Multi-scale modelling of weak snow layer mechanical behavior

Guillaume Chambon[1]

avec les contributions de :

Johan Gaume[3,4], Pascal Hagenmuller[2], Evgeny Podolskiy[5], Isabel Peinke[2], Tijan Mede[1], Mohamed Naaim[1], Nicolas Eckert[1], François Nicot[1], Alec van Herwijnen[3], …

[1]IRSTEA, Grenoble
[2]CEN, Grenoble
[3]SLF, Davos
[4]EPFL-CRYOS, Lausanne
[5]Hokkaido University

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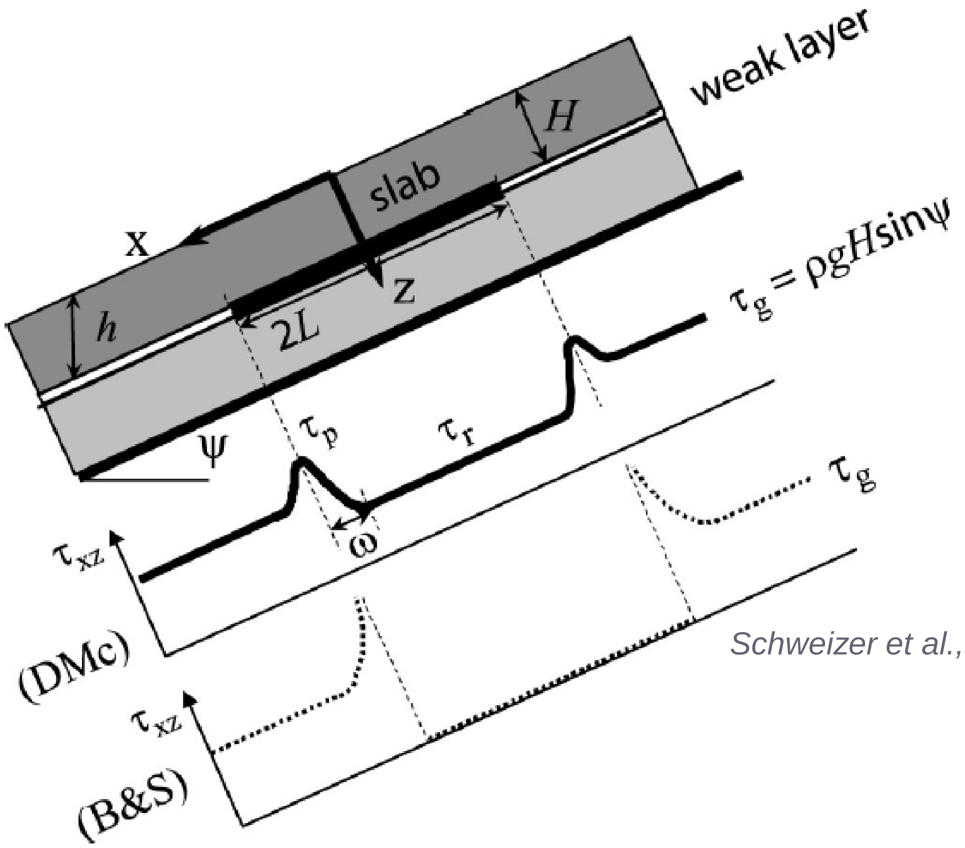
Slab avalanche release as a multi-scale problem

weak layer (WL):

variety of microstructures!

- Slab avalanches initiate through WL failure
  - ➢ shear failure propagates in the weak layer
  - ➢ tensile rupture of the slab is a secondary process

Super-weak zones



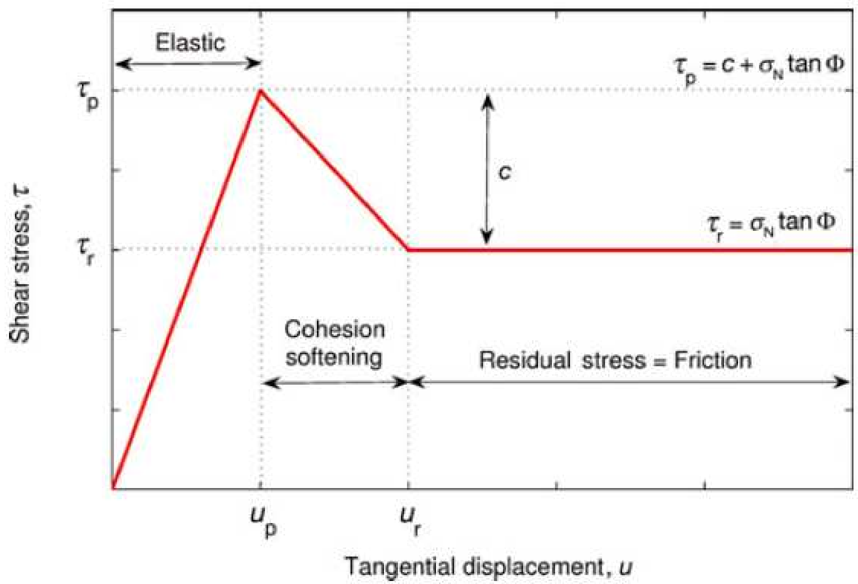
$$a_c \propto \left(\frac{K_{IIc}}{\tau_g}\right)^2$$

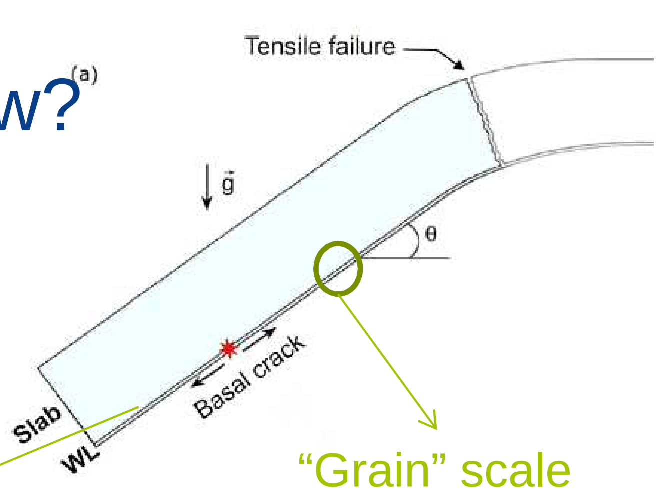
Schweizer et al., RG, 2013

- Slab elasticity induces stress concentration on WL defects
  - stability knock-down effect
  - critical crack length for self-propagation

Multi-scale constitutive law?

