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Experimental study on slope sliding and debris flow evolution with and without barrier

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Abstract

A constitutive model on the evolution of debris flow with and without a barrier was established based on the theory of the Bingham model. A certain area of the Laoshan Mountain in Nanjing, Jiangsu Province, in China was chosen for experimental study, and the slope sliding and debris flow detection system was utilized. The change curve of the soil moisture content was attained, demonstrating that the moisture content of the shallow soil layer increases faster than that of the deep soil layer, and that the growth rate of the soil moisture content of the steep slope is large under the first weak rainfall, and that of the gentle slope is significantly affected by the second heavy rainfall. For the steep slope, slope sliding first occurs on the upper slope surface under heavy rainfall and further develops along the top platform and lower slope surface, while under weak rainfall the soil moisture content at the lower part of the slope first increases because of the high runoff velocity, meaning that failure occurring there is more serious. When a barrier was placed at a high position on a slope, debris flow was separated and distributed early and had less ability to carry solids, and the variation of the greatest depth of erosion pits on soil slopes was not significant.

Keywords: Debris flow; Slope sliding; Geological disaster; Time domain reflectometry (TDR) technique; Detection system; Constitutive model

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1. Introduction

Debris flow is a very destructive geological disaster. Loose material moves in response to debris flow's shearing force, thereby creating a secondary disaster induced by erosion. Rainfall is the main reason for slope instability, which leads to large-scale landslides. Current research on processes of debris flow always focuses on numerical simulation and experiments (Yair and Klein, 1973−1974; Hottan and Ohta, 2000; Magnus and Oliver, 2012). Nicholas et al. (2014) analyzed seven debris flows initiated in proglacial gullies. Gartner et al. (2014) used multiple regressions to develop models for predicting volumes of sediment. Setting a barrier is an effective measure of controlling the process of debris flow. Based on the simulation and experiments, many scholars (Mancarella et al., 2012; Brighenti et al., 2013) discussed the barrier's effect on debris flow evolution. Salciarini et al. (2010) used the discrete element method to assess the effectiveness of earthfill barriers. Mancarella et al. (2012) studied barrier effects and their possible role in infiltration processes and slope stability. They have found that debris flow was separated when it went through a barrier, and the barrier's position and rotation angle could change the deposition areas. Time domain reflectometry (TDR) is an electrical measurement technique used to determine the spatial location and nature of various objects (Robert, 2009; Suits et al., 2010; Ragni et al., 2012). Research on the use of the TDR detection technology in monitoring geological disasters began

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in the mid-1990s (Dowding and Pierce, 1994). Pastuszka et al. (2014) determined the impact of the location of TDR probes in soil samples on moisture measurement. Results from some studies showed that TDR detection technology was valid for landslide monitoring (Liang et al., 2005). According to analysis of laboratory tests and field data, scholars have proposed a landslide monitoring method based on this technique, for example, Chen et al. (2009) measured the dielectric constant in highly conductive soils based on surface reflection coefficients.

In summary, real-time monitoring of landslides can be achieved using the TDR technology. However, results are mostly empirical. The scope of applicability of the regression formula needs further validation. Research on debris flow is difficult due to its sophisticated composition and the variability of dynamic processes. Studies that combine the constitutive theory of the erosion process with laboratory tests are few. Research on technology for detection of geological disasters can help to obtain related information and shed light on the process of slope sliding and evolution of debris flow.

In order to explore the process of slope failure under the influence of rainfall, a rainfall-controlled slope model was built based on the geological data of a certain area of the Laoshan Mountain in Nanjing, Jiangsu Province, in China, and a constitutive model of evolution of debris flow under the influence of barriers based on the theory of the Bingham model was also established. The rationality of the constitutive model was validated with experimental results and inversion analysis.

2. Establishment of constitutive model of debris flow evolution

The turbulence power of debris flow can be ignored because of high viscosity. Thus, the simplified Bingham model can be adopted:

$$\tau = \tau_{\mathrm{B}} + \eta \frac{\mathrm{d}v}{\mathrm{d}y} \tag{1}$$

where τ is the shear strength, τ_{B} is the yield strength, η is the coefficient of viscosity, and $\mathrm{d}v/\mathrm{d}y$ is the speed gradient in the y direction (the positive direction is downward). The Manning equation is used in the formula; the initial speed is (Han et al., 2012)

$$v_0 = 1.62\left[\frac{S_{\mathrm{v}}(1-S_{\mathrm{v}})}{d_{10}}\right]^{\frac{2}{3}} h^{\frac{1}{3}} \beta^{\frac{1}{6}} \tag{2}$$

where S_{v} is the volumetric concentration, d_{10} is the lower limit of particle size, h is the depth of mud, and β is the gradient of the slope. This formula has been verified with the measured data from the Jiangjia Gully and Hunshui Gully.

