Experimental Study on Tertiary Creep Behavior of Soils in Ring-shear Tests and Its Implication for the Failure-time Forecast of Landslides
地すべりの崩壊時刻予測に向けたリングせん断試験における土の三次クリープ変形に関する実験研究

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論文要約

CHAPTER 1 Introduction

Forecasting the time to failure of a landslide is a significant and critical goal of landslide science. A large number of inter-related variables and factors are involved and make the forecasting time of failure difficult (e.g., geometrical and geological complexities, nonlinearity of time-displacement relation, and seasonal variations). Although known as "slope creep", the persistent slow deformation can sometimes accelerate rapidly and fail catastrophically. Such accelerating behavior universally arises in various forms of failure and natural phenomena. On the basis of tertiary creep behavior that is commonly observed in landsliding and laboratory creep test, a series of phenomenological creep-failure models have been established to achieve the goal of forecasting the time of landslide failure. Among them, the Voight model ($\ddot{\Omega} = A\dot{\Omega}^{\alpha}$) is more generalized. Ω denotes a measurable quantity (e.g., displacement, tilting angle, acoustic emission counts) and the dot refers to time derivative. Values for controlling parameters of α and A, defined by accelerating movement, are representative of kinematics prior to material major failure. The Voight model represents a phenomenological approach as a wide-ranging and all-encompassing law that governs failure of diverse materials. It has been tested in many retrospective analyses of natural phenomena on a variety of scales, including earthquakes, volcanic eruptions, landslides, and laboratory creep tests. However, the model does not take account of material behavior and failure mechanisms, and the physical controls on the two kinematic parameters (α and A) are unknown. The Voight model is difficult to use for landslide early warning due to the elusive background of parameters, the uncertainties introduced by external triggers and the material complexities, and error in curve fitting. Particularly, the variation problem of the parameter α merits attention for the application of landslide and volcanic eruption forecasts, and the changes in basal shear mechanisms are believed to be the primary factors.

The key motivation of this study is to better understand the fundamental controls on landslide pre-failure kinematics through a systematic experimental examination of soils and to provide information that could assist in forecasting the time of landslide failure. I propose the major scientific questions as: (1) the possible physical controls on the parameters (α and A); (2) the connection between the variability of parameter α and the operating shear mechanisms within the shear zone. I address these questions by simulating tertiary creep of soils using novel ring-shear configurations and separating out the quantifiable features in consideration of the Voight model across tests. In this chapter, the major processes which are thought to be active during shear failure were reviewed and the relation between the pre-failure kinematics and shear zone development was inferred. The advanced knowledge of the Voight model would benefit the understanding of failure process and practice of forecasting the time of landslide failure.

CHAPTER 2 Materials and methods

Chapter 2 details the basic information of ring-shear configurations, properties of test materials, test protocols for simulations of the landslide initiation and for supplementary test, and finally the methods for data analysis.

In this study, two ring-shear configurations (DPRI-5 and DPRI-6) were employed to simulate the landslide initiation and reactivation that are triggered by rainfall or other factors. The structural features and controlling principle are schematically elucidated. Information on monitoring system and data acquisition is also introduced. The samples used for ring-shear tests were also introduced.

Two clayey samples (the Kinokawa and Shiraishi samples) were taken from two natural landslide sites. Four types of soil samples were prepared including Silica sand No.7 (abbreviated to SS hereafter), and three mixtures of Silica sand No.7 with different contents of Bentonite. The total weight ratio of bentonite was varied by 10%, 20%, and 30%, and the mixtures are termed M_1, M_2, and M_3, respectively. SS and mixtures (M_1, M_2, and M_3) were employed as analogues of landslide materials from sandy soils to clayey soils. In addition to the soil samples, spherical glass beads were also used to isolate the factors of particle shape.

The pre-defined total normal and shear stresses were applied on the sample to simulate in-situ stress state of a given slope before shear test. To simulate the landslide initiation triggered by rainfall or snowmelt (decrease in shear strength) and loading or incision at the toe of a slope (increase in shear stress), three types of loading protocols were adopted in ring-shear tests including pore-water pressure-controlled tests, normal-stress-controlled tests, and shear-stress-controlled tests. In pore-water pressure-controlled tests or normal-stress-controlled tests, samples were brought to failure by an monotonical increase in pore-water pressure or decrease in total normal stress in drained conditions. The two types of tests were aimed at replicating stress path of deceasing effective normal stress, as such they are referred to as rainfall simulation tests or "field-stress-path" tests. All of the pore-water pressure-controlled tests were conducted on the Kinokawa samples, and a normal-stress-controlled approach was applied to the rest of the samples (SS, M_1, M_2, M_3, and Shiraishi samples). A shear-stress-controlled approach was performed to simulate landslide failure induced by an increase in shear stress, and this approach was adopted to all of the samples. To simulate reactivated landslide where shear failure occurred along a pre-existing shear zone or sliding surface, shear tests were performed repeatedly with the three types of protocols, and the soil samples were re-consolidated with a complete dissipation of pore-water pressure before the next test. Apart from the main tests, several supplementary tests were conducted to observe the evolution of shear deformation by terminating the tests at different shear displacements.

