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Modeling of rainfall-triggered shallow landslide

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Abstract By integrating hydrological modeling with the infinite slope stability analysis, a rainfall-triggered shallow landslide model was developed by Iverson (Water Resour Res 36:1897-1910, 2000). In Iverson's model, the infiltration capacity is assumed to be equivalent to the saturated hydraulic conductivity for finding pressure heads analytically. However, for general infiltration process, the infiltration capacity should vary with time during the period of rain, and the infiltration rate is significantly related to the variable infiltration capacity. To avoid the unrealistically high pressure heads, Iverson employed the beta-line correction by specifying that the simulated pressure heads cannot exceed those given by the beta line. In this study, the suitability of constant infiltration capacity together with the beta-line correction for hydrological modeling and landslide modeling of hillslope subjected to a rainfall is examined. By amending the boundary condition at ground surface of hillslope in Iverson's model, the modified Iverson's model with considering general infiltration process is developed to conduct this examination. The results show that the unrealistically high pressure heads from Iverson's model occur due to the overestimation of infiltration rate induced from the assumption that the infiltration capacity is identical to the saturated hydraulic conductivity. Considering with the general infiltration process, the modified Iverson's model gives acceptable results. In addition, even though the beta-line correction is applied, the Iverson's model still produces greater simulated pressure heads and overestimates soil failure potential as compared with the modified Iverson's model. Therefore, for assessing rainfall-triggered shallow landslide, the use of constant infiltration capacity together with the beta-line correction needs to be replaced by the consideration of general infiltration process.

Keywords Landslide · Rainfall · Infiltration · Slope stability

Notation C: The change in volumetric water content per unit change in pressure head · C_0: The minimum value of C · c: Soil cohesion · D_0: K_{sat}/C_0 · d_Z: Water depth · d_{LZ}: Slope depth · FS: Factor of safety · I_Z: Rainfall intensity · K_L and K_Z: The hydraulic conductivities in the lateral and slope-normal directions · K_{sat}: Saturated hydraulic conductivity · T: Rainfall duration · x,y,z, and Z: The coordinates · ψ: Groundwater pressure head · θ: Soil volumetric water content · α: Slope angle · φ: Soil friction angle · γ_{sat} and γ_w: The unit weights of saturated soil and water · ΔZ: Grid size · Δt: Time step

Subscripts i: Z directional computational point index · NX: Grid point at slope base

Superscripts n: Time step index · NT: Time level at end of simulation

Introduction

Landslide often poses a serious threat to both lives and property in many places around the world. Although slope failures may happen due to human induced factors, such as the loading of the slope or cutting away of the toe for construction purposes, many failures occur simply due to the rainfall, especially in regions with residual soil subjected to a heavy rainfall. The soil failure happens while the strength of soil cannot resist the acting stress developed by rainfall infiltration. Therefore, the assessment of rainfall-triggered landslide strongly depends on the evaluation of infiltration during a rainfall.

With assumptions of steady or quasi-steady water table, and groundwater flows parallel to hillslope, various models (Montgomery and Dietrich 1994; Wu and Slide 1995; Borga et al. 1998), based on coupling the infinite slope stability analysis with hydrological modeling, were developed to assess landslide induced by land use and hydrological conditions. These assumptions are too restrictive for practical applications. For example, pore water pressure in hillslope can rapidly vary with time during the period of a rainfall event, and redistribute after a rainfall event. In order to release these limitations, Iverson (2000) developed a flexible modeling framework of landslide with different approximations of Richards' equation (1931) valid for more general hydrological conditions. In Iverson's model, one-dimensional linear diffusion equation instead of three-dimensional nonlinear Richards' equation was used for hydrological modeling of wet and shallow hillslope. The pressure heads were analytically obtained from solving the linear diffusion equation with ground surface of hillslope subjected to a uniform rainfall. The shallow landslide modeling was then conducted from the infinite slope stability analysis together with the obtained pressure heads. The extension version of Iverson's model was further developed to take variable intensity rainfall into account for hillslope with finite depth (Baum et al. 2002). Due to its simplicity and practicability, the Iverson's model became popular. For example, the Iverson's model was applied not only to assess the landslide triggered by intense rainfall (Crosta and Frattini 2003; Keim and Skaugset 2003; Frattini et al. 2004; Lan et al. 2005) but also to investigate the effect of hyetograph characteristics on landslide potential (D'Odorico et al. 2005).

For general infiltration process, the infiltration capacity should vary with time during the period of rain (Freeze and Cherry 1979; Chow et al. 1988). The rainfall will totally infiltrate, that is, the infiltration rate is identical to the rainfall intensity, if the infiltration capacity is greater than or equal to the rainfall intensity. However, when the infiltration capacity is less than the rainfall intensity, the infiltration rate equals the infiltration capacity, and the surplus rainfall will pond on ground surface and induce overland flow. In other words, the infiltration rate in a rainfall infiltration process is strongly related to whether the ponding happens or not, which is influenced by the variable infiltration capacity.