Slope scale





"Grain" scale

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- Interface law:
  - ➢ peak stress (strength): τ_p
  - ➢ residual stress (softening): τ_r
  - ➢ characteristic displacement: u_r

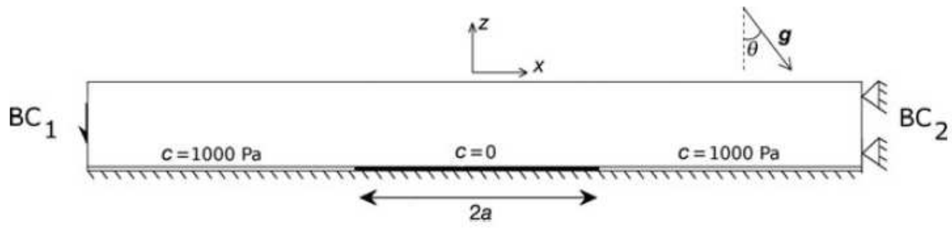
?

- Complex microstructure
- Normal collapse

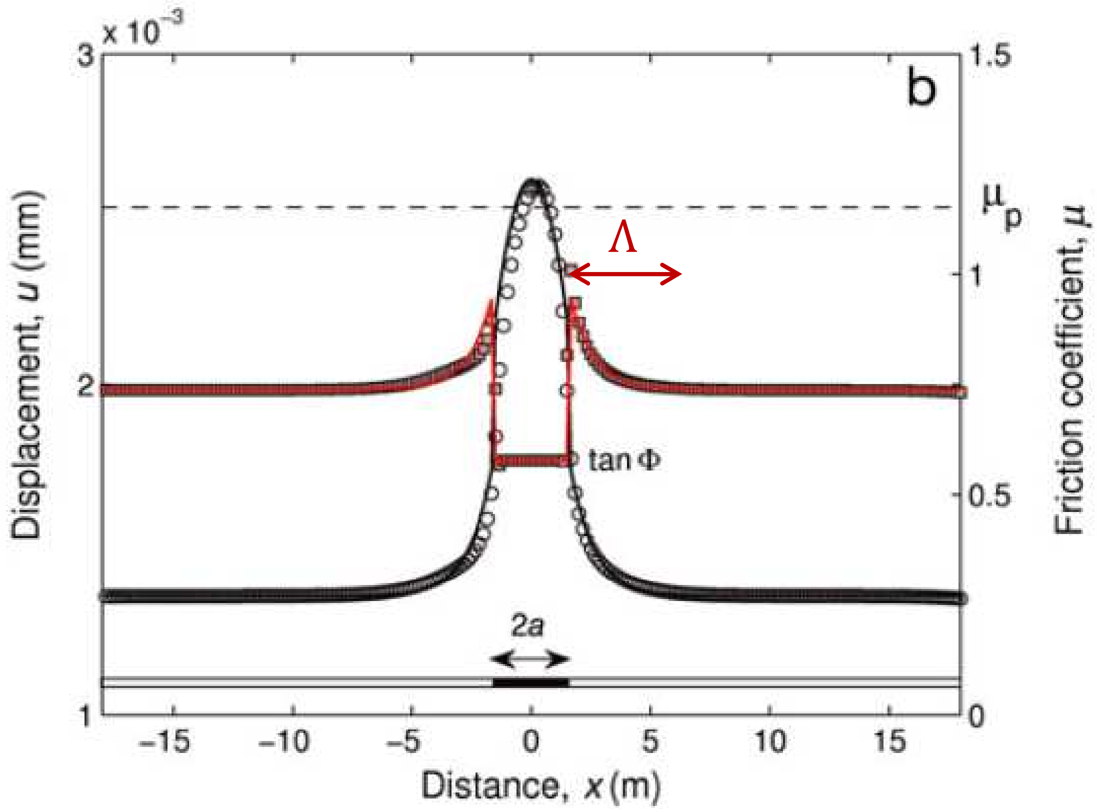
- Direct experiments on WL are difficult !

Gaume et al., JoG, 2013

A bi-layer system



- Elasticity of both slab and WL contribute to stress redistribution at crack tip



- Characteristic length of the system:

$$\Lambda = \sqrt{\frac{E' h h_{WL}}{G_{WL}}}$$

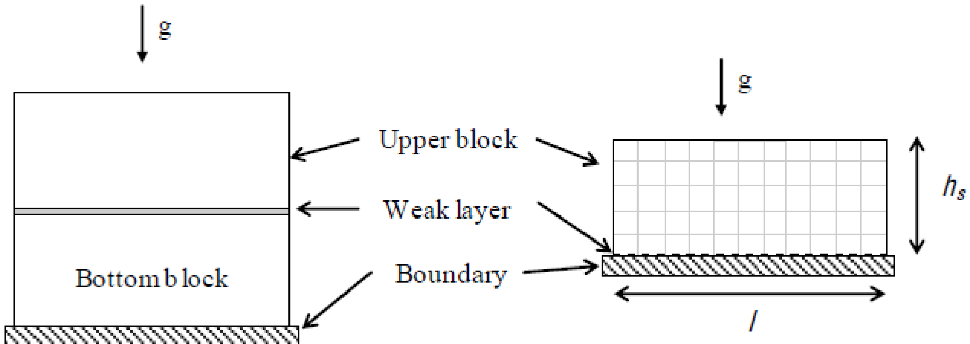
- ➢ stress concentration at crack tip
- ➢ critical crack length: $a_c = \Lambda \left(\frac{\tau_p}{\tau_g} - 1 \right)$
- ➢ crack interactions

