The flow of saturated geomaterials simulated with a DEM-fluid coupling

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Introduction

Context

Large movements of saturated geomaterials (e.g. debris flow) need advanced constitutive models, often including a so-called solid-fluid transition (and fluid-solid transition ?)

Objectives

A micromechanical model for saturated materials capturing both solid and fluid regimes in a unified framework

Tools

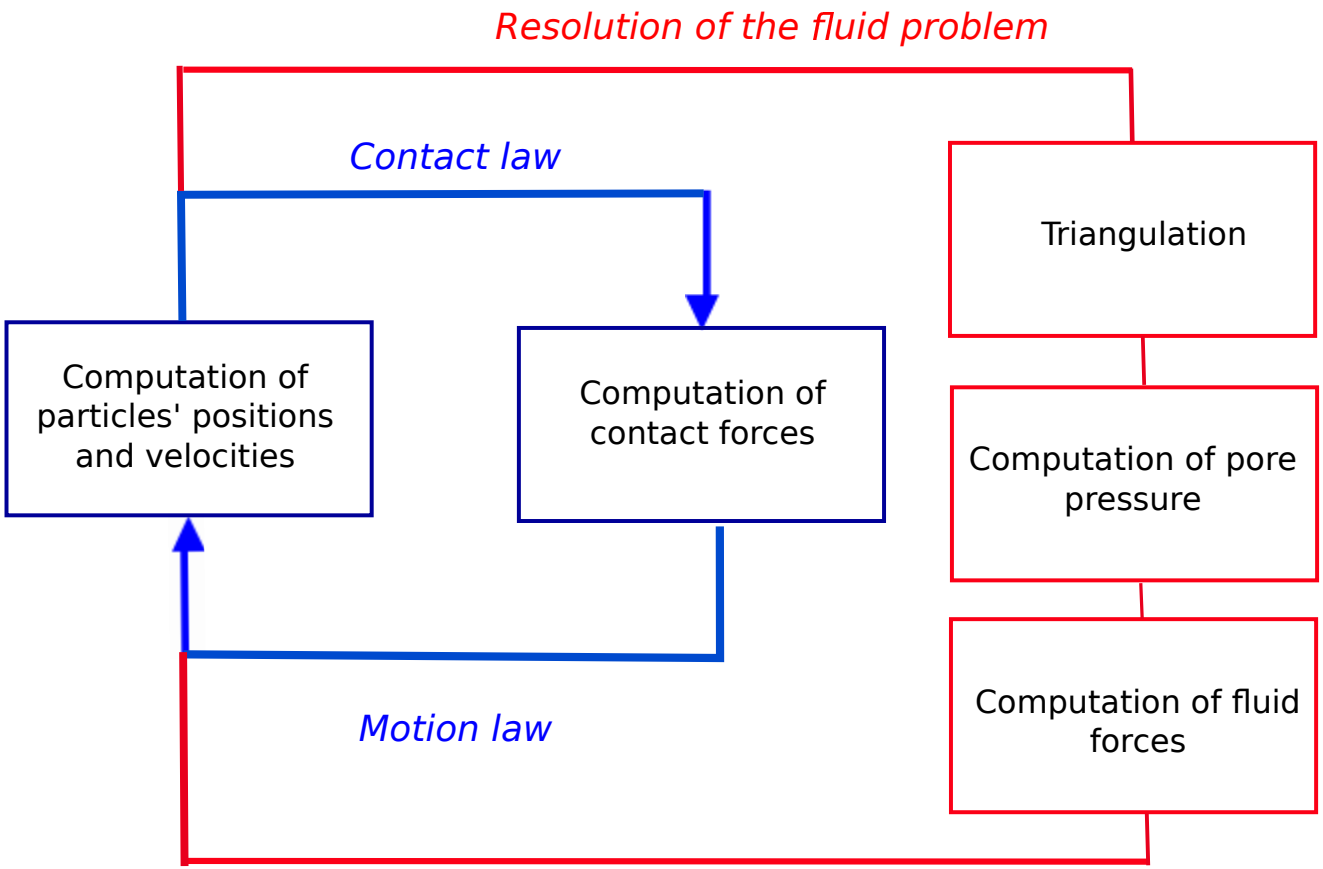
DEM-fluid coupled model.

