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A simplified physically based coupled rainfall threshold model for triggering landslides

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ABSTRACT

A number of rainfall threshold models for triggering landslides have been developed in either empirical or physical manner. The objective of an empirical rainfall threshold model is to establish a relationship between rainfall intensity and duration, which is a line on a log–log diagram, although the mechanism of the relationship following the power law is not yet well understood. The sufficiency of rainfall and landslide data is also a significant concern for empirical models. A simplified physically based rainfall threshold model is developed by coupling the Mohr–Coulomb law and Darcy's law based on the assumptions that the slope has an infinite length and that discrete water diffusion is physically based. The power-law mechanism for the relationship between rainfall intensity and duration for the initiation of a landslide is investigated using this physically based model. The rainfall threshold calculated with the model shows that the threshold follows the power law for short rainfall durations whereas it gradually tends towards a constant value for long rainfall durations. Case studies have shown that a plausible threshold for regions that lack sufficient landslide and rainfall data can be obtained via the model. The model is also applied to cases which occurred in regions geologically typical of Fujian Province, southeast China. The landslide distribution predicted by our model accords with the interpretation of high resolution satellite imagery, and this suggests that the proposed physically based model also effectively determines rainfall thresholds for triggering regional landslides.

1. Introduction

Rainfall-induced landslides are common in the southeast coastal areas of China. Typhoons carrying heavy rainfall from April to September can lead to landslides on a large-scale, which pose a severe threat to public safety (Wu et al., 2014). Thus, the prediction of rainfall-induced landslides is quite significant for these areas. Rainfall threshold is a lower boundary for triggering landslides and is essential for prediction of storm-induced landslides because there is an empirical relationship between rainfall threshold and landslides. There are multiple forms of rainfall threshold, e.g., intensity–duration (Caine, 1980; Guzzetti et al., 2007, 2008), daily precipitation (Crozier, 1999; Glade et al., 2000), and event rainfall (Bell and Maud, 2000). The form of a rainfall threshold is determined by monitoring equipments and local rainfall characteristics.

The rainfall threshold for landslides can be determined by two types of models: empirically based and physically based models (Guzzetti et al., 2007; Martelloni et al., 2012). Empirically based models are popular due to their simplicity. Most regional rainfall thresholds for triggering landslides are obtained by empirically based models (Aleotti, 2004; Caine, 1980; Guzzetti et al., 2008). The empirical rainfall threshold that is most commonly used is based on the relationship between rainfall intensity and duration, which is a line on a log–log diagram. Although intensive research demonstrates that the rainfall threshold for triggering landslides drops exponentially, the physical mechanisms associated with this phenomenon have not been made clear.

However, the empirically based model cannot give an accurate rainfall threshold with insufficient landslide information. Physically based models have been providing the best way to solve the problem, they are able to predict the time of landslides' possible occurrence, as well as their location. Models of this type take into account the dominant mechanical processes of landslides. Mechanical parameters, such as cohesion and friction angle, are involved. SINMAP (Pack et al., 1998; Terhorst and Kreja, 2009) and TRIGRS (Baum et al., 2002, 2005; Kim et al., 2010; Liao et al., 2011) are two widely used physically based models which use Factor of Safety as a criterion to evaluate landslides. However, these models cannot provide a rainfall threshold for triggering landslides in regions or for a specific landslide.

The Critical RainFall (CRF) model (Salciarini et al., 2008), a module of TRIGRS (Baum et al., 2002), which provides an intensity–duration threshold, can solve this problem. The assumption of the CRF model is

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that the peak pore pressure head on the failure surface is at the end of rainfall period. The CRF-v2 model (Salciarini et al., 2012) is an improved version of the CRF model. In the CRF-v2 model it is considered that the pressure head on the failure surface reaches a peak that is not at the end of the rainfall event. Thus, the CRF-v2 model provides more realistic results than the CRF model. However, the rainfall threshold calculated using the CRF models is slightly lower than that observed for long duration, since the model for long duration neglects lateral pore pressure transmission. Thus, these models are not suitable for predicting rainfall thresholds for triggering landslides for sites stricken by long-lasting rains. In addition, a daily rainfall threshold is more useful for predicting landslides in some regions, especially those where hourly rainfall data are lacking, and the CRF models cannot reflect changes in daily rainfall threshold upon changes in rainfall.

Obtaining the rainfall threshold is very difficult. This is because rainfall processes are complicated, and the soil parameters have uncertainties. Therefore, a Monte Carlo simulation was adopted to address the complexities of rainfall processes and the variability of soil parameters (Peres and Cancelliere, 2014). However, considering the time required for calculating the rainfall threshold at each cell, the Monte-Carlo approach is not suitable for determining rainfall thresholds for a region.

The aim of this study is to enhance the adaptive capacity of a physically based model and determine a rainfall threshold with a change in rainfall. Then, due to the decrease in effective stress and strength resulting from pore pressure, and we assume that the rainfall threshold is related to the ratio of the height of the saturated layer to the height of the sliding body and that water can infiltrate easily into the soil through macro-pores and cracks whereby the rainfall threshold on different spatial and time scales can be obtained via the model. A specific landslide and a region were selected for validating the proposed model. In addition, we intend to explain why the relationship between rainfall intensity and rainfall duration from our proposed physically based model differs a little from the relationship which the traditional power law indicates.