Gaume et al., JoG, 2013

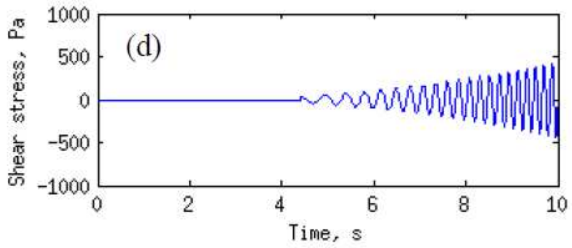
WL strength: influence of normal load

shaking plate experiments

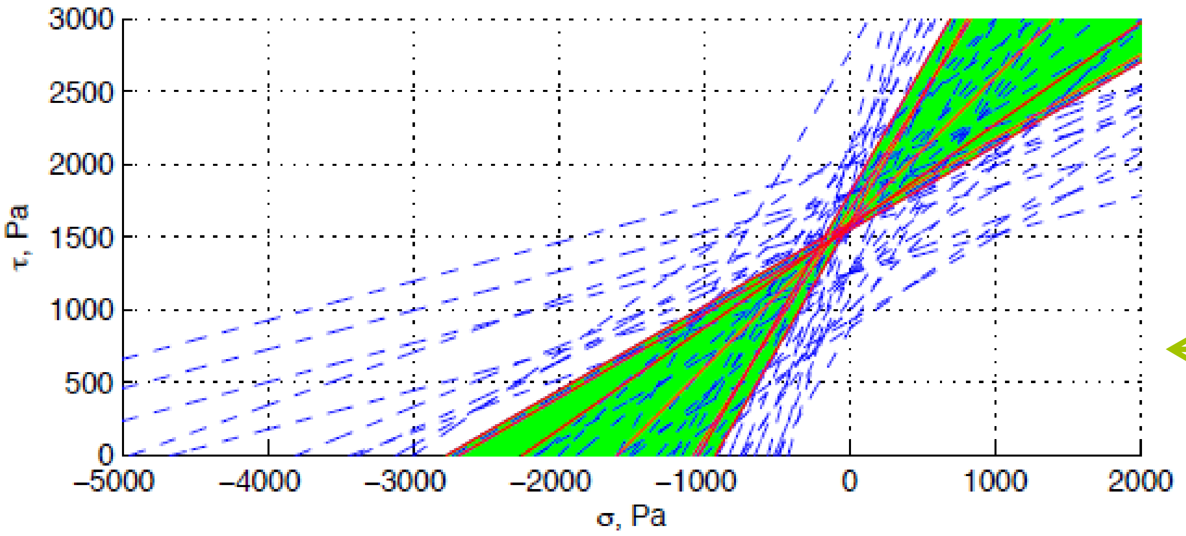
Podolskiy et al., JoG, 2010



FEM modelling



inverse analysis

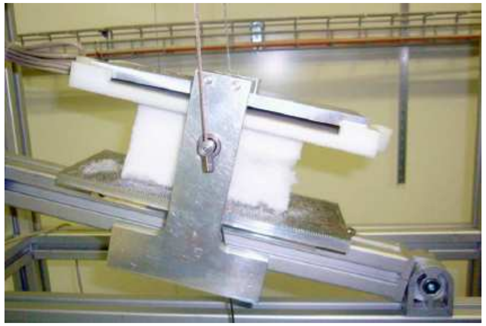


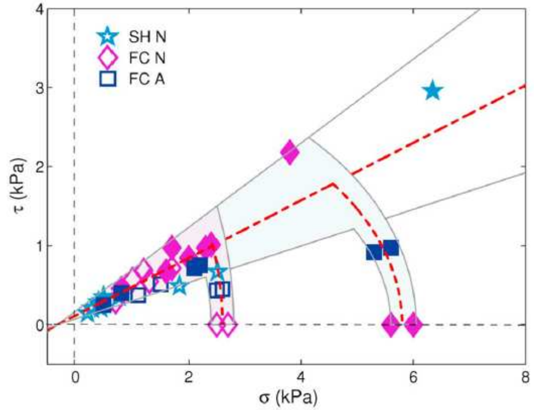
- Mohr-Coulomb failure envelope: $\tau_p = c + \sigma \tan \phi$
  - $\phi \approx 10 - 40°$
  - frictional behavior: cohesive granular material

