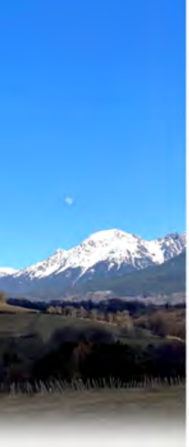

Rheology and depth-averaged modelling of wet snow avalanches on complex topographies

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Overview

Overview

1 Introduction

2 Research objectives

3 Numerical model

4 Idealised study
- FVM setup
- Results
- Summary

5 Full-scale study

6 Future work

Background

- Climate change is causing snow avalanches to become **wetter**

- Wet snow avalanches can interact with **structures**; we also have **channelisation**, **levée** & **ridge formation**, and **fingering**.

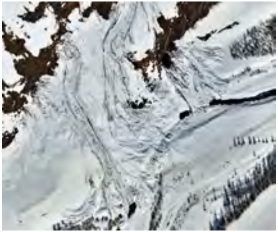
Background

- Climate change is causing snow avalanches to become **wetter**

- Wet snow avalanches can interact with **structures**; we also have **channelisation**, **levée** & **ridge formation**, and **fingering**.

Scientific challenges

- Most models so far are for dry avalanches → we need predictive continuum numerical models for wet ones too!
  - We need to account for the effects of **macroscopic cohesion**, and **increased density** on the bulk flow dynamics of the avalanche... including when it **comes to rest**
  - What is the relationship between these **parameters**, **definitions** and **complex topographies**?



Overview

Objectives

Objectives

- To develop and implement a rheology accounting for **macroscopic cohesion**, along with a **yield criterion** (fluid-solid transition)
- Hence use a depth-averaged Finite Volume Method model to explore behaviour of wet avalanches, especially with regards to the **arrest criteria**. Quantities to vary are:
  - **Macroscopic cohesion**
  - **The resolution of the mesh**
  - **Complexity of the terrain**, including barrier-like features

Overview

Governing equations

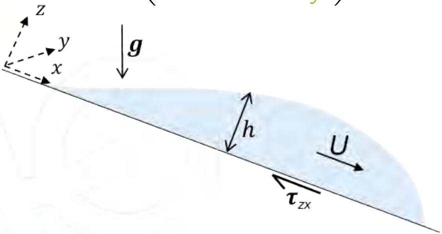
The incompressible depth-averaged Navier-Stokes equations for conserving mass (no entrainment)...

$$\frac{\partial h}{\partial t} + h\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right) = 0$$

...and momentum...

$$\rho h \frac{\partial U}{\partial t} + \rho h \left(U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y}\right) = \rho g_x h - \rho g_z h \left(\frac{\partial h}{\partial x}\right) - \tau_{zx}$$

$$\rho h \frac{\partial V}{\partial t} + \rho h \left(U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y}\right) = \rho g_y h - \rho g_z h \left(\frac{\partial h}{\partial y}\right) - \tau_{zy}$$



where ρ is bulk density; h is flow depth; U and V are velocities in an orthogonal two-dimensional space; g is gravitational acceleration; and τ_{zx} and τ_{zy} are resisting shear stresses.

Constitutive equation for shear terms

We use a modified Voellmy model, that includes a term for the macroscopic cohesion:

$$\tau_{zx} = \left[\rho g_z h(\mu) + \rho g_z h \left(\frac{|U|^2}{\xi h}\right) + \tau_c\right] \frac{U}{|U|}$$

Typical parameter ranges

Parameter	Value	Meaning
μ	0.15 to 0.50	Coulomb friction
ξ	500 to 2000 ms^{-2}	Turbulent friction
τ_c	0 to 300 Pa (?)	**Cohesion**

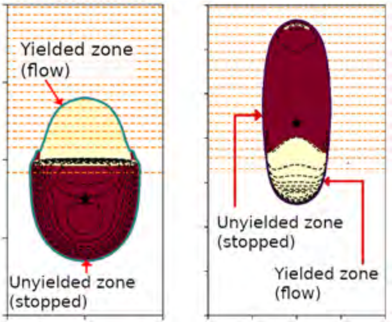
Note: we really need to be aware of **scale effects**! E.g. ρ and τ_c are scale-dependent (and their ratio governs flow dynamics).

