Instability phenomena linked to warming in ice–filled permafrost rock and run-out of rock avalanches

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Context

Joint PhD grant between:

- PEPR IRIMONT
- PEPR MathVives : PC ComplexFlows (D. Bresch, F. Radjai)

PhD candidate Chloé Gergely

- graduate student M2 “Maths en Action. Climat et environnement” (Université Claude Bernard Lyon I).
- M2 internship : coupling cohesive zone models and heat effects. INRIA TRIPOP.

Supervision

Franck Bourrier (DR INRAe, IGE Ecrins & INRIA TRIPOP) and myself

Starting date: 01/11/2024

Motivations

Rockfall at Mel de la Niva. Evolène, Switzerland 18 October 2015.

Motivations

Risk, climate change and thawing of permafrost

- Increased rock-avalanche size and mobility[1,2,3]
- Increased risk for mountain sports and tourist activities,
- Increased risk for infrastructure in the high mountains and valleys.

Modeling and simulation?

1. better understanding of the physical phenomena, that trigger the instability
2. predicting the rock-avalanche trajectory to measure the impact

[1] J. A. Coe, E. K. Bessette-Kirton, and M. Geertsema. "Increasing rock-avalanche size and mobility in Glacier Bay National Park and Preserve, Alaska detected from 1984 to 2016 Landsat imagery". In: *Landslides* 15.3 (2018), pp. 393–407.

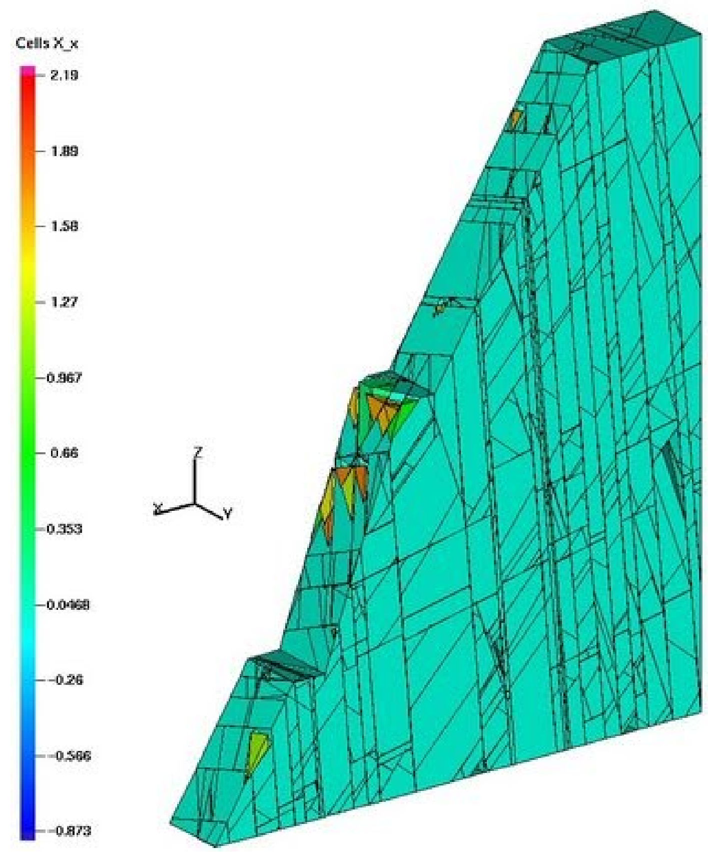
[2] R. Frauenfelder et al. "Ground thermal and geomechanical conditions in a permafrost-affected high-latitude rock avalanche site (Polvartinden, northern Norway)". In: *The Cryosphere* 12.4 (2018), pp. 1531–1550.

[3] E. K. Bessette-Kirton and J. A. Coe. "A 36-Year Record of Rock Avalanches in the Saint Elias Mountains of Alaska, With Implications for Future Hazards". In: *Frontiers in Earth Science* 8 (2020).

