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Tertiary Creep Reproduction in Back-Pressure-Controlled Test to Understand the Mechanism and Final Failure Time of Rainfall–Induced Landslides

Atitkagna DOK*, Hiroshi FUKUOKA, Takeshi KATSUMI* and Toru INUI*

*Graduate School of Global Environmental Studies, Kyoto University

Synopsis

Fukuzono (1985) developed a method for predicting final failure time of a slope based on the findings from large scale flume test series that log of acceleration and velocity of surface displacement immediately before failure are proportional, $d^2x/dt^2=A(dx/dt)^{\alpha}$. He proposed a simple method for predicting failure time by plotting the inverse velocity of surface displacement *(1/v)*. Yet, its mechanism is still unknown. To investigate the Tertiary creep mechanism in soils, a series of back-pressure controlled test on saturated sands were undertaken in ring shear apparatus. The tests were conducted under particular normal stress and shear stress with pore-water pressure changes to simulate the potential sliding surface condition in heavy rainfall. Sand and its mixture with clay material were used for specimen. Consequently, these tests could reproduce Tertiary creep to failure, in which similar log v-log α relationship and α value range was found. While, linear relationship of α and A values was found.

Keywords: Tertiary Creep, ring shear apparatus, back-pressure-controlled test, rainfall–induced landslides.

1. Introduction

Landslides are complex geo-disasters frequently triggered by earthquake and/or intense heavy rainfall or other related natural/ anthropogenic impacts. Such catastrophic disasters have not only claimed residents' lives, but also resulted in property damages and other socio-economic consequences, which significantly interrupts the development of the communities and nations. Since the social resources for preventing those threatening potential landslides is limited in every country, the best solution recently met is safe evacuation immediately before the final catastrophic failure of the landslide. To realize an effective evacuation, reliable prediction methodology must be established.

Accordingly, in landslide fields, failure-time prediction methods of landslide have been widely developed by many researchers including Saito and Uezawa (1960, 1966) as an initiation, Kawamura (1984), Fukuzono (1978, 1982, 1985), Voight (1988, 1989), Azimi (1988), Hayashi, et al. (1980). However, only two methods developed by Saito and Uezawa (1960, 1966) and Fukuzono (1985) were accepted world-wide. Based on Tertiary creep deformation theory through the findings getting from large scale flume tests for landslide studies, Fukuzono (1985) found logarithm of acceleration is proportional to the logarithm of velocity of surface displacement immediately before the failure, expressed as $d^2x/dt^2=A(dx/dt)^{\alpha}$, where x is surface displacement, t is time, and A and α are constant. Besides, he proposed a simple method for predicting the time of failure by the inverse velocity (*1/v*) mean. The curve of inverse velocity is concave at $1< \alpha<2$, linear at $\alpha=2$, and convex at $\alpha>2$. In spite of such exceptional achievements as well as great ability in estimating the failure time of a slope, these methods still need to be improved for higher accuracy, and the mechanism of creep deformation is not yet well-understood up to now.

Lately, to understand the story behind the empirical relationship discovered by Fukozono, Minamitani (2007) has accomplished further research on tertiary creep deformation by increasing shear-stress development in ring shear apparatus. He got consistent α value distribution (1.95–2.46) as declared by Fukuzono (1985) and a strong relationship between A and α values, $\alpha = 0.1781A+ 1.814$. He concluded that α value is not always constant throughout a test with proof of quite different variation trends of α value of dry and saturated samples in normal stress and Bentonite content test series, and even in OCR test series. Throughout his research findings on tertiary creep corresponding to the period of forming a sliding surface, Minamitani (2007) named α progressive acceleration parameter which alters depending on type of material and its condition in the initial and final stages of tertiary creep.

2. Objective of study

This study aims at figuring out the mechanism of landslides in tropical soils with respect to tertiary creep deformation theory by stress-controlled ring shear apparatus in help issue warning of rainfall–induced landslides in Southeast Asia countries through back-pressure-controlled test series under combined conditions of particular normal stress and shear stress with pore-water pressure changes to simulate the potential sliding surface condition in heavy rainfall.

