Catena 124 (2015) 1–8

Contents lists available at ScienceDirect

Catena

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

# The role of time in the hydrological behavior of residual soil slopes during rainfall events

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ARTICLE INFO

*Article history:*
Received 21 April 2014
Received in revised form 24 July 2014
Accepted 19 August 2014
Available online 16 September 2014

*Keywords:*
Soil moisture content
Residual soil slopes
Field instrumentations
Rainfall
Time factors

ABSTRACT

This study established an in-situ instrumentation program with an automatic logging system to monitor the variation of soil moisture content with time at different elevations in a residual soil slope. The role of time in the hydrological behavior of a residual soil slope during a rainfall event was investigated in terms of soil moisture content. A typical relationship between soil moisture content and time is identified for the soil in the slope during a rainfall event, and two key times are defined in the relationship: the time when the wetting front in the soil at a given depth develops during rainfall (Ts) and the time when the contribution of the unsaturated soil strength to the stability of slopes during rainfall reaches the lowest condition (Te). The distributions of Ts and Te with depth are analyzed and discussed. In addition, an increasing rate of soil moisture content with respect to time (Rm) is also defined as the variation of soil moisture content with time at a given depth during a rainfall event. Several notable findings drawn from the research are as follows: (1) in a single rainfall event, Ts and Te values increase with depth; (2) the distribution of the rainfall intensity in a rainfall event and topography of the slope affect Ts and Te values; and (3) the majority of the Rm values measured in the residual soil slope ranged from 3 to 10%/h; Rm values are mainly governed by soil constituents and permeability.



## 1. Introduction

Soils are considered as dry or saturated in conventional analyses of slope stability, whereas soils at a shallow slope depth are usually subject to alterations in moisture content because of rainfall events or temperature changes. In a natural slope, the groundwater table is normally fairly deep. Soils at a shallow depth are mainly unsaturated in the dry season, and the soil moisture content at the shallow zone of the slope may increase considerably in the rainy season. The change in the soil moisture content of a slope plays a critical role in its stability. Soil suction is significantly affected by changes in soil moisture content during a rainfall event. Rainfall-induced infiltration in the soil of a slope results in an increase in the soil moisture content and a decrease in suction. The decrease in soil suction during rainfall lowers the shear strength of the unsaturated soil. This process contributes to the failure of unsaturated soil slopes during a rainfall event. In the past decades, the failure mechanisms of unsaturated soil slopes have been investigated and discussed extensively (Finlay et al., 1997; Dai and Lee, 2001; Matsushi et al., 2006), with methods for analyzing the stability of the slope receiving considerable attention during the past 20 years. Rainfall is considered the most critical factor in triggering the instability of slopes, notably for shallow landslides at a depth less than 3 to 4 m. In addition to the mechanical properties of the soil, the hydrological behavior of the soil in the slope during rainfall events also affects the failure of slopes (Lumb, 1975; Gasmo et al., 2000; Collins and Znidarcic, 2004; Gao et al., 2011). Field studies monitored the unsaturated soil behavior during rainfall events (Ng et al., 2003; Li et al., 2005; Rahardjo et al., 2005). Most of the studies focused on the relationship between the mechanical properties (e.g., matric suction) of the soil during a rainfall event.

The role of time in the variation of the soil moisture content in a slope subject to rainfall event is an important issue, and it can be related to the time when a slope reaches unstable conditions. Orense et al. (2004) performed laboratory experiments on model sandy slopes to study the factors that affect the initiation of slope failure during an artificial rainfall event. The sandy slope was underlain by an impermeable plate. These test results showed that slope failures were induced when the soil moisture content at the toe of the slope nearly reached saturation, and the failure zone propagated toward other parts of the slope. The generation of pore water pressure and the increase in the saturation ratio of the soil associated with a rise in the water level were necessary to create the highly unstable soil zones. Towhata et al. (2005) attempted to correlate the soil moisture content and the soil displacement in a slope experiencing a rainfall event in model tests. The experimental results showed that the response of the soil moisture content at the toe area of the slope may be used as a precursor for early detection of minor displacements in the slope. Huang et al. (2008) performed model slope tests in the laboratory to investigate the responses of interior soil moisture in a soil layer underlain by a rockbed due to

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http://dx.doi.org/10.1016/j.catena.2014.08.014
0341-8162/

