Shear Strength Recovery of Clayey Soils Following Discontinuation of Shear at a Residual State

Deepak R. Bhat, Netra P. Bhandary, and Ryuichi Yatabe

Abstract

Residual shear strength is generally used for design and repairs on slopes containing pre-existing shear surfaces in large-scale landslides. Some recent research works suggest that the pre-existing shear surface of a large-scale landslide can regain strength with the passage of time, which should be considered in designing the slope stability measures. In this study, three landslide soils were tested in a ring shear apparatus with rest periods between shear of 1, 3, 7, 15, and 30 days, with the following main objectives (1) to understand the strength recovery behavior of landslide soils in residual state of shear after as long as 30 days of rest between shearing, (2) to understand the comparative pattern of strength recovery in highly plastic and less plastic soils, and (3) to understand the mechanism involved in strength recovery at residual state of shear. The obtained experimental results indicate that the recovery of shear strength in the residual state started to appear slightly after shear was discontinued for 3 days, and was lost immediately after a very small shear displacement. On the other hand, as understood from the experimental work in this study, the trend of strength recovery, is somewhat in increasing order with prolongation of the period that shear is discontinued.

Keywords

Landslide soils • Residual strength • Strength recovery • Ring shear test

Introduction

Based on the back-analysis of an ancient landslide in cohesive colluvial soil in West Virginia, D'Appolonia et al. (1967) reported 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 pre-existing shear surface, obtained from shallow portions of the slip surface, show peak strengths greater than drained residual strengths. Researchers have suggested that the shear surface in the cohesive colluvial soil underwent "recovery/healing", which caused an increase in shear strength beyond the drained residual value. 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. Using the Bromhead (1979) ring shear apparatus, the shearing occurs at the top of the specimen, at the soil-to-top bronze porous stone interface. Angeli et al. (1996) used a Bromhead (1979) 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. (1996,

D.R. Bhat (✉)
Geo-Disaster Research Laboratory, Graduate school of Science and Engineering, Ehime University, 3 Bunkyo-Cho, Matsuyama 790-8577, Japan
e-mail: deepakrajbhat@gmail.com

N.P. Bhandary • R. Yatabe
Graduate school of Science and Engineering, Ehime University, 3 Bunkyo-Cho, Matsuyama 790-8577, Japan
e-mail: netra@ehime-u.ac.jp; yatabe@cee.ehime-u.ac.jp

K. Sassa et al. (eds.), *Landslide Science for a Safer Geoenvironment*, Vol. 1,
DOI 10.1007/978-3-319-04999-1_42,

2004) concluded that there is an increase in the recovered shear strength with time during these direct and ring shear tests. Gibo et al. (2002) used a Bishop et al. (1971) type ring shear apparatus and concluded that a silt- and sand-dominated sample recovered its strength; however, the smectite-dominated sample did not recover its strength. Stark et al. (2005) presented Bromhead (1979) type ring shear test laboratory results for two soils of different plasticity for rest periods up to 230 days. 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 rest times of up to 30 days and found more strength gain in Montona flysch than in Rosazzo flysch. Nakamura et al. (2010) and Stark and Hussain (2010) discussed the application of recovered strength in the stability analysis of reactivated landslides.

For the design and repair of slopes containing pre-existing shear surfaces in large-scale landslides, the selection of shear strength parameters is important (Bhat et al. 2011, 2012, 2013b, d). The basic design principle based on the lab-determined drained residual shear strength is consistent with the back-calculated drained residual shear strength for a landslide slip surface. If a preexisting shear surface recovers its residual strength in a short period of time, that recovered strength may be used as a remedial measure for the problematic layer. The recovered strength is greater than the residual strength, which increases the resisting force. Thus, the factor of safety increases, which reduces the cost of remedial measures (Bhat et al. 2013c, 2014). The study of the strength recovery from a residual state of shear is extremely important.