www.yade-dem.org

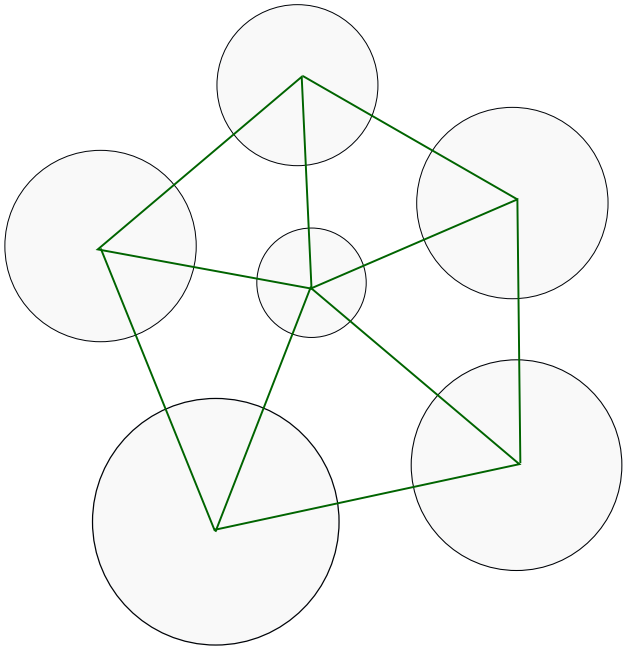
Plan

Plan

Coupled model



Regular triangulation



1 tetrahedron = 1 pore
vertices = centers of particles

Catalano et al, International Journal For Numerical and Analytical Methods in Geomechanics (2013)

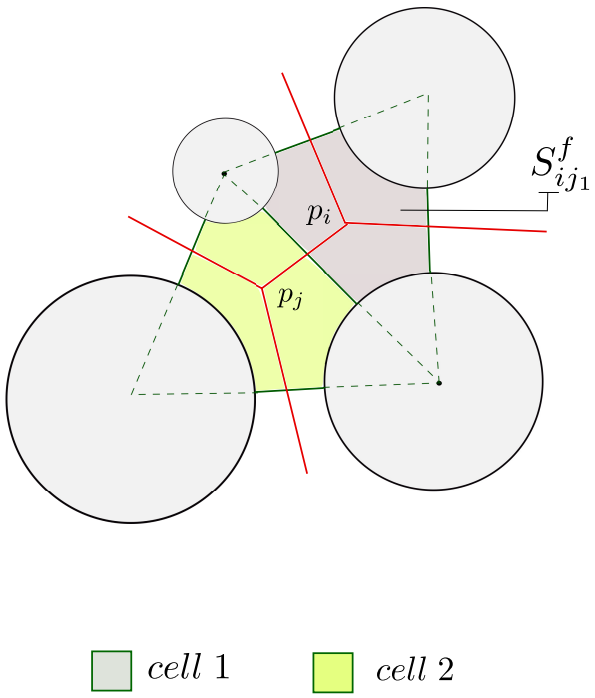
Coupled model

Continuity:

$$\Delta \dot{V} + \int_{S_{ij}} (u^f - u^s) \, . \, n \, ds = 0$$

Conductance:

