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Residual-State Creep Test in Modified Torsional Ring Shear Machine: Methods and Implications

Deepak Raj Bhat, Netra Prakash Bhandary, Ryuichi Yatabe, Ram Chandra Tiwari
Ehime University, Graduate school of Science and Engineering, Japan

ABSTRACT: Landslide mass are supposed to reach residual state which naturally demands residual-state creep study. To study the creep behavior of landslide soils, a method for residual-state creep test with a modified torsional ring shear machine was developed in laboratory, which can simulate the creeping landslide phenomena. To understand the creeping behavior of landslide soils, three representative landslide soil samples, which have higher percentage of Smectite, Chlorite, and Mica are taken in this study. A series of residual-state creep test (i.e. seven tests) with varying applied constant shear stress for each sample were conducted, the results thus obtained are interpreted in terms of Residual-State Creep Stress Ratio (RCSR), at which the soil samples fail at their residual state. The term RCSR is the ratio of applied constant shear stress with residual strength. The test results show that when RCSR ≤1, the soil does not show creeping behavior where as the soil undergo creeping behavior when RCSR>1.This paper mainly focus on the methods of residual-state creep test, its implications for the study of creeping displacement behavior, and further possibilities of landslide displacement prediction based on experimental findings.

Keywords: Landslide soils, Modified torsional ring shear machine, Residual-state creep test, Landslide displacement prediction

1. INTRODUCTION

Clayey soils exhibit creep behavior, in which the deformation of soil depends on time under any applied constant effective pressure or self weight. Clay soils show all the rheological properties, where the creep is the most typical, pronounced and readily observed. To understand the creeping displacement behavior of landslide soils, the ideal creep curve is divided into three sections: 1) Primary creep (damping or unsteady), 2) secondary creep (steady, at a constant rate), and 3) tertiary creep (undammed or progressive flow). In primary creep, rate of acceleration decrease and after a certain period of time, rate of acceleration becomes constant which is known as secondary creep. In tertiary creep, the rate of acceleration is sharply increases leading to failure.

Special soil properties such as strength parameters, physical parameters, mineralogical composition, and many others are required to evaluate mechanism and prediction of large-scale landslides. Field tests for these properties may be time consuming, expensive, tedious, and a difficult task, but laboratory investigation in most cases is affordable and convenient. The application of a ring shear apparatus to estimate the strength of a soil is preferred especially when the soil strength is governed by higher shear deformation. Creeping landslides, for example, possess very high shear strain at very low rate of deformation along the slip surface. The strength of slip surface soils in case of a slow-moving landslide is thus governed by the state of extremely slow rate of shear. Such a state of soil, when its strength is governed by shear deformation resulting in no change in volume is often known as residual state, at which the strength of a clayey soil is always less than its peak strength. Creeping landslides usually move with extremely slow rate of displacement, and they often undergo cumulative displacement of several meters. Theoretically, under similar conditions the residual strength for landslide clay in its field residual state measured in the laboratory must be equal to that in the field. The field residual strength value for the slip surface soil of landslide should be the same as the strength calculated from the back analysis of the landslide in which movement has been reactivated along a pre-existing slip surface [9]. It means the back analyzed and lab-determined strength parameters must be the same that the lab tests are carried out under precisely similar in-situ conditions. The drained residual shear strength measured in a ring shear machine is in agreement with the back-calculated drained residual shear strength for a landslide slip surface [3], [6], [10], [11], [13]. Hence, laboratory investigated shear strength can be useful for the study of creep landslide mechanisms and further possibilities toward displacement predictions.