The Bishop et al. (1971) type ring shear apparatus is best suited for investigating the strength recovery in the laboratory because the shear is confined and occurs at a soil-to-soil interface, which may represent the field condition of slip surfaces under slow-moving large-scale landslides (Bhat et al. 2013c, 2014). 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. They concluded that the strength recovery effect should be considered in the stability analysis of a reactivated landslide dominated by silt and sand particles at an effective normal stress of 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. The strength recovery observed for a normally consolidated Xuechengzhen specimen (i.e. silt and sand dominate) may have been caused by the presence of silt or sand particles along the shear surface; these particles 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. (2002) concluded that the Kamenose specimen (i.e., smectite-dominated) did not exhibit any strength recovery. This result contradicts the findings of Ramiah et al. (1973), which indicated that bentonitic soils exhibit higher strength gain. The Xuechengzhen specimen strength gain may have been more pronounced if Gibo et al. (2002) had used a longer rest period. The residual shear strength in pre-existing landslides is more common in overconsolidated soil, and rest periods longer than 2 days are necessary to simulate field conditions.

In this study, three clayey soils collected from large-scale landslide sites in Nepal and Japan are tested using the Bishop et al. (1971) type ring shear apparatus for rest (discontinued shear) 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 as follows (1) to test the soil strength recovery from the residual state of shear during the long rest period (i.e. up to 30 days) by using the Bishop et al. (1971) type ring shear apparatus, (2) to compare the strength recovery of high plasticity soils and low plasticity soils, and (3) to understand the strength recovery mechanisms at the residual state of shear.

Materials and Method

In this study, three landslide soils were obtained from the large-scale landslide areas in Japan and Nepal. The soil samples were from the Shikoku and the Toyooka-kita landslide areas of Japan, and from the Krishnabhir landslide area of Nepal. The physical properties of the tested samples are shown in Table 1. The solid densities of the Shikoku landslide and the Krishnabhir landslide samples are higher than the solid density of the Toyooka-kita landslide (Table 1). The plasticity index of the Krishnabhir landslide is lower than the Shikoku landslide and the Toyooka-kita landslide.

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 cm and 12 cm, respectively, and an average thickness of 3.2 cm. The specimen is sheared through a level of 0.7 cm above the base of the lower plate. The ratio of the outer to inner ring diameters is 1.5. 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.

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

Table 1 Physical properties of tested samples

Sample type	Solid density	Plasticity index (%)	Grain size classification (%)		
			Clay	Silt	Sand
Krishna-bhir landslide	2.74	13.41	21.0	59.7	19.3
Shikoku landslide	2.75	16.26	20.0	68.1	11.9
Toyooka-kita landslide	2.65	37.50	24.0	55.1	20.9

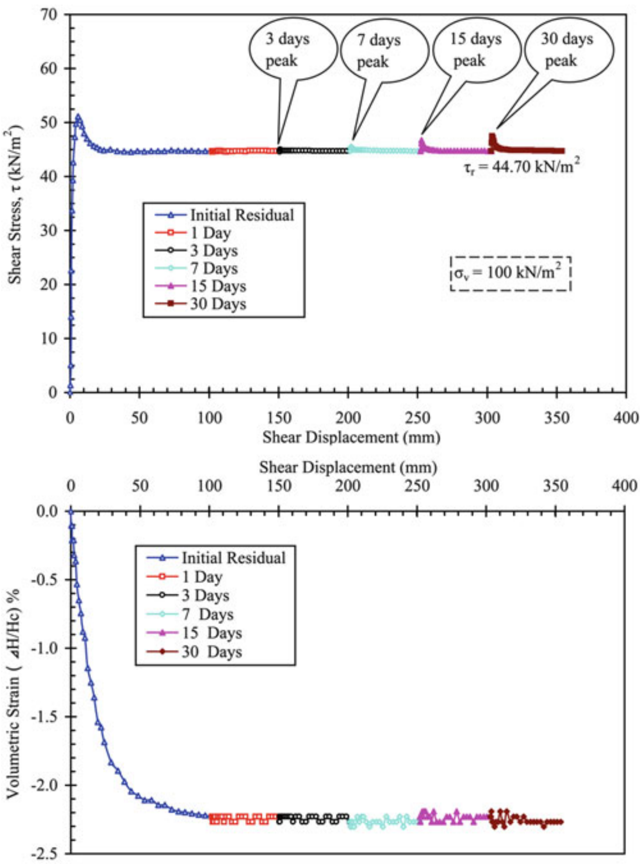

Fig. 1 Typical results of ring shear tests and strength recovery tests (on Krishnabhir landslide)

