RECENT ADVANCES IN MODELING SNOW AND AVALANCHES WITH THE MATERIAL POINT METHOD AND PRACTICAL IMPLICATIONS

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ABSTRACT: The Material Point Method (MPM) is an Eulerian-Lagrangian numerical technique used to solve partial differential equations in continuum mechanics. It was initially introduced by Sulsky and co-authors in 1994 (Sulsky et al., 1994) as an extension of the Particle-In-Cell method, and has since then mainly been used and further developed in the geomechanics and graphics communities. MPM can deal with problems involving large deformations, collisions, fractures and can naturally handle free-surface flows, concepts which require specific treatments in mesh-based methods like the finite volume or finite element method. In recent years, MPM has received a growing attention in snow and avalanche science. On the one hand, it was used to animate snow in a mesmerizing manner in the Disney movie Frozen, and on the other hand it has been used to simulate avalanche release and flow at the slope scale, in 3D with unprecedented physical details. Since then, the model has been continuously improved and used to simulate and better understand various important processes related to snow and avalanche mechanics and we review here these applications and discuss practical implications. These processes include 1) snow microstructure deformation and failure; 2) avalanche release; 3) avalanche dynamics over complex topography; 4) interaction between avalanches and obstacles, forests or lakes; 5) erosion and entrainment. Although it has mostly been used in research so far, we believe that MPM has a strong potential for engineering applications, especially related to impact problems and the design of sustainable artificial or natural mitigation measures. Finally, because capturing specific physical processes such as snow entrainment require significant computational resources, we developed a novel approach based on a depth-averaged version of MPM (DAMPM) for efficient avalanche release and flow simulations.

KEYWORDS: snow, avalanches, material point method, simulation, avalanche formation, avalanche dynamics.

1. INTRODUCTION

In 2013, Disney engineers collaborated with the Department of Mathematics at the University of California Los Angeles to develop a Material Point Method for snow animation (Stomakhin et al. 2013). In this work, they adopted a physics-based approach where the conservation equations (mass and momentum) were solved alongside a simple snow mechanical model. This model allowed for artistic control over results through mechanical properties like elastic modulus, critical tension and compression thresholds, and a hardening parameter. This model, suitable for graphic purposes, would have been challenging to parameterize and validate using state-of-the-art snow mechanical tests.

In 2017, the corresponding author of this ISSW paper visited UCLA and, in collaboration with local researchers, crafted a new constitutive snow model based on critical state soil mechanics. Validation was carried out using Propagation Saw Tests, and the model was successfully applied to simulate snow slab avalanches. Remarkably, the model managed to simulate, within a unified framework, avalanche initiation, encompassing intricate (anti)crack propagation mechanisms, along with subsequent flow dynamics at the slope scale (Gaume et al., 2018). Six years later, we revisit how this model has since been refined and applied to various processes related to snow slab

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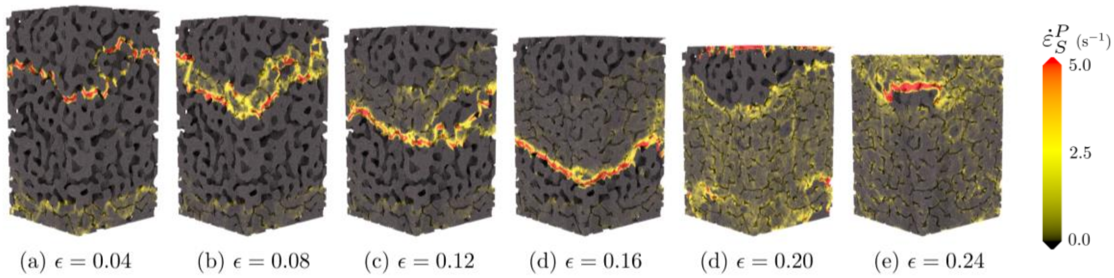

Figure 1: Snapshots of the plastic shear strain rate in a three-dimensional microstructure-based MPM simulation (Blatny et al. 2023).

avalanches, aiming for a deeper comprehension. This encompasses snow microstructure deformation and failure, crack propagation mechanisms, avalanche dynamics, erosion, and impact. Lastly, we delve into future tools planned for development and provision to engineers and practitioners. We do not assert conducting a comprehensive overview of MPM-based snow avalanche modeling. Our main emphasis lies in the recent endeavors carried out within our group.

