Nouvelles problématiques liées à la neige humide: avalanches et reptation du manteau neigeux

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Wet snow avalanches

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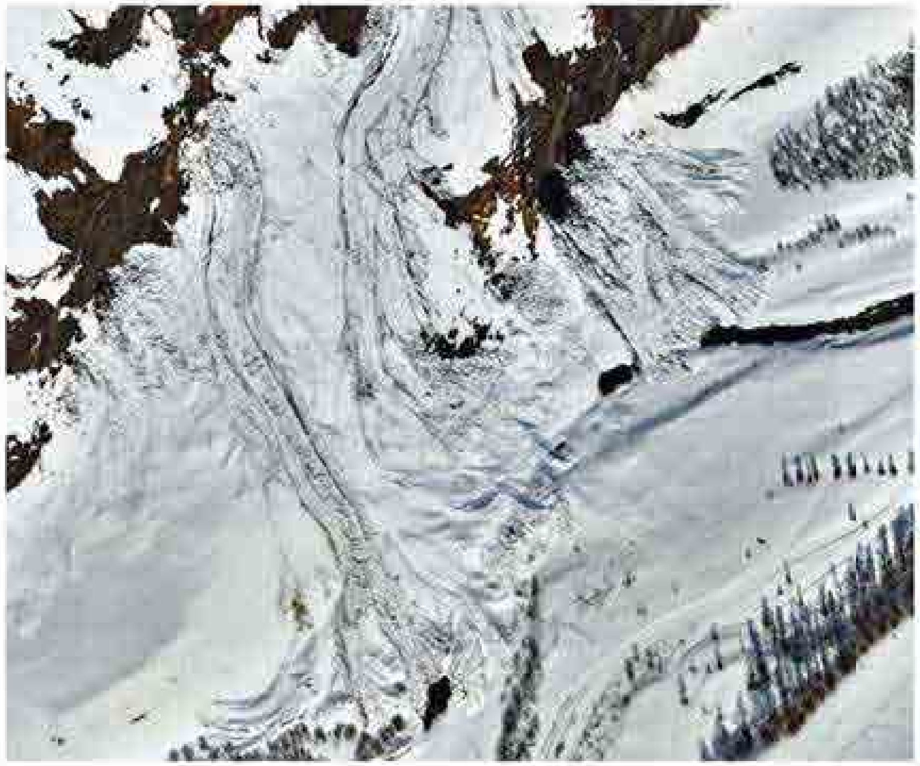
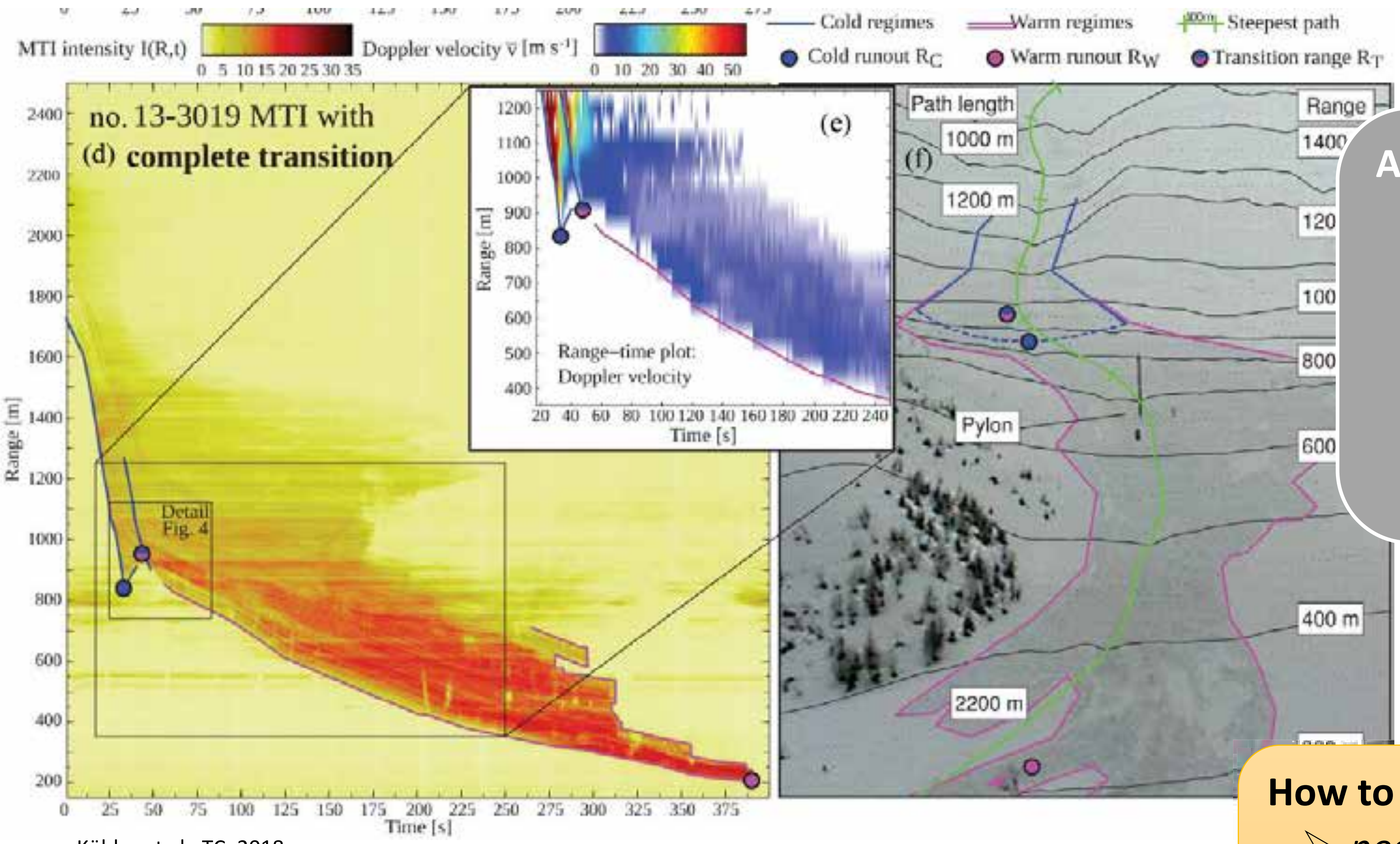


Distinctive characteristics:

- channelization (topography control)
- levées, ridges, fingering
- pasty-like dynamics, plug flows
- abrupt stopping of the front

Cold-to-warm flow transitions

GEODAR measurements (Vallée de la Sionne, SLF)



Köhler et al., TC, 2018

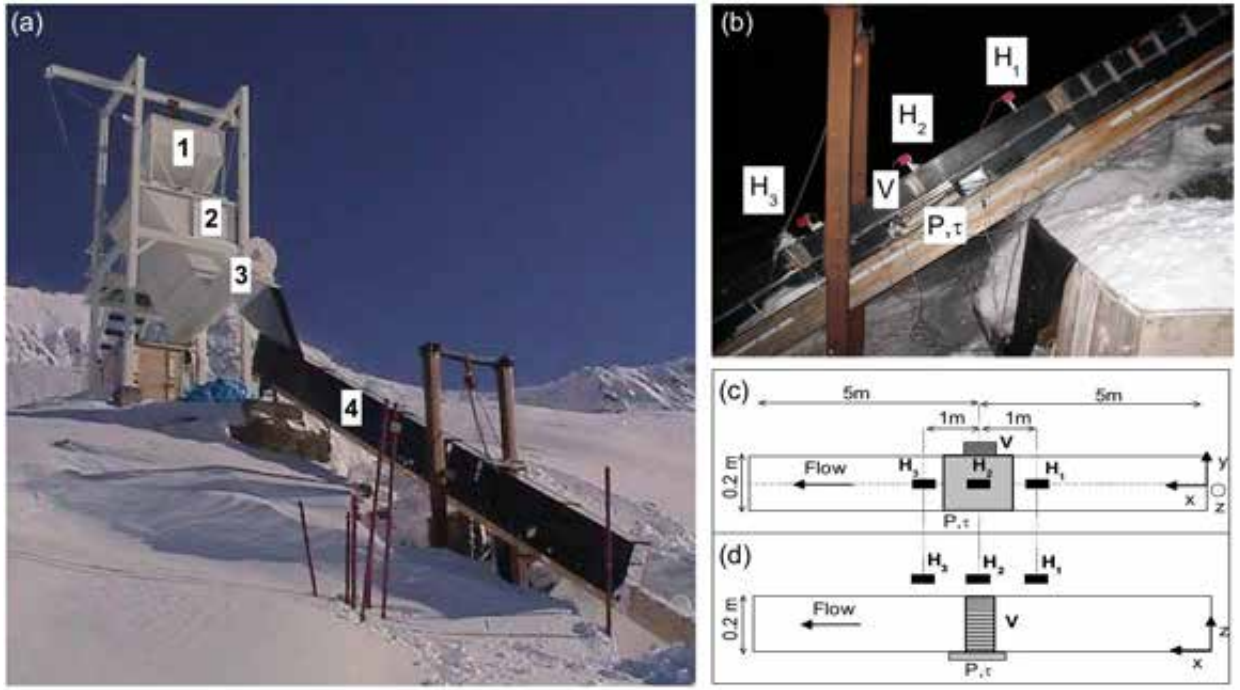
A “new” type of avalanche?

