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Research Paper

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

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ABSTRACT

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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regarding terrain or scope. Therefore, it is well suited for estimating the movement of debris flow at high speeds. In this study, a 3D FE analysis was conducted to evaluate the applicability of large deformation analysis to analyze the characteristics of debris flow, and the CEL technique was applied to simulate large deformation debris flow. To capture the increase in debris flow volume caused by entrainment, a softening mechanism with a velocity was applied to the erodible soil layer. The accuracy of this method was verified by comparing the results with measured values taken at the debris flow site.

2. Constitutive model for entrainment of the soil layer

Debris flow movement is affected by the slope curvature of the sliding surface [25,26], generation/dissipation of pore water pressure [27,28], erosion/deposition processes [6], and the existence of a blockage. Identifying the characteristics of the shear stress behavior is important for identifying the characteristics of the debris flow. The size of the debris flow is determined primarily by the amount of sediment flowing downward, and the debris flow volume can dramatically increase with the entrainment of the soil layer [6,15]. The entrainment of bed material is an important process in debris flows, as it can lead to a change in the material character of the soil layer of the moving mass and modify its mobility [5,7,8].

During debris flows, geomaterials evolve in a particular manner, because initially they behave as solids, and then they turn to flow as viscous fluids. Soils are known to obey elastoplastic constitutive relation and follow solid-like behavior. The solid-like regime is dominated by inertial forces and quasi-static stresses [29]. However, after failure, no behavior is proposed by the usual geomechanical models. When the soil is completely remolded, the soil strength is very close to the yield stress in rheology [30], and they turn to fluid-like behavior as viscous fluids. The fluid-like regime are generally affected by a complex kinematics deriving from a 'fluidification', due to the high speed relative motion and collisions within the shear layer [31,32]. In this study, transition between a solid-like and a fluid-like behavior is represented by the softening model within a single numerical framework. Strain-softening behavior is commonly observed when testing geotechnical materials, and numerous models that account for strain-softening behavior have been developed [33–35]. To consider solid-like elastoplastic behavior before failure and fluid-like viscous behavior after failure, the two constitutive equations are combined using the velocity of the soil caused by the debris flow (Fig. 1).

The shear strength of the soil layer changed from the solid state to the fluid state according to the velocity, which is expressed in Eq. (1).

$$\tau_e = \tau_s - \left(\frac{v - v_s}{v_f - v_s}\right)(\tau_s - \tau_f) \quad (1)$$

where τ_s is the shear resistance after the erosion and entrainment of the soil layer, v is the velocity of the soil layer, v_s is the velocity when the solid begins to change into a fluid, and v_f is the velocity when it behaves like a fluid.

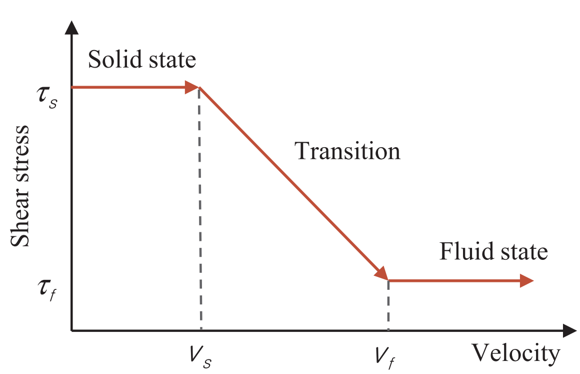

Fig. 1. Variation in shear strength with velocity.

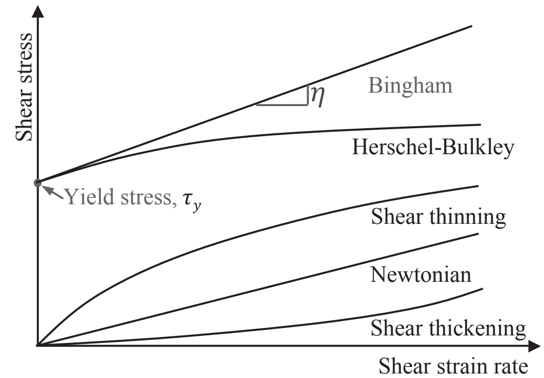

Fig. 2. Relationship between shear stress and shear rate.

The elastoplastic model called Mohr-Coulomb is chosen because it reproduces the main features of soils. The Mohr-Coulomb model can be expressed by plotting Mohr's circle for states of stress at failure in the plane of the maximum and minimum principal stresses. The Mohr-Coulomb failure criterion is defined by

$$\tau = c' + \sigma' \tan\phi' \quad (2)$$

where τ is the shear stress, c' is the cohesion intercept, σ' is the effective normal stress, ϕ' is the internal friction angle of a soil. The Mohr-Coulomb model is an elastic perfectly-plastic model and forms a combination of Hooke's law and the generalized form of Coulomb's failure criterion.

Several researchers ([36–39]) have characterized the movement of debris flow using non-Newtonian fluid models to explain its fast-moving characteristics over distances. The models generally used for debris flow analysis are the Bingham model and Herschel-Bulkley model, which are in the form of shear thinning (Fig. 2). The Herschel-Bulkley model is applicable, in which the speed of the shear increases as the viscosity decreases.

As shown in Eq. (3), the Bingham model and Herschel-Bulkley models are defined by the shearing resistance force and the rate of shear strain:

$$\tau = \tau_y + \eta\dot{\gamma} \quad (3)$$

where τ_y is the initial shear resistance force $\dot{\gamma}$ is the rate of shear strain η is the viscosity, and n is a dimensionless coefficient (where $n = 1$ corresponds to the Bingham model). Table 1 shows the states for which the constitutive models are applied (before the occurrence of the debris flow, when the debris flow begins to descend, when the soil layer is eroded and entrained). The v_s, which the velocity when the soil is completely destroyed, can be estimated by the ring shear test which can perform the large strain shear test, and v_f can be estimated from viscometer experiments. Reid et al. [14] and Iverson et al. [40] measured the deformation rate after erosion of the soil layer in a large laboratory experiment and found that it ranged from 0.05 to 0.1 m/s. Berger et al. [13] and McCoy et al. [15] measured the erosion velocity of the soil layer in the case of the entrainment of bed sediment by a debris flow in the watershed. As a result, erosion and entrainment of the soil layer show different behaviors depending on the particle size distribution, debris flow depth, and ground saturation. The deformation rate in dry soil is 0.002–0.005 m/s, and the deformation rate in saturated soil is 0.1–0.5 m/s.

The contact element provided by ABAQUS (Ver. 6.13) [41] is applied to the initial volume of debris flow and to the interface between the bedrock layers. The general contact interface model, which can be used for explicit dynamic analysis, is used to analyze debris flow since the contact surface changes fluidly. This approach has the considerable advantage that the elements are not torn. The condition for the contact surface is defined by the slip coefficient and by Coulomb friction theory,