Physical yielding criterion

We define $\tau_{xz,\ \mathrm{test}}$ using momentum conservation (the inertia and pressure gradient terms), assuming that the flow would instantaneously come to rest at the next timestep:

$$\left|\tau_{xz,\ \mathrm{test}}\right|(\rho U) < \tau_c + \rho g_z h\mu \rightarrow U = 0$$

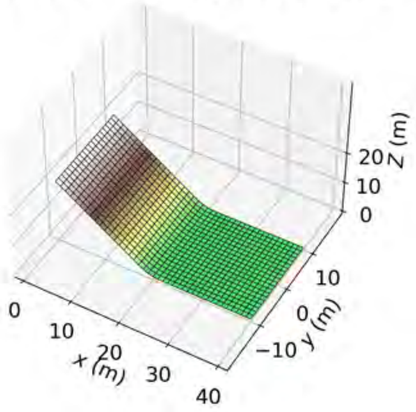
This enables unambiguous identification of flowing and stopped zones.

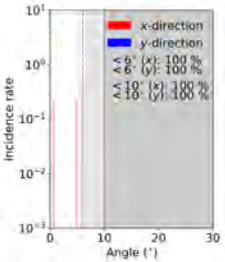


Overview

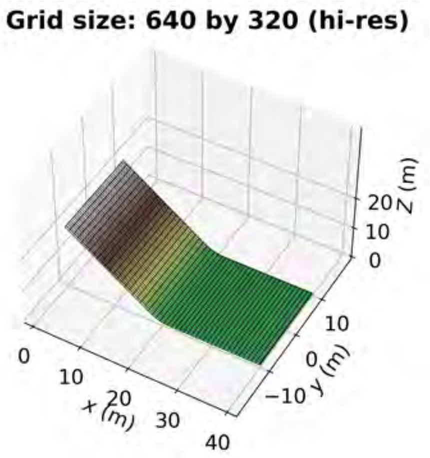
Finite Volume Grid: flat

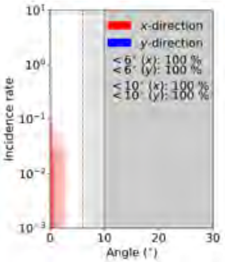
Grid size: 40 by 20 (low-res)



