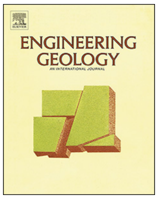
Engineering Geology 242 (2018) 34–43

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo



A physical model predicting instability of rock slopes with locked segments along a potential slip surface

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ARTICLE INFO

Keywords:
Landslide
Locked segment
Physical prediction
Accelerating displacement

ABSTRACT

Better understanding the evolutionary mechanism of landslides is very important to predict their occurrence based on firm scientific grounds. The stability of a rock slope is often dominated by one or more locked segments along a potential slip surface with a large bearing capacity to resist instability. We propose three preliminary categories for locked segments and develop a physical model for predicting the instability of rock slopes with locked segments, by coupling a one-dimensional renormalization group model with a strain-softening constitutive model, based on the Weibull distribution. We found that the ratio of the strain at the peak strength point of a locked segment to the strain at its volume dilation point is exclusively dependent on the Weibull shape parameter m and is approximately constant at 1.48. The accelerating displacement of the slope can be observed from the volume dilation point of the locked segment due to unstable fracture propagation. The physical model for slopes with multiple locked segments is only related to the displacement corresponding to the volume dilation point of the first locked segment and the number of locked segments. Applying this model to two typical cases, the Yanchihe rockslide in China and the wedge rockslide in Libby Dam, USA, the results are in agreement with field records. This work will help to better understand the failure mechanism of slopes with locked segments and may provide guidelines for disaster mitigation and prevention.

1. Introduction

A landslide is the movement of a mass of rock, debris, or soil down a slope under the influence of gravity (Cruden, 1991). Landslides cause significant damage and casualties every year. Brabb (1993) claimed that at least 90% of landslide damage can be avoided if the risk is recognized before the landslide event. There are two main strategies to prevent or reduce the loss caused by landslide hazards: hazard assessment and prediction of the landslide occurrence time. Great progress in hazard assessment (Mignelli et al., 2012; Mineo et al., 2017) has been made in recent decades. The commonly-used assessment approaches (Chacón et al., 2006) can estimate the spatial distribution, magnitude and outcomes of landslides in the form of probability in a reference time but cannot tell us about the specific occurrence time of a landslide. In this context, researchers have put forward a variety of approaches to predict the critical state or occurrence time of landslides, which primarily fall into two categories: phenomenological and physical approaches.

Phenomenological approaches include empirical and regression-only methods. Empirical methods often derive from the pre-failure accelerating phase of the strain–time (or displacement–time) creep curve. Saito (1965) performed the first successful prediction on a soil slope using a model where the time to failure in the tertiary creep phase was inversely proportional to the existing strain rate. On the basis of Saito's model, Fukuzono (1985) introduced an extended model which is expressed as the inverse-velocity of the displacement. This model has been improved and been extensively utilized in both soil and rock slopes (Voight, 1988; Crosta and Agliardi, 2003; Rose and Hungr, 2007; Mufundirwa et al., 2010) because of its simplicity. Compared to the empirical methods mentioned above, regression-only methods rely on regression functions, such as Lyapunov function (Huang et al., 2009) and artificial neural networks (Mayoraz and Vulliet, 2002), to represent complex correlations among several landslide-triggering factors. Generally speaking, phenomenological approaches do not take into account

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https://doi.org/10.1016/j.enggeo.2018.05.012
Received 31 December 2017; Received in revised form 9 April 2018; Accepted 11 May 2018

the mechanical behavior of the geological body or its boundary conditions. The lack of any specific relation with the physics of the phenomenon would make the prediction results mainly of academic interest, and the accuracy of the predicted time of the event seems to be merely a matter of coincidence (Federico et al., 2012). In contrast, the physical approach considering the landslide mechanism promises more reliable landslide prediction results.

Some researchers (Helmstetter et al., 2004; Sornette et al., 2004) introduced the state- and velocity-dependent friction law that describes the movement of a sliding block to predict the critical time of failure before a landslide; however, the time functions they used are still empirical. Currently, researchers have not been able to predict the occurrence time of landslides based on firm scientific grounds. Predictions of landslide occurrence time, as Fell et al. (2000) stressed, are clearly uncertain. We can infer that even if a potential landslide reaches its critical displacement value, its rapid sliding may not start immediately owing to the adhesion and residual friction effect (Wen et al., 2007; Xue et al., 2018) at the slip surface. However, external environmental factors such as rainfall and earthquakes, if any, could trigger its occurrence at any time. In other words, the critical displacement value for a particular landslide is probably a constant but the occurrence time may be a variable, implying that predicting the critical displacement of a landslide is more feasible than predicting its occurrence time.

Several studies constructed physical models representing the dynamic process of rock slopes, which is described by the kinematic (Herrera et al., 2009), dynamic (Yalçınkaya and Bayrak, 2003) or momentum equation (Corominas et al., 2005). These models considered the geological factors; however, they did not include certain criteria for slope instability, and often present an inaccurate representation of the mechanism of some landslides because they are based on the hypothesis of a continuous slip surface.

