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Debris Flows Introduced in Landslide Deposits under Rainfall Conditions: The Case of Wenjiagou Gully

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Abstract: Debris flows often occur in landslide deposits during heavy rainstorms. Debris flows are initiated by surface water runoff and unsaturated seepage under rainfall conditions. A physical model based on an infinitely long, uniform and void-rich sediment layer was applied to analyze the triggering of debris-flow introduced in landslide deposits. To determine the initiation condition for rainfall-induced debris flows, we conducted a surface water runoff and saturated-unsaturated seepage numerical program to model rainfall infiltration and runoff on a slope. This program was combined with physical modeling and stability analysis to make certain the initiation condition for rainfall-introduced debris flows. Taking the landslide deposits at Wenjiagou gully as an example, the initiation conditions for debris flow were computed. The results show that increase height of surface-water runoff and the decrease of saturated sediment shear strength of are the main reasons for triggering debris-flows under heavy rainfall conditions. The debris-flow triggering is affected by the depth of surface-water runoff, the slope saturation and shear strength of the sediment.

Keywords: Debris flow; Rainfall; Surface-water runoff; Unsaturated seepage; Physical modeling; Numerical modeling

Introduction

Debris flow is a mass movement consisting of water, mud, and debris that are suddenly pushed ahead with a vanguard of huge boulders. Many debris-flow events have been reported from mountainous areas throughout the world (Varnes 1978; Kotarba 1997; Sassa et al. 1997). Debris flows usually travel at high velocities. They are among the most dangerous types of geological disasters, causing significant losses of life and property (Takahashi et al. 1995; Cui et al. 2009), and may contribute a large fraction of long-term sediment yields from mountainous areas like southwestern China (Lu et al. 2011). After the Wenchuan earthquake, many loose landslide deposits accumulated on the slopes, and the probability of occurrence increased sharply. Furthermore, this situation will continue for a long time (Cui et al. 2011).

Debris-flow events occur after intense rainstorms in the period of prolonged rainfall (Sassa 1985; Jakob et al. 2005; Takahashi 2007). Much research has focused on the relationship of rainfall to debris flows, but less attention has been paid to the evolution of mechanical properties of sediment materials (Takahashi 1978; Fiorillo and Wilson 2004). To date, engineers and researchers have applied field and indoor monitoring data to establish the relationship between rainfall conditions and debris flows (Takahashi 1981; Cui et al. 2011). The initiation of a debris flow is influenced by several factors, such as the structural and mechanical properties of sediment material, rainfall conditions, topography and geomorphology (Pierson 1981; Kotarba 1997; Sassa et al. 1997; Iverson et al. 2000). Modeling the initiation and motion of debris flows is of both practical and

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scientific interest (Blijenberg 2007; Coe et al. 2008). Physically-based dynamic models have considered several key factors, such as rainfall intensity and duration, hydrological response and geotechnical properties of the sediment material (Iverson and Lahusen 1989; Anderson and Sitar 1995; Chen 2006; Zhang et al. 2011). An artificial, rainfall-induced debris flow studied by Crosta et al. (2003) showed that pore-water pressure decreases after an increase in the early stages of deformation.

The key issue for debris-flow initiation is to understand how such a change in the mechanical behavior of sediment material occurs (Bovis and Jakob 1999; Hungr et al. 2007). Sufficient rainfall intensity is a necessary condition for the sediment material to be saturated and for intense surface runoff to be formed on the slope. Shallow landslides can then occur and be transformed to debris flows by combination with the water flow. The significant increase in debris-flow frequency following the Wenchuan earthquake prompted the present study of the initiation conditions for flow of the loose landslide deposits. Decreasing strength parameters induced by seepage and large volumes of surface runoff can trigger debris flows in landslide deposits. The triggering mechanism is very complicated under rainfall conditions. In the present research, the Wenjiagou gully was selected as a case study. A physical model and numerical simulation were applied to elucidate the initiation of a debris flow in landslide deposits under rainfall conditions.

1 Landslide Deposits in the Wenjiagou Gully

On May 12, 2008, a large debris avalanche was triggered by the Wenchuan earthquake in the Wenjiagou gully, Mianzhu city, Sichuan province, China. The Wenjiagou gully is a typical post-earthquake debris-flow gully, and at least five disaster events occurred there between September 24, 2008, and September 18, 2010.

1.1 Study area

The Wenjiagou gully is located in Qingping town, Mianzhu city, Sichuan province, on the left bank of the Mianyuan River. Qingping town lies 36 km from Mianzhu city. It is very close to the Wenjiagou gully, and disasters caused by the geological hazards there have had huge impacts on the local residents. The height of the mountain is about 300-1,600 m, and the mountain valley is deeply cut by river flow. The inclination of the hill slope is about 30-70°. Before the Wenchuan earthquake, the mountain was covered by rich vegetation, geological disasters rarely occurred in the region, and there were many villages in the foothills. The channel of the Wenjiagou gully was smooth and covered by vegetation, the hill slope was stable, and the water flow dropped smoothly from the mountain to the Mianyuan River.

However, on May 12, 2008, the Wenchuan earthquake struck in Sichuan province, triggering many landslides. The strong shaking of the ground and its duration caused a large debris avalanche. The beautiful landscape was seriously destroyed, and abundant landslide deposits accumulated in the lower gully, providing a rich source of material for subsequent debris flows.

1.2 Loose landslide deposits after the Wenchuan earthquake

The Wenjiagou gully is very close (about 36 km) to the Longmenshan earthquake fault. The main rock masses of the hill slope are weak weathered limestone and dolomitic limestone. During the Wenchuan earthquake, the rock masses of the slope were strongly shaken for a long time by the seismic loading, resulting in the failure of the top of the slope along a weak rock layer and a landslide ensued (Figure 1).

In the initial stage of the landslide, the landslide type was a rock slide. As a consequence of the large slope inclination, the velocity of the sliding rock increased in a short time, and a projectile phenomenon occurred when the sliding rock mass reached a steep cliff; the flight distance was about 690 m (Figure 1c). The rock mass then crashed into the mountain or ground, the rock size was extensively broken down, and the landslide became a debris avalanche. Based on theoretical analysis, the maximum speed of the landslide was about 100 m/s, and the Wenjiagou landslide can be categorized as a high-speed landslide.