- abrupt change in flow regime and snow properties
- transition for $T_{snow} \gtrsim -1°C$
- *partial* and *complete* transitions
- important role played by erosion of “hot” snow

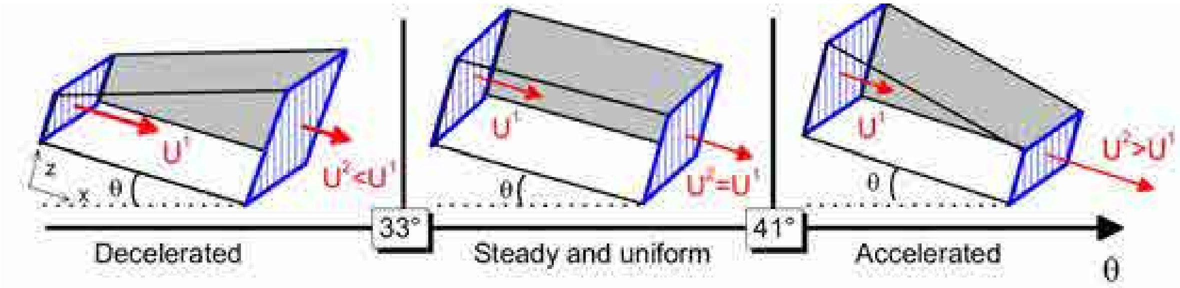
How to model these flows?

- *need for a characterization of snow flowing properties in a wide range of temperatures and LWC*

Channel experiments

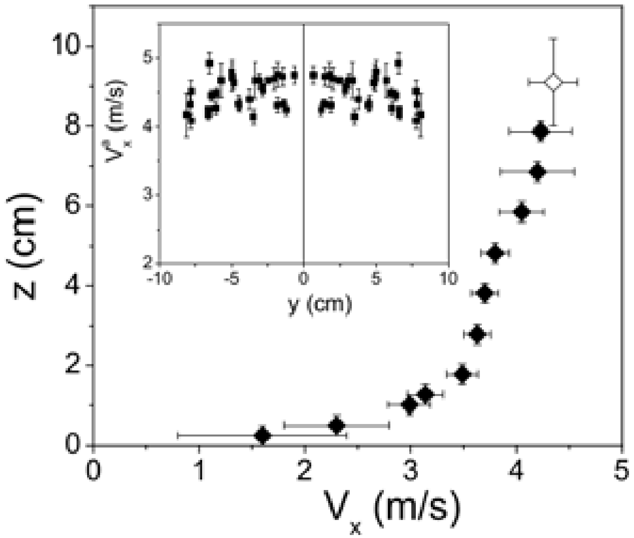


Rognon et al., JoR, 2008



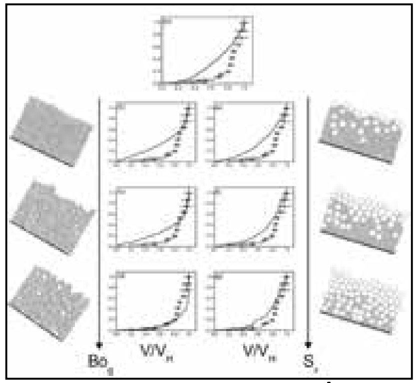
Rognon et al. (J. Rheol., 2008):

Chute-flow snow experiments



Rognon (PhD thesis):

Granular flows (DEM)



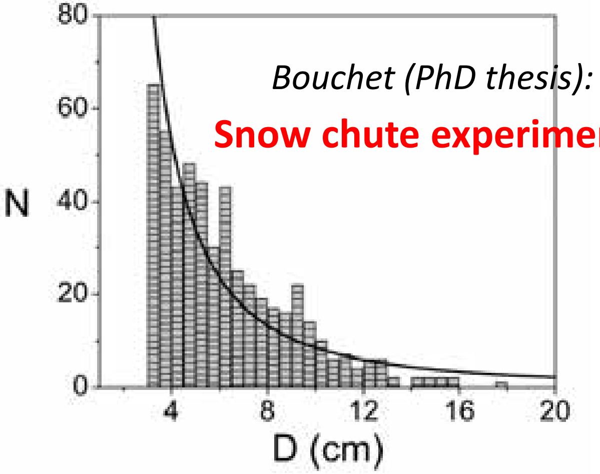
Cohesive *Bidisperse*

$$\frac{\Delta V_x}{\Delta z} \sim \frac{\sqrt{gd}}{d_{ag}} = \sqrt{\frac{g}{d_{ag}}}$$

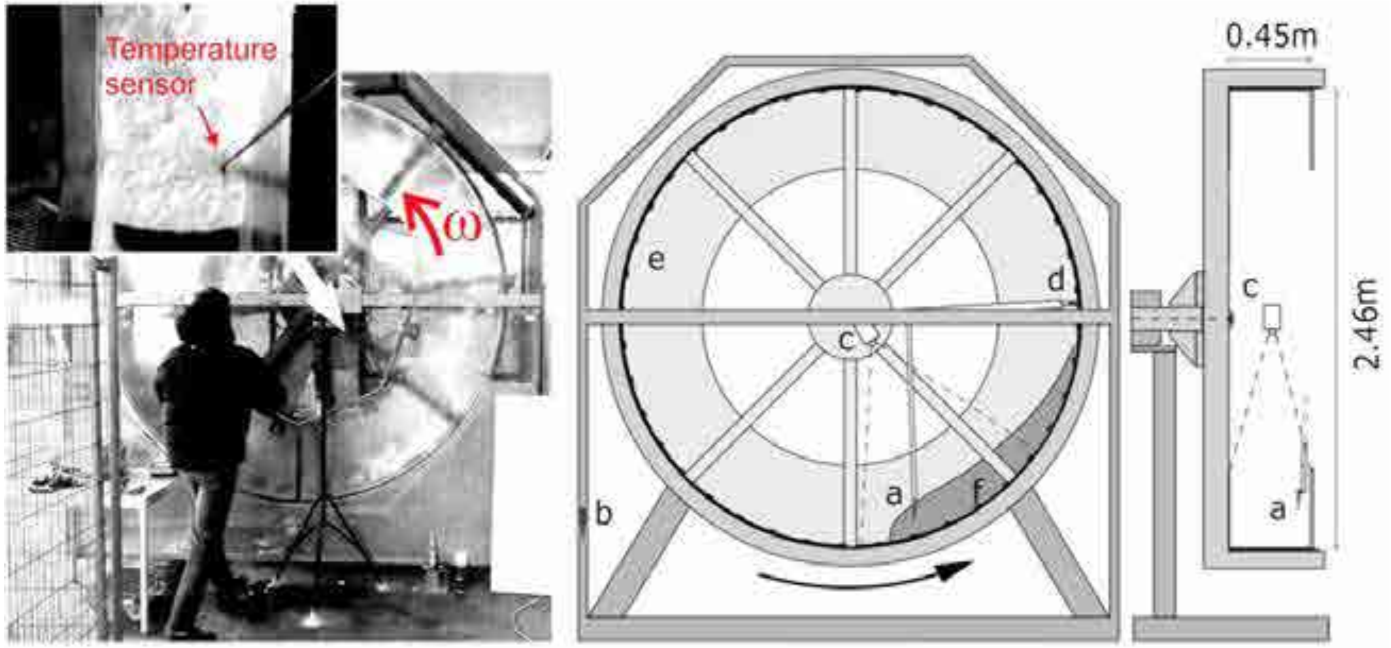
- **Cold (dry) snow flows**
  - **Snow aggregates**
  - **Segregation**
- **T°C → 0: problems !**

Bouchet (PhD thesis):

