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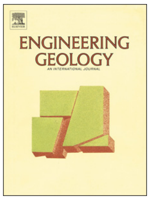

Numerical analysis of dynamics of debris flow over erodible beds in Wenchuan earthquake-induced area

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ABSTRACT

The basal entrainment of debris flows play a significant role in its amplification and the final volume of deposition could be several to hundred times of its initial volume. In this paper, the shallow water equations coupled with basal material entrainment applied in debris flows have been given to demonstrate the amplification. A new basal entrainment model taking advantage of both Coulomb and Voellmy frictional laws are proposed, providing a unified formula to simulate the stop-and-go process of debris flows. Both time and space second-order MacCormack-TVD finite difference method is suggested to solve the coupled equations. Numerical comparisons with USGS flume experiment and Hongchun gully debris flow in Wenchuan earthquake-induced area are carried out to prove its effectiveness. It is established that the momentum exchange term between the flows and the basal materials has a significant influence on the dynamic characteristics and the entrainment effects are essential to model the dynamic process of debris flows in an earthquake-induced area.

1. Introduction

A debris flow consists of poorly sorted sediment that is saturated with water and surges down slope with momentum accelerated by gravitational force, and has an intense impact on its base due to this acceleration (Iverson, 1997). Theoretical, experimental and field research have shown that the final debris flow volume could possibly be several-fold beyond its initial volume as it incorporates material from the basal beds (Iverson et al., 2011; Medina et al., 2008; Pirulli and Pastor, 2012; Scott, 1988; Takahashi, 1981; Wang et al., 2003). Nevertheless, when the debris flow is mainly triggered by intense rainfall, the catastrophic damage is still generally underestimated, especially in areas influenced by strong earthquakes, such as the 5.12 Wenchuan earthquake in 2008 (Chen et al., 2013; Cui et al., 2011; Tang et al., 2011; Xu et al., 2012). Therefore, research on the dynamics of debris flow in gullies, including the sediment entrainment and deposition, is becoming extremely vital to enhance public safety and reduce loss from debris flows.

An increasing number of researchers have been dedicated to finding a way to determine the run out distance and final deposition volume of landslides or debris flows over erodible beds (Iverson, 2012; McDougall and Hungr, 2005; Medina et al., 2008; Pitman et al., 2003; Rickenmann, 1999). Laboratory experiments of granular flows over dry erodible beds exhibit that the inclination of the plane and the thickness of the erodible layer are able to significantly change the flow mobility (Farin et al., 2013; Mangeney et al., 2010; Mangeney et al., 2007). Large flume experiments illustrate that the pore pressure evolution in wet or saturated erodible beds could induce positive or negative feedback to the debris flows (Iverson et al., 2011). Several authors utilize statistic-based empirical models to assess some important characteristics of debris flows such as the maximum deposition volume, the run out distance, and the mean flow velocity (Hungr et al., 1984; Prochaska et al., 2008; Rickenmann, 1999). Continuum-based numerical models are generally depth-integrated and reduced to two-dimensional problems utilized to simulate large scale earth surface flow because the ratio of flow height over run out distance is typically far less than 1 (LeVeque, 2002; Savage and Hutter, 1989). Takahashi (1991) and Takahashi and Kuang (1986) introduced the entrainment associated terms in the shallow water equations and the entrainment rate model was later applied broadly and further improved (Egashira et al., 2001; Shrestha et al., 2008; Takahashi et al., 1992). Some have taken the entrainment effect into account in their models and numerically compared these effects with laboratory avalanche experiments (Gray, 2001; Mangeney et al., 2007). Many have proposed amounts of basal entrainment model to simulate dam-breaks over erodible river beds (Cao et al., 2004;

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Swartenbroekx et al., 2013; Wu and Wang, 2007; Xia et al., 2010; Zech et al., 2008; Ouyang et al., under review). Advancements were made in simulating actual landslides or debris flows that incorporated basal material (Chen et al., 2006; Luna et al., 2012; McDougall and Hungr, 2005; Medina et al., 2008).

