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Numerical simulation of debris-flow behavior incorporating a dynamic method for estimating the entrainment

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ABSTRACT

There is a pressing need to estimate debris-flow entrainment because several lines of studies have substantiated that the magnitude of a debris flow may grow manyfold due to sediment entrainment. In this paper, we present a two-dimensional numerical model of debris-flow behavior for estimating entrainment over complex topography. The model is governed by a numerical integration of the depth-average motion equations using shallow water approximation. The governing equations are numerically solved using the semi-Lagrangian method in an explicit finite difference grid. Compared to previous models, the presented model highlights the importance of entrainment, and incorporates a physically-based dynamic method to estimate the entrainment rate. The entrainment rate can be predicted using reasonable assumptions regarding the velocity profile of the debris flow and the rapidly changing pore pressure of the bed sediment. The stability of the presented model is first illustrated by a hypothesized dam-breaking problem; the effectiveness of the implemented model entrainment process is subsequently tested on the 2010 Yohutagawa debris-flow event in Japan. The test indicates that the presented method can be satisfactorily used to simulate debris-flow behavior and the entrainment process. A discussion regarding the advantages and limitations of the model concludes the paper.

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1. Introduction

The immense impact of the debris flows often endangers human settlements and infrastructures worldwide (Huang and Tang, 2014; Han et al., 2014). A global analysis of debris-flow hazards from 1950 to 2011 indicated that fatalities in a debris flow are dependent on the transferred mass volume (Dowling and Santi, 2014). Despite several methods having been proposed to determine the probable volume of debris flow from a given basin, debris recharge rates over time and bed-sediment entrainment in basins are sometimes neglected, leading to an underestimation of debris-flow volumes. Several lines of evidence in previous studies (e.g., Hungr et al., 1984, 2005; VanDine and Bovis, 2002; Breien et al., 2008; Luna et al., 2012) suggest that the entrained material along the debris-flow trajectory may accumulate several times the initial volume. Many in-situ surveys and monitoring works support this viewpoint (e.g., King, 1996; Berti et al., 1999; O'Connor et al., 2001; Godt and Coe, 2007; Breien et al., 2008). The significance of these findings implies that ubiquity of sediment entrainment should be taken into account when determining debris-flow magnitude.

In recent years, several models for simulating debris-flow behavior have been developed and applied to volume estimation and risk assessment (e.g., Brufau et al., 2000; Imran et al., 2001; De Joode and van Steijn, 2003; Hungr et al., 2005; Kelfoun and Druitt, 2005; Mangeney et al., 2007; Medina et al., 2008; Wang et al., 2008; Bouchut et al., 2008; Armanini et al., 2009; Lin et al., 2009; Beguería et al., 2009; Crosta et al., 2009a,b; Pirulli and Pastor, 2012; Liu et al., 2013). These models are mainly physically based and numerically solved. They use the finite volume method or the finite difference method to solve the depth-average form of the shallow water equations over complex 3-D topographies. However, some of these models assume a constant volume during the debris flow process, ignoring the important role of entrainment along the trajectory, while some have to use empirical laws to estimate the entrainment rate. The difficulties with incorporating entrainment in the models can be explained in part by the fact that sediment entrainment is a complex process. On the one hand, erosion tracks are often hidden by subsequent flows, and it is difficult to distinguish the flow deposit and the underlying erodible layer to support further analysis (Mangeney, 2011). On the other hand, in addition to the uncertainties of defining the mechanism of entrainment itself, difficulties also arise from ambiguities in the definition of the governing factors of the process.

Previous studies have elucidated that the mechanism of sediment entrainment may be explained in part by rapid stress changes when the bed is overridden by debris flows, with rapid stress change causing destabilization and failure of the bed sediment (e.g., Hutchinson et al.,

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1971; Abele, 1997; Sassa, 1988; Wang et al., 2003). These studies provided new insight into the entrainment process. Up-to-date studies have also strongly improved the ability to estimate and predict entrainment rate and depth. These studies can be divided into two principal groups: 1) *field and laboratory studies* and 2) *physically based theoretical studies*.