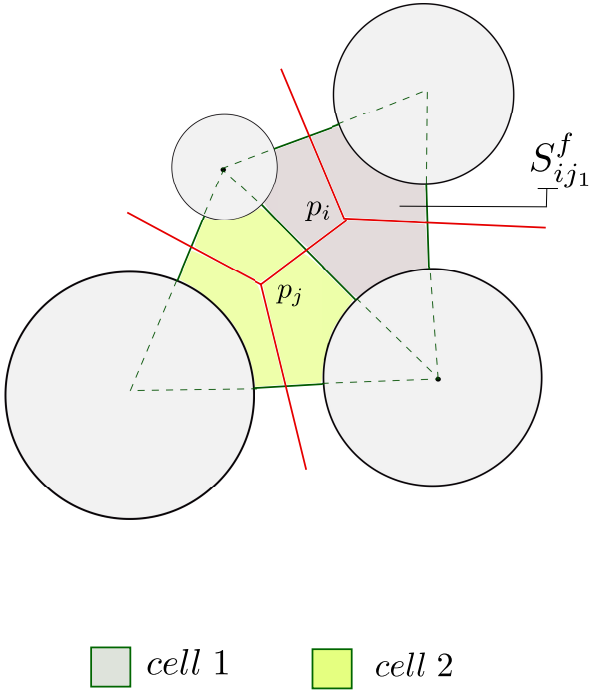
$$\int_{S_{ij}} (u^f - u^s) \, . \, n \, ds = K_{ij} \, (p_i - p_j)$$

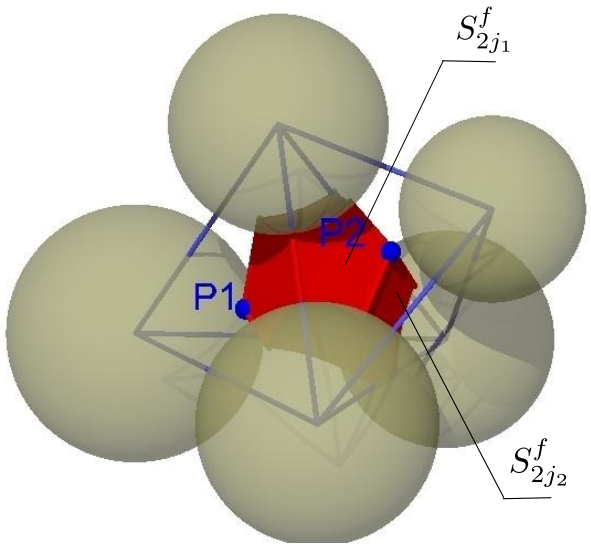


$$K_{ij} = f(R^h_{ij}).$$

Catalano et al, International Journal For Numerical and Analytical Methods in Geomechanics (2013)

Coupled model

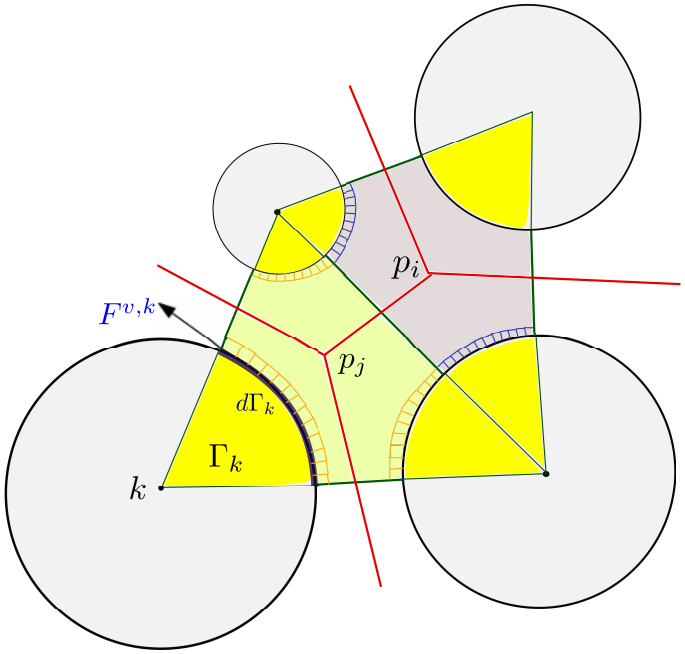




$$\dot{V} = \sum_{j=j_1}^{j=j_4} \int_{S^f_{ij}} (u^s - u^f) \,.\, n \; ds \; = \sum_{j=j_1}^{j=j_4} K_{ij} \, (p_i \; - \; p_j)$$

Catalano et al, International Journal For Numerical and Analytical Methods in Geomechanics (2013)

