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Combined roles of saturated permeability and rainfall characteristics on surficial failure of homogeneous soil slope

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ABSTRACT

Both rainfall characteristics (rainfall intensity and duration) and saturated permeability of soil may influence the type and mechanism of surficial slope failures. In general, the failures can be initiated by two mechanisms, i.e. loss of matric suction through propagation of wetting front, and rise of water table. Up to date, there are still no clear indicators to identify the dominant parameters that control the type of failure for these shallow landslides. This paper investigates the hydraulic responses of soils to the variations of rainfall characteristics and soil permeability through numerical analyses. The results showed that the hydraulic responses to rainfall for a homogeneous infinite slope underlain by an impermeable layer can be divided into two stages: 1) the propagation of wetting front, and 2) the rise of water table. Based on these hydraulic responses, the type and mechanism of failures were deduced from the analytical analyses. Both the rainfall characteristics and saturated permeability were found to be predominant in controlling the hydraulic responses of soil, and hence the occurrence time, depth of failure plane, and type of surficial slope failures.

1. Introduction

Instability of unsaturated soil slope triggered by rainfall is a common geohazard in many parts of the world (Au, 1998; Dai et al., 1999; Toll, 2001; Guzzeti et al., 2008; Rahardjo et al., 2009; Godt et al., 2012). Both rainfall characteristics (rainfall intensity, I and duration, t) and saturated permeability of soil, k_{sat}, may influence the type and mechanism of slope failure initiations (Pradel and Raad, 1993; Lee et al., 2009). In general, the long duration and moderate intensity rainfall is responsible for deep-seated failures, while the short duration and high intensity rainfall triggers shallow failures (Keefer et al., 1987; Wieczorek, 1987; Iverson, 2000; Leroueil, 2001; Aleotti, 2004). With respect to the saturated permeability of soil, the deep-seated failures normally occur in the soils of low saturated permeability, while the shallow failures are typical for the soil slopes with high saturated permeability (Cho and Lee, 2001).

Numerous researchers have attempted to quantify the combined effect of saturated permeability of soil and rainfall characteristics on the rainfall infiltration, suction distributions, and hence slope instability. Mein and Larson (1973) developed an infiltration model known as Mein–Larson model which suggested that the rainfall infiltration into a soil mass is governed by the infiltration capacity of the soil. At the start of a rainfall event when the near-surface soil is in the unsaturated state with high matric suction, the infiltration capacity is higher than the saturated permeability of the soil. As the result, runoff may not occur even if the rainfall intensity is higher than the saturated permeability of soil (i.e. $I > k_{sat}$). However, as the rainfall continues to saturate the near-surface soil, the infiltration capacity will be reduced to a minimum value equals to the saturated permeability. Beyond this point, the rainfall infiltration is controlled by the saturated permeability of soil. Kasim et al. (1998) performed a series of numerical simulations to investigate the influence of hydraulic properties of soil on the pore-water pressure distributions. They concluded that the steady state pore-water pressure was governed by the ratio of rainfall intensity to saturated permeability (i.e., I/k_{sat}) and the air-entry value of soil. Their finding was supported by Ng et al. (1999) who extended the research works by considering more parameters such as soil water characteristic curve, initial groundwater table, the presence of impeding layer etc. Lee et al. (2009) investigated the hydraulic responses of four typical types of soils under extreme rainfall conditions. They concluded that the ratio of rainfall intensity to soil saturated permeability (i.e., I/k_{sat}) plays an important role in determining the critical rainfall pattern for a soil slope. From the foregoing, it can be concluded that most of the previous researches have focused on the effects of rainfall characteristic and saturated permeability on

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the rainfall infiltration and suction distribution in unsaturated soil. Very few studies have addressed their roles on the type and mechanism of slope failure initiations.

Previous studies suggested that the rainfall-induced slope failure can generally be initiated by two mechanisms: 1) rainfall infiltration induces a rise of groundwater which exerts seepage force and adds weight to the slope, and eventually triggers the slope failure. (Cho and Lee, 2002; Crosta and Frattini, 2003; Soddu et al., 2003); 2) rainfall results in a propagation of wetting front causing an increase in water content and loss in matric suction, and subsequently leads to slope failure (Ng et al., 2001; Collins and Znidarcic, 2004; Rahardjo et al., 2007). These two mechanisms are responsible for shallow landslides on many occasions, particularly associated to pyroclastic or volcanic rocks as reported by numerous researchers across the world, i.e. Chigira et al. (2002) in northern Japan, Cardinali et al. (2006) in central Italy, De vita et al. (2012) in southern Italy, Apip et al. (2009) in West Java, Indonesia, etc. These slopes are commonly characterized by shallow volcanic deposits (<5 m), underlain by less permeable rocks. Rainwater tends to infiltrate into the volcanic deposits and flow laterally along the interface of the less permeable rocks. The soil would become saturated if rainfall is sufficiently intense, and eventually trigger a landslide. Despite of the fact that studies pertaining to the two failure mechanisms can be found in abundance, the dominant factors that govern the type of failure mechanism are still unclear. The understanding on the type of failure mechanism of slope is essential for anticipating the landslide occurrence.

This paper aims to investigate the combined effect of rainfall characteristics and saturated permeability on the hydraulic responses of soil slope to rainfall infiltration, and hence on the mechanism of slope failure. First, numerical simulations are carried out to assess the hydraulic responses of soil to various rainfall characteristics and soil permeability. Based on the hydraulic responses obtained, the type and mechanism of failures were deduced from the analytical analyses on the factor of safety equations developed from an infinite slope model.