Podolskiy et al., NHESS, 2015

A closed failure envelope

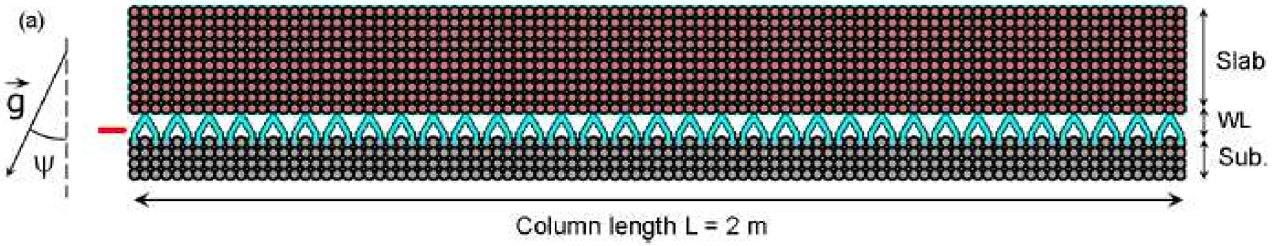
mixed-mode loading experiments



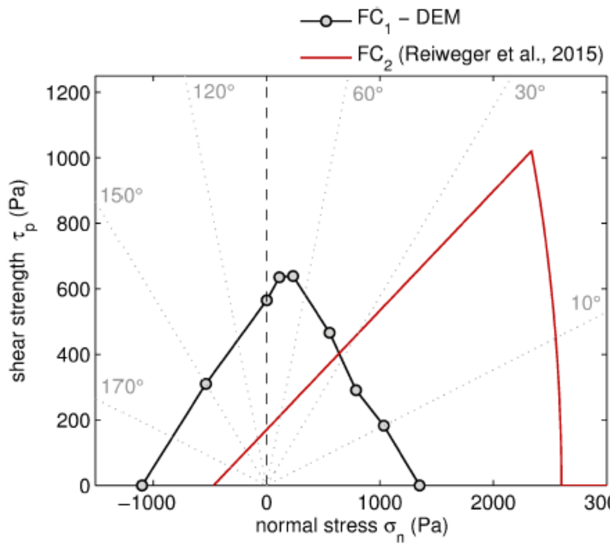


Reiweger et al., GRL, 2015

“academic” DEM simulations

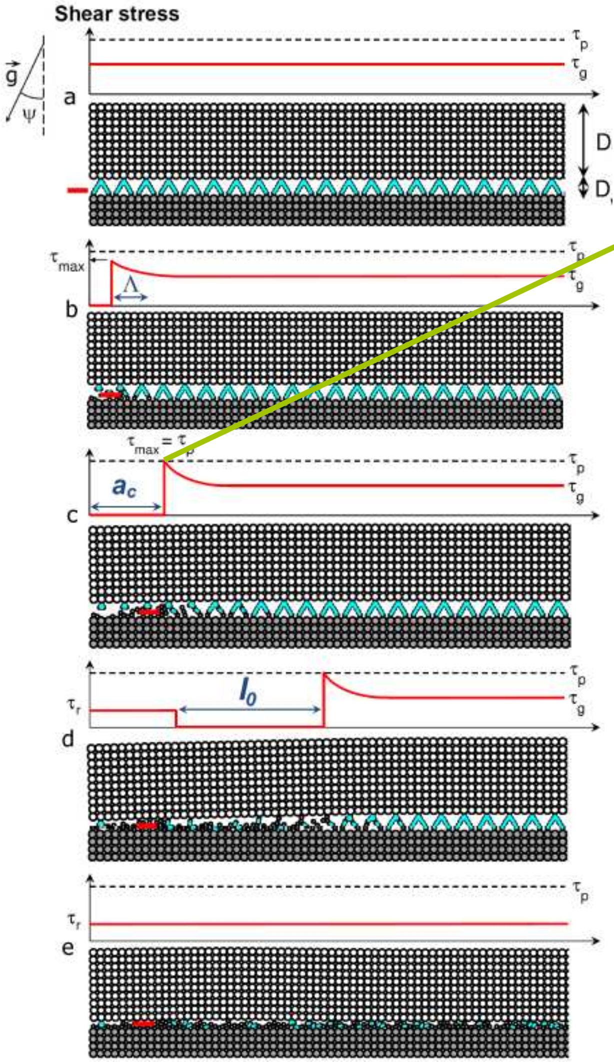


- Mohr-Coulomb-Cap envelope
  - ➢ compression failure
  - ➢ normal collapse
  - ➢ strong influence of microstructure



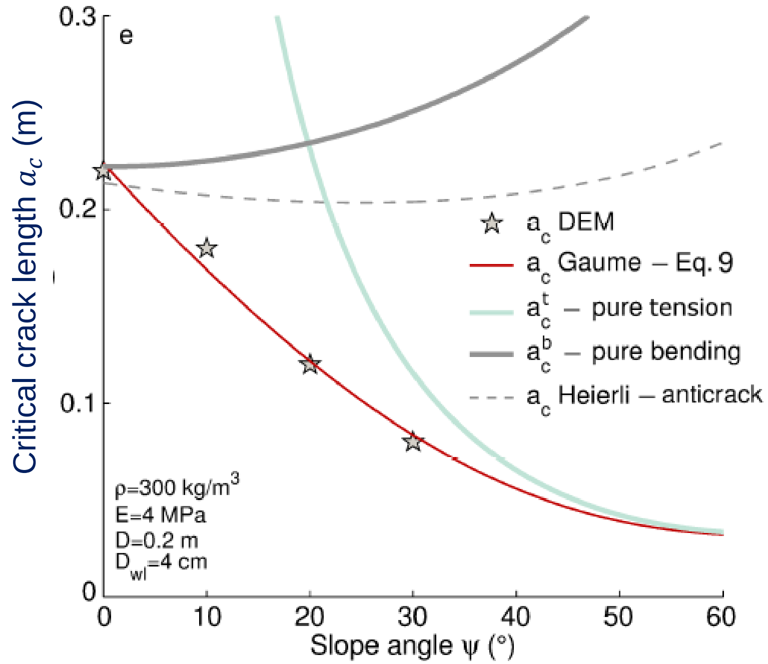
Gaume et al., TC, 2015

Is normal collapse important?



$$\tau_{max} = \tau_g \left(1 + \frac{a}{\Lambda}\right) + \frac{1}{2}\sigma \left(\frac{a}{\Lambda}\right)^2$$

