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ORIGINAL PAPER

Study on the effect of entrainment on the behavior of debris flows using a 3D Coupled Eulerian–Lagrangian finite element method

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Abstract
Debris flows are one of the most hazardous surface processes. The entrainment of bed sediment is an essential process in the debris flows. The volume and potentially destructive power of debris flows can be increased by the entrainment of bed sediment. Numerical analysis of debris flows with and without entrainment was conducted to confirm the effect of entrainment on debris flows mobility. To simulate entrainment of bed-sediments by debris flows, the numerical analysis was focused on the change in the properties of the soil layer. In order to take into account the solid-like elastoplastic behavior before failure and fluid-like viscous behavior after failure, the two constitutive models were combined using the deviatoric shear strain of the soil layer induced by the debris flow. The model for the simulation of debris flows over erodible beds was validated using published experimental data. To quantify the effects of entrainment on the behavior of debris flows, the flow length, angle of inclination, and erodible depth were controlled in numerical analysis. The depth of the entrained soil layer increased as the depth of the wetting band increased. The results of the analysis were represented in the velocity, thickness of debris flows reaching the bottom area, and impact pressure. It was confirmed that the velocity of debris flows decreases with increasing viscosity and the velocity of debris flows arriving later appears to be faster as the wetting depth increases. Entrainment of the bed-sediment by debris flowing could either increase or decrease its mobility depending on the flow length. The maximum velocity and thickness of debris flow increased with the increasing slope inclination angle.

Keywords Debris flows · Entrainment · Large deformation FE analysis · Coupled Eulerian–Lagrangian (CEL) · Flow length · Angle of inclination

Introduction

Debris flows are one of the most hazardous surface processes due to the economic losses and the number of human casualties they cause (Schürch et al. 2011; Iverson et al. 2011). The behavior of debris flows with entrainment and deposition processes is complex and dominant, but these processes are poorly understood (Mergili et al. 2020; Pudasaini and Fischer 2020). The magnitude of debris flows can be defined by flow velocity or thickness. Entrainment can increase the magnitude of debris flows and dramatically increase their volume and potentially destructive power; it causes a significant risk to populations (Hungr et al. 2005; McDougall and Hungr 2005; Reid et al. 2011). Entrainment of bed sediment is the process by which surface sediment is incorporated into a debris flow. The entrainment of bed sediment can strongly influence the flow dynamics and the characteristics of deposits with adverse environmental impacts (Rickenmann 2005; Godt and Coe 2007; Berger et al. 2011; Pirulli and Pastor 2012).

Several studies have investigated the entrainment of bed sediment using field (Rickenmann et al. 2003; Hungr and Evans 2004; Berger et al. 2010, 2011; McCoy et al. 2012) and flume tests (Egashira et al. 2001; Mangeney et al. 2010; Reid et al. 2011; Iverson 2012). Iverson (2012) theoretically conducted a study on entrainment rates, and McDougall and Hungr (2005) suggested an empirical model relating erosion velocity to the rate of volume increase. Christen et al. (2009) described an entrainment rate per unit flow velocity based on the thickness and densities of the different bed layers. Some research was conducted to investigate the influences of the properties of debris flows and sediment (Papa et al. 2004; Mangeney

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