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How the toe loading suppresses the movements of an instable slope: Mechanisms revealed from triaxial compression tests under varied strain rate condition

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ABSTRACT

Series of triaxial compression (TC) test on in situ retrieved soils were performed to reveal mechanisms of a toe loading. Due to toe excavation, an existing failed slope was reactivated with a sliding mass of over 2×10^6 m^3 and the maximum displacement rate of 35 mm/day. As an emergency countermeasure, 7000 m^3 of soil packed in bags was loaded at the toe of the slope, and led to a decrement of the displacement rate of more than 57%. TC test results showed a significant strain rate effect and stress relaxation at residual state. Quantitative analysis of the strain rate effect on the residual strength showed that if the stress is reduced by 1.9–5.6%, the displacement rate decreases by 90%. Based on the field investigation results and the experimental results, the range of the displacement rate decrement due to the toe loading was evaluated to be 46 to 84%. Comparison of the range of the evaluated decrement in the displacement rate and the measured decrement in the displacement rate verified that the strain rate effect may explain the significant remediation effect of toe loading on the sliding of the slope. This research provides a rough method of evaluating the remediation effect of toe loading.

1. Introduction

Toe loading (e.g. Hutchinson, 1984) is often used as a countermeasure for slope failure and has good technical feasibility. Compared to anchors (e.g. Justo et al., 2008) and piles (e.g. Ito et al., 1981), the construction period of toe loading is short. Therefore, toe loading is frequently used as an emergency countermeasure to mitigate the sliding of a slope. However, the effect of toe loading on the safety factor increment is quite small, so the remediation effect on the sliding slope is questionable. In order to evaluate the reliability of toe loading, it is necessary to study its mechanism. As the effect of toe loading is normally shown by the deceleration of the sliding of the slope, its mechanism is possibly related to the strain-rate or displacement-rate effect.

On the other hand, the viscous properties (e.g. creep, relaxation, and strain rate effect) of soils have been studied for several decades (e.g. Suklje, 1957; Saito, 1969; Skempton, 1985; Puzrin and Sterba, 2006; Tatsuoka et al., 2008, among others), although no conclusive results have been obtained by the existing studies related to the rate-dependent effect on the strength of a sliding surface. Skempton (1985) showed that if the displacement rate decreases by 90%, the residual strength may decrease by less than 2.5% in direct shear tests on clay. Similar test results were obtained in other researches (Leroueil, 2001; Suzuki et al., 2008; Duttine et al., 2008; Miao et al., 2014). In contrast to the abovementioned positive strain-rate or displacement-rate effect, Tika and Hutchinson (1999) observed a *negative* displacement rate effect: the residual strength at fast rates of displacement can be lower than that at slow rates of displacement. It is difficult to predict whether the strain rate effect will be positive or negative as the mechanism of the strain rate effect has not been fully identified (Duttine et al., 2008), and therefore experimental work is needed in the research on the strain rate effect of soils.

In this research, toe loading as a first emergency countermeasure was introduced in a field case study. Subsequently, triaxial compression (TC) tests were performed with an otherwise constant-strain-rate monotonic loading stage and relaxation stage to investigate the effect of the strain rate effect on the residual strength. The mechanism of the significant effect of toe loading on lowering the displacement rate was interpreted based on the test results and field investigation results.

2. Investigation results and countermeasures

The slope was located in Danba County Town, Sichuan Province, China. The climate of the area is dry with an average precipitation of 605.7 mm (Xu and Fan, 2008). The trigger for the reactivation may

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have been the toe excavation (Fig. 1) that started before 2004 (Xu and Fan, 2008). The previously existing Baijia-Shan Landslide was partly reactivated (Fig. 1), as significant slope deformation was observed in August 2004. The monitoring result showed that sliding accelerated in February 2005 (Xu and Fan, 2008). Directly ahead of the toe was a high-density residential zone, so the evacuation was performed within the dangerous area (Fig. 2).

Based on the observation results from fourteen boreholes (Fig. 2), four prospecting trenches, and more than seventy monitoring points, the investigation results were summarized as follows (Xu and Fan, 2008):

1) With a total volume of about 2×10^6 m^3, the sliding slope was divided into four parts (I-1, I-2, II, and III; Figs. 1 and 2) according to their kinematic characteristics.

2) The sliding plane was determined as shown in Fig. 3 based on the investigation results. For example, the monitoring results in Fig. 4 showed that the depth of the sliding plane at ZK12 (Figs. 3 and 4) was 29 m, whereas the depth of the existing plane was 36 m. The thickness of the sliding mass was around 30 m. At the toe, the sliding plane was slightly above the elevation of the street (Fig. 5).