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. (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 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 1 day, shearing is restarted with a shear and effective normal stress corresponding to the initial drained residual condition. The shearing rate of the specimen is fixed at 0.16 mm/min (Bhat et al. 2013a), and the maximum strength after recovery/healing (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 results of the ring shear tests and the strength recovery tests are presented in terms of shear stress variation and specimen depth with respect to shear displacement. The residual state of shear is obtained after 10.0 cm of shear displacement in the initial condition. The ring shear test results indicate that the peak strength and the residual strength of soil samples from the Krishnabhir landslide are 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 is the lowest, followed by the Shikoku landslide and then the Toyooka-kita landslide. It is observed that the Krishnabhir landslide is 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 demonstrates a low plasticity in its soil.

Typical results of ring shear tests and strength recovery tests of the Krishnabhir landslide are presented in terms of variation of shear stress and specimen depth with the shear

Table 2 Summary of strength recovery in terms of internal frictional angles

Sample type	Residual frictional angles (ϕ_r, deg)	Increase in internal frictional angles (deg) ($\Delta\phi_r = \phi_{Rec} - \phi_r$) 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 type	Shear displacement upon recovered strength (mm) 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

displacement (Fig. 1). The value of the residual friction angle (ϕ_r) and the difference between the drained recovered friction angle (ϕ_{Rec}) and residual friction angle (ϕ_r) (i.e., increase in the frictional angle, $\Delta\phi_r = \phi_{\text{Rec}} - \phi_r$) of the Krishnabhir, Shikoku, and the Toyooka-kita landslide soils are summarized in Table 2. For identical rest periods, the friction angle increase is slightly greater in the case of the Toyooka-kita landslide, followed by the Shikoku landslide and then the Krishnabhir landslide (Table 2). There are no frictional angle increases for the 3 days rest periods, but the frictional angles increase by only one degree 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 days 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 indicates that the shear strength was recovered from the residual state of shear after the 3 days 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 days 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 and Toyooka-kita landslides. The recovered strength of the Krishnabhir landslide reached a residual state of shear after a small shear displacement compared with the other landslides (Table 3).

The test results indicate that the measured recovered strength (τ_{Rec}) up to the rest time of 3 days is negligible (Table 2). After a rest time of 3 days, there was a minimal increase in the strength from the residual state of shear with respect to the increase in rest time (Table 2). The value of recovered strength is small and may not be used for back analysis of the reactivated landslides; relying on such recovered strength was judged to be unrealistic for design purposes. The recovered strength is not expected to exceed the critical state (i.e. fully softened shear strength) in the laboratory or field because of the presence of a pre-existing shear surface and the alignment of clay particles along the shear surface parallel to the direction of shear. If the strength recovery test will be conducted for a long rest period, the value of the frictional angle may increase up to the critical state. However, the experimental results indicated that the recovered strength of the residual state of shear gradually started to appear after a shear rest period of 3 days and was lost immediately after a small shear displacement. Hence, the use of a recovered strength for the design and repair of slopes containing pre-existing shear surfaces is not recommended in this study. However, the strength recovery phenomenon may be useful to understand the creeping behaviors of landslides or slope stability prior to reactivation as suggested by D'Appolonia et al. (1967). Therefore, Skempton's method (1964, 1985) should still be followed for remediation of reactivated landslides and for comparison with back-calculated shear strength parameters.