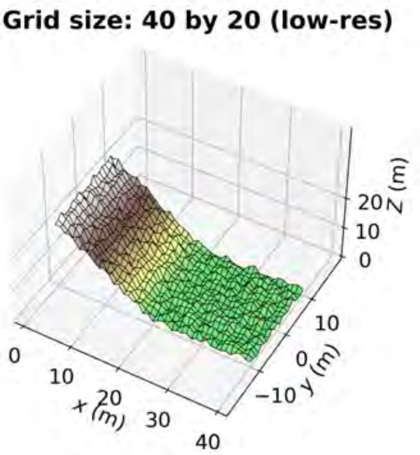


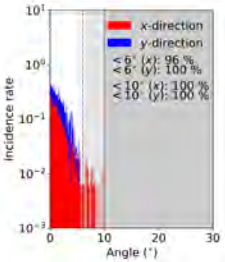
Finite Volume Grid: flat





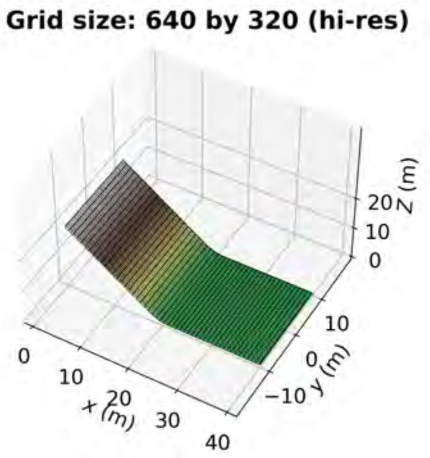
Finite Volume Grid: random

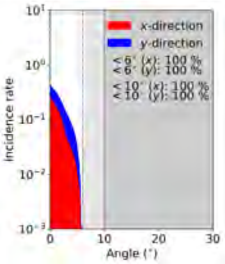




Magnitude of random terrain features: < 100 mm

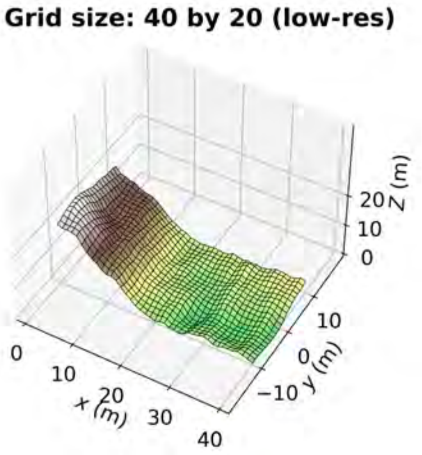
Finite Volume Grid: random

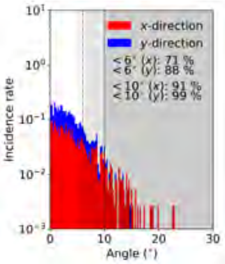




Magnitude of **random terrain features**: < 6 mm

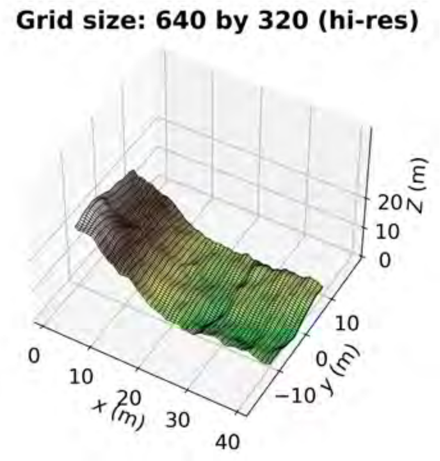
Finite Volume Grid: complex

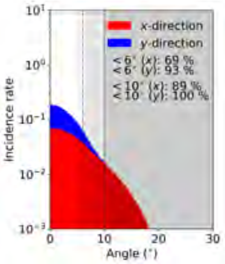




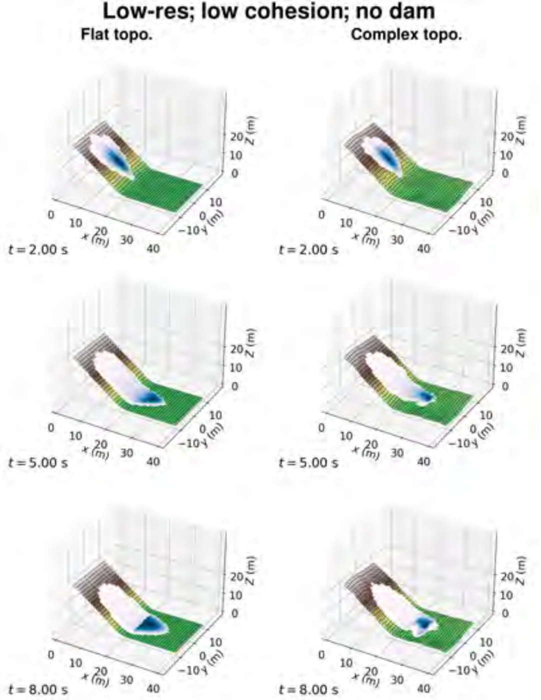
Magnitude of **complex terrain features**: < 0.5 m