However, in Iverson's hydrological modeling, for simply finding the analytical solution of pressure heads, the infiltration capacity is assumed to be equivalent to the saturated hydraulic conductivity during the period of rain. The hypothetical constant infiltration capacity is actually inconsistent with the general infiltration process. In addition, the unrealistically high pressure heads could be induced from Iverson's hydrological modeling. By specifying that the simulated pressure heads under downward gravity-driven flow cannot exceed those which would result from the water table at ground surface, Iverson (2000) proposed the beta-line correction to avoid this drawback. This amendment is rather ad hoc but necessary for the application of Iverson's model. We are interested in why Iverson's hydrological modeling could induce the unrealistically high pressure heads. In addition, whether it is suitable to apply the hypothetical constant infiltration capacity together with the beta-line correction to assess rainfall-induced shallow landslide needs further examinations as compared with the consideration of general infiltration process.

In the following sections, both hydrological modeling together with the beta-line correction and landslide modeling, based on Iverson's rainfall-triggered shallow landslide model, are first described briefly. How to consider general infiltration process in Iverson's hydrological modeling is then proposed. Finally, the differences between the use of constant infiltration capacity in conjunction with the beta-line correction and the consideration of general infiltration process for assessing rainfall-induced shallow landslide are examined.

Hydrological modeling and landslide modeling

The unsteady and variably saturated Darcian flow of groundwater in response to rainfall infiltration of hillslope can be governed by the Richards' equation with a local rectangular Cartesian coordinate system (Bear 1972; Hurley and Pantelis 1985) shown in Fig. 1. The governing equation can be written as follows:

$$\frac{\partial\psi}{\partial t}\frac{\mathrm{d}\theta}{\mathrm{d}\psi} = \frac{\partial}{\partial x}\left[K_{\mathrm{L}}(\psi)\left(\frac{\partial\psi}{\partial x}-\sin\alpha\right)\right]+\frac{\partial}{\partial y}\left[K_{\mathrm{L}}(\psi)\left(\frac{\partial\psi}{\partial y}\right)\right] + \frac{\partial}{\partial z}\left[K_z(\psi)\left(\frac{\partial\psi}{\partial z}-\cos\alpha\right)\right] \tag{1}$$

in which ψ is groundwater pressure head; θ is soil volumetric water content; α is the slope angle; t is time. The coordinate x points down the ground surface; y points tangent to the topographic contour that passes through the origin; z points into the slope, normal to the x-y plane. K_{L} and K_z, a function of soil properties or ψ, are hydraulic conductivities in lateral direction (x and y) and slope-normal direction (z), respectively.

For the case of shallow soil and a rainfall time shorter than the time necessary for transmission of lateral pore water pressure, (1) can be simplified for wet soil (i.e., $K_z \approx K_{\mathrm{sat}}$; K_{sat} is the saturated hydraulic conductivity) in vertical direction as follows:

$$\frac{\partial\psi}{\partial t} = D_0\cos^2\alpha\frac{\partial^2\psi}{\partial Z^2}, \tag{2}$$

where $D_0 = K_{\mathrm{sat}}/C_0$. C_0 is the minimum value of $C(\psi)$. $C(\psi) = \mathrm{d}\theta/\mathrm{d}\psi$ is the change in volumetric water content per unit change in pressure head. The elevation Z shown in Fig. 2 is vertically measured downward from a horizontal reference plane that passes through the origin on the ground surface.

A solution of Eq. 2 can be obtained with appropriate initial and boundary conditions. For an initial steady state with water table of d_Z in vertical direction shown in Fig. 3, the initial condition in terms of pressure head can be expressed as

$$\psi(Z,0) = (Z-d_Z)\cos^2\alpha \tag{3}$$

For a slope with depth of $d_{\mathrm{L}Z}$ measured in vertical direction, the boundary condition in terms of pressure head at impervious base can be written as

$$\frac{\partial\psi}{\partial Z}(d_{\mathrm{L}Z},t) = \cos^2\alpha \tag{4}$$

The ground surface of hillslope subject to a rainfall with intensity I_z yields

$$\frac{\partial\psi}{\partial Z}(0,t) = \begin{cases} -I_Z/K_{\mathrm{sat}}+\cos^2\alpha & t > T \\ \cos^2\alpha & t \leqslant T \end{cases}, \tag{5}$$

where T is the rainfall duration. The constraint of $I_Z/K_{\mathrm{sat}} \leq 1$ must be satisfied in Eq. 5. In other words, the rainfall totally infiltrates into the soil if the rainfall intensity is less than or equal to the saturated hydraulic conductivity. However, when the rainfall intensity exceeds the saturated hydraulic conductivity, the infiltration rate is identical to the saturated hydraulic conductivity. The surplus rainfall, the difference between the rainfall intensity and saturated hydraulic conductivity, runs off as overland flow. The solution of the initial boundary value problem posed by Eqs. 2, 3, 4, 5 is analytically obtained by Iverson (2000) and Baum (2002). In order to avoid the unrealistically high pressure heads, an additional physical limitation of pressure heads is given by

$$\psi(Z,t) \leq Z\cos^2\alpha \tag{6}$$

Equation 6, i.e., the so-called beta-line correction, shows that the simulated pressure heads under downward gravity-driven flow cannot exceed those which would result from the water table at ground surface.