3. Concept of creep in soils

In most landslide cases, failures are preceded by accelerated trend of displacement, which is associated with crack growth, soil particles rearrangement and shear surface evolution, often called progressive failure. Creep rupture theory was originated from material science, termed a time-dependent deformation. Creep generally consists of three phases as indicated in Figure 1.

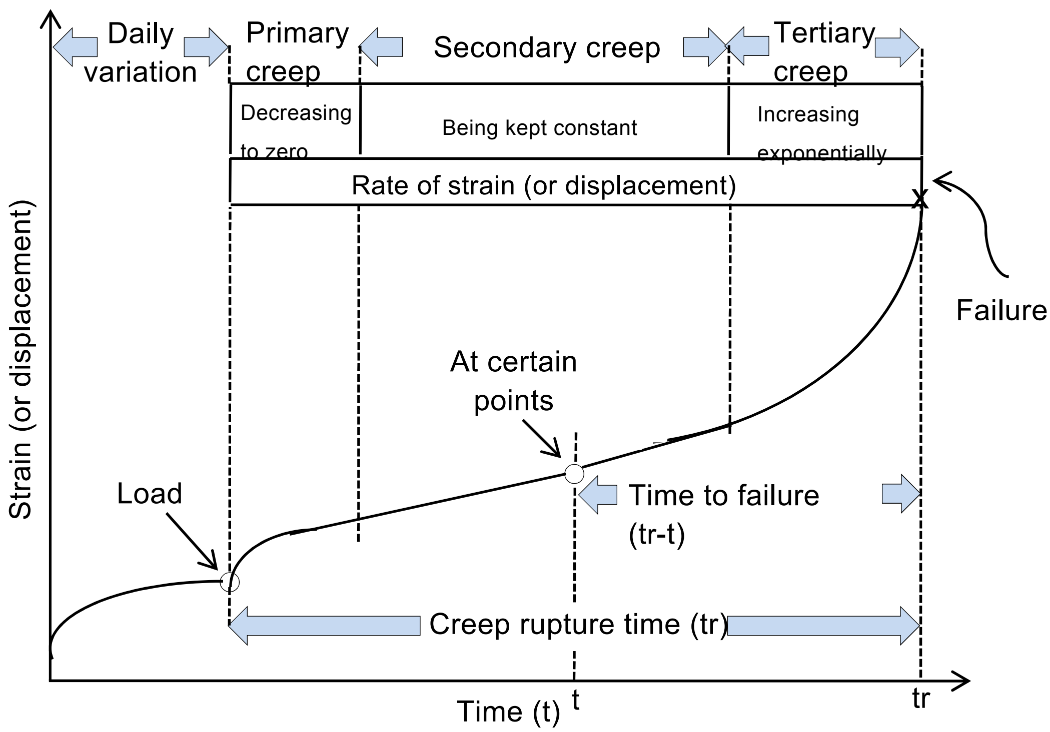

Figure 1: General relationship of strain and time of a series of creep deformation (Saito, 1965)

Primary creep is the initial stage of deformation when the strain rate is relatively high, but with minimum displacement. The strain rate eventually reaches a minimum and becomes nearly constant in secondary or steady-state creep, meaning that the mass is continuously deforming at constant volume, normal effective stress and velocity. It is archived only after all the particle orientation has reached a steady state condition and after all the particle breakage, if any, is complete, so that the shear stress needs to continue deformation and the velocity of deformation remains constant (Poulos, 1981). In tertiary creep, the strain rate exponentially increases through time, and finally failure occurs afterward.

4. Ring shear apparatus

The un-drained and stress-controlled ring shear apparatuses are unique and most advanced geotechnical simulation apparatus invented by Sassa, Fukuoka and their colleagues at the Disaster Prevention Research Institute (DPRI), Kyoto University. The latest device in the DPRI ring shear series, DPRI-7, is employed to reproduce tertiary creep deformation in this study. It was designed with special ability to simulate quantitatively the entire process of failure of a soil sample from initial static or dynamic loading through shear failure, pore pressure changes and possible liquefaction to large displacement, steady-state shear movement. The DPRI-7 were developed to simulate the formation of the shear zone and the post failure mobility of high speed landslides and to observe the consequence of mobilized shear resistance, as well as the post failure shear displacement and generated pore-water pressure as simplified Figure 2.

