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A theoretical model for the initiation of debris flow in unconsolidated soil under hydrodynamic conditions

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Abstract

Debris flow is one of the catastrophic disasters in an earthquake-stricken area, and remains to be studied in depth. It is imperative to obtain an initiation mechanism and model of the debris flow, especially from unconsolidated soil. With flume experiments and field investigation on the Wenjiagou Gully debris flow induced from unconsolidated soil, it can be found that surface runoff can support the shear force along the slope and lead to soil strength decreasing, with fine particles migrating and forming a local relatively impermeable face. The surface runoff effect is the primary factor for accelerating the unconsolidated slope failure and initiating debris flow. Thus, a new theoretical model for the initiation of debris flow in unconsolidated soil was established by incorporating hydrodynamic theory and soil mechanics. This model was validated by a laboratory test and proved to be better suited for unconsolidated soil failure analysis. In addition, the mechanism analysis and the established model can provide a new direction and deeper understanding of debris flow initiation with unconsolidated soil.

1 Introduction

Debris flow is a type of mixture that contains water, rock, and fragment material and is one of the catastrophic disasters that is possible in an earthquake-stricken area (Chanson, 2004). The reason for these disasters is that the substantial amounts of loose unconsolidated soil that are generated by an earthquake are usually in an unstable state and are likely to cause a landslide, collapse, and debris flow hazard in the presence of external excitation conditions, such as strong rainfall or floods. Debris flow from the unstable unconsolidated slopes can be initiated by rainstorms during the rainy season for 5 to 10 years after an earthquake (Cui et al., 2011; Zhuang et al., 2012). In recent decades, many debris flow disasters have been reported all over the world. Consider the target area of the 2008 Wenchuan earthquake (7.9 magnitude) in China, for example; the largest scale debris flow occurred on 13 August 2008, which caused 7 persons to die while 5 persons went missing, 39 persons were injured and 479 houses were buried or damaged (Tang et al., 2012). Large volumes of landslide deposits (unconsolidated soil) were formed after the Wenchuan earthquake (Zhou et al., 2013a); debris flow could easily occur under rainstorm conditions, which implies that it is very valuable to obtain an understanding of the initiation mechanisms of debris flow that is generated from unconsolidated soil after an earthquake.

Many scholars have studied the problem of the initiation of debris flow and have proposed failure models or prediction formulas (Armanini and Gregoretti, 2007; Huang et al., 2008; Lade, 2010). Takahashi considers the failure mechanism of loose soil to be formed under a condition in which the shear stress is larger than the resisting stress, and he proposed a formula that is based on the failure depth under surface runoff and no surface runoff (Takahashi, 1978). Based on laboratory experiments and field observations, Wang and Zhang (2000) considered strong rushing to be the main cause of debris flow. Using fluid mechanics theory, they obtained a flow movement equation for the deposit surface and shear stress, which is regarded as extending Takahashi's model to be more in-depth. However, these authors ignored the influence of the pore water pressure on the shearing strength and those parameters that could change with time. Some researchers considered the debris flow to be generated from a landslide and established a 1-D infinite slope failure model to describe the problem (Iverson et al., 1997; Gabet and Mudd, 2006; Huang et al., 2009). Moreover, some statistical models are presented based on many indoor and field experiments (Cui, 1992; Gregoretti and Fontana, 2008; Tognacca et al., 2000). The results from these models could have experimental and regional limitations due to the difficulty of their application.

As concerns research about the debris flow initiation mechanism from an unconsolidated soil or loose deposit, the current understanding is still at the level of superficial phenomena, and it is difficult to perform the corresponding numerical analysis. Zhou (2013b) considers the surface runoff and seepage process in the slope stability analysis to achieve the dynamic process of debris flow formation. Zhuang et al. (2012) simplified the debris flow initiation under runoff into three patterns and analyzed the mechanisms and process. Fang et al. (2012) found that the debris flow initiation process can be summarized into the appearance of surface runoff, fine particles moving, large particles falling, the whole slope moving and the debris flow forming. These analyses show that the surface runoff and internal seepage mainly contribute to the tumbling and moving of particles and shallow slope failure with loose deposits. Therefore, considering the surface runoff and internal water pressure, which are affected by seepage into the debris flow, an initiation model is feasible and is a significant achievement.

Based on several indoor experiments and field investigations, we determine that the surface runoff is a key factor for the debris flow that is generated from unconsolidated soil. After comparative analysis of the previous initiation model for debris flow, a new theoretical model for studying the initiation of debris flow in unconsolidated soil under hydrodynamic conditions is presented. This model is validated by a laboratory test and is applied to study the initiation of the debris flow in the Wenjiagou Gully in Sichuan, China.

2 Previous studies

Previous initiation models for debris flow can be organized into four types: (1) debris flow mobilization from landslides, which was first presented by Iverson et al. (1997), (2) coupling models of hydraulics and soil mechanics, first presented by Takahashi (1978); (3) statistical models from field investigations and indoor tests (Cui, 1992); and (4) surface runoff models, which are presented by Berti and Simoni (2005).

2.1 Debris flow mobilization from landslides

Iverson et al. (1997) indicated that landslides that mobilize to form debris flows can be divided into three processes: (a) widespread Coulomb failure within a sloping soil, rock, or sediment mass, (b) partial or complete liquefaction of the mass by high pore-fluid pressure and (c) conversion of landslide translational energy to internal vibration

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energy (i.e., granular temperature). The main reasons for soil failure are considered to be the increase in internal excessive pore water pressure that is caused by ground water and the local Coulomb failure and decreasing cohesion that results from particle liquefaction. The safety factor of soil can be determined by three parts:

$$F_s = T_f + T_w + T_c \tag{1}$$

where T_f describes the ratio of frictional resistance strength to gravitational driving stress; T_w describes the ratio of strength modification by groundwater to the gravitational driving stress, and T_c describes the ratio of cohesive strength to gravitational driving stress. These three parts can be computed as follows:

$$T_f = \frac{\tan\phi}{\tan\theta}, \quad T_w = \frac{\left[\frac{d}{Y} - 1\right]\frac{\partial p}{\partial y}\tan\varphi}{\gamma_t \sin\theta} \quad \text{and } T_c = \frac{c}{\gamma_t Y \sin\theta} \tag{2}$$

where c and φ are the cohesive and friction angle of the soil; θ is the inclination of the soil slope; Y is the slope failure depth; y is the direction perpendicular to the slope surface; d is the depth of the water table where the water pressure $p = 0$; the water table necessarily parallels the ground surface, as do all surfaces with constant p in infinite slopes; and γ_t is the depth-averaged total unit weight of the saturated and unsaturated soil below and above the water table.

This model must analyze the pore water pressure in unconsolidated soil when considering the liquefaction and dynamics of the sliding. However, owing to a relative lack of data for rigorous model tests, liquefaction and slide dynamics models remain immature compared to slope failure models.

2.2 Coupling models of hydraulics and soil mechanics

Coupling models of hydraulics and soil mechanics were presented by Takahashi (1978); this type of model is a Coulomb failure model. In this model, the shear stress

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τ and resisting stress τ_r at the depth a are measured from the surface of the sediment layer, which can be computed as follows:

$$\tau = g\sin\theta\{C_*(\sigma - \rho) + (h_0 + a)\rho\} \tag{3}$$

$$\tau_r = g\cos\theta C_*(\sigma - \rho)a\tan\phi + c \tag{4}$$

where g is the acceleration of gravity; σ, c and φ are the density, cohesive strength and friction angle of the soil, respectively; θ is the inclination of the soil slope; h_0 is the depth of the flowing water above the slope surface; ρ is the fluid density; and C_* is the concentration of the solids when packed.

