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A finite volume solver for three dimensional debris flow simulations based on a single calibration parameter

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Debris flows are frequent natural hazards that cause massive damage. A wide range of debris flow models try to cover the complex flow behavior that arises from the inhomogeneous material mixture of water with clay, silt, sand, and gravel. The energy dissipation between moving grains depends on grain collisions and tangential friction, and the viscosity of the interstitial fine material suspension depends on the shear gradient. Thus a rheology description needs to be sensitive to the local pressure and shear rate, making the three-dimensional flow structure a key issue for flows in complex terrain. Furthermore, the momentum exchange between the granular and fluid phases should account for the presence of larger particles. We model the fine material suspension with a Herschel-Bulkley rheology law, and represent the gravel with the Coulomb-viscoplastic rheology of Domnik & Pudasaini (Domnik et al. 2013). Both composites are described by two phases that can mix; a third phase accounting for the air is kept separate to account for the free surface. The fluid dynamics are solved in three dimensions using the finite volume open-source code OpenFOAM. Computational costs are kept reasonable by using the Volume of Fluid method to solve only one phase-averaged system of Navier-Stokes equations. The Herschel-Bulkley parameters are modeled as a function of water content, volumetric solid concentration of the mixture, clay content and its mineral composition (Coussot et al. 1989, Yu et al. 2013). The gravel phase properties needed for the Coulomb-viscoplastic rheology are defined by the angle of repose of the gravel. In addition to this basic setup, larger grains and the corresponding grain collisions can be introduced by a coupled Lagrangian particle simulation. Based on the local Savage number a diffusive term in the gravel phase can activate phase separation.

The resulting model can reproduce the sensitivity of the debris flow to water content and channel bed roughness, as illustrated with lab-scale and large-scale experiments. A large-scale natural landslide event down a curved channel is presented to show the model performance at such a scale, calibrated based on the observed surface super-elevation.