Once the pressure heads ψ (Z,t) are obtained from the hydrological modeling mentioned above, the hillslope failure potential can be estimated using the infinite slope stability analysis. The infinite slope stability analysis is a preferred tool to evaluate landslides due to its simplicity and practicability (Montgomery and

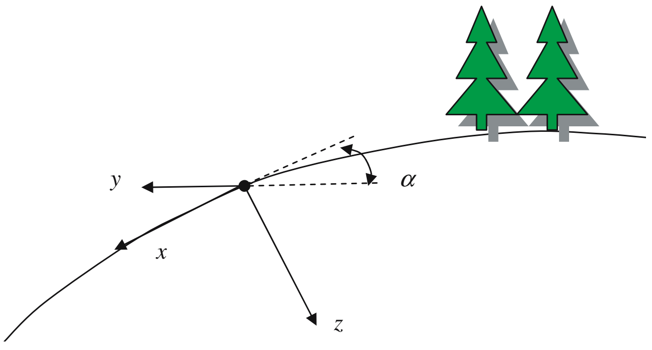

Fig. 1 Definition of the local rectangular Cartesian coordinate system

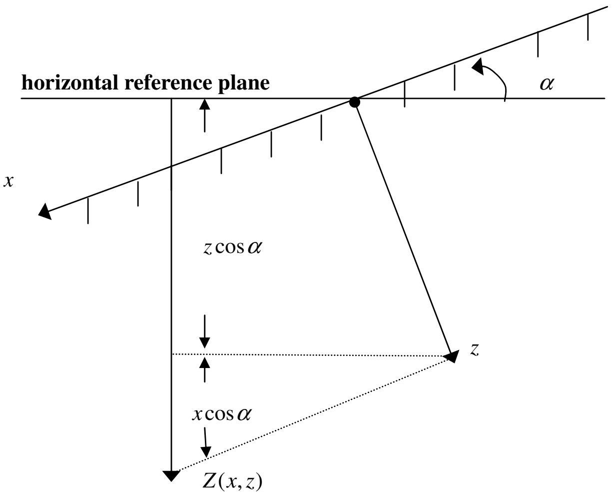

Fig. 2 Definition of the vertical coordinate $Z = x\sin\alpha + z\cos\alpha$

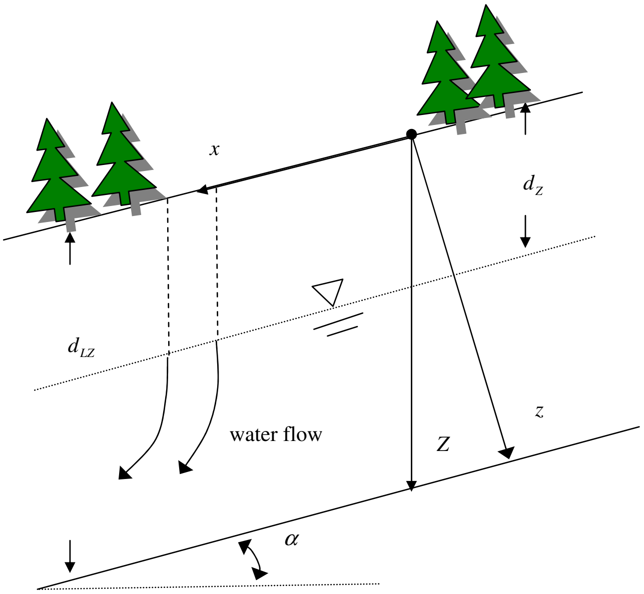

Fig. 3 Schematic illustration of the finite slope stability analysis integrated with hydrological modeling

Dietrich 1994; Wu and Slide 1995; Borga et al. 1998; Iverson 2000; Morrissey et al. 2001; Crosta and Frattini 2003; Collins and Znidarcic 2004). This concept is generally valid for the case of landside with a small depth compared to its length and width. This assumption is also compatible with that used to develop hydrological modeling of hillslope shown in Eq. 2. A hillslope failure at a certain depth Z occurs when the acting stress equals the resisting stress due to friction and cohesion. In other words, failure happens at a certain depth Z with satisfying

$$\mathrm{FS} = F_\mathrm{f} + F_\mathrm{w} + F_\mathrm{c} = 1, \tag{7}$$

where the dimensionless value FS is so-called safety factor. The gravity performing term F_f, the water pressure performing term F_w, and the cohesion performing term F_c in the safety factor can be expressed as

$$F_\mathrm{f} = \frac{\tan\varphi}{\tan\alpha} \tag{8a}$$

$$F_\mathrm{w} = \frac{-\psi(Z,t)\gamma_\mathrm{w}\tan\varphi}{\gamma_\mathrm{sat} Z\sin\alpha\cos\alpha} \tag{8b}$$

$$F_\mathrm{c} = \frac{c}{\gamma_\mathrm{sat} Z\sin\alpha\cos\alpha}, \tag{9}$$

where φ is the soil friction angle; c denotes the soil cohesion; γ_w and γ_sat represent the unit weights of water and saturated soil, respectively.