However, it has been found that two significantly important factors, the momentum exchange crossing the boundary and the entrainment-rate formulas, have been long ignored (Iverson and Ouyang, under review). One issue is that many researchers have included modified momentum exchange terms due to bed erosion and clearly distinguish boundary shear tractions with and without erosion in momentum conservation equations (Gray, 2001; Naaim et al., 2003; Tai and Kuo, 2008; Ouyang et al., under review), while others have not (Brufau et al., 2000; Cao et al., 2004; Shrestha et al., 2008). Second, most scholars suggest the entrainment rate is proportional to the flow velocity (McDougall and Hungr, 2005; Pirulli and Pastor, 2012; Pitman et al., 2003), while Iverson (Iverson, (2012)) deduces that the entrainment rate of sediment is reciprocal to the flow velocity. Further, it is derived that all the physical-based entrainment rate equations must satisfy a momentum jump condition which displays entrainment rate dependence on basal flow velocity, basal topography and shear and normal stress (Iverson and Ouyang, under review).

Therefore, here we will describe the depth-integrated mass and momentum conservation equations involving debris flow moving over erodible beds while incorporating a new basal entrainment rate expression, taking into account Coulomb friction criterion and Voellmy friction criterion. Numerical comparisons with USGS flume experiment and Hongchun gully debris flow in Wenchuan earthquake-induced area are calculated to verify the model.

2. Model descriptions

2.1. Governing equations of coupled model

The coordinate system adopted is a rectangular Cartesian coordinate, rotated along x- and y-axes with angles θ_x and θ_y relative in order to parallel to the mean slope angle, as shown in Fig. 1. A two-layer model with upper moving flow (designated by subscript 1) and bottom erodible sediment beds (designated by subscript 2) is defined on this coordinate. For brevity, subscript of variables associated with layer 1 is omitted except for clarity. The free surface of layer 1 is defined as z_s, and the basal boundary between layer 1 and 2 is z_b. u, v, w represent flow velocity components in the three individual coordinate axes. $h = z_s - z_b, \overline{\rho} = (1/h)\int_{z_b}^{z_s} \rho dz$ represent flow height and depth-averaged density. The moving flow in layer 1 must satisfy the mass and momentum conservation laws as the following:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{1}$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial\left(\rho u^2\right)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = \rho g_x + \left(\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right) \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial\left(\rho v^2\right)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = \rho g_y + \left(\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z}\right) \tag{3}$$

$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho wv)}{\partial y} + \frac{\partial\left(\rho w^2\right)}{\partial z} = \rho g_z + \left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}\right) \tag{4}$$

and kinematic boundary conditions at upper and bottom boundaries (Gray, 2001)

$$\frac{\partial z_s}{\partial t} + u_s \frac{\partial z_s}{\partial x} + v_s \frac{\partial z_s}{\partial y} - w_s = 0 \tag{5}$$

$$\frac{\partial z_b}{\partial t} + u_b \frac{\partial z_b}{\partial x} + v_b \frac{\partial z_b}{\partial y} - w_b = -\xi E \tag{6}$$

where τ_{ij} are conventional stress components in continuum mechanics. $\xi = \sqrt{1 + (\partial z_b/\partial x)^2 + (\partial z_b/\partial y)^2}$ can be integrated as geometric correction coefficient; E is basal material entrainment rate that assesses the volumetric flux per unit area of the basal boundary; (g_x, g_y, g_z) can be obtained by

$$\begin{pmatrix} g_x \\ g_y \\ g_z \end{pmatrix} = \begin{bmatrix} \cos(\theta_y) & 0 & -\sin(\theta_y) \\ 0 & 1 & 0 \\ \sin(\theta_y) & 0 & \cos(\theta_y) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_x) & \sin(\theta_x) \\ 0 & -\sin(\theta_x) & \cos(\theta_x) \end{bmatrix} \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix}. \tag{7}$$

Rotation of the coordinate can partially reduce the effects of gravitational acceleration from topography; accurate description of topography effects need more advanced technology and are beyond the scope of this paper (Bouchut et al., 2003; Favreau et al., 2010; Gray et al., 1999).

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