RIDERS AND AVALANCHES FLOATING ON POWDER SNOW: NEW INSIGHTS INTO AIR PORE PRESSURE MECHANISMS FROM HYDRO–MECHANICAL NUMERICAL SIMULATIONS

Hervé Vicari[1,2,3,*], Camille Huitorel[1,2,3], Quoc-Anh Tran[4], Betty Sovilla[1], Johan Gaume[1,2,3]

[1] *WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland*
[2] *Climate Change, Extremes, and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland*
[3] *Institute for Geotechnical Engineering, ETH Zürich, Zürich, Switzerland*
[4] *Norwegian University of Science and Technology, Trondheim, Norway*

ABSTRACT: Skiing or snowboarding down a mountain covered with fluffy new snow can provide a unique experience, reminiscent of floating above clouds. This sensation is often intuitively attributed to the supporting effect of the interstitial air loaded by the skis or snowboard, creating a feeling of weightlessness. Interestingly, this same principle may also account for the rapid descent and extensive runout distance of much less pleasant phenomena, such as powerful mixed snow avalanches. These avalanches exhibit a complex structure, characterized by a dense basal regime overlaid and preceded by an intermittent layer of coherent snow clusters, along with a lighter suspension layer of fine particles mixed with air. Despite their significance, the processes driving the formation of these structures and the reasons for the remarkable mobility of mixed snow avalanches remain incompletely understood. One prevailing theory proposes that this mobility could result from the fluidization of the porous snow cover, which is transiently weakened by the development of excess pore air pressures upon undrained loading by the avalanche. We test this hypothesis, by means of two-phase simulations. The solid ice grains are simulated using either the Discrete Element Method (DEM) or as a continuum through the Material Point Method (MPM). Compared to previous works, we simulate explicitly the air both within the pores and in the ambient, using CFD (specifically the Finite Volume Method) which is coupled to the conservation equations of the solid phase. Simple preliminary simulations are presented in this work. We simulate a snowboarder dropping over a fresh snow cover. The simulations show that, if the permeability of the snow cover is low enough, the pressurized pore air may lead to fluidization of the snow, favoring its mechanical weakening and suspension as a vertical jet. Instead, if the permeability of the snow is too high, pore air pressure quickly diffuses, which cannot generate significant suspension of the particles. Similar modelling approaches will be applied in future to model mixed snow avalanches interacting with an erodible snow layer. Ultimately, we expect this research to contribute to improved entrainment and fluidization models in depth-averaged numerical methods.

Keywords: Powder Snow Avalanche, Powder Skiing, MPM, DEM, CFD, Entrainment, Fluidization

1. INTRODUCTION

Gliding down a mountain slope blanketed with fresh, fluffy snow provides skiers and snowboarders with a sensation akin to floating in air. This experience is often attributed to the interstitial air within the snow, creating a feeling of weightless movement. As the skier or snowboarder carves through the snow, jets of snow are lifted into the air (Figure 1). However, this same principle of air pressurization and jet formation may play a critical role in more hazardous natural events, such as mixed snow avalanches. These avalanches are characterized by a dense basal layer and overlying suspended structures of snow and air (Sovilla et al., 2015). Understanding the mechanisms behind the formation and mobility of these avalanches is crucial for comprehending their high speed, volume growth, and extensive runout.

The entrainment of the snow cover has long been recognized to play a pivotal role in snow avalanche dynamics (Sovilla et al., 2001). Various entrainment mechanisms have been suggested, whose occurrence may be influenced by the characteristics of the snow cover and the snow avalanche (Gauer and Issler, 2004). Among these mechanisms, Gauer and Issler (2004) hypothesized that generation of pore air pressure gradients in the snow cover may play a significant role in the snow cover erosion and entrainment—similar to what is observed in debris flows with the development of excess pore water pressures in wet erodible sediments (Iverson et al., 2011). Building on this hypothesis, two analytical models related to snow cover fluidization were developed. The first focuses on the under-pressure created at the front of an avalanche (Louge et al., 2011), while the second examines the compression of the snow cover beneath the avalanche, which