2. SNOW MICRO-MECHANICS

Driven by the objective of better understanding the mechanical behavior of snow, different approaches to simulate snow microstructures under loading have been proposed by various researchers (e.g. Hagenmuller et al. 2015; Schneebeli et al. 2004; Gaume et al. 2017). In order to study the large deformation of non-particulate snow microstructures whose solid ice phase is (partially) continuous skeleton, the Material Point Method appears as an appealing continuum tool capable of treating the topological changes that the microstructures undergo. Blatny et al. (2021, 2022, 2023), showed that MPM is an excellent numerical scheme for this purpose, capable of handling both small and large deformations. In particular, the effective elastic modulus and strength of the snow could be evaluated as a function of density. In addition, a closed failure envelope was reported in line with previous experimental and numerical work. Furthermore, the plastic consolidation regime was investigated with a particular emphasis on its dependence on material and structural properties. Finally, propagating and reflecting compaction bands observed in snow experiments (Barraclough et al. 2017) were successfully simulated and their microstructural origin attributed to a universal process of pore collapse. This work did not only allow us to gain a better understanding of snow micro-mechanics but also serves as a microstructure-based framework to design improved constitutive models that can be implemented in large-scale avalanche release and flow models.

3. AVALANCHE RELEASE

3.1 Supershear avalanches

During the 2014 ISSW in Banff, Canada, Dave Hamre presented findings regarding fracture speeds derived from video analysis of triggered snow slab avalanches (Hamre et al. 2014). He documented speeds primarily ranging between 50 to 125 m/s, occasionally surpassing 200 m/s. In contrast, measurements of crack propagation speeds via Propagation Saw Tests (PST) (e.g. van Herwijnen and Birkeland 2014 and Gaume et al. 2015) seldom exceeded 50 m/s. During that period, Gaume maintained skepticism toward the substantial speed values reported by Hamre et al. (2014), challenging the speed measurement protocol linked to slab fracture locations. Nearly a decade later, he acknowledges his initial skepticism was misplaced.

Recently, Gaume et al. (2019) reported speeds obtained based on MPM simulation above 100 m/s. As this speed appeared to be above the slab shear wave speed, the authors initially questioned their code. However, after careful and in-depth verifications, extensive literature review in the field of earthquake science where similar phenomena had been previously reported, and fresh experimental analysis (also detailed in Simenhois et al. 2023), the authors subsequently proposed (Trottet et al. 2022) the occurrence of a transition from sub-Rayleigh anticrack to supershear crack propagation in snow slab avalanches. Interestingly, this theory would also reconcile the seminal shear model of McClung (1979) and the more contemporary anticrack concept of Heierli et al. (2008). On low-angle terrains, propagation stems from weak layer collapse and consequent slab bending (anticrack), resulting in propagation speeds below the Rayleigh wave speed. These speeds are typically on par with those reported from PST experiments. However, when the slope angle surpasses the friction angle of the weak layer, a transition is reported: for short propagation distances, the anticrack mechanism prevails.