3) The soils near the middle part of the slope surface were essentially the same as those in the vicinity of the sliding plane (Fig. 3; Xu and Fan, 2008). The stratum was Quaternary diluvium. Based on investigation results from fourteen boreholes (Fig. 2) and four prospecting trenches (1–3 m deep), the grain size distribution was evaluated. The investigation results from the prospecting trenches show that the material near the slope surface (except for the effects of vegetation) is nearly identical to that at relatively deep locations (e.g. 3 m). On the other hand, the sliding plane (band) cannot be detected based on observations of the material excavated in the borehole investigation (e.g. ZK12 in Fig. 3), because the material is almost identical in the relatively deep location and in the vicinity of the sliding plane (band). It should also be noted that before the displacement monitoring results (e.g. Fig. 4) were available, the current sliding plane was misevaluated as the existing sliding plane (Fig. 3) due to the nearly identical properties of the materials excavated in the borehole investigation. Based on the investigation results obtained from boreholes and prospecting trenches, it is argued that the materials near the slope surface, in the relatively deep location, and in the vicinity of the sliding plane (band) are nearly identical.

The sliding mass was mainly gravelly soil consisting of rock blocks (50–60%) with diameters of 0.2–0.5 m, or 1–6 m for the larger ones, angular cobbles (20–30%) with diameters of 3–10 cm; and silt and gravel, which filled the voids among the rock blocks and angular cobbles. As the whole sliding mass had a similar grain size distribution, most of the sliding plane was determined by referring to the displacement monitoring results from boreholes (e.g. Fig. 4), not the grain size distribution. The rock blocks and angular cobbles were mainly biotite metaconglomerate with grey colour (e.g. N2 to N8 according to the Munsell colour system), and secondly garnet two-mica schist with brown colour (e.g. 5YR according to the Munsell colour system). The unweathered rock was hard rock. The specific weight of the sliding mass was determined to be 19.5 kN/m^3 by in situ density test.

4) The sliding plane had completely formed and the soils in the vicinity of the sliding plane were at residual state before the construction of the toe loading. The evidence included the fact that the (resultant) displacement rate reached 35 mm/day on 22 February 2005 (e.g. the result from monitoring point J9, Fig. 6), the displacement rates measured at the toe, middle, and top were virtually the same, and the scarp at the top of Part I was more than 1.5 m (Fig. 7).

5) The sliding mass was loose with high permeability and low water content. Cavities were frequently observed in the loose sliding mass (Xu and Fan, 2008). Even in the rainy season, seeped water was not observed near the toe. The water content of soils was very low except for the shallow layer beneath the slope surface; ground water was not found in the sliding mass or in the vicinity of the sliding plane (band). Mainly based on this observation, the rainfall was not considered as the trigger of the reactivation (Xu and Fan, 2008).

Considering that the trigger for the reactivation may have been the toe excavation (Fig. 1), it was inferred that the reverse of toe excavation, that is, toe loading, could lead to a remediation effect.

With prudent monitoring of sliding to ensure workers' safety, 7000 m^3 of soil packed in bags was loaded at the toe of the sliding slope (Figs. 3 and 7) from 22 to 28 February. The displacement rate decreased very significantly (from 35 to 25 mm/day) with the

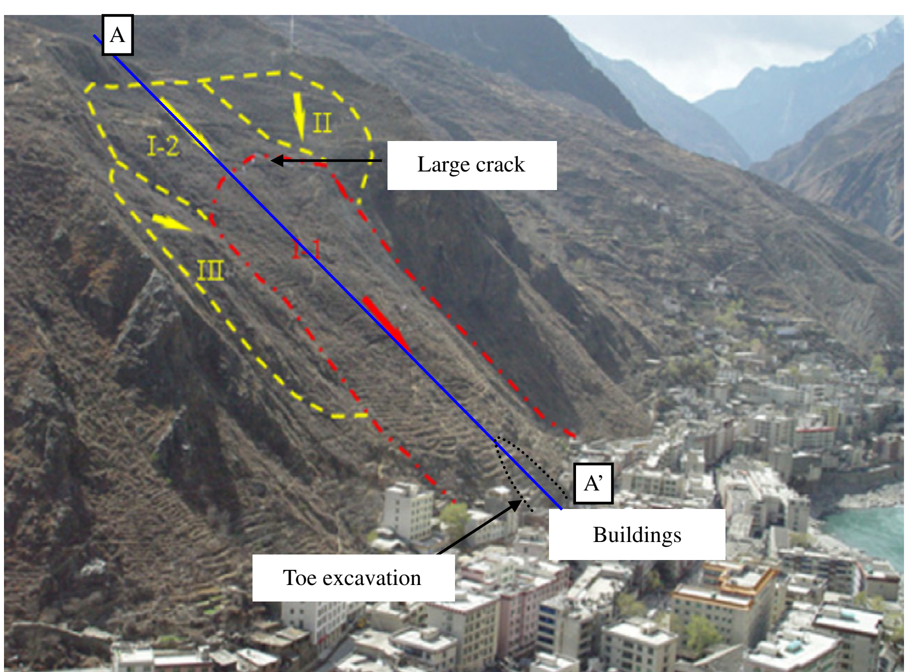

Fig. 1. The high-density residential zone and the sliding slope (after Xu and Fan, 2008).