- WL collapse induces **slab bending**:
  - increases shear stress at the tip



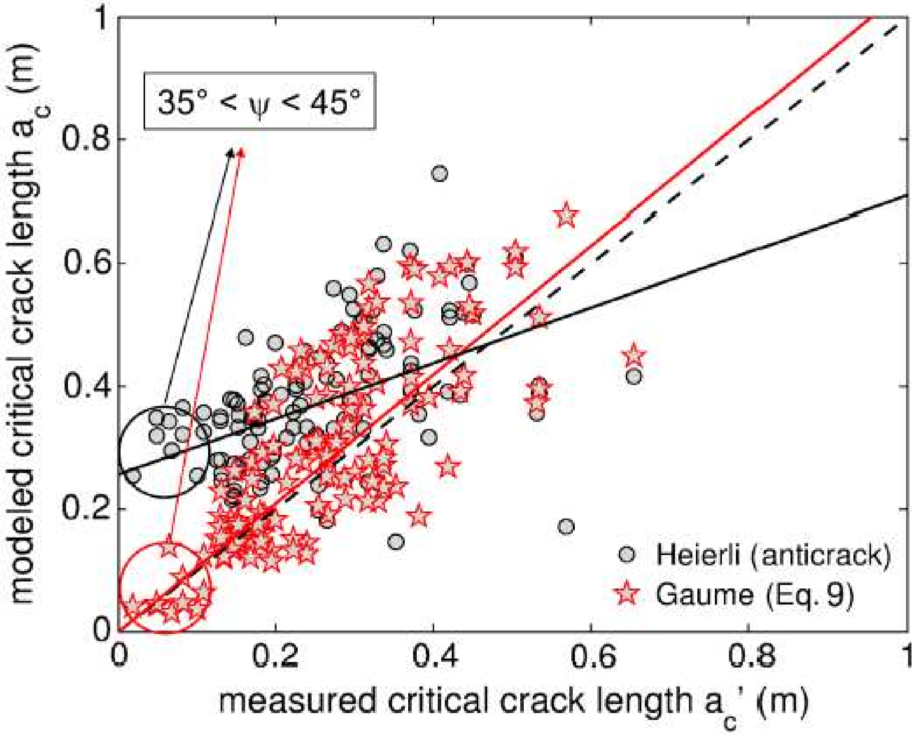
- For $\psi > 30°$: Mohr-Coulomb criterion is sufficient

Gaume et al., TC, 2016 (subm)

On the field

Propagation saw tests

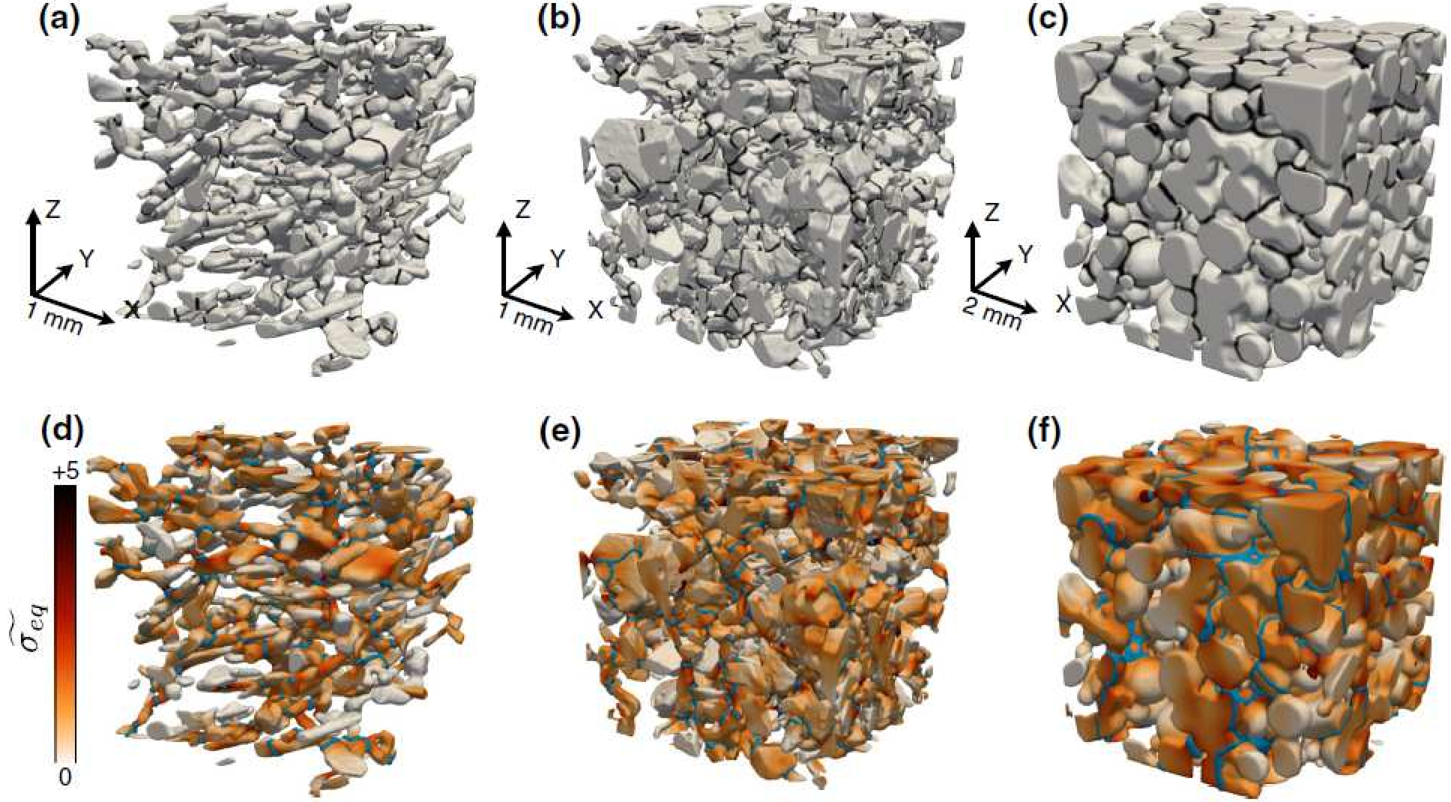
- direct measurement of critical crack length for different slope angles



- Supports the proposed model for τ_{max}
- Good agreement for $\psi > 30°$
  - ➢ Mohr-Coulomb criterion
- Larger dispersion for small slope angles
  - ➢ influence of WL microstructure

