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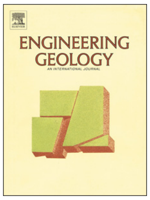

The mechanisms behind shallow failures in slopes comprised of landslide deposits

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ABSTRACT

In areas hit by the 2008 Wenchuan earthquake that occurred in Sichuan Province, China, debris flows are often generated from landslide deposits during heavy rainstorms. The broadly graded and unconsolidated landslide deposits respond to rainfall in very complex mechanical and hydraulic manners. An artificial rainfall test was conducted to simulate the rainfall infiltration and surface runoff processes occurring on the landslide deposit slope at the Wenjiagou Gully, China, with heavy rainfall rates (140 mm/h) incorporated. An innovative flume was designed to collect the slope interflow and surface runoff separately. Sensors to monitor the pore water content (PWP) and volumetric water content (VWC) were deployed. The results indicated that there were four stages in the hydrological response of landslide deposits during the artificial rain event: infiltration, a slow increase in interflow (surface runoff begins), a rapid increase in interflow (surface runoff slowly increases) and a steady state. Bed gradient increase will lead to PWP rapidly ascending and regressive failure happening. Concomitant with the observed increases in PWP and VWC, the shear strength of the landslide deposits decreased and led to the occurrence of small-scale shallow failures. Surface runoff, interflow and fine particle migration effects are presented to interpret the process of shallow failure. And although shallow slope failure is the result of interaction with the above three factors induced by rainfall, the key underlying factor is the characteristically loose structure of landslide deposits.

1. Introduction

Debris flows occur when masses of poorly sorted sediment, agitated and then saturated with water, surge down slopes in response to gravitational attraction. Large debris flows can exceed 10^9 m^3 in volume and release more than 10^{16} J of potential energy, but even more typical flows of around 10^3 m^3 can denude vegetation, clog drains, damage structures, and endanger humans and livestock (Iverson, 1997). Human lives and structures in mountainous areas prone to debris flows are regularly subject to debris flow hazards. In recent decades, many catastrophes caused by debris flow have been reported worldwide (Pierson et al., 1990; Cui, 1992; Zanchetta et al., 2004; Evans et al., 2009). For instance, a large-scale debris-flow hit the city of Zhouqu in Gansu Province, western China, on August 7, 2010. This resulted in 1765 fatalities, and 33 buildings with a total area of 11,472 m^2 were completely destroyed. In addition, 20 buildings were partially damaged. Most deaths and property losses were associated with the damage to buildings (Hu et al., 2012).

The 2008 Wenchuan earthquake occurred in the Longmenshan fault belt with a magnitude of 8.0 on the Richter scale on May 12, 2008 (Huang and Li, 2009). Numerous landslides were later triggered in the earthquake-affected area (Chen et al., 2009; Sato and Harp, 2009; Huang et al., 2012; Zhou et al., 2013a), and abundant co-seismic rock falls and landslides were deposited in gullies, which generated a large amount of loose, solid materials that were easily eroded and led to the development of debris flows (Collin and Znidarcic, 2004). As a result, significant debris flows were triggered during three of the wet seasons from June to September after the earthquake (Tang et al., 2009; Ni et al., 2012). Shieh et al. (2009) indicated that the amount of loose sediments, deposited by the co-seismic landslides, was the main reason for a lowering of the meteorological thresholds for debris flows. Debris flow activities in the earthquake-affected area are predicted to remain high for the first 5–10 years after such an earthquake (Huang et al., 2009; Wu et al., 2011). Some studies have suggested that increased debris flow activity may even last for 20 to 40 years (Cui et al., 2011). However, this remains an open question because no detailed research has been conducted on the temporal behavior of debris flows over an extended period after a strong earthquake. Some important questions associated with the activity, trigger thresholds, and magnitude of debris flows in the earthquake-affected areas need to be answered (Yu et al., 2013).

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Large-scale field monitoring and/or experiments have been performed to gain a better understanding of the relationships between in-soil pore water pressure or volumetric water response and rainfall-induced slope failures. Torres et al. (1998) pointed out that slope instability caused by rainfall infiltration may be highly related to the formation of a stable, unsaturated flow field, and that a pressure wave induced by rainfall results in a relatively quick response of the in-soil pressure head to the incoming rainfall. Tecca et al. (2003) measured the in-soil pore pressure in a shallow slope located at a debris flow initiation area and found the existence of an instantaneous and vertically upward pore pressure increase during debris flow mobilization. Hu et al. (2011) concluded that the soil moisture content was the key factor determining whether landslides transform into debris flows. Ochiai et al. (2004) conducted an experiment on a natural slope and found that the landslide mass first slid, then fluidized, and finally transformed into a debris flow. However, field experiments are impractical to operate and incorporate several uncertain factors. In addition, this makes it difficult to consider surface runoff and interflow separately.

Numerical and/or limit equilibrium analyses have been performed to investigate the stability of slopes following infiltration induced by rainfall (Springman et al., 2003; Sako et al., 2006). Blatz et al. (2004) analyzed two cases of shallow slope failure using a numerical model that considered time-dependent interflows in unsaturated soil. They concluded that dissipation of the suction (or negative pore water pressure) in the soil slope resulting in a reduction of the shear strength of the soil is the key trigger for shallow slope failures. Hydrological models incorporating topsoils and an impermeable stratum are frequently utilized to address the issue of slope failure (Cai and Ugai, 2004). However, these classic hydrological models are not suitable for widely graded, loose landslide deposits, which are characterized by the presence of macro-pores and discontinuous geological features (Simunek et al., 2003).