Snow chute experiments



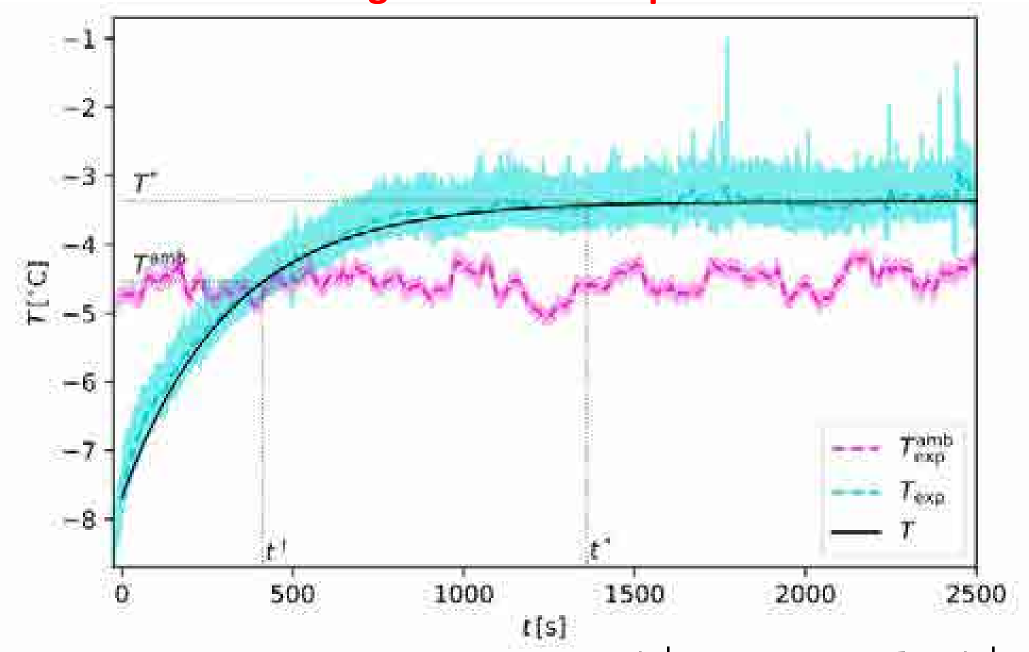
Rotating drum experiments



Fischer et al., GRL, 2018

Fischer et al. (GRL, 2018):

Rotating drum snow experiments



$$T(t) = T^* - (T^* - T^0)^{1-t/t^+}(T^* - T^{amb})^{t/t^+}$$

- **Cold (dry) snow flows**
  - **Thermal equilibrium**
  - **Ambient cooling compensates frictional heating**
- **T°C → 0: problems !**

Tumbler granulation

Steinkögler et al. (JRR, 2015):

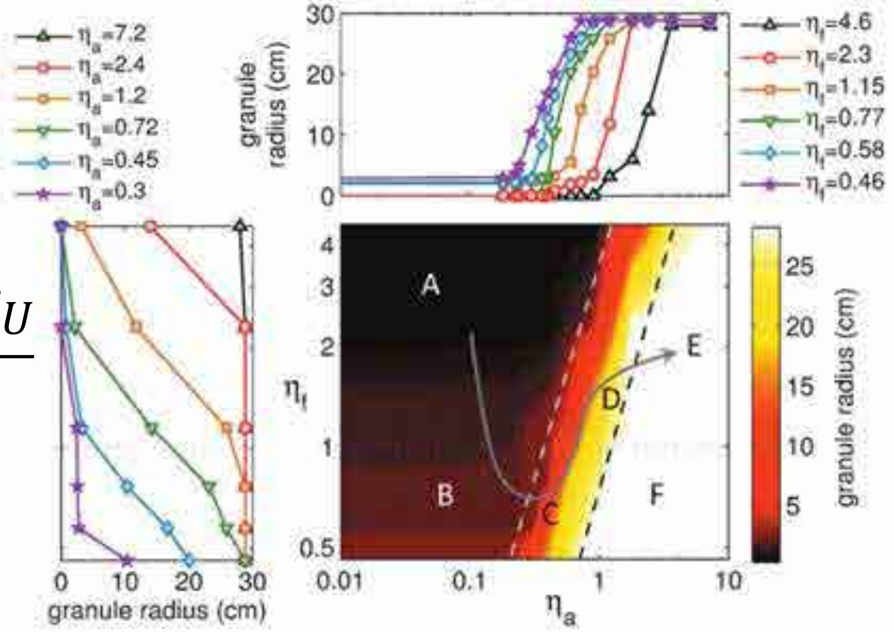
Cohesive granular samples in a tumbler (DEM)

$T_{neige} < -1°C$ | $T_{neige} > -1°C$ | $T_{neige} = 0°C$

Steinkögler et al., JGR, 2015

- **Active granulation due to cohesion**
- **Snow flows are not possible in small-scale models close to T°C = 0**

$$\eta_f = \frac{\sqrt{mkU}}{F_f^t}$$

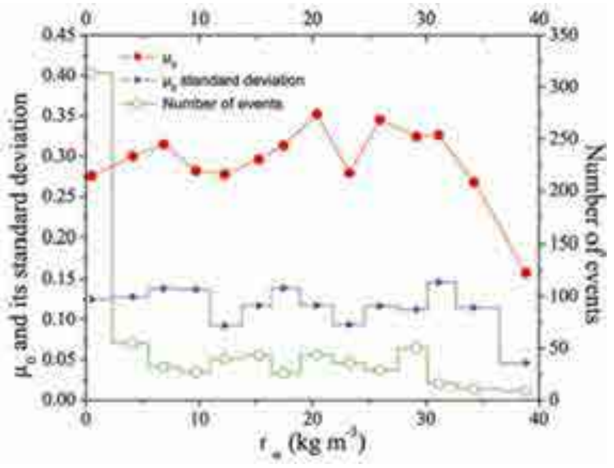


$$\eta_a = \frac{Pd^2}{F_a}$$

	cohesionless granular	granular	granular / viscous	pasty / viscous
η_f	>1	<1	>1	>1
η_a	<0.5	0.2-1	≈ 1	>2

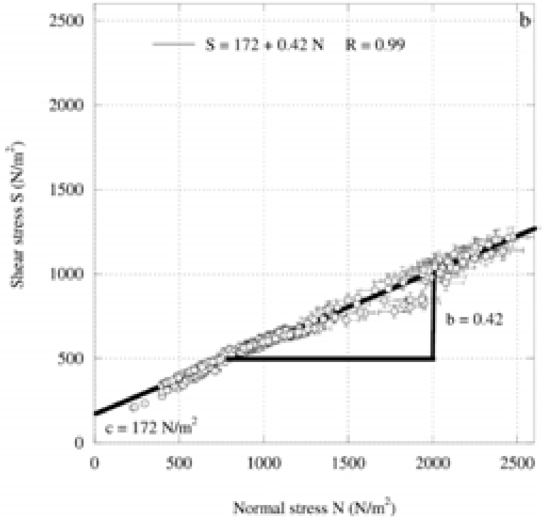
Flow rheology : basal shear-to-normal stress ratio (S/N)

Different proposals in the literature:



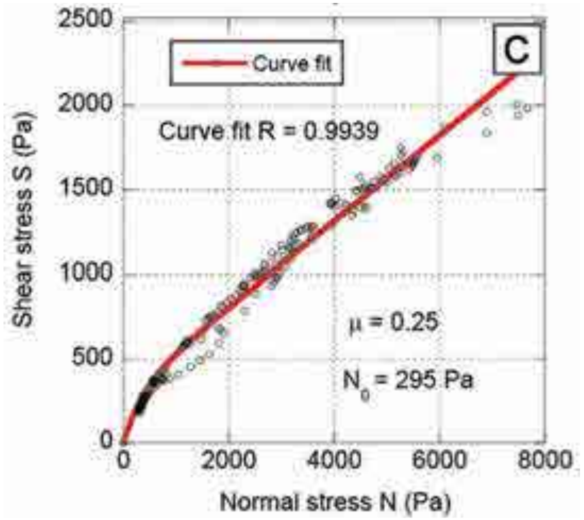
Naaim et al. (J. Glaciol., 2013):

Voellmy model with coefficients (μ, ξ) depending on liquid water content r_w



Platzer et al. (Geophys. Res. Lett., 2007):

Introduction of a cohesion for wet snow



Bartelt et al. (J. Glaciol., 2015):

Effect of cohesion vanishing for $N \rightarrow 0$

➢ **Implementation and test of a cohesive Voellmy model:**

❖ **analysis of cohesion influence**

$$S = \left(\tau_c + K \frac{|\bar{\boldsymbol{u}}|}{h} + \mu \rho g_z h + \frac{\rho g}{\xi} |\bar{\boldsymbol{u}}|^2 \right) \frac{\bar{\boldsymbol{u}}}{|\bar{\boldsymbol{u}}|}$$

viscous contribution

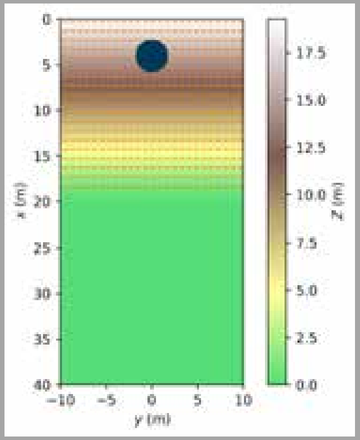
cohesion

Voellmy

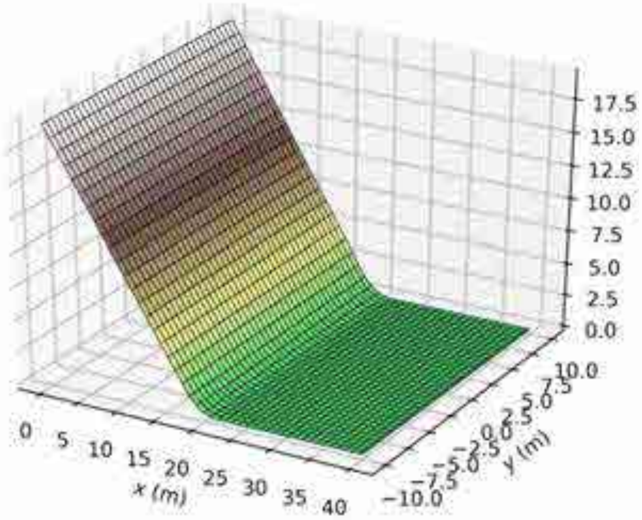
Benchmark numerical simulations

Depth-averaged modelling approach:
- robust, shock capturing numerical scheme
- model topographies
- systematic sensitivity analyses

