UNIFIED MODELING OF THE RELEASE AND FLOW OF SNOW AVALANCHES USING THE MATERIAL POINT METHOD

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Figure 1: Three dimensional simulation of the remote triggering of a slab avalanche by a snowman.

ABSTRACT: Snow slab avalanches start with the failure of a weak snow layer buried below a cohesive snow slab. After failure, the very porous character of the weak layer leads to its volumetric collapse and thus closing of crack faces due to the weight of the overlaying slab. This complex process, generally referred to as anticrack, explains why avalanches can be remotely triggered from flat terrain. On the basis of a new elastoplastic model for porous cohesive materials and the Material Point Method, we accurately reproduce the dynamics of anticracks observed in propagation saw tests as well as the subsequent detachment of the slab and the flow of the avalanche. In particular, we performed two and three dimensional slope scale simulations of both the release and flow of slab avalanches triggered either directly or remotely. We describe in details the fracture and flow dynamics on a realistic topography and focus on the plastic strain, stress invariants, propagation speed and flow velocity. Furthermore, we show that slab fracture always starts from the top in the Propagation Saw Test while it systematically initiates at the interface with the weak layer at the crown of slope-scale simulations in agreement with field observations. Our unified model represents a significant step forward as it allows simulating the entire avalanche process, from failure initiation to crack propagation and to solid-fluid phase transitions, which is of paramount importance to mitigate and forecast snow avalanches as well as gravitational hazards in general.

KEYWORDS: Snow avalanche, crack propagation, slab, weak layer, elastoplasticity, MPM

1. INTRODUCTION

Snow is a complex and fascinating material which can sustain stresses like a solid or flow like a fluid depending on the applied loading (Louchet et al. 2013). The solid-fluid transition in snow can have dramatic consequences such as snow slab avalanches which are responsible for most of damage

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and fatalities related to avalanche activity. Although slab avalanches can be devastating phenomena of large scale (> 100 m), their release is controlled by failure mechanisms at the microscopic scale (< 1 mm) in the snowpack. It is thus intrinsically a multiscale issue. Snow slab avalanches result from a sequence of fracture processes including (i) failure initiation in a weak layer underlying a cohesive snow slab, (ii) the onset of crack propagation, (iii) dynamic crack propagation through the weak layer across the slope, and (iv) detachment and sliding of the slab, followed by the flow of the avalanche (Schweizer et al. 2003).

Although a lot of progress has been made in avalanche science in the past decade (Schweizer 2017), classical modelling methods used in snow science such as DEM (Discrete Element Method, e.g. Hagenmuller et al., 2015), FEM (Finite Element Method, e.g. Podolskiy et al., 2013) or FV (Finite Volumes, Christen et al., 2010) fail to model the whole avalanche process, from quasi-static failure initiation to dynamic crack (or anticrack, Heierli et al. 2008) propagation and flow at the slope scale. In contrast, the Material Point Method (MPM, Sulsky et al., 1995) is a continuum and hybrid Eulerian-Lagrangian method which is ideal for modelling fractures, impacts and coexistence between solid- and fluid-like behaviors. Indeed, the collective behavior (friction and collisions) of fractured solid materials can lead to a viscous fluid aspect at the macroscopic scale.

The recent developments in snow science (Schweizer et al. 2016) and with MPM allow to consider for the first time breaking a critical science barrier in avalanche research and animation, namely simulating both solid- and fluid like behaviors in a unique and multiscale physically-based framework. Here, we conducted numerical simulations based on MPM and a new homogenized elastoplastic constitutive model for porous cohesive materials which accounts for cohesion softening and volume reduction. Our new model accurately reproduces the onset and dynamics of propagating anticracks monitored in snow fracture experiments and is able, for the first time, to simulate both the release and flow of slab avalanches at the slope scale (Gaume et al. 2018a).

2. METHODS

2.1 The Material Point Method (MPM)

MPM consists in using particles (material points) to track mass, momentum and deformation gradient. The Lagrangian character of these quantities facilitates the discretization of the mass conservation equation as well as the acceleration term in the momentum conservation equation. However, the lack of mesh connectivity between material points complicates the computation of spatial derivatives. This is thus performed through a regular background Eulerian grid and interpolation functions over this grid using classical FEM and the weak form. The explicit MPM algorithm from Stomakhin et al., (2013) is used with a symplectic Euler time integrator. The main difference is the elastoplastic constitutive model (see below) i.e. how stress is computed and processed under the plastic flow. We refer to Jiang et al., (2016) and Gaume et al. (2018a) for more details about the MPM time stepping algorithm.

