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Determination of the runoff threshold for triggering debris flows in the area affected by the Wenchuan Earthquake

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Abstract

We constructed an experiment to determine the critical runoff discharge for debris flow initiation in Wenchuan Earthquake area. A single dimensionless discharge variable was integrated to incorporate influential parameters, including channel width, median particle diameter, and surface flow discharge. The results revealed that relationship with the debris flow density, slope and discharge required. Taking into account the behaviors of debris flow formation corresponding to different ranges of slopes, the critical runoff thresholds for debris flow initiation were calculated for three different scenarios. The thresholds were validated against actual debris flow events, and the use in this study is applicable.

1 Introduction

The Wenchuan Earthquake (magnitude 8.0) on 12 May 2008 in Sichuan, China, was a massive event that triggered exceeding 3×10^4 geohazards, including rock avalanches, rock flows, and landslides (Cui et al., 2011). The soil particles originating from these depositional processes are widely distributed in the debris flow source region with sizes ranging from 10^{-6} m to 10^{1} m (Cui et al., 1999). Flooding easily mobilizes these particles, a phenomenon that has led to a major increase in the frequency of debris flows and in the magnitude of material discharges; this in turn increases the risk for major destructive events. Relatively minor rainfall events are capable of triggering gigantic debris flows in this area. Further, simultaneous debris flows often result in a complex damage process that is accompanied by multiple hazards. For instance, the deposition of debris flows on 13 August 2010, throughout the study area, blocked rivers and destroyed entire towns (Tang et al., 2012; Cui et al., 2013). For disaster mitigation, it is vital to study the threshold criteria and develop initiation models for debris flows caused by surface water movement, and thus accurately forecast debris flow occurrences.

Rapidly moving surface water is considered to be one of the three major factors influencing the initiation of debris flows, because it initiates the movement of unconsolidated materials in channels (Takahashi, 1991). Therefore models of debris flow initiation in channels (Takahashi, 1978; Rice et al., 1998; Gregoretti, 2000; Tognacca et al., 2000; Gregoretti and Fontana, 2008) have been widely studied, using both dynamics/physics and empirical observations/statistics. However, models are overwhelmingly favored, due to the impracticability of conducting in-situ observations and experiments for debris-flow occurrences. The key factors incorporated into such models are the generation of loose materials, slope gradients, median particle diameter (D_{50}), and flood discharges (Takahashi, 1978; Cui, 1992; Martin and Moody, 2001). By defining the critical flood conditions that trigger debris flows as a function of the aforementioned factors, the model can be presented as a formula (Gregoretti, 2000; Tognacca et al., 2000):

$$q^* = \frac{a}{\tan\theta^b}$$

Where q^* is a dimensionless unit of width discharge, θ is the slope gradient, and a and b are constants. This formula, which is characterized by the two constants, is generally applicable locally for studying variation in loose soil generation and in calibrating experimental devices.

Most of the aforementioned studies used coarse (non-clayey) soil samples in their experiments. The exclusion of fine particles in analyzing debris flow initiation likely leads to a misrepresentation of critical discharge thresholds (Rice et al., 1998; Gregoretti, 2000; Tognacca et al., 2000). Further, the criteria for debris flow initiation vary between areas. Therefore, a new model to predict these thresholds must be developed for the area affected by the Wenchuan Earthquake.

The objective of this paper is to identify the relationships among debris-flow generation and its causal factors, and to propose a model of critical runoff that triggers debris flows, by considering the role of fine particles. The results of this study will assist in disaster mitigation in the area affected by the Wenchuan Earthquake.

2 Study area

The study area is located along the major Longmenshan Fault; this area was subjected to both an earthquake and large landslides triggered by the former. It has become a significant focal point for debris flow formation, due to the presence of abundant unconsolidated soil materials in catchments. We focused our study on the mountainous county of Beichuan, which was particularly severely affected by the earthquake (Fig. 1). Soon after the earthquake, 72 gully debris flows were induced by a storm on 24 September 2008, leading to the deaths of 42 people in Beichuan County and the destruction of several roads (Tang et al., 2011). Experiments were conducted on materials deposited in the Huashiban Gully, because they are representative of the loose, widely graded soil that is abundant in the affected area.

Soils were collected from the landslide deposition area, and the sampled particles were physically characterized. The basic characteristics of the materials are shown Table 1.

3 Experiment

3.1 Parameter selection and dimensional analysis

Several researchers have identified the critical parameters influencing debris flow initiation based on statistical analyses and experiments (Takahashi, 1991; Rice et al., 1998; Tognacca et al., 2000; Gregoretti, 2000; Gregoretti and Fontana, 2008). Consequently, several empirical relationships have been proposed to estimate these parameters. The consensus is that the key parameters controlling debris flow initiation are the slope angle, surface water discharge, and particle composition (Takahashi, 1978; Wang et al., 1989; Cui, 1992; Martin and Moody, 2001). The mean particle size, D_M, which is defined as the sum of the products of the mean particle class diameter multiplied by the corresponding particle class frequency, is the most common parameter used to reflect the particle composition of the material.