Most of large-scale landslides show the creeping behaviour due to the presence of greater composition of clayey minerals such as Smectites, Chlorites, and Micas and illites because of their higher surface area, cation exchange capacity and affinity for water. The past works (e.g. [1], [7], [8], [12], [14]) are confined to pre-peak creep study; however, landslide mass is supposed to reach residual state which naturally demands post-peak creep study, especially residual-state creep study. The residual-state creep test set-up is developed in the laboratory using a modified torsional ring shear machine, which is adequately capable of measuring the displacement with respect to time under the application of constant creep load. In this study, three representative landslide soils, which have higher percentage of Smectite, Chlorite, and Mica are tested using newly developed residual-state creep testing procedures. To understand the creeping behaviour of landslide soils, creep load is varied until the specimen fails keeping the effective normal stress constant. A series of residual-state creep test (i.e. seven tests) for each sample are conducted, and the results thus obtained are interpreted in terms of Residual-state Creep Stress Ratio (RCSR), at which the soil samples fail at their residual state. The term RCSR is the ratio of applied constant shear stress to residual strength. The test results show that when RCSR ≤1, the soil does not show creeping behaviour where as the soil undergo creeping behaviour when RCSR>1. This paper mainly focuses on method of residual-state creep and its implications for the study of creeping displacement behavior of large-scale landslide, and finding the possibilities of predicting landslide displacement.

2. MATERIALS AND METHODS

In this study, three representative landslide soil samples collected from the landslide areas in Japan and Nepal are taken. The landslide soil from Shikoku area in Japan is confirmed to have comparatively high amount of Chlorite, and is named "Chlorite-rich sample" and the landslide soil from Kobe area in Japan is confirmed to have high amount of Smectite, which is named "Smectite-rich sample". Similarly, the landslide soil from Krishnabhir landslide area in Nepal is confirmed to have high amount of Mica, and is named "Mica-rich sample". All test samples are prepared with over consolidated under the effective normal stress 196.20kN/m^2, and effective normal stress (98.10 kN/m^2) is uniformly applied to the entire specimen during shear and creep test.

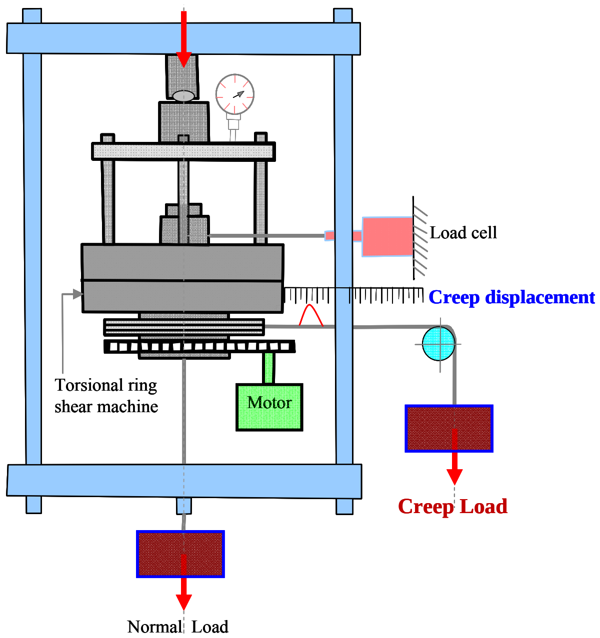

Fig. 1. Modification of torsional ring shear machine

Bishop et al. (1971) type ring shear machine is modified based on transitional change of strain-controlled motor-driven shear into creep load shearing without completely releasing the applied shear stress which is capable of measuring of the creep displacement with respect to time under the application of constant creep stress as shown in Fig. 1[1]. In residual-state creep test, there are mainly two steps: (1) ring shear test, and (2) residual-state creep test. Ring shear test is done to determine the residual shear strength of landslide soils under the fully saturated state. This state is confirmed when the shearing has reached the residual state indicating the constant values in load-cell reading and dial gauge reading after a large displacement; then, the specimen is ready for the residual-state creep test. The lower part of ring shear has developed in such a way that the overall effect of creep load is directly acting on the slip surface of test specimen and the small displacement due to the application of constant creep load is recorded in displacement recorder unit. The deformation of the specimen with respect to time and the corresponding changes in volume if any during creep tests recorded automatically. The controlled shearing of the specimen is done until the specimen reaches to the residual state after the large displacement of shearing; then, shearing process is stopped to start the residual-state creep test. Initially, the creep load is applied 85 % of its residual state which is equivalent to RCSR, 0.8500. Then, it is left for a couple of hours in the same condition to check the significant effect of creeping behaviour or not. Similarly, creep load is applied accordingly with RCSR values 0.9000, 0.9500, 1.000, 1.0025, 1.0050, 1.0100, 1.0125, 1.01500, 1.0200 until the specimen reach to fail. Fig. 2 shows the overall experimental flow of residual-state creep test.