Objective 1: Run-out of the granular flows with fragmentation

Geological/geometrical modeling

- Use geological statistics of the rock slope to generate jointed rock masses.



Jointed rock mass[4]

- Two types of interfaces (at least) : rock fracture and joints.

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[4] M. Vinches, A. Rafiee, and C. Bohatier. "Numerical Analysis of the Mechanical Behavior under Seismic Loading of Discrete Element Structures: Application to 3D Fractured Rock Masses, and Large Stone Course Buildings". In: *ECCOMAS 2009*. Rhodes, Greece, June 2009.

Objective 1: Run-out of the granular flows with fragmentation

Nonsmooth Discrete Element Method (DEM)

- particle breakage modeling with unilateral contact and friction
  - Particle breakage modeling or;[5]
  - Cohesive Zone Modeling(CZM) (also termed “bonded–cell method”)[6,7,8]
- NSCD (Nonsmooth Contact Dynamics) method[9] in Siconos
  - energy consistency
  - implicit method large time-step and energy

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[5] D.-M. Kuang et al. “A discrete element method (DEM)-based approach to simulating particle breakage”. In: *Acta Geotechnica* 17.7 (2022), pp. 2751–2764.

[6] M. Jean, V. Acary, and Y. Monerie. “Non-smooth contact dynamics approach of cohesive materials”. In: *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 359.1789 (2001), pp. 2497–2518.

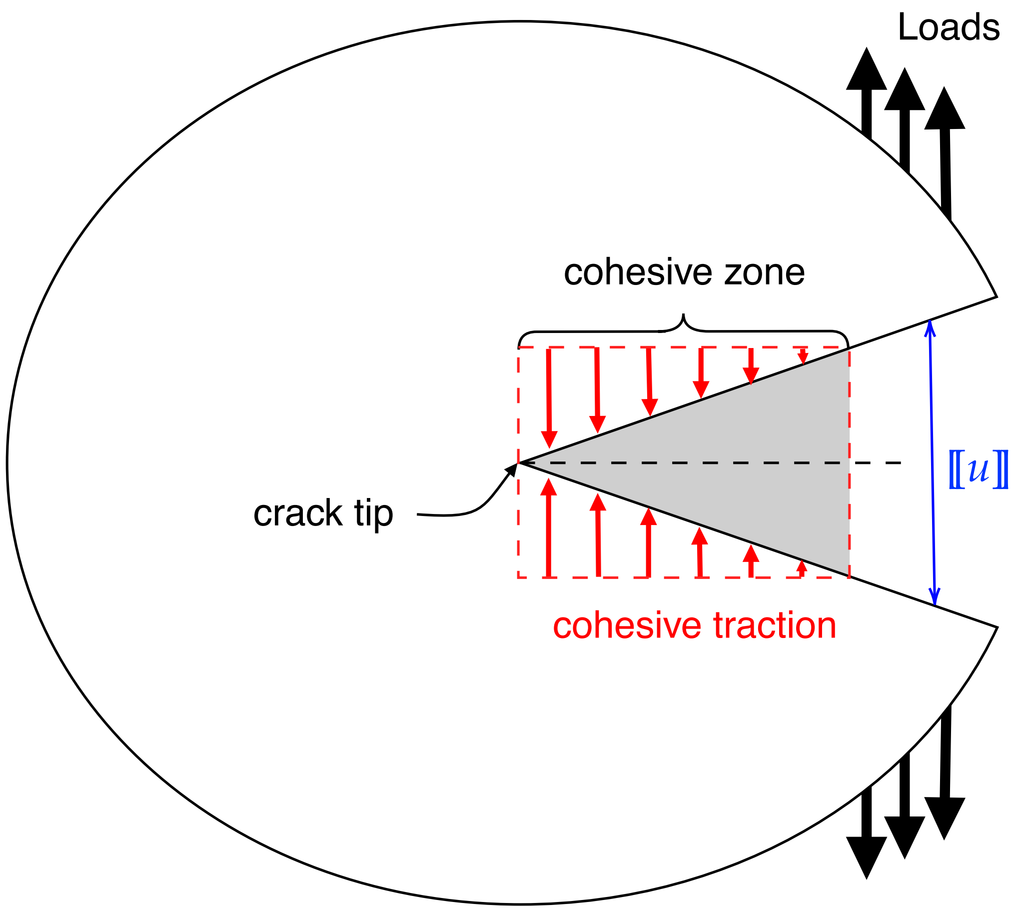
[7] N. A. Collins-Craft, F. Bourrier, and V. Acary. “On the formulation and implementation of extrinsic cohesive zone models with contact”. In: *Computer Methods in Applied Mechanics and Engineering* 400 (2022), p. 115545.