Considering the modeling flexibility and model application, we constructed a dimensionless surface discharge variable as follows:

$$q^* = Q/dg^{0.5}D_{\mathrm{M}}^{1.5} \quad (1)$$

Where q^* is the dimensionless surface water discharge; Q ($\mathrm{m^3\,s^{-1}}$) is the surface water discharge; g ($\mathrm{m\,s^{-2}}$) is the acceleration due to gravity; D_{M} (m) is the mean particle size; and d (m) is the width of the channel bed. Using this equation, the causal parameters are condensed to the discharge and the channel slope.

3.2 Experimental design

It is difficult to develop a prototype experiment for studying the threshold criteria for debris flow initiation because of the high speed (up to $15\,\mathrm{m\,s^{-1}}$) and volumes of discharges, and a wide range in particle sizes (ranging from 1×10^{-6} m to 10 m) (Cui et al., 1999); thus, mini-simulation experiments are commonly favored (Takahashi, 1978; Mainali and Rajaratnam, 1994; Cui, 1992; Tognacca et al., 2000). We used a straight slope mini-simulator in this study. The laboratory flume (Fig. 2) had a length of 300 cm a width of 20 cm and a depth of 250 cm depth; the inclination angle varied from 10 to 25°. The flume was used to optimize parameter adjustment in the model. Meanwhile, the discharge of surface water was adjusted by changing the water level in the source tank.

About 100 kg of unconsolidated soil was used in the experiment. Soil samples were air-dried and the particle sizes were measured. Analysis revealed that gravel and sand were dominant, with silt and clay accounting for about 5 %. Particles smaller than 5 mm in diameter comprised approximately 50 % of the soil; these particles significantly influence the internal mechanical responses to water. Therefore, considering the width of the experimental flume and scale effects, all particles larger than 5 mm in diameter were screened out. Particle sizes were measured as shown in Fig. 3.

In the simulation, the water discharge, debris flow discharge and debris-flow bulk density were recorded. The water discharge was recorded after adjusting the water level of the source tank, using the following equation:

$$q = \mu b e \sqrt{2 g H_0} \tag{2}$$

$$\mu = 0.6 - 0.18 \frac{e}{H_0} \tag{3}$$

Where, q is the water-flow discharge ($\mathrm{m^3\,s^{-1}}$), b is the width of the sluice (m), e is the height of the sluice (m), and H_0 is the water level in the source tank.

The debris-flow discharge was measured by the cross-section method as follows:

$$Q = V \times D \times W \tag{4}$$

where, Q ($\mathrm{m^3\,s^{-1}}$) is the debris-flow discharge, W (m) is the channel width, D (m) is the mean hydraulic depth, and V ($\mathrm{m\,s^{-1}}$) is the mean flow velocity

4 Results

4.1 Experimental data

Sixty-one experiments (with 16 failures) were conducted to test the critical values of the selected parameters (Table 2).

4.2 Relationships among debris-flow bulk density, water flow, and slope

We considered 1.3 $\mathrm{g\,cm^{-3}}$ to be the lowest reasonable value for the bulk density of debris flows (Kang et al., 2004). Next, we analyzed the debris flow density after factoring the causal parameters into the model, namely, the slope and water discharge. Under all slope conditions, the debris flow density increased in a nearly linearly manner with the water discharge rate, but the rates of increase were affected by the slope (Fig. 4). These rates were significantly greater at high slope angles and accelerated exponentially; the effect of slope on the bulk density of debris flows is indicated in Fig. 5.

4.3 Critical equations for debris-flow formation

As indicated earlier, we considered the debris flow to have formed when the bulk density of the fluid exceeded 1.3 g cm^{-3} (Kang et al., 2004). By analyzing the slope angles and water discharge conditions, the criteria for the formation of debris flows were identified as shown in Fig. 6. The main finding was that the dimensionless critical surface water flow decreases with increasing slope. In other words, debris flows are more easily formed on steeper slopes. The graphical relationship between the two was divided into three sections, as indicated in Fig. 6:

The graph displays the best-fit curves to denote the critical thresholds for debris flow formation across different slope subsections.

$$\begin{aligned} q^* &= \frac{40}{\tan\theta^{0.1}} \quad \Theta = 12 \pm 2 \\ q^* &= \frac{2.4}{\tan\theta^{2.1}} \quad \Theta = 17 \pm 3 \\ q^* &= \frac{6.3}{\tan\theta^{1.08}} \quad \Theta = 22.5 \pm 2.5 \end{aligned} \tag{5}$$