The stability of the soil slope is determined by the following equations:

$$\frac{d\tau}{da} \geq \frac{d\tau_r}{da} \text{ (Stable)} \tag{5a}$$

$$\frac{d\tau}{da} < \frac{d\tau_r}{da} \text{ (Failure)} \tag{5b}$$

Additionally, when the shear stress is greater than the cohesion of the soil on the slope surface ($a = 0$),

$$\tau = \rho g h_0 \sin\theta > c \tag{6}$$

and shear failure of the slope will occur.

If considering the surface runoff, we must add the gravity component in the shear stress direction and in the resisting stress direction to the shear stress and resisting stress separately. Here, the water above the slope is expected to be parallel to the slope surface. This model considers the surface runoff to be in a static condition and ignores its dynamic effects.

2.3 Empirical statistical model

There are several empirical statistical models for studying the initiation of debris flow. For example, Cui (1992) defined the concept of a quasi-debris flow body and presented an initiation model by fitting the experiment results. The soil failure criterion is that when the shearing stress τ_f is equal to the resisting stress τ_r, the soil begins to fail. This model considered the fine-grain content C (< 1 mm), the soil saturation S_r (which equals the volume of the water divided by the volume of the pores in the material) and the bed slope θ to be the factors that impact the initiation of the debris flow:

$$\theta - 8.0062 S_r - 2.4859 S_r^2 - \frac{3.4896}{C - 0.0996} + 7.0195 = 0. \tag{7}$$

By the use of Eq. (7), we can be drawn into the space of θ, S_r and C, and this curved surface is called S. For every quasi-debris flow body, there is a point $P(\theta, S_r, C)$ in the space of θ, S_r and C. When the point P is on the curved surface S, the quasi-debris flow body is in the critical start-up state. When the point P is below or above the surface S, the quasi-debris flow body is stable or unstable, respectively.

Empirical statistical models are determined from indoor tests; because of the special soil samples and test conditions, these models are subject to significant soil type influences.

2.4 Surface runoff model

Debris flows can be initiated by the surface runoff in unconsolidated soil. This phenomenon is best described in terms of the equilibrium of single particles with the hydrodynamic forces rather than using the classical limit equilibrium analysis of a Mohr–Coulomb material employed for shallow slope stability (Chiew and Parker, 1994; Buffington and Montgomery, 1997; Armanini and Gregoretti, 2000). Although poorly sorted, such debris contains a low fine fraction (less than 10–20 % silt and clay) compared to soils that are involved in landslide-induced debris flows, and it has a much higher hydraulic conductivity. Because of their ability to drain the rain water that infiltrates from the surface, the moisture content of these materials is always far from saturation; therefore, failure is very unlikely unless it occurs as a result of surface flow.

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Through direct observations and real-time data collection, Berti and Simoni (2005) found the relationship between the debris flow initiation and runoff discharge and developed a simple model that is based on kinematic wave theory to compute the hydraulic condition.

$$\frac{\partial Q_R}{\partial x} + \frac{1}{c}\frac{\partial Q_R}{\partial t} = q \tag{8}$$

where Q_R is the surface discharge; q is the flow per unit length of the channel (which is lost by infiltration into the bed); and c is the kinematic wave celerity. This equation can obtain the surface flow charge at an arbitrary length and time through the discrete length of the channel x and time t.

Compared with the empirical models presented by Cui (1992), Tognacca et al. (2000) or Gregoretti and Fontana (2001), this model has fewer empirical parameters and has been verified by field observations.

2.5 Comparative analysis

The main feature, critical condition and application range of the above four initiation models for debris flow are summarized in Table 1.

The four kinds of debris flow initiation model have different application ranges with various methods. As shown in Table 1, before we fully get the debris flow initiation mechanism, the ESM can strengthen the understanding of the initiation mechanism of geotechnical debris flows. Then CM and DFMFL achieved some progress in understanding the failure process with water flow and debris flow transforming from landslides. Moreover, the SRM helped us to realize that unconsolidated materials can also form a debris flow in a small gradient channel.

However, the debris flow initiation is still not widely accepted by the researchers despite its achievement in hazard area. The main reason is that the soil properties have complex effects influencing debris flow initiation which have not been clearly understood, and hydrodynamic conditions are always omitted in the models. For example,

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ESM provides a clear physical concept of debris flow initiation by focusing on the governable parameters (slope, material composition and water in soil) but needs to be specifically refined with other external hydrodynamic conditions. The SRM model can consider the surface flow; however, the appearance of the runoff effect is obtained from statistical data rather than a mechanics mechanism, which may not apply in other regions. CM adds the weight of runoff on the slope in the model, regarding it as a stable stage and ignoring the real dynamic effect.

Hence, to sum up, though the hydrodynamics condition of the surface runoff, which is very important for the initiation of debris flow in unconsolidated soil, has now begun to be taken into account, the particular mechanism and process inducing debris flow from surface runoff should be studied in greater depth.

3 Flume experiment for unconsolidated soil

Here, we design an artificial rainfall test for unconsolidated soil to study the failure mechanism and initiation condition of debris flow.

3.1 Experimental design

We took the unconsolidated soil from the Wenjiagou Gully in China as the study soil, with conditions of rainfall intensity of 140 mm h^{-1} (the rainfall intensity that occurs every 5 years in this area is 70 mm h^{-1}), slope angle 39.1°, bed gradient 5 % and 10 %, and rainfall duration of 3 h. An artificial rainfall system and flume and monitoring sensors are shown in Fig. 1. A total of 12 sets of pore water pressure and volumetric water content sensors were arranged in the slope.

Table 2 shows the particle size distribution of the soil samples that are used in the artificial rainfall tests (maximum particle size is 60 mm, and particles larger than 60 mm are first excluded).

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In addition to rainfall condition, water flow of approximately 1.70 m s^{-1} and 0.05 m depth is used to simulate surface runoff in the field. And a new flume is designed for separating surface runoff and seepage, as shown in Fig. 1.

3.2 Flume experiment with rainfall

When the unconsolidated slope is under the rainfall condition, only small shallow slope failures occur, such as particle tumbling, small slides or collapse in the whole rainfall process (see Fig. 2). Here, the rainfall intensity is 140 mm h^{-1}, which is sufficiently large, but no large slope failure or debris flow happens.

To find the reason why large slope failure and debris flow are not forming, variations of the pore water pressure (PWP) and volumetric water content (VWC) at the slope toe are tested, as illustrated in Fig. 3.

As shown in Fig. 3, PWP and VWC variations can be summarized into three stages during rainfall of 2 h: (1) the initial steady stage, (2) a rapidly increasing stage and (3) steady again stage. The rapidly increasing and steady again stages are ahead of the time at a high gradient of 10 %, which can reach a maximum value at 50 min. With the gradient increasing, the water-holding capacity of the loose deposit decreases, and water flows out more rapidly, which leads to the water content increasing (reaching 34.5 % with a 10 % gradient at T = 180 min), and the surface soil of the slope is almost saturated. However, the pore water pressure at the slope toe is approximately 0.8 kPa, and might not be large enough to induce slope toe failure or regressive failure. Comparing the large-scale debris flow triggered in the field of Wenjiagou Gully with the same conditions, it is found that failure of the large loose deposit may depend on not only the increasing internal pore water pressure but also the external hydrodynamic effect of surface runoff.