*Corresponding author address:
Hervé Vicari, WSL Institute for Snow and Avalanche Research SLF
7260 Davos Dorf, Switzerland;
email: herve.vicari@slf.ch

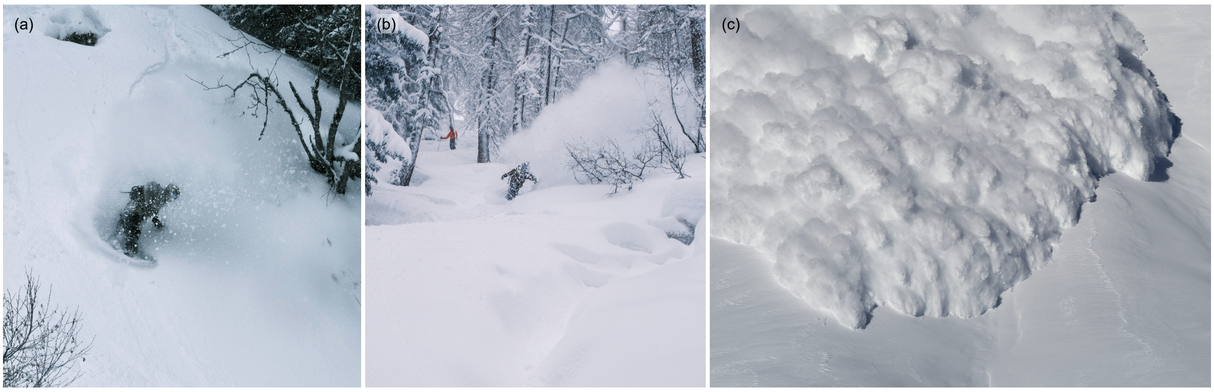

Figure 1: (a, b) Snow jets and particles suspension following a snowboarder's landing on fresh snow. (c) Mixed snow avalanche in Vallée de la Sionne (photo: KEYSTONE/Gaëtan Bally).

generates excess pore air pressures (Issler, 2017). In particular, such pore air pressures within the snow cover can reduce the effective stresses within the snow cover and also promote fluidization of the avalanche body, leading to a decrease in its density and to an increase in flow mobility (Issler and Gauer, 2008).

Simple depth-averaged models exist which consider the influence of snow cover shear strength on avalanche entrainment and dynamics (e.g., Vicari and Issler, 2024). Furthermore, in recent years, full-3D simulations have arisen modelling explicitly the snow avalanche and snow cover mechanical behaviour (Cicoira et al., 2022; Li et al., 2022; Ligneau et al., 2024), making entrainment and flow mobility emerge naturally from the interplay between the avalanche and the initially static snow cover. However, these models are one-phase, and have hence not explicitly considered the role of pore and ambient air in the entrainment mechanisms. In this study, we perform a preliminary analysis in a more simplified scenario than a snow avalanche (which would necessitate substantial computational resources): a snowboarder falling over a snow cover. We apply two numerical approaches, based on both continuum and discontinuum mechanics to model both the solid and air phases within snow. We therefore compare one- and two-phase numerical simulations to address the question: Does pore air play a role in the snow cover's fluidization and entrainment?

2. METHODS

<u>*2.1 Numerical methods*</u>

Two different numerical approaches are employed to model a snowboard falling on a snow cover.

2.1.1 MPM–CFD model

The first approach (MPM–CFD) is based on continuum mechanics and specifically involves the coupling between Material Point Method (MPM) and Computational Fluid Dynamics (CFD)—this latter using the Finite Volume Method (FVM). MPM is utilized to represent the solid phase within snow (i.e., ice crystals, modeled as a continuum). FVM is applied to simulate the fluid phase, specifically the ambient air and the air within the snow pores. The MPM–CFD approach is applied using the Uintah code by Tran et al. (2024).