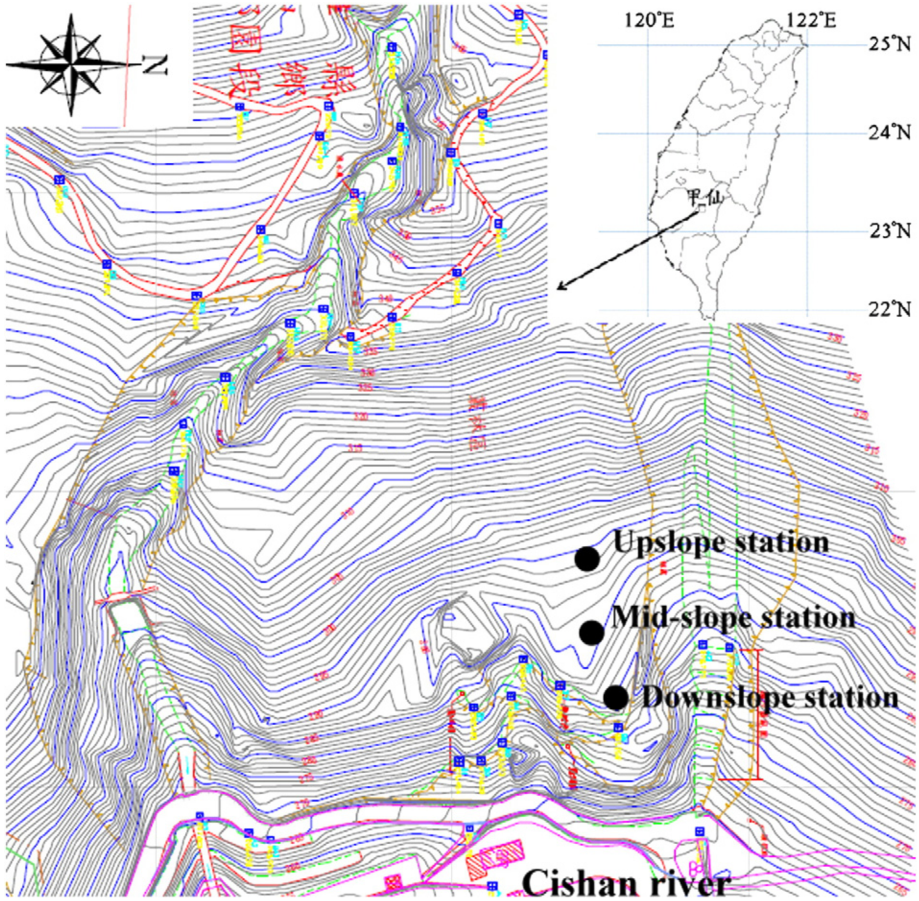


**Fig. 1.** Topography of the experimental site and layout of the instrumentation stations.

rainfall-induced slope failure. This study found that the response of soil moisture content to a rainfall event consists of three major phases: (I) the formation of a downward wetting front, (II) the transition from a downward wetting front to an upward saturation front at the impermeable base of the slope, and (III) a rise of the saturation front toward the slope surface. The arrival time of the wetting front at the soil–bedrock interface of the slope is defined by the inflection point of the variation of soil discharge vs. time during a rainfall event; this arrival time provides an early warning for the onset of slope failure. Additionally, Huang and Yuin (2010) further indicated that the time of peak soil moisture along the impermeable base was an accurate indicator for the onset of slope failure. Hawke and McConchie (2011) established an instrumentation program to monitor soil moisture content and suction at the regolith of a slope prone to failure. In addition, sensors for measuring the positive water pressure were installed at the bedrock interface, which is the potential shear plane. The results indicated that increases in soil moisture content were more important in the triggering of slope instability than a rise in the positive pore water pressure in the soil. The pore-water pressure generated in the soil during a rainfall event was not enough to trigger slope failure. The response of soil moisture content during a rainfall event can be relevant to the antecedent moisture content, topographic location, soil properties, and rainfall characteristics. Uchimura et al. (2013) attempted to establish a relationship between the soil moisture content and soil shear deformation for soils in slopes subjected to rainfall infiltration. This relationship is independent of the time history of the rainfall. Shear deformations in the soil developed when the moisture content of the soil exceeded the previous highest value. In addition, simple shear tests were conducted on unsaturated sandy soil specimens to observe their pre-failure behaviors. Shear deformations increase with an increase in soil moisture content, and the pattern of the relationship depends on the stress ratio in the soil.

The majority of past studies investigated model slopes. This current study aims to investigate the role of time in the variation of soil moisture content during a rainfall event in residual soil slopes. An instrumentation program with an automatic logging system was established in a natural slope. Variations of the soil moisture content and precipitation with time were recorded. This research attempts to establish key times from the relationship between the soil moisture content and time at a given depth during a rainfall event. The behavior of key times with respect to depth at various elevations of the slope is


**Fig. 2.** Photo of the experimental site.