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3.3 Flume experiment with runoff

In order to reproduce the initiation process of the Wenjiagou Gully debris flow, water flow at 1.7 $m\,s^{-1}$ and a depth of 5 cm is applied in addition to the artificial rainfall condition above.

It is found that the deeper sensors (PWP and VWC) show fluctuations while the soil failure happens, which corresponds with the previous findings (Iverson, 2000; Chen, 2006). Experimental tests shown in Fig. 4 indicate that the soil failure is occurring at the shallow layer, about 5 cm. This failure is so minor that it is usually regarded as a type of erosion (Bryan, 2000). In fact, erosion is the process of a small amount of particles slowly moving, and may last for a few minutes or even a few years, such as sheet wash, rill erosion, piping erosion, etc. But, in our tests, the slope failure is happing at a shallow position on a small scale. When the runoff flows across the slope, fine particles are first to detach and liquefy (the maximum flow concentration reaches about 1.8 $g\,cm^{-3}$). At the same time, the runoff entrains surface particles, even leading to shallow landslide. Then debris flow is easily triggered along the slope surface, with abundant loose particle material and water flow. This process also indicates that initiation of the debris flow is not a simple erosion failure but a complex disaster chain with various transformations.

In addition, debris flow initiation forms instantaneously and is difficult to catch even with a video camera (20 fps). Moreover, the soil failures are of several types, such as shallow landslide, flowslide, and particles migration, which are difficult to differentiate in the current research (Hungr et al., 2001, 2014; Wang, 2003; Take, 2004; Klubertanz, 2009).

In a word, in the runoff condition, the unconsolidated soil forms failures, especially the shallow landslide, flowslide, and even debris flow, more easily than with rainfall only. At the process of debris flow initiation, fine particles migrate with hydrodynamic force vertically apart from along the slope surface, which can be verified by grading analysis of the slope after the experiment. From the grading curve, we find that the fine particles (< 2 mm) increase from 18 to 23 %, which shows their great influence on the slope failure and debris flow initiation. A similar conclusion can also be found in flume tests with rainfall (Cui et al., 2014).

4 Initiation mechanism and numerical model for the debris flow

4.1 Debris flow initiation mechanism

From the flume experiment with no runoff being generated, the slope stays in a stable state with strong rainfall. Comparing the slope physics properties before and after the tests, the resisting strength decreases only a little, as shown in Table 3, and the slope is still stable even with a peak pore water pressure of about 0.9 kPa (upper soil). And considering debris flow occurring in the field situation, it indicates that the factors triggering debris flow involve the hydrodynamic condition, like huge runoff or flood besides rainfall.

For the flume experiment under runoff, an obvious soil failure and debris flow appears. In fact, when the runoff flows through the slope surface, there are two effects: on the one hand, fine particles (less than 2 mm) migration leads to a coarse layer (the surface soil is in a saturated state and its cohesion is close to zero); on the other hand, the moving fine particles block the soil pores and cause saturation of the top soil, increased pore water pressure and uplift pressure, and decreased soil shear strength. Moreover, the fine particles liquefying and integrating into water flow will increase the viscosity and enlarge the hydrodynamic effect. However, this effect is usually ignored in our research.

Besides the hydrodynamic effect, soil shear strength will be reduced by the coarse particle gradation. And a perched water table and water film will form with the pores blocked, and then provide lubrication (Lu and Cui, 2010; Lu et al., 2010). In addition to the detachment of fine particles by erosion and scour, the soil failure will happen through the interaction of hydrodynamic and self-weight.

During the process of soil failure with the runoff, the failure soil will disintegrate in a moment, or integrate into the water flow (the liquidation and suspension effect), and/or move down to the slope toe with the run off, leading to the large particles aggregating at the slope toe. And with the fine particles integrating into the water flow and constantly increasing in concentration, it can build up greater power with the loose material joining, and then form a destructive debris flow. In the field, with steep terrain, the requisite hydrodynamic conditions, and a long motion distance, the huge debris flow triggered in the channel will cause major disasters such as the Wenjiagou debris flow in 2010 (Zhou, 2013b).

To verify the important role of runoff, after the experiment with only rainfall, the shear strength parameters of unconsolidated soil are tested by direct shear testing under four normal stress conditions (200, 400, 800 and 1200 kPa), as shown in Fig. 5. The sample is the original soil in the flume after rainfall, which has a density of 1.909 g cm^{-3} and water content of 4.5–6.5 % (approximately). The water content of natural soil is about 1.0–2.0 % and for saturated soil is about 15–17 %.

Experimental results show that the cohesion and friction angle for unsaturated soil (water content 4.5–6.5 %) are 22.3 kPa and 37.6°, respectively, and 42.5 kPa and 38.1° for natural soil (water content 1.0–2.0 %). Laboratory tests indicate that the cohesion reduced sharply with both runoff and rainfall, but the friction angles changed less. For the saturated soil behind the surface runoff, the cohesion is assumed equal to 0, and the friction angle is determined by the experimental test for unconsolidated soil when the water content is 15–17 %. Table 3 summarizes the shear strength parameter of unconsolidated soil in different water content conditions, which are used for numerical analysis.

The stability of the unconsolidated soil slope is influenced by three main factors: a decrease in the shear strength of the unconsolidated soil, an increase in the pore water pressure in the slope and erosion of the surface runoff. Here, we apply the limit equilibrium method to the analysis of the stability of the unconsolidated slope under different shear strength parameters (Fig. 6). As shown in Fig. 6a, a shallow failure

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of the landslide slope will occur when the shear strength parameters are very low. Sensitivity analysis for the impact of the shear strength parameters on the safety factor of the slope is conducted based on a certain sliding surface (Fig. 6b). As shown in Fig. 6c, the safety factor decreases with a decrease in the cohesion and friction angle of the unconsolidated soil, which is a linear relationship.

As shown in Fig. 6a and c, in most cases, the safety factor of the unconsolidated slope is larger than 1.0; decreasing the shear strength of the unconsolidated soil is only one factor that has an impact on the failure of the slope. The hydrodynamic effect of the surface runoff is another key factor in the failure of the slope, especially for the initiation of the debris flow. For unconsolidated soil with wide grading and loose structure, the triggering factors for the debris flow are floods or large runoff besides a strong rainfall even in a long period.

Therefore, wide grading loose soil inducing debris flow is a process involving the interaction of its own and outside conditions. Especially in high mountain areas like those of West China and Italy, the runoff on the slope surface can be ignored. When the slope stability is analyzed, hydraulic calculation of parameters such as peak discharge, flow velocity and depth should first be executed, and then coupled with the self-weight. Though Berti (2005) introduced experimental evidence and a numerical model for predicting debris flow initiation through hydraulic calculations, the author's prediction model still required the help of an empirical formula and is difficult to apply in other areas.

In this paper, we regard the hydraulic calculation as a known condition, and add the hydrodynamic effect to the current model for a more widely applicable debris flow initiation model.

4.2 Model assumption and construction

In order to simplify this problem, we here consider the soil which is in a critical state with a failure shape of a rectangle; the cohesion in the top soil is regarded as zero because of the low clay content (in practice, the value should be adjusted for different soils).