The key issue regarding debris flow initiation is to understand how changes in the mechanical behavior of sediment material occur (Bovis and Jakob, 1999; Hungr et al., 2008). Sufficient rainfall intensity is a necessary condition for sediment material to be saturated and for intense surface runoff to be formed on the slope. Shallow slope failure can then occur and be transformed into debris flows by combination with the water flow. The significant increase in debris flow frequency following the Wenchuan earthquake prompted us to study the initiation conditions for debris flows in such loose landslide deposits. The decreasing strength parameters induced by interflow and large volumes of surface runoff have the potential to trigger slope failure and even debris flows. However, the triggering mechanisms under heavy rainfall are complex. Before a debris flow is triggered, the mechanisms of rainfall infiltration, runoff generation and shallow slope failure in such loose landslide deposits should be properly understood. In this study, innovative flume equipment, capable of measuring surface runoff and interflow separately, was designed. Combined with an artificial rainfall simulation system and volumetric water and pore water pressure sensors, the external and internal physical mechanisms influencing landslide deposits in the presence of heavy rainfall were illustrated.

2. Method

2.1. Landslide deposits at the Wenjiagou Gully

The Wenjiagou Gully (N31°33′04.7″, E104°06′58.5″) is located at north of the town of Qingping, Mianzhu County, Sichuan Province, southwestern China. The gully is located on the left bank of the Mianyuan River (Lu et al., 2011). Fig. 1 indicates the geographical and topographical conditions of the gully. The inclinations of the slopes at both sides are very steep, which means rainfall is easily collected at the gully (Figure 1b). At the center of the gully, large volumes of landslide deposits have accumulated (Figure 1c), owing their formation to the Wenchuan earthquake and the subsequent huge landslide that occurred in the Wenjiagou Gully (Zhou et al., 2013b). These landslide deposits provide rich source materials for the rain-induced triggering of debris flows in this. At the bottom of the gully, the inclination of the slope is gentler, but the surface materials are primarily composed of loose landslide deposits (Figure 1d).

Fig. 2 indicates the geological characteristics of the main longitudinal section of the Wenjiagou Gully, with an average longitudinal gradient of about 467.4‰ (25.1°), a maximum elevation of about 2402 m and a minimum elevation of about 900 m above sea level. There are three platforms in the gully; most of the landslide deposits are located at the level 2 and level 3 platforms (Figure 1c), with the corresponding longitudinal gradients being 140.3‰ (8.0°) and 322.5‰ (17.9°), respectively. In this area, meteorological records indicate that the maximum 24 h rainfall was 496.5 mm, recorded on August 15, 1995 (Zhuang et al., 2012). Thin layers of siliceous rocks, inter-bedded gray calcium phosphate rock and limestone are the main rock masses in the gully. The volume of landslide deposits in this gully is about 2.75×10^7 m^3 (Zhou et al., 2013b). After the Wenchuan earthquake, five large debris flows took place during the past three wet seasons in this region. The largest debris flow occurred on August 13th, 2010, which led to 57 people being reported as lost or missing, 39 people hurt, and 479 dwellings being damaged (Chen et al., 2011). Therefore, with respect to loose landslide deposits, the mechanisms behind rainfall infiltration and runoff generation are the most important aspects to analyze for understanding and predicting the hazards involved. We selected the landslide deposits at the Wenjiagou Gully as the test medium.

2.2. Physical and mechanical properties

The landslide deposits in the study area are a mixture of fragmented limestone, clay and silty clay soils, with a complex composition. Particles larger than 200 mm comprise 31.4% of the total, those between 20 mm and 200 mm 35.4%, and those smaller than 20 mm the remaining 33.2% (Zhou et al., 2013b). These landslide deposits are characteristically widely graded, and possess a loose particle structure and high content of fine particles (the maximum proportion of particles <2 mm in size is about 20%) with a dry bulk density of 1.91 g/cm^3, water content of about 5.39%, and porosity of about 0.36. Fig. 1c indicates that the landslide deposits at the gully are easily carried by surface runoff with incision depth more than 30 m.

As shown in Fig. 3,six curves indicate the particle size distribution of the Wenjiagou landslide deposits (particles larger than 80 mm were screened out). Particles larger than 20 mm comprised about 28.0–42.5% of the total, those smaller than 2 mm about 10–20%, and those smaller than 0.075 mm about 0.15–1.5%.

Under rainfall, the mechanical and hydraulic responses of landslide deposits are influenced by the structure and the material composition of the soil. Research has indicated that the shear strength of landslide deposits decreases with increasing water content (cohesion and friction angles decrease, particularly the former), and the pore water pressure increases. These two factors are the key reasons for the failures of landslide deposit slopes. These deposits combine with surface runoff and result in debris flows.

2.3. Experimental system

Fig. 4 depicts the design of the artificial rainfall system. The rectangular section of the flume (length of 4.5 m, height of 1.0 m and width of 0.4 m) and both sides of the front and rear boards were made of clear tempered glass, while the bottom and middle boards were composed of opaque material. The outlet of the flume was located 0.1 m above the ground and the height of the other port was offset by an angle of about 0–25°. The movable clapboard was set 30 cm above and parallel to the bottom board. Further, waterproof material was

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