al. (2010) discussed the application of recovered strength in the stability analysis of reactivated landslides.

In the Bishop et al. (1971) type ring shear apparatus, the shear is confined and occurs at a soil-to-soil interface which may simulate the field condition of the preexisting shear surface of slow moving landslides. But in the Bromhead (1979) ring shear apparatus, the shearing occurs at the top of the specimen, at the soil-to-top bronze porous stone interface. Hence, the Bishop et al. (1971) type ring shear apparatus is best suited for investigating the strength recovery in the laboratory. Gibo et al. (2002) used a Bishop et al. (1971) type ring shear device to first observe the strength recovery effect on soil samples obtained from two different reactivated landslides. Gibo et al. (2002) concluded that the strength recovery effect should be considered in the stability analysis of a reactive landslide dominated by silt and sand particles at an effective normal stress less than 100 kN/m^2. However, the use of normally consolidated specimens and the short test duration (i.e., 2 days) may not be sufficient to reach this conclusion.

In this study, three landslide soil samples are tested using the Bishop et al. (1971) type ring shear apparatus for rest periods of 1, 3, 7, 15, and 30 days. This paper describes the ring shear strength recovery laboratory test procedure and the observed strength recovery behaviors of three soil samples. The main objectives of this study are to compare the strength recovery of high plasticity soils and low plasticity soils, and to discuss the strength recovery mechanisms at the residual state of shear.

MATERIALS AND METHOD

In this study, three soil samples are taken from the large-scale landslide areas in Japan and Nepal as the representative samples. The soil sample from the Shikoku landslide area of Japan was named "shikoku landslide, and the soil sample from the Toyooka-kita landslide area of Japan was named "toyooka-kita landslide". Similarly, the sample from the Krishnabhir landslide area of Nepal was named "krishnabhir landslide". The physical properties of soil samples are shown in Table 1.

Table 1. Physical properties of soil samples.

Sample type	Solid density (g/cm^3)	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Soil classification (%)		
					Clay	Silt	Sand
Krishnabhir landslide	2.74	34.10	20.69	13.41	21	60	19
Shikoku landslide	2.75	47.50	31.24	16.26	20	68	12
Toyooka-kita landslide	2.65	96.50	59.00	37.50	24	55	21

The torsional ring shear apparatus (based on the concept reported by Bishop et al. (1971)) was used in this study. In this apparatus, the specimen container has inner and outer diameters of approximately 8.0 cm and 12.0 cm, respectively, and an average specimen thickness of 3.2 cm. The specimen is sheared through a level of 0.7 cm above the base of the lower plate. In this study, all tests are conducted in a drained condition. The excess pore water pressure is assumed to dissipate and to have no influence on the normal stress in the drained condition. Thus, the effect of pore water pressure is negligible. Consequently, the total applied pressure works as effective pressure and the entire test system is under an effective stress condition.

In the strength recovery test. First, the ring shear 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 the value of minimum shear, as indicated by constant values for both the load-cell and dial gauge readings after a large displacement. The specimen is then ready for the strength recovery test. Then, the shearing is stopped, and the specimen is allowed to rest in the ring shear apparatus. The specimen is subjected to the applied effective normal stress and the measured residual shear stress for the duration of the rest period. The shear force applied at the end of the residual strength test is maintained 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. The effective normal stress applied during the tests is 100 kN/m^2.

After a rest period of one day, shearing is restarted with a shear and effective normal stress corresponding to the initial drained residual condition. The specimen is sheared at the same rate of 0.16 mm/min (Bhat et al. 2013a), and the maximum strength after recovery (which may or may not be greater than the residual value) is measured. 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 is allowed to rest under the imposed shear and effective normal stress for the next rest period. The recovered shear strength for the other rest periods, i.e., 3, 7, 15, and 30 days, is measured after repeating the 1 day rest period procedure.

RESULTS AND DISCUSSION

In the strength recovery test, the ring shear test was initially performed to obtain the residual state of shear. The residual state of shear is obtained after 10.0 cm of shear displacement in the initial condition. The ring shear test results indicated that the peak strength and the residual strength of the krishnabhir landslide was the highest, followed by the shikoku landslide, and then the toyooka-kita landslide. However, the difference between the peak strength and the residual strength of the krishnabhir landslide was the lowest, followed by the shikoku landslide and then the toyooka-kita landslide. It is observed that the krishnabhir landslide was the strongest and that the toyooka-kita landslide is the weakest. The toyooka-kita landslide and the shikoku landslide demonstrate the high plasticity in the soil’s nature. Similarly, the krishnabhir landslide demonstrated a low plasticity in its soil’s nature.