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According to the experimental results, Fig. 7 shows the simplification of assumptions for the stress distribution of unconsolidated soil under hydrodynamic conditions.

As shown in Fig. 7, three simplification assumptions are introduced: (1) the surface runoff is parallel to the slope surface, and the failure face is also parallel, (2) the superficial soil of the unconsolidated soil is in the saturated stage; and (3) underground water is omitted here. The first assumption is applied in the model to reduce the complexity of this problem because the surface runoff shape does not have a large influence on the slope stability. Through the field investigation (Tang et al., 2012; Zhou et al., 2013b) and indoor experiments above, we find that the soil is almost completely saturated when shallow failures are occurring. For the second simplification assumption, it is known that the failure of unconsolidated soil is always in the valley, which indicates that the main factor is not the increase in the underground water level; thus, the underground water can be omitted here.

To consider the unit length and width, as shown in Fig. 7, assuming that there is an unconsolidated soil failure with a slope failure depth of a, a surface runoff depth h, a pore water pressure u_w on the failure surface (details are in Sect. 4.3), a slope angle θ, a cohesion c, a frictional angle φ with saturated soil, and water unit weight r_w, and the soil surface friction provided by the surface flow f (details are in Sect. 4.2) (and with the small buoyancy and seepage force omitted here), using the *Fredlund* soil strength theory (Fredlund and Rahardio, 1993) and the principle of effective stress, the soil resisting stress at a depth of a can be expressed as follows:

$$\tau_f = c + (\sigma - u_w)\tan\phi, \quad \text{and } \sigma = (r_{sat}a + r_w h)\cos\theta, \quad u_w = r_w(a+h) \tag{9}$$

Combining the above, we can then obtain the resist stress of the unconsolidated soil,

$$\tau_f = c + [(r_{sat}a + r_w h)\cos\theta - u_w]\tan\phi \tag{10}$$

and the shear stress can be computed as follows:

$$\tau = (r_{sat}a + r_w h)\sin\theta \tag{11}$$

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Considering the effect of surface runoff, if the shear stress is less than the resist stress of the unconsolidated soil, the slope is stable:

$$\tau + f \leq \tau_f \tag{12}$$

Takahashi (1978) thinks that the cohesion of a saturated unconsolidated soil can be ignored, but in fact, this is an important parameter that cannot be ignored. If the shear stress is greater than the resisting stress at a depth of $a > 0$, a failure of the unconsolidated slope will occur.

Since the 1970s, many scholars have done a lot of research on the overland flow resistance with indoor or outdoor rainfall and erosion tests, by means of different concepts and expressions such as the *Darcy–Weisbach*, *Chezy* and *Manning* friction factor. Due to the complexity of this problem, the Darcy–Weisbach friction factor is mainly used in their models because of its concise form and wide application, suitable for laminar flow and turbulent flow.

At present, it is broadly accepted that the overland flow resistance in different surfaces can be divided into four sources, namely the grain resistance f_g, form resistance f_f, wave resistance f_w and rainfall resistance f_r. Grain resistance is the resistance formed by soil particles and micro aggregate. The form resistance f_f contains the dissipation of energy by microtopography, vegetation, gravel and so on. Wave resistance f_w forms by vast scale surface deformation. And rainfall resistance is generated by the raindrop.

However, these resistances are difficult to measure and quantify in experiments. And the factors may have an interaction effect. So, to simplify, the *Darcy–Weisbach* friction factor λ is chosen to indicate the overflow resistance.

According to hydraulics theory, the shear force F that is generated by the surface flow on the slope surface can be calculated as follows:

$$f = \lambda \rho v^2 / 8 \tag{13}$$

where ρ is the density of water; l is the slope length; λ is the friction loss factor of the hydraulically open channel, and when the runoff is laminar flow ($Re <$

2000, Re is Reynolds number), $\lambda = 64/Re$; when it is turbulent flow ($Re > 2000$), $\lambda = 1/[2lg(3.7R/\Delta)^2]$ (*Nikuradse* empirical formula). $R = A/\chi$ is the hydraulic radius of the cross-section; and Δ is the roughness (slope surface sand diameter), which is usually close to 30–60 mm in a pebble river bed.

4.3 Sensitivity analysis of the parameters

The physical model above shows that the slope stability condition (safety factor) is related to the grains' physical characteristics, the slope, runoff velocity, runoff depth, water flow unit weight, etc. For a specific type of soil, its physical characteristics are determinate. Therefore, for a physical model, it is important to find out which are the most sensitive factors for slope failure. Here, we assume that the fluid has a laminar flow, and the safety factor is shown as follows:

$$F_s = \frac{c + (r_{sat} - r_w)a\cos\theta\tan\phi}{(r_{sat}a + r_w h)\sin\theta + \lambda\rho v^2/8} \tag{14}$$

The values of the model parameters that are used for sensitivity analysis are shown in Table 4.

Considering the safety factor F_s to be a function of the sensitive factors, we can use the usual form $S_i = \Delta F_s/\Delta x_i$ to conduct sensitivity analysis (Δ represents a tiny variable; F_{si}, x_i respectively represent the ith safety factor and a sensitive factor influencing the F_s. To compare all of the factors, which have different units, the common method is to normalize S_i to $I_i = \frac{\Delta F_s/F_{si}}{\Delta x_i/x_i}$. A high absolute value of I_i stands for the high sensitivity of the ith factor. Through the relationships between $\Delta F_s/F_{si}$ and $\Delta x_i/x_i$ (Fig. 8), we can find how the model parameter affects the initiation of the debris flow.

As shown in Fig. 8, we can obtain that the sensitivity, from high to low, is as follows: slope angle, runoff depth, runoff velocity, failure depth, cohesion, water unit weight, surface roughness, viscosity and angle of internal friction. The cohesion, which has a negative correlation with the slope stability, makes a certain contribution and cannot be ignored. Besides the slope angle, which is well known for its important effect, the following runoff depth and velocity indicate that the runoff that can produce the shear stress should also not be omitted in the model, especially as, when the runoff runs down the slope, it can carry fine particles away and decrease the cohesion, leading to slope instability.

This model is derived from soil mechanics and experimental results and is suitable for slopes where there is a low impervious surface angle and the debris flow is triggered by a large surface runoff.

5 Simulation of laboratory testing

In this section, we use the presented model to simulate laboratory testing. According to the artificial rainfall test for the unconsolidated slopes, the values of the model parameters are shown in Table 3.

Because the slope failure did not occur with a strong rainfall condition (no runoff generated) and did occur with a large surface runoff condition, we simulate the slope stability under two stages (no runoff, non-uniform runoff). For the no-runoff condition, the cohesion is found to be 22.3 kPa as measured by the shear tests after tests shown in Sect. 3.2. And it is zero under the runoff condition because of the surface runoff's sand-carrying effect, which leads to the soil coarsening, giving the cohesion c a value of nearly zero. This phenomenon is also observed in the tests shown in Fig. 8. Moreover, a shallow failure pattern for loose deposit under rainfall is usual. Here, the position 0.05 m below the slope surface is chosen for analyzing the slope stability. Through the formula Eq. (14), the safety factors under no-runoff and runoff conditions are respectively 32.51 (no-runoff, $c = 22.3 \times 10^3$ kPa, $h = 0$ m, other parameters are the same as Table 3) and 0.19 ($c = 0$ kPa, with runoff, detailed parameters are shown in Table 5). Thus, the results show that the slope is stable under the no-runoff condition and fails with the runoff condition, which is consistent with the experiment results and indicates the rationality of this hydrodynamic model.