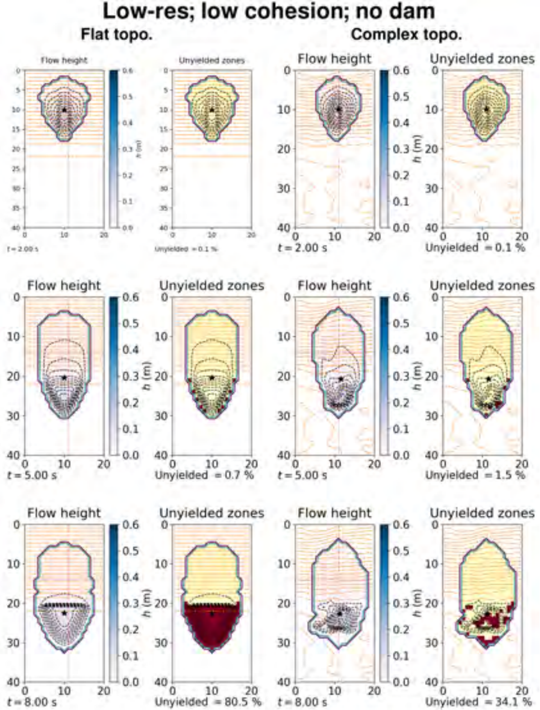
Finite Volume Grid: complex

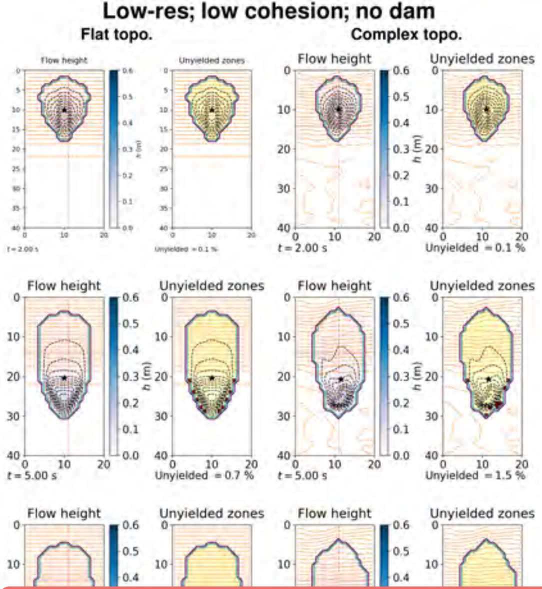




Magnitude of **complex terrain features**: < 0.4 m

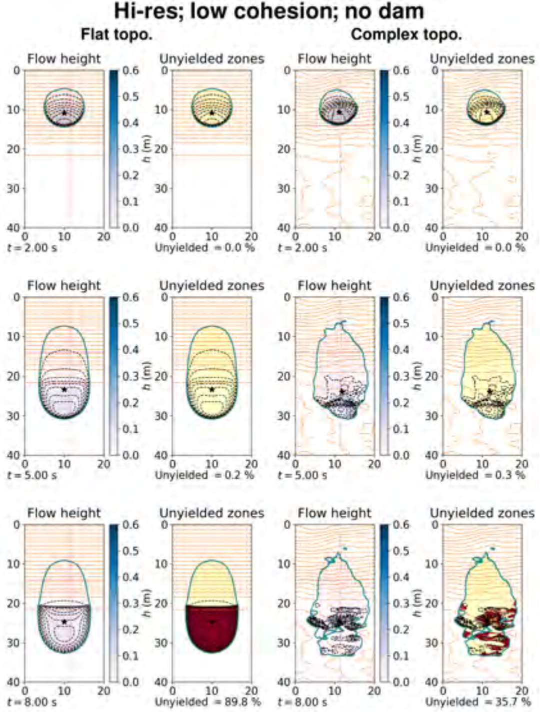

Low-res; low cohesion; no dam
Flat topo.
Complex topo.
t = 2.00 s
t = 5.00 s
t = 8.00 s
x (m)
y (m)
Z (m)
0
10
20
30
40
-10


Low-res; low cohesion; no dam
Flat topo.
Complex topo.
Flow height
Unyielded zones
h (m)
t = 2.00 s
Unyielded = 0.1 %
t = 5.00 s
Unyielded = 0.7 %
Unyielded = 1.5 %
t = 8.00 s
Unyielded = 80.5 %
Unyielded = 34.1 %

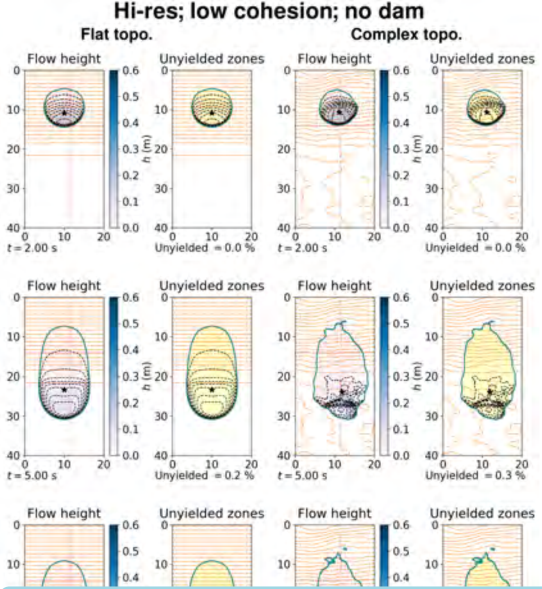


Problem

The proportion of "unyielded material" is much lower on the **complex topography**.