Air (a) is modelled using an ideal gas equation of state, with density $\rho_a = 1.17$ kg/m^3 at a reference atmospheric pressure of $p_a = 101325$ Pa at 300 K (temperature is kept constant in the simulation). The dynamic viscosity of the air phase is assumed equal to $\eta_a = 18 \cdot 10^{-6}$ Pa · s.

The solid phase (s) is assumed incompressible, with the density of ice $\rho_s = 917$ kg/m^3 and occupies an initial volume fraction $\Phi_{s0} = 0.11$. Hence, the initial bulk density of the snow cover is

$$\rho_0 = \rho_s \Phi_{s0} + \rho_a(1 - \Phi_{s0}) = 100 \text{ kg/m}^3, \quad (1)$$

corresponding to fresh snow.

The mechanical behaviour of the solid phase is governed by a Mohr-Coulomb yield criterion:

$$\tau_s = \sigma'_s \tan \varphi'_s, \quad (2)$$

where τ_s is the shear stress, σ'_s is the normal effective stress, and $\varphi'_s = 30°$ is the effective friction angle, which is kept constant during the simulation. A non-associative flow rule is used, with a constant dilatancy angle $\psi_s = -10°$, representative of a contractive material (i.e., compacting under shearing).

The solid–fluid interactions are expressed through a drag force (per unit volume):

$$\boldsymbol{f}_{s\text{–}a} = \frac{(1 - \Phi_s)\eta_a}{k}(\boldsymbol{u}_s - \boldsymbol{u}_a), \quad (3)$$

where $\boldsymbol{u}_s$ and $\boldsymbol{u}_a$ are the solid and air velocities respectively and k is the intrinsic permeability, implemented according to the model of Beetstra et al. (2007):

$$k = \frac{(1 - \Phi_s)D_p^2}{18\Phi_s F(\Phi_s, \mathrm{Re}_p)}, \quad (4)$$

where $F(\Phi_s, \mathrm{Re}_p)$ is a function of the solid fraction and of the particle-Reynolds number Re_p. D_p is the typical ice particle diameter, which is assumed equal to 10^{-4} m, corresponding to a permeability $k \approx 1.7 \cdot 10^{-9}$ m^2. Using this value, one obtains a similar magnitude and trend of the permebility k as a function of the solid fraction, when compared to permeability measurements in snow (e.g., Sommerfeld and Rocchio, 1993), and to the empirical function proposed by Calonne et al. (2012). To study the impact of smaller permeability, an additional simulation is carried out with $D_p = 10^{-5}$ m, corresponding to a permeability $k \approx 1.7 \cdot 10^{-11}$ m^2.

A supplementary simulation is run with CFD turned off, meaning that only MPM is used. The MPM particles are therefore given the bulk density of snow ρ, the pore air pressure is zero, and the effective stress matches the total stress.

2.1.2 DEM–CFD model

The second coupling approach (DEM–CFD) is based on the Discrete Element Method (DEM) and on Computational Fluid Dynamics (CFD). DEM is used to model a bonded assembly of snow particles, directly solving their motion and interactions through a Lagrangian approach. FVM is still used to model air in the ambient and in the snow pores. The DEM–CFD model is implemented in Ansys Rocky and Ansys Fluent software.

Air is modeled with density $\rho_a = 1.225$ kg/m^3 at a reference atmospheric pressure $p_a = 101325$ Pa without considering temperature variations.