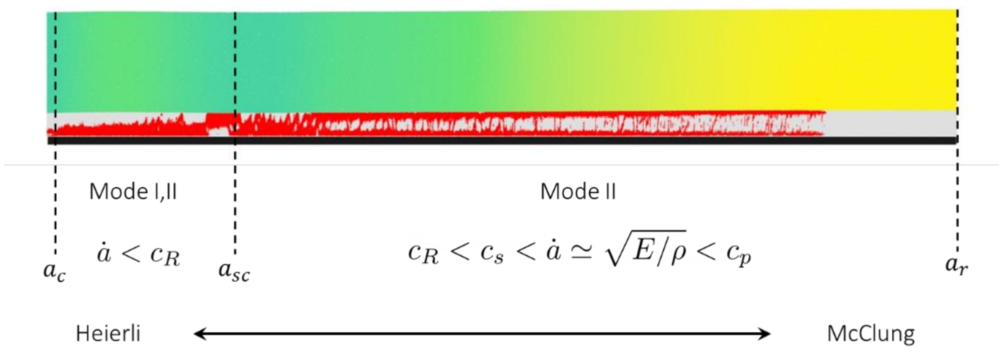

Figure 2: MPM simulation of a large-scale Propagation Saw Test (length 50m) showing two regimes of crack propagation on steep slopes: 1) sub-Rayleigh anticrack propagation between a_c and a_{sc} and 2) a supershear (intersonic) crack propagation regime for distances of propagation above the super-critical crack length a_{sc}. The anticrack concept of Heierli et al. (2008) thus seems valid on low angle and terrain and on stepper terrain for short propagation distance. On the hand the concept of shear failure (McClung 1979) appears valid at a larger scale on steep slopes.

Nevertheless, if the propagation distance exceeds the so-called supercritical crack length a_{sc}, slab tension becomes the driving factor, leading to weak layer failure primarily under shear. In this scenario, the propagation speed aligns closely with the longitudinal wave speed $\sqrt{E/\rho}{\sim}1.6\,c_s$ which exceeds the shear wave speed c_s. This outcome was demonstrated to remain applicable even when considering slab fractures, for relatively dense snow slabs (Trottet et al. 2022). Interestingly, slab fractures in the anticrack regime start from the surface, because of slab bending, while for the supershear regime slab fracture generally occur from the bottom of the slab, in line with field observations (Gaume et al. 2019).

3.2 DAMPM

Despite the promise of our 3D MPM model for the simulation of avalanche formation, simulations at the slope scale still require several hours or days, because of the fine discretization needed for the weak layer. Hence, it remains challenging to evaluate avalanche release sizes. This quantity is important for avalanche forecasting and is also a crucial input for hazard mapping model chains. To tackle this challenge, we developed in Guillet et al. (2023) a numerical method based on shallow water equations that simulates efficiently the release of slab avalanches over complex topography based on snow properties and terrain characteristics. Motivated by the findings presented above, we modeled the weak layer as an external shear force acting at the base of an elastic-brittle slab. The model was verified based on theoretical and numerical analysis of the PST. Then large-scale simulations were conducted to evaluate the shape and size of avalanche release zones over different topographies. Given its low computational cost, we expect our model to have operational applications in hazard assessment.

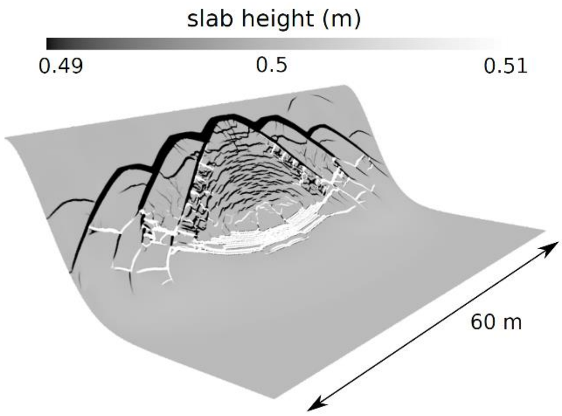

Figure 3: Simulation outputs with variation of the topography. The color scale represents the height distribution in the slab. From Guillet et al., 2023.

4. AVALANCHE DYNAMICS

4.1 Modeling different flow regimes

Three-dimensional MPM simulations were conducted to explore snow avalanches in different regimes on a complex real terrain (Li et al. 2020, 2021, Cicoira et al. 2022). Flow features of the snow avalanches from release to deposition were comprehensively characterized for identification of the different regimes. In particular, brittle and ductile fractures are identified in the different modeled avalanches shortly after their release. During the flow, the analysis of local snow density variation reveals that snow granulation requires an appropriate combination of snow fracture and compaction. In contrast, cohesionless granular flows and plug flows are mainly governed by expansion and compaction hardening, respectively. Distinct textures of avalanche deposits are characterized, including a smooth surface, rough surfaces with snow granules (Fig. 4), as well as a

Figure 4: Rendered MPM avalanche simulation over 3D topography (Vallée de la Sionne) showing naturally emerging processes such as snow granulation and compacting shear bands.

surface showing compacting shear planes often reported in wet snow avalanche deposits. Finally, MPM simulations were compared to a real snow avalanche that occurred at Vallée de la Sionne, Switzerland. The comparison showed an excellent agreement between simulated and experimental results in terms of the avalanche front velocity, the avalanche extent and run-out-distance but also the avalanche density which almost doubled from the release zone to the deposition area (Li et al. 2021). Currently, the model is being extended to include rate-dependency through the $\mu(I)$ rheology model initially introduced for granular flows (GDR MiDi 2004).

