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Physics of slip triggering: from DEM to friction into granular gouges

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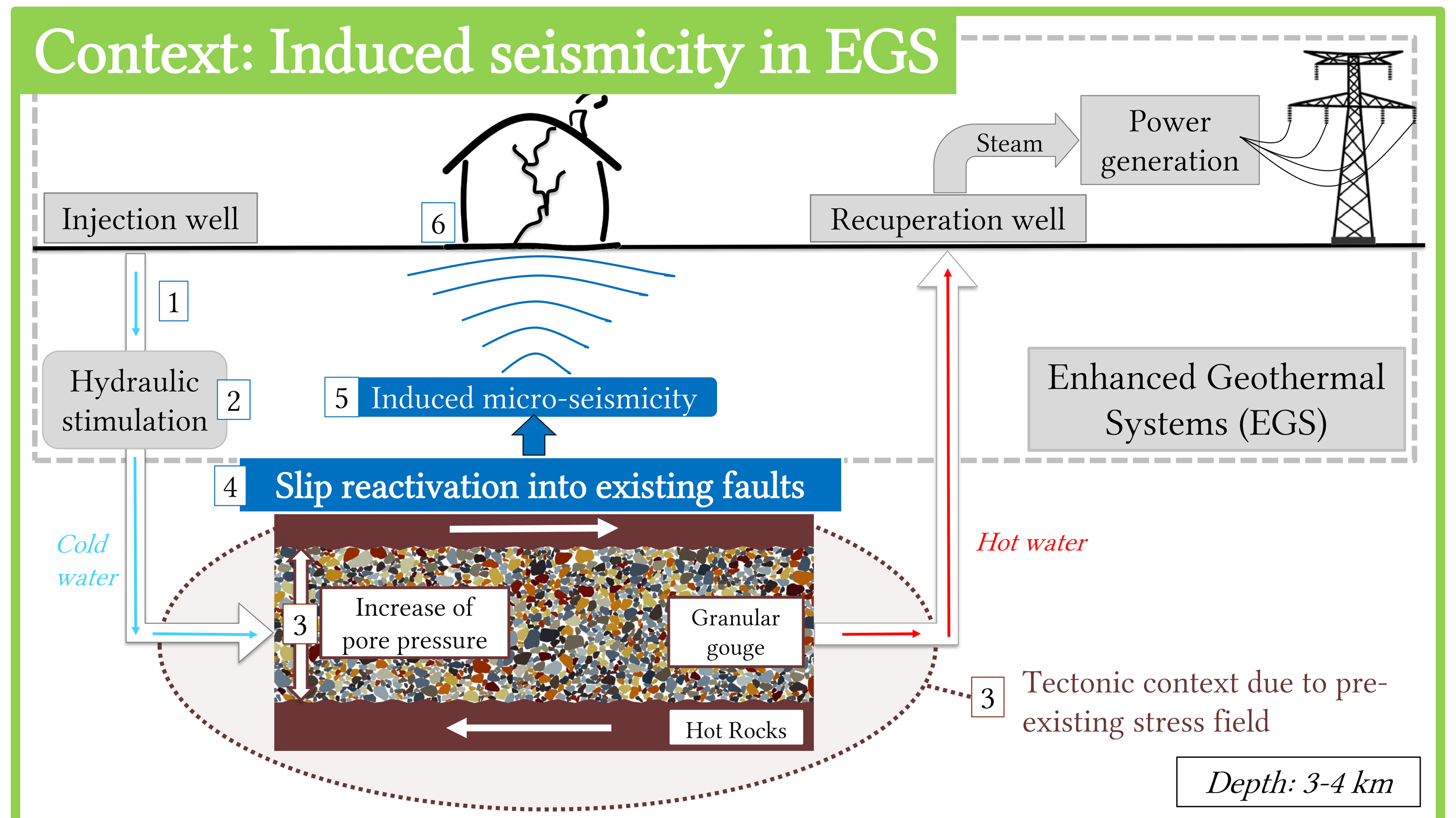
Context: Induced seismicity in EGS