Typical results of ring shear tests and strength recovery tests of the krishnabhir landslide is presented in terms of variation of shear stress and specimen depth with the shear displacement as shown in Fig. 1. The value of the drained residual friction angle (ϕ_r) and the difference between the drained recovered friction angle

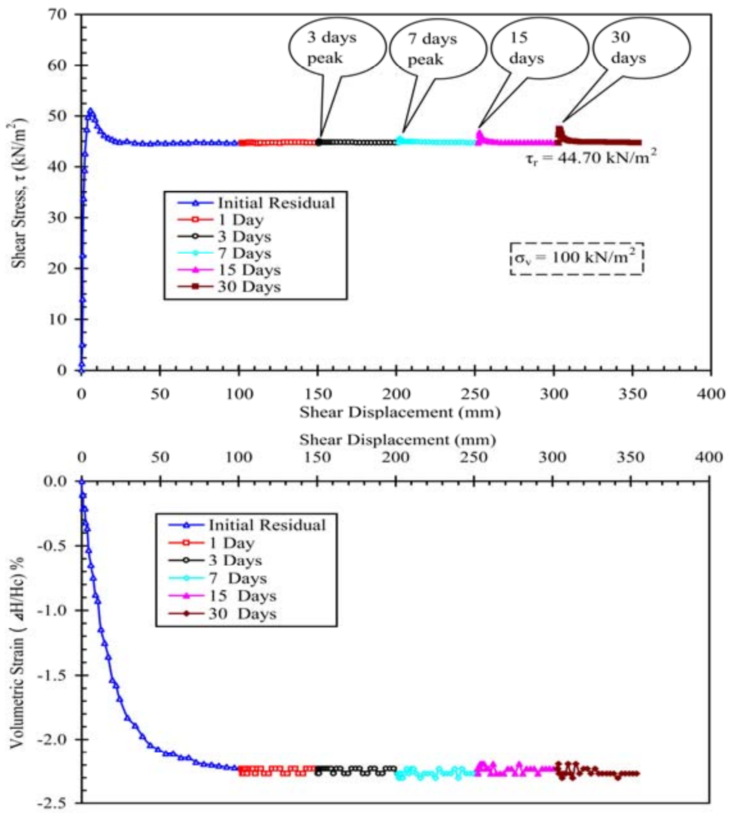

Fig. 1. Typical results of ring shear tests and strength recovery tests (on Krishnabhir landslide).

(ϕ_{Rec}) and residual friction angle (ϕ_r) (i.e., increase in the frictional angle, $\Delta\phi_r = \phi_{Rec} - \phi_r$) of the krishnabhir landslide, the shikoku landslide, and the toyooka-kita landslide are summarized in Table 2. For identical rest periods, the friction angle increase was slightly greater in the case of the toyooka-kita landslide, followed by the shikoku landslide and then the krishnabhir landslide (Table 2). There were no frictional angle increases for the 3-day rest periods, but the frictional angles increase by only one or so for the rest periods of 30 days.

The shear displacement during the strength recovery test results are summarized in Table 3. The peak strength (i.e., 51.09 kN/m^2) was obtained after the initial shear displacement of 5.83 mm in the case of the krishnabhir landslide. After the rest period of 1 day, the maximum value of the shear strength was identical to the residual strength (i.e., 44.86 kN/m^2). Thus, the recovered strength was not observed after the 1-day rest period. After the 3-day rest period, the maximum shear strength value of 44.98 kN/m^2 was achieved, after the shear displacement of 0.48 mm, which was slightly greater than the residual strength. Similarly, little increase in shear strength from the residual shear strength was recorded (Table 2) after the small shear displacements of 0.73 mm, 0.73 mm, and 0.97 mm for the rest periods of 7, 15, and 30 days, respectively (Table 3). The small increase in shear strength from the residual shear strength indicated that the shear strength was recovered from the residual state of shear after the 3-day rest periods, but the shear displacement up to the recovered strength was small compared to the initial shear displacement (i.e., 5.83 mm) up to the peak strength (Table 3). The recovered strength was lost after shear displacements of 0.73 mm and 0.97 mm for the 15-day rest period in the case of the krishnabhir landslide and the shikoku landslide, but the shear displacement in which the recovered strength was lost was slightly greater (i.e., 1.46 mm) for the toyooka-kita landslide (Table 3). At the rest period of 30 days, the recovered strength was lost after the 1.46 mm of shear displacement in the case of the shikoku landslide and the toyooka-kita landslide. The recovered strength of the krishnabhir landslide reached a residual state of shear after a small shear displacement compared with the other landslides.