To be sure, with the runoff condition, the fluid is regarded as laminar flow ($Re \approx 1214$). And generally, soil internal friction is less influenced by water content. So the soil parameter with no-runoff is the same as the runoff condition except for the cohesion.

When unconsolidated soil is in the saturated state, the cohesion and friction angle of the soils are decreased to a certain small value, but the loose unconsolidated soil is still stable. This finding indicates that the decrease in the shear strength is a necessary condition for the soil failure, but the most necessary feature is the hydrodynamic effect of the surface runoff. Considering the variables slope angle θ, and runoff depth h, we can get the critical failure depth for the initiation of the debris flow through the formula Eq. (15)

$$a \le \frac{c - r_w h \sin\theta - \lambda\rho v^2/8}{r_{sat}\sin\theta - (r_{sat} - r_w)\cos\theta\tan\phi} \tag{15}$$

where the parameters are the same as Table 3 except for the variables slope angle θ, and runoff depth h.

Then, we can use Eq. (15) to determine the initiation condition of the debris flow in the unconsolidated slope by the use of laboratory testing. Figure 9 shows the critical failure depth of the initiation condition for the debris flow in the unconsolidated slope under laboratory testing conditions. The critical failure depth decreases with the increase in the slope and runoff depth. On the other hand, below a certain failure depth, it reflects the critical slope and surface runoff conditions, which have the same relationship as in Sect. 4.2.

To sum up, not only the shear force of runoff but also its sand-carrying effect is considered in the hydrodynamic model, which shows a conservative and safe method for slope safety analysis. Compared with the current method with the runoff effect neglected, this method can be applied in the analysis of loose deposit failure under rainfall or runoff in the future. If there is no runoff generated, the hydrodynamic parameters (such as runoff depth, runoff velocity, etc) can be omitted from the common slope safety analysis.

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6 Conclusion and discussion

6.1 Conclusion

To find the debris flow triggering mechanism, previous studies about the debris flow initiation model are first summarized. The current numerical models which almost all have specific application in their respective regions have all ignored the hydrodynamic effect with fine particles and slope stability. With the experiments under rainfall and runoff, the important role of the hydrodynamic effect in the debris flow initiation has been found and clearly understood. For example, on the one hand, it carries away the fine particles which lead to the soil coarsening and soil strength decreasing; on the other hand, it increases the unit weight and viscosity of water flow, which will increase the shear stress to the slope. However, these processes are sudden, invisible and always omitted in practice. Finally, a theoretical model for debris flow initiation considering the hydrodynamic effect is built and verified by test data. The simulation results show that this model is much more appropriate for unconsolidated soil failure analysis by considering the hydrodynamic condition and simplifying other soil properties.

6.2 Discussion

Debris flow initiation is usually classified into two types: the landslide transforming type and water erosion type. In fact, these initiation mechanisms exist widely and simultaneously in the field. Though the large water flow can lead to huge erosion and entrainment, the hydrodynamic effects which add the shear force along the slope and lead to soil strength decreasing, with fine particles migrating and forming local relatively impermeable faces, have not been well known in the current literature (Iverson et al., 2010, 2011; Huang et al., 2009, 2010; Lade, 2010). The surface runoff resulting in soil failure in this way is usually regarded as an erosion effect. In practice, this process (soil failure, from sliding to flowing) is sudden and relatively complex in nature (Malet, 2005). Moreover, unconsolidated soil with a loose structure is all the more easily dispersed, incorporated by water flow and mistaken for erosion or entrainment. So the findings in this paper will provide a new view of the debris flow initiation and unconsolidated soil failure.

Based on hydraulic theory, an unconsolidated soil failure model has been established that incorporates the hydrodynamics shear stress and pore water pressure. This model has improved on a defect in the hydraulic and soil mechanics coupling model (Takahashi, 1978), which omits the hydrodynamics and has an insufficient surface runoff model (Berti and Simoni, 2005), in which the critical condition is not able to prevent the debris flow from forming when there is a low velocity surface runoff.

In classical slope analysis, the sliding face can always be fixed by geological analysis such as the soft layer or stability computation. However, the sliding surface is random and shallow, existing in the wide grading loose soil and this needs to be analyzed and estimated by simulation experiments. Here, the sliding surface is assumed to be a plane at a depth of 5 cm. In the future, it will be studied in depth and defined using a precise numerical model rather than by estimation. Moreover, though our realization of the debris flow initiation considering the hydrodynamic effect can provide a physical basis for understanding the debris flow triggering threshold, it must be admitted that the loose unconsolidated soil forming the debris flow is notably complex and other unknown factors should be considered in our model.

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References

Armanini, A. and Gregoretti, C.: Triggering of debris flow by overland flow: a comparison between theoretical and experimental results, in: Proceedings of the 2nd International Con-

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2, 4487–4524, 2014

Initiation of debris flow in unconsolidated soil

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ference on Debris Flow Hazards Mitigation, Taipei, Taiwan, 16–18 August 2000, 117–124, 2000.
Berti, M. and Simoni, A.: Experimental evidences and numerical modelling of debris flow initiated by channel runoff, Landslides, 2, 171–182, 2005.
Bryan, R. B.: Soil erodibility and processes of water erosion on hillslope, Geomorphology, 32, 385–415, 2000.
Buffington, J. M. and Montgomery, D. R.: A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers, Water Resour. Res., 33, 1993–2029, 1997.
Chanson, H. (Ed.): Hydraulics of Open Channel Flow, Butterworth-Heinemann, Oxford, UK, 2004.
Chen, X. Q., Cui, P., Feng, Z. L., Chen, J., and Li, Y.: Artificial rainfall experimental study on landslide translation to debris flow, Yanshilixue Yu Gongcheng Xuebao/Chinese Journal of Rock Mechanics and Engineering, 25, 106–116. 2006.
Chiew, Y. M. and Parker, G.: Incipient sediment motion on non-horizontal slopes, J. Hydraul. Res., 32, 649–660, 1994.
Cui, P.: Study on condition and mechanisms of debris flow initiation by means of experiment, Chinese Sci. Bull., 37, 759–763, 1992.
Cui, P., Chen, X. Q., Zhu, Y. Y., Su, F. H., Wei, F. Q., Han, Y. S., Liu, H. J., and Zhuang, J. Q.: The Wenchuan earthquake (12 May 2008), Sichuan province, China, and resulting geohazards, Nat. Hazards, 56, 19–36, 2011.
Cui, P., Guo, C. X., Zhou, J. W., Hao, M. H., and Xu, F. G.: The mechanisms behind shallow failures in slopes comprised of landslide deposits, Eng. Geol., 11, 3779, doi:10.1016/j.enggeo.2014.04.009, 2014.
Fang, H., Cui, P., Pei, L. Z., and Zhou, X. J.: Model testing on rainfall-induced landslide of loose soil in Wenchuan earthquake region, Nat. Hazards Earth Syst. Sci., 12, 527–533, doi:10.5194/nhess-12-527-2012, 2012.
Fredlund, D. G. and Rahardjo, H. (Eds.): Soil Mechanics for Unsaturated Soils, John Wiley & Sons, USA, 1993.
Gabet, E. J. and Mudd, S. M.: The mobilization of debris flows from shallow landslides, Geomorphology, 74, 207–218, 2006.