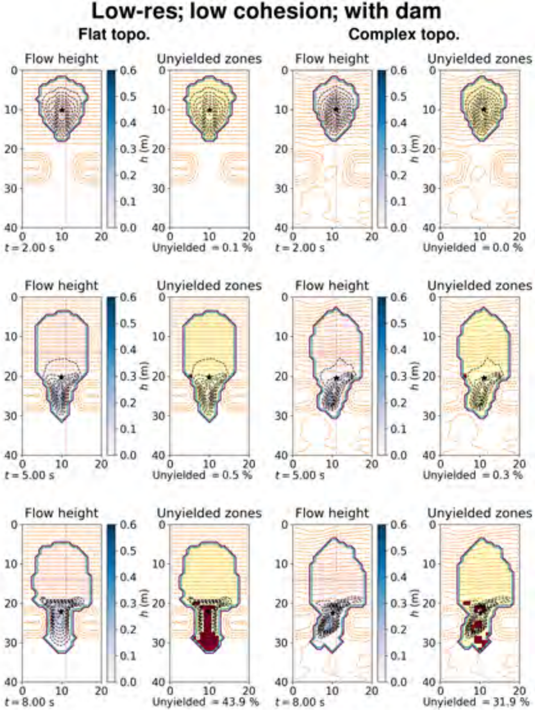


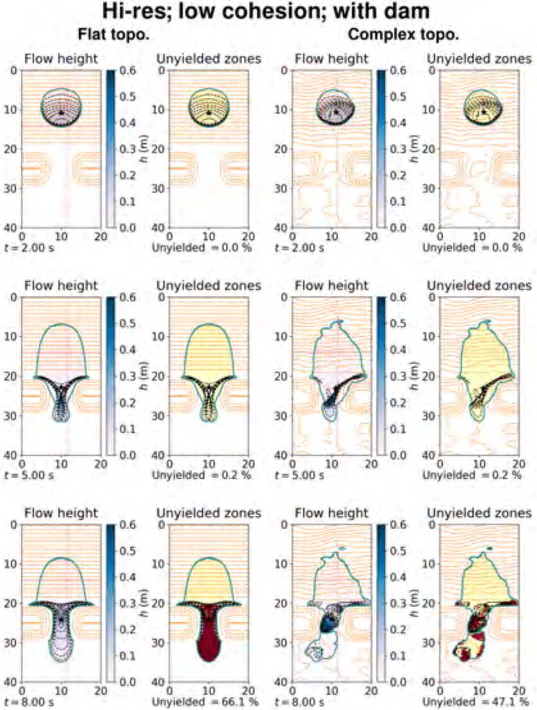
Hi-res; low cohesion; no dam
Flat topo.
Complex topo.
Flow height
Unyielded zones
h (m)
t = 2.00 s
Unyielded = 0.0 %
t = 2.00 s
Unyielded = 0.0 %
t = 5.00 s
Unyielded = 0.2 %
t = 5.00 s
Unyielded = 0.3 %
t = 8.00 s
Unyielded = 89.8 %
t = 8.00 s
Unyielded = 35.7 %



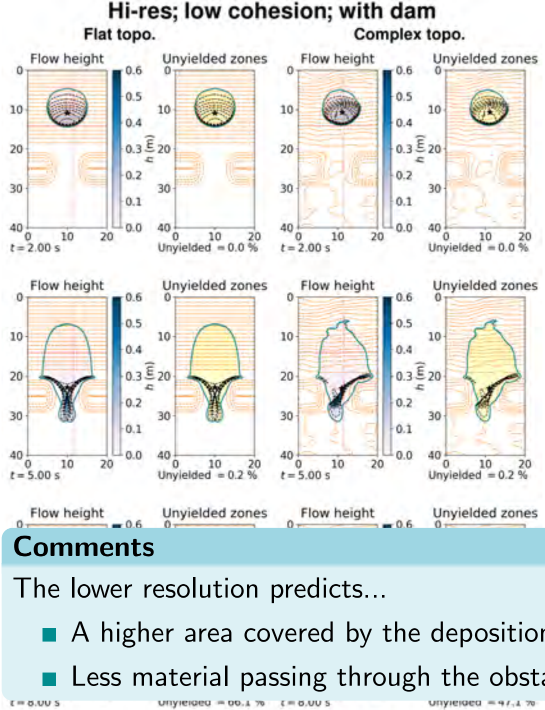
Comment

The higher resolution leads to a better-defined flow, especially on the **complex topography**.