The above hydrological modeling and landslide modeling are developed based on Iverson (2000) and Baum et al.'s framework (2002). It must be noticed that the initial condition of wet soil in Iverson's model satisfies the most prevalent landslide triggered by rainfall infiltration. Owing to the fact that the linear diffusion equation rather than the highly nonlinear Richards' equation is employed, the relation between the hydraulic conductivity and the pressure head is not needed for hydrological modeling of hillslope. In addition, the linear diffusion equation can be easily and efficiently solved in comparison with the nonlinear Richards' equation. Therefore, the Iverson's model is simpler and more practical than the Richards' equation integrated with the infinite slope stability analysis for rainfall-triggered shallow landside modeling (Collins and Znidarcic 2004).

The proposed rainfall-triggered shallow landslide model

Although Iverson's model is simple and practical, the assumption of constant infiltration capacity, even together with the beta-line correction for hydrological modeling and landslide modeling may still not be realistic to the real problems. A further examination as compared with the consideration of general infiltration process may be needed. The modified Iverson's model taking general infiltration process into account is developed herein to perform this examination. For considering general infiltration process in Iverson's hydrological modeling, the boundary condition at ground surface of hillslope shown in Eq. 5 needs to be modified as (Hsu et al. 2002; Wallach et al. 1997)

$$\frac{\partial\psi}{\partial Z}(0,t) = \frac{-I_Z}{K_\mathrm{sat}} + \cos^2\alpha \quad \text{if} \quad \psi(0,t) \le 0 \text{ and } t<T \tag{10}$$

$$\psi(0,t) = 0 \quad \text{if} \quad \psi(0,t) > 0 \text{ and } t<T \tag{11}$$

$$\frac{\partial\psi}{\partial Z}(0,t) = \cos^2\alpha \quad \text{if} \quad t > T. \tag{12}$$

The rainfall with intensity I_Z entirely infiltrates, that is, the ponding does not happen, when the calculated pressure head at ground surface of hillslope $\psi\,(0,t)$ from hydrological modeling is less than or equal to zero during the period of rain. In this case, the infiltration rate which is identical to the rainfall intensity is used as flux-type boundary condition at ground surface shown in Eq. 10. However, when the ponding occurs, the pressure-head-type boundary condition shown in Eq. 11 instead of the flux-type one is applied due to the unknown infiltration rate. Neglecting the water depth of overland flow, $\psi\,(0,t) = 0$ is set as boundary condition at ground surface of hillslope for hydrological modeling when the ponding happens.

For the modified Iverson's model, the hydrological modeling with considering general infiltration process shown in Eqs. 2, 3, 4 and 10, 11, 12 is a nonlinear problem. The Crank-Nicholson Galerkin finite-element method (Gersho and Sani 1998; Tsai et al. 2002) together with an iterative solution procedure shown in Fig. 4 is applied to solve this problem without difficulty. The pressure head at ground surface of hillslope $\psi\ (0,t)$ is first obtained by assuming that the infiltration rate equals the rainfall intensity shown in (10). If $\psi\ (0,t)$ is less than or equal to zero, that is, the ponding does not happen, the calculated results are accepted. The computation moves forward to the next time step. If the calculated $\psi\ (0,t)$ is greater than zero, that is, the ponding occurs, $\psi\ (0,t)=0$ is used as boundary condition to recalculate once more for the same time step. In the modified Iverson's model, soil failure potential can be evaluated by applying the infinite slope stability analysis shown in Eq. 9 together with the simulated pressure heads from hydrological modeling mentioned above. It must be noticed that when the ponding happens, the infiltration rate, which is less than the rainfall intensity, can be obtained from applying Darcy's law with the simulated pressure heads at ground surface of hillslope.

Demonstrations

Model verification

A case of hillslope subjected to a uniform rainfall is first used to verify the modified Iverson's model. The hillslope has slope angles of 17° and depth of 4 m. The initial water table is 2 m below the ground surface of hillslope. The following soil parameters based on Iverson (2000) are adopted: $\varphi = 25°$, $c = 4{,}000\ \mathrm{N/m^2}$, $\gamma_{sat} = 21{,}000\ \mathrm{N/m^3}$, $\gamma_w = 9{,}800\ \mathrm{N/m^3}$, $D_0 = 0.0004\ \mathrm{m^2/s}$, $K_{sat} = 10^{-5}\ \mathrm{m/s}$. The rainfall with intensity of 7.2 mm/h, i.e., $I_Z/K_{sat} = 0.2$, lasts for 12 h. $\Delta t = 10$ s and $\Delta Z = 0.8$ cm are used in this simulation. One can clearly see from Fig. 5 that the simulated pressure heads from the modified Iverson's model agree well with those from Iverson's model (Baum et al. 2002). The pressure heads continuously increase with time during the period of rain due to infiltration, and redistribute after the rain. The steady state is reached at 6 h after the end of the rainfall event. In addition, it can be found from Fig. 5 that the simulated pressure heads do not exceed the beta line at any time in this simulation. From the same simulated pressure heads, one can infer that the two models have identical soil failure potential.