Since $q^* = Q/dg^{0.5}D_\mathrm{M}^{1.5}$, these can be rewritten as:

$$\begin{aligned} Q &= 40\frac{dg^{0.5}D_\mathrm{M}^{1.5}}{(\tan\theta)^{0.1}} \quad \Theta = 12 \pm 2 \\ Q &= 2.4\frac{dg^{0.5}D_\mathrm{M}^{1.5}}{(\tan\theta)^{2.1}} \quad \Theta = 17 \pm 3 \end{aligned} \tag{6}$$

$$Q = 6.3\frac{dg^{0.5}D_{\mathrm{M}}^{1.5}}{(\tan\theta)^{1.08}} \quad \Theta = 22.5 \pm 2.5$$

This classification of the critical conditions can be explained as follows: under slope angles of 10–14°, debris flow formation occurs as intense rainfall initially causes rill erosion on the slopes, which is followed by the gradual failure of the soil structure along the rill channels slowly. Thereafter, a debris flow develops. When slope angles are between 14 and 20°, the headward and down-cutting erosion on the slopes is drastic and evident; this erosion permits the formation of debris flows. Lastly, when slope angles are larger than 20°, materials on these slopes readily slide due to the effects of overland runoff and infiltration, leading to the suspension of soil particles in the flowing water.

5 Comparison and validation

5.1 Comparison with other studies

Debris flows due to channel failures triggered by runoff are ubiquitous phenomena in mountainous areas. Due to regional variability, it is impractical to develop a uniform model to predict debris flow initiation. Therefore, interpretation of research findings has to take into account the unique characteristics of each region, and differences in the types of materials used and experimental methods.

Tognacca et al. (2000), following the approach of Schoktlitsch (1943), Graf (1971), and Bathurst et al. (1987), used a mixture of sand and gravel as experimental material to provide a threshold criterion for the formation of a debris flow front. This defined the minimum surface discharge, Q, a necessary condition to initiate mobilization of debris materials along a channel and thereby trigger debris flows as a function of the bed slope, Θ, and the mean particle size, D_{M}, of the debris material:

$$q^* = \frac{1.0}{\tan\theta^{1.17}} \tag{7}$$

Where $q^* = Q/\left(\left(\rho_s/\rho - 1\right)^{0.5} g^{0.5} D_{\mathrm{M}}^{1.5}\right)$ is the dimensionless critical discharge per unit width, and ρ_{s} and ρ are the sediment and water densities, respectively.

A similar relationship was also obtained by Gregoretti (2000), who used uniform sand with a narrow diameter range of 0.023 to 0.034 m as the experimental material:

$$q^* = \frac{0.195}{\tan\theta^{1.27}} \tag{8}$$

Besides these, Lanzoni and Tubino (1993) and Rice et al. (1998) used uniform gravel as the experimental material, whereas Takahashi (1978) generated a uniform debris flow with heterogeneous experimental material. In this study, we compared our results with those of the models established by Takahashi (1978), Tognacca et al. (2000), and Gregoretti (2000). Our results are similar to those of Takahashi (1978), and intermediate between Gregoretti (2000) and Tognacca et al. (2000), as shown in Fig. 7.

Comparing our results with those of other studies, one of the most notable differences is the criterion of debris flow formation. As the flow conditions for incipient sediment motion are exceeded, the hydrodynamic forces exerted by the current on the gravel overlying an impermeable surface coupled with the relatively marked action of gravity tend to consistently erode this layer, thereby dispersing the particles. The intense inter-particle collisions caused by this constant mass movement increase the shear stress at the bottom of the layer. This strengthens erosion and associated transport processes before sliding occurs. Therefore, from this aspect, Takahashi's criterion (1978, 1991) for the triggering of debris flows should be regarded as an upper limit, one that is likely to be reached when the increase in water flow over the sediment bed is relatively quick and sudden. On the contrary, Gregoretti's criterion (2000) is a lower limit because it is hypothesized that the beginning of the scouring process represents the initiation of the debris flow. In our study, we assumed that a debris flow forms at a bulk density greater than 1.3 g cm^{-3}, which is a widely used convention in China (Kang et al., 2004).

Differences in the type of experimental material used are an important factor influencing the calculations of thresholds. As indicated above, we used a loose soil comprising about 3.5 % clay, which is similar to that used by Takahashi (1978) but different from other studies. The tendency for runoff to transport debris lying at the bottom of the channel with the initiation of a debris flow depends on the particle size of the deposits. Fine particle transportation leads to their accumulation at the foot of slopes. Therefore, shallow regressive failures form easily, a finding that is apparently confirmed by the cited studies. However, a mixture of sand and gravel does not interact with water in a similar manner. Therefore, the proportion of clay is inversely correlated to the runoff discharge threshold at which debris deposits are mobilized.

