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A General Two-Fluid Debris Flow Model

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Starting with the phase-averaged dynamical equations of Ishii (1975) and Drew (1983), we develop a new general two-fluid debris flow model that includes most of the essential physical phenomena. The model employs the Mohr-Coulomb plasticity for the solid stress and the fluid extra stress is modelled as a Newtonian viscous stress that is enhanced by the solid volume fraction gradient. The generalized interfacial momentum transfer is modeled by including the force on the particulate phase due to viscous drag, buoyancy force, and the relative acceleration between the solid and the fluid particles (the virtual mass). Richardson and Zaki (1954) relationship between the sedimentation and the terminal velocity of a solid particle falling in the fluid and Kozeny-Carman expression for fluid flows through densely packed grains are combined to develop and implement a new generalized drag force. The new drag force; which is expressed explicitly in terms of several essential physical parameters associated with the solid and the fluid phases; reveals the most basic features, and can be applied to problems ranging from linear to quadratic drag forces, and relatively dilute to dense flows of solids. The drag expression serves as a generalized drag force for two-phase viscous debris flows and dispersive particle laden flows as it covers both the solid-like and fluid-like contributions.

The new three- and depth-averaged two-dimensional two-phase debris flow models are presented in well structured conservative hyperbolic-parabolic form for mass and momentum balance equations. The model equations are written in a newly developed multi-curvature curvilinear coordinate system that fits exactly and directly with the basal topography, but without any reference surface. There are strong couplings between the solid and the fluid momentum transfer, both through the interfacial momentum transfer and the solid concentration gradient enhanced viscous fluid stresses. The model includes both advection and diffusion of the solid volume fraction. The intensity of diffusion depends on the magnitude of the relative velocity between the phases, the fluid density and viscosity, and the mobility of the fluid at the interface. Inclusion of the viscous stresses in the model equations is important in several aspects. For dilute flows, there are no grain-grain contacts, grain shear stresses disappear, and there is no Kozney-Carman contribution in the drag force. This leads to the gravity driven dispersive grain flows through the continuum fluid that is resisted only by the enhanced viscous forces, Richardson-Zaki-type viscous drag, and the virtual mass forces. For neutrally buoyant particles, the basal friction becomes zero, and the drag force vanishes identically. The gravity and the enhanced viscous forces are effective. In this situation, the importance of the solid volume fraction as a field variable becomes clear. The new model can reproduce most of the previous model equations for single and two-phase avalanche and debris flows (e.g., Savage and Hutter, 1989; Iverson and Denlinger, 2001; Pitman and Le, 2005; and Pudasaini et al., 2005). The new model equations constitute the most general two-fluid flow model, and are potentially able to adequately describe the dynamics of debris flows, avalanches, and particle-laden and dispersive flows.