4.2 Interaction with obstacles

Our MPM framework allows us to easily introduce obstacles and to compute impact pressures for a vast variety of obstacle geometies. Such obstacles can be houses (Fig. 5a), dams, avalanche galleries or a forest (Fig. 5b). In particular, mountain forests provide natural protection against avalanches. They can both prevent avalanche formation in release zones and reduce avalanche mobility in runout areas. Although the braking effect of forests has been previously explored through global statistical analyses on documented avalanches, little is known about the mechanism of snow detrainment in forests for small and medium avalanches (Feistl et al., 2014). Hence, we investigated the detrainment and braking of snow avalanches in forested terrain, by performing three-dimensional MPM simulations (Vedrine et al. 2022). Our results suggest that for both the cold and warm snow parameterized in our simulations, the detrainment mass decreases with the square of the avalanche front velocity before it reaches a plateau value. Furthermore, the detrainment mass significantly depends on snow properties. It can be as much as 10 times larger for warm snow compared to cold snow. By examining the effect of forest configurations, it is found that forest density and tree diameter have cubic and square relations with the detrainment mass, respectively. The outcomes of this study may contribute to the development of improved formulations of avalanche–forest interaction models in popular operational simulation

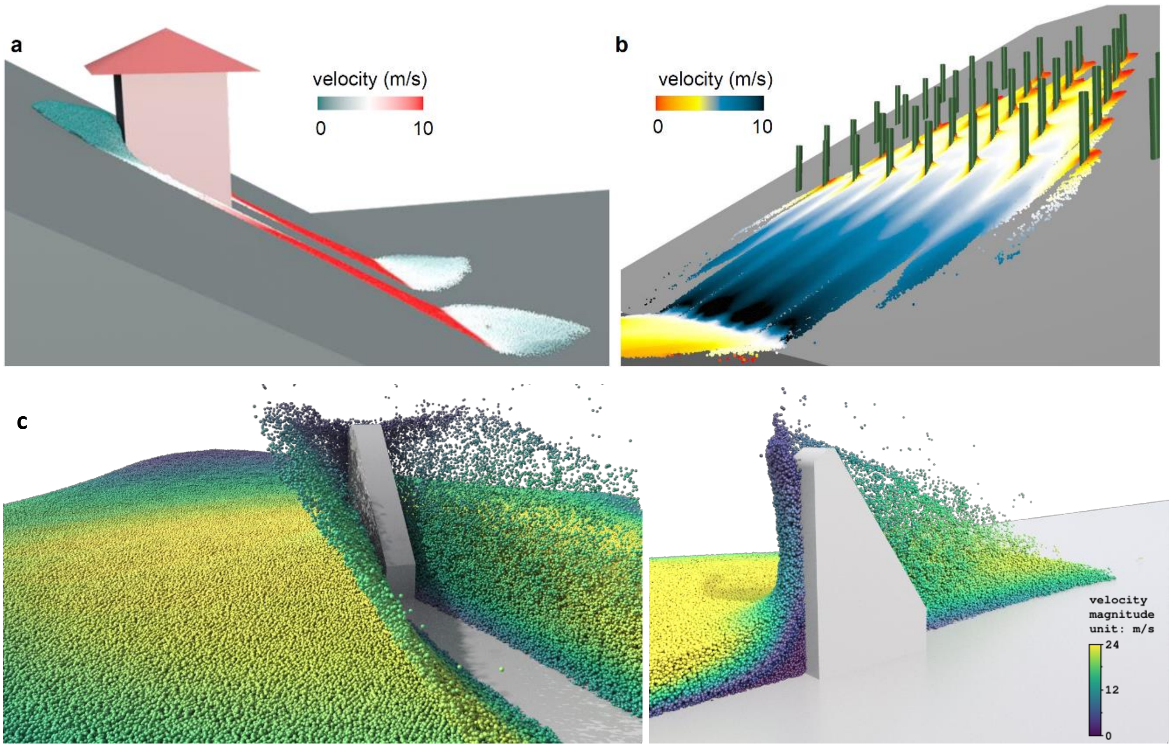

