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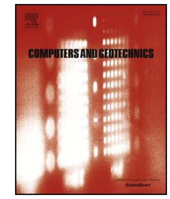

Research Paper

Large deformation FE analysis of a debris flow with entrainment of the soil layer

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A B S T R A C T

A study was conducted to understand the fundamental characteristics of debris flow in a watershed with entrainment of the soil layer. This paper presents the application of the coupled Eulerian-Lagrangian (CEL) technique to simulate three-dimensional debris flow with entrainment of the soil layer. To simulate the erosion and entrainment of the soil bed sediment, a softening model was adopted for the soil layer to describe the strength reduction of the erodible soil layer as a function of the velocity. The analytical method is validated using published data from a laboratory experiment [1]. This comparison shows that the proposed model is in good agreement with laboratory data. Furthermore, FE analysis is conducted to ensure its ability to simulate the watershed scale debris flow. The validity of the analytical technique and model was evaluated by comparing the simulation against measured [2] debris flow. The results of the analysis show that the erosion and entrainment of the soil layer increase the volume of debris flow. The results are in good agreement with the measured phenomenon.

1. Introduction

Global climate change, including rising temperatures and heavy rainfall, could trigger catastrophic debris flows [3,4]. Debris flows are gravity-driven mixtures of soil, rock, and water that have properties intermediate between flooding and dry rock avalanches [5]. Debris flows, which exhibit high speeds and pressures due to their bulk volume, threaten human life and cause considerable damage to both the infrastructure and environment, which are important to modern living conditions. Debris flow volume can dramatically increase during the soil-moving processes of the erosion and entrainment of the soil layer in mountainous areas, and this volume constitutes a great risk to populations [6,7]. Entrainment mechanisms can significantly change the mobility of the flow via changes to the flow volume and rheological behavior [5–8]. Entrainment occurs when debris moves along an erodible layer and applies a shear stress that surpasses the strength of the layer material. Researchers have long recognized that debris flows can gain much of their mass and destructive power by entraining material (e.g., [6,9]). Iverson [10] evaluated entrainment rates theoretically, and McDougall and Hungr [7] proposed an empirical rule relating erosion velocity to the rate of volume increase. Christen et al. [11] defined an entrainment rate per unit flow velocity based on the heights and densities of the different bed layers. The erosion and entrainment effect is critical to the motion of debris flows, and this phenomenon and the associated case studies have long been topics of interest. Diverse studies have been conducted to understand the characteristics of debris flow with the erosion and entrainment of the soil layer and to reduce potential damage. Both experimental studies (e.g., [6,12–15]) and numerical modeling, including simulations incorporating entrainment terms (e.g., [7,16–19]), have been performed. Nevertheless, numerical approaches for evaluating the entrainment of the soil layer have remained tenuous.

Most studies regarding debris flow and analysis of the deposit characteristics are conducted using a 2D or semi-3D finite difference method (FDM). This analysis method is used to estimate the flow and damage scale caused by debris flows. Programs based on the FDM determine the direction of the flow with a D8 (eight-direction flow model) method. Meshless methods without mesh distortion problems, such as the Material Point Method (MPM) or Smoothed Particle Hydrodynamics (SPH), are applied to the analysis of debris flow ([20–22]). SPH is the oldest meshless method and was developed by Gingold and Monaghan [23] and Lucy [24] for simulations of astrophysical problems.

However, the accuracy of this method is lower than that achieved by finite element (FE) analysis. Recently, finite element methods (FEMs) have been developed for analysis to overcome the problem of large deformations. The coupled Eulerian-Lagrangian (CEL) analysis, one of the large deformation analysis techniques, combines the advantages of Lagrangian and Eulerian analysis and has no limitations

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