Fluid forces



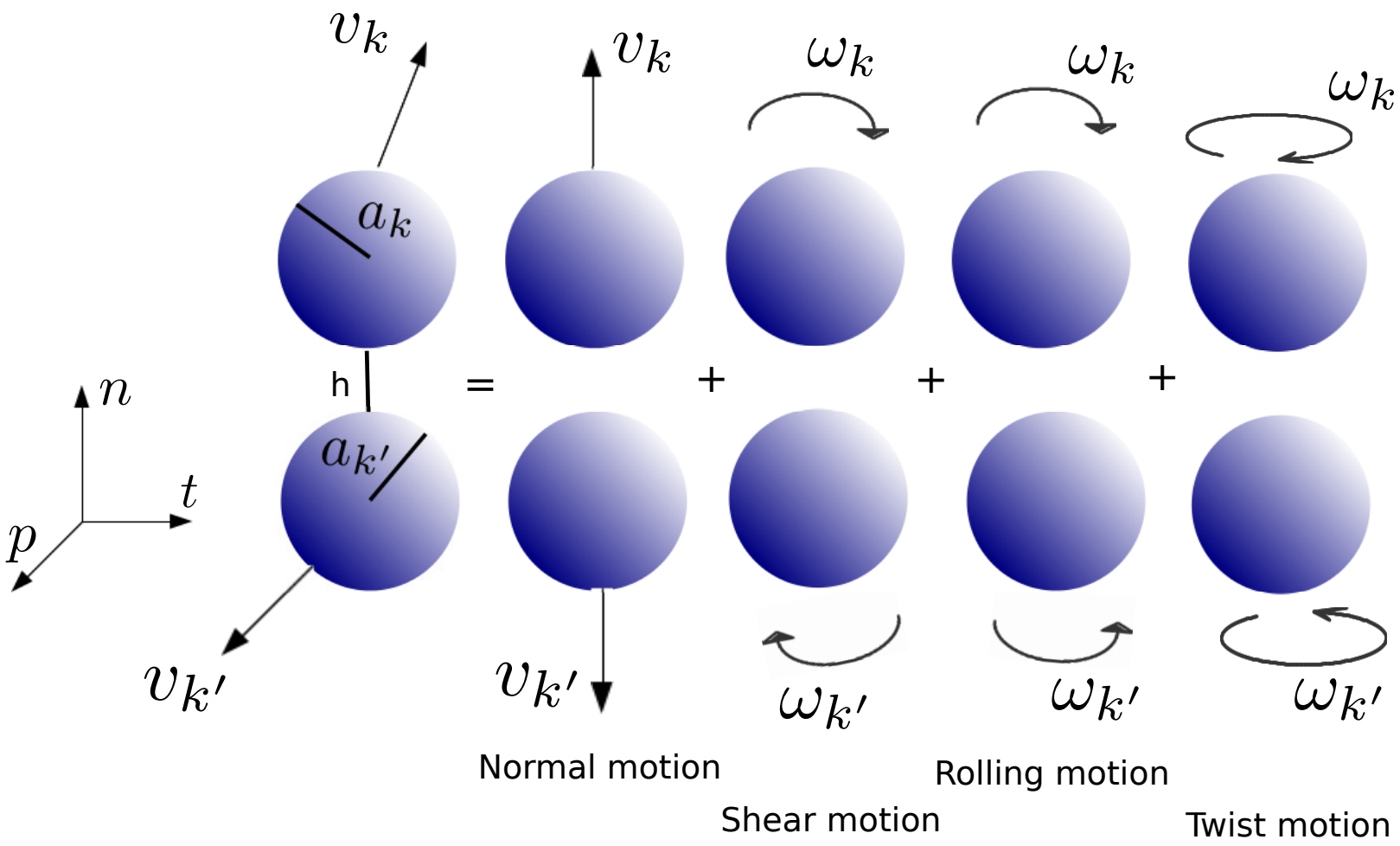
$$F^k = \int_{\partial\Gamma_k} p \ \mathbf{n} ds + \int_{\partial\Gamma_k} \tau \ \mathbf{n} ds$$

$$F^k = \underbrace{F^{p,k}}_{pressure} + \underbrace{F^{v,k}}_{viscous\ stress}$$

