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Simulating debris flow mobility in urban settings

L. Gao [a], L.M. Zhang [a,*], H.X. Chen [a,b], P. Shen [a]

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong
[b] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China

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ABSTRACT

Debris flows may run into urban areas where the flows are affected by the presence of buildings and urban hard surfaces. This study aims to simulate debris flows in the urban environment by considering different natural and urban superficial geomaterial conditions and building blockage effects. The analysis model adopts shallow water equations to describe debris flows, including the bed erosion and debris deposition processes. A target analysis area is characterized using a three-dimensional digital elevation model (DEM) and discretized into cells with different bed material parameters. A computational scheme is then developed to take into account erosion on different surface beds and building blockage effects. The analysis model and the parameters are evaluated by two historical debris flow cases on Hong Kong Island. Using the verified model and parameters, detailed simulations of debris flows in an urban catchment are conducted. The buildings increase the maximum depth and the maximum velocity as the debris tends to run up and deposit in front of the buildings and the flow path tends to be narrowed due to building blockage. The entrainment of the underlying surface materials increases the debris-flow intensity significantly, leading to larger affected areas and travel distances.

1. Introduction

A debris flow is defined as a fast or extremely fast flow of sediment and water mixtures driven by gravity (Jakob and Hungr, 2005; Takahashi, 2009). Rainfall-induced debris flows can be classified into two general types; namely, hill-slope debris flows and channelized debris flows. Due to the subtropical weather and hilly terrains in Hong Kong, hundreds of slope failures could occur during a severe storm, providing a large amount of materials which may transform into debris flows. For example, the June 2008 rainstorm hit Lantau Island and resulted in about 2400 natural terrain landslides, of which 900 were channelized debris flows (Wong, 2009). Some debris flows may run into the urban areas where the flows are affected by the presence of buildings and urban hard surfaces. The effective management of natural hazards requires all relevant threats and their interactions to be considered (Liu et al., 2015).

A debris flow can grow dramatically in size along its flow path due to entrainment (Iverson et al., 2011), and therefore it is important to consider the erodible surface bed materials during the debris flow process. Depth-averaged continuum models, solved with finite difference schemes, have been demonstrated to be a viable tool for the analysis of the mobility and entrainment of debris flows (Takahashi et al., 1992; Hungr, 1995; Luna et al., 2012; Kwan et al., 2013; Chen and Zhang, 2015; Pellegrino et al., 2015; Pudasaini, 2016). In particular, Kwan et al. (2013) examined the runout characteristics of selected mobile debris flows by assuming that the amount of entrainment is proportional to the debris velocity. Chen and Zhang (2015) presented a model, EDDA (Erosion-Deposition Debris flow Analysis), to simulate debris flow erosion, deposition and material property changes by solving the shallow water equations. Pudasaini (2016) derived a dynamical model for sub-diffusive and sub-advective fluid flow in porous media and debris material in which the solid matrix is stationary.

Limited attention has been paid to urban debris flow analysis (Takahashi and Nakagawa, 1987; O'Brien et al., 1993). Takahashi and Nakagawa (1987) developed a numerical simulation method for overland flood flows, in which the effects of buildings are considered by introducing an equivalent roughness coefficient or a flux correction factor. O'Brien et al. (1993) proposed a numerical model for both flash floods and debris flows, by which the building blockage effects can be evaluated using an area reduction factor. Nevertheless, insufficient attention has been paid to simulating debris flows in the urban environment with the consideration of both the erosion on different underlying-surface beds and the building blockage effects. Efforts have to be made to include urban settings into debris flow simulation.

This paper aims to develop a computational scheme for simulating possible scenarios of urban debris flows considering building blockage effects and materials from bed erosion. The analysis of entrainment and erosion of debris flows is based on a model, EDDA. Five different underlying-surface zones are considered: buildings, granitic deposits, volcanic deposits, vegetation-covered bedrock and hard surface. The

* Corresponding author.
E-mail addresses: lgaoab@ust.hk (L. Gao), cezhangl@ust.hk (L.M. Zhang), cechenhx@ust.hk (H.X. Chen), pshen@connect.ust.hk (P. Shen).

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building blockage effects are considered when a debris flow travels into urban areas. The model is evaluated using a historical debris flow case and used to predict probable future scenarios. The maximum flow depth, maximum velocity and erosion depth are calculated as the basis for debris-flow hazard evaluation.

2. Analysis methodology

A debris flow process is recognized to include four mechanisms: initiation in the source area, transportation of the mobilized debris, entrainment of bed and additional debris, and deposition of the debris. As shown in Fig. 1, one or more of these mechanisms may dominate in different zones along the debris-traversing path (Franks, 1999; Lo, 2000). The flow zone can be divided into three parts: initiation, transportation and erosion, and deposition. Debris flows are often triggered by landslide transformation, erosion by surface runoff, or collapse of a landslide dam (e.g., Takahashi, 2009). The flows gain mass and descend along steep slopes and channels. When the debris materials flow to flat areas, the materials gradually deposit on a debris fan and the mobile sediment volume decreases. Typical slope gradients for the initiation, transportation and erosion, and deposition zones in Hong Kong are $>28°$, $>16°$, and $<16°$, respectively (Franks, 1999). On a mobile (erodible) bed, the bed changes due to erosion and deposition, which in return affects the debris flow by changing its volume or flow route. The erosion and deposition processes in the transportation and erosion zone and the deposition zone can be accounted for by taking the sediment concentration of surficial materials and the bed elevation as variables.

