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Boundary effects of rainfall-induced landslides

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ABSTRACT

In the study of landslides, it is generally assumed that an impermeable boundary exists at a certain depth and failure occurs at this boundary. In reality this is not always the case and failures can occur at any depth. This paper aims to study the effect of boundary conditions on landslides, using a series of seepage and stability analyses performed over a range of rainfall intensities, and for different failure mechanisms, by studying the failure time and depths corresponding to fully drained, partially drained, and impermeable boundaries. It is shown that these conditions can significantly affect the occurrence and depth of rainfall-induced landslides.

1. Introduction

Landslides are responsible for causing loss of life and extensive damage to property in many regions throughout the world. Even though an otherwise stable slope may fail due to human-induced factors, such as excavation at the toe or loading due to construction, many slopes simply fail due to rainfall infiltration [2,6]. 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 [14]. In an unsaturated soil, these negative pore water pressures contribute toward its shear strength and thus help to maintain stability [7]. 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 [25].

Rainfall-induced landslides are characterized as failures occurring along a plane parallel to the ground surface. Given the physics involved in landslides, various infinite slope models have been used to assess their stability after heavy rainfall [4,8,11,17,21,25,26]. These models are based on the premise that each slice of an infinitely long slope receives the same amount and intensity of rainfall [5], the time required for infiltration normal to the slope is far less than that required for flow parallel to the slope, the wetting front propagates in a direction normal to the slope [25], and the failure depth 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 [11,26]. The present study is based on an infinite slope model.

Research indicates that several factors affect the stability of a slope subjected to rainfall infiltration. The characteristics of the rainfall (duration, intensity and pattern), the saturated hydraulic conductivity of soil, the slope geometry, the initial conditions and the boundary conditions have all been identified as influential factors.

Studies on rainfall-induced landslides have considered different types of boundary conditions: an impermeable boundary condition (e.g. [11,13,25]), fixed water table (e.g. [12,26]) or a drained boundary condition (e.g. [5,18]). Few studies [20,26] have also reported that when a soil slope is underlain by a less permeable layer, the interface (between the soil and the less permeable layer) acts as a pseudo-boundary, (generating positive pore water pressures, thus) causing the slope to fail at the interface. In such a case, the location of the interface could significantly affect the stability of a layered slope [26]. In addition, rainfall-induced landslides could be shallow (i.e. at an intermediate depth in the soil profile) or deep

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Nomenclature

a	scaling suction
c'	effective cohesion
D_f	depth of failure
dt	incremental time step
F_N	normal force
F_T	tangential force
FS	factor of safety
FS_1	factor of safety at the depth of failure
I	rainfall intensity
K	hydraulic conductivity
K_r	relative hydraulic conductivity
K_s	saturated hydraulic conductivity
m	van Genuchten model parameter
n	soil porosity
N	van Genuchten model parameter
q	flux infiltrating the slope
S	degree of saturation
S_e	effective degree of saturation
S_r	residual degree of saturation
t	rainfall duration
t_f	time of failure
u	pore water pressure head
u_w	pore water pressure
u_a	pore air pressure
W	weight of failing soil mass
D	slope depth
z	slope normal direction
z'	vertical direction
α	slope angle
γ	unit weight of soil
γ_s	unit weight of soil solids
γ_w	unit weight of water
θ	soil volumetric water content
θ_r	residual water content
θ_s	saturated water content
σ	total normal stress
σ'	effective normal stress
τ	soil shear stress
τ_f	soil shear strength
ϕ'	effective friction angle
χ	coefficient of effective stress

(i.e. at the bottom of the soil profile). Some researchers (e.g. [5,13,22]) have reported the generation of positive pore water pressures (at shallow depths) during rainfall infiltration and considered it to be the cause of shallow landslides. However Cheng [3] showed that the positive pore water pressures that are generated during infiltration in a homogeneous soil profile, are in fact due to the high nonlinearities associated with the solution (of seepage flow problem (both spatial and temporal) and if a sufficiently fine mesh was considered, no positive pore pressures would be generated). Therefore, shallow failures during infiltration in homogeneous soils occur due to a reduction in the negative pore water pressures [11,12]. Li et al. [11] reported that if failure does not occur during propagation of wetting front then it will occur at the boundary (as they considered an impermeable boundary in their study) due to a rise in the water table. A study which systematically evaluates the response of a slope having different failure mechanisms, to various boundary conditions has still not been performed.

Therefore, this paper addresses the effects of the boundary conditions on rainfall-induced landslides. Three different types of boundaries are considered: fully drained, partially drained and impermeable. Although the factor of safety is an important aspect, it is also imperative to know what would be the location and the timing of the collapse mechanism if a slope was to fail. Thus, in the present study, the time of failure t_f and the depth of failure D_f are studied for different boundary conditions. The depth of failure can be used to estimate the volume of the failing soil mass. Four case studies are performed to assess the effect of the boundary conditions on the depth of failure and time of failure for different rainfall intensities, slope inclinations and soil properties. The different boundary conditions are approximated by adopting different ratios of the saturated hydraulic conductivity of the overlying soil layer relative to the underlying rock. It is shown that the boundary conditions significantly affect the failure process by influencing either the occurrence of failure or the failure depth for a given rainfall intensity. To obtain the pore water distributions for a slope subjected to rainfall, numerical simulations of 1D seepage have been performed using the HYDRUS 1D [16] software.

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 [15]. Therefore, the flow in an unsaturated infinite soil slope can be described by the 1D equation (e.g. [26]):

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

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 assumed to vary with the pore water pressure head u according to the van Genuchten [23] 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 ($\theta = nS$), 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 [23]:

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