2. Theoretical model

For shallow landslides, the failure surface is approximately parallel to the slope surface and the bedrock can be considered impermeable (Chang et al., 2014; Pack et al., 1998). As most of the rainfall can easily infiltrate into the deeper parts of channels through the cracks and failure surfaces (Montrasio and Valentino, 2008), rainfall, which can influence the pore water pressure on a crack or failure surface, is an important triggering factor.

The infinite-slope model (Fig. 1) is therefore adopted in this work. Factor of Safety (F_s), is defined by the ratio of the stabilizing force F_r to the destabilizing force F_d. The stabilizing force F_r is calculated by the Mohr–Coulomb strength criterion, and the destabilizing force F_d is the sum of the gravitational forces along the slope and the seepage force. The expression for Factor of Safety is:

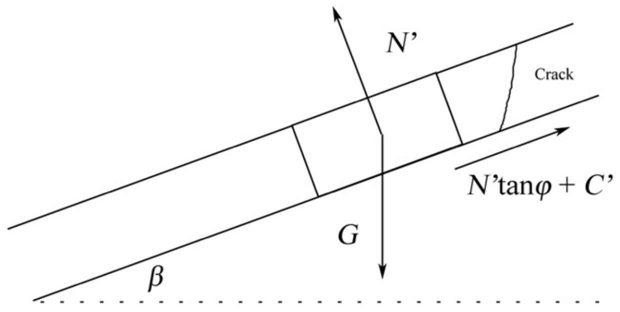

Fig. 1. Diagram of a single slice of an infinite slope with acting forces.

$$F_s = \frac{F_r}{F_d} = \frac{N' \tan\varphi + C'}{G \sin\beta + F'} \tag{1}$$

where N' is the normal effective force, C' is the effective cohesion, φ is the friction angle, G is the weight of the sliding body including both soil and water, β is the slope of slip surface and F' is the seepage force.

The expression of G (Fredlund and Rahardjo, 1993), under the assumption that the effective stress is equal to the total stress, is:

$$G = \gamma_w \cdot \cos\beta \cdot H \cdot \Delta s \cdot [m(n-1) + Gs(1-n) + n \cdot S_r(1-m)] \tag{2}$$

in which H is the thickness of the sliding body, Δs is the area of the sliding surface, m is the dimensionless thickness of the saturated layer which lies between 0 and 1, n is the porosity, Gs is the specific weight and S_r is the degree of saturation of the soil. Then, the expression of N' is:

$$N' = G \cdot \cos\beta = \gamma_w \cdot \cos^2\beta \cdot H \cdot \Delta s \cdot [m(n-1) + Gs(1-n) + n \cdot S_r(1-m)]. \tag{3}$$

The seepage force F' can be expressed as:

$$F' = \gamma_w \cdot \sin\beta \cdot \cos\beta \cdot m \cdot H \cdot \Delta s \tag{4}$$

where γ_w is the unit weight of the water. The effective cohesive force is:

$$C' = c' \cdot \Delta s. \tag{5}$$

Then, substituting Eqs. (2), (3), (4) and (5) into Eq. (1), we have:

$$F_s = \frac{\cot\beta \cdot [m(n-1) + Gs(1-n) + n \cdot S_r(1-m)] \tan\varphi + \dfrac{2c'}{\sin 2\beta \cdot H \cdot \gamma_w}}{[m(n-1) + Gs(1-n) + n \cdot S_r(1-m)] + m}. \tag{6}$$

When a landslide is in a critical condition, i.e., $F_s = 1$, a critical dimensionless thickness of the saturated layer m_{cr} is given by:

$$m_{cr} = \frac{(\cot\beta \tan\varphi - 1)[Gs \cdot (1-n) + n \cdot S_r] + \dfrac{2c'}{\sin 2\beta \cdot H \cdot \gamma_w}}{n \cdot (1-S_r) - [n \cdot (1-S_r) - 1] \cot\beta \tan\varphi}. \tag{7}$$

The slope is stable when $m < m_{cr}$ and unstable when $m > m_{cr}$. As $0 \le m \le 1$, the slope will always be stable under any rainfall condition if $m_{cr} > 1$, while the slope will be unstable even under dry conditions if $m_{cr} < 0$.

In real situations, as rainfall depth (h_i) was recorded by the interval Δt which is commonly either 1 h or 1 d, m can be expressed by each increment of rainfall depth (h_i). Therefore, a model adopting Darcy's law (Montrasio and Valentino, 2008; Montrasio et al., 2009, 2012) was used to calculate the evolution of m during the rainfall process. In the model, assuming the current time is t_0 and the dimensionless thickness of the saturated layer at t_0 is m_0, the contribution of rainfall at t_i to m_0, which is denoted by $m_{i,0}$, will be:

$$m_{i,0} = \frac{h_{i-1,i}}{n \cdot H \cdot (1-S_r)} \cdot \exp\left[-k \cdot \frac{\sin\beta}{n \cdot (1-S_r)}(t_0 - t_i)\right], (i = 0, -1, -2, \ldots) \tag{8}$$

where k is the infiltration rate. This equation suggests that the contribution of the rainfall between t_{i-1} and t_i to m_0 decreases exponentially