[8] D. Cantor et al. “Three-dimensional bonded-cell model for grain fragmentation”. In: *Computational Particle Mechanics* 4 (2017), pp. 441–450.

[9] F. Dubois, V. Acary, and M. Jean. “The Contact Dynamics method: A nonsmooth story”. In: *Comptes Rendus Mécanique* 346.3 (2018), pp. 247–262.

Objective 1: Run-out of the granular flows with fragmentation

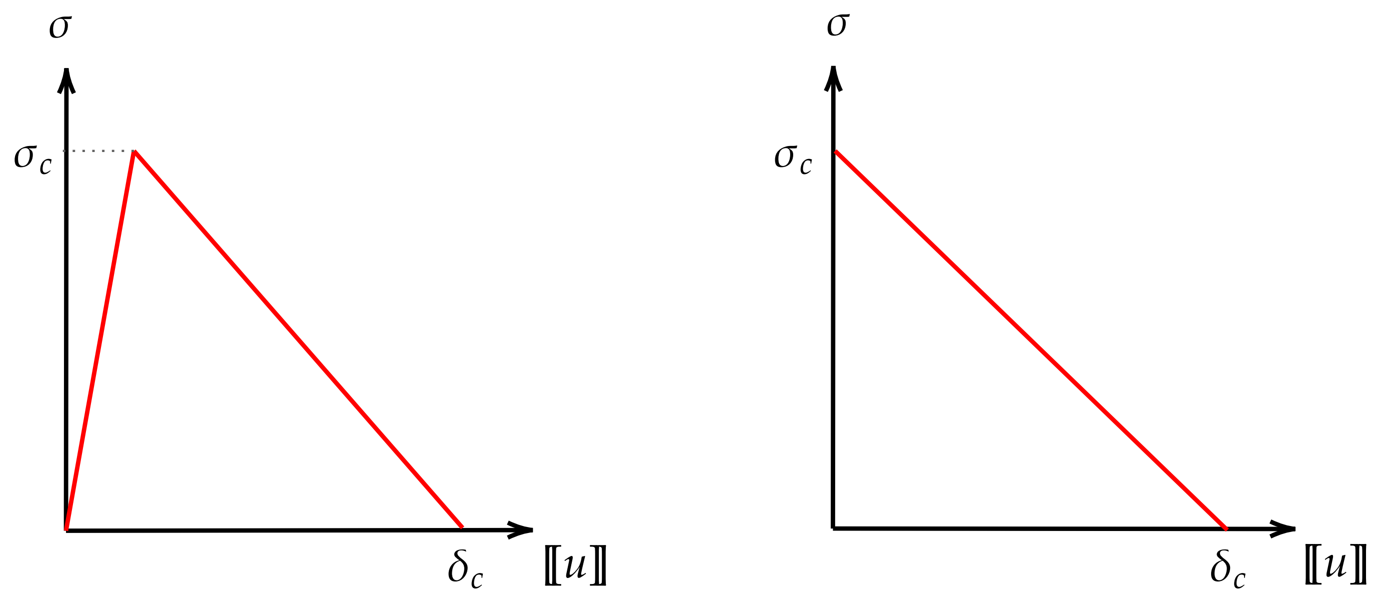
Cohesive Zone Modeling (CZM)



pacman : principles of cohesive zone modeling

Objective 1: Run-out of the granular flows with fragmentation

Cohesive Zone Modeling (CZM)

