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Two-dimensional simulation of debris flow impact pressures on buildings

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ABSTRACT

This paper presents a computational scheme for simulating debris-flow impact pressures on buildings in urban areas. The debris flow mobility is described using depth-averaged mass and momentum equations considering the erosion and deposition processes and changing solid concentrations. The total impact pressure consists of a dynamic impact pressure from the moving debris flow mixture and a static pressure from the deposited debris material. A target analysis area on Hong Kong Island, including a large number of buildings in that area, is characterized precisely using a three-dimensional high-resolution digital elevation model, and discretized into a grid of 5 m square cells with different bed material parameters. Using the model, the flow patterns of a large debris flow around nearly 20 buildings along the flow path and the impact pressures against the facades of these buildings are simulated. The buildings increase the flow depth and flow 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 impact pressures are high on the building facades that face the main traversing path of the debris flow. Deposition of debris in front of the buildings increases the impact pressure.

1. Introduction

Buildings in mountainous regions are often exposed to debris flows. The assessment of the safety of the buildings and the design of countermeasures against debris-flows require the determination of several important factors, such as total debris flow volume, debris-traversing zones, size of the debris fan, debris flow velocity, impact pressure, and so on (Hu et al., 2012; Chen et al., 2012; Hong et al., 2015; Zhang and Zhang, 2017). Investigating the impact pressures of a debris flow against a building or a rigid debris-flow barrier is a key step for structural design and hazards mitigation.

Three categories of methods have been developed to evaluate the debris-flow impact pressure: empirical formulas based on historical information (e.g. Hungr et al., 1984; Hong, et al., 2015; Kang and Kim, 2016), flume tests (e.g. Choi, 2013; Cui et al., 2015) and numerical modelling (e.g. O'Brien et al., 1993; Armanini, 1997). Analytical or empirical formulas have been used under the assumption that there is little lateral velocity variation. An amplification dynamic pressure coefficient (e.g. GEO (Geotechnical Engineering Office), 2012) is often assigned to consider the heterogeneous nature of debris flows. A small-scale flume test represents well the physics of idealised debris flows but may not describe well the rheology of natural debris flows, complex urban topographic conditions and buildings along the debris flow path. The kinetic characteristics of a debris flow and its impacts against an obstacle can be analysed using a physically-based representation of the debris-flow movements. Modelling the impact pressure against an obstacle mathematically consists of two steps: process modelling which quantifies relevant debris flow variables spatially and temporally, and impact modelling which represents the dynamic and static impact loadings.

More than one building could be affected if a large debris flow occurs. Furthermore, a debris flow can gain much of its mass with destructive power from entrainment along the debris-traversing path (Iverson et al., 2011; Iverson, 2012; Gao et al., 2016; Shen et al., 2017; Zhang et al., 2016). However, limited attention has been paid to urban debris flow analysis considering the erosion and deposition processes. Efforts have to be made to include urban settings and erosion and deposition processes in simulating debris flow impact pressures.

This paper presents a depth-integrated scheme for estimating the impact pressures of a debris flow against a number of buildings along the debris flow path in the metropolitan setting. The calculation scheme employs a two-dimensional continuum model with the consideration of building blockage effects, bed erosion, and debris deposition (Chen and Zhang, 2015; Gao et al., 2016). The computational scheme is validated with a flume test, in which the debris flow mobility and flow pattern around baffles were monitored. The computational scheme is applied to

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Table 1
Summary of parameters.

Parameters	Values	References
Volume fraction of solids in erodible bed, C_{v_*}	0.65	Chen and Zhang (2015)
Degree of saturation of erodible bed, S_b	1	
Coefficient of erodibility, K_e (m^3/Ns)	1×10^{-6}–1×10^{-7}	Chang et al. (2011)
Mean particle size of debris material, d_{50} (mm)	33	King (2013)
Soil density, ρ_s (kg/m^3)	2650–2680	GCO (1982)
Effective cohesion of bed material, c' (kPa)	3.5	GCO (1982)
Internal friction angle of erodible bed, ϕ_{bed} (°)	36–42	GCO (1982)
Coefficient of deposition rate, δ_d	0.02–0.03	Chen and Zhang (2015)
Manning coefficient, n	0.05–0.15	FLO-2D Software Inc. (2009)
Resistance parameter for laminar flow, K	2500	FLO-2D Software Inc. (2009)
Coefficient of suspension of solid particles, C_s	0.4	Chen and Zhang (2015)

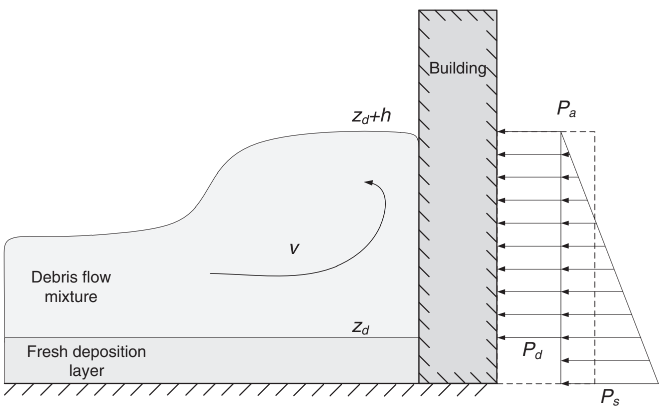

Fig. 1. Illustration of the impact pressure model.