The initial landslide volume was about 2.75×10^7 m^3. The maximum landslide distances of

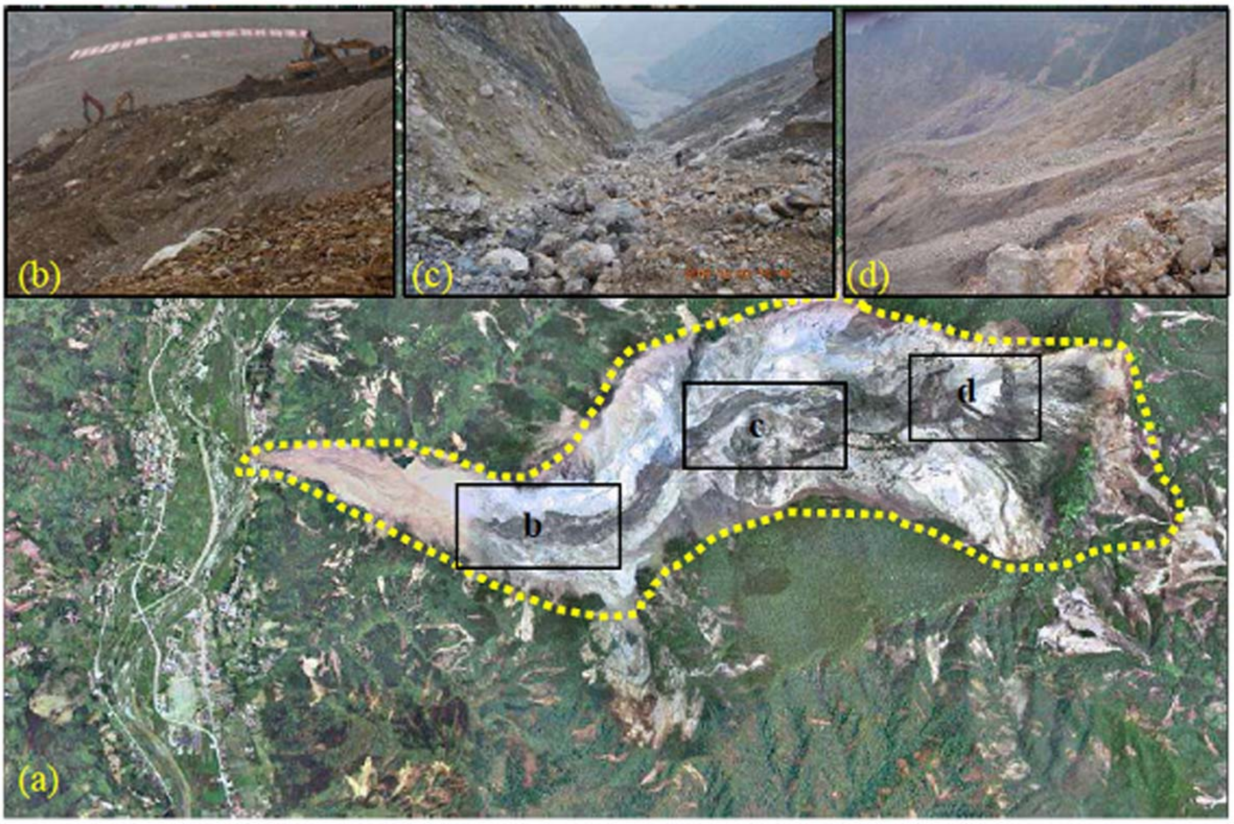


Figure 1 The Wenjiagou landslide triggered by the Wenchuan earthquake: (a) remote image of the Wenjiagou landslide; (b) landslide deposits on the lower slope; (c) landslide deposits on the middle slope

horizontal and vertical movement were about 4,170 m and 1,360 m, respectively. During the high-speed landslide, shallow geo-materials along the landslide path were entrained and contributed significantly to the total landslide deposit. Figure 2 shows the geological condition of the Wenjiagou gully after the Wenchuan earthquake. The total volume of the landslide deposit is about 7.26×10^7 m^3, and the maximum deposit thickness is about 150 m (Figure 2a).

After the Wenchuan earthquake, huge volumes of landslide deposits were generated at the Wenjiagou gully (Figures 2a and 2b), especially at an elevation of 1,300 m. The inclination of the landslide deposits is very large, and the material can easily fail under rainfall conditions. As shown in Figure 2c, the debris flow is generated at the landslide deposit zone, and the surface water is collected at the initiation zone.

As shown in Table 1, static volume is the total volume of landslide deposits after the landslide triggered by the Wenchuan earthquake, and dynamic volume is the estimated volume of landslide deposits available for the initiation of debris flow under rainfall conditions. During a rainstorm in the Wenjiagou gully, there would first be failure of the landslide deposit, and then there would be downward transport by the surface water runoff, causing a large debris flow.

Table 1 Landslide deposit volume in the Wenjiagou gully, Sichuan Province, China

Location	Static volume (10^4 m^3)	Dynamic volume (10^4 m^3)
Upper gully	2,260	0
Middle gully	2,225	1,330
Lower gully	2,775	1,024

1.3 Mechanical properties of landslide deposits

Based on the field investigation, the landslide deposit is a mixture of broken limestone, clay and silty clay, and its composition is very complex (Figure 3a). Particles larger than 200 mm make up 31.4% of the total, those between 20 mm and 200