Due to computational cost constraints, we employed rather coarse particles, with diameter $D_p = 0.02$ m. In line with the approach of Bobillier et al. (2020) for creating weak snow layers, we used 3D cohesive ballistic deposition to produce highly porous snow samples. This technique achieved an initial porosity of $\Phi_s = 0.2$. Hence, to ensure an initial bulk density of $\rho = 100$ kg/m^3—i.e., similar to that of the MPM–CFD simulation—, the particle density is set to $\rho_s = 500$ kg/m^3. The cohesion between particles is modeled through bonds (using the Parallel Bond Model, Potyondy and Cundall, 2004) with cylindrical, massless, spring-dashpot connections to simulate the elastic–brittle mechanical behaviour of snow. The mechanical parameters assigned to the so-created snow particles include the restitution coefficient $e_s = 0.1$ and friction angle $\varphi'_s = 27°$. The bonds between particles are characterized by an elastic bond strength

$$\boldsymbol{F}_b = -K_b A_b \boldsymbol{s}_b, \tag{5}$$

where A_b is the cross-sectional area of the bond, $\boldsymbol{s}_b$ is the bond's linear displacement, and $K_b = 10^{10}$ N/m^3 is the stiffness per unit area. These bonds may break during the simulation if the tensile or shear stresses exceed prescribed values, $\tau_{b,\mathrm{limit}} = \sigma_{b,\mathrm{limit}} = 2 \cdot 10^6$ Pa. Once a bond breaks, particles interact only through friction, and no new bonds may recreate.

The solid–fluid interactions are expressed through turbulent drag and pressure gradient forces:

$$\boldsymbol{F}_{s-a} = \frac{1}{2} C_D \rho_a A \|\boldsymbol{u}_s - \boldsymbol{u}_a\| (\boldsymbol{u}_s - \boldsymbol{u}_a) + V_s \nabla p_a \tag{6}$$

where A is the projected particle area in the flow direction, C_D is the drag coefficient, V_s is the particle volume and ∇p_a is the local pressure gradient.

Because DEM particles are larger than ideal ice particles, it is anticipated that pore air pressures would dissipate more rapidly due to the larger pores. In reason of this, in order to keep the initial snow cover's diffusivity,

$$\kappa = \frac{k}{m_v \eta_a}, \tag{7}$$

comparable to that used in the MPM–CFD simulations—and tentatively assuming that snow permeability can be adequately represented by Eq. 4 in the DEM–CFD simulation as well—the air viscosity is adjusted to $\eta_a = 0.18$ Pa · s in the DEM–CFD simulations[1]. The higher air viscosity will produce additional drag on the snowboard during its free fall in the ambient air, but ensures slower pore air pressure diffusion within the loaded snow cover despite the abnormally large DEM particles.

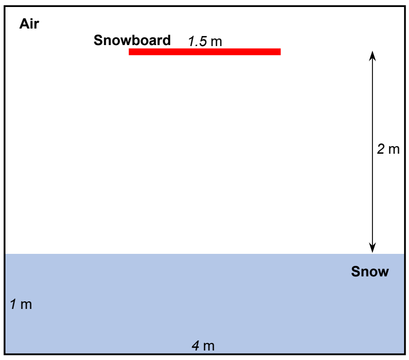

Figure 2: Geometry of the simulation.

2.2 Simulation setup

Figure 2 shows the 2D (quasi-plane strain) model geometry, where a snowboard of length 1.5 m falls from a height of 2 m over a 1 m-thick snow cover. Supposing that the snowboard width is 0.2 m (in the out-of-plane direction), the snowboard thickness and density are set so that the snowboard weight is 90 kg. All materials (including ambient air) are contained in a 4 m-wide, 3.1 m-tall box. In reason of the symmetry, half of the geometry is modelled when using the DEM–CFD approach.

[1] We hereby also assumed that the snow bulk drained compressibility m_v is similar when using the two approaches.