The ratio between the recovered shear strength and the initial residual shear strength as a function of rest time is shown in Fig. 2. The strength ratio of the toyooka-kita landslide is the highest, followed by the shikoku landslide and then the krishnabhir landslide (Fig. 2). The strength ratio values at rest times of 15 days for the krishnabhir landslide, the shikoku landslide, and the toyooka-kita landslide were found to be 1.03, 1.08, and 1.12, respectively. The differences between the peak strength and the residual strength of the krishnabhir landslide, the shikoku landslide and the toyooka-kita landslide were 6.30 kN/m^2, 19.57 kN/m^2, and 32.19 kN/m^2, respectively. The toyooka-kita landslide demonstrated a highly plastic soil nature compared with the shikoku landslide and the krishnabhir landslide. From Fig. 2, it can be concluded that the soil with the smallest difference between the peak strength and the residual strength shows a lower value of recovered strength when compared with the soil with a larger difference between the peak strength and the residual strength. Thus, the recovered strength from the residual state of shear will be higher in high plasticity soils when compared with low plasticity soils.

Table 2. Summary of strength recovery in terms of internal friction angles.

Sample type	Residual frictional angles	Increase in internal frictional angles (deg) ($\Delta\phi_r = \phi_{Rec} - \phi_r$)				
	(ϕ_r, deg)	1 Day	3 Days	7 Days	15 Days	30 Days
Krishnabhir landslide	24.50	0.00	0.13	0.40	0.96	1.33
Shikoku landslide	13.82	0.00	0.25	0.49	1.14	1.65
Toyooka-kita landslide	5.16	0.00	0.38	0.65	1.25	1.96

Table 3. Summary of shear displacements during strength recovery tests.

Sample	Increase in internal frictional angles (deg)					
type	Initial	1 Day	3 Days	7 Days	15 Days	30 Days
Krishnabhir landslide	5.83	0.00	0.48	0.73	0.73	0.97
Shikoku landslide	4.37	0.00	0.48	0.73	0.97	1.46
Toyooka-kita landslide	2.43	0.00	0.73	0.97	1.46	1.46

The normalized strength ratio (NSR) is given by the following equation as a function of rest time is presented in Fig. 3.

$$\text{Normalized Strength Ratio (NSR)} = \frac{(\tan\phi_{Rec} - \tan\phi_r)}{(\tan\phi_r)} \quad (1)$$

The NSR value relates the strength gain to the residual value. When the NSR is equal to zero, there is no recovery of strength, and if the NSR is greater than zero, the value represents the ratio of recovered strength to the residual value. Here, the toyooka-kita landslide shows the maximum increase in the NSR, followed by the shikoku landslide and then the krishnabhir landslide. The higher plasticity soils, such as the toyooka-kita landslide and the shikoku landslide, demonstrated a noticeable strength recovery from residual shear strength compared with the krishnabhir landslide (Fig. 3). The recovered friction angle (ϕ_{Rec}) at 100 kN/m², using the measured residual friction angle (ϕ_r), can be estimated using the NSR. A limitation in using the NSR to estimate ϕ_{Rec} is that ϕ_r has to be measured in the laboratory.

