Normal stress-dependent frictional weakening of large rock avalanche basal facies

Y.F. Wang & Q.G. Cheng
Southwest Jiaotong University, Chengdu

ABSTRACT

To explore the mechanism behind the volume effect of rock avalanches observed in field data, a series of rotary shear tests were conducted at a shearing velocity of 0.87 m/s and varying normal stress levels (from 0.29 to 1.85 MPa) on soil collected from the basal facies of the Yigong rock avalanche in Tibet, China. This experimental study reveals that (1) as normal stress increases, the steady-state apparent friction coefficient (μeq) of the soil decreases, indicating a normal stress-dependent feature of μeq; (2) the higher the normal stress, the lower the decay rate of μeq; (3) water vaporization induced by frictional heating is commonly observed in the tests accompanied by large decreases in μeq, and excess pore pressure is generated in the shearing zones of the samples due to vapor accumulation; and (4) with increases in normal stress and decreases in soil permeability, an increasing feature of excess pore pressure is reached. Based on the experimental results, we propose that the coupled effects of water vaporization induced by frictional heating in avalanche basal facies and depth-dependent permeability of avalanche basal facies should be contributed to the volume effect of rock avalanches.

1 INTRODUCTION

Rock avalanches, as an important geological hazard in mountainous regions, have drawn much scientific interest, especially in recent decades (Lucas et al. 2014). According to rough statistics, rock avalanches have caused billions of dollars in damage and many casualties over only the past few decades (Huang and Li 2009), highlighting the importance of rock avalanche studies. As reported in the literature, enormous volumes, extremely high velocities, and unexpectedly long runouts are three prominent features of rock avalanches (Pudasaini and Miller 2013), which are the main contributors to rock avalanche devastation.

To learn the hypermobility of rock avalanches, rotary shear tests at shearing velocities (Veq) of 0.07–1.31 m/s and a normal stress (σ) of 1.47 MPa were conducted by Wang et al. (2017) using soil collected from the Yigong rock avalanche basal facies. In this experimental study, marked frictional weakening of the soil was attained at Veq ≥ 0.61 m/s, and concurrent large temperature increases, water vaporization, and high porosity layers were observed in the deformed samples. Accordingly, our research team proposed that thermal pressurization induced by frictional heating may be a key factor in the frictional weakening of the avalanche basal facies samples, which provides insight into rock avalanche hypermobility mechanisms. This discovery brings to mind another rock avalanche feature revealed by field data statistics: the reduction of Fahrböschung with increasing rock avalanche volume, i.e., rock avalanche volume effect (Pudasaini and Miller 2013; Lucas et al. 2014). Therefore, a pursue study on the role of normal stress in high-speed rock avalanche frictional sliding is conducted here to discover the mechanism behind the rock avalanche volume effect. With this study, some insights into the avalanche volume effect will hopefully be discovered through laboratory observations and theoretical analysis, which will enhance our understanding of rock avalanche dynamics.

2 MAIN TEXT

2.1 Experimental setup

A third-generation low- to high-velocity rotary shear apparatus (Marui Co. Ltd, Osaka, Japan, MIS-233-1-78) installed at the National Central University (Taiwan) was used to examine the volume-related hypermobility of rock avalanches. And soil samples collected from the Yigong rock avalanche basal facies, representing the main shearing zones of rock avalanches, were prepared for this experimental study. Fig. 1 shows a vertical
profile of the Yigong rock avalanche deposits with an expanded view of the soil collection basal facies. As reported in Pudasaini and Miller (2013), the thickness ($H$) of a rock avalanche is proportional to its volume ($V$) (i.e., $H = V^{1/3}$). Thus, normal stress is used herein to explore the rock avalanche volume effect. Based on the deposited thicknesses of typical reported rock avalanches, this experimental study used $\sigma$ values of 0.29, 0.64, 0.99, 1.47, and 1.85 MPa. The shearing velocity is designed as $V_{eq} = 0.87$ m/s based on our previous results in Wang et al. [2017]. A 15% water content was used for most samples based on a previous field investigation. To evaluate the reliability of the data, 3 replicate tests were performed under each of the 5 test conditions; a total of 15 tests were conducted. All tests were performed at room temperature and ambient humidity conditions.

Fig. 1. (a) Vertical profile of the Yigong rock avalanche deposits with (b) an expanded view of its basal facies

2.2 Experimental results and analysis

Fig. 2 exhibits the test data obtained in this experimental study. In order to quantify the dynamic mechanical behavior of the soil under varying normal stress levels, the steady-state apparent friction coefficient ($\mu_{ss}$) values of the deformed samples were determined, which were calculated as the averaged value of the apparent friction coefficient ($\mu_{app}$) at $D \geq 7.5$ m. And Fig. 2f presents variations in $\mu_{ss}$ with changing $\sigma$ and shows that $\mu_{ss}$ tends to decrease as $\sigma$ increases. When $\sigma = 0.29$ MPa, the average $\mu_{ss}$ of the samples is approximately 0.51, which is slightly lower than the normal Coulomb friction value of 0.62 ($Hsü$ 1975). As $\sigma$ increased to 1.47 MPa and 1.85 MPa, the average $\mu_{ss}$ values of the samples decreased to 0.16 and 0.23, which are only 26% and 37% of the normal Coulomb friction of 0.62, respectively. Furthermore, the decline rate of $\mu_{ss}$ decreased with increasing $\sigma$ (Fig. 2f), indicating that the $\mu_{ss}$ of the tested samples will approach a low, stable value when $\sigma$ is sufficiently high. This feature is similar to the relationship observed between the Fahrböschung and rock avalanche volume in field data, such as Fig. 7 in $Hsü$ (1975) and Fig. 2 in Lucas et al. (2014).