Objective

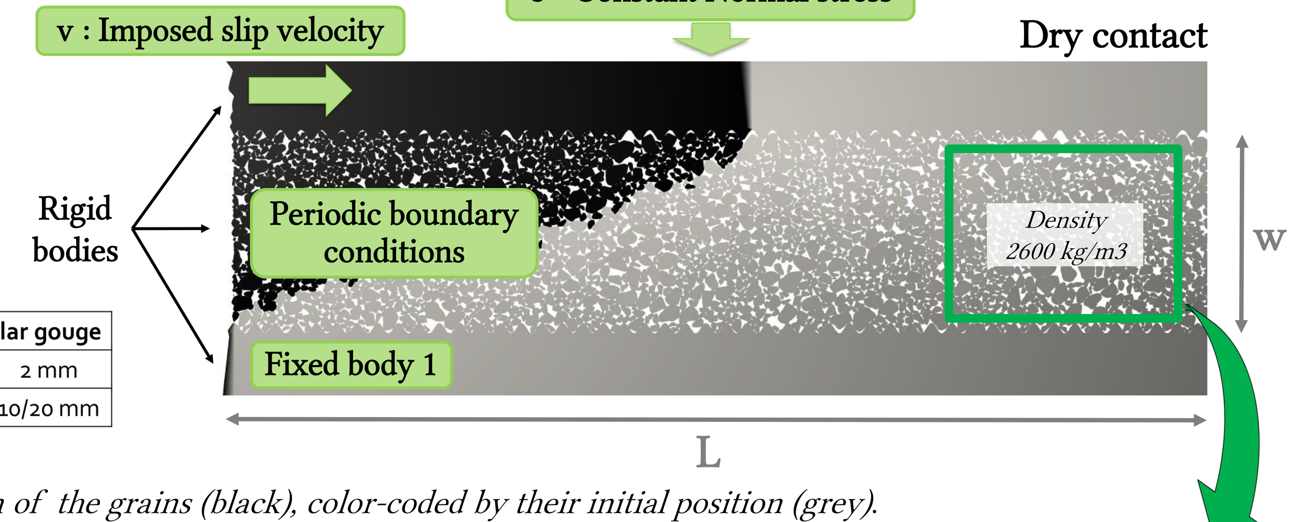
Slip triggering study of fault gouges by a micro-mechanical approach, using 2D DEM simulations.

DEM gouge simulation

Discrete Element Modelling (DEM) → Code MELODY [1](Mollon, 2016)

→ Multibody Dynamic

σ	40 MPa
v	1 m/s

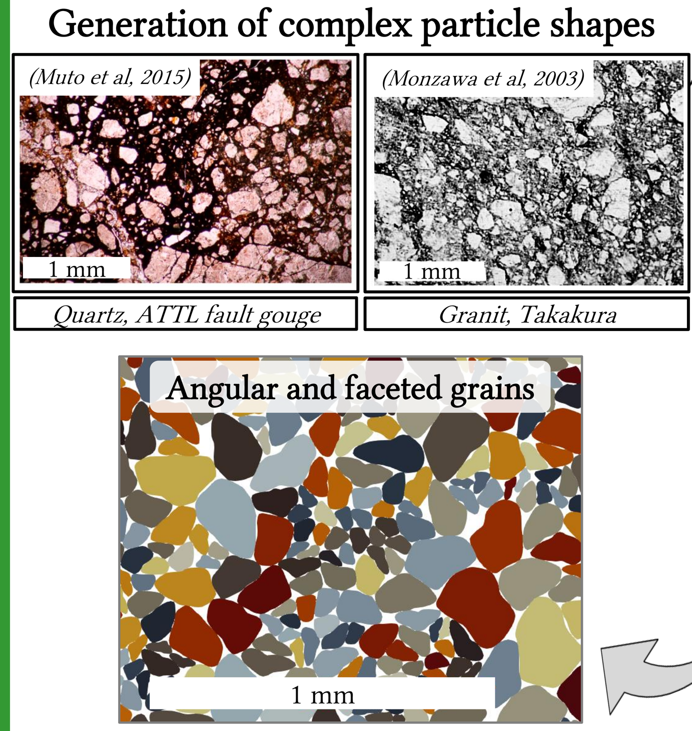


Initial granular gouge	
Width W	2 mm
Length L	10/20 mm

Final position of the grains (black), color-coded by their initial position (grey).

Particle generation

Generation of complex particle shapes



Code Packing2D [2](Mollon et al, 2012)

2D grains generator with "Fourier-Voronoi" method

1) Generation of a Voronoï Tessellation

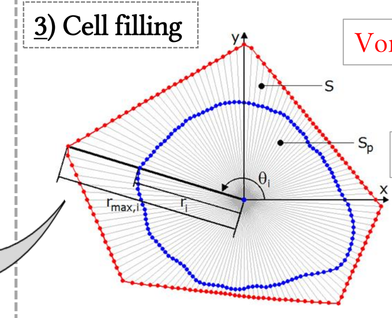
Bounded Voronoï tessellation + Inverse Monte-Carlo Method

2) Spectrum of morphologic descriptors: Fourier descriptors

Normalized amplitude for each harmonics n:

$D_n = \frac{\sqrt{A_n + B_n}}{r_0}$ ⟹ "Fourier descriptor"

