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Simplified quantitative risk assessment of rainfall-induced landslides modelled by infinite slopes

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ABSTRACT

Rainfall induced landslides vary in depth and the deeper the landslide, the greater the damage it causes. This paper investigates, quantitatively, the risk of rainfall induced landslides by assessing the consequence of each failure. The influence of the spatial variability of the saturated hydraulic conductivity and the nature of triggering mechanisms on the risk of rainfall-induced landslides (for an infinite slope) are studied. It is shown that a critical spatial correlation length exists at which the risk is a maximum and the risk is higher when the failure occurs due to a generation of positive pore water pressure.

1. Introduction

Landslides cause damage to buildings, infrastructure, agricultural land and crops. In the majority of cases the main trigger for landslides is heavy or prolonged rainfall (Brand, 1984; Fourie, 1996). Rainfall-induced landslides are common in tropical and subtropical regions where residual soils exist in slopes and there are negative pore water pressures in the unsaturated zone above the water table (Rahardjo et al., 1995). In an unsaturated soil, these negative pore water pressures contribute towards its shear strength and thus help to maintain stability (Fredlund and Rahardjo, 1993). The infiltration of rainwater causes a reduction in this negative pore water pressure and an increase in the soil unit weight (due to an increased saturation), both of which have a destabilizing influence.

Research on rainfall-induced slope failure indicates that several factors affect the stability of a slope subjected to rainfall infiltration. Published research in the area (Zhang et al., 2011; Zhan et al., 2012; Li et al., 2013) shows that the rainfall characteristics (duration, intensity and pattern), the saturated hydraulic conductivity of the soil, the slope geometry, the initial conditions, and the boundary conditions are the factors that influence the stability of a slope subjected to rainfall. Among these factors, the hydraulic conductivity is a very important parameter in seepage and stability problems involving unsaturated soils (Tsaparas et al., 2002; Rahardjo et al., 2007; Rahimi et al., 2010).

Most studies involving rainfall-induced landslides are deterministic in nature, where the soil is assumed to be homogeneous and averaged (or design) soil properties are considered in the analysis (Gui et al., 2000). The uncertainties associated with the soil parameters are usually dealt with by adopting "reasonably averaged" parameters, coupled with practical experience (Duncan, 1996). In reality, soil is inherently heterogeneous with its properties varying from point to point due to different depositional and post-depositional processes (DeGroot and Baecher, 1993; Lacasse and Nadim, 1996). A few studies focused on the effects of the spatial variability of the hydraulic conductivity on rainfall infiltration and subsequent slope stability by using random field theory (e.g. Santoso et al., 2011; Zhu et al., 2013; Cho, 2014), but those studies did not investigate the nature of the triggering mechanism or quantified the risk associated with a rainfall-induced landslide when the saturated hydraulic conductivity varies spatially.

It is now commonly believed that there are two mechanisms that trigger failure in slopes subject to rainfall infiltration (Li et al., 2013); loss of suction during propagation of the wetting front and the rise of the water table (which generates a positive pore water pressure).

Generally, a loss of suction (i.e. reduction in negative pore water pressure) causes a shallow failure while a rise in the water table (i.e. generation of a positive pore water pressure) causes a deep failure. However, this may not be true when the saturated hydraulic conductivity varies spatially, as the water may accumulate at shallow depths

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(Huang et al., 2010) leading to a positive pore water pressure and a shallow failure. To the authors' knowledge, this important effect has not been studied systematically. Another key aspect of the risk assessment of rainfall-induced landslides is the assessment of consequence. Rainfall-induced landslides can be shallow or deep. It is clear that a deep-seated landslide will tend to cause more damage and thus has a more severe consequence. Therefore, the consequence associated with a shallow or deep failure should be assessed individually.

The changes in the near-surface pore water pressures caused by rainfall may be determined using field-observations, analytical solutions or numerical methods. This steady-state pore-pressure field is then used to determine the slope stability either analytically or numerically. Among these uncoupled approaches, the infinite slope model combined with a one-dimensional hydrological model is popular (e.g. Collins and Znidarcic, 2004; Tsai and Chen, 2010; Tsai, 2011; White and Singham, 2012; Zhan et al., 2012; Zhang et al., 2012; Li et al., 2013; Zhang et al., 2014) and will be adopted in this study. In the infinite slope model, the landslide is characterized as a slope failure occurring along a plane parallel to the ground surface. It assumes that each slice of an infinitely long slope receives the same amount and intensity of rainfall (Collins and Znidarcic, 2004); that the time required for infiltration normal to the slope is much less than the infiltration time required for flow parallel to the slope; that the wetting front propagates in a direction normal to the slope[1] (White and Singham, 2012); and that the depth of failure is small compared to the length of the failing soil mass. The validity of these assumptions has been checked against the predictions of two-dimensional numerical models, with the conclusion that an infinite slope approximation may be adopted as a simplified framework to assess failures due to the infiltration of rainfall (Zhan et al., 2012; Li et al., 2013).