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2, 4487–4524, 2014

Gregoretti, C. and Fontana, G. D.: The triggering of debris flow due to channel-bed failure in some alpine headwater basins of the Dolomites: analyses of critical runoff, Hydrol. Process., 22, 2248–2263, 2008.

Huang, C. C., Lo, C. L., Jang, J. S., and Hwu, L. K.: Internal soil moisture response to rainfall-induced slope failures and debris discharge, Eng. Geol., 101, 134–145, 2008.

Huang, C. C., Ju, Y. J., Hwu, L. K., and Lee, J. L.: Internal soil moisture and piezometric responses to rainfall-induced shallow slope failures, J. Hydrol., 370, 39–51, 2009.

Hungr, O., Evans, S. G., Bovis, M. J., and Hutchinson, J. N.: A review of the classification of landslides of the flow type, Environ. Eng. Geosci., 7, 221–238, 2001.

Hungr, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, Landslides, 11, 167–194, 2014.

Iverson, R. M., Reid, M. E., and LaHusen, R. G.: Debris-flow mobilization from landslides 1, Annu. Rev. Earth Pl. Sc., 25, 85–138, 1997.

Iverson, R. M., Reid, M. E., Iverson, N. R., LaHusen, R. G., Logan, M., Mann, J. E., and Brien, D. L.: Acute sensitivity of landslide rates to initial soil porosity, Science, 290, 513–516, 2000.

Iverson, R. M., Reid, M. E., Logan, M., LaHusen, R. G., Godt, J. W., and Griswold, J. P.: Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment, Nat. Geosci., 4, 116–121, 2011.

Klubertanz, G., Laloui, L., and Vulliet, L.: Identification of mechanisms for landslide type initiation of debris flows, Eng. Geol., 109, 114–123, 2009.

Lade, P. V.: The mechanics of surficial failure in soil slopes, Eng. Geol., 114, 57–64, 2010.

Lu, X. B. and Cui, P.: A study on water film in saturated sand, Int. J. Sediment Res., 25, 221–232, 2010.

Lu, X. B., Cui, P., Hu, K. H., and Zhang, X. H.: Initiation and development of water film by seepage, J. Mt. Sci., 7, 361–366, 2010.

Malet, J. P., Laigle, D., Remaître, A., and Maquaire, O.: Triggering conditions and mobility of debris flows associated to complex earthflows, Geomorphology, 66, 215–235, 2005.

Takahashi, T.: Mechanical characteristics of debris flow, J. Hydr. Eng. Div.-ASCE, 104, 1153–1169, 1978.

Tang, C., Van Asch, T. W. J., Chang, M., Chen, G. Q., Zhao, X. H., and Huang, X. C.: Catastrophic debris flows on 13 August 2010 in the Qingping area, southwestern China: the com-

bined effects of a strong earthquake and subsequent rainstorms, Geomorphology, 139, 559–576, 2012.
Take, W. A., Bolton, M. D., Wong, P. C. P., and Yeung, F. J.: Evaluation of landslide triggering mechanisms in model fill slopes, Landslides, 1, 173–184, 2004.
Tognacca, C., Bezzola, G. R., and Minor, H. E.: Threshold criterion for debris-flow initiation due to channel bed failure, in: Proceedings of the 2nd International Conference on Debris Flow Hazards Mitigation, Taipei, Taiwan, 16–18 August 2000, 89–97, 2000.
Wang, G. H. and Sassa, K,: Pore-pressure generation and movement of rainfall-induced landslides: effects of grain size and fine-particle content, Eng. Geol., 69, 109–125, 2003.
Wang, Z. Y. and Zhang, X. Y.: Initiation and laws of motion of debris flow, in: Proceedings of the International Symposium on the Hydraulics and Hydrology of Arid Lands in conjunction with the 1990 National Conference on Hydraulic Engineering, San Diego, California, 30 July–3 August, 596–601, 1990.
Zhou, J, W., Cui, P., and Fang, H.: Dynamic process analysis for the formation of Yangjiagou landslide-dammed lake triggered by the Wenchuan earthquake, China, Landslides, 10, 331–342, 2013a.
Zhou, J. W., Cui, P., Yang, X. G., Su, Z. M., and Guo, X. J.: Debris flows introduced in landslide deposits under rainfall conditions: the case of Wenjiagou gully, J. Mt. Sci., 10, 249–260, 2013b.
Zhuang, J. Q., Cui, P., Peng, J. B., Hu, K. H., and Iqbal, J.: Initiation process of debris flows on different slopes due to surface flow and trigger-specific strategies for mitigating post-earthquake in old Beichuan county, China, Environmental Earth Sciences, 68, 1391–1403, 2012.

Table 1. Comparative analysis of the previous initiation model for debris flow.

Model	Authors	Main feature	Critical condition	Range of application
Debris flow mobilization from landslides (DFMFL)	Iverson et al.	Failure face is parallel to the slope surface; the underground water is considered	Solving the safety factor	Debris flows form landslides
Coupling model of hydraulics and soil mechanics (CM)	Takahashi	Slope runoff surface and failure face are parallel to the slope surface	Solving the critical debris flow initiation depth	Water rock flow
Surface runoff model (SRM)	Berti and Simoni	Debris flow is triggered by surface runoff	Critical discharge of surface runoff	Channel debris flow
Empirical statistical model (ESM)	Cui	Soil failure is Column failure	Slope, saturation and fine particle content	–

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Table 2. Particle size distribution characteristics of the soil used in the experimental test.

Grain size (mm)	Cumulative ratio (%)			
	First layer	Second layer	Third layer	Original soil
80	100	100	100	100
60	100	100	100	91
40	100	90	82	82
20	40	60	72	71
5	10	28	40	26
2	10	18	10	10

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Table 3. Shear strength parameters of unconsolidated soil at different water content conditions.

Shear strength parameter	Unsaturated soil (water content 4.5–6.5 %)	Saturated soil (water content 15–17 %)	Natural soil (water content 1.0–2.0 %)
Cohesion (kPa)	22.3	~ 0	42.5
Friction angle (°)	37.6	32.3	38.1

Table 4. Model parameters for sensitivity analysis.

Sensitive factor	minimum value	maximum value	symbol	unit
Runoff velocity	0	10	v	$m\,s^{-1}$
Runoff depth	0.01	0.6	a	m
Slope angle	5	30	θ	°
Water unit weight	1×10^4	2×10^4	r_w	$N\,m^{-3}$
Surface roughness	0.03	0.07	Δ	m
Cohesion	5.0×10^3	3.5×10^4	c	Pa
Viscosity	8.0×10^{-6}	1×10^{-3}	ν	$m^2\,s^{-1}$
Angle of internal friction	20	50	φ	°
Failure depth	0.01	0.1	a	m

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Table 5. Model parameters that are used to simulate laboratory testing.