Low-res; low cohesion; with dam
Flat topo.
Complex topo.
Flow height
Unyielded zones
h (m)
t = 2.00 s
Unyielded = 0.1 %
Unyielded = 0.0 %
t = 5.00 s
Unyielded = 0.5 %
Unyielded = 0.3 %
t = 8.00 s
Unyielded = 43.9 %
Unyielded = 31.9 %



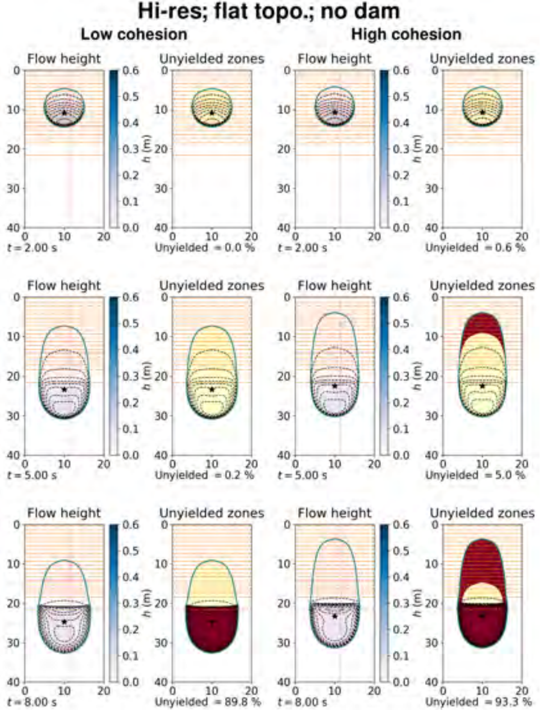
Hi-res; low cohesion; with dam
Flat topo.
Complex topo.
Flow height
Unyielded zones
h (m)
t = 2.00 s
Unyielded = 0.0 %
t = 5.00 s
Unyielded = 0.2 %
t = 8.00 s
Unyielded = 66.1 %
Unyielded = 47.1 %



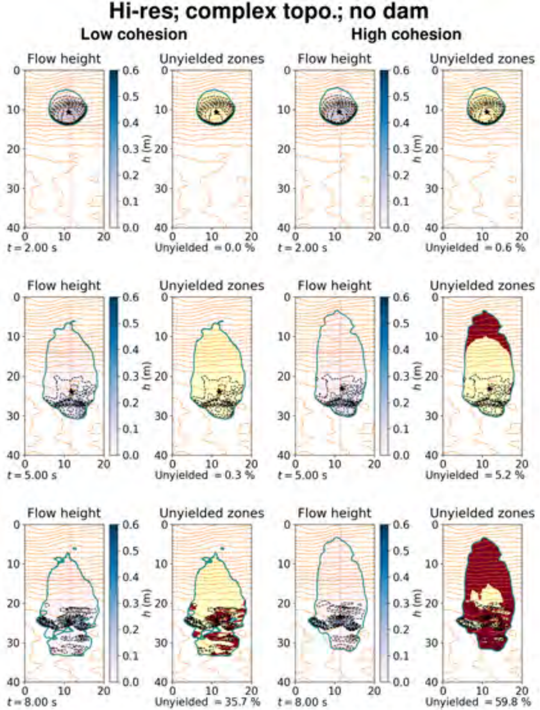
Comments

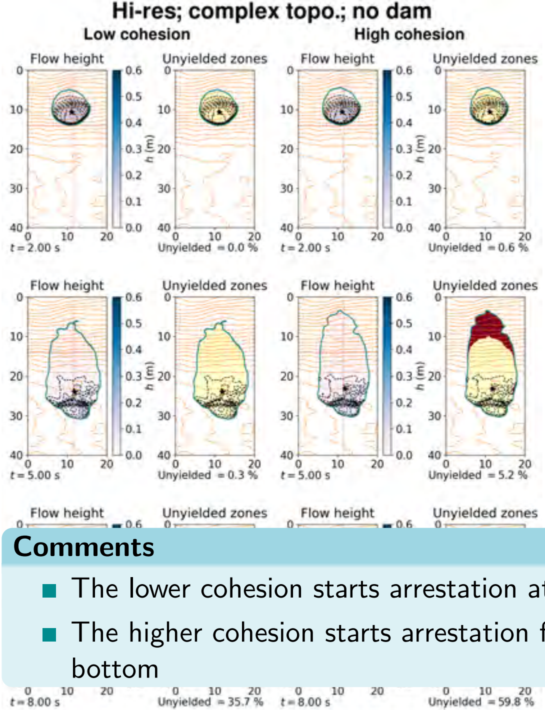
The lower resolution predicts...