2.2 Finite strain elastoplastic model

The mechanical model is described in details in Gaume et al. (2018a). We recall the main characteristics below.

For both the slab and the weak layer, we use a mixed-mode shear-compression yield surface in agreement with laboratory experiments (Reiweger et al., 2015) and simulations based on X-ray computed tomography (Hagenmuller et al., 2015; Chandel et al., 2015; Hagenmuller et al., 2017; Srivastava et al., 2017).

At failure, hardening and softening is performed by expanding or shrinking the yield surface, respectively. For the slab, compression leads to hardening, promoting compaction, while tension leads to softening, promoting fracture.

For the porous weak layer, the hardening rule of the slab was modified to allow softening and collapse under compression. Once stresses reach zero, cohesion is removed and a standard hardening rule is used leading to a purely frictional/compaction behaviour (Gaume et al. 2018a). This new softening rule mimics bond breaking in the weak layer and subsequent grain rearrangement leading to volumetric collapse due to the compressive weight of the overlaying snow slab. Physically, this mechanical behavior is related to the fact that even under compression, the solid matrix of porous solid is mostly under tension and shear (Gaume et al., 2017b).

2.3 Simulated geometries and mechanical parameters

Our model was already presented and validated using data of the Propagation Saw Test (PST, van Herwijnen et al., 2010, 2016) in Gaume et al., (2018a). Hence, here, we will focus on the analysis of slope-scale simulations. First, we modelled a two dimensional slope of length $L = 25$ m and height $H = 13$ m with a constant slab depth $D = 0.4$ m. The maximum slope angle is $45°$. For three dimensional simulations (Fig. 1), the geometry was chosen to mimic a concave slope with a maximum snow depth in the middle of the path. It was reported by Vontobel et al., (2013) that this type of slope shape was most commonly associated with avalanches. The length $L = 22$ m and height $H = 9$ m. Spatial variability of snow depth was added with using a simplex Perlin terrain noise model (Perlin 2002) with a resulting standard

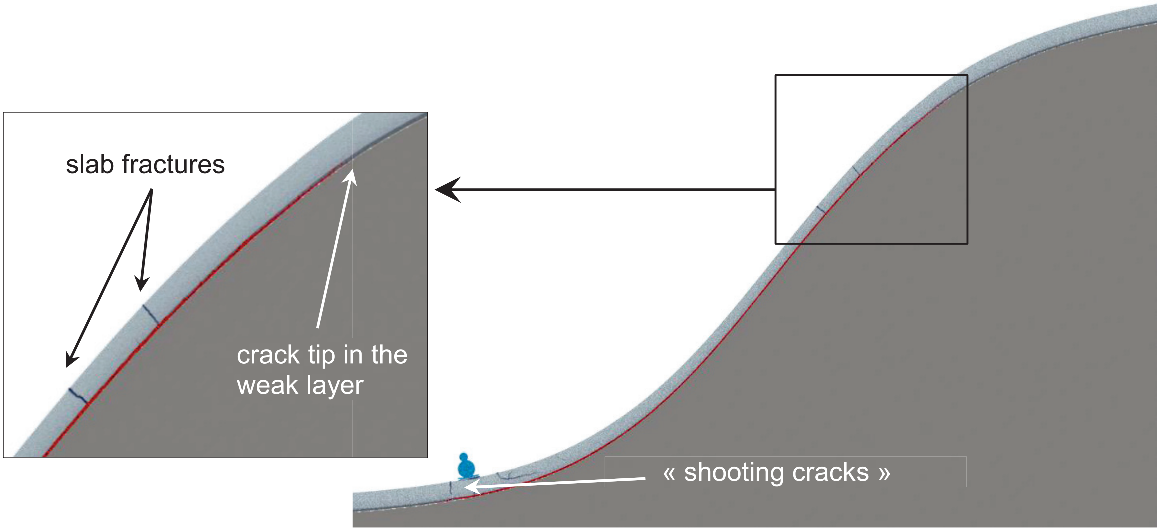

Figure 2: Simulation of remote avalanche triggering with shooting cracks and en-echelon fractures.

deviation of ~25% and correlation length ~10 m. The mechanical parameters are presented in Gaume et al. (2018a).