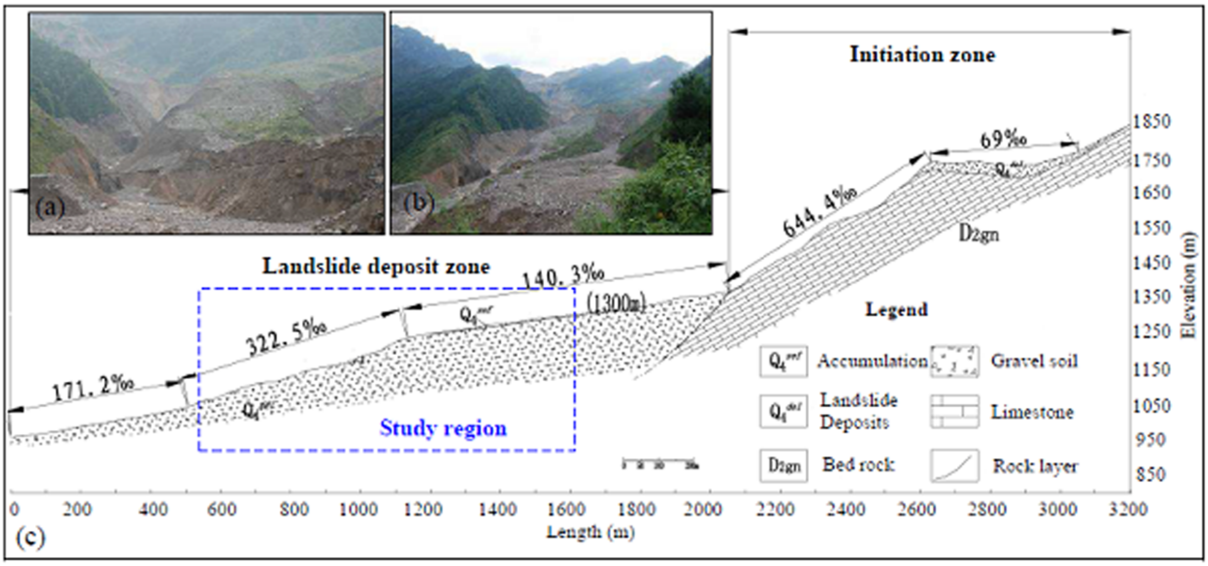
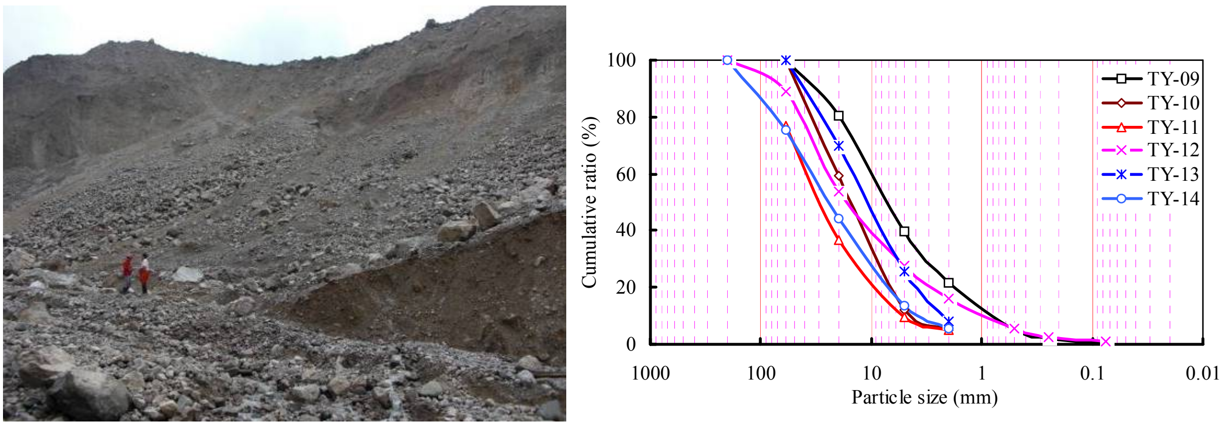


Figure 2 Geological condition of the Wenjiagou gully after the Wenchuan earthquake: (a) landslide deposits at the lower slope; (b) view of the whole Wenjiagou gully and (c) main cross section of the Wenjiagou gully.



(a) (b)

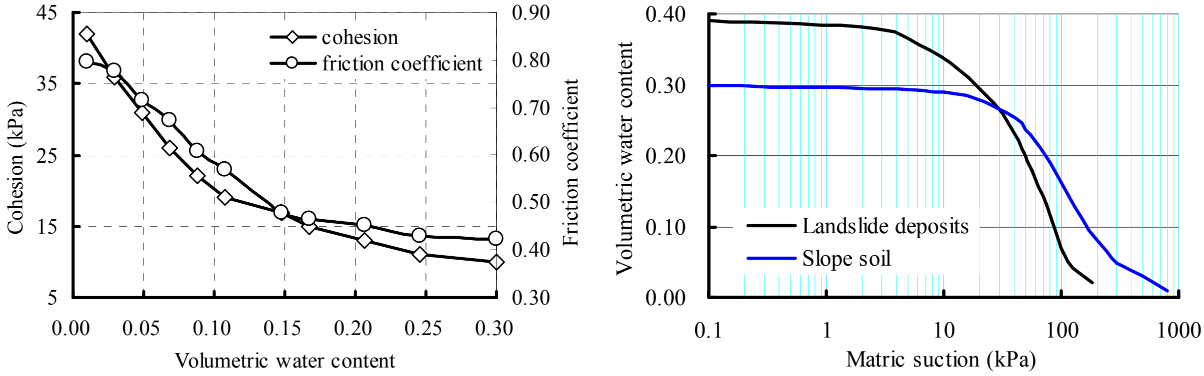
Figure 3 Physical characteristics of landslide deposits in the Wenjiagou gully: (a) field investigation of the structural characteristics of the landslide deposits; (b) statistical results of particle-size distribution of the landslide deposits (TY-09 is one set of field tests of the landslide deposits)

mm 35.4%, and those smaller than 20 mm 33.2%. Figure 3b shows the particle-size distribution of the Wenjiagou landslide deposits (particles of size larger than 200 mm were removed before the tests).

As shown in Figure 3b, six sets of tests were carried out for the particle-size distribution of the landslide deposits. Particles larger than 20 mm make up 42.6% of the total, those between 0.075 and 20 mm 56.45%, and those smaller than 0.075 mm 0.95%.

During rainfall, the mechanical and hydraulic response of landslide deposits is very complex. It is influenced by the structure and material composition of the soil, and so several field tests and indoor tests were carried out to determine them. Here we select typical test results for numerical simulation. Figure 4a shows typical relationships between shear-strength parameters of landslide deposits and volumetric water content obtained from indoor tests. Figure 4b shows typical soil-water characteristic curves of landslide deposits and slope soil.

The shear parameters were computed from the indoor test results for the total stress-strain curves. The test samples were reconstructed according to the particle-size distribution of the landslide deposit and a dry density of about 1.80-1.90 g/cm^3.



(a) (b)

Figure 4 Mechanical characteristics of landslide deposits: (a) relationship between shear-strength parameters of landslide deposits and volumetric water content; (b) soil-water characteristic curve of landslide deposits and comparison of slope soil (fitting curve)

The cylindrical specimen had a height of 600 mm and a diameter of 300 mm, and the maximum particle size was 60 mm. The consolidated, undrained, triaxial compression test was used. The relationship between shear-strength parameters of the landslide deposits and volumetric water content is shown in Figure 4a. The cohesion and friction coefficient decreased with increasing volumetric water content. Figure 4b shows the soil-water characteristic curve of the landslide deposits and slope soil (fitting result based on field-test data). The matric suction of the landslide deposits decreased sharply with increasing volumetric water content, and there were different characteristics at different locations along the gully. Here the fitting curve for the middle of the gully was selected for numerical simulation. There is an obvious difference in soil-water characteristics between the landslide deposits and the slope soil.