5.2 Validation of the model

The abundant loose materials triggered by Wenchuan Earthquake in the debris flow source region are primarily responsible for stimulating debris-flow occurrences, since local climatic conditions and topography have not changed significantly since the earthquake. As a result, both the frequency and magnitude of such debris flows have dramatically increased since the earthquake, with associated casualties and property losses. A series of debris flow events after the earthquake, leading to heavy losses of life and property, serve as the evidence both to explain the processes of debris flow development on unconsolidated deposits and to validate the experimental results from our study. To validate the critical Eq. (6), several catchments in the study area were sampled. First, we calculated the runoff thresholds for debris flows in catchments using Eq. (6) as Q_1 in Table 3; this was based on the actual soil particle composition in samples collected in the debris flow source region. Next, the debris flow initiation region was identified on the topographical map of the region. Based on topographical parameters, including the runoff concentration area, slope length and average slope gradient, we calculated the runoff at different rainfall frequencies by the method known as the "Flood Calculation of Medium and Small Basins in Sichuan Province" (Eq. 7), which was originally proposed by the Sichuan Hydraulical Department and has been widely used in small watersheds in Sichuan Province (Zhou et al., 1991; Wu et al., 1993). Finally, we conducted tests of precision by comparing the results of the two models. The results show that the critical runoff threshold calculated by Eq. (6) is lower than but comparable to the runoff calculated at a rainfall frequency of $P = 99\,\%$ by Eq. (7), (Fig. 8) – which is reasonable given the behavior of debris flows following the earthquake. This suggests that Eq. (6) can be applied to the area affected by the Wenchuan Earthquake.

$$Q = 0.278\psi i A \tag{9}$$

Where Q ($\mathrm{m^3\,s^{-1}}$) is the runoff, and ψ is the peak runoff coefficient, which is determined by the rainfall intensity and duration of flow, and can be calculated based on topographical parameters. Finally, A ($\mathrm{km^2}$) is the area of the catchment.

In Table 3, the corresponding number for each gully is indicated in Fig. 1; d (m) is the width of the channel bed, measured in situ; Slope (°) is the average channel slope gradient in the debris flow initiation regions; Q_1 ($\mathrm{m^3\,s^{-1}}$) is the surface water discharge calculated by Eq. (6); A ($\mathrm{km^2}$) is the area of the runoff concentration region in the watershed; L (m) is the length of the gully channel; Q_2 ($\mathrm{m^3\,s^{-1}}$) is the water discharge calculated using Eq. (7).

The above analysis reveals our classification of critical thresholds based on slope conditions accurately reflects actual observations. Combined with the hydrological model, these criteria can be used to forecast debris flows for disaster mitigation in the area affected by the Wenchuan Earthquake.

6 Discussion and conclusion

The abundant, unconsolidated, widely graded soil produced by the landslides generated by the Wenchuan Earthquake make the catchments prone to generating frequent debris flows. Therefore, it is expected that debris flows will continue to occur in this area for a long time due to the large amounts of sediment available. Determination of critical thresholds is essential to forecast debris flow formation. By analyzing data on fluid discharges and bulk densities under different slope gradients, the following conclusions can be drawn:

There are positive correlations between the debris flow density with slope angle and initial water discharge. There is a linear increase in the debris flow density as the initial water discharge increases. The relationship between the increase in debris flow density and slope angle generally obeys an exponential law. Considering the behaviors and processes of debris flow formation in relation to different slope ranges during our experiments, the criteria for debris-flow initiation can be defined by three separate equations for the three slope ranges as follows: $Q = 40\frac{dg^{0.5}D_{\mathrm{M}}^{1.5}}{(\tan\theta)^{0.1}}$ at a slope of 12 ± 2°, $Q = 2.4\frac{dg^{0.5}D_{\mathrm{M}}^{1.5}}{(\tan\theta)^{2.1}}$ at a slope of 17 ± 3°, $Q = 6.3\frac{dg^{0.5}D_{\mathrm{M}}^{1.5}}{(\tan\theta)^{1.08}}$ at a slope of 22.5 ± 2.5°. The differences between the findings of this study and those of other studies pertain to the criteria governing debris flow formation. In addition, our experimental material contained clay, which more closely resembles natural materials in the study area. Validation using data from actual debris flow events in several gullies in the study area illustrates that the actual thresholds are comparable to but lower than the runoff thresholds calculated at a rainfall frequency of $P = 99\,\%$. This illustrates that these criteria can be used in catchments with abundant supplies of loose materials, with the assumption that debris flows are primarily influenced by the surface water flow.

