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Simulation of rainfall-induced debris flow considering material entrainment

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ABSTRACT

In order to simulate soil erosion and sedimentation processes of debris flow, a depth-integrated particle method with soil-water mixing model is proposed. In the model, each numerical particle represents a mixture of soil grains and water with a certain soil volume concentration and can exchange the soil mass with the neighboring particles according to the diffusion equation. A unique relationship is also assumed between the soil volume concentration and its critical deposition angle to compute the bottom shear stress acting on the flowing numerical particles. Therefore, the model only contains three major mechanical parameters: the classical Manning coefficient, the critical slope angle for the loose soil deposit at the base of valley, and the diffusion coefficient to control the soil water mixing process. In addition, a two-step simulation method is proposed to evaluate the initial distribution of the loose soil deposit in the valley bottom. The model is initially validated by a laboratory flume experiment taken from the open literature, and adequate values of the mechanical parameters are determined. Next, the model is applied into the case study of the 2010 debris flow event in Zhouqu, and the simulation results are compared with the field investigation, as well as the post-event satellite images. The affected area, the travel distance, and the flow velocity statistics exhibit good agreement.

1. Introduction

Debris flows are a common natural geo-hazard in mountainous terrains worldwide. The flows initiate from upland slopes due to earthquakes or torrential rains and often travel long distances and cause serious damage in downstream residential areas. Because of these flows' large flow velocity, they cause significant soil erosion in the bottom of upland valleys and are able to increase their volume rapidly via entrainment (Hungr et al., 2005; Iverson et al., 2011; Crosta et al., 2009; Luna et al., 2012; Zheng et al., 2015). Such soil mass entrainment also causes changes in the composition of the flowing soil water mixture, which in turn, significantly influences the flow speed and drag force as well as having major consequences on the deposition zone (McDougall and Hungr, 2005). Therefore, it is highly important to consider the soil entrainment from the point of view of disaster mitigation. Meanwhile, debris flows are regarded as one of the most important land-forming processes in mountainous areas because of this material transport feature, and understanding this process is essential for earth science, as well as environmental engineering.

Although considerable effort has been made to understand the soil entrainment behavior of debris flows (Hungr et al., 2005; Iverson, 2014; Iverson and Ouyang, 2015), it is still very difficult fully to model the processes involved because of their complexity. Soil is composed of solid grains of various sizes, and the grain mobility in the flow differs in different grain sizes. Large particles have larger kinetic energy and tend to entrain other grains on the valley base into the flow more easily, causing the increase of the entrainment ratio. Such complexity prevents us from fully understanding and modeling the process.

The present study does not aim to establish such a complicated material entrainment model but to simplify it as much as possible. When we apply a numerical simulation method into actual natural geo-hazard evaluations, the most difficult issue is the determination of material parameters. Geomaterials are natural materials and their physical and mechanical properties differ spatially, horizontally and also vertically. Accordingly, a complicated model with many parameters may be prohibitively difficult to apply. Conversely, a simple model with a smaller number of parameters is easy to handle and may still keep a certain level of predictability if the model captures the most essential features of the process. We believe that such an approach is important in the interests of engineering applicability.

For this purpose, the present study adopts a depth-integrated particle method, which is a simple and efficient method to simulate actual debris flow based on accurate topographic data (Zhang et al., 2014a). In the model, each numerical particle (or column) represents a mixture of soil grains and water with a certain soil volume concentration. The mechanical interaction between two neighboring numerical particles is described by a model based on their hydraulic gradient. Additionally,

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to take into account the entrainment and mixture of soil grains in the flow, we propose a simple model, called a soil-water mixing model, in which the neighboring particles exchange their soil contents according to the diffusion equation. By assuming a unique relationship between the soil volume concentration and critical deposition angle to compute the bottom shear stress acting on the flowing numerical particles, the whole model only contains three major mechanical parameters describing debris flow: the classical Manning coefficient, the repose angle of the loose surface soil, and the diffusion coefficient in the soil water mixing process.

In the following sections, the proposed model is firstly detailed and is subsequently validated by a laboratory experiment in the literature. Next, the model is applied to a case study of an actual debris flow event in Zhouqu, in 2010, and the simulation results are compared with the field investigation, as well as the post-event satellite images.

2. Depth-integrated particle method with soil-water mixing model

The depth-integrated assumption (or shallow water assumption) has been widely used in river flow simulations and has also been applied in debris flow simulations with actual topographic data (Pudasaini and Hutter, 2003; McDougall and Hungr, 2004; Pastor et al., 2009, 2014; Hoang et al., 2009). In particular, Pastor et al. (2009, 2014) developed a Smoothed Particle Hydrodynamics (SPH) model coupled with the depth-integrated model and showed its performance by comparing with theoretical solutions, laboratory experiments, and disaster case studies. In such Lagrangian particle methods, continuum flow is discretized with numerical particles (or columns) that move along the topographic surface, keeping information on their material and mechanical properties. Therefore, it is a quasi-3D simulation, and the conservation laws easily hold without dealing with the advection term. In the author's opinion, the biggest advantage of the particle method is their structural simplicity and flexibility. This advantage makes it possible to construct a simple, efficient and stable particle method, in which a material entrainment model is easily included (Zhang, 2015), as described in the following subsections in detail.