2 Initiation Model of Debris Flow

Debris flows can be triggered in many ways. Slope failure will happen under rainfall conditions, and landslides can be transformed into debris flows by dilatancy or liquefaction during movement. The effect of surface-water runoff is a key factor for the formation of a debris flow. Usually an increase of pore pressures caused by a supply of water to the material provides the force for triggering movement, and the surface-water runoff provides the force for debris-flow formation.

2.1 Physical model

Takahashi (1978, 1981) described the spontaneous triggering of a debris flow by dilatancy when a water film of a certain thickness appears at the surface of a saturated body of debris in a channel (Takahashi model). This model was based on an indoor test with a shallow channel. It presumed the soil to be saturated and failure to occur at the bottom of a channel with a plane surface. In fact, slope failure does not usually happen in a saturation region with a plane surface (Coe et al. 2008; Zhang et al. 2011). Here we present a theoretical model to solve the debris-flow initiation problem (Figure 5).

As shown in Figure 5a, the failure surface of layered landslide deposits (which can be regarded as one type of sediment) is assumed to be a circular surface, not a plane surface. The wetting front is the boundary between the saturated zone and the unsaturated zone; h_0 is the height of surface-water runoff; β is the slope inclination; y_f is the depth of the saturated surface; and y_s is the depth of the failure surface. The failure surface can be divided into several blocks (the number of blocks is n); each block is vertical to the bottom of the sediment. With continued rainfall, the wetting front moves deeper into the sediment layer. The initiation of a debris flow is determined by the safety factor of the failure surface, which is computed from the shear stress and shear resistance:

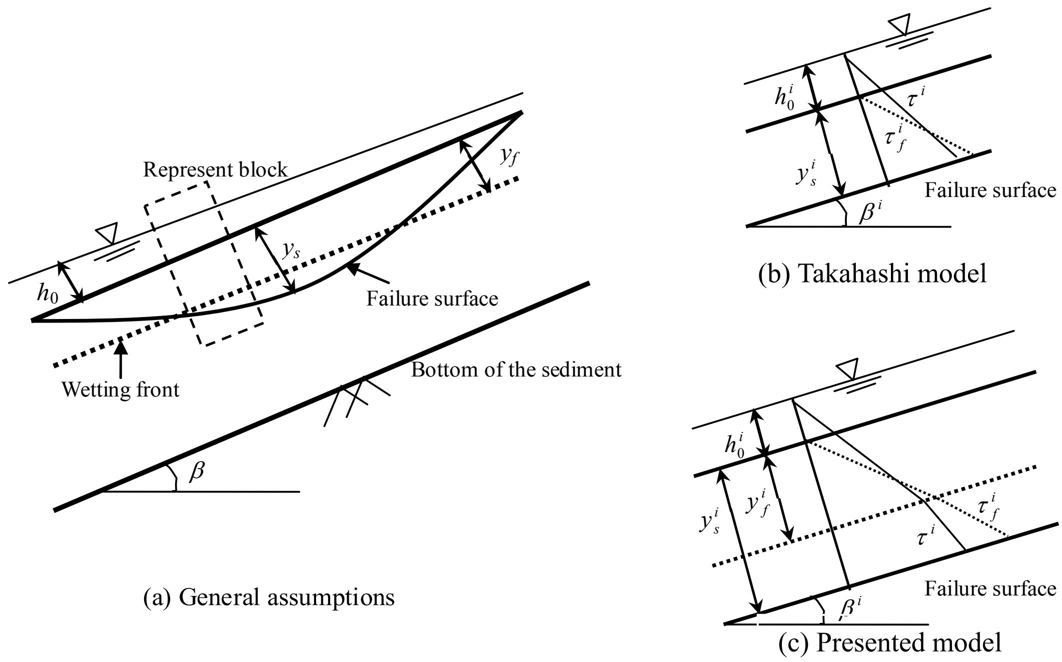


Figure 5 Theoretical model for the initiation of debris flow in landslide deposits: (a) general assumptions; (b) Takahashi model and (c) presented model for one representative block

$$F_s = \sum_{i=1}^{n} \tau_f^i \Big/ \sum_{i=1}^{n} \tau^i \tag{1}$$

where F_s is the safety factor of the failure surface; i is one representative block; τ_f^i is the shear resistance of block i; and τ^i is the shear stress of block i.

As shown in Equation (1), if the safety factor F_s is less than 1.0, a debris flow is triggered, and if not, no debris flow occurs. This is a simple model for formation of a debris flow; the failure of landslide deposits can generate a debris flow combined with surface-water runoff under rainfall conditions. In fact, the triggering mechanism of debris flows is very complex; failure of landslide deposits does not generate debris flow under rainfall conditions all the time.

If the failure surface of block i is in the saturated zone (see Figure 5b), the shear stress and shear resistance can be computed as in the Takahashi model:

$$\tau^i = \left(c_*\left(\rho_s - \rho_f\right)y_s^i + \rho_f\left(y_s^i + h_0^i\right)\right)g \sin\beta^i \tag{2}$$

$$\tau_f^i = c_*\left(\rho_s - \rho_f\right)y_s^i g \cos\beta^i \tan\varphi_s^i + c^i \tag{3}$$

where ρ_s is the solids density; ρ_f is the fluid density; g is the gravity acceleration; β^i is the slope inclination; h_0^i is the height of surface-water runoff; y_s^i is the depth of the failure surface; φ_s^i is the effective static angle of internal friction; c^i is the cohesion of solids; and c_* is the volumetric solids content of static, coarse debris, which can be determined as follows:

$$c_* = 1 - \theta_s \tag{4}$$

where θ_s is the porosity of coarse debris, which is equal to the maximum volumetric water content (landslide deposits fully saturated).