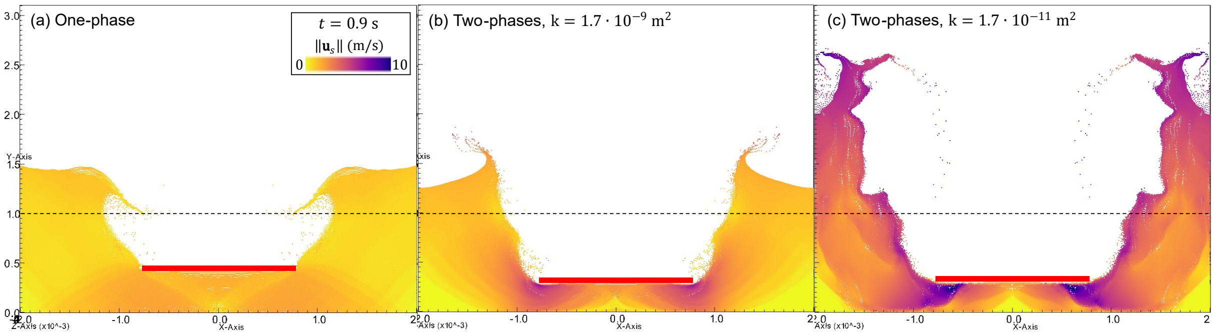

Figure 3: MPM–CFD simulation results showing the particles speed for: (a) One-phase (MPM only) simulation; (b) Two-phase simulation with higher snow permeability; (c) Two-phase simulation with lower snow permeability. All results are shown at $t = 0.9$ s.

3. RESULTS

3.1 MPM–CFD simulations

Figure 3 shows the results of the MPM–CFD simulations at $t = 0.9$ s. The simulations show that the snow beneath the snowboard becomes compacted. Additionally, as the snowboard penetrates the snow cover, snow is displaced upward on either side, forming vertical jets. The snow jets appear qualitatively similar to what observed when skiing or snowboarding in fresh snow (Figure 1). However, the runup height and shape of these jets differ significantly in the three simulations. For the one-phase simulation with MPM (Figure 3a), the runup is limited to approximately 0.5 m above the initial height of the snow cover. The two-phase simulation with larger snow permeability ($k = 1.7 \cdot 10^{-9}$ m^2, Figure 3b) shows larger sinking of the snowboard and similar jet height compared to the one-phase simulation. Decreasing the snow permeability ($k = 1.7 \cdot 10^{-11}$ m^2, Figure 3c) instead produces significantly higher jets of approximately 1.5 m above the initial height of the snow cover.

3.2 DEM–CFD simulations

Figure 4 shows the results of the DEM–CFD simulations at $t = 0.95$ s. As in the MPM–CFD simulation, significant compaction occurs beneath the snowboard. However, no jet formation is observed. Instead, a distinct vertical failure plane forms on the side of the sinking snowboard (see also the broken bonds in the figure). The two-phase simulation shows slightly higher snow uplift compared to the one-phase simulation, with bond breakage extending more extensively along the side of the snowboard.

4. DISCUSSION

The MPM–CFD and DEM–CFD simulations focused on examining the role of pore air in snow jet formation when a snow cover is subjected to dynamic loads, such as from a snowboarder, skier, or snow avalanche. With the MPM–CFD method, vertical jets appeared in all simulations. In the two-phase simulation with realistic snow permeability values, the jets were similar to those in the one-phase simulation. However, when low snow permeability is used in the two-phase approach—up to two orders of magnitude smaller than literature values—the jets were significantly taller. This indicates that pore *air* pressure may, in some situations, substantially contribute to snow cover weakening. Such mechanical weakening can be attributed to pore air pressure's effect on reducing effective stresses. The DEM–CFD simulations indicated considerably less snow runup upon snowboard impact. This difference could be due to the macroscopic cohesion introduced by the Parallel Bond Model in the DEM approach which may be too large. On the other hand, no cohesion was used in the MPM approach and the selected friction may have been too small. However, similar to the MPM–CFD simulations, it is evident that pore air pressure contributed to the weakening of the snow cover up to approximately 1 m from the board—an effect not observed in the single-phase case. The differences between MPM–CFD and DEM–CFD suggest that the constitutive model and properties of snow particles may be as important as, if not more significant than, the presence of pore air in influencing snow dynamics. Performing a dedicated experiment of a load drop on a snow cover and comparing it to numerical simulations would be extremely beneficial in the future to validate the model simulations.

