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Effects of rainwater softening on red mudstone of deep-seated landslide, Southwest China

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ABSTRACT

Red mudstone landslides are widespread in southwest of China. The development and distribution of deep-seated landsides with slow inclination are closely related to the special soft rock properties of the red mudstone layers. Most previous studies focused on the failure mechanisms of rain-induced shallow landslides. Studies on deep-seated landslides in red layer zones are still limited. In order to ascertain the basic failure mechanisms of red layer landslides with a gentle inclination, a fatal landslide named as Shibangou landslide, which occurred in Sichuan, China, was investigated. This paper aims to (1) conduct laboratory tests on the reduction in shear strength of a red layer to identify the water–rock coupling effect; (2) investigate variations in the microscopic structure of the soft rock found within a red layer after rainfall infiltration; (3) discuss the failure mechanisms of red layer landslides with slow inclination. Results from shear test of mudstone from the Shibangou landslide revealed that there is a tendency that behavior of soft rock can be transferred to soil in different days of immersion. The delineation threshold of shear strength of the red layer is determined as 6 days of immersion. Microstructures of clay minerals become loose and porous due to the contacts between the particles transferred from the face–edges, face–face associations into edge–edge, and face–edge associations. Therefore, the intramolecular and cemented expansions of illite are the basic mechanisms which lead to structural damage, structural decay, and strength attenuation of soft rock in red layer under the condition of rainwater infiltration.

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1. Introduction

The red layer is composed of interbedded red mudstone and sandstone. Due to its weak resistance against weathering and impermeability, the red layer often suffers from high to complete weathering. Presence of the red layer makes overlying slopes prone to sliding easily along a bedding plane with slow inclination during rainy seasons. Red-layered landslides are widely distributed in Southwest of China. On 16 September 2011, a heavy rainfall triggered a deep-seated slow-inclination landslide, named Shibangou landslide, in Nanjiang County, Bazhong City in Sichuan (Fig. 1).

Most previous studies focused on the failure mechanisms of rain-induced shallow landslides. Studies on red-layer deep-seated landslides are still limited. It is necessary to explore deep into the mechanism of a slow-inclination red-layer landslide. According to an investigation conducted by Hutchinson (1961) on a slow inclination landslide that occurred in Norway, the sliding surface is a highly sensitive sandwich clay layer. Michael (2000) suggested that the failure process of a landslide occurs in the horizontally layered sedimentary rock with horizontal shear surface, which can be divided into five stages: unloading rebound, creep deformation of the weak layer, progressive deformation, mudding expansion, and gravity-induced differential settlement. Huang et al. (2008) studied the occurrence of large-scale landslides with gentle inclination, and proposed that the failure is mainly caused by wedging and tearing due to the influence of water pressure on the tectonic fissure fracture and the cushion effect of ground water.

However, even though these studies have considered the hydrostatic pressure at the trailing edge combined with uplift force acting on the slip surface, as the major cause that promotes the occurrence of translational landslide, they fall short of explaining the most essential failure mechanism of red-layer landslides especially for the deep-seated slope failure. In fact, the influence of rainfall infiltration on slope stability is not only mechanical but also physicochemical; in particular, the physicochemical aspect provides the main explanation for the reduction in shear strength. Shear strength reduction of mudstone caused by rainwater infiltration is associated with physicochemical interactions between the minerals in clay and water. Over tens of years in the past, a lot of attention has been placed on such interactions and their effects (e.g., Kenney, 1967; Rosenqvist, 1984; Skempton, 1985; Moore, 1991; Laurence and Simon, 2001; Dewoolkar and Huzjak, 2005; Rahardjo et al., 2005; Spagnoli et al., 2010; Xu et al., 2011; Wen and He, 2012; Miao et al., 2014). The development and distribution of deep-seated

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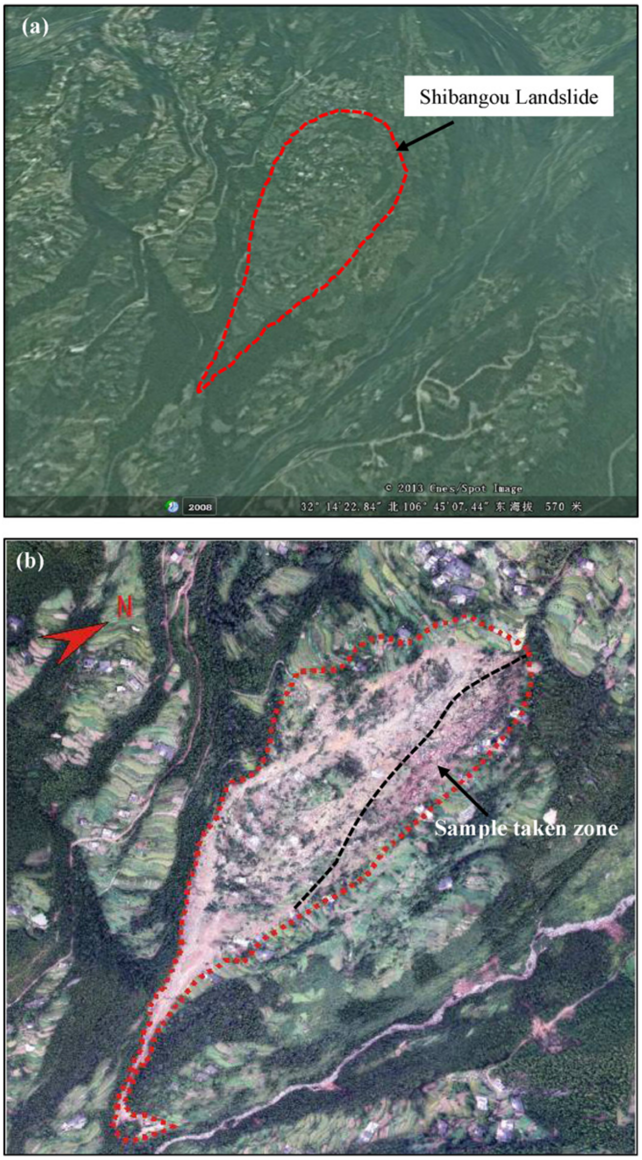