If the failure surface of block i is below the saturated zone (see Figure 5c), the shear stress and shear resistance can be computed as follows:

$$\tau^i = \left(c_*\left(\rho_s - \rho_f\right)y_f^i + \rho_f\left(y_f^i + h_0^i\right) + \rho_s\left(y_s^i - y_f^i\right)\right)g \sin\beta^i \tag{5}$$

$$\tau_f^i = \left(c_*\left(\rho_s - \rho_f\right)y_f^i + \rho_s\left(y_s^i - y_f^i\right)\right)g \cos\beta^i \tan\varphi_s^i + c^i \tag{6}$$

where y_f^i is the depth of the wetting-front surface.

During rainfall, the surface-water runoff and saturated depth vary with time and rainfall intensity. The shear-strength parameters of solids and the water conditions (height of surface-water runoff and depth of wetting front) are very important in determining the initiation of a debris flow. In this research we have adopted a surface-water-runoff and saturated-unsaturated-seepage numerical program to model the rainfall infiltration and runoff on a slope. When this is combined with the previously presented physical model, the initiation of debris flows in landslide deposits can be determined.

2.2 Impact of volumetric water content and slope inclination

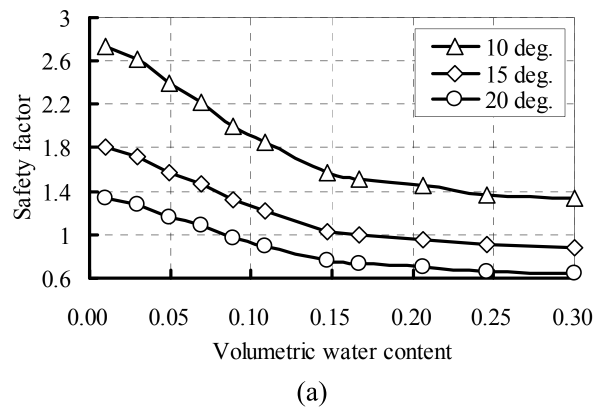
Firstly, we adopted the Takahashi model to study the influence of the volumetric water content on the initiation of a debris flow. The simulation results in this section are based on Equations (1), (2) and (3). The debris flow is initiated in a layer of landslide deposits, the failure surface is parallel to the slope surface, and the whole initiation zone is saturated (see Figure 5b). However, the shear-strength parameters of the landslide deposits are varied with the volumetric water content (see Figure 4a).

The computation parameters are: $c_* = 0.7$; $y_s^i = 3.0$ m; $h_0 = 0.1$ m; $\rho_s = 2{,}600$ kg/m^3; $\rho_f = 1{,}000$ kg/m^3; and $\theta_s = 0.3$ (these parameters are assumed the same in all the scenarios). There are three slope inclinations: 10°, 15° and 20°. At the beginning, the landslide deposits are unsaturated. During the rainfall process, the volumetric water content of the landslide deposits increases, and the cohesion and friction angle of solids decrease gradually. The decreased mechanical parameters and increased volumetric water content are the key factors for the debris-flow formation. Other conditions which impact the safety factor of the debris flow initiation zone are not considered here. The computed results of the safety factor of the debris flow initiation zone are shown in Figure 6.

As shown in Figure 6a, if the slope inclination is 20°, the initiation condition is a volumetric water content of 0.085; if the slope inclination is 15°, the initiation condition of debris flow is a volumetric water content of 0.165. However, if the slope inclination is 10°, even if the whole landslide deposit layer is fully saturated, a debris flow is not triggered (the flow velocity of surface-water runoff is not considered in the physical model). The computed results show that, with continuous rainfall, the increasing volumetric water content and decreasing shear-strength parameters of the landslide deposits lead to the initiation of a debris flow.

Secondly, we adopted the Takahashi model to study the influence of slope inclination on debris-flow initiation. The computation parameters are: $c_* = 0.7$; $y_s^i = 2.0$ m; $h_0 = 0.06$ m; $\rho_s = 2{,}600$ kg/m^3; $\rho_f = 1{,}000$ kg/m^3; and $\theta_s = 0.3$ (these parameters are assumed the same in all the scenarios). The shear parameters of landslide deposits are considered in different invariants. There are four cases of shear parameters: cases 1, 2, 3 and 4 of shear parameters when the volumetric water contents are 0.05, 0.09, 0.15 and 0.21, respectively (Figure 4a). Figure 6b shows the relationship between the safety factor of the debris flow initiation zone and the slope inclination.

As shown in Figure 6b, the safety factor of the debris-flow initiation zone decreases in a nonlinear relationship with increasing slope inclination. When the slope inclination is larger than about 21°, a debris flow easily occurs under rainfall conditions, so the triggering of a debris flow is clearly influenced by topography. Computation results show that the slope inclination for initiation of a



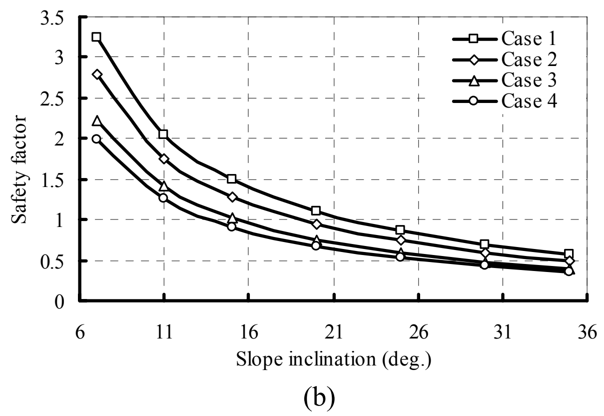


Figure 6 Safety factor of debris flow initiation zone during rainfall: (a) impact of volumetric water content; (b) impact of slope inclination

debris flow decreases with increasing volumetric water content.

3 Debris Flow Initiation of Landslide Deposits under Rainfall Conditions

In this section, rainfall infiltration and runoff on a slope are simulated by a surface-water-runoff and saturated-unsaturated-seepage numerical program. The simulation is then combined with the physical model for debris-flow initiation, and the initiation condition for debris flow of landslide deposits in the Wenjiagou gully under rainfall conditions is determined.

The analysis procedure for the debris flow initiation of landslide deposits under rainfall conditions are as follow: (1) to simulate the infiltration process and runoff process to get the surface runoff height and the volumetric water content profile; (2) to determine the friction angle and cohesion under different volumetric water content; (3) to search potential slip surfaces using limit equilibrium method; (4) to apply Equations (1)-(6) to compute the safety factor of debris flow initiation zone in different time.