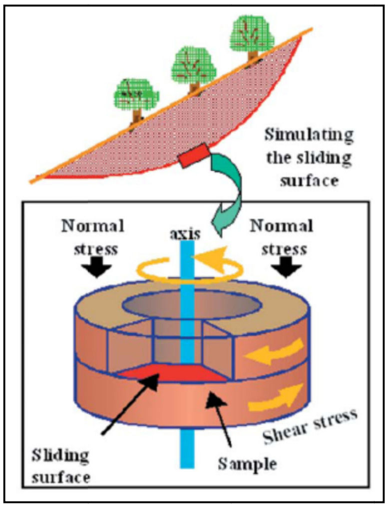

Figure 2: Design concept of the ring shear apparatus (Sassa, Fukuoka, et al., 2004)

Typical designed features of the DPRI-7, which allow the reproduction of shear zone formation and the resulting motion along the shear zone, are obviously diescribed as follows:

- Shear box: inner and outer diameters: 27cm and 35cm.
- Unlimited shearing
- Un-drained testing under rapid shearing and pore pressure monitoring.
- Shear speed: 33–300cm/sec.
- Rapid loading and high-speed data acquisition 12–1,000 readings/sec.
- Transparent shear box made of acrylic basin enables observation of shear zone during the initiation and post-failure motions of landslide.
- Cyclic shear-displacement control, torque control, and shear speed control tests are possible.

5. Back-pressure-controlled test

5.1 Sample Characteristics

Commercial fine grained silica sand No.8 (SS8), Bentonite as well as natural soil samples taken from sliding surfaces of actual landslide sites were utilized in back-pressure control test series of this study. There are four types of specimen: (I) SS8, (II) SS8 with 10% Bentonite, (III) SS8 with 20% Bentonite, and (IV) volcanic and silty soils taking from El Salvador, Shobara and Tandikat cities.

5.2 Test Conditions

25 back-pressure controlled tests were

performed in this study under different over consolidation ratios (OCR) and pore-water pressure increase rate in drained condition that the sample can change its volume, with slope inclination θ= 30°. Table 1 outlines initial conditions of each test depending on sample type.

5.3 Test Procedures

(1) Sample Setting

The ready-mixed dry sample was freely placed into the shear box layer by layer with the insertion of filter papers on the top and bottom of the sample.

(2) Sample Saturation

The sample was saturated with help of carbon dioxide (CO_2) and de-aired water. After the sample was completely packed, the CO_2 gas was gradually percolated through the sample to expel the air in the sample pores for about 30 minutes to 2 hour(s) until all air was replaced by CO_2. De-aired water was then infiltrated from the lower part of sample box and kept circulating into the sample to drive out the CO_2 from the sample pores. This injection process has to be at a very low rate, which takes at least one overnight to finish. Small amount of the remaining gas will be easily dissolved when normal stress is applied.

(3) Checking Degree of Saturation

Saturation degree was checked by B_D value. As proposed by Sassa (1988), B_D is a pore pressure parameter which is related to the degree of saturation in the direct-shear state, formulated as $B_D=\Delta u/\Delta\sigma$, where Δu and $\Delta\sigma$ are increments of pore pressure and normal stress respectively in un-drained condition. While checking, the sample was initially consolidated under normal stress of 50kPa in drained condition. Next, the normal stress increment of $\Delta\sigma$=50kPa was successively applied under un-drained condition, and the resultant increment of excess pore pressure (Δu) was accordingly measured. Hence, the saturation degree was determined indirectly by the ratio of excess pore pressure and normal stress increments ($\Delta u/\Delta\sigma$), which is preferably to be ≥0.95 due to necessity in acquiring correct monitoring data. The B_D value acquired in this test series varies from 0.95 to 0.99.

(4) Sample Consolidation

In this test series, all the samples were consolidated with respect to the targeted value of OCR as denoted in Table 1. After checking the B_D value, the normal stress was decreased to a value where the excess pore pressure is reaching zero, then switch on the upper drainage valve. Afterward, slowly load the normal stress to a decided value, and then subsequently reduced applied normal stress to the predefined normal stress (σ=100kPa) in case the OCR>1.0. A particular shear stress τ=50kPa was applied soon after some time of consolidation process. It takes longer time for sticky material while consolidating. This is due to the fact that in most cases the soil layers, in which sliding surfaces were formed, were weathered or fully softened (Sassa, Fukuoka, et al., 2004). The sample taken from the landslide sites were therefore normally consolidated before the test.