Figure 5: MPM simulations of a) avalanche-house interaction; b) avalanche – forest interaction and c) avalanche – thin obstacle interaction.

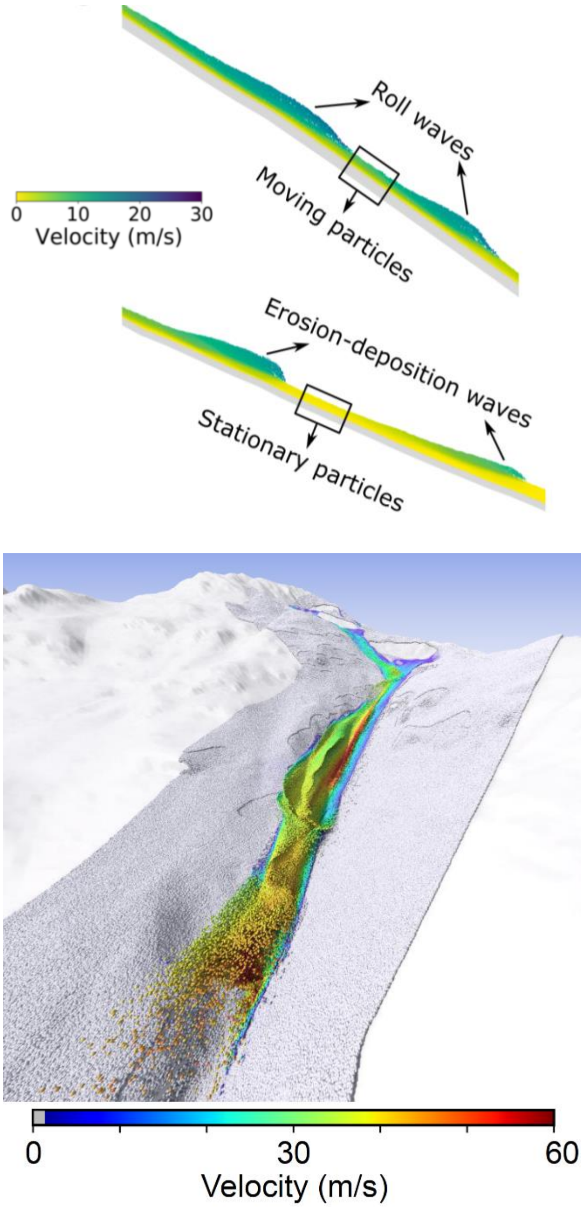

Figure 6: MPM simulations of snow avalanches over an erodible bed in a) 2D showing the natural emergence of rollwaves and erosion deposition waves and b) 3D on complex topography for the 2019 Salezer avalanche (Kyburz et al., 2023).

tools and thus improve hazard assessment for alpine geophysical mass flows in forested terrain. In order to propose new practical guidelines, the model is currently used to evaluate the effect of avalanche flow regimes as well as snow compaction on the avalanche impact pressure and run-up height. The basis for this work are previous investigations based on the Discrete Element Method carried by Kyburz et al. (2020, 2022). The interaction between snow avalanches and mountain lakes is also of current interest.

4.3 *Erosion and entrainment*

Erosion significantly affects the dynamics of gravity-driven mass flows. In snow avalanches, the snow cover can be substantially eroded but only partially entrained, however, there are very limited investigations to substantiate this difference. We performed MPM simulations in which we explicitly simulated the bed material (Li et al. 2022). With varied snow properties, distinct erosion patterns were obtained and the mass change rate could be analyzed. Both enhanced and inhibited avalanche mobilities due to erosion and entrainment were captured under different conditions of snow properties and lengths of release and erodible zones.