Our study proposed an improved experimental model to predict the critical thresholds for debris flows, based on the interaction between slope angle and the critical water discharge. However, it must be noted that this model is an oversimplification of natural conditions, since other factors, such as changes in material supplied, variation in channel conditions, and fluid characteristics, must also be considered. For debris flow initiation, as pointed out by Crosta and Frattini (2001), it is difficult to clearly explain the critical threshold and its relation to the debris flow process because a multitude of factors are involved. Therefore, the critical conditions proposed in this paper are restricted to catchments with abundant supplies of loose materials, especially those in the area severely stricken by the Wenchuan Earthquake.

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Table 1. Physical characteristics of the soil materials used in the experiment.

Material	Soil moisture (%)	Porosity (%)	Bulk density (g cm^{-3})	D_{50} (m)
Quasi-debris	12.8	22.1	1.8	0.0053

Table 2. Experimental data on debris flows initiating using a flume.

Slope (°)	Dimensionless surface water discharge	Debris flow bulk density ($g\,cm^{-3}$)	Slope (°)	Dimensionless surface water discharge	Debris flow bulk density ($g\,cm^{-3}$)
10	54	1.53	17.5	33.1	1.55
10	52.7	1.51	17.5	31.7	1.42
10	51.2	1.47	17.5	30.2	1.36
10	49.6	1.42	17.5	28.6	1.26
10	48.1	1.4	17.5	26.9	1.19
10	46.3	1.28	20	26.9	1.76
10	44.7	1.26	20	25.4	1.69
10	43.2	1.2	20	23.8	1.57
12.5	51.2	1.56	20	22.3	1.48
12.5	49.6	1.47	20	20.9	1.34
12.5	48.1	1.41	20	19.2	1.27
12.5	46.6	1.33	20	17.6	1.19
12.5	45	1.28	22.5	20.9	1.77
12.5	43.4	1.2	22.5	19.5	1.69
15	45.6	1.7	22.5	18	1.55
15	43.7	1.63	22.5	16.6	1.47
15	42.2	1.52	22.5	15	1.23
15	40.6	1.4	25	19.4	1.82
15	38.9	1.32	25	17.9	1.77
15	37.4	1.28	25	16.4	1.61
15	35.8	1.24	25	15	1.47
17.5	36.4	1.73	25	13.3	1.22
17.5	34.8	1.67			

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Table 3. Comparison of critical thresholds at different locations in Wenchuan Earthquake area, based on a widely used rainfall–runoff model (described in the text).

No.	Gully Name	Slope (°)	d(m)	D_M (m)	Q_1 ($m^3 s^{-1}$)	A (km^2)	L (m)	Q_2 ($m^3 s^{-1}$)
1	Niujuan	13.2	20	0.018	6.99	0.55	0.8	10.01
2	Mozi	16.4	20	0.018	4.74	0.53	0.6	7.47
3	Ergou	10.4	30	0.019	11.66	0.57	0.9	13.57
4	Chediguan	14.8	25	0.019	8.06	5.34	3.1	9.50
5	Bayi	11.8	25	0.021	11.14	3.61	2.9	16.74
6	Gangou	15.1	20	0.021	7.21	2.43	1.9	12.95
7	Shenxi	12.0	30	0.021	13.34	3.38	2.1	18.88
8	Xiangshuidong	20.0	15	0.019	2.31	1.64	1.6	3.69
9	Yinchang	10.6	30	0.019	11.63	1.55	1.5	18.71
10	Baiguoping	17.7	12	0.021	2.47	3.16	2.3	4.09
11	Shaoyaogou	16.2	15	0.02	4.29	4.92	5.2	8.69
12	Xiaogangjian	21.3	12	0.02	1.85	2.87	3.1	3.37
13	Zoumaling	15.9	15	0.02	4.48	5.70	7.1	8.42