3.1 Numerical method for rainfall infiltration and runoff

During rainfall on a slope, the water can be divided into two parts: surface-water runoff and slope infiltration. The pore pressure and mechanical parameters of the landslide deposits will be influenced by the slope infiltration, and the debris-flow triggering will be influenced by the surface-water runoff. For the simulation of surface-water runoff, the Saint Venant theory is adopted:

$$\frac{\partial h}{\partial t}+\frac{\partial vh}{\partial x}=q_e \quad (7a)$$

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}+g\frac{\partial h}{\partial x}=g\left(S_o-S_f\right)-\frac{v}{h}q_e \quad (7b)$$

where q_e is the net rain rate; g is the gravity acceleration; S_o is the slope ratio; S_f is the slope ratio of flow friction; x is the slope length; t is the time; v is the flow velocity; and h is the flow depth.

The Saint Venant theory is widely used, but it is only applicable to gentle slopes (slope inclinations less then 3°), so a modified control equation is applied to simulate surface-water runoff:

$$\frac{\partial h}{\partial t}+\frac{\partial vh}{\partial x}=I(t)\cos\beta-f \quad (8a)$$

$$q=\frac{1}{n}h^{5/3}\sin\beta^{1/2} \quad (8b)$$

where q is the discharge per unit width; β is the slope inclination; $I(t)$ is the rainfall intensity; f is the infiltration rate; and n is the roughness coefficient of the slope.

For the simulation of slope infiltration, a saturated-unsaturated-seepage equation based on Darcy's law is adopted (two-dimensional problem):

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[k_x(\theta)\frac{\partial\phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y(\theta)\frac{\partial\phi}{\partial y}\right] \quad (9)$$

where ϕ is the total water head; k_x and k_y are the permeability coefficients in the x and y directions; and θ is the volumetric water content.

For saturated soil, the volumetric water content is a constant, and then the constitutive equation is as follows:

$$\frac{\partial}{\partial x}\left[k_x(\theta_s)\frac{\partial\phi}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y(\theta_s)\frac{\partial\phi}{\partial y}\right]=0 \quad (10)$$

where θ_s is the porosity of coarse debris, the maximum volumetric water content when the soil is fully saturated, and k_x and k_y are keep constant.

For unsaturated soil, the volumetric water content is determined by the soil-water characteristic curve, and then the constitutive equation is as follows:

$$\frac{\partial}{\partial x}\left[k_x(h)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[k_y(h)\frac{\partial h}{\partial y}\right]=C\frac{\partial h}{\partial t} \quad (11)$$

where C is the capacity for water retention.

The coupling of surface-water runoff and slope infiltration is implemented by the Galerkin weighted residual method and finite element method (FEM). The infiltration rate (f) in Equation (8a) is the water input for saturated-unsaturated seepage simulation, so that the coupling of surface-water runoff and slope infiltration can be achieved.

3.2 Simulated rainfall results

Figure 7 shows the numerical model for the Wenjiagou landslide-deposit slope (Figure 2c). Because of the large size of this slope, here we reduce the size by a factor of 10 (Figure 7a).

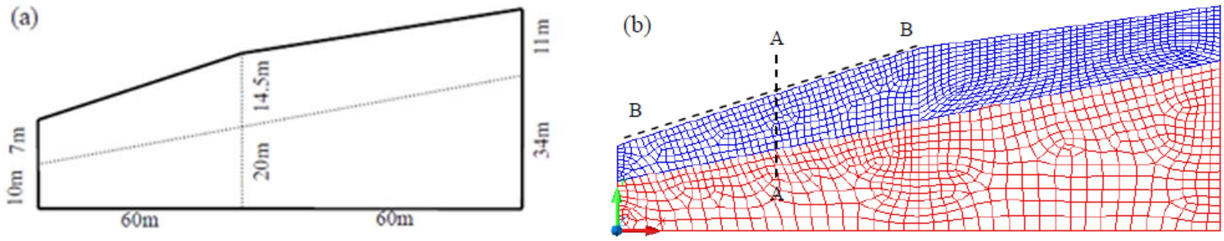


Figure 7 Numerical model for the Wenjiagou landslide-deposit slope: (a) slope geometry; (b) FEM mesh

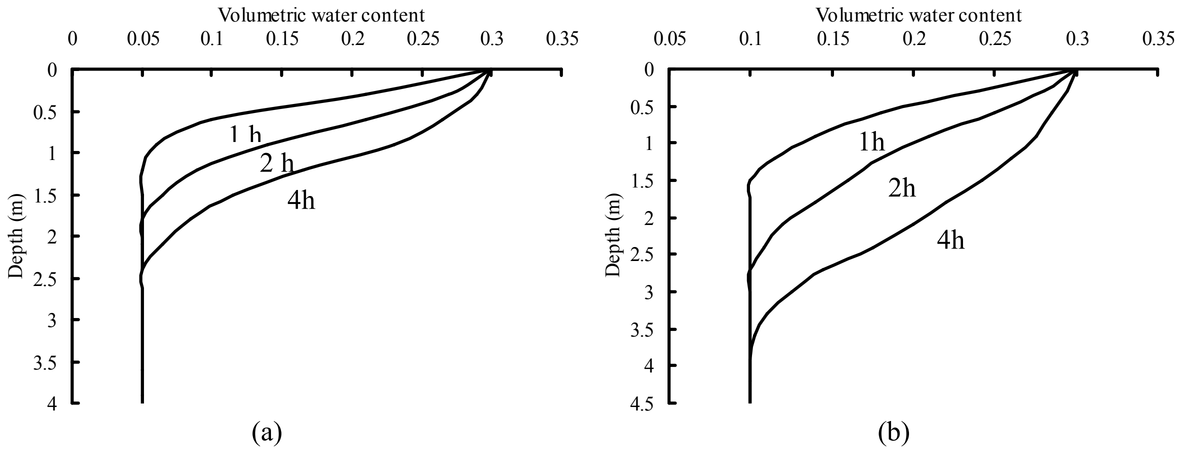


Figure 8 Evolution of the soil volumetric water content versus depth at section A-A: (a) for initial volumetric water content of 0.05; (b) for initial volumetric water content of 0.10

As shown in Figure 7a, the model length is 120 m, the left height is 17 m, and the right height is 45 m. There are two layers in the model: the upper layer is landslide deposits, and the lower layer is bedrock. As shown in Figure 7b, the model has 1,741 nodes and 1,650 elements. The right and bottom boundaries are impermeable, and the left and upper boundaries are permeable. The permeability coefficient of the bedrock is 10^{-5} cm/s, and that of the landslide deposit is 10^{-3} cm/s. The roughness coefficient of the slope is assumed to be a constant value of 0.42. There are two monitoring sections: the A-A section is used to analyze the evolution of slope infiltration, and the B-B section is used to analyze the evolution of surface-water runoff.

