Engineering Geology 222 (2017) 102–110

Contents lists available at ScienceDirect

Engineering Geology

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

Unsaturated hydro-mechanical behaviour of rainfall-induced mass remobilization in post-earthquake landslides

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ARTICLE INFO

Keywords:
Hydro-mechanical behaviour
Mass remobilization
Rainfall-induced landslide
Unsaturated slope

ABSTRACT

Clarifying the hydro-mechanical characteristics of the mechanism associated with mass remobilization is a major step towards landslide early warning, but this clarification is usually hampered by a lack of in situ evidence. In this study, shallow rainfall-triggered slope failures under partially saturated conditions were documented by combining instrumental evidence from field experiments on a natural co-seismic landslide and hydro-mechanical slope stability analysis in an earthquake-affected region. The results revealed the transient processes and unsaturated conditions associated with mass movement in response to rainfall, and preferential flow paths were found to dominate the hydrological processes during rainfall infiltration in the landslide deposit. The results also demonstrated the importance of certain hydrological parameters, including soil matric suction and moisture content, in landslide early warning. This study reveals a partially saturated hydro-mechanical behaviour to predict the initiation of rainfall-induced landslides during post-earthquake disaster relief.

1. Introduction

The Ms8 Wenchuan earthquake on May 12th, 2008, caused the greatest number of large-magnitude co-seismic mountain hazards ever documented in China, resulting in considerable damage in the earthquake-affected regions. Moreover, tens of thousands of fractured slopes and co-seismic landslide deposits became more susceptible to storm-induced landslides and debris flows for 3 main reasons. Firstly, these deposits feature a high porosity, including cracks and fissures caused by the ground shaking, providing preferential flow paths that are more rapid than matric flow infiltration. According to laboratory tests, the porosity of soil reaches 0.49, and the permeability can reach $8 * 10^{-5}$ m/s in the Wenchuan earthquake region. Secondly, landslide deposits lack established vegetation, biofilms and microbiological elements, and consequently lack root strength. The total area of vegetation loss associated with the Wenchuan earthquake region was 1249.465 km^2, accounting for 4.76% of the total area (Cui et al., 2012). This vegetation loss reduced cohesive forces within deposits. Finally, these deposits were emplaced relatively fast, which may create a metastable fabric that is more susceptible to failure. The post-earthquake effects of rainfall-induced mass remobilization were reported to be the most dangerous threat and caused massive damage in the Wenchuan earthquake-affected region in Sichuan Province (Cui et al., 2012, 2014).

Rainfall-induced mass remobilization contributes greatly to the initiation of post-earthquake debris flows. The rainfall-triggered debris flow mechanism has been reported to involve the evolution of mass remobilization in the form of shallow slope failures as a source of debris flows (Iverson, 2000; Baum et al., 2010) and the effects of internal erosion triggered by preferential flows (Cui et al., 2014). These mass movement processes can evolve into a material source for debris flows because mass in the form of some co-seismic landslide deposits and fractured slopes is easily eroded at the free surface by rainfall and water flowing in the channels at the edge of the slope in the hollow of a debris flow. The enlarged free surface leads to retrogressive failures caused by the effects of rainfall and gravity on the depression, and the debris deposit in the hollow can be transformed into a debris flow by heavy rainfall and/or stream flow. Many examples of this phenomenon can be found in the literature (Cui et al., 2012; Hu et al., 2014).

High-intensity precipitation is the most commonly cited trigger of landslides in the Wenchuan earthquake-affected region. Recent studies on the initiation of rainfall-induced shallow landslides have broadly proposed that most of the shallow failures in the soil take place under unsaturated conditions and that the stress state of the deposit mass is altered by the infiltration of rain water and the decrease in matric

Abbreviations: VWC, Volumetric water content; SWRC, Soil-water retention curve

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http://dx.doi.org/10.1016/j.enggeo.2017.04.001
Received 28 October 2016; Received in revised form 27 March 2017; Accepted 2 April 2017
Available online 04 April 2017
0013-7952/

suction, leading to shallow slope failures on steep slopes above the water table without the development of positive pore pressures (Iverson, 2000; Godt et al., 2008; Sorbino and Nicotera, 2013; Bordoni et al., 2015). According to large-scale field investigations following the Wenchuan earthquake, shallow rainfall-induced landslides less than one metre thick are the typical form of gravitational erosion in the depression areas of debris flows. Additionally, although many scientists have researched unsaturated soil mechanics with respect to slope stability and landslides (Cascini et al., 2008; Cuomo and Della Sala, 2013), the classical soil mechanism used to predict landslides in practice generally assumes saturated conditions and neglects partially saturated conditions and the effects of matric suction on shallow slope stability. These assumptions are thus far too conservative to accurately predict shallow landslides under conditions in which suction plays an important role in the stress field (Lee et al., 2009; Damiano et al., 2012; Song et al., 2016) and make it difficult to predict disasters. As a result, an increasing number of questions related to disaster prediction and mitigation have been proposed, including early warning threshold and design of mitigation measures for rainfall-induced mass remobilization in the Wenchuan earthquake region. Therefore, characterizing the mechanisms of rainfall-induced landslides is a primary key to landslide early warning. After the Wenchuan earthquake, fractures, cracks and fissures in seismic landslides provided paths for preferential flow. This preferential flow is associated with rainfall-induced landslide initiation based on modelling (Krzeminska et al., 2013; Shao et al., 2015). The presence of preferential flow can lead to mass remobilization by affecting the hydro-mechanical behaviour and rainfall infiltration patterns. Preferential flows may enhance vertical infiltration, lead to a faster response of the deep groundwater and increase the pore pressure, thereby reducing soil effective stress. Under unsaturated conditions, internal erosion (i.e., fine particle migration triggered by fast preferential flows within deposits) may deteriorate the soil fabric, and the deposition of fine particles may lead to pore blocking, creating a relatively impermeable region that may generate a positive excess pore pressure above the water table.