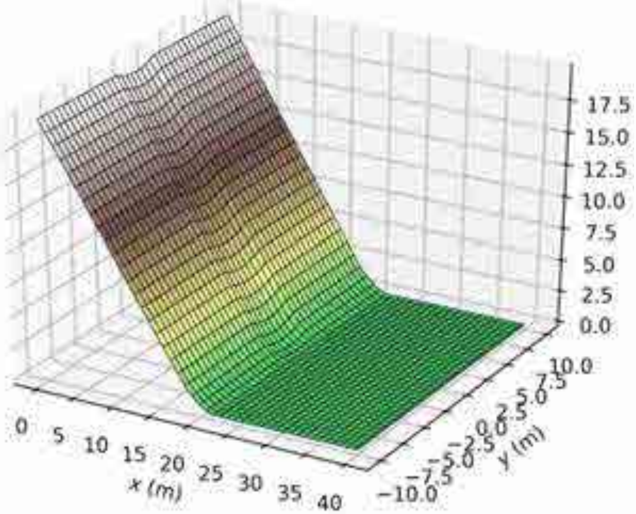
- Initial condition:
  - cylindrical pile
  - $h_0 = 0.6$ m
- $V \approx 8.5$ m^3
- $\mu = 0.5,\ \xi = 2000$ m.s^{-2}
- $\tau_c = 0\ - 200$ Pa



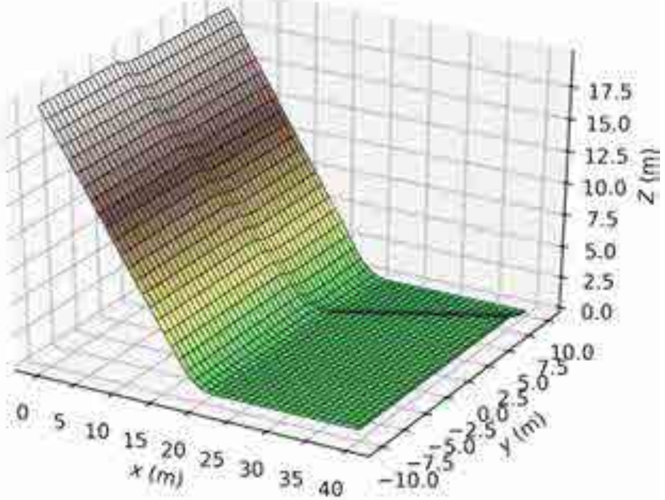
Incline with smooth transition



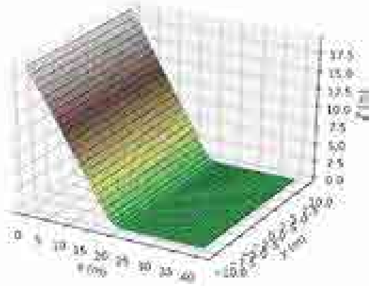
Channeled slope



Oblique ridge

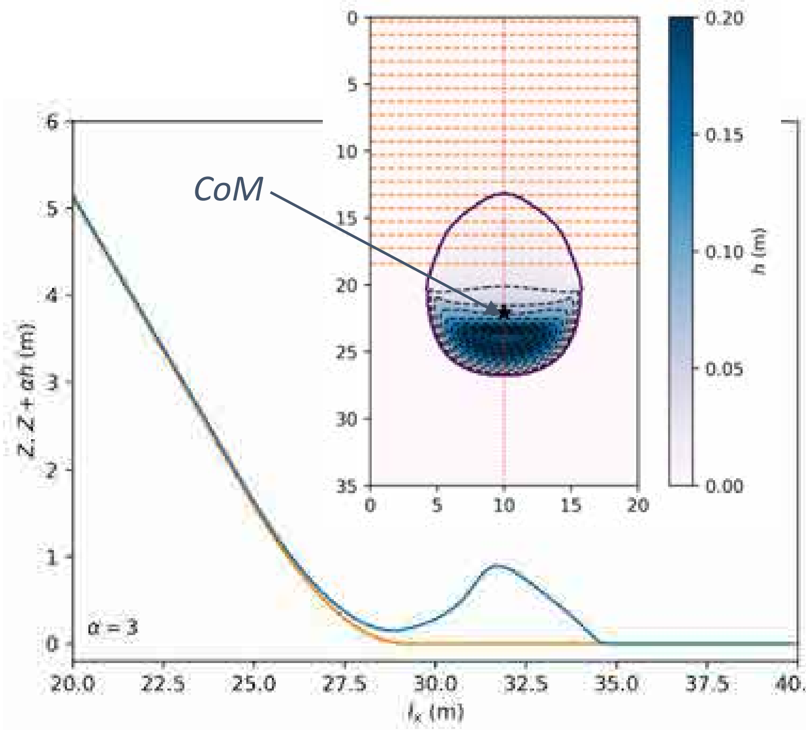


Avalanche runout

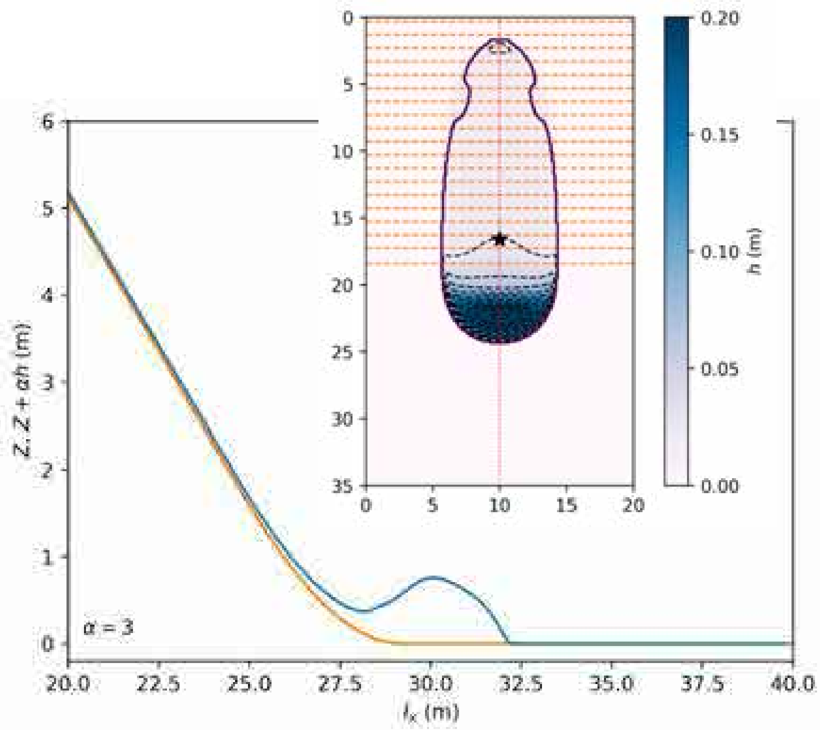


Longitudinal profiles:

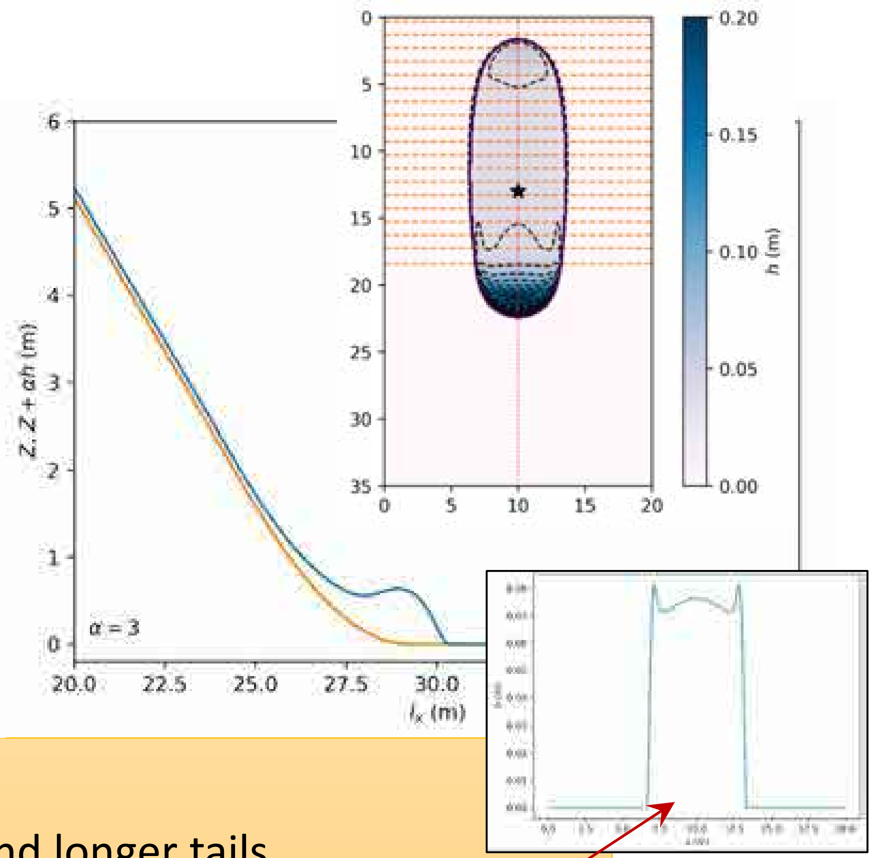
$\tau_c = 0$ Pa



$\tau_c = 50$ Pa



$\tau_c = 100$ Pa



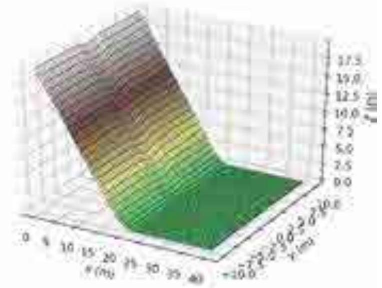
- ➢ Cohesion induces shorter runouts …

  … and longer tails

❖ *Note progessive shift in center of mass (CoM) location*

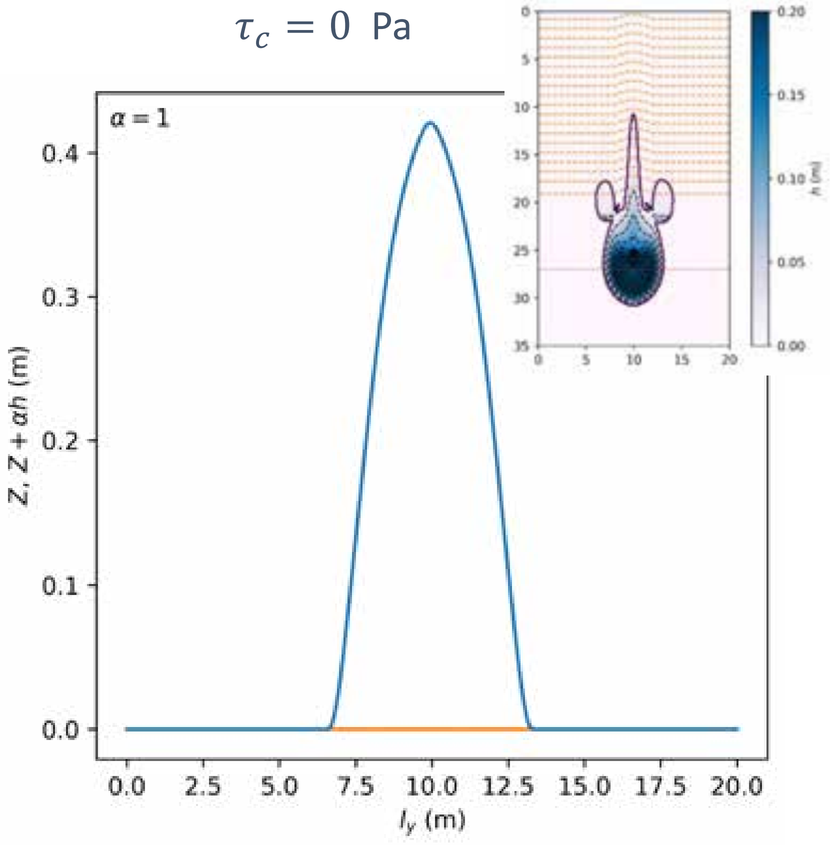
❖ *Note appearance of levées in the cohesive deposit*

Channelization

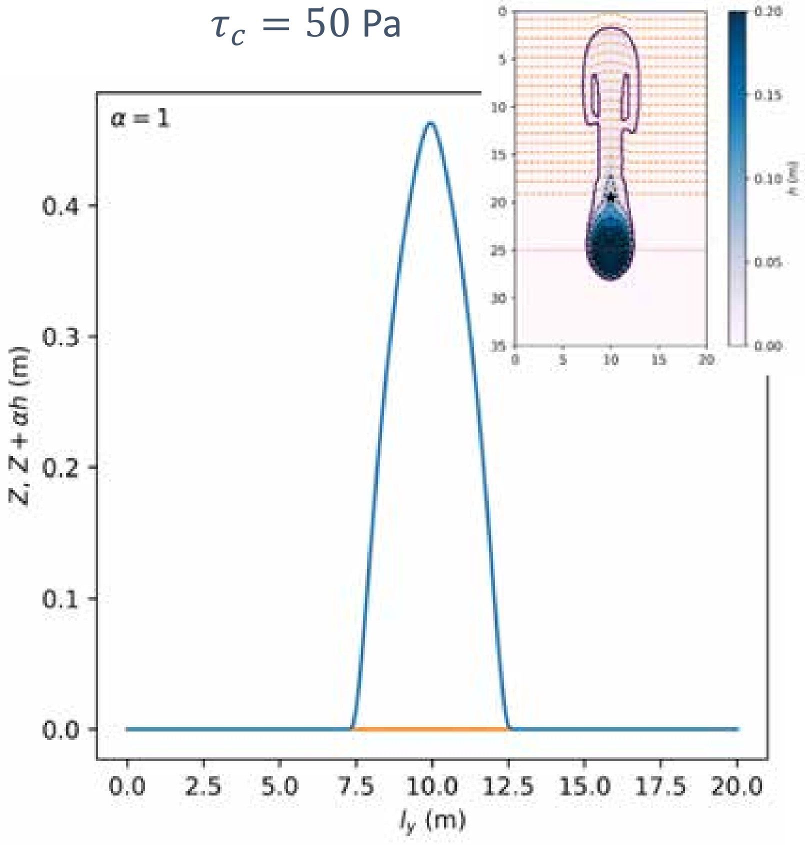


Transversal profiles:

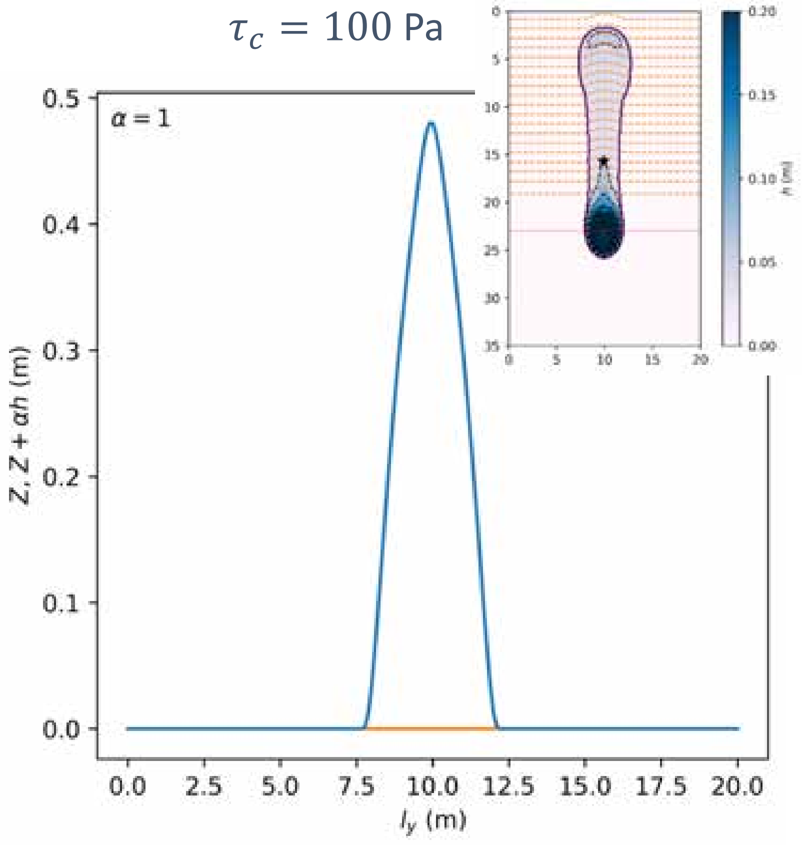
$\tau_c = 0$ Pa



$\tau_c = 50$ Pa



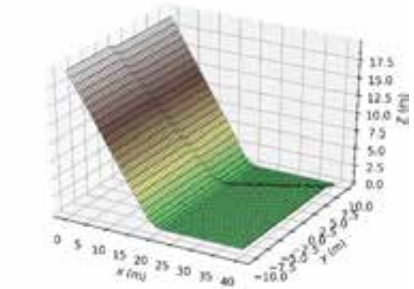
$\tau_c = 100$ Pa



- Cohesion promotes flow channelization

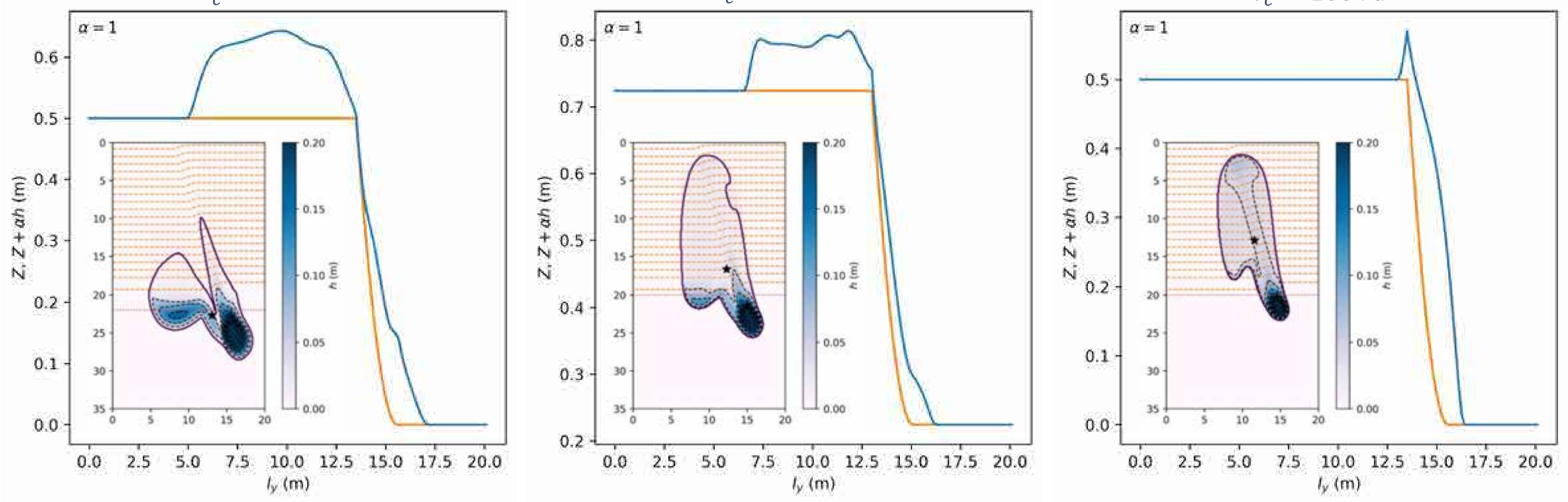
❖*Note progressive concentration of the deposit (fingering)*

Influence of topography



Transversal profiles:

$\tau_c = 0$ Pa $\qquad$ $\tau_c = 50$ Pa $\qquad$ $\tau_c = 100$ Pa



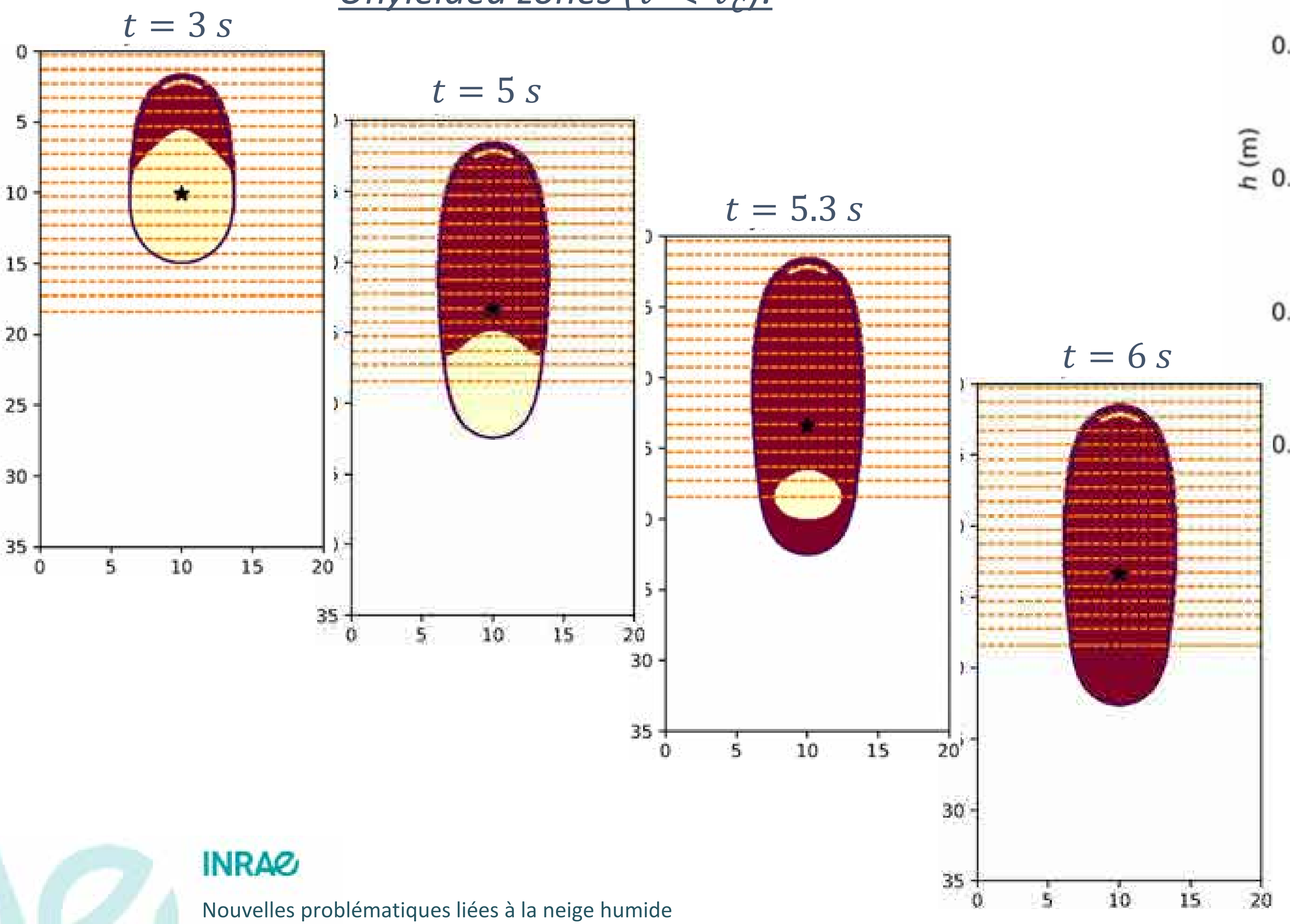
- Cohesion promotes topographical control of the flow

❖ *Note decrease in lateral spreading of the deposit*

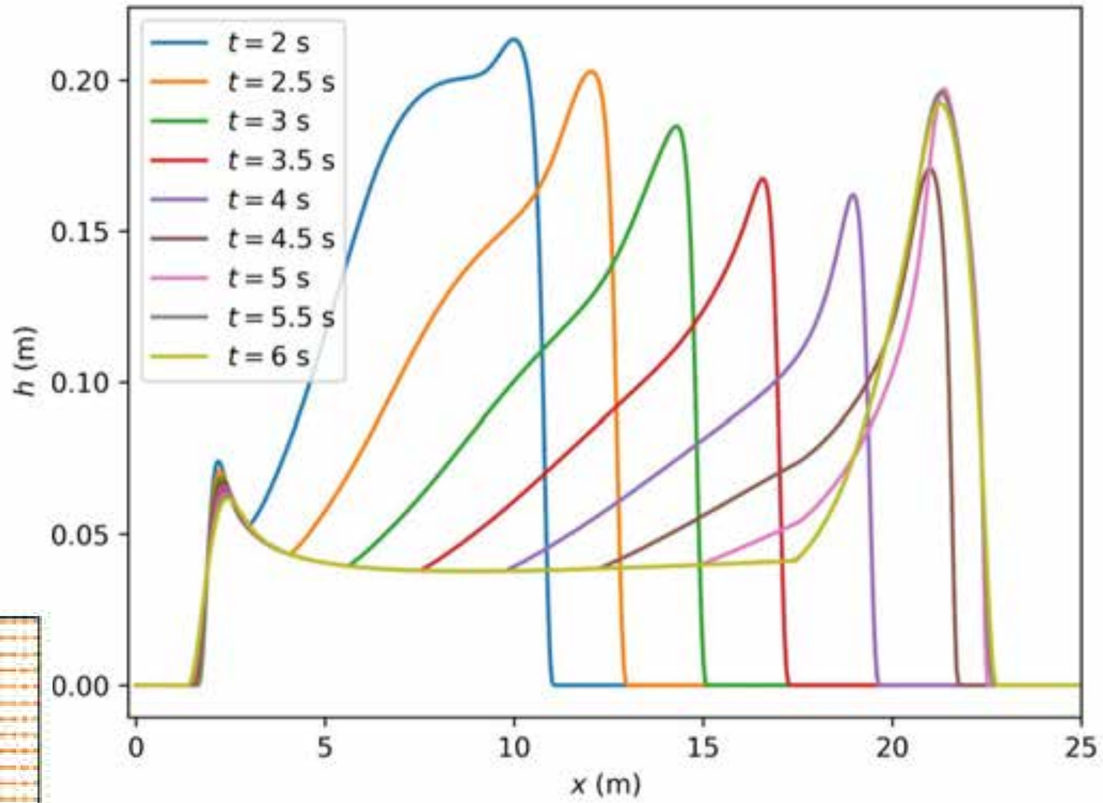
Stopping mechanism

$\tau_c = 100$ Pa

Unyielded zones ($\tau < \tau_c$):