3) Cell filling

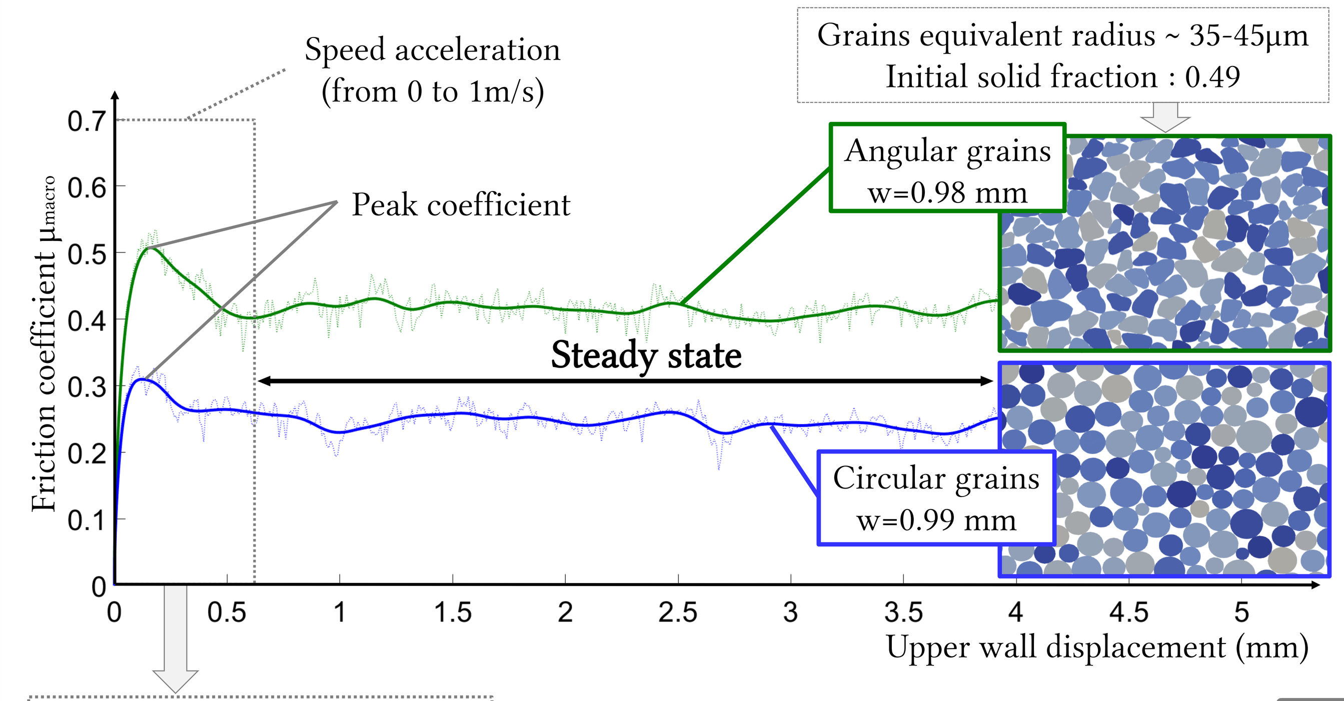


To reproduce given properties (size, orientation, target solid fraction...)

Perspectives

- To represent the stiffness of the surrounding rock (stiffness of the loading system). The gouge will be able to store energy until the slip triggering point, the main objective is to see the diffusion of the break.
- To represent the morphology of rock walls in order to see their influence on permeability.
- To simulate the role of water in slip triggering, adding pore pressure effects.

- Particle shape -



Angular grains exhibit resisting forces and friction coefficients on the upper wall higher than those found for circular grains.

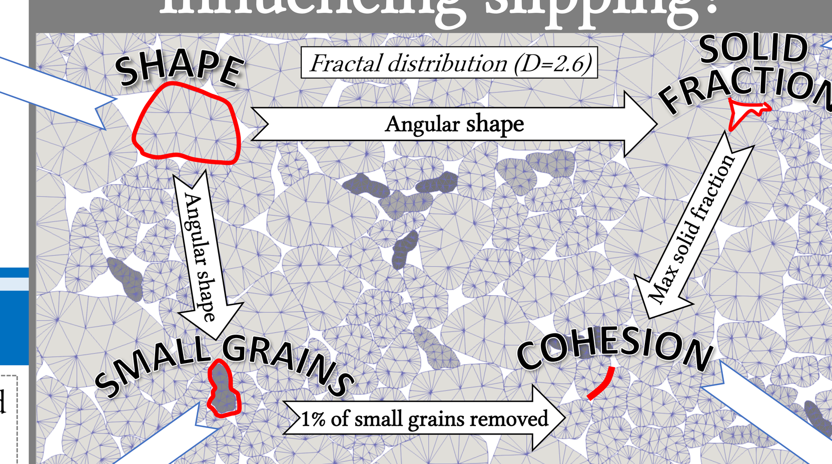
$$\mu_{macro}(t) = \frac{\sum F_{Tangential}(t)}{\sum F_{Normal}(t)}$$ (upper rock wall)

3D experiments with real grains ⇒ µ ~ 0,6 [3]*(Mair et al., 2002)*

Numerical angular grains ⇒ More realistic values (µ =0.5)

→We need to represent realistic morphology of particles!