In this study, a new computation scheme is developed to consider urban settings in the continuum-based model, EDDA (Erosion-Deposition Debris flow Analysis) proposed by Chen and Zhang (2015), which can be used to describe property changes of debris flow materials caused by erosion and deposition. The debris-traversing zones and the surface bed materials are specified by dividing the targeted area into several zones with different parameters. The soil properties and hydrological parameters in different underlying-surface zones are evaluated for debris flow simulations. The flow around buildings is captured. The new computation scheme is then calibrated with two historical cases on western Hong Kong Island. After that, a benchmark study on the effects of urban settings on debris flow mobility is conducted.

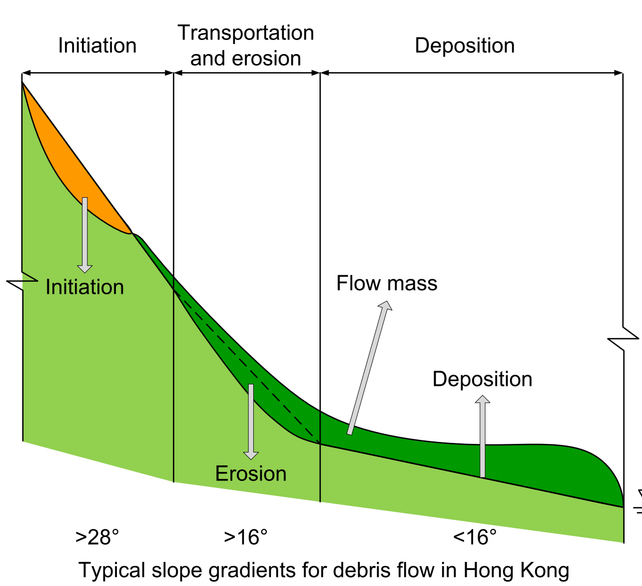

Fig. 1. Zones and mechanisms of debris flows (adopted from Franks, 1999).

2.1. Governing equations

EDDA (Chen and Zhang, 2015) simulates the movement of debris mixtures by solving the following shallow water equations, which include depth-integrated mass conservation equations (Eqs. (1) and (2)) and momentum conservation equations (Eqs. (3) and (4)):

$$\frac{\partial h}{\partial t}+\frac{\partial (hv_x)}{\partial x}+\frac{\partial (hv_y)}{\partial y}=f_e+f_s \tag{1}$$

$$\frac{\partial (C_v h)}{\partial t}+\frac{\partial (C_v hv_x)}{\partial x}+\frac{\partial (C_v hv_y)}{\partial y}=iC_{v*}+AC_{vA} \tag{2}$$

$$\frac{\partial (v_x)}{\partial t}+v_x\frac{\partial v_x}{\partial x}=g\left[-\mathrm{sgn}(v_x)S_{fx}-\frac{\partial (z_b+h)}{\partial x}\right]-\frac{v_x(f_e+f_s)}{h} \tag{3}$$

$$\frac{\partial (v_y)}{\partial t}+v_y\frac{\partial v_y}{\partial y}=g\left[-\mathrm{sgn}(v_y)S_{fy}-\frac{\partial (z_b+h)}{\partial y}\right]-\frac{v_y(f_e+f_s)}{h} \tag{4}$$

where h is the flow depth; t is time; v_x and v_y are the depth-averaged flow velocity in the x and y directions, respectively; f_e and f_s denote respectively site-specific functions of mass changes due to bed erosion and entrained surficial materials, where $f_e=i[C_{v*}+(1-C_{v*})s_b]$ and $f_s=A[C_{vA}+(1-C_{vA})s_A]$; i is the erosion rate (>0) or the deposition rate (<0); A is the rate of surficial material entrainment from collapse of bank materials or detached landslide materials; C_{v*} and C_{vA} are the volume fractions of solids in the erodible bed and the entrained surficial materials, respectively; s_b and s_A are the degrees of saturation of the erodible bed and entrained surficial materials, respectively; C_v is the volumetric sediment concentration of the debris flow mixture; g is the gravitational acceleration; S_{fx} and S_{fy} are the flow resistance slopes in the x and y directions, respectively; z_b is the bed elevation; the sgn function is used to indicate that the direction of the flow resistance is opposite to that of the flow direction.

The above governing equations adopt a global coordinate system which has been proved to be effective (O'Brien et al., 1993; Chen and Zhang, 2015). Since this study does not involve the process from a water flow to a hyperconcentrated flow, a momentum term related to density changes during the erosion and deposition process is neglected (Ouyang et al., 2015). However, this effect cannot be neglected if one intends to simulate large changes in solid concentration.

The bed elevation changes in the erosion and deposition processes and is expressed as

$$\frac{\partial z_b}{\partial t}=-i \tag{5}$$

The erosion rate can be described by the following equation:

$$i=K_e(\tau-\tau_c) \tag{6}$$

where K_e is the coefficient of erodibility describing the erosion speed, which can be determined by field erosion tests (e.g., Chang and Zhang, 2010; Chang et al., 2011; Zhu and Zhang, 2016); τ and τ_c are the shear stress and the critical erosive shear stress, respectively.

The shear stress, τ, can be computed as (Graf, 1971)

$$\tau=\rho ghS_f \tag{7}$$

where ρ is the debris flow density and can be computed by $\rho=C_v(\rho_s-\rho_w)+\rho_w$; ρ_s and ρ_w are the mass densities of the solids and water, respectively; S_f is the flow resistance slope, which can be calculated using a rheological model.

The critical erosive shear stress, τ_c, can be calculated by taking the bed erosion as a Mohr-Coulomb failure process (Medina et al., 2008;