Rainfall-induced Infiltration in Planar Slopes

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1. Introduction

Rainfall-induced shallow landslides frequently occur on soil-mantled hillslopes, particularly in the tropical region of Southeast Asia which is characterized by very intense long duration rainy seasons. Previous studies aimed at revealing the underlying mechanisms of rainfall-induced landslides in tropical regions have tended to focus on hydrological and geotechnical aspects, mainly through: (1) field monitoring and measurement of the hydrological response to rainfall (e.g. Rezaur *et al.*, 2002; Tsaparas *et al.*, 2003; Matsushi *et al.*, 2006); and (2) experimental simulation of the field conditions (e.g. Zhu and Anderson, 1998; Dai *et al.*, 1999).

Some researchers (e.g. Matsushi *et al.*, 2006) have demonstrated the contrasting mechanisms of landslides in adjoining hills with permeable and impermeable bedrock, as follows. (1) In slopes with the permeable bedrock, infiltrated rainwater percolates through the bedrock as an unsaturated gravitational flow, of which the wetting band migration from the soil surface downward results in soil suction decrease and causes landslides when deep soil becomes sufficiently wet to form a failure plane at the forefront of the wetting band. (2) In contrast, the impermeable bedrock beneath a thin soil layer generates a saturated subsurface flow, of which the transient groundwater table from the bedrock upwards results in pore-water pressure increase and causes landslides when the groundwater table reach sufficiently high to trigger a slip upon the bedrock.

The infiltration process of the first case may be described by a full nonlinear unsaturated flow equation, the analytical solution of which for a problem of infiltration into a planar hillslope of homogeneous isotropic soil subject to constant moisture content at the soil surface is given by Philip (1991) in the form of series solution appropriate to small and moderate values of time, and travelling wave solution for large values of time. This paper mainly concerns on a uniform analytical solution of that subject to, however more realistic condition, constant rainfall intensity at the soil surface, for further analyses of slope stability reduced by rainfall-induced infiltration.

2. Problem Formulation

As shown in **Fig. 1**, consider a long planar hillslope of homogenous isotropic soil with a slope angle, α, subject to the boundary conditions. The equation governing unsaturated soil water flow (Philip, 1991), which is essentially independent of x and dependent on only z, rewritten in the form

$$-\frac{\partial z}{\partial t}=\frac{\partial}{\partial\theta}\left(\frac{D}{\partial z/\partial\theta}+K\cos\alpha\right) \tag{1}$$

is solved subject to the boundary conditions

$$\begin{cases}\theta=\theta_i, & t=0,\ z\le 0\\ \dfrac{D}{\partial z/\partial\theta}+K\cos\alpha=R\cos\alpha, & t=0,\ z=0\end{cases} \tag{2}$$

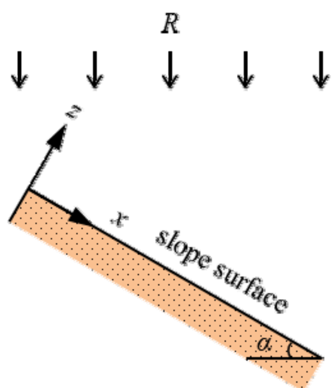

Fig. 1 Rectangular coordinates

D is the diffusivity and K the conductivity, which are two given functions of the water content, θ. $z(\theta, t)$ is the position of a point where the water content is θ at time t. θ_i is the initial moisture content. The rainfall intensity R is a given constant which represents the imposed flux at the slope surface. The iteration method follows the general procedure described earlier (Parlange, 1971)

$$z_{p+1}\left(\theta,t\right)=\int_{\theta}^{\theta_0(t)}\frac{D\left(\gamma\right)}{K\left(\gamma\right)\cos\alpha+\int_{\theta_i}^{\gamma}\frac{\partial z_p\left(\beta,t\right)}{\partial t}\mathrm{d}\beta}\mathrm{d}\gamma \tag{3}$$

3. Analytical Solution

First, the term ($\partial z/\partial t$) is neglected in Eq. (1) as a first approximation

$$z_1\left(\theta,t\right)=\frac{1}{\cos\alpha}\int_{\theta}^{\theta_0(t)}\frac{D\left(\gamma\right)}{R-K\left(\gamma\right)}\mathrm{d}\gamma \tag{4}$$

The quantity $\theta_0(t)$ is the water content at the slope surface which varies with time and is taken to satisfy an integrated form

$$t=\frac{1}{\cos^2\alpha}\int_{\theta_i}^{\theta_0(t)}\frac{D\left(\gamma\right)\left(\gamma-\theta_i\right)}{R\left[R-K\left(\gamma\right)\right]}\mathrm{d}\gamma \tag{5}$$

The term ($\partial z_1/\partial t$) is now calculated from the first approximation of Eq. (4)

$$\frac{\partial z_1\left(\theta,t\right)}{\partial t}=-\frac{R\cos\alpha}{\theta_0\left(t\right)-\theta_i} \tag{6}$$

Eq. (6) can be substituted into Eq. (3) at once and gives,

$$z_2\left(\theta,t\right)=\frac{1}{\cos\alpha}\int_{\theta}^{\theta_0(t)}\frac{D\left(\gamma\right)}{K\left(\gamma\right)-R\frac{\gamma-\theta_{\mathrm{i}}}{\theta_0\left(t\right)-\theta_{\mathrm{i}}}}\mathrm{d}\gamma \tag{7}$$

Eq. (3) and Eq. (7) can be used for iteration until the result meets the precision prescribed.

4. Results and Discussions

From the form of Eq. (5) and Eq. (7), some general remarks can be made:

(1) Eq. (5) shows that as $t\rightarrow\infty$, it is necessary that $K\rightarrow R$. This is physically possible only if $R\leq K_{\mathrm{s}}$ where K_{s} is the maximum value of the conductivity, i.e. at saturation. Thus, the analytical solution applies only when $R\leq K_{\mathrm{s}}$ or until ponding occurs if $R>K_{\mathrm{s}}$.

(2) Eq. (5) shows that the slope with an angle, α, produces an extension of $1/\cos^2\alpha$ for the values of time, compared with that produced in flat land.

(3) Eq. (7) shows that the limiting profile is identical to the "profile at infinity" (Philip, 1991) which would be obtained by imposing θ_0=*constant* at the slope surface for all times.

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