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Field monitoring of rainfall infiltration in a loess slope and analysis of failure mechanism of rainfall-induced landslides

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ABSTRACT

A full-scale field experiment involving artificial rainfall has been conducted in an instrumented loess cut slope in an expressway in a loess plateau, Northwest China. Instrumentations including soil moisture probes, tensiometers, piezometers, vacuum sensors, water level sensors, and rain gauge were installed in the slope. After monitoring for about 2 years, artificial rainfall was induced at the site in April 2007. This paper presents the results from soil moisture probes, tensiometers, and water levels to reveal the surface infiltration process in an unsaturated soil. The results show that the top 0.7 m in loess is an active zone under the process of infiltration and evaporation, when subjected to a maximum rainfall intensity of 40 mm/day. The depth of the "wetting front" during the wet season was limited to the top 2 m of soil. During high rainfall intensity of 120 mm/day, the depth of the "wetting front" is about 3 m. Based on the variation of volumetric water content and matric suction in soil, a method to analyze the rainfall infiltration is proposed. By means of Gravity-Predominant Flow (GPF) concept, the infiltration rate is analyzed in the deeper soil. The results explain well the observations that loess slopes could be stable in the wet season, but it may tend to slide about 3–6 months later in the dry season. The surface infiltration has a very limited effect on the permanent groundwater table, which is at a greater depth.

1. Introduction

Rainfall-induced slope failure is a common form of landslide (Brand et al., 1984; Crozier, 1986; Au, 1998; Crosta, 1998; Crozier, 1999; Dai and Lee, 2001; Tsaparas et al., 2002; Dai et al., 2003; Salciarini et al., 2006; Tsai and Yang, 2006). Slope stability problems due to rainfall are often encountered in geotechnical engineering, either in the tropic region with frequent rainfall or the arid region (Derbyshire, 2001; Tsaparas et al., 2002). Slope failure in unsaturated soil is mostly related to intensive rainfall and infiltration. The infiltration characteristics in a slope shall be thoroughly considered for slope stability analysis in unsaturated soil (Fredlund and Rahardjo, 1993; Iverson, 2000; Cho and Lee, 2001; Huat et al., 2006). For a rainfall-induced landslide, the failure mechanism may be: 1) the dynamic and hydrostatic pressure due to infiltration is unfavorable for slope stability; 2) the water content increases due to rainfall infiltration, and the matric suction decreases or even disappears, which results in the decrease of soil shear strength and subsequently leads to slope failure (Crosta, 1998; Crozier, 1999; Iverson, 2000; Collins and Znidarcic, 2004; Li et al., 2005a).

Nowadays, some simulation tools are well developed (Montgomery and Dietrich, 1994; Ng and Shi, 1998b; Tsaparas et al., 2002; Tsai and Yang, 2006). However, due to variation of boundary conditions, it is extremely difficult or impossible to obtain representative simulation parameters. Hence, the simulation results inevitably deviate from the real situation. Owing to the time-consuming nature of field experiments, in-situ infiltration test in unsaturated soil is a laborious work. A number of field experiments have been conducted to study the effects of rainfall infiltration on slope stability (Krahn et al., 1989; Lim et al., 1996; Zhang et al., 2000; Gasmo et al., 2000; Tsaparas et al., 2003; Kim et al., 2004; Walker et al., 2004; Gvirtzman et al., 2008; Trandafir et al., 2008). Although some field experiments and laboratory test data were reported in the literature, the relationships between rainfall infiltration and the variation of water content, matric suction and groundwater table are still not clearly defined (Li et al., 2005b; Trandafir et al., 2008). In this area of research, other than the ponding infiltration test carried out in loess by Gvirtzman et al. (2008), most infiltration tests were conducted in saprolite or completely decomposed granite (or igneous rock).

Loess is a typical type of unsaturated soil (Fredlund and Rahardjo, 1993), which distributes extensively in the arid region in Northwest China. In the loess land, it is very common to see that very steep slopes can be stable for a long time. However, after the monsoon season, large-scale landslides may occur even for very gentle loess slopes. In

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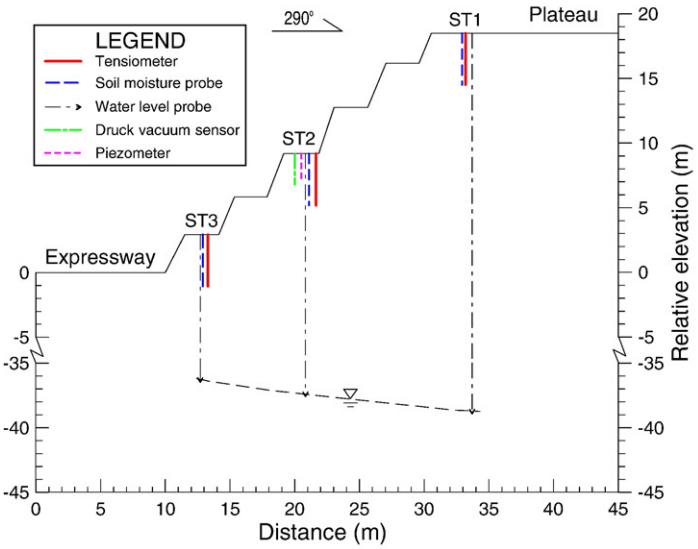
(a) Site photograph showing the monitoring locations on the slope



(b) Cross sectional view of the monitoring slope. The coordinate system is in the plane perpendicular to the expressway, with the origin at the centerline of the pavement.

Fig. 1. Overview of the monitoring site.

order to analyze the rainfall infiltration process in loess quantitatively and to investigate the failure mechanism of rainfall-induced landslides, long-term field monitoring was carried out for a cut slope of an expressway through a loess plateau. For a better understanding of the response of pore pressure and infiltration depth, artificial rainfall was also induced to observe the infiltration process.

This paper describes the instrumentation of the monitoring site and design of the artificial rainfall. The monitoring results are reported and analyzed to give a quantitative understanding of the rainfall infiltration process in unsaturated soil and the failure mechanism of rainfall induced landslides.

2. Site description and soil properties

The site is located at a cut slope in an expressway through a loess plateau in Northwest China (Fig. 1a). The annual rainfall amount is about 600 mm in the area. The slope was formed with six berms from the plateau surface down to the expressway pavement. The height between each berm is not the same, while the slope angle at each berm is always 63°. The total slope height is 18.55 m with an overall slope angle of 42°. The cross-section of the cut slope is shown in Fig. 1b. Instruments were installed at three different berms, ST1, ST2 and ST3, as shown in Fig. 1b.