In this case, the simulated pressure heads at ground surface of hillslope at any time from the modified Iverson's model are all less than zero. This outcome indicates that the rainfall entirely infiltrates into the soil, that is, the infiltrate rate is identical to the rainfall intensity. In other words, the infiltration capacity is

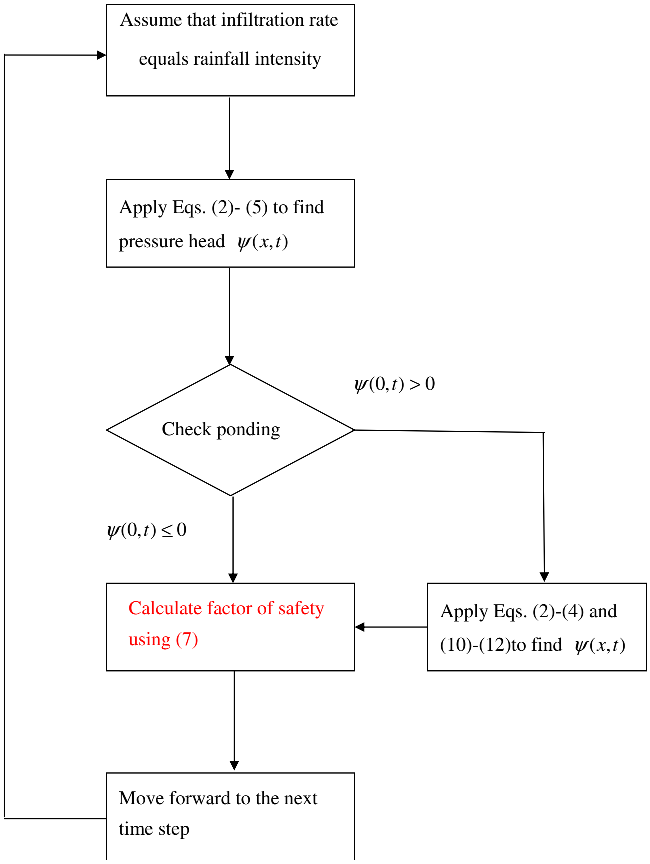

Fig. 4 Flow chart of hydrological modeling with considering general infiltration process

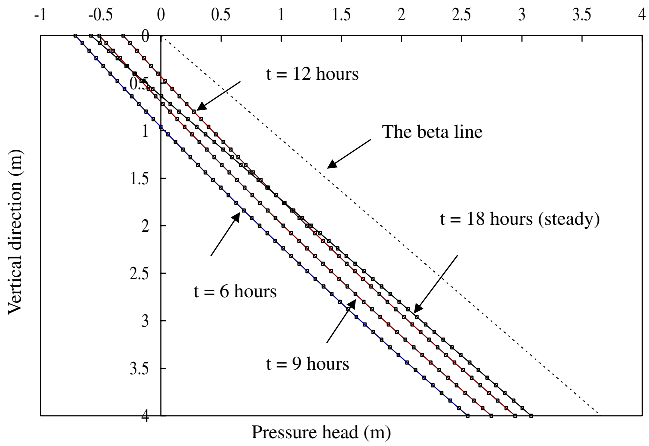

Fig. 5 Simulated pressure heads from the two models (*solid line* the Iverson's model, *hollow block* the modified Iverson's model)

always greater than the rainfall intensity during the period of rain, and the ponding does not happen. In addition, with the fact that the rainfall intensity is less than the saturated hydraulic conductivity, the infiltration rate from Iverson's model is also equal to the rainfall intensity during the period of rain. Thus, one could conclude that the two models have the same simulated pressure heads and soil failure potential when the ponding does not happen. In the following, we will further examine whether the two models still have the identical pressure heads and soil failure potential while a ponding-induced rainfall occurs.

Importance of general infiltration process

After the modified Iverson's model is verified, the same case studied above with a rainfall of $I_Z/K_{\mathrm{sat}} = 0.5$ is applied to examine the differences between Iverson's model and the modified Iverson's model for assessing shallow landslide triggered by rainfall infiltration. The simulated infiltration rates and pressure heads from the two models are shown in Figs. 6 and 7, respectively. The soil failure potential in terms of safety factor from the two models is displayed in Fig. 8.