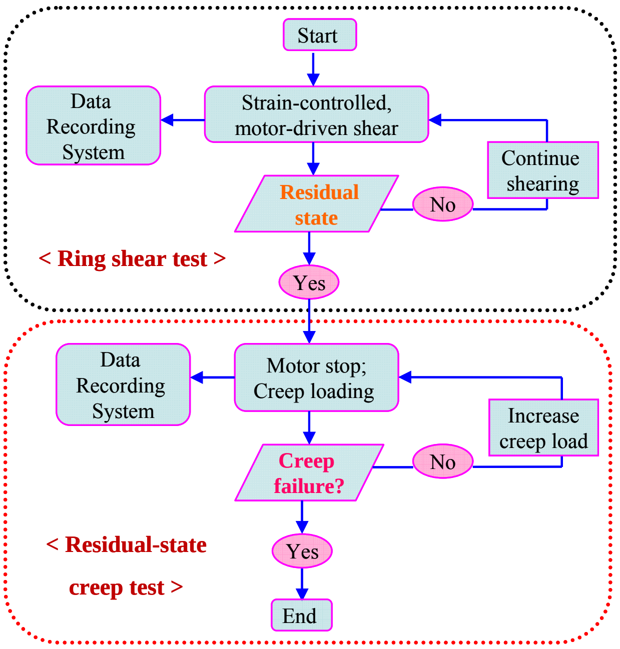

Fig. 2. Overall experimental flow of creep test

3. RESULTS AND DISCUSSIONS

Typical ring shear test results on Smectite-rich sample, Chlorite-rich sample, and Mica-rich sample are presented in terms of variation of shear stress and specimen depth with the shear displacement (as shown in Fig. 3). Residual state of the shear have obtained after 10.0 cm of shear displacement in the case of Chlorite-rich sample and Mica-rich sample but after 15.00 of shear displacement in the case of Smectite-rich sample. For the confirmation of residual, residual-state creep tests of Smectite-rich soil specimen is preceded up to 20.0 cm of shear displacement and up to 15.0 cm for remaining soil specimens. Since the sample preparation and test procedures are conducted in certain set procedure, the residual strength of each samples are found in close agreement. Result shows that Mica-rich sample has higher value of residual shear strength and followed respectively by Chlorite -rich sample, and Smectite-rich sample (as shown in Fig. 3).