Returning to the initial research question: Does pore air influence snow avalanche entrainment mechanisms? Possibly. We were unable to reach a definitive conclusion due to the lack of well-defined mechanical parameters for the snow cover, but we still observed distinct qualitative variations in the formation of snow jets when applying a two-phase model compared to a one-phase model. It is also crucial to note that both snow avalanches and snowboarders move down slopes driven by gravity and impact the fresh snow also frontally at even higher speeds than in our simulations. Hence, a more realistic model

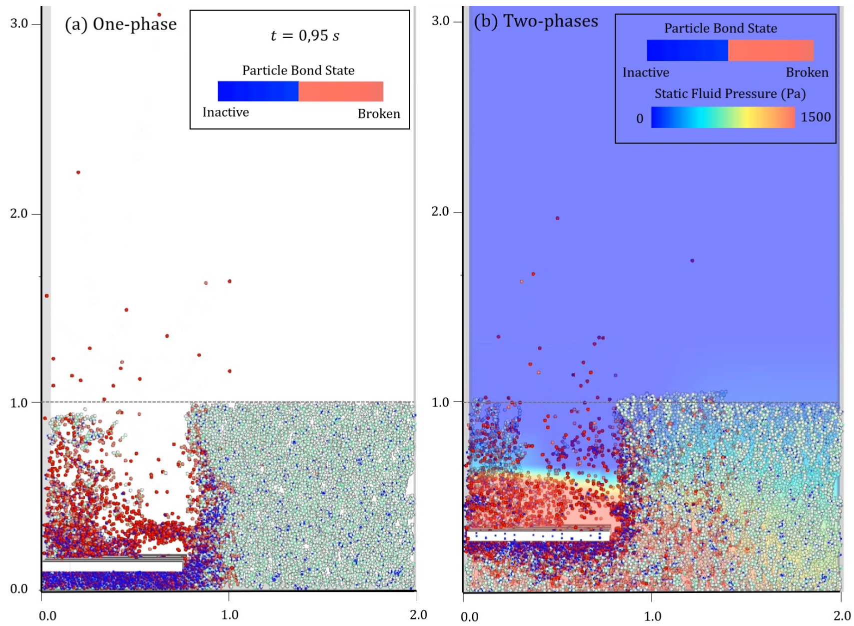

Figure 4: DEM–CFD simulation results showing the particle bond state: (a) One-phase DEM simulation; (b) Two-phase simulation with high air viscosity. All results are shown at $t = 0.95$ s.

of a snowboarder or a snow avalanche descending a sloped snow cover might reveal that pore air could significantly amplify entrainment mechanisms and ultimately the runout dynamics. This should be investigated in future studies.

5. CONCLUSION

In this research, we employed both continuum and discrete-based 3D two-phase models to reproduce a snowboarder falling over snow. To our knowledge, this represents the first attempt to use a two-phase approach to simulate the interactions between solid and air phases during snow impact processes, which carries strong implications for entrainment mechanisms in snow avalanches. This is rather remarkable considering that fresh snow is mainly composed of air. However, we were unable to arrive at a conclusive determination on whether the hydro-mechanical influence of the pore air in the snowpack is essential for the entrainment processes and jet formation when skiers and snow avalanches interact with fresh snow. This uncertainty stems mainly from the absence of a reference experimental case for comparison. Nevertheless, it is anticipated that two-phase simulations could be effectively used to model other phenomena in mixed snow avalanches. These include the formation of coherent structures and the suspension layer (powder snow cloud), where the interactions between solid and air phases, along with turbulence, might naturally generate such structures and flow patterns.

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