The model also naturally simulate roll-waves, erosion-deposition waves, and their transitions in large-scale snow avalanche on real terrain (Fig. 6a). It appears that the wave mechanics is not only controlled by the Froude number and local topography but also by the mass of the wave which impacts the entrainment propensity. These new results may stimulate the development of advanced erosion and entrainment models for large-scale avalanches (Fig. 6b). In addition, it offers new insights to wave mechanisms of snow avalanches and provides a novel and promising pathway for exploring transient waves in granular mass movements.

5. DISCUSSION: TOWARDS PRACTICE ORIENTED TOOLS

We contend that the work presented herein is poised for practical applicability. For instance, the DAMPM model stands out as an efficient instrument with the potential for slope-scale application, automating the assessment of snow avalanche release zones. Additionally, its utility extends to evaluating the effectiveness of diverse mitigation strategies within the initiation zone to limit the avalanche size (Meloche et al., 2023). Furthermore, the model can simulate snow avalanche dynamics at the slope scale, offering spatial resolution finer than 0.5 meter and unprecedented physical detail.

Our 3D MPM model is ready to be used for external projects upon interest; Such projects encompass:

- Simulation of avalanche dynamics across intricate topography, including steep landscapes and substantial topographical variations.
- Computation of avalanche impact pressures for specific case studies.

- Oversight of avalanche protective forest management: we possess the capacity to simulate individual trees and thus scenarios within forested terrain, optimizing reforestation strategies by evaluating the impact of targeted tree removal on protective efficacy.

To enhance accessibility for practitioners, plans are underway for the development of a Graphical User Interface (GUI) and a GPU version of the code. However, it is reasonable to anticipate a timeframe of approximately 5 years before its availability.

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REFERENCES

Barraclough, T.W., Blackford, J.R., Liebenstein, S., Sandfeld, S., Stratford, T.J., Weinländer, G. and Zaiser, M. Propagating compaction bands in confined compression of snow. Nature Physics, 13(3), pp.272-275. 2017

Blatny, L., Löwe, H., Wang, S. and Gaume, J. Computational micromechanics of porous brittle solids. *Computers and Geotechnics*, *140*, p.104284. 2021

Blatny, L., Berclaz, P., Guillard, F., Einav, I. and Gaume, J. Microstructural origin of propagating compaction patterns in porous media. *Physical Review Letters*, *128*(22), p.228002. 2022

Blatny, L., Löwe, H. and Gaume, J. Microstructural controls on the plastic consolidation of porous brittle solids. *Acta Materialia*, *250*, p.118861. 2023

Cicoira, A., Blatny, L., Li, X., Trottet, B. and Gaume, J. Towards a predictive multi-phase model for alpine mass movements and process cascades. Engineering Geology, 310, p.106866. 2022

Hagenmuller, P., Chambon, G. and Naaim, M. Microstructure-based modeling of snow mechanics: a discrete element approach. The Cryosphere, 9(5), pp.1969-1982. 2015

Hamre, D., Simenhois, R. and Birkeland, K., Fracture speeds of triggered avalanches. In *Proceedings ISSW* (Vol. 585). 2014

van Herwijnen, A. and Birkeland, K.W. Measurements of snow slab displacement in Extended Column Tests and comparison with Propagation Saw Tests. Cold Regions Science and Technology, 97, pp.97-103. 2014

Feistl, T., Bebi, P., Teich, M., Bühler, Y., Christen, M., Thuro, K., and Bartelt, P.: Observations and modeling of the braking effect of forests on small and medium avalanches, J. Glaciol., 60, 124–138, 2014.