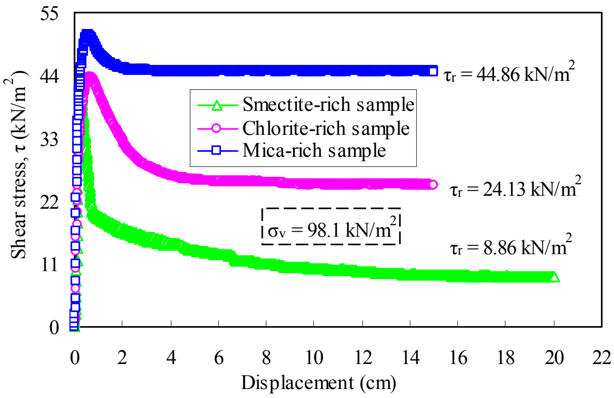

Fig. 3. Typical ring shear test of representative landslide soil samples

Fig. 4 - Fig. 6 show the typical residual-state creep test on Smectite-rich sample, Chlorite-rich sample, and Mica-rich sample respectively. Similarly, more than six tests for each sample are conducted with varying applied constant creep load. The results thus obtained are summarised in tabular form as shown in Table 1-Table 3. Table 1-Table 3 show the summary of residual-state creep tests on Smectite-rich sample, Chlorite-rich sample, and Mica-rich sample respectively. Test results show that the creeping process is initiated from the residual state and there is no significant creeping effect on and below the residual state. That means when RCSR ≤ 1, the soil does not show creeping behaviour, and the soil undergo creeping behaviour when RCSR>1. When the application of constant creep load is higher, the clayey soils begun to fail immediately with small displacement, but with lower value of applied constant stress, it takes long time to reach the failure state. For the same applied constant creep load, Smectite-rich sample is failed in short time and Chlorite-rich sample, and Mica-rich sample are taken some longer time reach to fail respectively.

The nature of curve in primary stage of creep consists of logarithmic curves, secondary stage of creep shows linear, and in tertiary creep of parabolas. In primary creep, Smectite-rich sample shows the smooth curve nature and Chlorite-rich sample and Mica-rich sample are followed it. Mica-rich sample shows the steep curve nature in the stage of tertiary creep. The nature of secondary creep for all tested samples is almost similar pattern; however, Smectite-rich sample and Chlorite-rich sample show slightly steep slope than Mica-rich sample. In tertiary creep, Smectite-rich sample shows the smooth parabolic curve with higher radius of curvature, and Chlorite-rich sample and Mica-rich sample are followed it. Smectite-rich sample and Chlorite-rich sample show tertiary creeping behaviour in long period of time with maximum displacement with compare to Mica-rich sample before leading to failure, that means range of tertiary creep in Smectite-rich sample and Chlorite- rich sample are higher than Mica-rich sample.

The prediction curves (Time to complete failure Vs RCSR) based on the tertiary creep is presented in Fig. 7. This curve can predict the time to complete failure (sec) with corresponding to RCSR value. For example, if RCSR is 1.0025, Smectite-rich sample will reach to fail after 89948 sec but in case of Chlorite-rich sample, test specimen resists the applied constant creep stress up to 170900 sec and up to 300784 sec in case of Mica-rich sample. Failure trends show that Smectite-rich sample is failed in short time with respect to other tested sample. The range of failure time with varying RCSR; 1.0025-1.0200, are 22 sec-89948 sec, 42 sec-259440 sec, and 72 sec-300784 sec on Smectite-rich sample, Chlorite-rich sample, and Mica-rich sample respectively. This graph shows that a landslide soil which have minimum residual strength shows the significant creeping behaviour. Hence, Smectite-rich test sample is failed first in short time; then, Chlorite-rich sample, and Mica-rich sample are failed respectively.

Similarly, the prediction curve (Displacement until complete failure with respect to RCSR) is purposed based on test results as shown in Fig. 8. In this prediction curve, Smectite-rich sample has maximum displacement before the failure and Chlorite-rich sample and Mica-rich sample are followed it respectively. The range of displacement is 1.5 mm-4.15 mm, 1.20 mm-2.99 mm and 0.67 mm-2.44 mm with varying RCSR; 1.0025-1.0200, on Smectite-rich sample, Chlorite-rich sample, and Mica-rich sample respectively. It can be concluded that the landslide soils which has higher-percentage of weak clayey minerals such as Smectite and Chlorite shows the significant role in reactivation and displacement behavior of the large-scale landslide.