2.1. Governing equations

First, we set a horizontal coordinate system, (x,y), and a numerical particle (or column) of soil water mixture whose initial height is h_0 and bottom width is d_0, as shown in Fig. 1. Then, the commonly used depth-integrated or shallow water equation is adopted to each particle:

$$\begin{aligned} \frac{Dv_x}{Dt} &= \frac{\partial v_x}{\partial t} + v_x\frac{\partial v_x}{\partial x} + v_y\frac{\partial v_x}{\partial y} = g_x - \frac{\partial p}{\rho \partial x} - \frac{\tau_{bx}}{\rho h} \\ \frac{Dv_y}{Dt} &= \frac{\partial v_y}{\partial t} + v_x\frac{\partial v_y}{\partial x} + v_y\frac{\partial v_y}{\partial y} = g_y - \frac{\partial p}{\rho \partial y} - \frac{\tau_{by}}{\rho h} \end{aligned} \quad (1)$$

where, $\boldsymbol{v} = (v_x, v_y)$ is a depth-integrated flow velocity vector, h is the surface height of debris flow, $\boldsymbol{\tau}_b = (\tau_{bx}, \tau_{by})$ is the bottom shear stress vector, ρ is the density of the mixture, p is the hydraulic pressure, and $\boldsymbol{g} = (g_x, g_y)$ is the gravitational acceleration. Note that the mass conservation equation is quite easily described in Lagrangian particle methods as $\rho d^2 h$ = constant.

In this analysis, we adopt a particle-wise discretization for the hydraulic pressure gradient (Fig. 1), which is modeled by the following inter-particle force:

$$\nabla \boldsymbol{p} = \rho g \nabla h = \begin{cases} -2\rho g h_0 (1 - \|\mathbf{d}\|/d_0)/(1 + \|\mathbf{d}\|/d_0) \dfrac{\mathbf{d}}{\|\mathbf{d}\|} & (\|\mathbf{d}\| < d_0) \\ -2\rho g h_0 \left[(\|\mathbf{d}\|/d_0 - 1.25)^2 + 0.0625 \right] \dfrac{\mathbf{d}}{\|\mathbf{d}\|} & (d_0 \le \|\mathbf{d}\| < 1.5 d_0) \\ 0 & (\|\mathbf{d}\| \ge 1.5 d_0) \end{cases} \quad (2)$$

where $\mathbf{d}$ is the distance vector between two interacting particles. Fig. 2 is a graphical representation of Eq. (2). The equation describes how the repulsive force acts on the two particles closer than the initial distance d_0, while the attractive force acts on the particles further than d_0, based on the hydraulic gradient effect. Moreover, two particles further than $1.5d_0$ is assumed to have no interaction. This threshold was determined by the preliminary simulation of 1-D wave propagation (Zhang, 2015).

Next, the bottom shear stress is expressed based on the Manning equation as follows:

$$\begin{aligned} \boldsymbol{\tau}_b &= \left(\tau_{cr} \|\boldsymbol{v}\|^m + \rho g \frac{n^2}{{R_h}^{1/3}} \|\boldsymbol{v}\|^2 \right) \frac{\boldsymbol{v}}{\|\boldsymbol{v}\|} \\ \tau_{cr} &= \rho g R_h i_{cr} \end{aligned} \quad (3)$$

where n is the Manning coefficient, R_h is the hydraulic radius (assumed to be equal to d_0) and i_{cr} is the critical slope angle of deposition. The Manning coefficient has been widely used in the field of river engineering (Limerinos, 1970), providing the suggested values of water flow on floodplains (0.07 to 0.10 for medium to dense brush and 0.15 for trees) (Chow, 1959) and on natural channels (0.060 to 0.075) (Barnes, 1967). A numerical parameter, m, is introduced such that the model approaches the Bingham model when m approaches to zero (Fig. 3). In the present study, m is set to 0.01. This is sufficiently small to reproduce

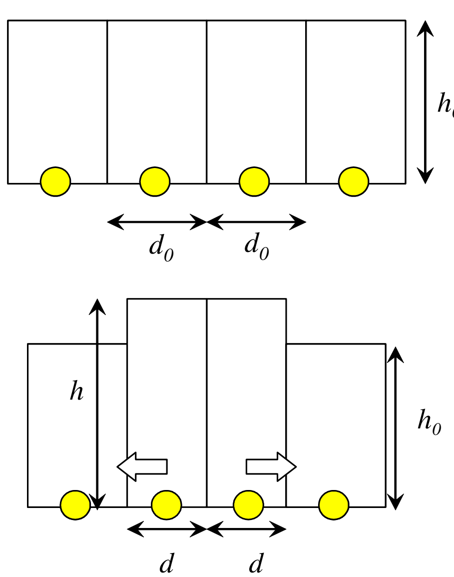

Fig. 1. Particle interaction model based on hydraulic pressure gradient.

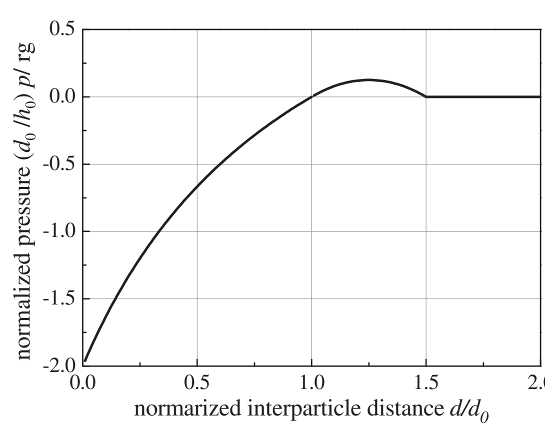

Fig. 2. Relationship between the normalized interparticle pressure and the normalized interparticle distance.