Lajtai (1969) pointed out that potential slip surfaces are usually discontinuous. Intact “rock bridges” are commonly found between joints that constitute the slip surface; slope failure occurs when the stressed rock bridges reach their shear strength (Eberhardt et al., 2004). The failure probability of an unstable rock mass depends mainly on the proportion of rock bridges (Frayssines and Hantz, 2006) along the potential slip surface. Here, we define any unbroken part of a slope along its potential slip surface that has a large bearing capacity and governs the slope stability as a “locked segment” (Qin et al., 2010a; Huang, 2015), such as “rock bridge”, “retaining wall” and “sustaining arch” (see Section 2). The bearing capacity of a locked segment is dependent on both its scale proportional to the length and width along a potential slip surface, and its material strength. Thus, the locked segments are the key to the analysis of progressive failures in many slopes. For example, in the Jiweishan rockslide in Chongqing, southwestern China, the movement of the upper rock blocks was restricted by a lower rock block (Tang et al., 2015), i.e., a locked segment. When the locked segment failed, massive blocks of rock slid subsequently. Unfortunately, this mechanism was not clearly recognized before the slope instability, and the volume (~5 million m^3) and travel distance (~2.2 km) of the sliding masses were underestimated. In less than 1 min, 74 people were killed in the rockslide (Xu et al., 2010). This example shows that complete failure of the locked segment usually produces large-scale and high-speed landslides, leading to huge losses in lives and property, and emphasizes the significance of research on the damage mechanism of locked segments.

Hence, a growing number of studies have focused on the locked segment. Pan et al. (2014) analyzed the formation mechanism of locked segments observed in a number of landslide cases. Laboratory physical modeling experiments (Huang et al., 2016) demonstrated that macroscopic failure of locked segments resulted in high-speed rock slides. The failure process of the slope was influenced by the location (Huang et al., 2015), number and length of the locked segments and the distance between them (Pan et al., 2017).

However, our understanding of both the geological characteristics and mechanical behavior of locked segments is still lacking, the geological characterization of the locked segments is not systematic, and predicting the instability of slopes with locked segments is still difficult. The unstable failure of a locked segment is accompanied by abrupt and intensive release of energy, which is occasionally characterized by nearly instantaneous displacements in short time intervals. The inverse-velocity method cannot be used to model such a process (Rose and Hungr, 2007; Federico et al., 2012). A locked segment may not fail even after heavy rainfall; therefore, false alarms may be issued based on rainfall threshold estimates. Some physical models based on continuum mechanics (Lajtai, 1969; Einstein et al., 1983) and fracture mechanics (Kemeny, 2005) were established to describe the rupture of rock bridges, but their complicated expressions contain variables, such as the friction coefficient and critical strength of the rock, which are difficult to measure. Currently, no specific approaches have been universally accepted to predict landslides with locked segments.

In recent years, a physical prediction model (Qin et al., 2010a; Qin et al., 2010b; Xue et al., 2014a; Xue et al., 2017; Xue et al., 2018), which couples a renormalization group model with the constitutive relation based on Weibull distribution, was established. Back analysis showed that this model is promising for predicting the instability of slopes with locked segments. In this paper, based on analysis of reported landslide cases as well as large-scale slopes that had been investigated in detail, a systematic classification of locked segments is conducted, and then a model for rock slopes with one or multiple locked segments is introduced with a specific limit placed on Weibull shape parameter. This work will help to better understand the failure mechanism of slopes with locked segments and may provide guidelines for disaster mitigation and prevention.

2. The geological categorization of locked segments

Locked segments may be categorized into various types depending on the geological conditions of the slopes, such as the geomorphology, structure and lithology. Without clarifying these complex characteristics and categorizing the locked segments, it is difficult to correctly identify slopes with locked segments and understand their mechanisms of instability; thus, the prediction of landslides in slopes with locked segments is currently unreliable.

Here we summarize the types of locked segments for many typical landslides and slopes (Wang et al., 1988; Cheng et al., 2004; Pan et al., 2014; Huang, 2015; Pan et al., 2017; Xue et al., 2017; Xue et al., 2018) in terms of engineering geology, and preliminarily classify them into three categories (Fig. 1): “rock bridge”, “retaining wall” and “sustaining arch.”

Generally speaking, the lithology of a rock bridge is identical with the surrounding lithology. We subdivided rock bridges into the following three types according to their geological characteristics. (i) In a stratified slope, a potential slip surface usually intersects with the layered strata that play the role of the locked segment, such as an anti-dip stratified slope (Fig. 1a) and a dip stratified slope whose dip angle is larger than the slope angle (Fig. 1b). (ii) In a stratified slope that tends to move along a bedding plane, the sliding is usually controlled by an intact rock bridge, i.e., a locked segment on the bedding plane (Fig. 1c). (iii) When a slope consists of massive rock without distinct bedding planes, as illustrated in Fig. 1d, the locked segment is similar to a relatively homogeneous rock bridge.

When a hard stratum occurs in the middle of a slope, it acts as a locked segment, preventing the upper part of the slope mass from moving and acting like a “retaining wall” (Fig. 1e). Once the locked segment fails, the soft lower part is unable to resist the movement of the upper block, leading to slope instability.

The “sustaining arch” mechanism (Fig. 1f) was first presented in the study of the Xintan landslide (Wang et al., 1988). The relatively narrow geomorphology in the middle of the Xintan slope led to a local zone of stress enhancement where a sustaining arch structure was formed. The