- A higher area covered by the deposition
- Less material passing through the obstacle



Hi-res; flat topo.; no dam
Low cohesion
High cohesion
Flow height
Unyielded zones
h (m)
t = 2.00 s
Unyielded = 0.0 %
Unyielded = 0.6 %
t = 5.00 s
Unyielded = 0.2 %
Unyielded = 5.0 %
t = 8.00 s
Unyielded = 89.8 %
Unyielded = 93.3 %


Hi-res; complex topo.; no dam
Low cohesion
High cohesion
Flow height
Unyielded zones
h (m)
t = 2.00 s
Unyielded = 0.0 %
Unyielded = 0.6 %
t = 5.00 s
Unyielded = 0.3 %
Unyielded = 5.2 %
t = 8.00 s
Unyielded = 35.7 %
Unyielded = 59.8 %



Comments

- The lower cohesion starts arrestation at the bottom
- The higher cohesion starts arrestation from the bottom

Summary

- Even a small amount of **macroscopic cohesion** affects flow dynamics.
- Furthermore:
  - Lower τ_c causes flows to arrest from the bottom-up.
  - Higher τ_c causes flows to arrest from the top-down.

Summary

- An increased **mesh resolution** is associated with:
  - Smoother, more detailed flow bounds
  - A higher proportion of material becoming **unyielded**.
- **Random noise** of within $\pm$ 10 % of the cell width makes little difference to the flow dynamics.
- In constrast, superimposing even “mild” **topographical complexity** on mountains causes large differences on the flow dynamics, especially in terms of the **arrest criterion**.

Overview

Future work – full-scale

Features

1. Release zone
2. Debris fan
3. Storage basin
4. Bourgeat dam

Future work – full-scale

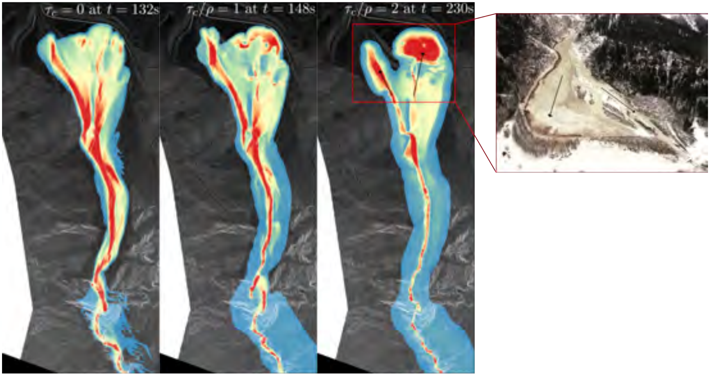
Same depth-averaged modelling approach

- Bourgeat avalanche track and protection dam (Haute-Savoie, France)
- Systematic sensitivity analyses

Parameters

- Release area of about 275 000 m^2
- $h_0 = 2.0$ m
- 2 m digital terrain model
- $\mu = 0.15$, $\xi = 1000$ ms^{-2}
- $0 \leq \tau_c/\rho \leq 2$

Future work – full-scale



Time of impact with the Bourgeat dam

Cohesive flow → better match

- Voellmy flow induces a deposit which spreads over the whole storage basin
- Cohesive flow induces heteregeneous deposits with two main branches and adjacent "voids" formed

Overview

Future work

- Compare full-3D and depth-averaged solutions, given **topographical complexity** is substantial. (Note though that materials can smooth out at least part of this complexity through the formation of dead zones, etc.)
- Further improvements can be made the current improved Voellmy model to attempt to **separate phenomena** which are currently lumped together.
- Move to unstructured meshes and massively-parallelised solvers.
- Investigate **scale effects**, and use the findings to help interpret **full-scale analyses**.