Towards a predictive 3D model for alpine mass movements: Insights from recent events in the Swiss Alps

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Abstract: We present a newly developed numerical model [1,2] designed to address the practical needs of engineers evaluating risks related to alpine mass movements. Based on the Material Point Method (MPM) and finite-strain elasto(visco)plasticity, our model can incorporate various material models representing snow, ice, rock, and water. This enables detailed simulations of a wide range of materials under different flow regimes. Rate-dependent cohesive Drucker–Prager and Modified Cam Clay models, which both recover the liquid $\mu(I)$ granular rheology under flow conditions, have been implemented and validated. Key features of the model include: 1) physical input data that can be derived from classical geotechnical or field experiments; 2) explicit simulation of bed entrainment; and 3) the ability to simulate interactions with complex terrain and mitigation structures at very high resolution, achieving scales as fine as decimeters and evaluating the resulting impacts. The model is designed with practical applications in mind, integrating seamlessly with GIS tools to automate the visualization and interpretation of results in three-dimensional terrain [3]. Validation against well-documented cases demonstrates our model's potential to replicate and predict real-world phenomena with high fidelity. Notably, its successful application to the 2023 Brienz rock avalanche and the 2025 Blatten rock–ice avalanche has shown good runout predictions, while in the Blatten case, discrepancies in deposit distribution and seismic signals highlighted limitations of the single-phase frictional model. These observations suggested potential liquefaction and the need for additional physical ingredients, which were effectively captured phenomenologically by adopting a $\mu(I)$-type rheology, though future two-phase formulations are expected to provide further improvements [4]. Additionally, its application to future potentially catastrophic rock avalanche events and to dam overflow analysis highlights its capacity for supporting predictions and simulation-guided recommendations for the design and optimization of mitigation measures. As a tool for hazard assessment and engineering design, our model represents a promising step forward in modeling alpine mass movements, enabling tailored simulations and providing practical, versatile solutions for engineers.

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