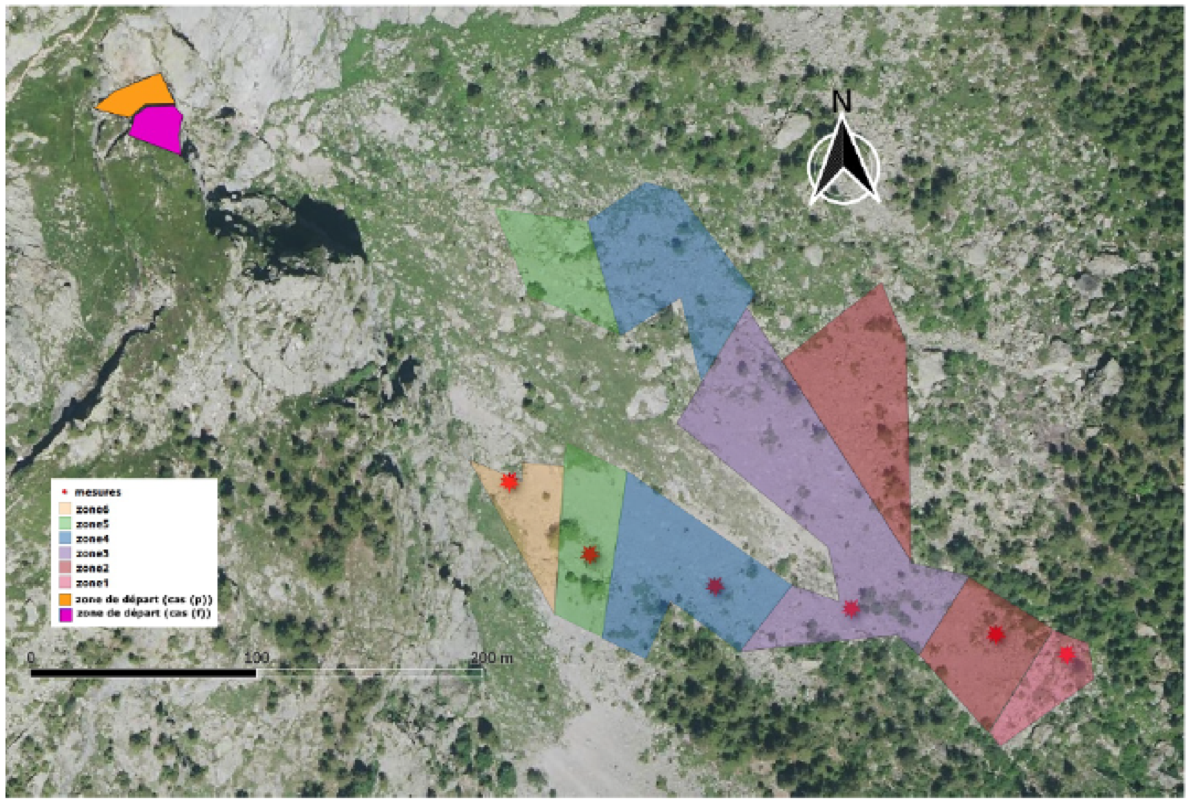


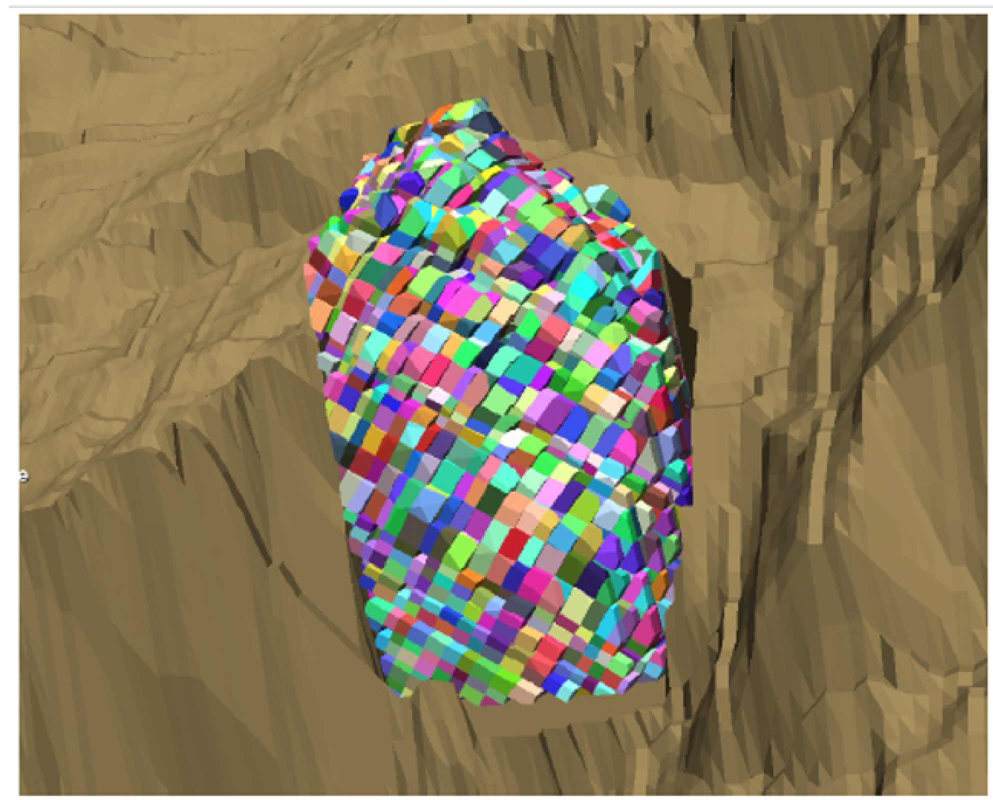
Intrinsic and extrinsic cohesive zone model

Main mechanical parameters

- cohesion strength σ_c, cohesion length δ_c, Dupré's energy w
- tangential cohesion ratio, coefficient of friction (μ)
- Weibull's distribution of mechanical parameters for defects