Microstructure-based modelling

- Use of µ-tomography images as inputs to numerical simulations

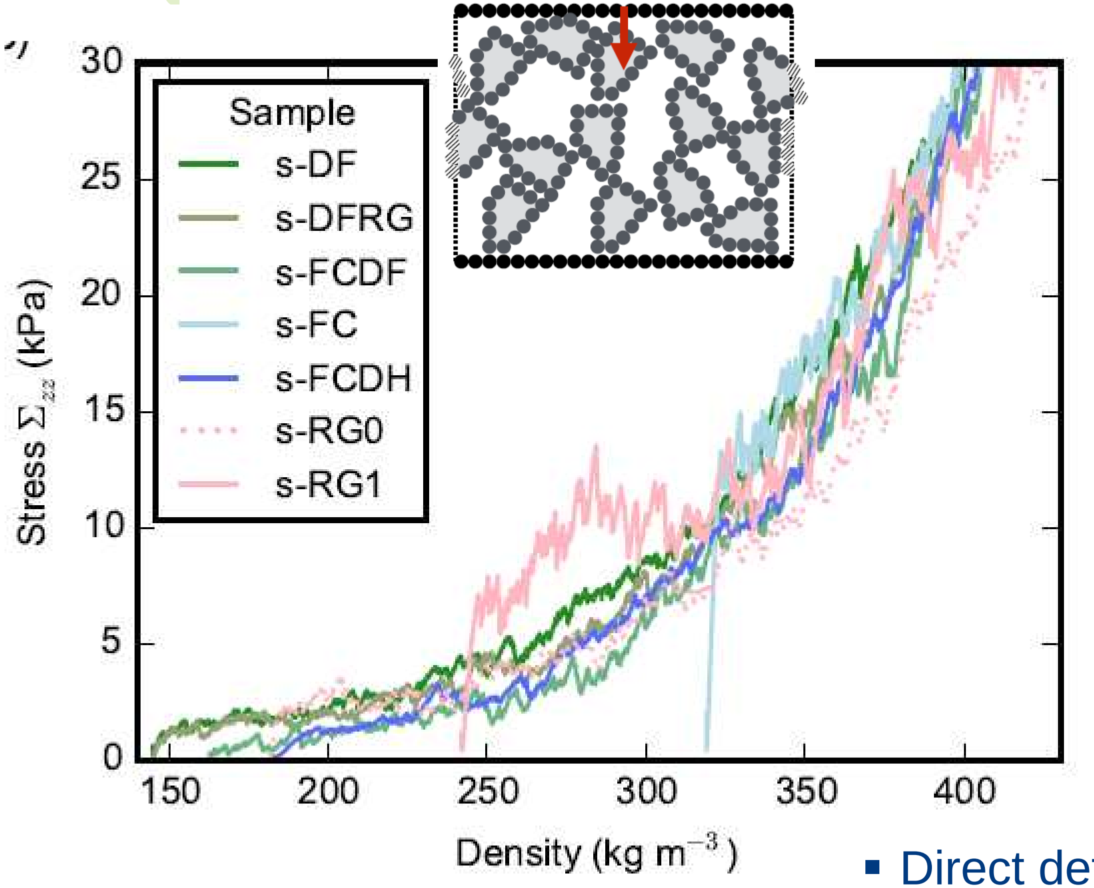


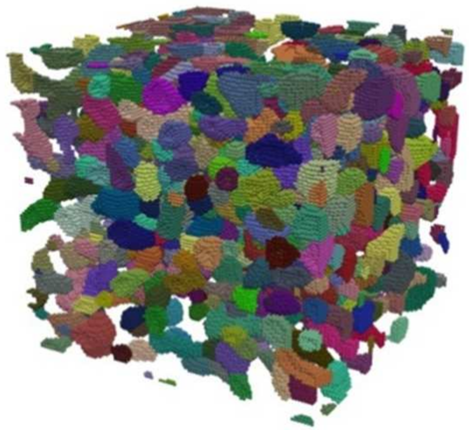
- Definition of mechanically-relevant **grains** in the ice-matrix
  - microstructure rearrangement (granular approach)
  - FEM validation

Hagenmuller et al., Granul. Mat., 2014

Microstructure-based DEM

DEM oedometric tests



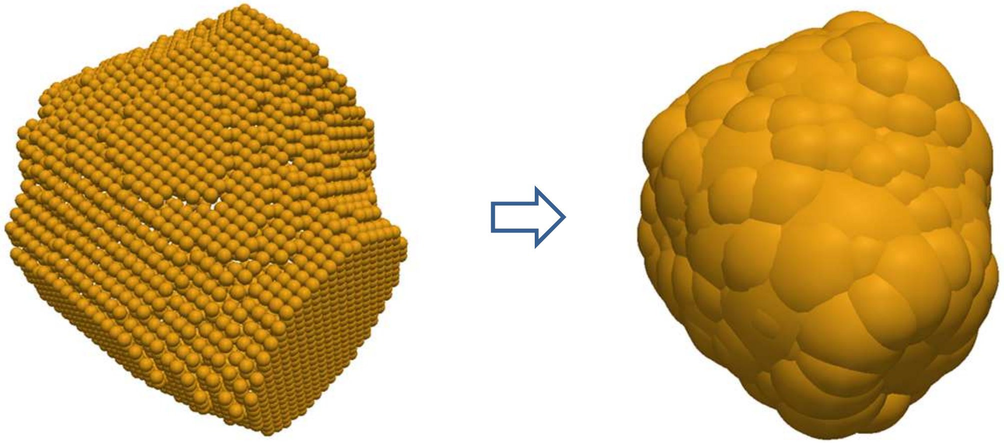


- Direct determination of mechanical response of “real” snow samples
  - primary role of density
  - influence of snow type

Hagenmuller et al., TC, 2015

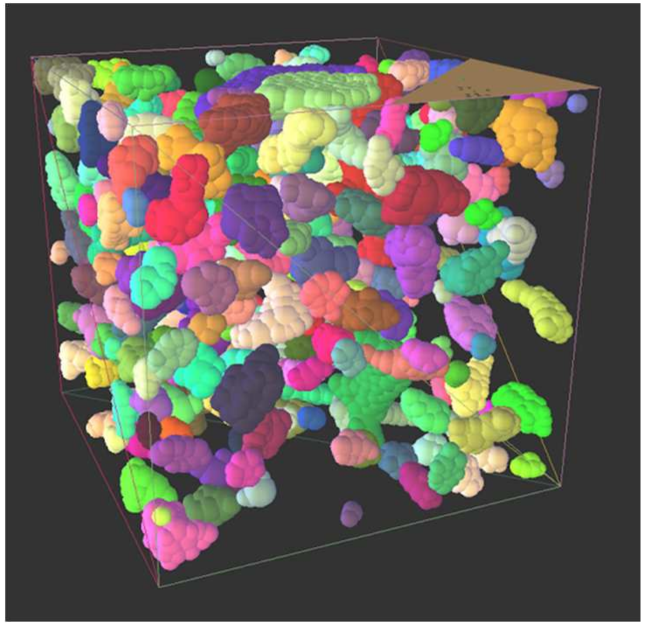
Ongoing work: numerical experiments

PhD Tijan Mede (Irstea – CEN)