3. RESULTS

3.1 Release

In both 2D and 3D cases, we simulate the remote triggering of a slab avalanche by a snowman (in blue in Fig. 2). The snowman initiates a failure in the weak layer which then propagates along the slope as a mixed-mode anticrack. The collapse of the weak layer around the snowman induces local slab fractures similar to the "shooting cracks" often observed in the field (Fig. 2). The average crack propagation speed was found around 60 m/s but it locally increases in steep parts of the slope where the propagation speed can reach more than 100 m/s. We observe "en-echelon" types fractures i.e. crack propagation in the weak layer is subsequently followed by slab fractures below the crack tip, as shown in Fig. 2. Once the crack in the weak layer has propagated across the slope, the slab releases where the slope angle exceeds the friction angle of the weak layer. The crown slab fracture has very interesting features. It starts branching from the bottom of the slab at the interface with the weak layer as shown in Fig. 3. This contrasts with the slab fracture in PST experiments which systematically starts branching from the top, in MPM simulations and experiments (Gaume et al. 2018a, Fig. 3). Finally, as shown in Figs. 1 and by Gaume et al. (2018a), the release zone has an arc crown line, jagged flanks and staunchwall which are commonly observed. In the slab, the first fracture occurs at the crown in tension and is followed by the staunchwall and flank shear fractures.

3.2 Flow

It is the collective behavior and interactions between broken pieces of the released slab which can further collide, fracture or stick with each other which leads to a macroscopic fluid-like behavior. For both 2D and 3D simulations (Figs. 1 and 4), we get a maximum

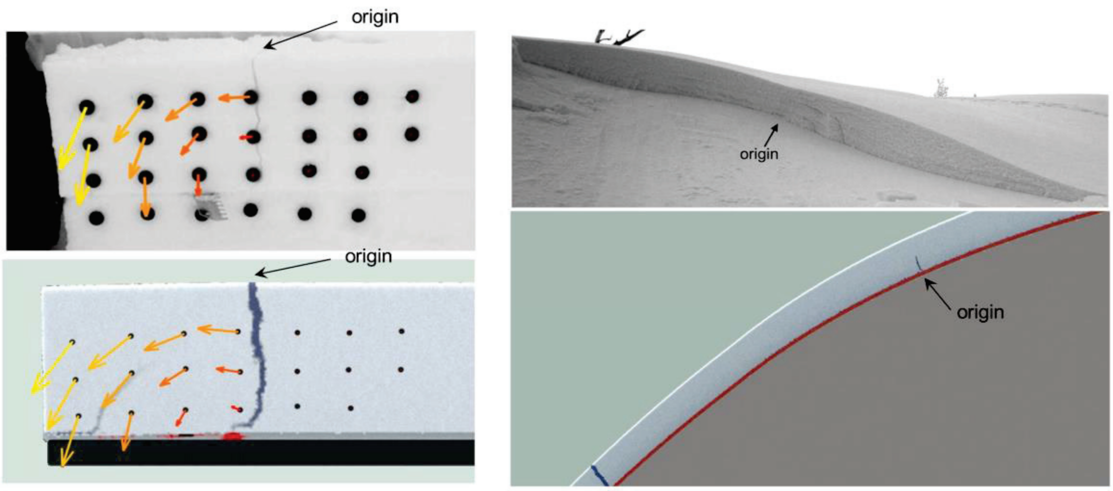

Figure 3: Differences in slab fracture opening in small scale PST experiments and simulations (left) and in real-scale avalanche crown fracture measurements (Bair et al. 2016) and simulations (right).