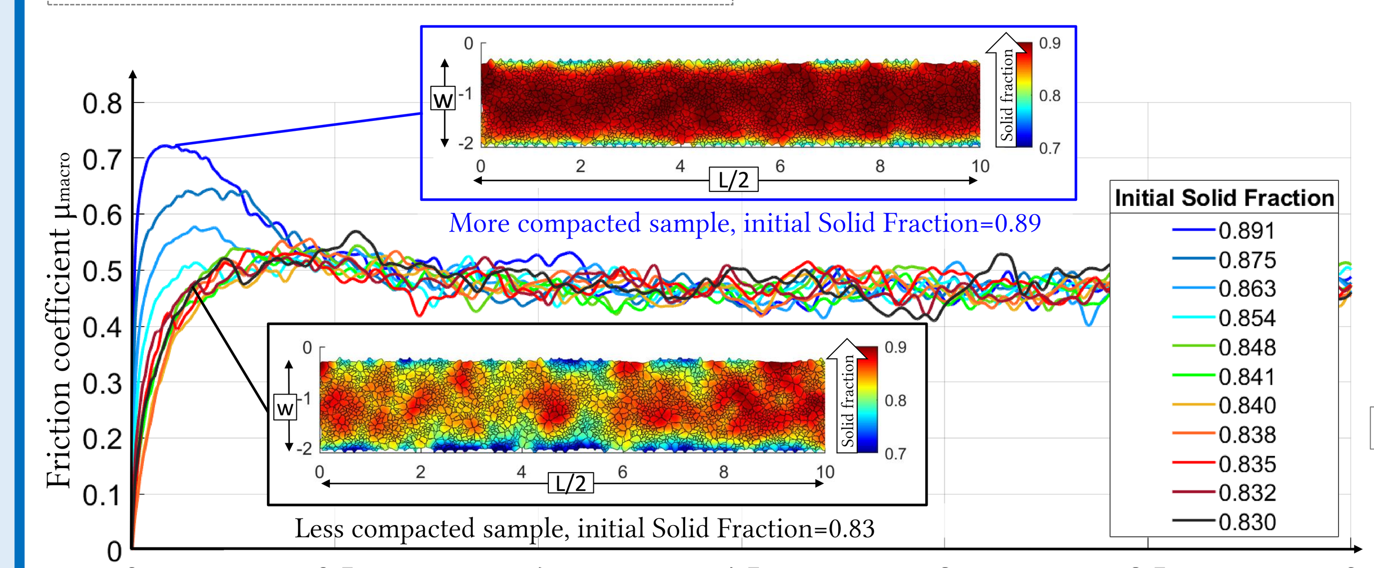
What are the parameters influencing slipping?