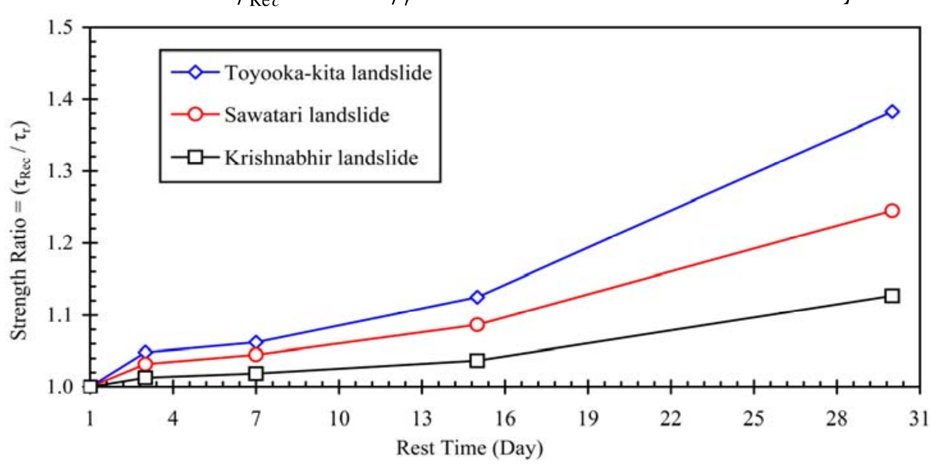

Fig. 2. Strength ratio versus rest time.

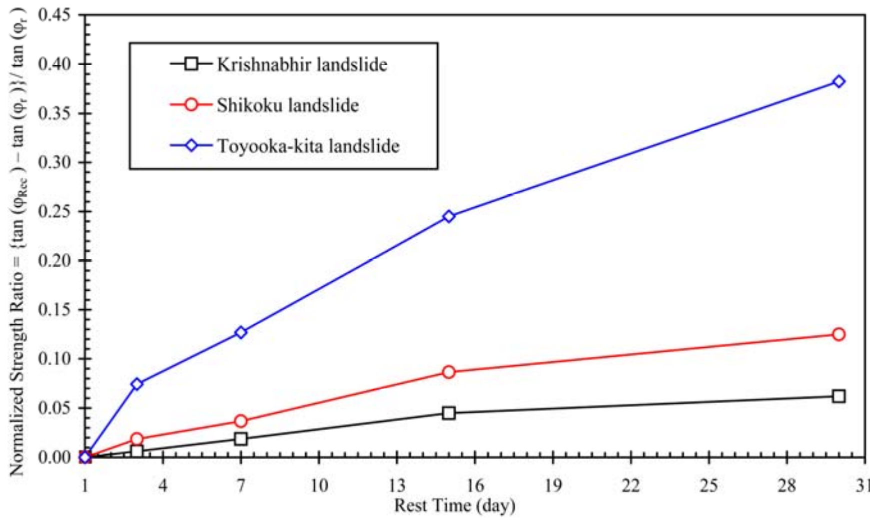

Fig. 3. Normalized strength ratio versus rest time.

Although some researchers have recognized that strength recovery above the residual value occurs over time, the actual mechanisms that cause this phenomenon remain unknown. However, a few hypotheses are proposed to discuss the mechanisms of strength recovery. Primary and secondary compression has a role in strength recovery (Mesri et al., 1987). 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 recover should be higher at a higher effective normal stresses. However, Strack and Hussain (2010) reported that strength recovery is minimal at a low effective stress of less than 100 kN/m^2 and that the strength recovery effect is negligible at an effective stress greater than 100 kN/m^2. These results suggest that the effect of primary and secondary compression of the slip surface soil on strength recovery may not be considerable. In an over consolidated specimen, the magnitude of secondary compression will be reduced during the rest period; thus, the strength recovery may not be the cause of primary and secondary compression.

A smooth, shiny slickensided surface exhibits more van der Waals attraction than the rough particle surfaces (Czarneck and Dabros, 1980). It is assumed that oriented clay particles with smooth platy and shiny surfaces have greater van der Waals attraction than randomly arranged clay particles. Thus, the strength recovery mechanism may be the cause of van der Waals attraction between soil particles. However, further investigation is needed to understand the strength recovery mechanism of a soil material.

CONCLUSIONS

In this study, three soil samples collected from the large-scale landslide sites were tested using the Bishop et al. (1971) type ring shear apparatus. The test rest periods were 1, 3, 7, 15, and 30 days. The test results indicated that the soil strength recovery at an effective normal stress of 100 kN/m^2 in a torsional ring shear test was minimal after a rest period of 3 days. The strength recovery from the residual value would be greater in high plasticity soils than in low plasticity soils at an effective normal stress of 100 kN/m^2. However, the strength recovery was lost after the specimen undergoes a small shear displacement. The strength recovery from the residual state of shear may be the result of rebounding or reorienting of clay particles that are already oriented parallel to the direction of shear. However, the reason why the resheared strength increases with the increase in rest periods from the residual state of shear is needed further investigation.

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