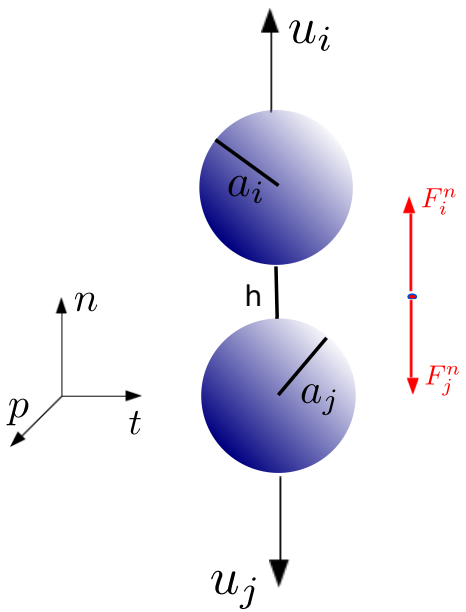
cell 1 *cell 2*

Chareyre et al, Transport in porous media (2012)

Plan

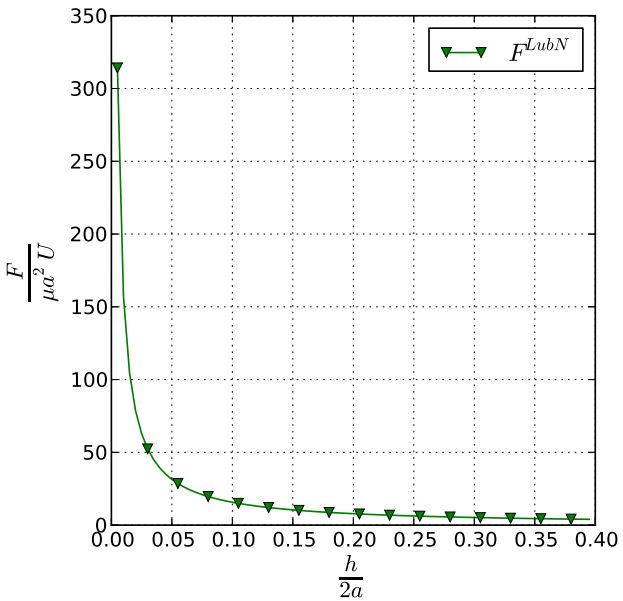

v_k
a_k
h
$a_{k'}$
$v_{k'}$
n
t
p
=
v_k
$v_{k'}$
Normal motion
+
ω_k
$\omega_{k'}$
Shear motion
+
ω_k
$\omega_{k'}$
Rolling motion
+
ω_k
$\omega_{k'}$
Twist motion

Normal motion

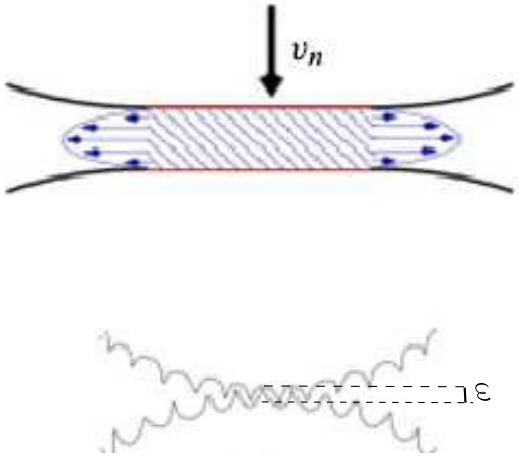


$$F^L_{i,n} = -F^L_{j,n} = \frac{3}{2}\,\pi\,\eta\,\frac{a^2}{h}\,\mathbf{u}_n$$

$$\mathbf{u}_n = \left(\left(\mathbf{u}_j - \mathbf{u}_i\right)\cdot\mathbf{n}\right)\mathbf{n}$$