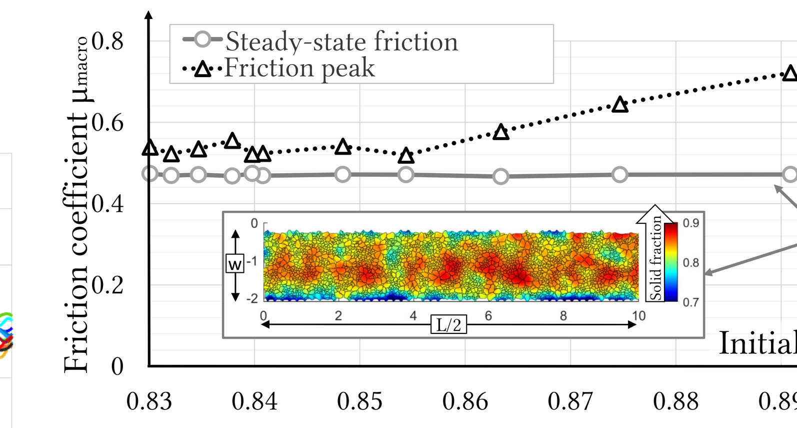


- Initial solid fraction -

« Damped Mohr-Coulomb » contact law

Deformations due to friction between the different bodies





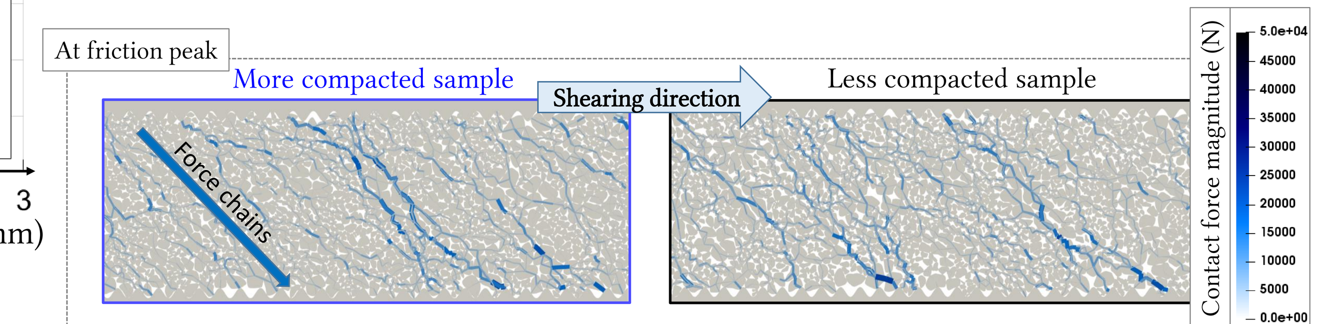
Increase of the initial compaction = more effort needed to disturb the initial grains assembly and to reach a steady state regime.

All the samples exhibit the same behaviour for a certain time of experiment.

Solid fraction

$F_s = \frac{S_{grains}}{S_{app}} = \frac{S_{grains}}{S_{grains} + S_{pores}}$

S=surface area

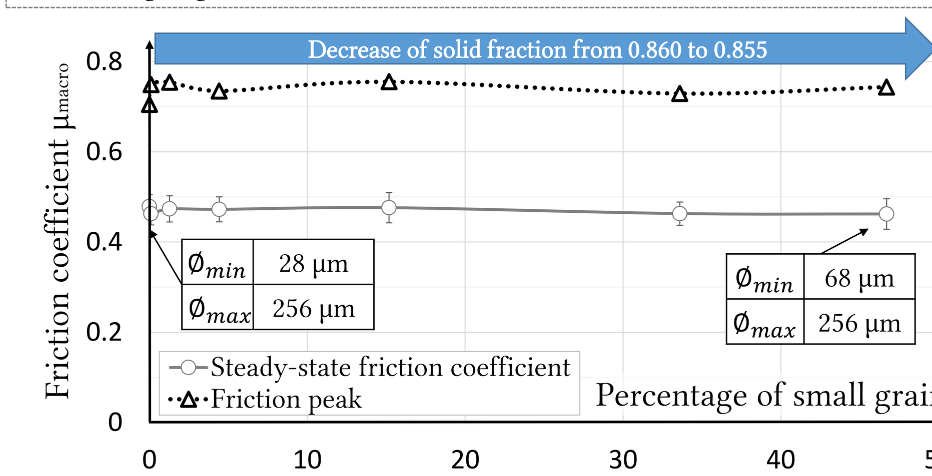


The number of force chains is more important in the less compacted sample. At the peak, the gouge already begun to dilate and grains are re-organising themselves. There is no force chain passing through the smaller grains.

- **Slip triggering:** initial solid fraction of the sample is important, macroscopic behaviour can be different.
- **Active slip:** no need to know the solid fraction, behaviour is similar.

- Small particles (without cohesion) -

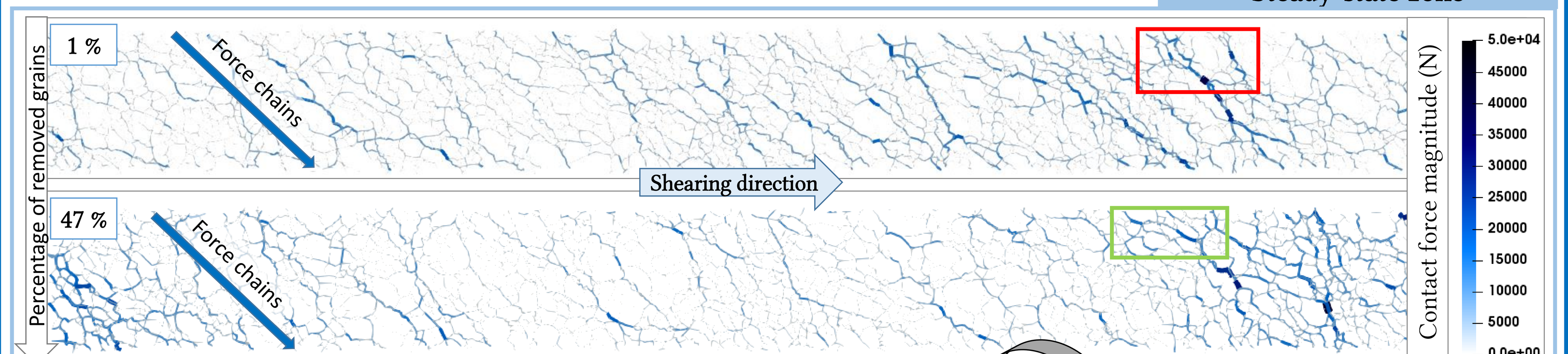
Influence of the removal of small grains. At constant initial Solid Fraction (0.89) and constant gouge width (2 mm)