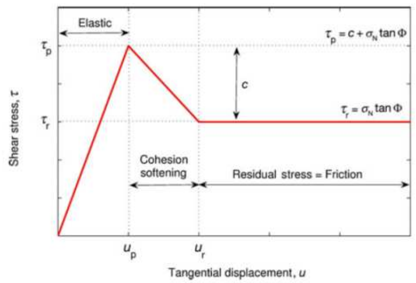
2683 spheres

223 spheres



- More efficient approximation of grain shape

- Systematic exploration of WL constitutive relation
  - softening
  - collapse

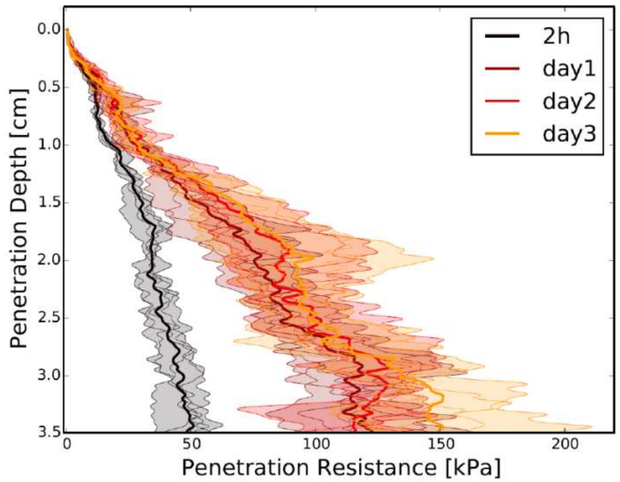


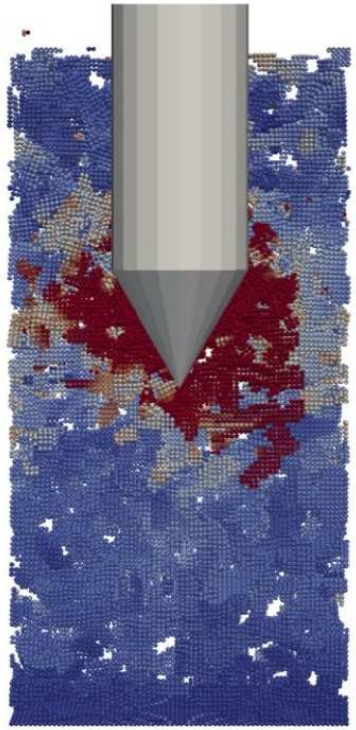
Ongoing work: comparison with experiments

PhD Isabel Peinke (CEN – Irstea)

Micro-penetrometer tests (SMP)

DEM model

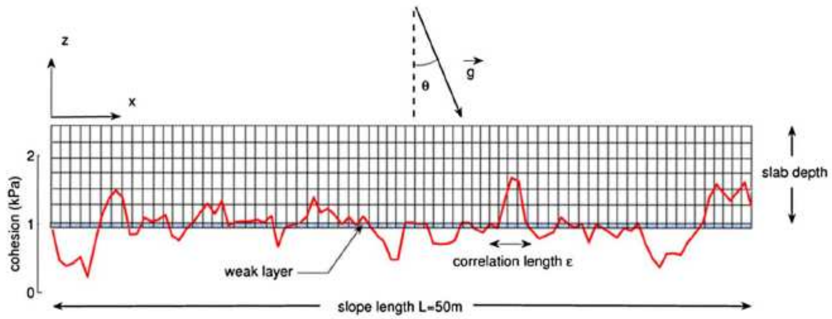




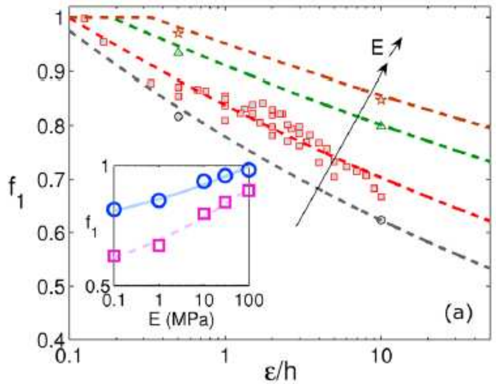
- Validation of DEM approach
  - force signal
  - microstructure evolution (µ-tomo)

Spatial heterogeneity

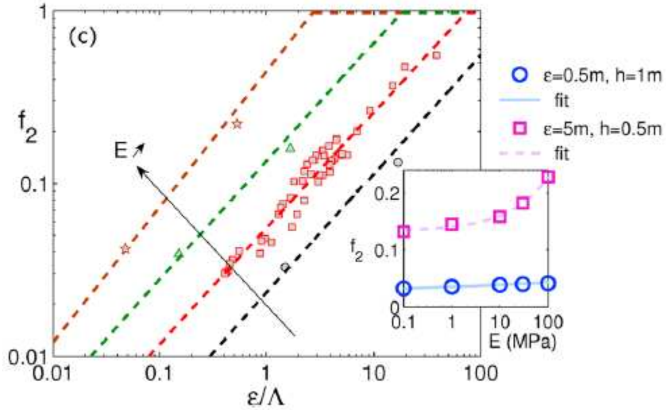
FEM model with random distribution of WL strength



- Strong interplay between heterogeneity and elastic effects
  - knock-down effect: $c_{app} = f_1 \langle c \rangle$
    (generalization of super-weak zones)