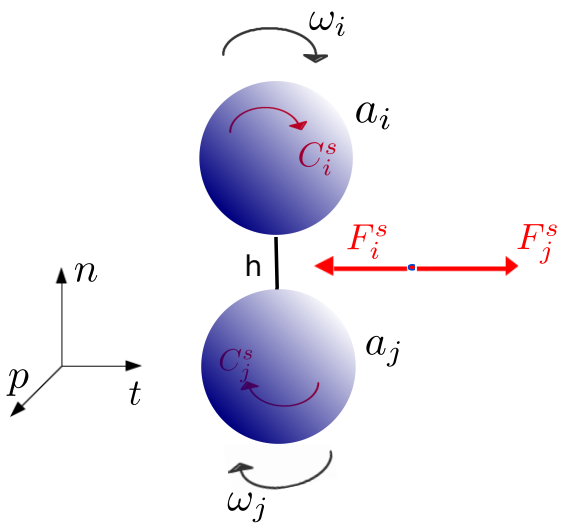
Frankel & Acrivos (Chemical Engineering Science, 1967): the hydrodynamic interactions are developed from the balance equation of the energy dissipation in small gaps between particles



(up): Normal approach and Poiseuille flow in the gap, (bottom): contact between a few solid surface asperities for rough grains

Rognon et al, JFM, 2011

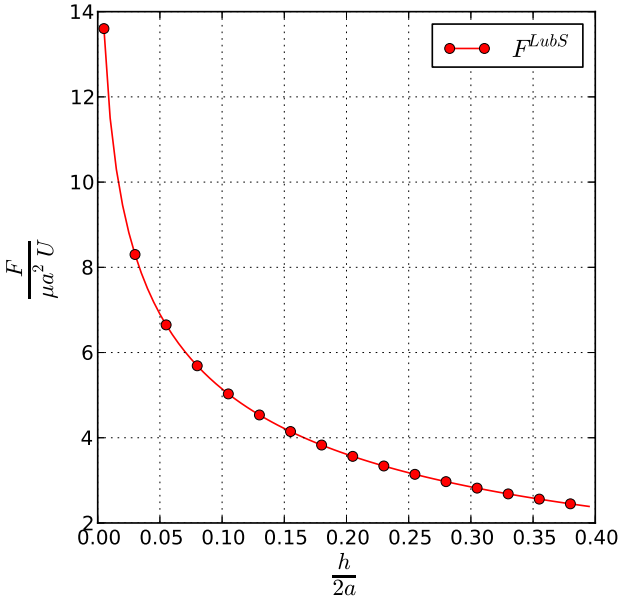
Shear motion



$$F^L_{i,s} = -F^L_{j,s} = \frac{\pi\eta}{2}\left(-2a + (2a+h)\, ln\left(\frac{2a+h}{h}\right)\right)\mathbf{u}_t$$

$$C^s_{i,j} = \left(a_{i,j} + \frac{h}{2}\right) F^L_{i,j,s}$$

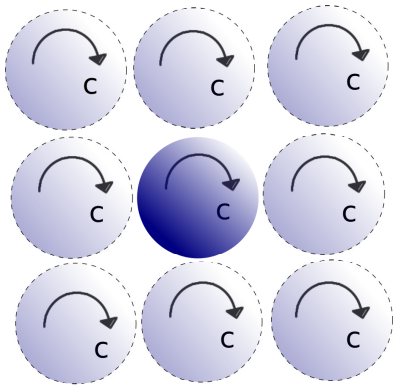
$$\mathbf{u}_t = ((\mathbf{u}_j - \mathbf{u}_i)\cdot\mathbf{t})\mathbf{t} + (a\omega_i + a\omega_j)\mathbf{n}\times\mathbf{t}$$