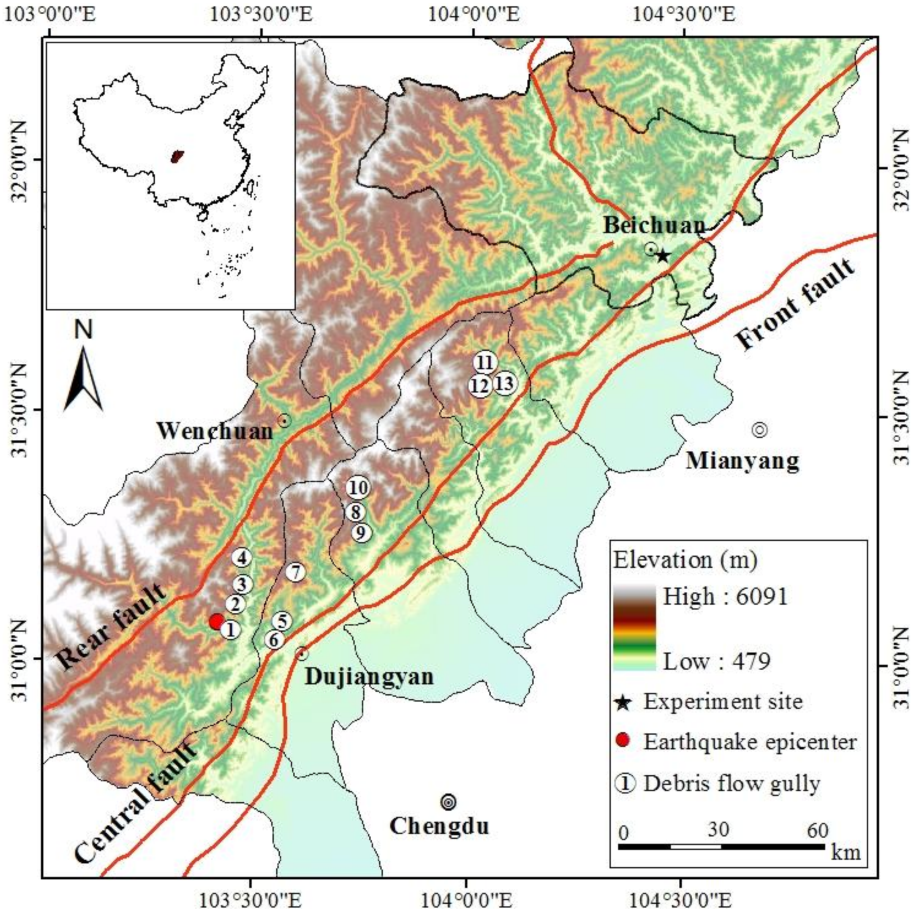

Figure 1. Location of the experimental site.

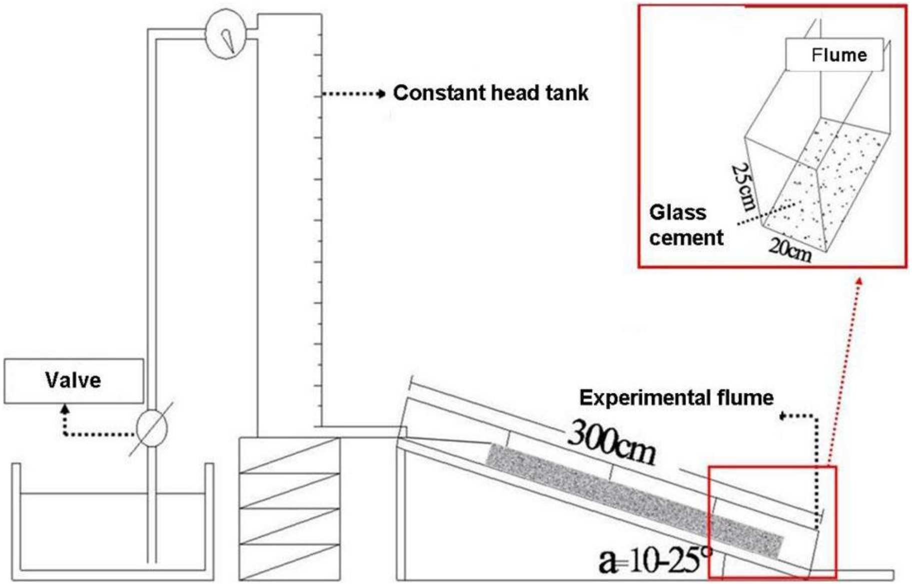

Figure 2. The experimental setup to establish critical thresholds for debris flow initiation.