Although the unsaturated aspects associated with the loss of suction, the SWRC and the reduction in shear strength are well established, in situ evidence and field data on the partially saturated preferential flows and their hydro-mechanical characteristics in post-earthquake landslides remain limited. Additionally, studies on the hydro-mechanical behaviour of the mass-movement processes in the unsaturated soil in debris flow source areas, especially using scientifically instrumented experiments in a natural setting, are extremely rare in the Wenchuan earthquake region. Moreover, few studies have used partially saturated slope failure mechanism to determine the hydrological parameter criteria of moisture content and matric suction as early warning indicators of mass remobilization.

The main aim of this paper is to reveal the hydrological characteristics and mechanisms of rainfall-induced mass remobilization in post-earthquake landslides in terms of a systematic naturalfield test and unsaturated slope stability analysis framework. This study provides hydrologic threshold criteria for early warning predictions and its in situ evidence of erosion-based partially saturated landslides and debris flows in earthquake-affected regions in China. To obtain real in situ evidence and field data on the hydro-mechanical behaviour and preferential flows in landslide deposits, this study performed field experiments on the responses of a natural landslide by artificial rainfall to 1) explore the preferential flows and matrix flows associated with hydro-mechanical parameter variations related to the infiltration of rainfall, 2) simulate rainfall-induced shallow failures in the depression channels of a debris flow catchment in an earthquake-affected region, and 3) identify the hydrologic parameter thresholds and critical criteria of gravitational erosion in mass remobilization-prone areas acting as sources of debris flows. To better predict shallow landslides, the correlation between the hydrologic properties and moisture content associated with slope destabilization in depressions was investigated by adopting an unsaturated hydrological model in combination with a stability model that includes soil suction and moisture content, which vary with rainfall intensity. Thus, this research proposes a threshold model for the initiation of mass remobilization.

2. Methodology

2.1. Field experiments

To obtain in situ data on hydro-mechanical behaviour in landslides, including preferential flows and instability, field experiments were conducted on a natural landslide to ensure that the data represent the real hydro-mechanical characteristics of seismic landslide deposits. The test slope was transformed and reformed after each failure into a slope with a height of 1.4 m and a gradient of 60° to simulate the real topography of gully depressions in the Wenchuan earthquake region under different initial conditions. Compared with laboratory model tests, field tests are favoured for investigating hydrological mechanisms because the dimension, scale and distribution of the soil grains have significant effects on the hydrological mechanisms and behaviours. Unfortunately, these factors are generally a limitation of the smaller-scale laboratory model tests.

Experiments are commonly used to study the hydrological and mechanical processes and behaviours of hillslopes and mountain hazards (Torres et al., 1998; Cui et al., 2014; Hu et al., 2014). In this study, the in situ experimental slope is located on the slope of the Taziping landslide in Dujiangyan County, which is located in the central part of Sichuan Province (Fig. 1). The experimental fractured slope of the Taziping landslide features some sliding and pre-failure symptoms, and the resulting debris flows threaten the totally rebuilt community residences of Hongse Village, Dujiangyan County. The slope failure was triggered by the Wenchuan earthquake and is composed of deeply weathered granite and andesite gravel and sand. In terms of grain size distribution, fine grains are rare in the soil (Fig. 2). The slope angle of the test slope is on average approximately 10°. The lower end of the slope was excavated to a depth of 1.4 m to create a slope angle of 60° to simulate the natural slope angle of debris flow gullies in the region, according to field investigations. An artificial rainfall test was conducted on the weathered andesitic deposit to observe its hydro-mechanical behaviours and critical hydrological threshold value for partially saturated failure. The artificial rainfall was simulated using a Norton Rainfall Simulator (VeeJet 80-100), and rainfall data were collected using a rain gauge. To establish the SWRC, the matric suction and moisture content were collected using tensiometers (Tensiomark TS2) and soil moisture sensors (DecagonEC-5), respectively. The Decagon EC-5 sensors have an accuracy of ± 0.01–0.02 VWC and a resolution of 0.001 VWC with soil, and the Tensiomark TS2 sensors have an accuracy of ± 0.35 pF (approximately 0.15 kPa). Consequently, these sensors are able to detect even small changes in the matric suction and moisture content during our test, and both types of sensors were inserted into the ground at depth intervals of 25 cm. Fig. 3 shows a cross-section and a photograph of the site, and the instruments and their placement are indicated.

By controlling the water supply of the rainfall simulator, five different categories of rainfall intensity were simulated. The first rainfall category simulated a long-duration downpour in association with the residual soil conditions on the first day. The rainfall lasted for 5 h, and approximately 509.6 mm of rainfall was applied on the first day. On the second morning, after draining over night, the second rain simulated a short-duration torrential rain following antecedent precipitation, with a total rainfall of 55 mm applied over 12 min. Subsequently, two shower-like rain events were simulated in rapid succession, and each delivered approximately 20 mm of rainfall over 10 min. Finally, a storm delivering 130 mm of total rainfall over1 h was simulated (Fig. 4).