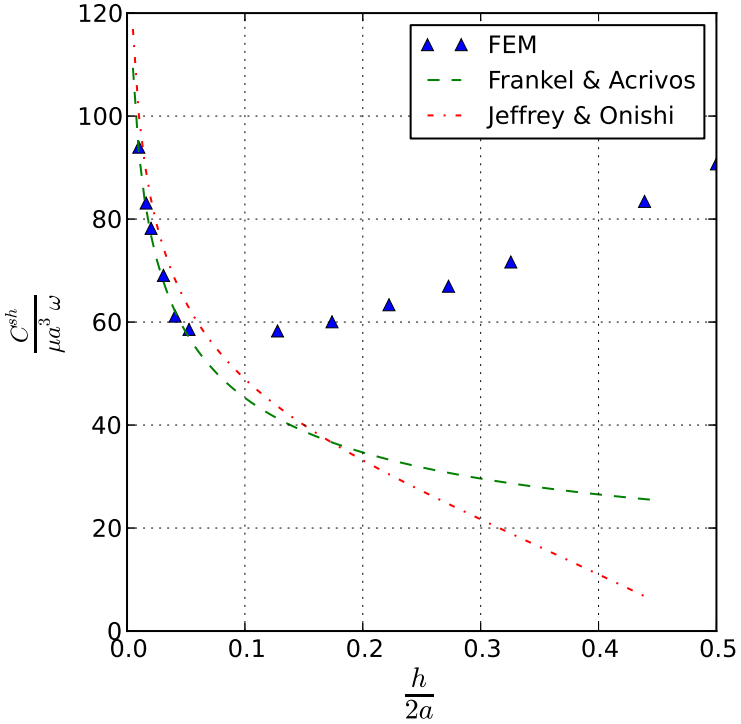


Frankel & Acrivos (Chemical Engineering Science, 1967): the hydrodynamic interactions are developed from the balance equation of the energy dissipation in small gaps between particles

Shear motion

Comparaison with the FEM solution (Stokes solver of Comsol)





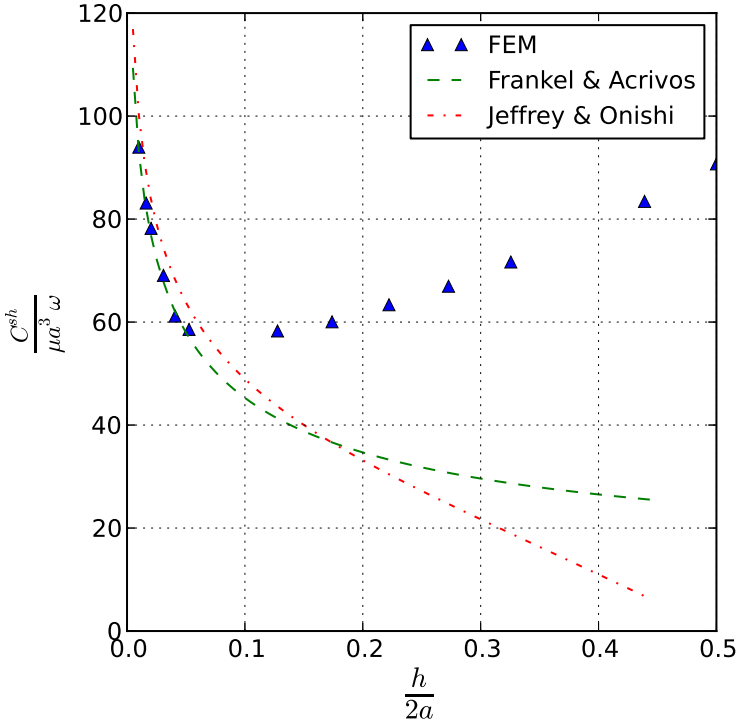
Frankel & Acrivos (Chemical Engineering Science, 1967): the hydrodynamic interactions are developed from the balance equation of the energy dissipation in small gaps between particles

Jeffrey & Onishi (Stokesian Dynamics)

Shear motion

Comparaison with the FEM solution (Stokes solver of Comsol)

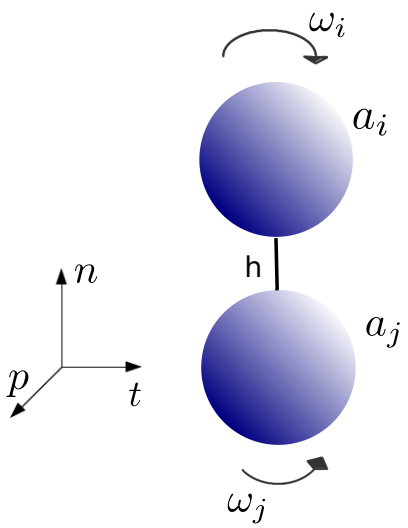
- J&O expression is negative for $h > a$: False!
- F&A expression suits well with the FEM solution and tends to zero for high h.



