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A Real Two-Phase Mechanical Model for Rock-Ice Avalanches

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Rock-ice avalanches in high mountain permafrost environments are a hazardous and poorly understood process. Their hazard potential derives from the large volume, high velocities, the potential entrainment of large amounts of rock-debris, ice, snow and water during the flow, high impact pressures, and unpredictable flow paths and deposition patterns. In contrast to the usual single-phase model of rock avalanches, the solid phase (ice) in rock-ice avalanches can transform to fluid (water or slurry) during the course of the debris-avalanche and fundamentally alter the multiple mechanical processes. We postulate that a real two-phase debris flow model could much better address the dynamic interaction of solid (rock and ice) and fluid (water, snow, slurry and fine particles) rather than a simple single-phase Voellmy- or Coulomb-type model. For this, we enhance the general two-phase debris flow model proposed by Pudasaini (2011) by additionally introducing two new mechanical aspects typical for the rock-ice avalanches: (a) the dynamic strength weakening including the internal fluidization and basal lubrication, as well as (b) the internal mass and momentum exchanges between the phases. In these models, the effective basal and internal friction angles are variable and are described in terms of evolving effective solid volume fraction (rock and ice), friction factors, volume fraction of the ice, true friction coefficients and the lubrication and fluidization factors. These factors are functions of several physical parameters and mechanical and dynamical variables, including the volume fractions of the solid, shear-rate and the normal stresses. Rock-ice avalanches are a unique scenario in geophysical mass flows, where phase exchange and material strength weakening occurs and can dominate the flow dynamics. Here, we present an innovative approach to model and simulate these two special aspects. Additionally, in the model, the inertial terms include the hydraulic pressure gradients and the virtual mass. The source in the solid momentum includes gravity, the Coulomb friction, slope gradient, buoyancy, and the generalized drag. The source term for the fluid momentum includes gravity, fluid pressure and topographic gradients, enhanced non-Newtonian viscous stresses, and the drag. There are strong couplings between the solid and fluid momentum transfer.

The new enhanced two-phase model can better explain dynamically changing frictional properties of rock-ice avalanches that occur internally and along the flow path. Both mass and momentum exchanges allow for a much more realistic simulation, especially during the critical initial and final stages of avalanche propagation. Benchmark numerical simulations demonstrate that the dynamics of permafrost rock-ice avalanche is fundamentally different form that of pure rock avalanches. The model simulations reveal special features of rock-ice avalanche propagation form and dynamics, similar to those observed, e.g., in the 2007 Bliggspitze rock-ice avalanche event. Numerical results also reveal that mass and momentum exchange between the phases and the associated internal and basal strength weakening offer a new explanation for the exceptionally long run-out distances leading to higher flow mobility typical for high-mountain rock-ice avalanches. These new results substantially improve modelling run-out distances and inundation areas, and could significantly contribute to hazard prediction and mitigation in high-mountain permafrost environments. Here we show that the new two-phase rock-ice avalanche model can yield a novel and enhanced representation of multiple processes that lead to the high and changing mobility of rock-ice-avalanches.