(5) Pore-Water-Pressure Increase to Failure

Pore water pressure inside the shear box was progressively increased up to 95kPa with various increase rates as written in Table 1 with constant normal stress and shear stress. It is to formulate the potential sliding surface condition corresponding to rain storms in naturally drained condition. The pore pressure is monitored from the controlled computer to water tank connected to the nearby air tank with a servo-controlled air regulator (see Figure 3). The water pressure was provided through the soil sample via the tube linked between the water tank and the sample box of the ring shear apparatus. Failure may occur at any time while stress condition is attaining the failure criteria. Maximum shear displacement was limited to 200cm to stop shearing automatically after failure.

Figure 3: Frontal view of the employed ring shear apparatus DPRI-7

6. Test results and Discussions

6.1 Ring Shear Test Results

In each test, the investigation is principally focused on the curve of inverse velocity and shear displacement in several seconds immediately before failure, and the increment of acceleration and velocity observed in a few thousand seconds before failure to quantify Tertiary creep deformation analysis. Failure point is the point at which shear resistance is reaching its peak and after which shear displacement starts to increase cumulatively through constant time interval.

The examined outputs of this test series are initial shear displacement, A and α values getting before failure of every test as summarized in table 1. Figures 4–7 show a selected test results–test No.3. Figure 4 views the overall test record that appears the accelerating displacement curve of typical Tertiary creep, while Figure 5 indicates relatioonaship between shear stress and effective normal stress before and after reaching failure line. Figure 6 exaggerates inverse velocity and shear displacement at the final stage of Tertiary creep from 1625–1765 seconds. The inverse velocity displays almost linear decreasing trend, which is also observed in Fukuzono's flume tests. Figure 7 illustrates the logarithm of acceleration and velocity. Linear relationship appeared 0.00008–0.07cm/s and the α value was calculated to be 2.107 in this range.

