Soils and Foundations 2012;52(4):634–643

The Japanese Geotechnical Society

Soils and Foundations

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Effect study of cracks on behavior of soil slope under rainfall conditions

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Received 28 October 2011; received in revised form 20 March 2012; accepted 1 May 2012
Available online 15 August 2012

Abstract

Deep-seated landslides in slopes are often induced by rainfall due to pre-existing cracks or weak layers. A series of centrifuge model tests under rainfall conditions were conducted on slopes with different types of cracks. The histories of suction and displacement of the slope were measured during the tests to investigate the infiltration–deformation–failure process of the slopes. The wetting front curved notably near the crack under rainfall conditions. The deformation of the slope was mainly caused by the saturation of soil and crack-affected water infiltration under rainfall conditions. The displacement process of the slopes with cracks can be divided into a small displacement stage, a rapid increase stage, and a stable stage. The influence of the crack on the infiltration and deformation of the slope decreased with increasing distance from the crack. Rainfall induced significant vertical deformation near the vertical crack rather than horizontal deformation. In contrast to the oblique crack, the vertical crack on the slope top was unlikely to lead to global landslide under rainfall conditions. The deformation–failure behavior of the slope with cracks was also affected by the rainfall style and rain intensity.

Keywords: Slope; Rainfall; Crack; Failure; Deformation; Infiltration; Centrifuge model test

1. Introduction

Rainfall is a major cause of slope failures that claim the lives of many and lead to significant economic losses around the world. Laboratory and field tests have indicated that a homogeneous slope under rainfall conditions is prone to suffer from surface erosion or shallow landslides (e.g., Yuki et al., 2006; Montrasio et al., 2009; Zhang et al., 2011), whereas surveys of landslides have demonstrated that deep-seated failures are often induced by rainfall in slopes with pre-existing cracks or weak layers (e.g., Hu, 2000; Fan et al., 2005; Wang et al., 2010b). For example, Rogers and Selby (1980) described landslides in New Zealand caused by pore pressures within cracks after rainstorms. It can be concluded that cracks have a significant effect on the rainfall-induced failure behavior of the slope. While the stability level of slopes with cracks should be reasonably evaluated under rainfall conditions, such an evaluation is dependent on a thorough understanding of the infiltration–deformation–failure response of such a slope. Unfortunately, the effect of cracks on these behaviors of soil slopes under rainfall conditions has yet to be systematically investigated.

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Peer review under responsibility of The Japanese Geotechnical Society.

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http://dx.doi.org/10.1016/j.sandf.2012.07.005

Table 1
List of centrifuge model tests for slopes with cracks.

No.	Rainfall style	Rain intensity (mm/min)	Crack style	Final rainfall amount
1#	Common	2.5	Vertical	35 mm
2#	Common	1.5	Vertical	40 mm
3#	Common	1.0	Vertical	40 mm
4#	Concentrated		Oblique	0.6 L
5#	Concentrated		Vertical	1.8 L

Field observations and full-scale tests have been widely used to study the deformation response and failure modes of the slope under rainfall conditions. For example, it has been generally discovered that rain infiltration induced an evident reduction in the suction of the soil and the shear strength of the soil decreases accordingly, and that this preceded the rainfall-induced failure of soil slopes (e.g., Lim et al., 1996; Trandafir et al., 2008). A full-scale landslide test indicated that the rapid increase of rainfall-induced pore water pressure is critical to the initiation of the slope's failures (Moriwaki et al., 2004).

The rainfall-induced deformation of the slope, as well as the main influential factors, could be further analyzed using the finite element method or other numerical methods (e.g., Anderson and Pope, 1984; Iverson, 2000). The stability level of the slope under rainfall conditions was usually estimated using the limit equilibrium method (e.g., Zolfaghari et al., 2005); however, the reliability of such a method is significantly influenced by a few factors, such as a reasonable analysis of the infiltration field of the slope.

The model test is an important approach for investigating the behavior of a slope during rainfall because the processes of infiltration, deformation, and failure can be observed and measured with well-controlled boundary conditions (e.g., Wang and Sassa, 2001; Tohari et al., 2007). Centrifuge model tests have been widely employed in studies on the slopes under different conditions as similar stress levels of the prototype can be simulated in a small-scale model by increasing centrifugal acceleration (e.g., Take et al., 2004; Viswanadham and Rajesh, 2009; Wang et al., 2010a). A challenge of the rainfall centrifuge model test is to simulate rainfall with good uniformity and controlled intensity. A few researchers (e.g., Kimura et al., 1991; Take et al., 2004; Hudacsek et al., 2009) achieved the simulation of rainfall in centrifuge tests through arranging spray nozzles above the slope and investigated slope responses to both medium- and long-term rainfall events. Zhang et al. (2011) provided an alternative method for rainfall simulation in the centrifuge and conducted a series of centrifuge tests to analyze the deformation mechanism of homogeneous cohesive soil slopes.

Previous studies have placed the majority of their focus on homogeneous slopes under rainfall conditions. The deformation response and failure mechanism of the slope with pre-existing cracks under rainfall conditions have not been thoroughly clarified, though cracks are widely distributed in practical slopes and these have potential to accelerate the failure of the slopes. In this paper, a series of centrifuge model tests was conducted on slopes with different types of cracks under rainfall conditions. The histories of suction and displacement of the slope were measured during the tests. Thus, the effect of cracks on the rainfall-induced infiltration–deformation–failure of the slopes was analyzed according to the test observations.

2. Test models

2.1. Schemes

Table 1 lists the test schemes for the slope with cracks. Two types of cracks, vertical and oblique, were simulated in the tests to consider the effect of the crack types. The inclination of the oblique crack was chosen to be 42°, close to the inclination of the slope and significantly different from that of the vertical crack. The centrifuge model tests used two rainfall styles. One was a common rainfall with three different intensities that was realized through the rainfall simulator, and the other was concentrated infiltration through the crack of the slope. It should be noted that the concentrated infiltration case was chosen as an extreme case of increased rainfall infiltration at the crack to study the effect on slope deformation of water seeping through the crack. The centrifuge model tests were conducted at 50 g of centrifuge acceleration, and the prototype height of the slope was 15 m, which is considered a moderate size. In addition, the observation results of homogeneous slopes with the same slope geometry were used for possible comparisons with the slopes with cracks (Wang et al., 2010b).

2.2. Devices

The centrifuge model tests were conducted using the 50 g t geotechnical centrifuge of Tsinghua University with a maximum centrifugal acceleration of 250 g. The model container was 500 mm long, 200 mm wide, and 500 mm high.

A rainfall simulation system was used to realize uniform rainfall during the centrifuge model tests (Zhang et al., 2011). Rainfall is initiated and maintained through an air pressure system and dispersed as tiny raindrops through a layer of a low permeability textile with densely covered tiny pores. The rain intensity can be adjusted by changing the air pressure, and the evenness of the rainfall on the