It can be found from Fig. 6 that with the assumption that the infiltration capacity is identical to the saturated hydraulic conductivity, the simulated infiltration rate from Iverson's model is equal to the rainfall intensity during the period of rain because the rainfall intensity is less than the saturated hydraulic conductivity. However, for the modified Iverson's model, the ponding happens at about 7 h after the rainfall. The infiltration rate, the same as that from Iverson's model, is identical to the rainfall intensity before the ponding, whereas it is less than the rainfall intensity after the ponding, and continuously decreases to only about one fourth of the rainfall intensity at the end of the rainfall event.

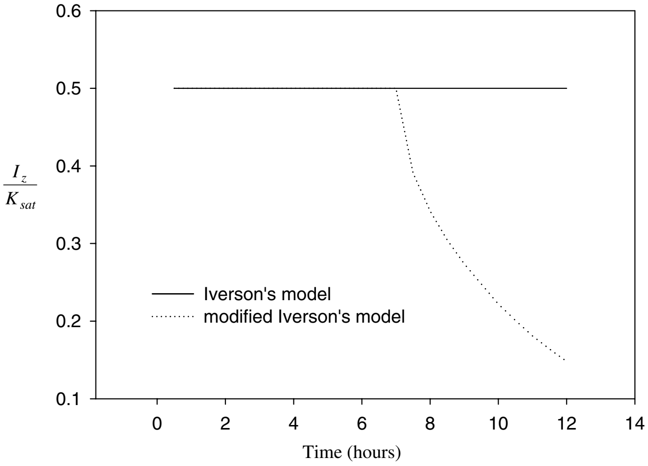

Fig. 6 Nondimensional infiltration rates from the two models

From the simulated infiltration rates mentioned above, one can see from Fig. 7 that the two models have the same simulated pressure heads at 4 h after the rainfall because the infiltration rates are identical. However, after the ponding happens, the two models do not have the identical pressure heads any more. The maximum difference in pressure heads between the two models occurs at ground surface of hillslope at the end of the rainfall event. The steady state is reached at 6 h after the end of the rainfall event. At the steady state, with greater cumulative rainfall infiltration, Iverson's model produces higher water table than the modified Iverson's model. In addition, one can also see from Fig. 7 that the unrealistically high pressure heads are induced from Iverson's model. For example, at the end of the rainfall event the pressure head at ground surface is 1 m, that is, the ponding water with 1 m depth occurs at ground surface. This outcome seems to contradict the fact that the rainfall totally infiltrates shown in Fig. 6. However, with considering general infiltration process, the modified Iverson's model does not have such unacceptable results. Therefore, one could conclude from the simulated infiltration rates and the pressure heads mentioned above that the unrealistically high pressure heads from Iverson's model is due to the overestimation of infiltration rate induced from assuming that the infiltration capacity is identical to the saturated hydraulic conductivity. The beta-line correction can be applied to avoid the drawback from Iverson's model. However, one can clearly find from Fig. 7 that the simulated pressure heads from Iverson's model with the beta-line correction are not identical to those from the modified Iverson's model. The modified Iverson's model always has less simulated pressure heads than Iverson's model with the beta-line correction. The outcome shows that for hydrological modeling of rainfall infiltration, the hypothetical constant infiltration capacity with the beta-line correction seems not equivalent to general infiltration process. From mentioned above, it can be expected that the large difference in simulated soil failure potential from the modified Iverson's model and Iverson's model with and without the beta-line correction can be obtained.

It can be found from Fig. 8 that because of the identical simulated pressure heads, the two models have the same soil failure potential at 4 h after the rainfall. However, with greater simulated pressure heads due to the overestimation of infiltration rate, Iverson's model has less safety factor than the modified Iverson's model after the ponding happens. In other words, Iverson's model is more likely to trigger soil failure as compared with the modified Iverson's model. For example, at 2 h after the end of the rainfall event, Iverson's model induces hillslope failure