In the first group, Hungr et al. (1984, 2005) introduced a concept of yield rate (which denotes the volume eroded per meter of the path) and discussed its range based on data collection from 14 debris-flow events in the literature. Rickenmann et al. (2003) adopted this concept, analyzing six sets of data from in-situ experiments and pointing out that debris flows with a high sediment concentration tend to be less erosive than are more fluid mixtures. Wise (1997) collected forensic data of erosion depth from 449 debris-flow events, and Guthrie et al. (2008) later examined the distribution of these data, declaring that a debris flow can grow more erosive when overriding a steeper bed. Abancó and Hürlimann (2014) substantiated the dominant factors influencing the entrainment process, and proposed a decision-tree model to estimate the yield rate. In-situ and laboratory studies (e.g., Egashira et al., 2001; Papa et al., 2004; Mangeney et al., 2007, 2010; Iverson et al., 2011; McCoy et al., 2012) provided precious monitoring data and substantiated some important features of entrainment process. These studies are instrumental for later researchers in the development of empirical formulas (e.g., McDougall and Hungr, 2005; Chen et al., 2006; Crosta et al., 2009a,b; Christen et al., 2010; Wu et al., 2013a,b).

The physically based studies include both static and hydrodynamic approaches. Static approaches consider that entrainment occurs only when the bed shear stress of flow is sufficiently high to overcome the basal resistance of the bed and incorporate this part of the bed into the flow. Sassa (1988) proposed a model that takes into account this consideration using pore-pressure development. His work leads to a better understanding of the entrainment mechanism. Later researchers (Sovilla et al., 2006; Medina et al., 2008; Luna et al., 2012) use similar approaches to estimate the entrainment depth of the bed sediment. Despite extensive studies on this aspect, questions still remain regarding whether the strength parameters of bed soil, to which static approaches are rather sensitive, may vary spatially and temporally in the basin, making the computed results implausible. For this reason, other researchers optimized static approaches with the Monte-Carlo method, e.g., Blijenberg (2007). In terms of hydrodynamic approaches based on a similar hypothesis, they analyze the momentum exchange of the bed-layer (Bouchut et al., 2008; Medina et al., 2008; Iverson, 2012). However, dynamic approaches are likely to lead to a discrepancy indicating that entrainment rates decline as basal flow velocities increase. Iverson (2012) provided an insight into the entrainment mechanism, giving a plausible explanation of this discrepancy, i.e., that conventional wisdom based on the observation is derived from a near-equilibrium system.

In this paper, we present a two-dimensional numerical model for simulating debris-flow behavior over complex topography. The model takes into account a dynamic entrainment concept based on momentum conservation of the flow-bed system, and indicates that the rapid change of pore pressure in bed sediment controls the developing of entrainment. Two cases, a dam-breaking problem and the 2010 Yohutagawa debris-flow event in Japan, are used to demonstrate the capability and performance of the model.

2. Model description

The fundamental theory of the numerical model is based on mass and momentum conservation with a shallow-water assumption that is applied to where the horizontal length scale (length of flowing mass) is much greater than the vertical length scale (thickness of the flowing mass). The assumption is commonly used to describe the motion of fluid-type granular flows (e.g., Medina et al., 2008; Wang et al., 2008; Lin et al., 2009; Beguería et al., 2009; Pirulli and Pastor, 2012; Liu et al., 2013). Integration over the flow depth allows this assumption to reduce the problem of a complex 3-D fluid motion to a much simpler 2-D description with a height-field representation.