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

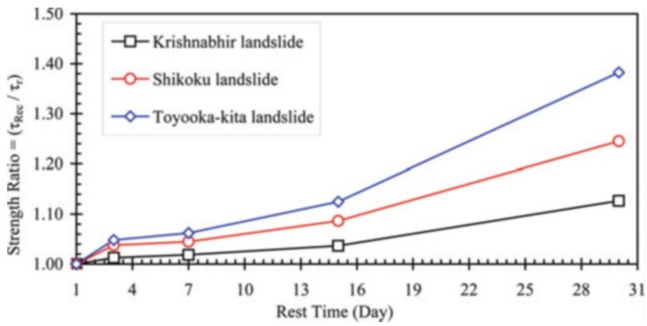

Fig. 2 Strength ratio versus rest time

and then the Krishnabhir landslide (Fig. 2). The strength ratio versus rest time curves of the Krishnabhir, the Shikoku, and the Toyooka-kita landslides are approximately equal, but the strength ratio value of the Toyooka-kita landslide is slightly greater than for the Shikoku and the Krishnabhir landslides (Fig. 2). For example, the strength ratio values at rest times of 15 days for the Krishnabhir, the Shikoku, and the Toyooka-kita landslides 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, the Shikoku, and the Toyooka-kita landslides were 6.30 kN/m^2, 19.57 kN/m^2, and 32.19 kN/m^2, respectively. The Toyooka-kita landslide demonstrates a highly plastic soil nature compared with the Shikoku and the Krishnabhir landslides. From Fig. 2, it can be concluded that the soil with the smaller 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.

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 for the mechanisms of strength recovery. Primary and secondary compression has a role in strength recovery (Gibo et al. 2002). Under the application of normal stress, secondary compression will occur even if no significant primary consolidation occurs (Mesri and Castro 1987). In secondary compression, the strength will increase due to decrease in void ratio, micro-interlocking, and inter-particle contacts (Schmertmann 1991). 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 higher effective normal stresses. However, Stark 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 overconsolidated 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 (Czarnecki 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. Mitchell and Soga (2005) reported that clay particles absorb cations under the given environmental conditions (pressure, temperature, chemical and biological composition of the water). The net negative charge on the surface of soil particles is neutralized by cations in water (Terzaghi et al. 1996). The exchange reaction generally depends upon the electrovalence of the cations and the relative concentration of cations in the water. The physical and physicochemical properties of the soil may be changed during the exchange reaction, but the clay particle structures are not ordinarily affected (Mitchell and Soga 2005). The strength recovery along the failure surface may also be the cause of cation exchange. Most soils contain cementing agents, such as free carbonates, iron oxides, alumina, and organic matter, which may precipitate at inter-particle contacts (Mitchell and Soga 2005). Cementation may be a strength recovery mechanism of an ancient landslide (D'Appolonia et al. 1967). For the cementation process to occur, sufficient time would be required, hence the remolded specimen in the laboratory may not have experienced cementation because of insufficient time. The bond formed by cementation tends to be brittle and can be destroyed by a small shear displacement. External agents (i.e. admixture) would thus be required for cementation to occur; however, cementing agents were not added during this test. Moreover, all test conditions, e.g. application of effective normal stress, room temperature, etc., were kept constant during the experiments. Hence, the recovery of strength in this study may not be a result of cementation.

Conclusions

In this study, three soil samples collected from three different large-scale landslides in Nepal and Japan 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 main findings of this study are summarized below:

1. 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.
2. The present study re-establishes that the strength recovery from the residual value would be greater in high plasticity soils, with a large difference between the peak strength and the residual strength, 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.
3. 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 residual strength increases with the increase in duration of discontinued shear needs further investigation.

Acknowledgements The first author would like to acknowledge the Special Graduate Course on Disaster Mitigation Study for Asian Students, Graduate School of Science and Engineering at Ehime University, Japan for funding the project.