Parameter Name	Unit	Value
Soil unit weight r_{sat}	$N\,m^{-1}$	2.10×10^4
Water unit weight r_w	$N\,m^{-1}$	1.00×10^4
Slope angle θ	°	42
Cohesion c	kPa	0
Angle of internal friction φ	°	32.3
Runoff depth h	m	0.05
Runoff velocity v	$m\,s^{-1}$	1.70
Channel width	m	0.40
Roughness	mm	0.06
Viscosity ν	$m^2\,s^{-1}$	7×10^{-5}

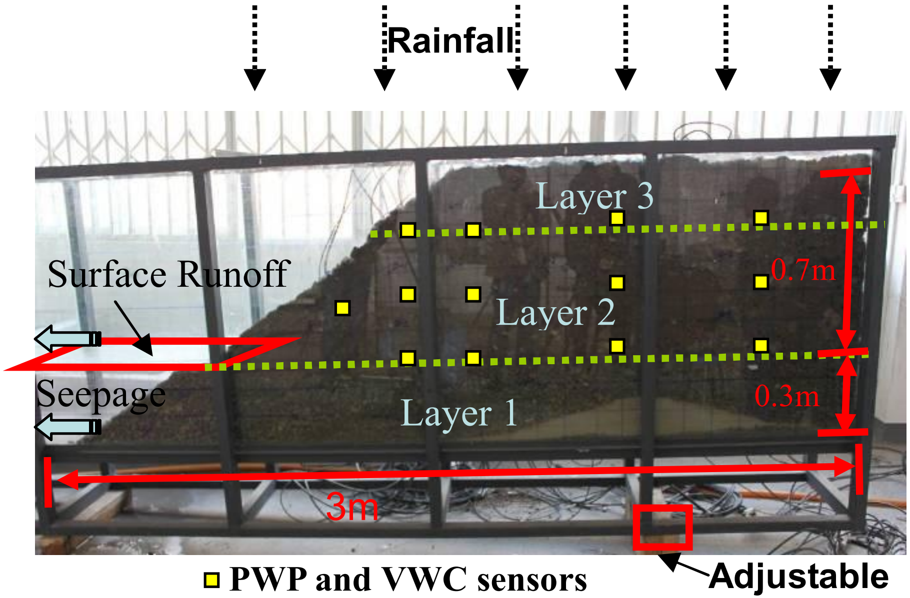

Figure 1. Artificial rainfall test equipment for unconsolidated soil (PWP and VWC are the pore water pressure and volumetric water content, respectively).

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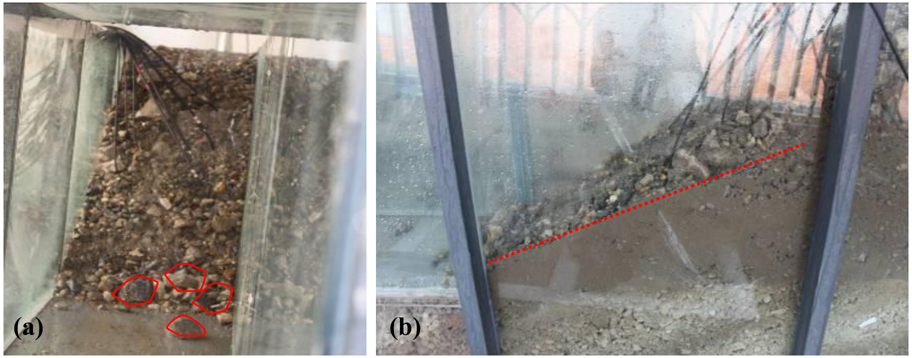

Figure 2. Shallow failure of the unconsolidated slope under a strong rainfall condition: **(a)** particle movements and small slide (front view) and **(b)** grain coarsening (side view).

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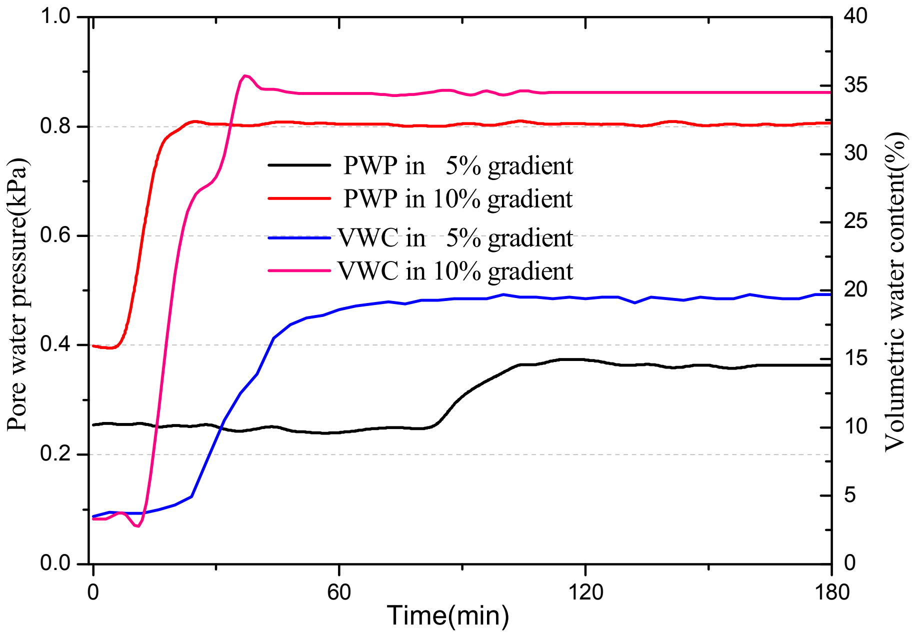

Figure 3. Variations in the pore water pressure and volumetric water content at slope toe during the rainfall process.

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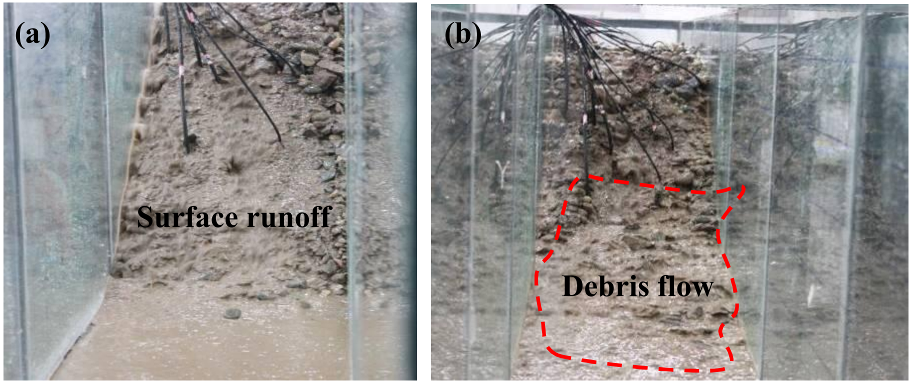

Figure 4. Debris flow initiated by the surface runoff: **(a)** surface runoff along the slope surface (front view) and **(b)** movement of the debris flow.

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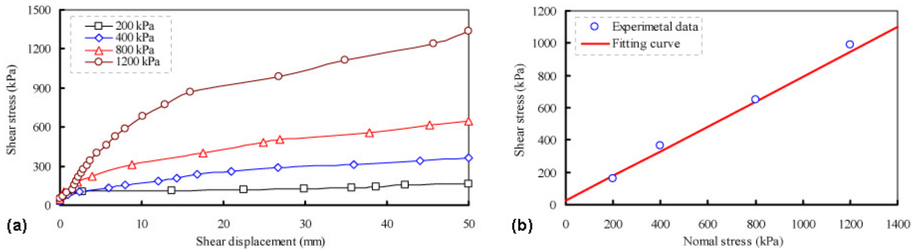

Figure 5. Experimental results of the shear tests for unconsolidated soil: **(a)** variation in the shear stress with the shear displacement and **(b)** shear strength parameters of the unconsolidated soil.