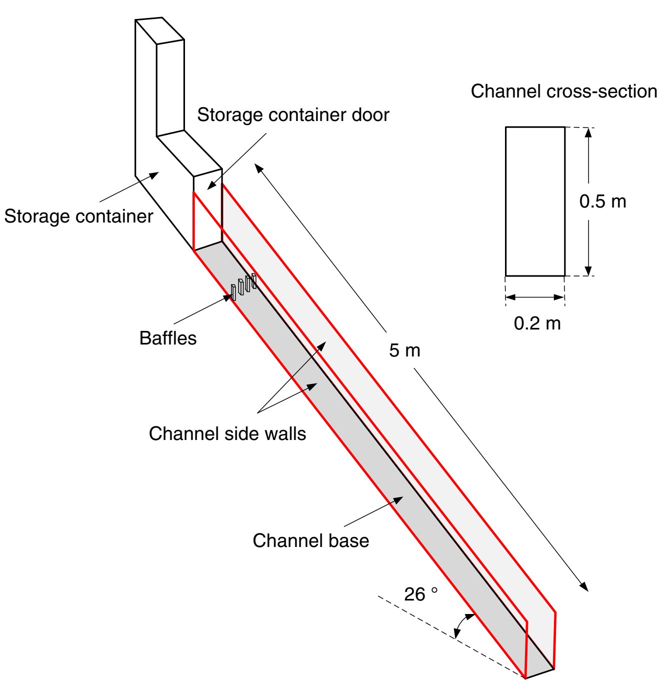

Fig. 2. Flume model setup (adopted from Choi, 2013).

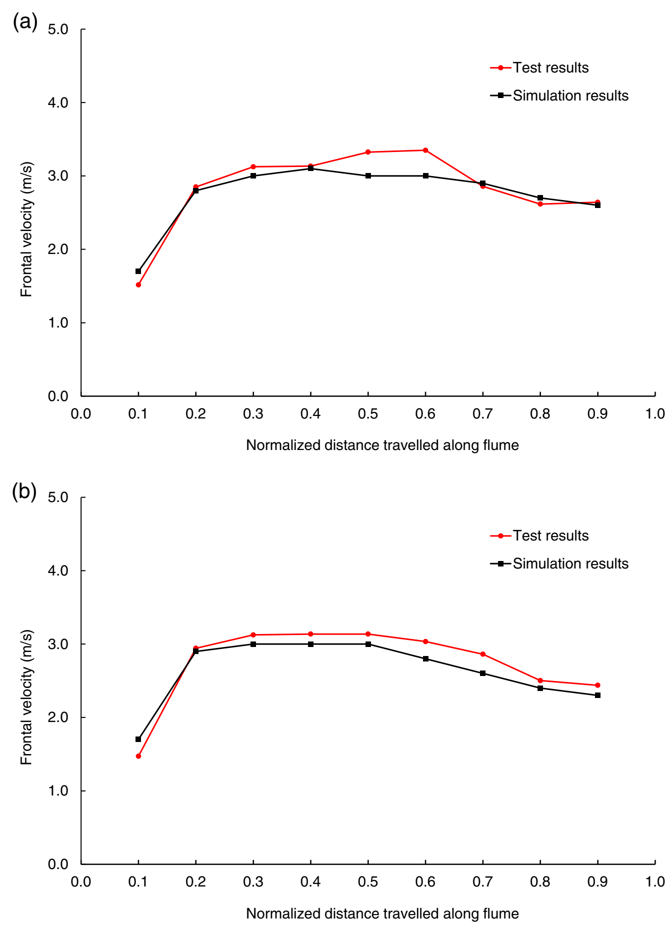

Fig. 3. Comparison of mobility simulation results with test results: (a) without baffles; (b) with baffles.

a watershed on Hong Kong Island. The kinetic characteristics of a debris flow and the impact pressures on the affected buildings in the study area are simulated and analysed.

2. Debris flow analysis model

In this study, a computational scheme is proposed to compute debris-flow impact pressures based on a continuum-based model, EDDA (Erosion-Deposition Debris flow Analysis) developed by Chen and Zhang (2015), which can be used to describe the erosion and deposition processes of debris flows. A target analysis region is characterized using a three-dimensional high-resolution digital elevation model (DEM) and discretized into square cells with assigned information of soil properties and hydrological conditions. The flow process and patterns around the blocked cells (e.g. buildings or baffles) are captured, and the impact pressures against the buildings are computed based on the simulated results of flow process.

The movements of the debris mixture are described using the following equations:

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