Fig. 1. Overview of Shibangou landslide: (a) prior to the event (source from Google Earth); (b) after the event.

landslides with slow inclination are closely related to the special material properties of the red layers. According to our field investigations, most slope failures occur along the weak surface of the red layer in the study area.

In order to ascertain the basic failure mechanism of red layer landslides with a slow inclination, a deadly landslide known as the Shibangou landslide, was investigated (Fig. 1). This paper aims (1) to conduct laboratory tests on the reduction of shear strength of the red layer due to the water–rock coupling effect; (2) to investigate variations in microscopic structure of the soils after rainfall infiltration; and (3) to explore the fundamental failure mechanism of red layer landslides with slow inclination.

2. Study area and samples

The Shibangou landslide occurred in Nanjiang, Sichuan, which geographic coordinates are longitude 106°44′45″ and latitude 32°14′27″ (Fig. 1). The study area is underlain by mudstone in the Cretaceous Jianmenguan group (Fig. 2) with attitude of 170°∠12° (Fig. 3). From September 6 to 15, 2011, a total cumulative rainfall of 268.1 mm was recorded, and on September 17 and 18, a total rainfall of 250.4 mm and 179.1 mm was recorded respectively. According to local residents who witnessed the landslide, the slope failure began at about 10:20 on September 18. The landslide slid along the bedrock layer with an initial sliding direction of S10°E to a final direction of S45°E. Sliding surface of the landslide is a weak interlayer, which mainly consists of mudstone mixed with thin layer of silty mudstone (Fig. 3). Runout materials destroyed 487 buildings and carried a local resident away for approximately 300 m. The landslide resulted in 4 deaths and 8 people missing.

In order to explore the reduction of shear strength of the red layer due to the water–rock coupling effect, rock samples were taken from the belt area on the left side of the sliding zone at the back of the Shibangou landslides (Fig. 1b), which is defined as a lateral secondary sliding zone during the filed investigation. Due to the existence of vertical structural joints, rock mass in this zone was isolated from the main sliding body (Fig. 4a). Therefore, the sliding surface in this area kept at their original state, and the rock materials of the sliding surface haven't been disturbed relatively (Fig. 4b).

3. Description of experiments

Water–rock physical and chemical effects are softening and chemical effects of water on the reduction of shear strength of rock layers, by decreasing cohesion, *c*, and friction angle, φ. It has an important potential for triggering landslides (i.e., rain; water level variation; earthquakes, etc.). Clay materials such as silty mudstone and mudstone that are distributed in the red layer are sensitive to water, especially during rainy seasons. With long-term exposure to water, the physical and mechanical strength of mudstone can be changed significantly by softening and mudding effect, which becomes a controlling factor of slope failure.

In the study area, strongly hydrophilic clay is distributed throughout the red layer, which can be easily softened, such as illite and chlorite. With effect of rainfall infiltration over a long period, drastic reductions in shear strength due to softening of soft rock become the main cause of deep-seated slope failure with slow inclination. In light of this, the experiments in this paper are conducted to test the variation of peak shear strength under various saturation rates and immersion conditions.

In order to simulate the long-term saturation with rainwater of red layer under the condition of various durations of rainfall, the samples were saturated with eight immersion periods, i.e. one day, two days, three days, five days, seven days, 10 days, 15 days, and 20 days.

3.1. Test equipment

Currently, direct shear test is used as a standard method in many places, such as UK, China, Japan, and the US (e.g., British Standard Institution (BSI), 1990; Standardization Administration of China (SAC) et al., 1999; Japanese Geotechnical Society (JGS), 2010; United State Army Corps of Engineers (USACE), 2011). In this study, due to low mechanical strength of the rock layer in this study, the soft rock of the red layer tends to disintegrate and soften in water. It is difficult to get a fully qualified specimen with regular shape during field sampling. Therefore, traditional direct shear test instruments are not suitable in this study since a regular specimen cannot be provided.

This test adopted a new shear instrument developed by the State Key Laboratory of Geological Disaster Prevention at the Chengdu University of Technology (Fig. 5), i.e., XJ-2 portable shear instrument. The apparatus is a new method to test the peak and residual shear strength of a weak rock layer. It is suitable for conducting the direct shear tests on the undisturbed rock samples with irregular shapes.

Details of the portable shear apparatus are shown in Fig. 5:

(1) Because regular geometry is not required for the specimens, this test equipment is applicable to weak and soft rock samples taken from the structural surface of a landslide (e.g., bedding layer; fault fracture zone; sliding surface; soft interlayer; shale; phyllite,

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