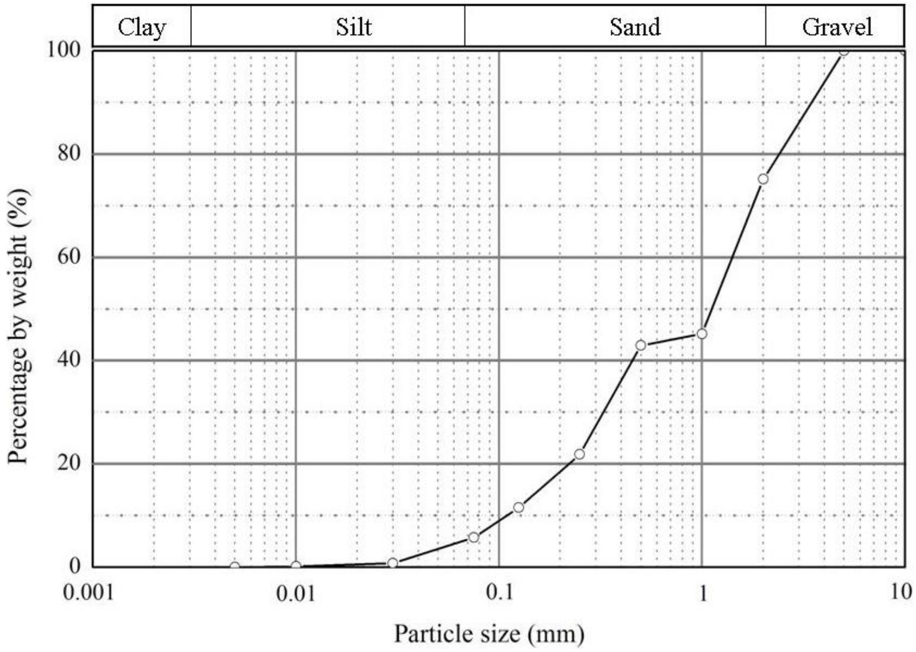

Figure 3. The particle size distribution of the unconsolidated soil used in this study.

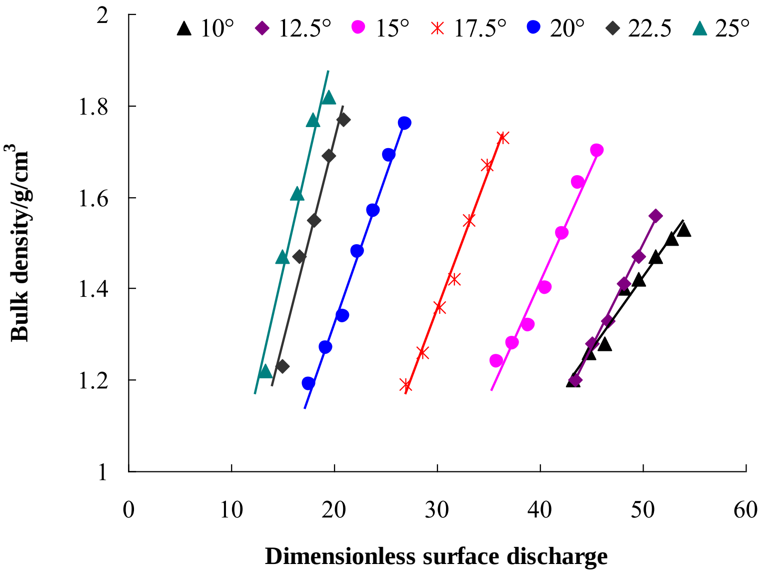

Figure 4. Rate of increase in debris flow bulk density in response to water discharge under different slope angles.

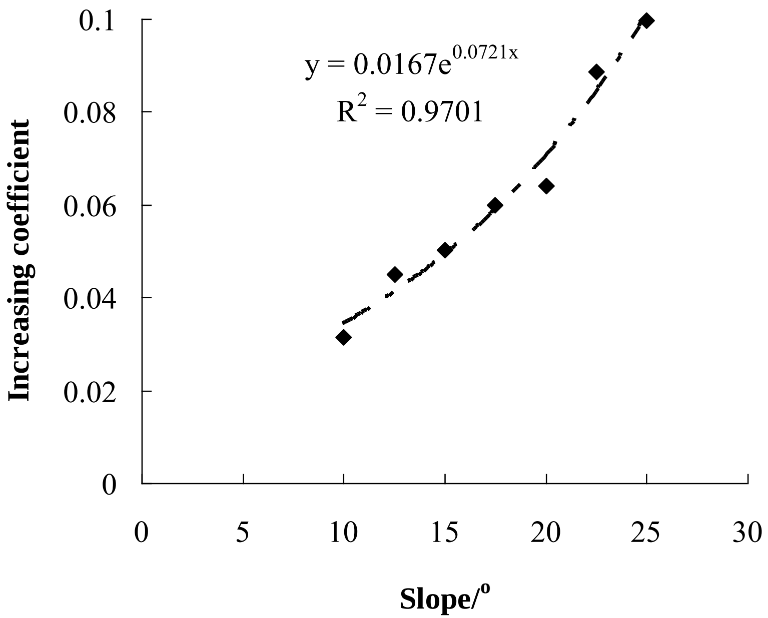

Figure 5. The relationship between the slope angle and the rate of debris flow density with increasing water discharges.