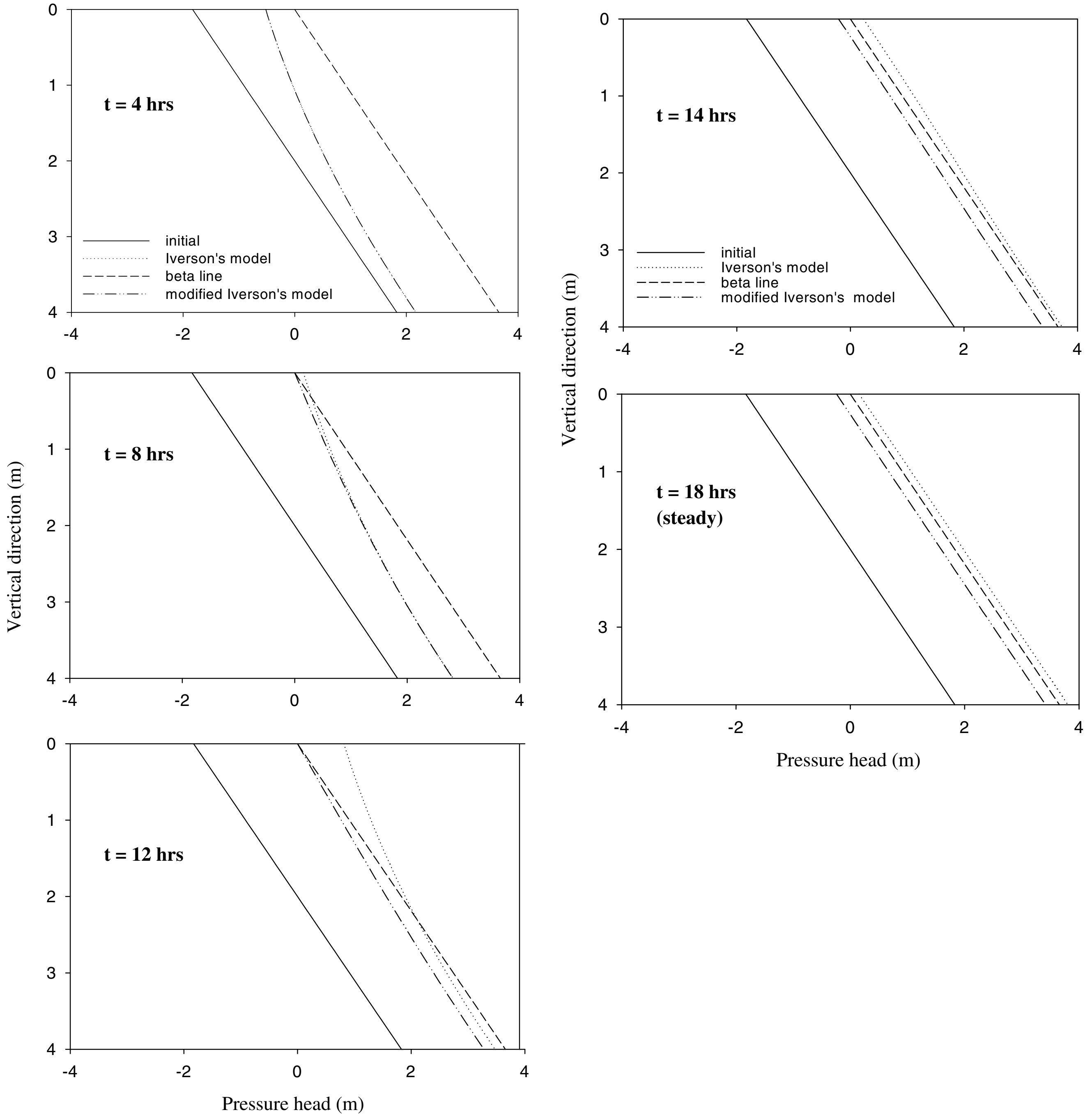

Fig. 7 Pressure head distribution along the vertical direction

since the safety factor is less than unity near the bottom of hillslope. However, the modified Iverson's model does not trigger hillslope failure in this rainfall event. In addition, one can also find from Fig. 8 that the application of the beta-line correction can largely decrease the overestimation of soil failure potential from the Iverson's model, but Iverson's model with the beta-line correction still has less safety factor than the modified Iverson's model. Although the beta-line correction is employed, the hillslope failure is still induced by Iverson's model at 2 h after the end of the rainfall event. Thus, one could conclude that as