References

Angeli MG, Gasparetto P, Menotti RM, Pasuto A, Silvano S (1996) A visco-plastic model for slope analysis applied to a mudslide in Cortina d'Ampezzo. Q J Eng Geol 29:233–240

Angeli MG, Gasparetto P, Bromhead N (2004) Strength-regain mechanisms in intermittently moving slides. In: Proceedings of the IXth international symposium on landslides, Rio de Janeiro 1. Taylor and Francis, London, pp 689–696

Bhat DR, Bhandari NP, Yatabe R, Tiwari RC (2011) Residual-state creep test in modified torsional ring shear machine: methods and implications. Int J Geomate 1(1):39–43

Bhat DR, Bhandari NP, Yatabe R, Tiwari RC (2012) A new concept of residual-state creep test to understand the creeping behavior of clayey soils. Geocongress 2012:683–692. doi:10.1061/9780784412121.071

Bhat DR, Bhandari NP, Yatabe R (2013a) Effect of shearing rate on residual strength of Kaolin Clay. Electron J Geotech Eng 18 (G):1387–1396

Bhat DR, Bhandari NP, Yatabe R (2013b) Residual-state creep behavior of typical clayey soils. Nat Hazards 69:2161–2178. doi:10.1007/s11069-013-0799-3

Bhat DR, Bhandari NP, Yatabe R (2013c) Study of preexisting shear surfaces of reactivated landslides from a strength recovery perspective. J Asian Earth Sci 77:243–253, http://dx.doi.org/10.1016/j.jseaes.2013.08.023

Bhat DR, Bhandari NP, Yatabe R (2013d) Method of residual-state creep test to understand the creeping behaviour of landslide soils. Landslide Sci Pract 2:635–642. doi:10.1007/978-3-642-31445-2_83

Bhat DR, Bhandari NP, Yatabe R (2014) Strength recovery from residual-state of shear on soils. Indian Geotech J 44:94–100. doi:10.1007/s40098-013-0066-2

Bishop AW, Green E, Garge VK, Andresen A, Brown JD (1971) A new ring shear apparatus and its application to the measurement of residual strength. Geotechnique 21(4):273–328

Bromhead EN (1979) A simple ring shear apparatus. Ground Eng 12 (5):40–44

Carrubba P, Del Fabbro M (2008) Laboratory investigation on reactivated residual strength. J Geotech Geoenviron 134 (3):302–315

Czarnecki J, Dabros T (1980) Attenuation of the van der Waals attraction energy in the particle/semi-infinite medium system due to the roughness of the particle surface. J Colloid Interface Sci 78 (1):25–30

D'Appolonia E, Alperstein R, D'Appolonia DJ (1967) Behavior of a colluvial slope. J Soil Mech Found Div 93(4):447–473

Gibo S, Egashira K, Ohtsubo M, Nakamura S (2002) Strength recovery from residual state in reactivated landslides. Geotechnique 52 (9):683–686

Mesri G, Castro A (1987) C_a/C_c concept and K_0 during secondary compression. J Geotech Eng 113(3):230–247

Mitchell JK, Soga K (2005) Fundamentals of soil behavior, 3rd edn. Wiley, New York

Nakamura S, Gibo S, Yasumoto J, Kimura S, Vithana S (2010) Application of recovered strength in stability analysis of reactivated landslide, Xuechengzhen, China. GeoFlorida 2010:3149–3154

Ramiah BK, Purushothamaraj P, Tavane NG (1973) Thixotropic effects on residual strength of remoulded clays. Indian Geotech J 3 (3):189–197

Schmertmann JH (1991) The mechanical ageing of soils. J Geotech Eng 117(12):1288–1330

Skempton A (1964) Fourth rankine lecture: long term stability of clay slopes. Geotechnique 14(2):77–101

Skempton AW (1985) Residual strength of clays in landslides, folded strata and the laboratory. Geotechnique 35(1):3–18

Stark TD, Hussain M (2010) Shear strength in preexisting landslides. J Geotech Geoenviron 136(7):957–962

Stark TD, Choi H, McCone S (2005) Drained shear strength parameters for analysis of landslides. J Geotech Geoenviron 131(5):575–588

Terzaghi K, Peak RB, Mesri G (1996) Soil mechanics in engineering practice, 3rd edn. Wiley, New York