The prediction curves have a potential to predict the failure initiated time period and its corresponding displacement for any value of RCSR. Although, the prediction curves are obtained from the lab test results of representative landslide soils, it certainly gives the possible direction toward

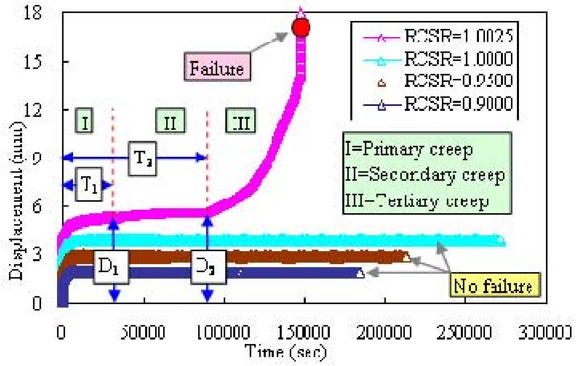

Fig. 4. Typical residual-state creep test on Smectite-rich sample

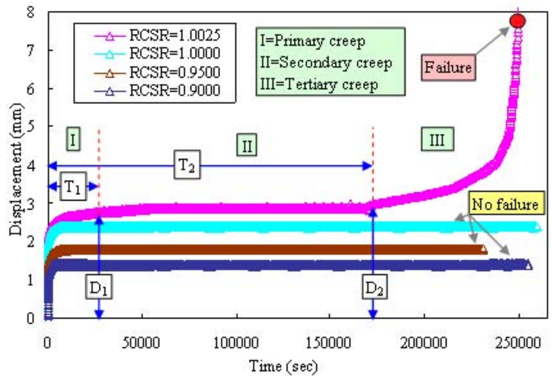

Fig. 5. Typical residual-state creep test on Chlorite-rich sample

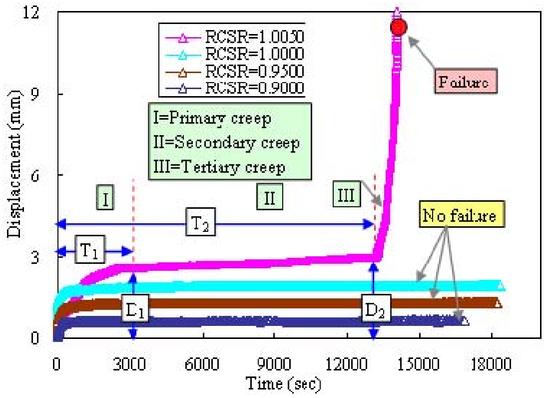

Fig. 6. Typical residual-state creep test on Mica-rich sample

deformation prediction of a landslide soils mass with to time under any applied constant effective pressure or self weight. In this residual-state creep test, the increment of the creep load is done by directly increasing the applied creep load, but in the real field, the effective stress is being changed with the fluctuation of ground water table by rainfall or seismic event.

Table 1. Summary of residual-state creep test on Smectite-rich sample

Test No.	RCSR	T1 sec	D1 mm	T2 sec	D2 mm	Remarks
7	1.0200	10	0.90	22	1.50	Failure
6	1.0150	16	1.37	58	1.80	Failure
5	1.0125	32	1.60	100	2.21	Failure
4	1.0100	144	1.96	322	3.04	Failure
3	1.0075	318	2.65	926	3.61	Failure
2	1.0050	1122	2.61	3962	4.08	Failure
1	1.0025	32584	2.98	89948	4.15	Failure
1	1.0000	6054	2.36	207552	2.36	No failure
1	0.9500	5700	2.17	212500	2.17	No failure
1	0.9000	5420	1.86	184520	1.86	No failure

Table 1. Summary of residual-state creep test on Chlorite-rich sample

Test No.	RCSR	T1 sec	D1 mm	T2 sec	D2 mm	Remarks
7	1.0200	18	0.70	42	1.20	Failure
6	1.0150	28	1.07	110	1.39	Failure
5	1.0125	58	1.36	190	1.51	Failure
4	1.0100	250	1.76	802	2.07	Failure
3	1.0075	554	2.56	1758	2.79	Failure
2	1.0050	1964	2.59	7528	2.97	Failure
1	1.0025	57020	2.90	170900	2.99	Failure
1	1.0000	7398	1.89	259440	1.89	No failure
1	0.9500	6850	1.81	255050	1.81	No failure
1	0.9000	6950	1.37	230880	1.37	No failure