The governing equations are all written in a conservative form in a topography-linked coordinate system (Fig. 1) in which x and y are parallel to the local ground surface and z is perpendicular to it. Detailed derivations of Eqs. (1) to (3) are well described in our previous work; see Wu et al. (2013a,b) for details. The mass conservation equation is

$$\frac{\partial}{\partial t}h+\frac{\partial}{\partial x}(uh)+\frac{\partial}{\partial y}(vh)=\frac{\partial d_{sc}}{\partial t} \tag{1}$$

and the momentum conservation equations along the x and y directions are

$$\frac{\partial}{\partial t}uh+\frac{\partial}{\partial x}u^2h+\frac{\partial}{\partial y}uvh=-\frac{\partial H}{\partial x}gh+\frac{\mu k}{\rho}\left(\frac{\partial^2 uh}{\partial x^2}+\frac{\partial^2 uh}{\partial y^2}\right)-\frac{T_x}{\rho} \tag{2}$$

$$\frac{\partial}{\partial t}vh+\frac{\partial}{\partial x}uvh+\frac{\partial}{\partial y}v^2h=-\frac{\partial H}{\partial y}gh+\frac{\mu k}{\rho}\left(\frac{\partial^2 vh}{\partial x^2}+\frac{\partial^2 vh}{\partial y^2}\right)-\frac{T_y}{\rho} \tag{3}$$

where h is the thickness of the flow mass; H is the height of the bed below the flow mass (above zero-level); and $H + h$ is defined as the height of the free surface. (u, v) denote the average velocities of the debris flow in the x and y directions, and $\partial d_{sc}/\partial t$ is the time-dependent rate of bed erosion (or "erosion rate"), which is, the rate at which path material is added to the moving mass (Pirulli and Pastor, 2012) (see Section 3 for details). t is time; ρ is the density of the flow mass; μ is the dynamic viscosity; g is the gravity acceleration; k is the earth pressure coefficient, which represents the ratio of the vertical normal stress to the horizontal one; and T_x and T_y represent the bed-shearing stress of the debris flow in two directions. In this conservative form, the two distinct parts of the equations can be identified: the left side describes the advection within the momentum field (u, v), while the right side computes an additional acceleration term.

The terms T_x and T_y in Eqs. (2) and (3) are responsible for the energy dissipation when debris flow is propagating. Here, we assume that the debris flow follows a viscous and Coulomb friction flow resistance (Wang et al., 2008; Wu et al., 2013a,b):

$$\begin{pmatrix}T_x\\T_y\end{pmatrix}=\begin{pmatrix}\mu\rho\sqrt{gh}\cos\theta_x\tan\varphi_{\mathrm{int}}\\\mu\rho\sqrt{gh}\cos\theta_y\tan\varphi_{\mathrm{int}}\end{pmatrix} \tag{4}$$

where θ_x and θ_y denote the slope angle of inclination at the bed along the x and y directions. The viscous and Coulomb friction flow resistance matches the description of the shearing behavior of granular debris flow (Naef et al., 2006).

One difference between the model in this paper and our previous one is the criterion of earth pressure coefficient k. In the previous research, we assumed that the debris flow is induced by rainfall and that it behaves as a perfect fluid. In this way, k should be 1.0 as elucidated by Wang et al. (2008). However, a more realistic assumption is that debris flow sometimes behaves as a plastic material (Savage and Hutter, 1989; Hungr, 1995; Kelfoun and Druitt, 2005; Beguería et al., 2009) and that k may vary between two extreme values corresponding to the loading states of flow mass in the Rankine theory. This theory is expressed as $k_a \le k \le k_p$, where k_a and k_p are the active and passive earth pressure coefficients, respectively. These depend on the dynamic friction angle of debris flow mass φ_{int} and bed φ_{bed}. If $\varphi_{int} > \varphi_{bed}$, they follow the law below (Iverson and Denlinger, 2001):

$$\left.\begin{matrix}k_a\\k_p\end{matrix}\right\}=2\frac{1\pm\left[1-\cos^2\varphi_{\mathrm{int}}\left(1+\tan^2\varphi_{bed}\right)\right]^{1/2}}{\cos^2\varphi_{\mathrm{int}}}-1 \tag{5}$$

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