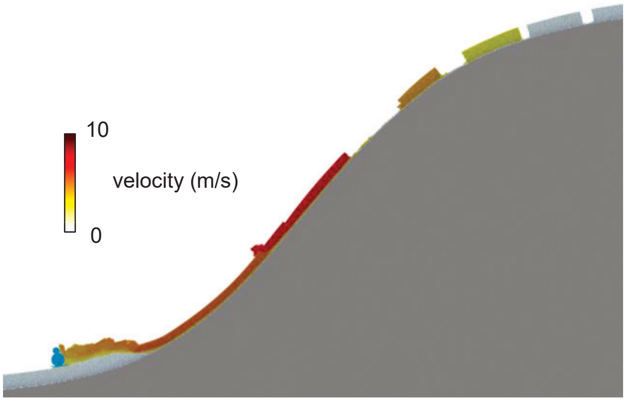

Figure 4: Flow velocity at the moment of impact .

flow speed $u_m \sim 8$ m/s which is in excellent agreement with the model and data of McClung and Gauer (2018) ($u_m \sim 1.5L^{1/2} \sim 2.2H^{1/2}$). Note that a larger 2D simulation with $L = 350$ m and $H = 180$ m (not shown here) led to a maximum flow speed of 27 m/s, again in agreement with the results of McClung and Gauer (2018). In this larger slope simulation, we also observed a granulation phenomenon (Steinkogler et al. 2015) which could not be captured in the presented slopes due to their limited flow development potential. For all simulations, we found the α-angle between 25 and 30°, also consistent with McClung and Gauer (2018).

4. DISCUSSION

4.1 Shear vs. collapse: time to close the debate?

The recent studies of Gaume et al. (2015, 2017, 2018a, 2018b) and Gaume and Reuter (2017) showed that both shear failure and weak layer collapse were required to completely simulate the processes of slab avalanche release. The structural collapse of the weak layer is the only explanation for crack propagation and remote triggering from flat or low angle terrain. However, on steep slopes, typically steeper than 35°, collapse is negligible and the original shear model of McClung (1979) is sufficient. It is also now clear that the collapse of the weak layer is a secondary process occurring after weak layer has failed. However, observation of different patterns of slab fractures in the field are still feeding this "shear – collapse" debate. Indeed, systematic observations of slab fractures from top to bottom in the Propagation Saw Test tend to justify collapse approaches while observations of real avalanche crown fracture (based on near infrared photogrammetry, Bair et al, 2016; Gauthier et al. 2014) from bottom to top tend to justify pure shear models. Our model which includes both mixed-mode shear-compression failure and weak layer collapse reproduces all these observations and thus reconciles a priori contradictory observations of slab fracture from small scale field tests (top to bottom) and from real avalanches (bottom to top).

4.2 Long term outlook: operational and engineering potential

Our new model has several perspectives of applications for operational avalanche forecasting and hazard management. The first aspect is that we can for the first time evaluate the position and volume of the release zone which is currently missing from operational avalanche forecasting and risk management procedures (or based on expert opinion or empirical observations). Future work and validation efforts could allow to define the release volume of the avalanche as a function of topographical parameters, mechanical properties of the system and their spatial distribution which could ultimately lead to a potential release size index in avalanche bulletins. Coupled with a snow cover model and a digital elevation model, our new approach could also pave the road towards local forecasting and hazard management of dangerous avalanche paths. In addition, different snow types (e.g. dry, wet snow, slush) can be naturally simulated with our approach together with granulation, erosion and deposition processes which do not require additional implementations. Yet, although the release part of the model was validated on small-scale experiments (PST, Gaume et al. 2018a), a complete and rigorous validation of the simulated avalanche release and flow dynamics at the slope-scale will be required.

Finally, given that we can simulate the behaviour of several snow types, the model has also promising applications in snow tire engineering.

4.3 Limitations

The main limitation of the current version of the model is that the strength of the weak layer is not strain rate dependent. Hence, the model can only be used for fast loading cases such as skier triggering or explosives. A new version of the model is currently under validation and includes the competition between compaction hardening, bond breaking and ageing (sintering) based on Barraclough et al. (2017) which will allow to simulate natural avalanche release as well.

5. CONCLUSION

We developed a Material Point Method for snow and avalanche simulations. The model is based on finite strain elastoplasticity and allows to reproduce the complex mechanical behavior of different snow types including weak snowpack layers with a mixed-mode failure followed by strain softening and structural collapse allowing to simulate dynamic anticrack propagation. Preliminary simulations of remote triggering and flow of slab avalanches were in good qualitative agreement with field observations which opens a promising route towards improving avalanche forecasting and risk management.

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