Gaume, J., van Herwijnen, A., Chambon, G., Birkeland, K.W. and Schweizer, J. Modeling of crack propagation in weak snowpack layers using the discrete element method. The Cryosphere, 9(5), pp.1915-1932. 2015

Gaume, J., Löwe, H., Tan, S. and Tsang, L. Scaling laws for the mechanics of loose and cohesive granular materials based on Baxter's sticky hard spheres. Physical Review E, 96(3), p.032914. 2017

Gaume, J., Gast, T., Teran, J., Van Herwijnen, A. and Jiang, C. Dynamic anticrack propagation in snow. Nature communications, 9(1), p.3047. 2018

Gaume, J., van Herwijnen, A., Gast, T., Teran, J. and Jiang, C. Investigating the release and flow of snow avalanches at the slope-scale using a unified model based on the material point method. Cold Regions Science and Technology, 168, p.102847. 2019

GDR MiDi. On dense granular flows. *Eur. Phys. J. E* **14**, 341–365. 2004

Guillet, L., Blatny, L., Trottet, B., Steffen, D., & Gaume, J. A Depth-Averaged Material Point Method for Shallow Landslides: Applications to Snow Slab Avalanche Release. Journal of Geophysical Research: Earth Surface, 128, e2023JF007092. 2023

Heierli, J., Gumbsch, P. and Zaiser, M. Anticrack nucleation as triggering mechanism for snow slab avalanches. Science, 321(5886), pp.240-243. 2008

Kyburz, M.L., Sovilla, B., Gaume, J. and Ancey, C. Decoupling the role of inertia, friction, and cohesion in dense granular avalanche pressure build-up on obstacles. Journal of Geophysical Research: Earth Surface, 125(2), p.e2019JF005192. 2020

Kyburz, M.L., Sovilla, B., Büher, Y., and Gaume, J. Potential and challenges of depth-resolved three-dimensional MPM simulations: A case study of the 2019 “Salezer” snow avalanche in Davos. Under review. 2023

Kyburz, M.L., Sovilla, B., Gaume, J. and Ancey, C. Physics-based estimates of drag coefficients for the impact pressure calculation of dense snow avalanches. Engineering Structures, 254, p.113478. 2022

Li, X., Sovilla, B., Jiang, C. and Gaume, J. The mechanical origin of snow avalanche dynamics and flow regime transitions. The Cryosphere, 14(10), pp.3381-3398. 2020

Li, X., Sovilla, B., Jiang, C. and Gaume, J. Three-dimensional and real-scale modeling of flow regimes in dense snow avalanches. Landslides, 18, pp.3393-3406. 2021

Li, X., Sovilla, B., Ligneau, C., Jiang, C. and Gaume, J. Different erosion and entrainment mechanisms in snow avalanches. Mechanics Research Communications, 124, p.103914. 2022

McClung, D.M. Shear fracture precipitated by strain softening as a mechanism of dry slab avalanche release. Journal of Geophysical Research: Solid Earth, 84(B7), pp.3519-3526. 1979

Meloche, F., Guillet L., Gauthier F., Langlois A. and Gaume J. Influence of slab depth spatial variability on the probability and release size of skier-triggered avalanches. in: Proceedings of the International Snow Science Workshop, Bend, OR, 8-13 October 2023, 2023

Schneebeli, M. Numerical simulation of elastic stress in the microstructure of snow. Annals of Glaciology, 38, pp.339-342. 2004.

Simenhois, R., Birkeland, K.W., Gaume, J., van Herwijnen, A., Bergfeld, B., Trottet, B. and Greene, E. Using video detection of snow surface movements to estimate weak layer crack propagation speeds. *Annals of Glaciology*, pp.1-11. 2023

Sulsky, D., Chen, Z. and Schreyer, H.L., 1994. A particle method for history-dependent materials. Computer methods in applied mechanics and engineering, 118(1-2), pp.179-196.

Stomakhin, A., Schroeder, C., Chai, L., Teran, J. and Selle, A.,. A material point method for snow simulation. *ACM Transactions on Graphics (TOG)*, *32*(4), pp.1-10. 2013.

Trottet, B., Simenhois, R., Bobillier, G., Bergfeld, B., van Herwijnen, A., Jiang, C. and Gaume, J. Transition from sub-Rayleigh anticrack to supershear crack propagation in snow avalanches. Nature physics, 18(9), pp.1094-1098. 2022

Védrine, L., Li, X. and Gaume, J. Detrainment and braking of snow avalanches interacting with forests. Natural Hazards and Earth System Sciences, 22(3), pp.1015-1028. 2022