Table 1. Summary of residual-state creep test on Mica-rich sample

Test No.	RCSR	T1 sec	D1 mm	T2 sec	D2 mm	Remarks
7	1.0200	22	1.53	72	0.67	Failure
6	1.0150	36	0.56	190	0.82	Failure
5	1.0125	66	0.60	330	0.94	Failure
4	1.0100	260	1.23	1390	1.50	Failure
3	1.0075	570	1.39	3060	2.22	Failure
2	1.0050	2402	1.95	13174	2.40	Failure
1	1.0025	54840	0.54	300784	2.44	Failure
1	1.0000	8440	0.95	191930	0.95	No failure
1	0.9500	7990	0.65	182208	0.65	No failure
1	0.9000	6840	0.59	163480	0.59	No failure

If some relationships between this experiment results and real field scenario can be established, displacement prediction is analytically possible.

The shear strength of the slip-surface zone was recovered in a stable period before re-sliding [4]. The recovery of the shear strength for the clayey soil under the normal stress below 100 kPa. The soil containing the large amount of clay particles and dominated by Smectite, there was a large fall in shear strength to the residual state, but the strength recovery was negligible for the whole range of normal stress [5]. Strength recovery is not considered in this study.

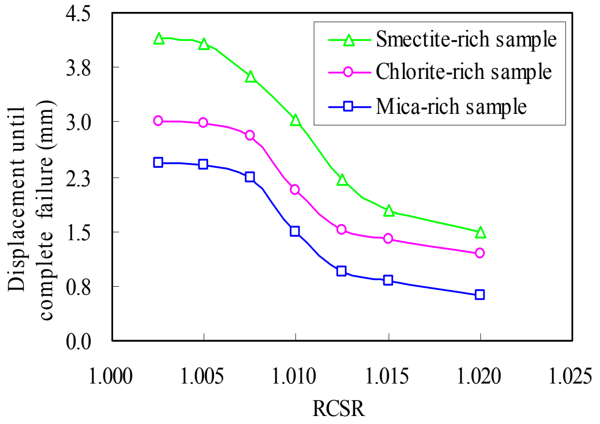

Fig. 8. Prediction curve (Displacement until complete failure

4. CONCLUSION

Based on test results, the main findings of this study are as: 1) the residual-state creep test set up is developed in the laboratory using a modified tortional ring shear machine, which is adequately capable of evaluating the residual-state creep behavior of landslide soils, 2) new concept of residual-state creep test and its testing procedures are developed, 3) the ideal creep curve for a soil material was verified in the test procedure and was found to perfectly matching with obtained results, 4) when a soil material is in residual state, the creeping behavior is exhibited only under a shear stress greater than the residual strength., 5) prediction curves are purposed for predicting the time until complete failure and its corresponding displacement.

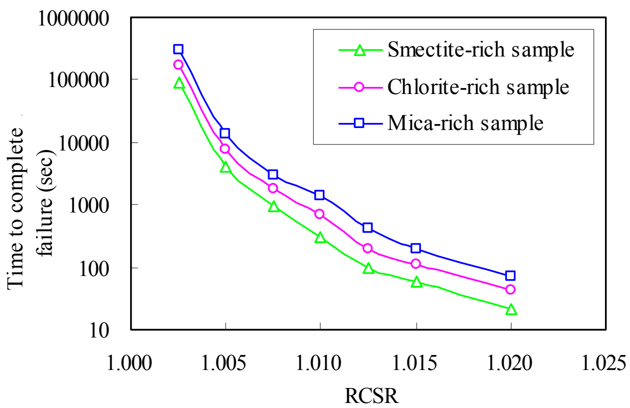

Fig. 7. Prediction curve (Time to complete failure Vs RCSR)

5. ACKNOWLEDGMENT

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Corresponding Author: Deepak Raj Bhat