Time-series data of displacement was used to calculate the parameters of α and A by retrospective analyses of the kinematic features in tertiary creep (accelerating creep) preceding material failure. The parameters were determined by linear regression of the relationship between velocity and acceleration in a double-log plot.

CHAPTER 3 Results

In chapter 3, representative results obtained from three types of tests are introduced. In each experimental setting, the test conditions and parameters calibrated are summarized in corresponding tables. The kinematic features were analyzed both in the time domain and the displacement domain, and typical kinematic patterns (i.e., divergence, non-divergence, and multi-accelerations) were recognized and documented according to the relationship between velocity and acceleration in the double-log plot. The pattern of divergence denotes the piece-wise linearity identified in the plot, while a non-divergence pattern refers to the single linear relationship. A kinematic pattern of multi-accelerations indicates alternative accelerating-decelerating phases in the velocity curve. Since distinct shear behavior and kinematic pattern were observed in repeated shear tests, results from the pre-sheared sample are presented separately in each section for comparison. Finally, the results of supplementary tests for observing the development of shear deformation are introduced.

In pore-water pressure-controlled tests and normal-stress-controlled tests that were aimed at simulating rainfall-triggered landslides, evolution of the α value was clearly indicated by a 3-stage log-linear relationship between velocity and acceleration (divergence) in first-time shear failure. The samples (Kinokawa, SS, and M_1 samples) showed an apparent dilation with small shear displacement in the first stage, and the dilation decreased in the subsequent two stages with further progress of shear displacement. A smaller value of α arose in the first stage and evolved to a larger one in the third stage. In contrast, a transition of the kinematic pattern from divergence to non-divergence was observed by the presence of high contents of clay (M_2, M_3, and Shiraishi samples), and the volumetric variation of the sample became smooth in relation to shear displacement.

For first-time failure in shear-stress-controlled tests, the velocity curves fluctuated in tests on SS samples and the kinematic pattern is described as “multi-accelerations”, and SS samples showed the most significant volumetric variation before shear failure. Global values of α were calculated to represent the kinematic feature of SS samples. By contrast, both the variations in the velocity curve and volume curve diminished gradually with the increase in clay contents of the samples. A kinematic pattern of non-divergence was favored for clayey samples, which suggests a more accurate α value for forecasting the time of failure.

Furthermore, it was found that the pre-sheared sample frequently manifested the kinematic pattern of non-divergence. The variations in α and volume of the sample during shear became fewer for the pre-sheared samples irrespective of the loading protocols and the types of material.

In supplementary tests, a more homogeneous shear deformation was observed after the consolidation stage; and the occurrence of localized shear deformation prior to failure was revealed by the curved marker within a zone parallel to the boundary in the center of the sample that was subjected to a normal-stress-controlled test.

CHAPTER 4 Discussion

Chapter 4 begins with the comparison of the typical kinematic patterns and volumetric change trends that were documented through tests. I make a hypothesis that the pre-failure kinematics is correlated with the volumetric change trend of the samples during shear. I discuss the background for the sample volumetric change observed in ring-shear test by integrating a literature review of studies on the shear zone development and observations obtained in supplementary tests. I conduct analyses to isolate the effects of stress path, clay content, and the pre-existing shear zone on the volume variation and kinematics. I demonstrate that the pre-existing shear zone is of central importance in setting pre-failure kinematics, and the process of shear localization is the primary factor in the variability of α. Consequently, I combine the subjects to approach the key issues of the physical controls on the parameter α and the reasons for its variation. Meanwhile, I examined the statistical variability of parameters in relation to test conditions. Then I provide the implications for forecasting the time of landslides and highlight the general significance of this study.

Furthermore, the limitations in this study and future perspectives are discussed. I summarize several scientific questions arising from the connection between shear dilatancy and kinematics, the statistical variabilities of the parameters, and the post-failure behavior and landslide mobility, which warrant research perspectives in the future and might benefit the subject of landslide kinematics and forecasting the time of landslide failure. In addition, I provide a brief discussion about the similarities of shear zones of different magnitudes, and emphasize the importance of the knowledge of localized shear zone for a better understanding of the landslide controls and kinematics.