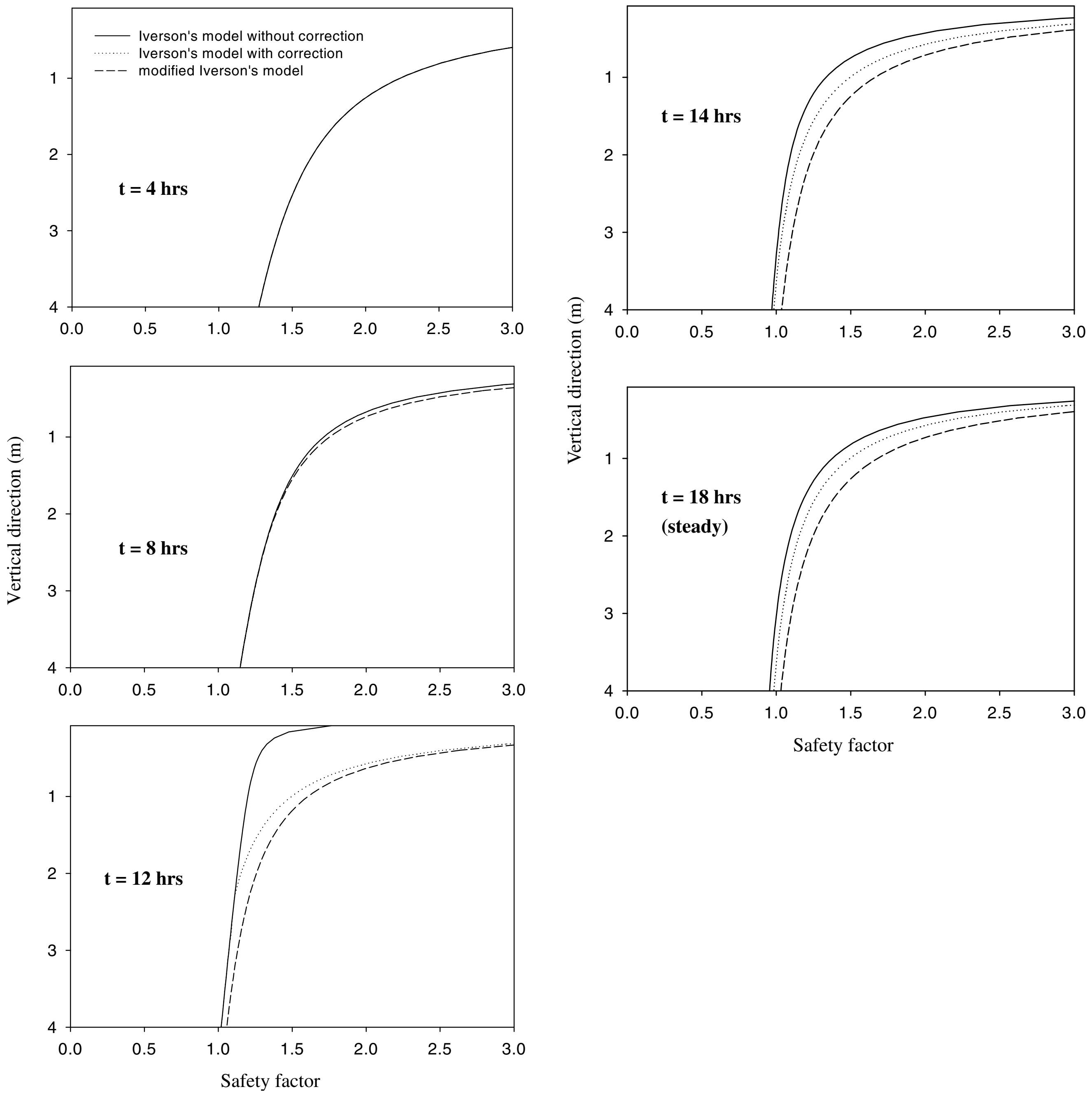

Fig. 8 Safety factor distribution along the vertical direction

compared with the modified Iverson's model, Iverson's model may still overestimate soil failure potential even if the beta-line correction is applied.

Conclusions

Rainfall is one of the major cause of landslide. Applying the infinite slope stability analysis integrated with hydrological modeling, a rainfall-triggered shallow landslide model was developed by Iverson (2000). In Iverson's model, one-dimensional linear diffusion equation instead of three-dimensional nonlinear Richards' equation was used for hydrological modeling of wet and shallow hillslope subjected to rainfall. In Iverson's model, for simply finding the analytical solution of pressure heads, the infiltration capacity is assumed to be identical to the saturated hydraulic conductivity. However, the assumption of constant infiltration capacity seems not consistent with general rainfall infiltration process in which the infiltration capacity varies with time during the period of rain, and the occurrence of ponding is strongly related to the variable infiltration capacity. In addition, the unrealistically high pressure heads could be induced from Iverson's model. The beta-line correction was applied to avoid this drawback.

In this study, the reason for the occurrence of unrealistically high pressure heads is investigated. The suitability of constant infiltration capacity in conjunction with the beta-line correction for assessing rainfall-triggered landslide is examined. The modified Iverson's model, based on amending the boundary condition at ground surface of hillslope in Iverson's model for considering general infiltration process, is developed to conduct this examination. If the ponding does not happen, the infiltration rate which is identical to the rainfall intensity is used as flux-type boundary condition at ground surface of hillslope. However, when the ponding occurs, the pressure-head-type boundary condition instead of flux-type one is used since the infiltration rate is unknown.

The results show that the occurrence of unrealistically high pressure heads from Iverson's model is because that the infiltration capacity is assumed to be identical to the saturated hydraulic conductivity which overestimates the infiltration rate. With considering general infiltration process in which the infiltration rate and the occurrence of ponding depend on the variable infiltration capacity, the modified Iverson's model does not have such unacceptable results. The application of the beta-line correction can avoid the unrealistically high pressure heads from Iverson's model, but Iverson's model with the beta-line correction still gives greater simulated pressure heads than the modified Iverson's model. In other words, despite the application of the beta-line correction, Iverson's model can overestimate soil failure potential as compared with the modified Iverson's model. One could conclude that for accurate assessment of rainfall-induced shallow landslide, the consideration of general infiltration process is needed to substitute the application of constant infiltration capacity together with the beta-line correction. Owing to the use of one-dimensional linear diffusion equation for hydrological modeling, the modified Iverson's model proposed herein, like Iverson's model, is simpler and more practical than the Richards' equation integrated with the infinite slope stability analysis for evaluating hillslope failure potential. In addition, it must be noted that the modified Iverson's model can not consider the soil heterogeneity due to strata parallel at the slope surface (Guadagno et al. 2003). By imposing interface matching conditions between strata, the modified Iverson's model can be applied to hydrological modeling and landslide modeling of heterogeneous hillslope in future work.

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