Objective 1: Run-out of the granular flows with fragmentation





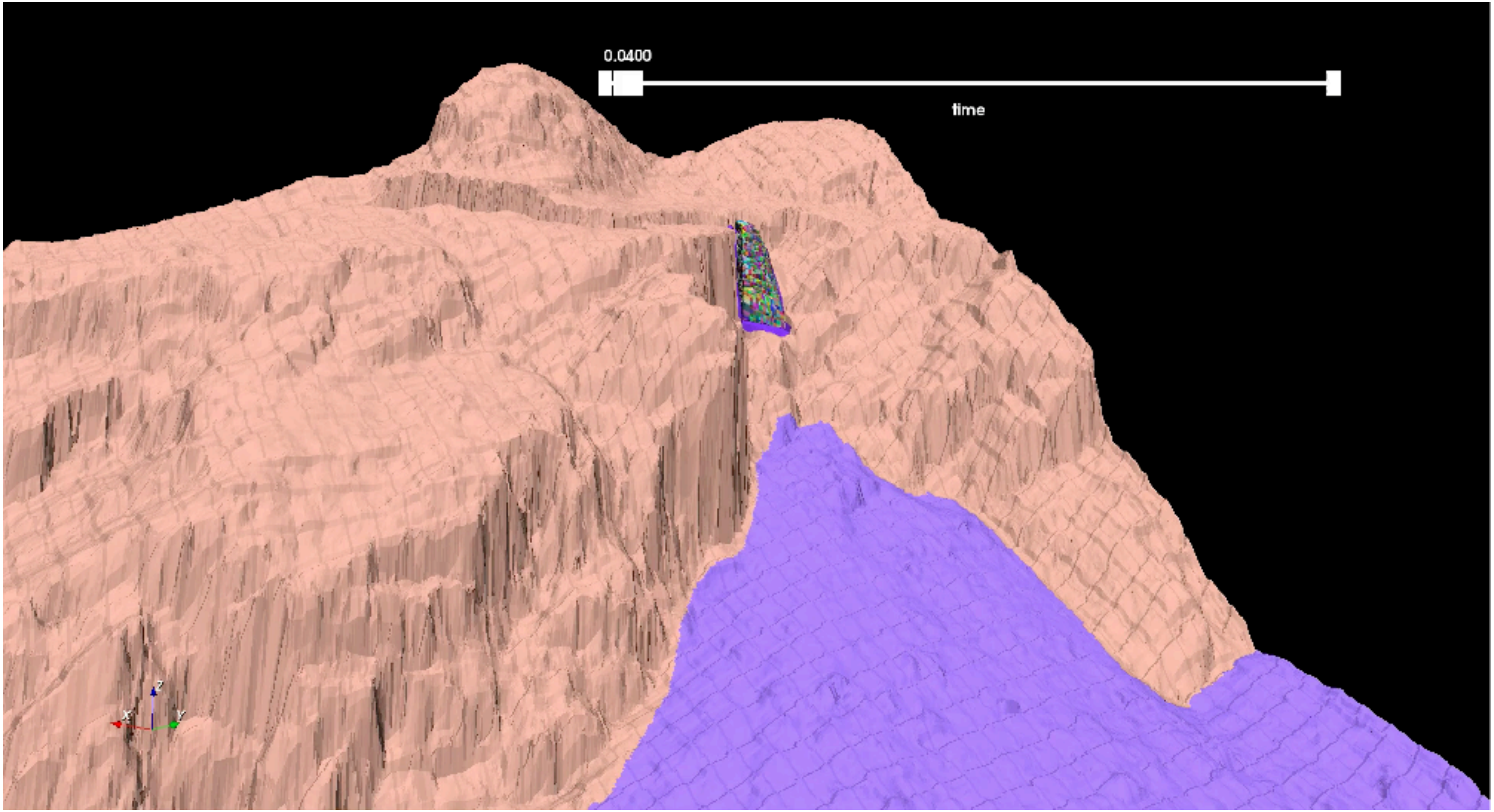
Discrete simulation of rockfalls (C. Gallay, F. Bourrier)
Argentière crevasse, Chéserys area, Argentière.[10]

Expected results

- characterize the shape and the volume of the "big blocks" after fragmentation
- perform the trajectory simulation of the rock-avalanche

[10] L. Courtial-Manent et al. "Late Holocene initiation of a deep rock slope failure in an alpine valley revealed by 10Be surface exposure dating (Chamonix, France)". In: *Quaternary International* 652 (2023), pp. 52–62.

Objective 1: Run-out of the granular flows with fragmentation



Objective 2: Prediction of instability phenomena

Enhanced cohesive zone modeling

- starting from extrinsic CZM models with contact and Coulomb friction[11]
- take into account the effect of heat (and temperature) on the mechanical properties of interface
- experimental results of Mamot *et al.* for a Mohr-Coulomb model of ice-filled permafrost rock joints[12]
- modeling the evolution of cohesion and friction angle with external heat flux
- coupling with heat equation in the rock mass

NSCD method

- extrinsic CZM modeling without spurious regularization
- efficient for quasi-static simulations and triggering instabilities

[11] N. A. Collins-Craft, F. Bourrier, and V. Acary. "On the formulation and implementation of extrinsic cohesive zone models with contact". In: *Computer Methods in Applied Mechanics and Engineering* 400 (2022), p. 115545.

[12] P. Mamot et al. "A temperature-and stress-controlled failure criterion for ice-filled permafrost rock joints". In: *The Cryosphere* 12.10 (2018), pp. 3333–3353.

Objective 2: Prediction of instability phenomena

Expected results

- understanding and quantifying the effect of temperature on the stability of permafrost rock mass
- understanding whether other phenomena need to be added (freeze/thaw cycle, water flow and porous media, . . .)

Thank you.