2.1. Constitutive model of debris flow erosion without barrier

Debris flow is affected by friction resistance and internal viscous forces. The slope surface resistance and mass of debris flow at time t_i can be written as

$$\begin{cases} f_i = \mu_0\left(m_{i-1} + \dfrac{\mathrm{d}m}{\mathrm{d}t}\Delta t\right) g \cos\beta \\ m_i = m_{i-1} + \dfrac{\mathrm{d}m}{\mathrm{d}t}\Delta t \end{cases} \tag{3}$$

where f_i and m_i are the slope surface resistance and mass of debris flow at t_i, respectively; μ_0 is the friction coefficient of the slope surface; $\mathrm{d}m/\mathrm{d}t$ is the change ratio of the mass of debris flow; g is the acceleration of gravity; and Δt is the time interval, where $\Delta t = t_i - t_{i-1}$.

The law of conservation of energy can be expressed as follows:

$$\begin{cases} \dfrac{1}{2}m_{i-1}v_{i-1}^2 + m_{i-1}g(Y-y_{i-1}) - m_i g(Y-y_i) - \dfrac{1}{2}m_i v_i^2 = W_{\mathrm{f}i} + W_{\mathrm{s}i} \\ W_{\mathrm{f}i} = \mu_0 g \cos\beta \displaystyle\int_{t_{i-1}}^{t_i} \left(m_{i-1} + \frac{\mathrm{d}m}{\mathrm{d}t}t\right)\mathrm{d}t \end{cases} \tag{4}$$

where v_i is the velocity at t_i, Y is the initial height (relative to the ground) of debris flow, y_i is the decreasing height of debris flow at t_i, $W_{\mathrm{f}i}$ and $W_{\mathrm{s}i}$ are the amounts of energy consumed in overcoming the slope surface resistance and viscous force from t_{i-1} to t_i, respectively.

Another expression of energy (Legros, 2002) at t_i is

$$E_i = h_{\mathrm{c}i} + \frac{v_i^2}{2g} \tag{5}$$

where $h_{\mathrm{c}i}$ is the height of the center of mass of debris flow at time t_i. Then, the energy consumption of debris flow from t_{i-1} to t_i is

$$\Delta E_i = E_{i-1} - E_i = h_{\mathrm{c}i-1} - h_{\mathrm{c}i} + \frac{v_{i-1}^2 - v_i^2}{2g} \tag{6}$$

Combining Eq. (4) with Eq. (6) leads to the recursive expression Eq. (7) regarding v_i^2:

$$v_i^2 = \frac{v_{i-1}^2(m_{i-1}g - 1) + Am_{i-1} + B(\mathrm{d}m/\mathrm{d}t)\Delta t + C}{m_{i-1}g + g(\mathrm{d}m/\mathrm{d}t)\Delta t - 1} \tag{7}$$

where A, B, and C are expressed as $2g^2(y_i - y_{i-1})$, $2g^2(y_i - Y)$, and $2g(h_{\mathrm{c}i} - h_{\mathrm{c}i-1})$, respectively. The common expression of v_t^2 can be obtained:

$$v_t^2 = \frac{v_0^2(m_0 g - 1) + 2m_0 g^2 y_t + 2g^2(y_t - Y)(\mathrm{d}m/\mathrm{d}t)t + C_1}{m_0 g + g(\mathrm{d}m/\mathrm{d}t)t - 1} \tag{8}$$

where v_t and y_t are the velocity and decreasing height of debris flow at time t, respectively; C_1 is expressed as $2g(h_{\mathrm{c}t} - h_{\mathrm{c}0})$, where $h_{\mathrm{c}0}$ is the initial height of the center of mass of debris flow, and $h_{\mathrm{c}t}$ is the height of the center of mass of debris flow at time t; and m_0 is the initial mass of debris flow. A new equation of shear strength can be obtained by substituting the derivation of Eq. (8) into Eq. (1):