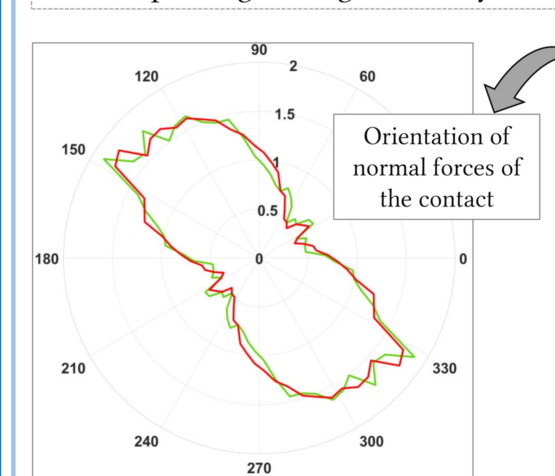
Small grains (without interparticular cohesion) do not seem to contribute to the mechanical behaviour of the gouge. Steady state friction and peak friction into the gouge have similar values for all samples.

The largest particles are more important in the determination of fault motion [4]*(Sammis et al, 1987)*

Steady-state zone

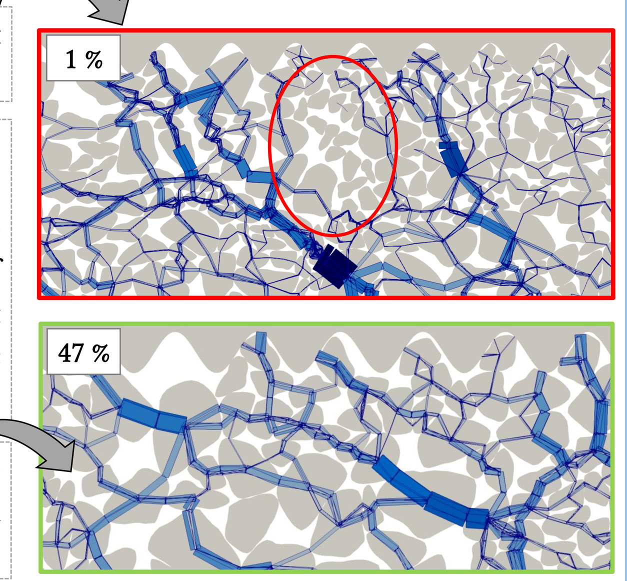


The larger chains of forces go through the larger grains. Almost no contact force is passing through the very small grains.



Normal contact force orientations have been plotted on a diagram to see the influence of small grains on the fabric of the sample. The removal of small grains doesn't seem to affect the main characteristic of the fabric when steady-state is reached.

The solid fraction decreases with the removal of small grains, leading to a more permeable gouge.