  - heterogeneity smoothing: $std_{app} = \sqrt{f_2}\, std_c$
    (depends on ratio ε/Λ)

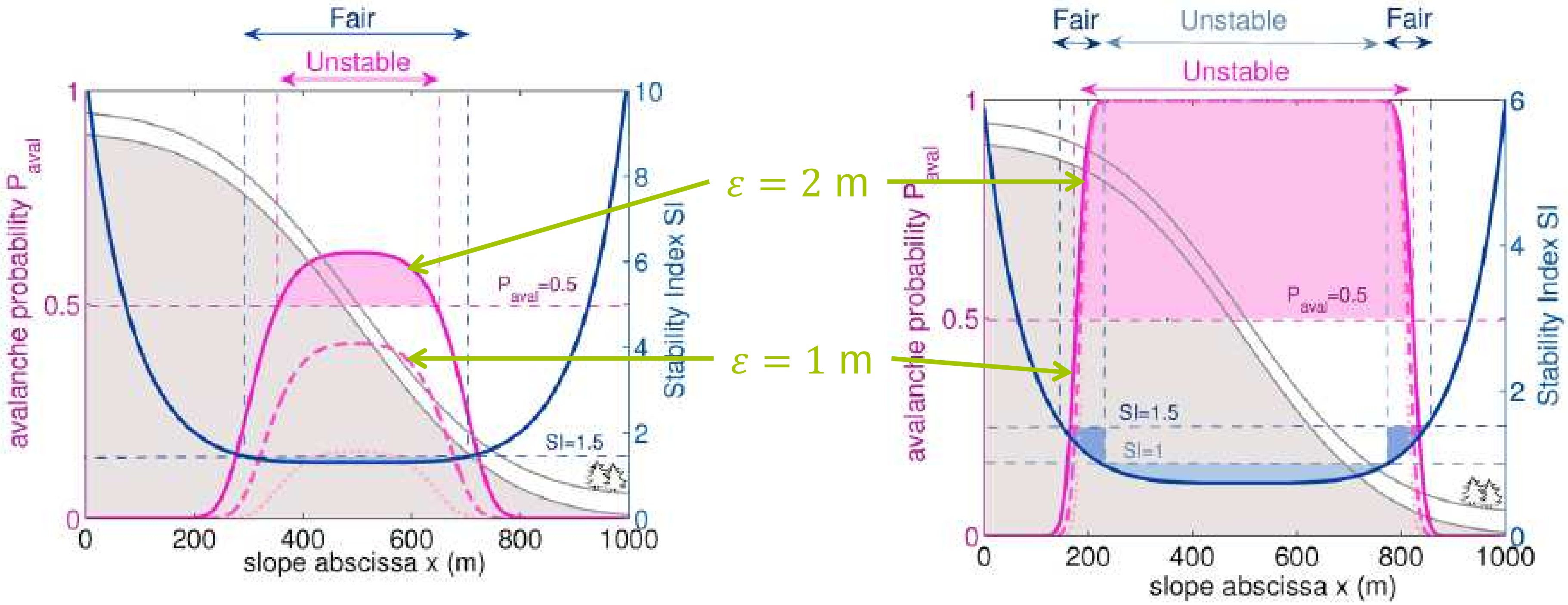


Gaume et al., JGR, 2014

Avalanche propensity

$\langle c \rangle = 0.8$ kPa

$\langle c \rangle = 0.5$ kPa



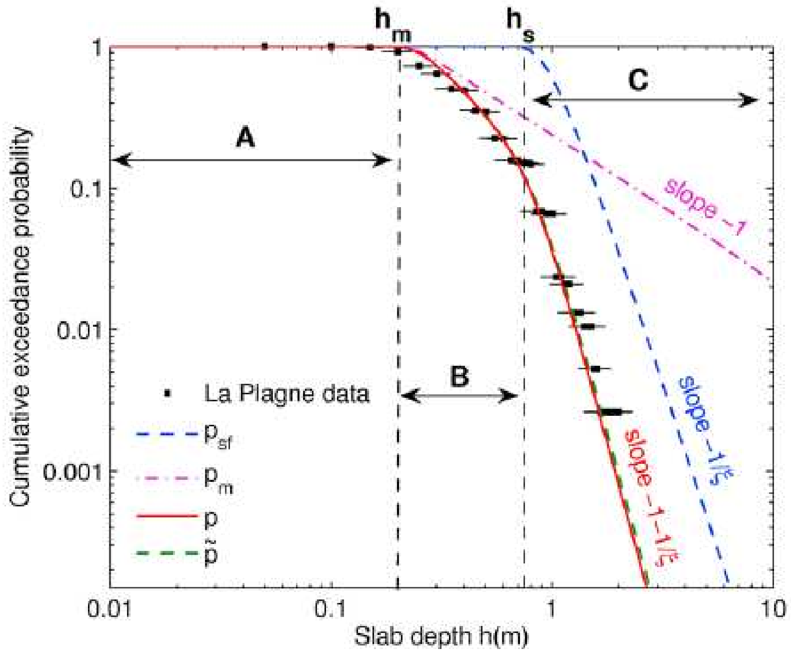
- Both **WL strength** and **heterogeneity correlation length** play a critical role on avalanche probability

Gaume et al., JGR, 2014

“Operational” outcomes

Slab depth distribution

- accounting for coupling with snowfall distribution



Avalanche release area

- accounting for coupling with slab tensile failure

Finally, the results of the presented model suggest that the majority of the releases would be full slope, i.e., not influenced by WL heterogeneity, especially for high densities. Hence, the potential extent of slab avalanche release areas will be controlled by topographical and geomorphological features of the path such as rocks, trees, ridges or local curvatures induced by the terrain and the snow cover distribution.

➢ Relevance of geomorphic indicators

- Justify research efforts to improve knowledge on WL (and slab) mechanical behavior!
- Towards coupled multi-scale mechanical models

Gaume et al., GRL, 2012 ; TC, 2014

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