CHAPTER 5 Conclusions

In chapter 5, the conclusions are drawn from observations and analyses.

In brief, this study provides the findings of a laboratory-based examination of a variety of soils to determine critical parameters (α and A) in the Voight model and their implications for how these findings may assist in forecasting the time to failure of landslides. The main conclusions could be summarized as follows.

1) In pore-water pressure-controlled tests and normal-stress-controlled tests that were aimed at simulating rainfall-triggered landslides, a piece-wise log-linear model for the velocity and acceleration (i.e., the kinematic pattern of divergence) during the tertiary creep period was identified, which indicated the evolution of the α value. The tertiary creep behavior could be subdivided into three stages, namely, with the increase of velocity, the acceleration increases slowly (Stage I), decreases transitorily (Stage II), and increases quickly (Stage III). In Stages I and III, the relationships between velocity and acceleration could be well described by the Voight model. It is

found that in Stage I, α is small, then it became larger in Stage III. However, the phenomena of 3-stage relationship disappeared and the kinematic pattern of non-divergence dominated by the presence of high contents of clay materials within the sample. For the tests in which the 3-stage relationship was identified, the dilation of the sample was predominant in Stage I and then decreased in the following stages. It is inferred that the pervasive particle realignment accompanied by shear zone broadening and the localized particle slip are the dominant operating mechanisms with the progress of shearing. The evolution of shear mechanisms might be the reason for the variation of the α value. The appearance of change in α indicated that the start of the final stage of creep, which could be followed by a catastrophic failure, and the α value obtained from this final stage can be used for more accurate forecasting of time to failure of landslides triggered by rainfall or snowmelt.

2) In shear-stress-controlled tests, multiple accelerating-decelerating phases were observed in sand samples (i.e., the kinematic pattern of multi-accelerations), and the characterization of tertiary creep could be identified in individual accelerating phases, which permits forecasting of failure time of landslide triggered by loading or toe incision. However, the fluctuations on the time-velocity curve became fewer for the samples consisting of a higher content of clay material, and a considerably steady value of α was favored for forecasting the failure time.
3) In all tests, the kinematic behavior was in close association with the volumetric change in samples. The kinematic features become less variant in the presence of a high content of clay, and the volumetric change in samples became monotonic and small. The relatively invariant volume suggests more localized shear deformation and fewer contact asperities, and a more accurate α value for failure-time forecast could be anticipated at a stage of localized shear. The process of shear localization is inferred to be the physical control on the variability of α.
4) Irrespective of loading scenarios and materials, the kinematic pattern of non-divergence was observed throughout the tests on pre-sheared samples, which indicate that the kinematic behavior was strongly regulated by the pre-existing shear zone. The variations in kinematics and volume diminished for the pre-sheared samples, which implies that the pre-existing shear zone would localize the shear deformation in successive shear failure and reduce the contact asperities within the shear zone. Namely, the pre-existing shear zone introduced starting heterogeneity to the material, such that the time-velocity curve became smooth prior to shear failure and a relatively unchanged value of α is favored, which makes the subsequent failure-time forecast more reliable by using a constant α value. These observations obtained from tests on the pre-shear sample also suggests that the identifying the existence of pre-existing shear zone is of great importance for understanding the creep behavior resulting from landslide reactivations, and then make proper forecasting for the time to failure of reactivated landslides.
5) The effects of loading rate (rate change of pore-water pressure, total normal stress, or shear-stress) on the value of α were not profound. The variation in the α value became fewer for the pre-sheared sample when the experienced shear displacement

before the shear test was larger. Evident proportionalities between α and log A were derived in this study, and the constant of proportionality varied depending on the materials and the loading approaches.

These results provide further information for understanding the progressive failure process and establishing early warning criteria for different types of landslides. The variations in parameter α are associated with the phenomena of shear localization within the shear zone. For clayey landslides, promising forecasts of time to failure could be obtained by using relatively constant values of α. The piece-wise log-linearity of velocity and acceleration in the tertiary creep revealed by this study provides basic understanding on those sliding behavior of primary landslides triggered by rainfall or snow melt, and then may enable us to distinguish and employ a proper α value for forecasting the time to failure with high precision. To achieve this, monitoring the sliding behavior with high time and displacement resolutions will be necessary, and advanced data processing protocol will be needed. The results in this study also revealed that in forecasting the time to failure for a landslide, it is critical to identify whether the landslide is a reactivated one or a primary one. For the reactivated one, effort should be focused on distinguishing the non-varying value of α.

Supporting information

Supporting information is available for some results that are not entirely included in the main chapters.