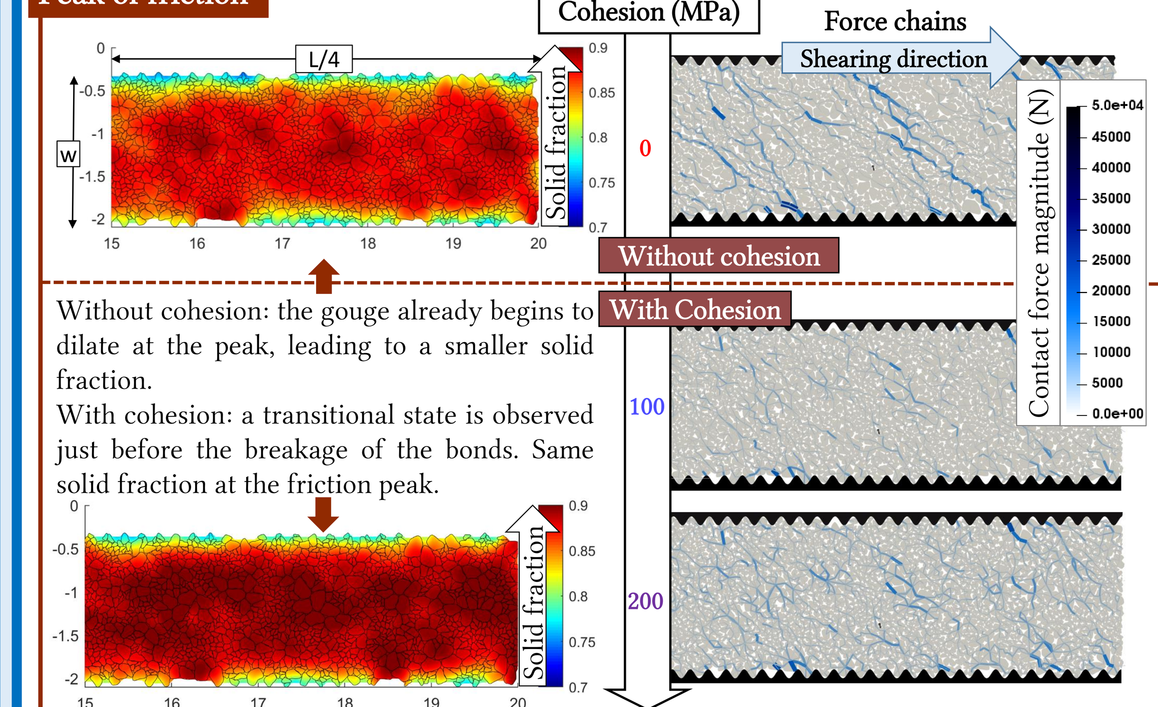


- Interparticular cohesion -

"Bonded Mohr Coulomb" contact law:

- Unbroken bond: constant value of cohesion and no friction
- Broken bond: only interparticular friction (µmicro=0.5)

