Landslides
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Modeling of rainfall-induced landslides using a full-scale flume test

Abstract A flume test was conducted to evaluate the failure mechanism of a rainfall-induced landslide and to develop a physically based warning system. The test was performed at full scale to prevent scale effects, and the flume was a rectangular channel that was 20 m long, 4 m wide, and 2.5 m deep. The volumetric water content and the matric suction were measured at various depths to determine the rainfall infiltration into partially saturated soil. The displacement and tilt were measured at the slope surface, and a video camera was installed to record the slope failure. The results showed that the rainfall infiltration caused the volumetric water content to gradually increase and the matric suction to decrease. The resulting decrease in the soil strength caused soil deformation. Thus, the rainfall induced a landslide. The matric suction and the degree of saturation were used to calculate the generalized effective stress of the solid skeleton to develop a warning system. The stress paths were calculated using the effective mean stress and the deviatoric shear stress. The inflection point of the stress paths can be used to define a threshold for a rainfall-induced landslide warning system.

Keywords Rainfall-induced landslide · Full-scale flume test · Warning systems · Partially saturated soil · Effective stress · Stress paths

Introduction

Landslides are common mass movement processes in mountainous areas, particularly those covered by residual soils overlying extensively weathered granite. Global climate change has affected rainfall patterns and intensity, which can trigger catastrophic landslides (Jeong et al. 2008; Borga et al. 2002). Over 70% of the Republic of Korea is mountainous, and heavier rainfall during the summer season has increased the occurrence of landslides throughout the country (Jeong et al. 2008).

Many studies have been conducted on the failure mechanisms of rainfall-induced landslides (e.g., Skempton 1985; Rahardjo et al. 2005; Miao et al. 2014). Rainfall-induced landslides are produced by complex hydrological and geotechnical processes that depend on the slope geometry, the initial state of the slope, and the hydromechanical properties of the soil (Sorbino and Nicotera 2013). These landslides occur as a result of a reduction in the mean effective stresses because of an increase in the pore water pressure or a reduction in the matric suction because of the direct infiltration of rainfall along a sloped surface, which then propagates into the soil through groundwater flow (Alonso et al. 1996; Iverson et al. 1997; Nuth and Laloui 2007).

Many laboratory experiments have been performed to elucidate the mechanism of rainfall-induced landslides.

Iverson et al. (2000) investigated the contraction of loosely packed soils during rainfall infiltration. Huang et al. (2009) performed a flume test to show that the collapse and washout of the slope toe initiated retrogressive shallow slope failure. Cui et al. (2017) used small-scale model experiments to show that the migration of fines can induce slope failure during rainfall events. Zhang et al. (2017) conducted a rainfall infiltration simulation test, used a modified Green-Ampt (G-A) infiltration model to calculate the rainfall infiltration depth, and considered atmospheric effects on slope failure. The rainfall infiltration depth was found to be a controlling factor in a shallow landslide. Wang and Sassa (2003) conducted a series of tests to trigger rainfall-induced landslides. The grain size and fine particle content were found to significantly impact the mobility of rainfall-induced landslides.

However, these experimental studies have involved in small-scale flume tests (e.g., Parsons et al. 2001; Manzella and Labiouse 2009). Scale effects in small-sized experiments can disrupt sensors and their cables. Therefore, it is desirable to use a model scale as close as possible to the actual size to reproduce real landslide phenomena (Moriwaki et al. 2004). Moriwaki et al. (2004) conducted a full-scale failure experiment using a laboratory slope that was approximately 23 m long. The limitations of the experiment were that partially saturated soil was not used, and changes in the matric suction and saturation or volumetric water content were not measured.

Lade (1992) defined the instability line as the loci of effective stress maxima. This definition is based on the fact that plastic yielding occurs along a stress path of decreasing stress. This concept has used to formulate interpretative frameworks based on instability boundaries defined in the effective stress space.

In this study, a full-scale flume test was conducted to evaluate the failure mechanism of a rainfall-induced landslide, and a warning system with minimal scale effects was developed. The volumetric water content and the matric suction were measured at various depths to determine the rainfall infiltration into partially saturated soil. The displacement and tilt were measured at the slope surface, and a video camera was installed to record the slope failure. The results showed that rainfall infiltration into partially saturated soil gradually increased the volumetric water content and decreased the matric suction. The resulting reduction in the soil strength caused soil deformation. Thus, the rainfall induced a landslide. The matric suction and the degree of saturation were used to calculate the generalized effective stress (Laloui and Nuth 2009) of the solid skeleton to develop a warning system. The stress paths were calculated using the effective mean stress and the deviatoric shear stress. The inflection point of the stress paths can be used to define a threshold for a rainfall-induced landslide warning system.

Methods

Scale effects are significant in experiments on landslides. Thus, these experiments should be conducted at the largest possible feasible scales (Iverson 2015) to maximize geomorphological relevance. Scale effects were reduced in this study by performing a full-scale flume test. A rainfall-induced landslide was simulated

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