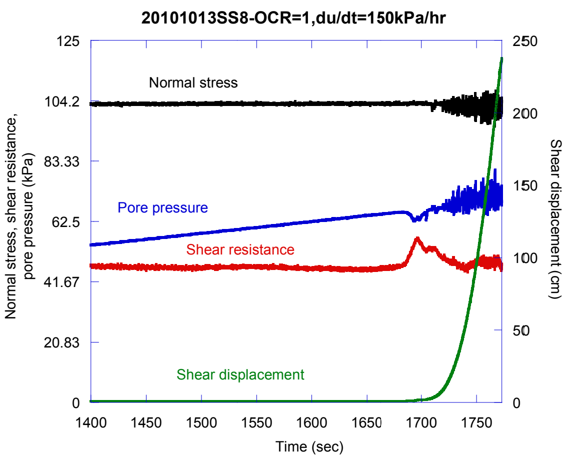

Figure 4: Temporal change of shear displacement

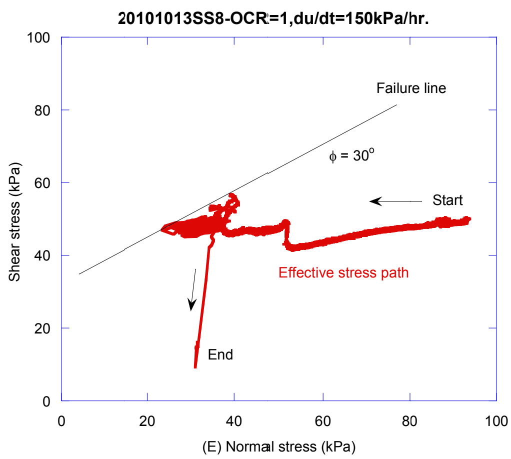

Figure 5: Stress path propagation

Table 1: Back-pressure-controlled test conditions and results

Test no.	Samples	OCR	Pore pressure increase rate (du/dt, kPa/hr.)	Initial shear displacement (cm)	A value	A value
1	SS8	1.0	100	717	2	189.09
2	SS8	1.0	100	967	2.019	1,310.345
3	SS8	1.0	150	1	2.107	146.875
4	SS8	1.0	150	239	2.124	245
5	SS8	1.0	150	473	2	183.333
6	SS8	2.0	100	1,028	1.977	140
7	SS8	2.0	100	1,285	1.983	172.727
8	SS8	2.0	100	0	2.159	200
9	SS8	2.0	150	255	2.077	220.833
10	SS8	2.0	150	510	2.009	166.667
11	SS8	2.0	150	767	2	164.286
12	SS8	4.0	150	513	2.059	253.333
13	SS8	4.0	150	0	2.017	80
14	SS8	4.0	150	258	1.99	143.636
15	SS8+Ben10%	1.0	150	0	2.59	600
16	SS8+Ben10%	1.0	150	135	1.77	8.333
17	SS8+Ben10%	1.0	150	250	1.63	1
18	SS8+Ben10%	5.0	150	668	2.32	540
19	SS8+Ben20%	1.0	75	146	2.517	1,000
20	El Salvador	1.0	25	23	2.38	289.286
21	Shobara	1.0	150	0	2.317	400
22	Tandikat 1	1.0	100	256	2.095	200
23	Tandikat 1	1.0	150	0	2.41	462.5
24	Tandikat 2	1.0	100	260	1.963	100
25	Tandikat 2	1.0	150	0	2.459	600

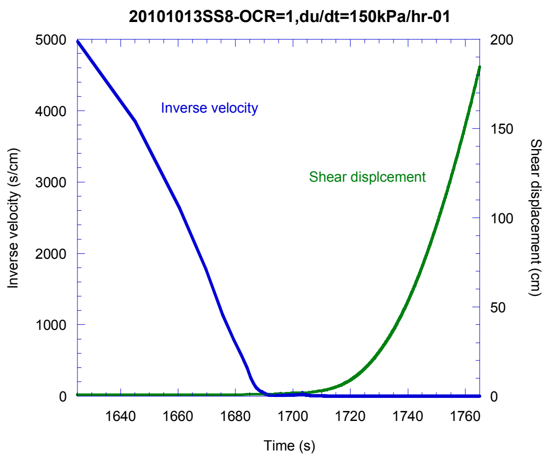

Figure 6: Inverse velocity and shear displacement at final stage of Tertiary creep

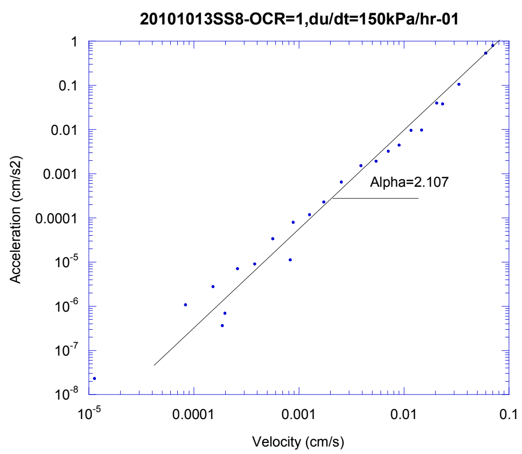

Figure 7: Relationship between acceleration and velocity in log scale

6.2 Velocity-Acceleration Analysis

The values of A and α produced in back-pressure control tests of this study are in range of 1–1310.345 and 1.63–2.59, chronologically. The inverse velocity curve and the relationship between velocity and acceleration in doubled-log scale are almost linear in all tests. Variation of alpha value v.s. initial shear displacement showed big scatter (Figure 8), including repeated creep tests of same specimens. When longer shear displacement, less variation was observed. Value of A and α obtained in the test series showed obvious relationship, and they are no longer independent. Their values follow nearly identical trend with that revealed in the shear-stress development test by Minamitani (2007) and with those found by previous researchers in spite of variation of A value (Figure 9). Figure 10 interprets the effect of OCR on α value that greater OCR results in smaller α value. However, the variations of α value corresponding to OCR effect inspected in various sample types draw very wide range, which is commonly correlated with soil sample density.