Longitudinal profiles:

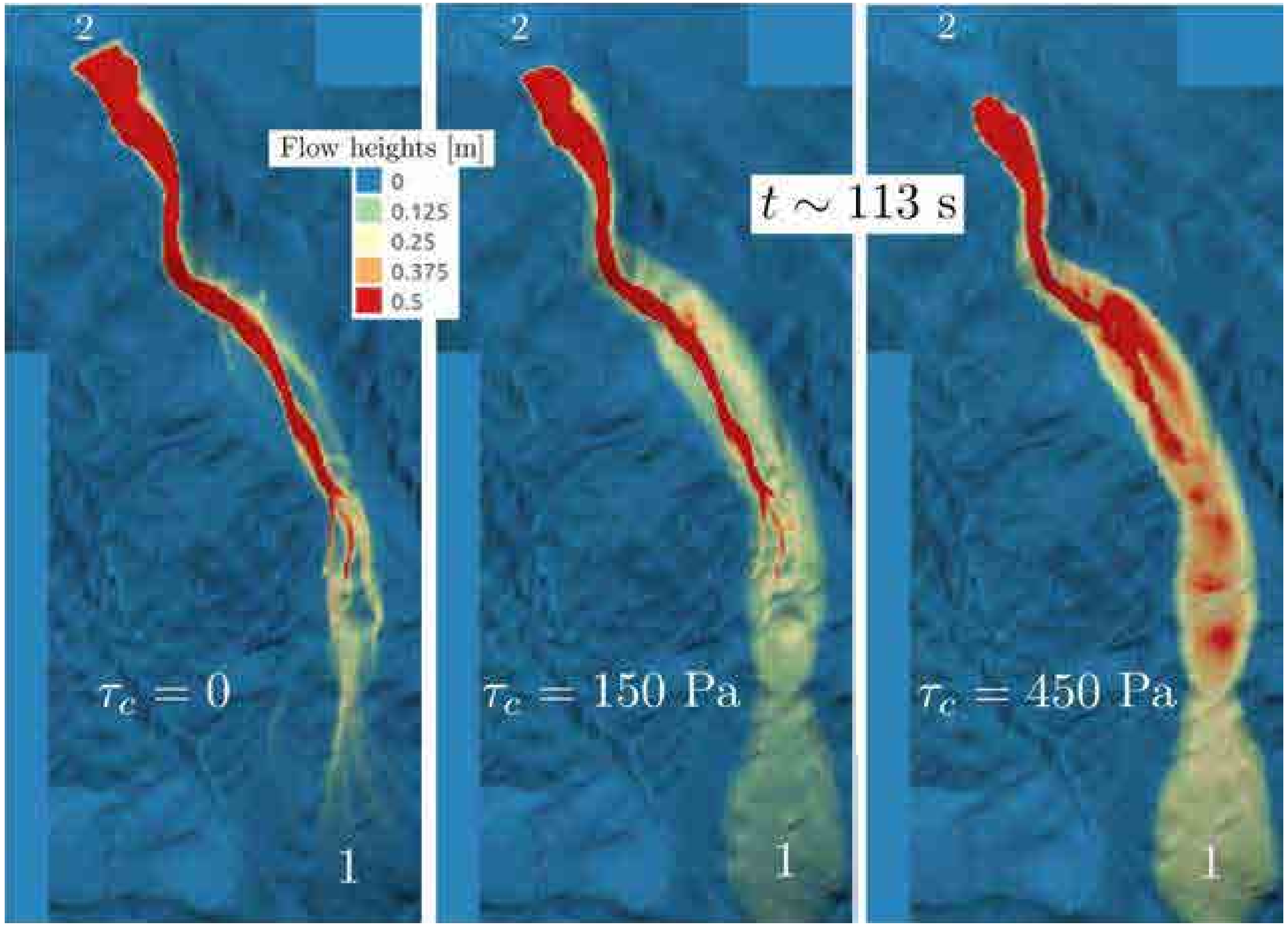


- Abrupt stopping ("freezing") of the front

❖ *Note pile-up mechanism*

Full-scale simulations of snow avalanches

Bourgeat avalanche track (Chamonix, France):



- Initial conditions:
  - Release area of about 175 000 m^2
  - $h_0 = 2.0$ m
- 10 m digital terrain model
- $\mu = 0.3,\ \xi = 2000$ m.s^{-2}
- $\tau_c = 0 - 600$ Pa

Flow heights during avalanche propagation:

- in the run-out zone (debris fan), upstream of the storage basin and Bourgeat dam
- nearly two minutes after avalanche release

➢ Cohesive flow induces much longer tails

Note the significant time lag between Voellmy model flow and cohesive flows

Forces on obstacles

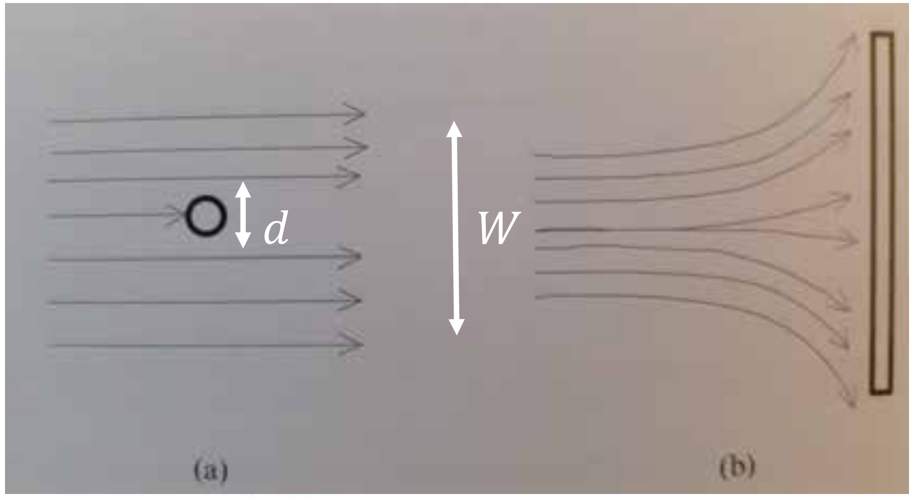
Faug (EPJE, 2015): **obstacles immersed in (dry) granular flows**

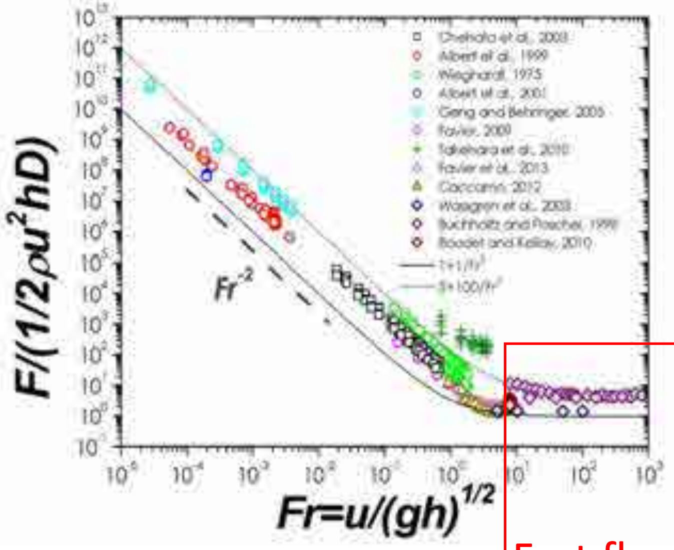
Fast flows (*inertial* regime)