2. Surficial slope stability analysis

Rainfall-induced slope failures are generally shallow and the failure planes are commonly parallel to the slope surface. For this reason, the surficial stability of slope is often evaluated using a single layered infinite slope model (Skempton and DeLory, 1957; Cho and Lee, 2002; Lu and Godt, 2008; Godt et al., 2009).

Fig. 1 shows a section of a typical infinite slope model (Cho and Lee, 2002). The factor of safety (FOS) of the slope is defined by the ratio of resistance force (quantified by the shear strength of soil) to the mobilized force. The resistance force or shear strength of soil computed from the conventional Mohr–Coulomb failure criterion and effective stress concept (Terzaghi, 1936) is expressed as:

$$\tau_f = c' + \sigma' \tan\varphi' \tag{1}$$

where

τ_f	shear stress at failure
c'	effective cohesion
σ'	effective normal stress
ϕ^b	effective friction angle

Based on the Mohr–Coulomb failure criterion in Eq. (1) and the limit equilibrium approach, the factor of safety (FOS) of the infinite slope shown in Fig. 1 can be expressed as:

$$\text{FOS} = \frac{c' + \sigma' \tan\varphi'}{W \sin\alpha \cos\alpha} \tag{2}$$

where α is the slope angle and W is the weight of the soil slice. To extend the effective stress concept to unsaturated soil mechanics, several functional relations between the effective stress and matric suction have been proposed by numerous researchers (Bishop, 1959; Aitchison, 1960; Jennings and Burland, 1962; Fredlund et al., 1978). Recently, a unified effective stress under both saturated and unsaturated conditions has been suggested by Lu and Likos (2006) and Lu and Godt (2008):

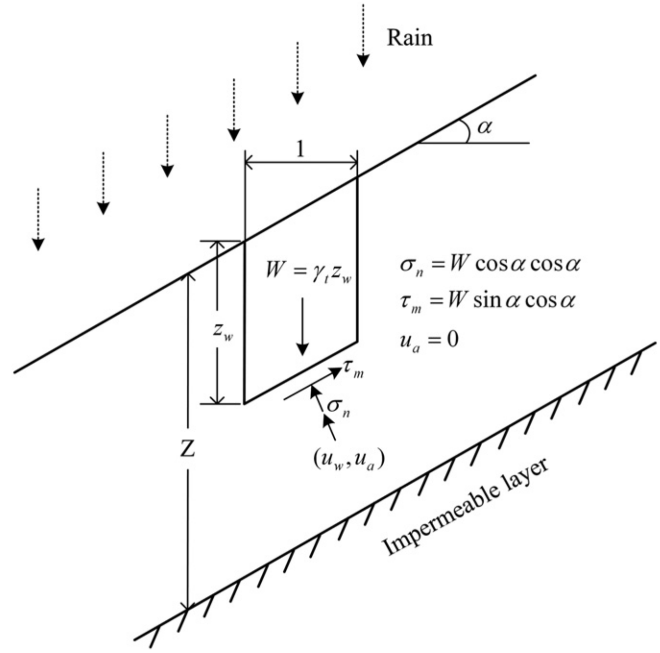

Fig. 1. Surficial stability analysis of infinite unsaturated soil slope (reproduced from Cho and Lee, 2002).

$$\sigma' = (\sigma_n - u_a) - \sigma^s \tag{3}$$

where u_a is the pore-air pressure which can be conveniently taken as 0 (equal to atmospheric), σ_n is the total stress due to self weight of soil, and σ^s is defined as the suction stress characteristic curve of soil with a general functional form of (Lu and Godt, 2008):

$$\begin{aligned} &\sigma^s = -\frac{\theta-\theta_r}{\theta_s-\theta_r}(u_a-u_w) = -S_e(u_a-u_w) \\ &\sigma^s = S_e u_w < 0 \quad \text{for unsaturated conditions } (u_w<0) \\ &\sigma^s = u_w \geq 0 \quad \text{for saturated conditions} (u_w \geq 0) \end{aligned} \tag{4}$$

whereby u_w is the pore-water pressure, θ is the volumetric water content, θ_r is the residual volumetric water content, θ_s is the saturated volumetric water content, and S_e is the degree of saturation.

By substituting the modified effective stress (Eq. (3)) into Eq. (2), the unified FOS equation for unsaturated and saturated soils can now be expressed as:

$$\text{FOS} = \frac{c' + \left[(\sigma_n - u_a) - \sigma^s\right]\tan\varphi'}{W\sin\alpha\cos\alpha} \tag{5}$$

As $W = \gamma_t z_w$, $\sigma_n = \gamma_t z_w \cos^2\alpha$, and $u_a = 0$ at atmospheric (where z_w is the vertical depth of soil slice, γ_t is the total unit weight of soil), Eq. (5) can be rewritten as:

$$\text{FOS} = \frac{c' + \left(\gamma_t z_w \cos^2 a - \sigma^s\right)\tan\varphi'}{\gamma_t z_w \sin\alpha\cos\alpha} \tag{6}$$

The advantage of using Eq. (6) for assessing stability of unsaturated slope is that the analysis can account for both the reduction in matric suction and development of positive pore water pressure in a continuous