In this study, the saturated hydraulic conductivity is modelled as a random field and coupled with Monte-Carlo simulations for the determination of failure probability, consequence and risk. The rainfall-induced landslide risks of two slopes having different triggering mechanism are studied by adopting the quantitative risk assessment framework proposed by Huang et al. (2013). To obtain the pore water distributions, the modified form of one-dimensional Richards equation (Richards, 1931) is solved numerically by the HYDRUS 1D software (Simunek et al., 2013).

2. Seepage analysis

Assuming that the effect of pore-air pressure is insignificant and that water flow due to thermal gradients is negligible, one-dimensional uniform flow in a variably saturated soil can be described by a modified form of Richards equation (Richards, 1931). Therefore, the flow in an unsaturated infinite soil slope can be described by the 1D equation (e.g. Zhan et al., 2012):

$$\frac{d\theta}{dt} = \frac{d}{dz}\left(K\left[\frac{du}{dz} + \cos\alpha\right]\right) \tag{1}$$

where θ is the volumetric water content, t is time, u is the pore water pressure head, α is the inclination of the slope to the horizontal, K is the hydraulic conductivity and z is the spatial coordinate as shown in Fig. 1. To solve the above equation numerically, the water content θ is

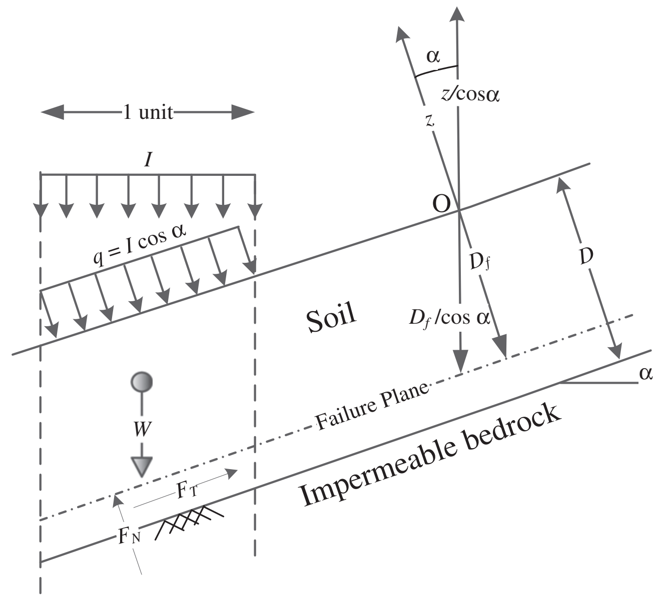

Fig. 1. Limit-equilibrium set up.

assumed to vary with the pore water pressure head u according to the van Genuchten (1980) model as:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (au)^N}\right]^m \tag{2}$$

where S_e is the effective degree of saturation, θ_s and θ_r are the saturated and residual water content respectively, a is the suction scaling parameter and N, m are the parameters of the van Genuchten model. Noting that the volumetric water content is related to the degree of saturation S and the porosity n (by the relation $\theta = nS$), the effective degree of saturation can also be expressed in terms of the degree of saturation S in the following form:

$$S_e = \frac{S - S_r}{1 - S_r} \tag{3}$$

where S_r is the residual degree of saturation. To complete the description, the hydraulic conductivity K can be estimated as:

$$K = K_s K_r \tag{4}$$

where K_s is the saturated hydraulic conductivity and K_r is the relative hydraulic conductivity given by van Genuchten (1980):

$$K_r = S_e^{1/2}\left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2. \tag{5}$$

In this study, the saturated hydraulic conductivity is modelled as a random field and Eq. (1) is solved by HYDRUS 1D. The distribution of pore water pressure and the degree of saturation are then used in the infinite slope model to assess the slope stability.

2.1. Slope stability assessment

Once the pore water pressure distribution is obtained through seepage analysis, the factor of safety FS at any given time t can then be determined by limit-equilibrium techniques. The stability of an infinite slope is estimated by using a closed form solution similar to that proposed by White and Singham (2012), where the failure is considered to occur along a plane parallel to the ground surface. A soil column of a unit width is considered, where the self-weight W is used to obtain the normal force F_N and tangential force F_T at any depth. The expression

[1] The use of an infinite slope model implies that the pore water pressure at a certain depth is same along all lateral extents of the slope i.e. the pore pressure contours are parallel to the ground surface when the slope is subjected to rainfall (e.g. Zhan et al., 2012). Pore pressure contours parallel to the ground surface also imply that any variability in the hydraulic conductivity (parallel to the slope surface) is neglected. If flow is not strictly one-dimensional, then the pore water pressures will vary along the lateral extent of the slope, even at the same depth. The problem in such a case will no longer be one-dimensional in nature and the use of an infinite slope model would be inappropriate.