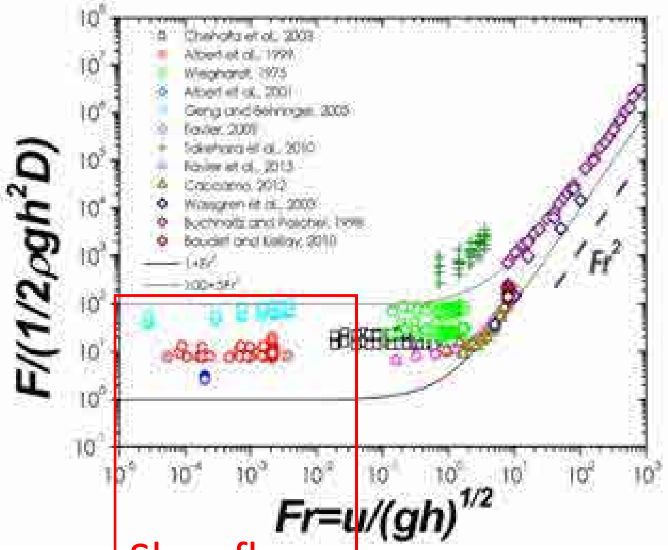
$$F = \boldsymbol{C_D} \frac{1}{2} \rho u^2 S$$

Slow flows (*gravitational* regime)

$$F = \boldsymbol{k} \, (\rho g h \cos\theta) S$$





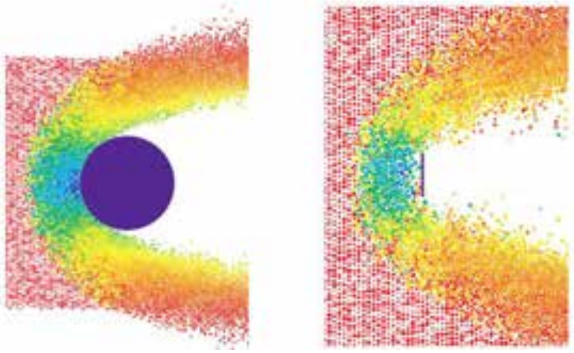


Fast flows

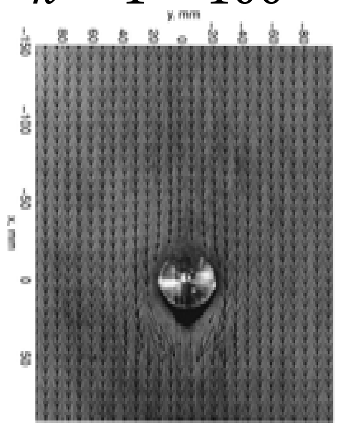
$C_D = 1 - 5$

Slow flows

$k = 1 - 100$

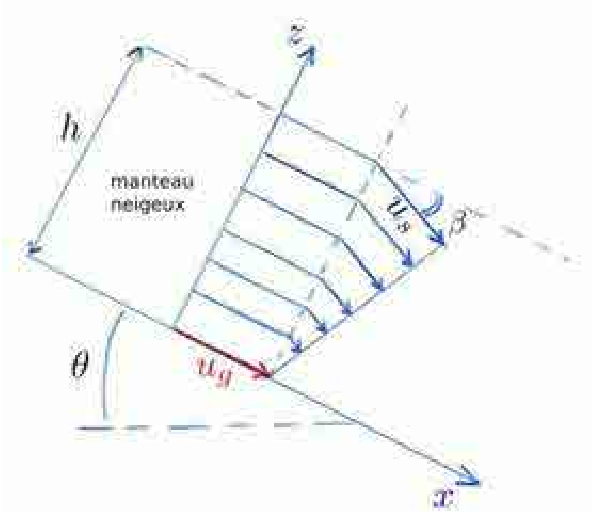


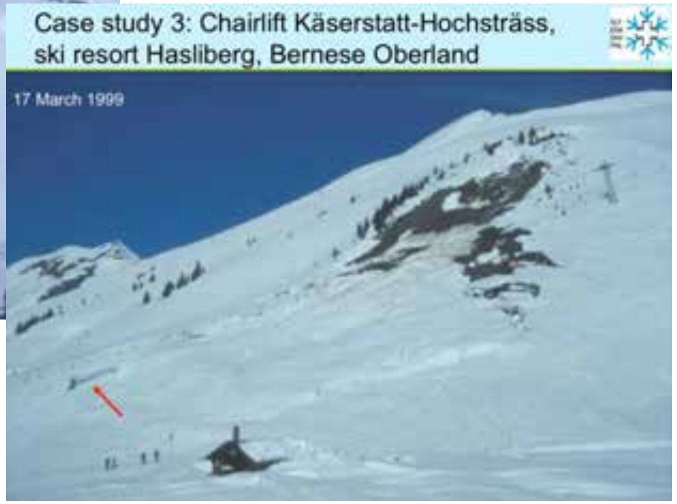
- Fast cold (dry) avalanches



- Slow cold (dry) avalanches
- Wet avalanches
- Snowpacks

Reptation processes in wet snowpacks

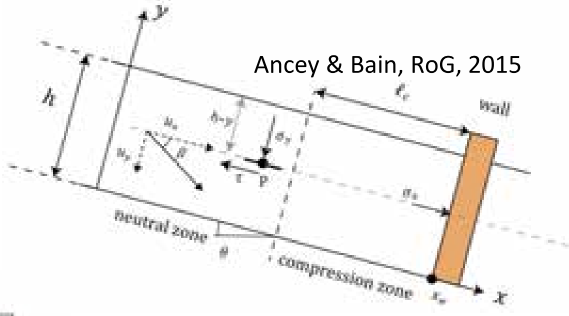




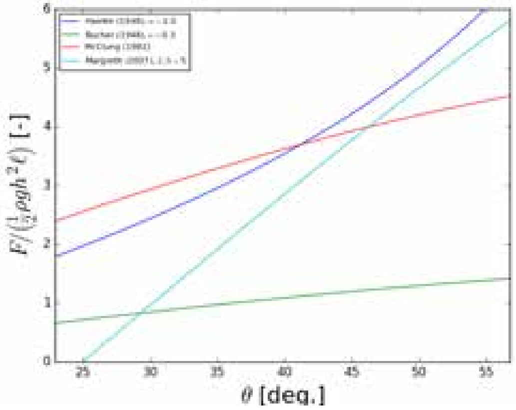
S. Margreth, SLF

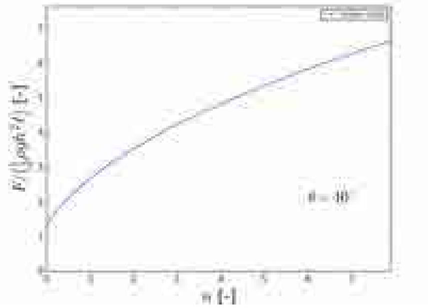
- wall-like obstacles

$$n = \frac{u_g}{u_s - u_g} = \frac{1}{\frac{u_s}{u_g} - 1}$$



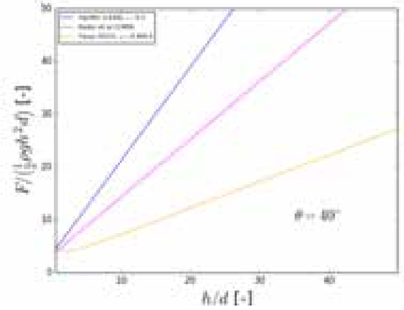
Ancey & Bain, RoG, 2015



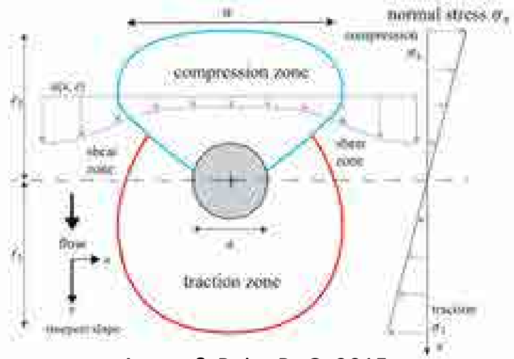


Faug, rapport DGPR 2020

- slender obstacles



Faug, rapport DGPR 2020



Ancey & Bain, RoG, 2015

Conclusions

- New challenges entailed by increased prevalence of wet snowpacks:
  - *Evolution of avalanche processes (trajectories, transitions, forces, etc.) and induced risks*
  - *Protection of infrastructures against creep and sliding processes*

- Need to improve knowledge on wet snow rheology in quasi-static and inertial flow regimes
  - *Difficulty of performing small-scale rheometrical experiments (granulation, etc.)*
  - *Interest of combining modelling, experiments and field measurements at different scales*

- Addition of cohesion is key to capture specific features of wet snow flows
  - *Flowing behavior (slower velocities, long tails, topography control)*
  - *Stopping mechanisms*
  - *Deposit morphology (concentration, levées)*

- To go further:
  - *Improve cohesion parameterization*
  - *Addition of a viscous contribution (quasi-static regime)*
  - *Relations with material properties (T, LWC, etc)*
  - …