Firstly, the impact of the initial volumetric water content on the evolution of slope infiltration and surface-water runoff is analyzed. Two initial volumetric water contents are considered: 0.05 and 0.10. The rainfall intensity is 100 mm/h.

Figure 8 shows the simulated results for the evolution of the soil volumetric water content versus depth at section A-A under rainfall conditions.

As shown in Figure 8, the slope infiltration increases with time (rainfall duration), the saturated depth increases, and the wetting front moves deeper. At 2 h, the saturated depth is about 1.5 m when the initial volumetric water content is 0.05, but it is about 2.4 m when the initial volumetric water content is 0.10. The computed results show that, for given mechanical parameters and rainfall intensity, slope infiltration is strongly influenced by the initial volumetric water content. The saturated depth and speed also increase with increasing initial volumetric water content.

About 30 min after the start of rainfall, surface-water runoff is generated, and the water depth increases with time. Figure 9 shows the simulated results for the depth evolution of surface-water runoff during rainfall (section B-B).

As shown in Figure 9a, the height of surface-water runoff increases with time, especially in the first 2 h, but it is gradually stabilized after 4 h. The height on the lower slope is larger than it is on the upper slope. As shown in Figure 9b, over the whole slope surface, the height when the initial

1h

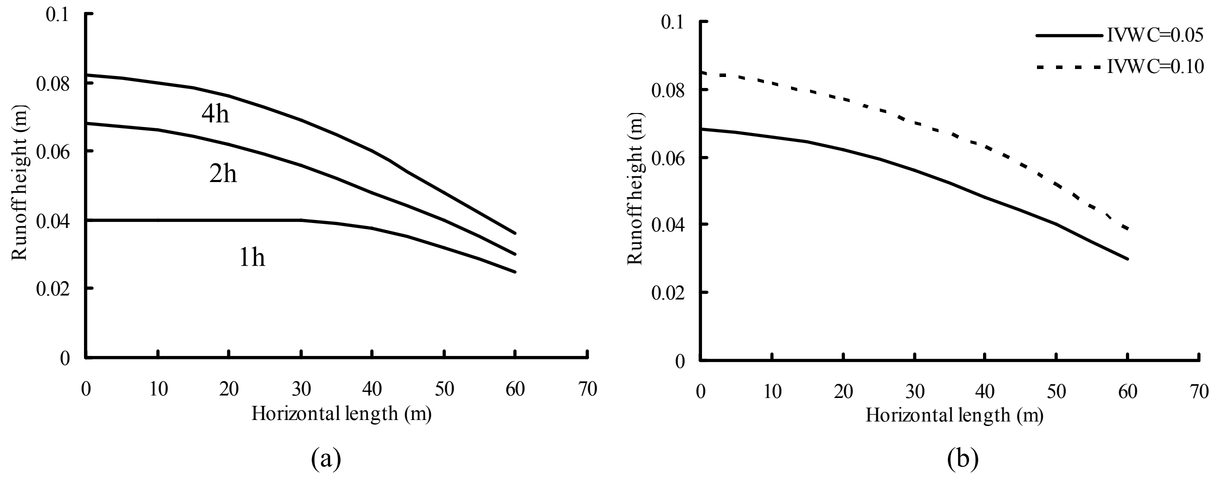


Figure 9 Simulated results for the depth evolution of surface-water runoff during rainfall: (a) for initial volumetric water content (IVWC) of 0.05; (b) surface-water runoff under different IVWC conditions (after 2 h)

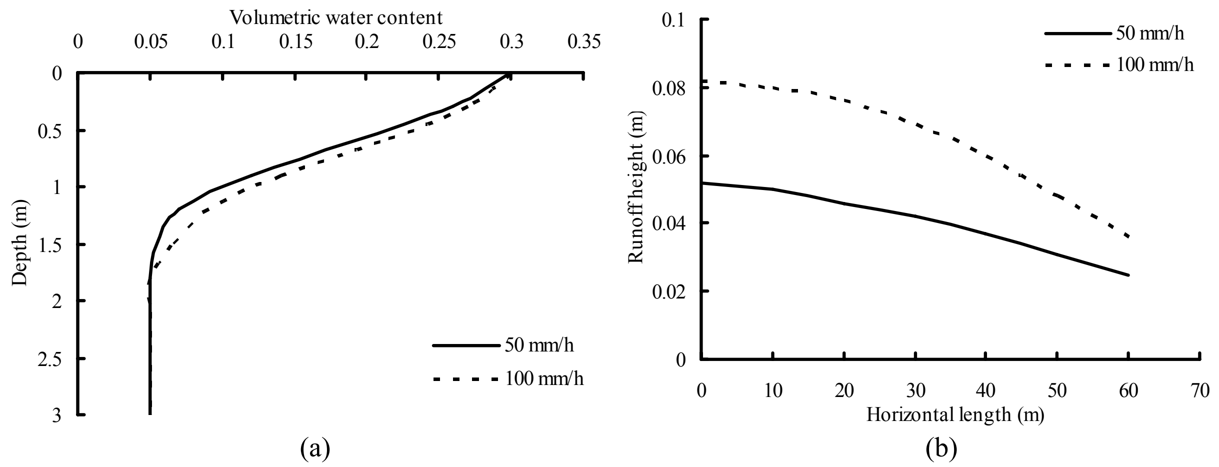


Figure 10 Results of the simulations of the saturated depth and the height of surface-water runoff: (a) soil volumetric water content versus depth for two different rainfall intensities (after 2 h); (b) the height of surface-water runoff for the two rainfall intensities (after 4 h)

volumetric water content is 0.10 is larger than it is when the initial volumetric water content is 0.05, so that a larger initial volumetric water content of landslide deposits easily leads to saturation.

Secondly, the impact of rainfall intensity on the height of surface-water runoff and the saturated depth is analyzed. Two rainfall conditions are used, 50 mm/h and 100 mm/h, and the initial volumetric water content in each case is 0.05.