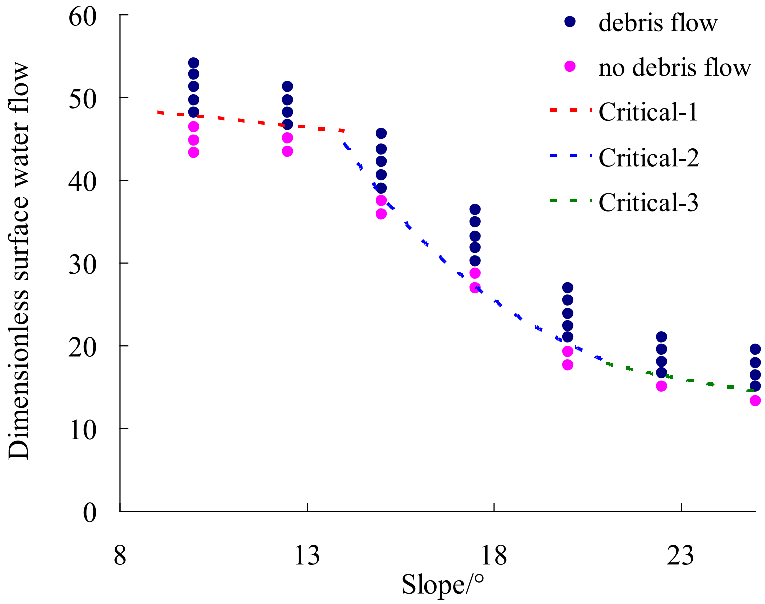

Figure 6. The relationship between water discharge and slope.

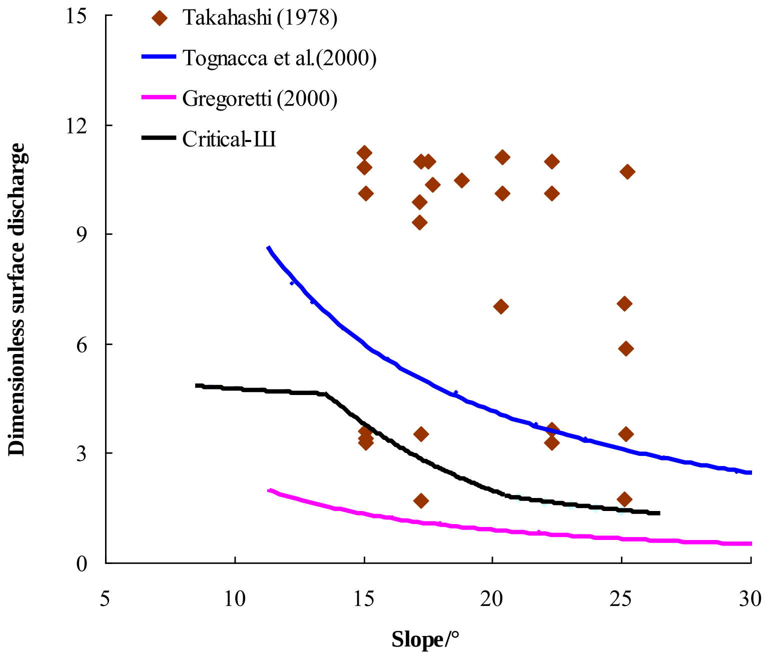

Figure 7. Comparison of the equations from different studies for calculating the discharge threshold.

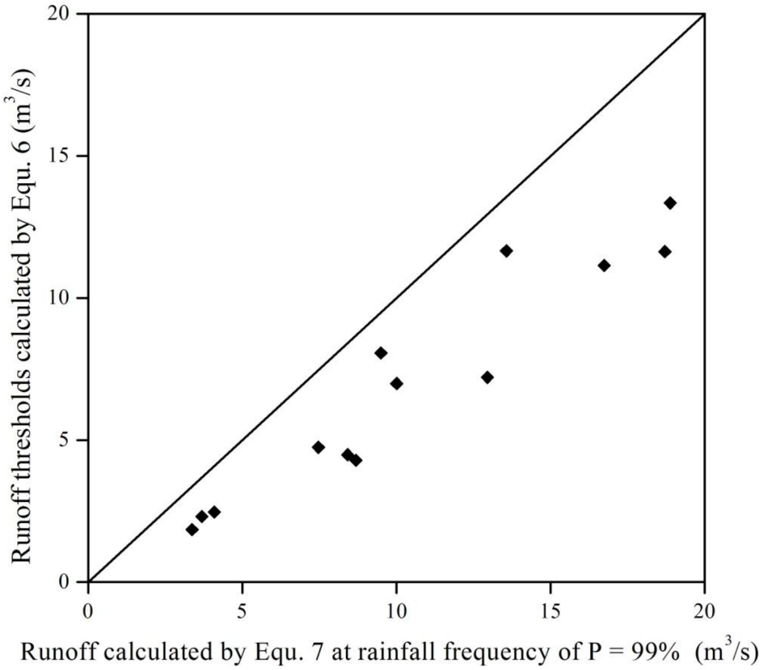

Figure 8. Comparison of the critical thresholds with the runoff calculated using Eq. (7) at a rainfall frequency of $P = 99\,\%$.