2.3 Possible mechanism for normal stress-dependent frictional soil weakening

This experimental study shows that soil collected from the Yigong rock avalanche basal facies undergoes dynamic slip weakening under high normal stress (Figs. 2d-e) and reveals an exponential decrease in friction with increasing normal stress (Fig. 2f). Wang et al. (2017) proposed that the marked frictional weakening of soil collected from the Yigong rock avalanche basal facies was caused by the coupled effects of thermal pressurization and thermal moisture fluidization induced by frictional heating. In this study, high temperature rises and water vaporization are found in the samples sheared at $\sigma \geq 0.64$ MPa. The higher normal stress is, the greater temperature rises and the more intense water vaporization occurs. Additionally, condensation and extruded water are commonly observed during the shearing processes of the sample when $D$ exceeds 7.0 m, which is larger than the slip displacement ($D < 4$ m) needed for water vaporization initiation. Therefore, we posit that the dynamic frictional weakening of the samples observed herein is dominated by thermal pressurization and thermal moisture fluidization instead of flash heating, frictional melting, or thermal decomposition. Thermal pressurization induced by water vaporization is contributed to the normal stress-dependent frictional weakening of the soil.
Fig. 2. (a-e) Apparent frictional coefficients and axial displacements versus slip displacement for samples sheared under different normal stresses and (f) steady-state apparent friction coefficients versus normal stress.

To quantify the effect of thermal pressurization, various equations have been proposed in the literature for the calculation of excess pore pressure (Noda and Shimamoto 2005; Rice 2006). And the equations proposed in Rice (2006) are used here to calculate the excess pore pressures generated in the shearing zones of samples deformed at different normal stress. Fig. 3a is the variations of the calculated excess pore pressures. From Fig. 3a, it is reached that as \( \sigma \) increases, water vaporization occurs at \( T \) greater than 100 °C and excess pore pressure is generated rapidly due to the accumulation of water vapor. The higher normal stress is, the more rapidly excess pore pressure increases and the larger maximum value is (Fig. 3a). It is reached that the maximum \( \Delta P \) values generated in the shearing zones of samples deformed at \( \sigma = 0.64, 0.99, \) and 1.47 MPa are 0.25, 0.58, and 0.83 MPa, respectively. The calculated maximum value of \( \Delta P \) (up to 0.83 MPa) can cause a drop in \( \mu_{ss} \) to approximately 0.26, which would contribute significantly frictional soil weakening. Fig. 3b shows the variations of \( \Delta P, T, \) and \( k \) versus \( \sigma \). From Fig. 3b, it can be seen that, as \( k \) decreases, the growth rate...
of \( \Delta P \) is obviously higher than that of \( T \). This indicates that soil permeability also has a significant influence on the increase in \( \Delta P \). Through the comparison of \( \Delta P, T, \) and \( k \) versus \( \sigma \) shown in Fig. 3b, both of the mechanisms controlling \( \Delta P \) can be identified. One is the increase of \( T \) with increasing \( \sigma \), which intensifies \( \Delta P \) increases in the sample shearing zone. The other is the decrease of \( k \) with increasing \( \sigma \), which reduces the diffusion rate of water vapor and accelerates the growth of \( \Delta P \) in the shearing zone. These coupled mechanisms result in the increased growth rate of \( \Delta P \) with \( \sigma \) and contribute to the \( \sigma \) - dependent feature of \( \mu_{ss} \).

**Fig.3.** (a) Excess pore pressure versus slip displacement and (b) soil hydraulic conductivity, frictional heating, and excess pore pressure versus normal stress at \( D = 10 \) m for the selected samples

### 3 CONCLUSIONS

The experimental study herein reveals a significant decreasing trend of \( \mu_{ss} \) with increasing \( \sigma \), which indicates normal stress-dependent weakening. Accompanied by decreases in \( \mu_{ss} \), great temperature rises and water vaporization are generally observed in the tests, and thermal pressurization attributed to vapor accumulation in the sample shearing zones is proposed as one key factor for the soil frictional weakening. Through simplified theoretical calculations, the variations of excess pore pressure generated in the sample shearing zones are reached and an increasing feature of excess pore pressure with increasing normal stress is achieved corresponding to decreases in \( \mu_{ss} \). Meanwhile, it is observed that the growth rate of \( \Delta P \) with decreasing \( k \) is clearly higher than that of \( T \).

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