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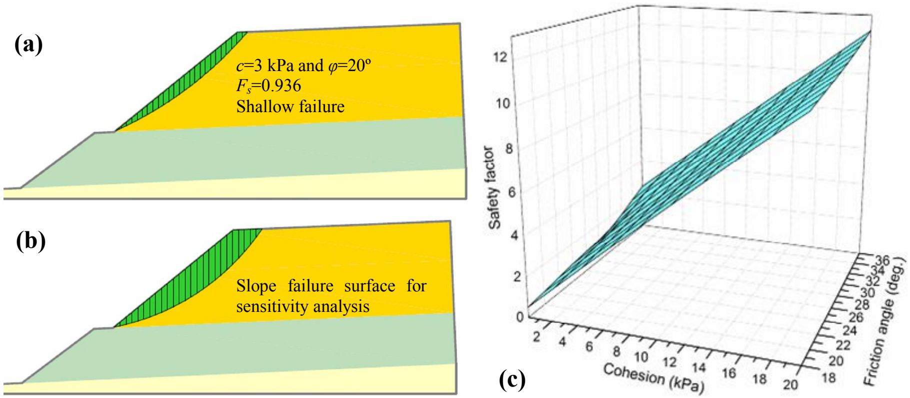

Figure 6. Slope stability analysis results of the experimental unconsolidated slope.

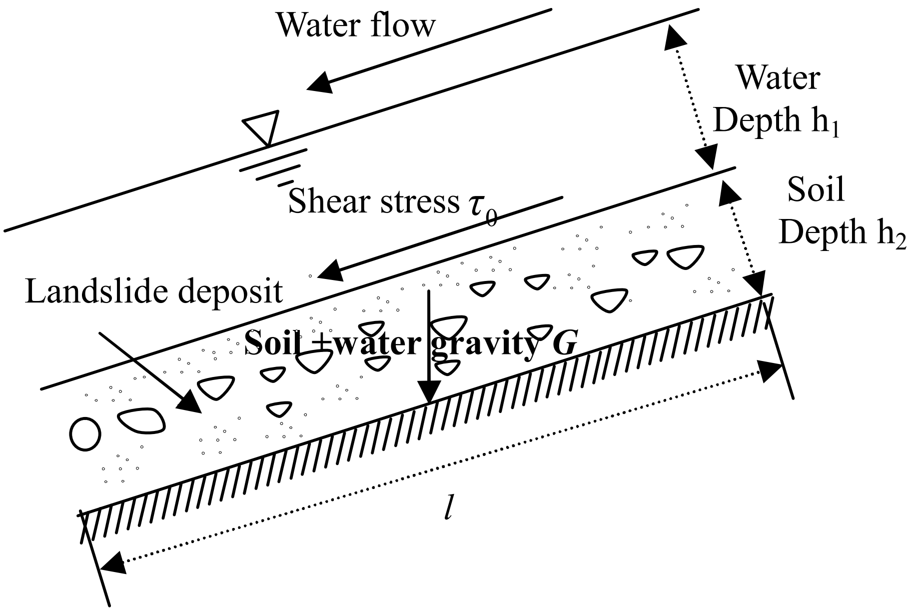

Figure 7. Simplification assumptions for the stress distribution of unconsolidated soil under hydrodynamic conditions.

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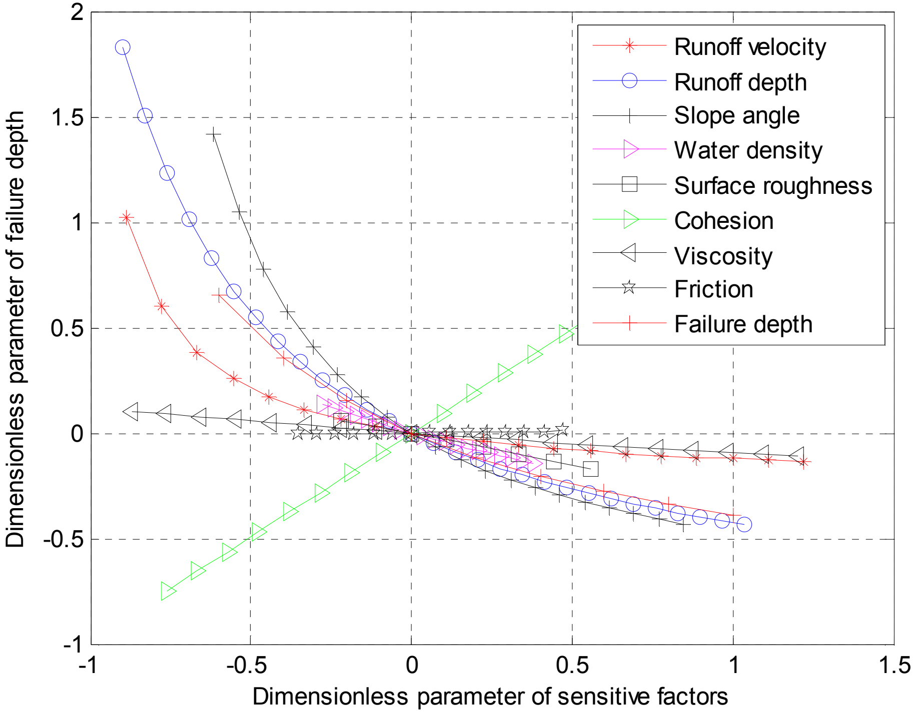

Figure 8. Sensitivity analysis results of the model parameters.

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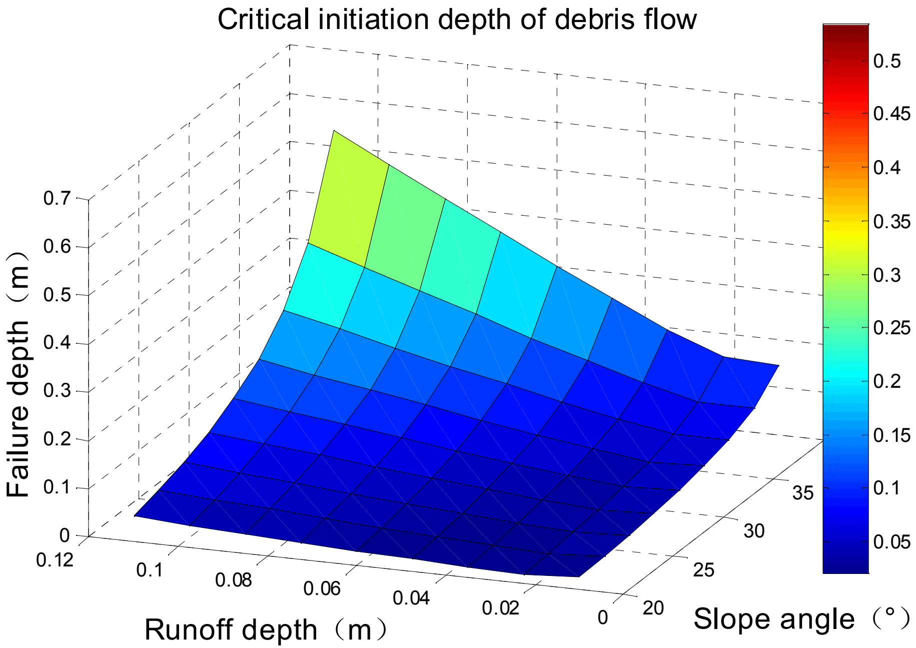

Figure 9. Critical failure depth in unconsolidated slopes under laboratory test conditions.

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