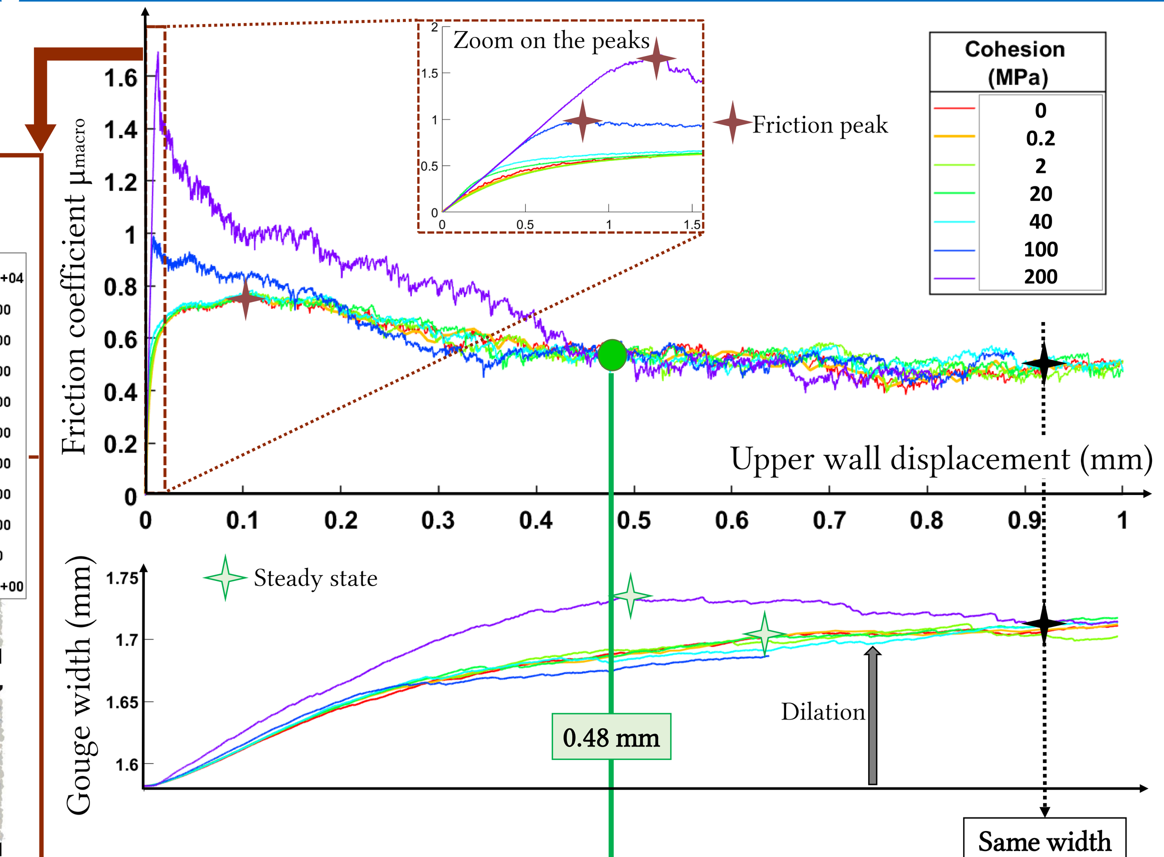
Peak of friction



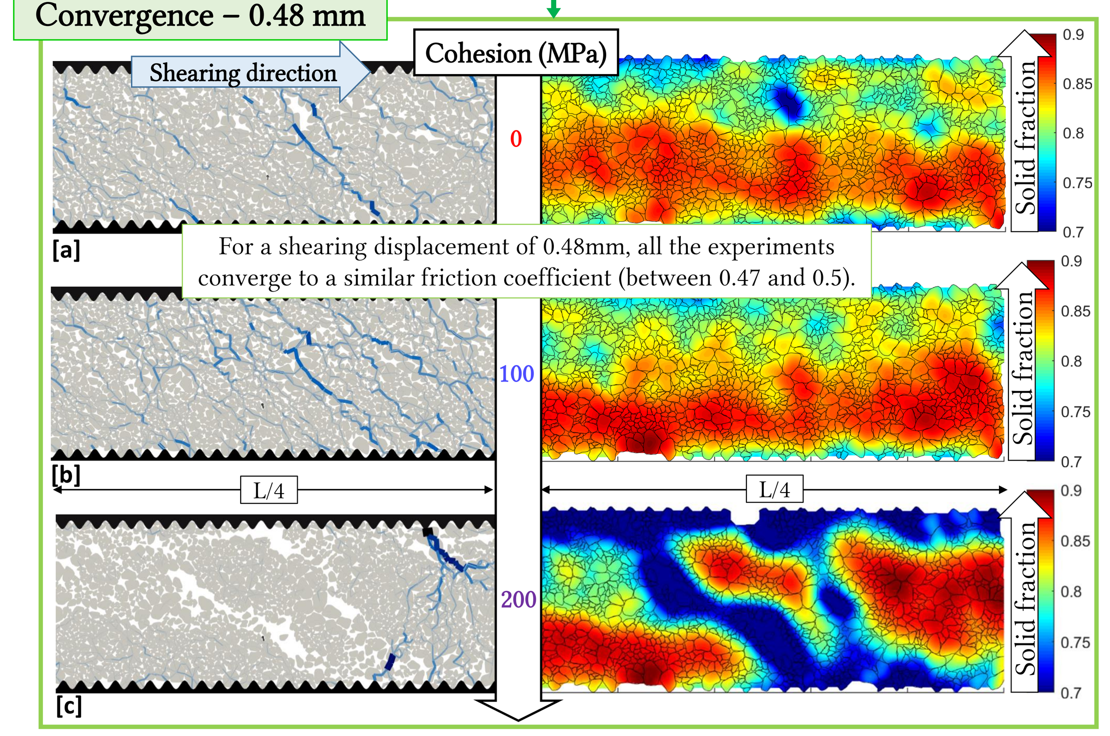
Without cohesion: the gouge already begins to dilate at the peak, leading to a smaller solid fraction.

With cohesion: a transitional state is observed just before the breakage of the bonds. Same solid fraction at the friction peak.

Force chains are more important in the cohesionless case. Indeed, the friction peak appears later than in the cohesive case. At that moment, the gouge already begun to dilate and grains are re-organising themselves in order to create force chains opposed to the slip movement. In the cohesive cases, the friction peaks are observed earlier in the slip. Contact forces are present, but they are smaller and homogeneously distributed into the gouge. Most of the cohesive bonds are still active and grains are just about to re-organise.



Convergence – 0.48 mm



For a shearing displacement of 0.48mm, all the experiments converge to a similar friction coefficient (between 0.47 and 0.5).

- **From cohesionless to small cohesion** (0 to 40 MPa)
  Cohesion negligible under 40 MPa (same behaviour).
  Similar forces are needed to disturb the initial grains assembly and to reach a steady state regime. There are no bonds or weak bonds to break.
- **Important cohesion** (>100 MPa)
  Similar friction coefficient is reached at steady state but higher at the peaks.
  Some active bonds are observed after the peak of friction, creating clusters of cohesive grains → Solid fraction decreased.
  Permeability of the gouge might increase.

[1] G. Mollon, A multibody meshfree strategy for the simulation of highly deformable granular materials, Int. J. Numer. Methods Eng. (2016). doi:10.1002/nme.
[2] G. Mollon, J. Zhao, Fourier-Voronoi-based generation of realistic samples for discrete modelling of granular materials, Granul. Matter. (2012) 621–638. doi:10.1007/s10035-012-0356-x.
[3] K. Mair, K.M. Frye, C. Marone, Influence of grain characteristics on the friction of granular shear zones, J. Geophys. Res. Solid Earth. 107 (2002) ECV 4-1-ECV 4-9. doi:10.1029/2001JB000516.
[4] C. Sammis, G. King, R. Biegel, The kinematics of gouge deformation, Pure Appl. Geophys. PAGEOPH. 125 (1987) 777–812. doi:10.1007/BF00878033.