As shown in Figure 10, for a rainfall intensity of 50 mm/h, about 100 min after the rainfall begins, surface-water runoff is generated, and the height of the runoff is gradually stabilized after 10 h. As shown in Figure 10a, at the same time, a larger rainfall intensity results in a deeper saturated region, but the saturation speed is influenced by the permeability of the landslide deposits. Both rainfall intensities are very large, so the difference is not very obvious. As shown in Figure 10(b), larger rainfall intensity will result in a bigger height of surface-water runoff, and it becomes very easy for a debris flow to be triggered if slope failure of the landslide deposits occurs.

3.3 Initiation condition of debris flow

By combining the physical model and the numerical simulation results, it can be seen how the initiation of a debris flow is based on the safety factor of the slope failure surface. Firstly, the slope failure surface should be determined. The limit equilibrium method is adopted to search the slope failure surface, which we know it depends on the rainfall duration, but this is difficult to simulate during rainfall. Thus three initial volumetric water contents are considered, 0.01, 0.15 and 0.30, but the cohesion of the landslide is assumed to have a very small value, 0.01 MPa. The friction decreases with increasing volumetric water content, as shown in Figure 4a.

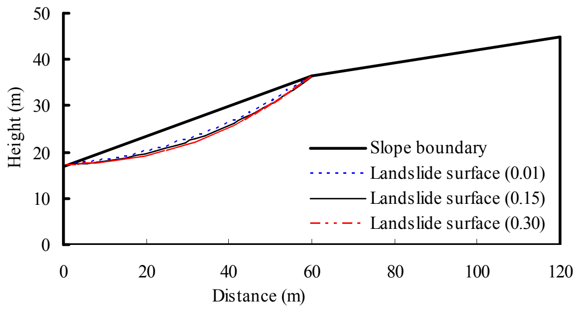


Figure 11 Simulated results for slope failure surface for different initial volumetric water contents

As shown in Figure 11, the slope failure surfaces for different initial volumetric water contents are very similar, and during rainfall, the slope failure surface is assumed to be determined. Figure 12a shows the evolution of the safety factor for different IVWCs when the rainfall intensity is 50 mm/h. Figure 12b shows the evolution of the safety factor for different rainfall intensities when the initial volumetric water content is 0.05.

As shown in Figure 12, the safety factor of the failure surface decreases with increasing rainfall duration. Larger initial volumetric water content results in a smaller safety factor. As shown in Figure 12a, for the same rainfall intensity (50 mm/h), a debris flow will occur at 4.2 h when the initial volumetric water content is 0.05, but the debris flow is triggered at 3.1 h when the initial water content is 0.10. As shown in Figure 12(b), for the same initial volumetric water content (0.05), the debris flow will occur at 2.0 h when the rainfall intensity is 100 mm/h. The simulation results show that a debris flow will easily occur for landslide deposits at higher rainfall intensities and initial volumetric water contents.

4 Conclusions

Debris flow events occur after intense rainstorms in the period of prolonged rainfall. Sufficient rainfall intensity is a necessary condition for the sediment material saturated and intense surface runoff formed on the slope, and a shallow landslide can occur and be transformed to a debris flow by combining with the water flow. In this paper, the Wenjiagou gully was selected as a case study for determining the initial condition for debris flow under rainfall conditions. During a rainfall, the cohesion and friction coefficient of landslide deposits decrease with increasing volumetric water content.

Because slope failure does not usually occur in

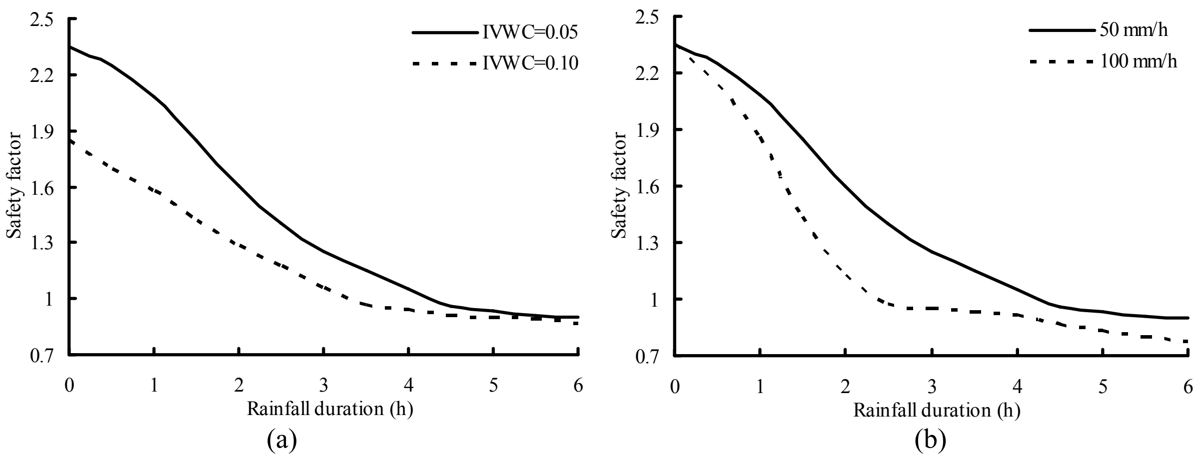


Figure 12 Evolution of the safety factor: (a) for different IVWCs when the rainfall intensity is 50 mm/h; (b) for different rainfall intensities when the initial volumetric water content is 0.05

a saturation region with a plane surface, we presented a theoretical model based on the Takahashi model to solve the problem of debris flow initiation. If the slope inclination is less than 10°, even though the whole landslide deposit layer is fully saturated, no debris flow is triggered. When the slope inclination is larger than about 21°, a debris flow is easily triggered under rainfall conditions. The triggering of a debris flow is clearly influenced by the topography. The slope angles for debris flow initiation are based on specific conditions in this paper.

We then adopted a surface-water-runoff and saturated-unsaturated-seepage numerical program to model the rainfall infiltration and runoff on a slope. Simulation results show that infiltration increases with time (rainfall duration). At the same time, the saturated depth increases, and the wetting front moves deeper in the slope. The slope infiltration is clearly influenced by the initial volumetric water content. Larger rainfall intensity results in a deeper saturated region. The height of surface-water runoff increases with time, but the height is gradually stabilized after several hours. A larger rainfall intensity will result in a greater height of surface-water runoff. A debris flow will easily be triggered in landslide deposits under conditions of high rainfall intensity and initial volumetric water content. In this study, the simulated rainfall is not necessarily the same as real rainfall scenarios. Nor does the simulation consider the runoff convolution in the entire catchment. These should be considered in future studies.

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