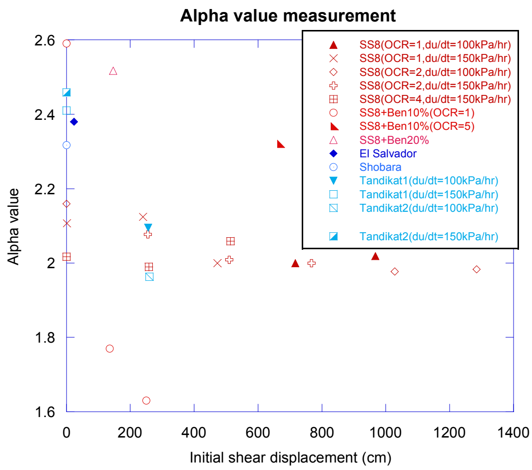

Figure 8: Summary of α value measurement

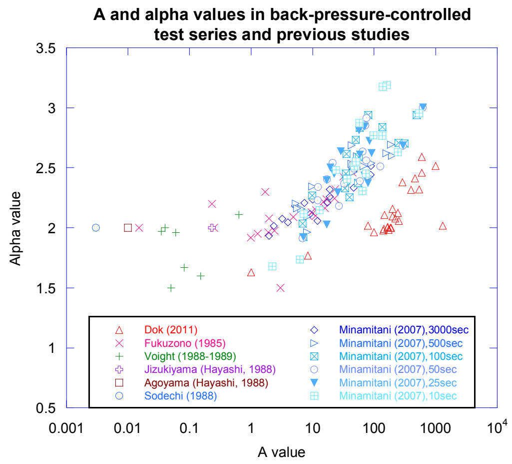

Figure 9: Relationship between A and α values of this test series and previous studies.

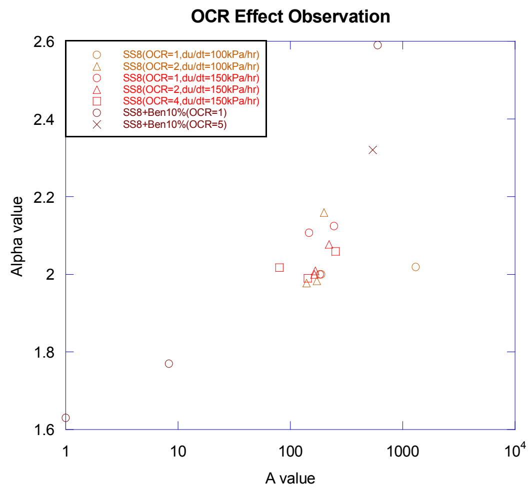

Figure 10: Examination of OCR effect on α value

7. Conclusions

The primary attempt in reproducing the Tertiary creep behaviour of sands similar to previous flume tests with artificial rainfall and previous progressive failure tests under shear stress development conditions was succeseded by raising back pressure in ring shear apparatus. The power-law relationship of velocity and acceleration was found to be similar to Fukuzono's law in spite of certain variation of A value. The reason of A value variation could be attributed by: (a) finer grain portion, (b) slightly higher rubber edge friction of the shear box compared to previous ring shear tests, (c) increase rate of pore water generation due to time. In addition, the repeated test revealed that A and α values are not much dependent to displacement after large shear displacement. More, obvious relationship of *A* and *α* values point out that they are no longer constant and independent. Alpha value does parralelly alters depending on OCR as confirmed in Minamitani's shear stress development test.

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背圧制御リングせん断試験による三次クリープの再現と豪雨時地すべり発生時刻の予知

アティカーニャ・ドク*・福岡浩・勝見武*・乾徹*

*京都大学地球環境学堂

要 旨

人工降雨による室内地すべり実験によって福囿が1985年に発見した速度と加速度の間にべき関係があることがわかり，速度の逆数を用いた地すべり崩壊時刻 の予知方法が開発され，広く用いられている。しかしその発現機構は未解明であり，土の三次クリープの発現機構を調べるため，背圧制御リングせん断試験を行い，豪雨時の地すべり発生時のすべり面の状態を再現した。試料には砂と砂・シルト混合試料を用いた。実験結果より，福囿の実験と同様の速度・加速度関係が 得られ，べきの値の範囲も同程度ということがわかった。一方べき値と線形係数の対数の間に線形関係があることもわかった。

キーワード: 三次クリープ，リングせん断試験機，背圧制御試験，豪雨時地すべり