Frankel & Acrivos (Chemical Engineering Science, 1967): the hydrodynamic interactions are developed from the balance equation of the energy dissipation in small gaps between particles

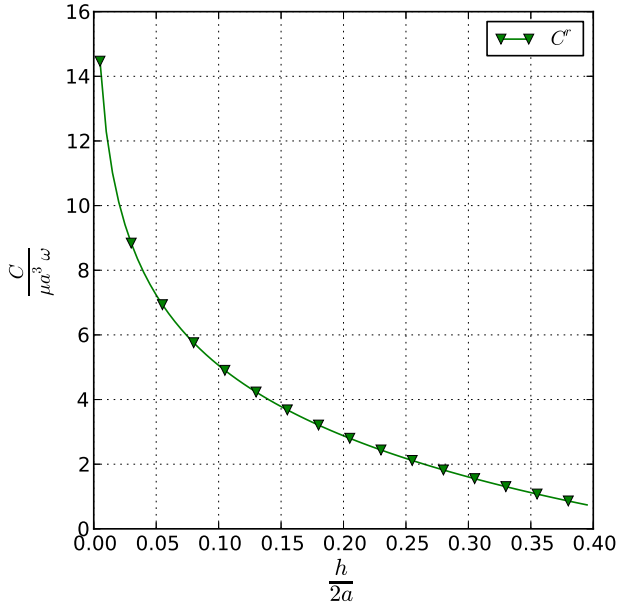
Jeffrey & Onishi (Stokesian Dynamics)

Rolling motion



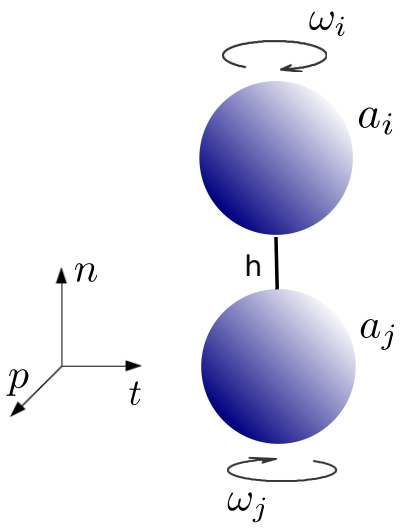
$$C_i^r = -C_j^r = \pi\eta a^3 f^r\left(\frac{h}{a}\right)(\omega_i - \omega_j)\cdot\mathbf{tt}$$

$$f^r\left(\frac{h}{a}\right) = \frac{3}{2}\,ln\frac{a}{h} + \frac{63}{500}\,\frac{h}{a}\,ln\frac{a}{h}$$



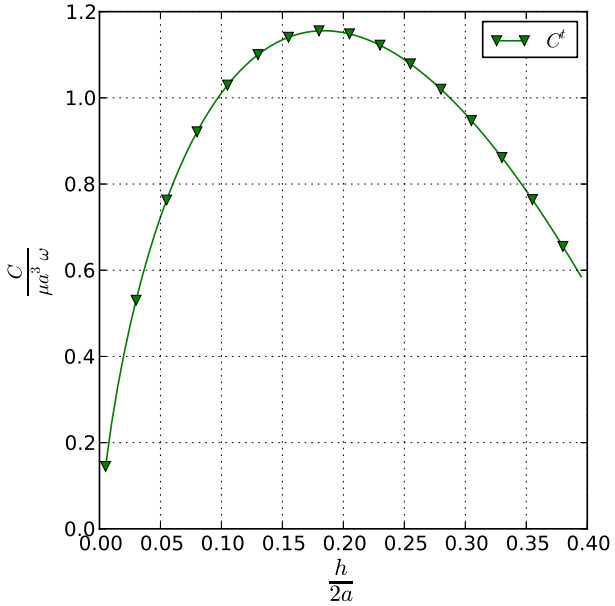
Jeffrey & Onishi (JFM, 1984): Stokesian Dynamics for small gaps between particles

Twist motion

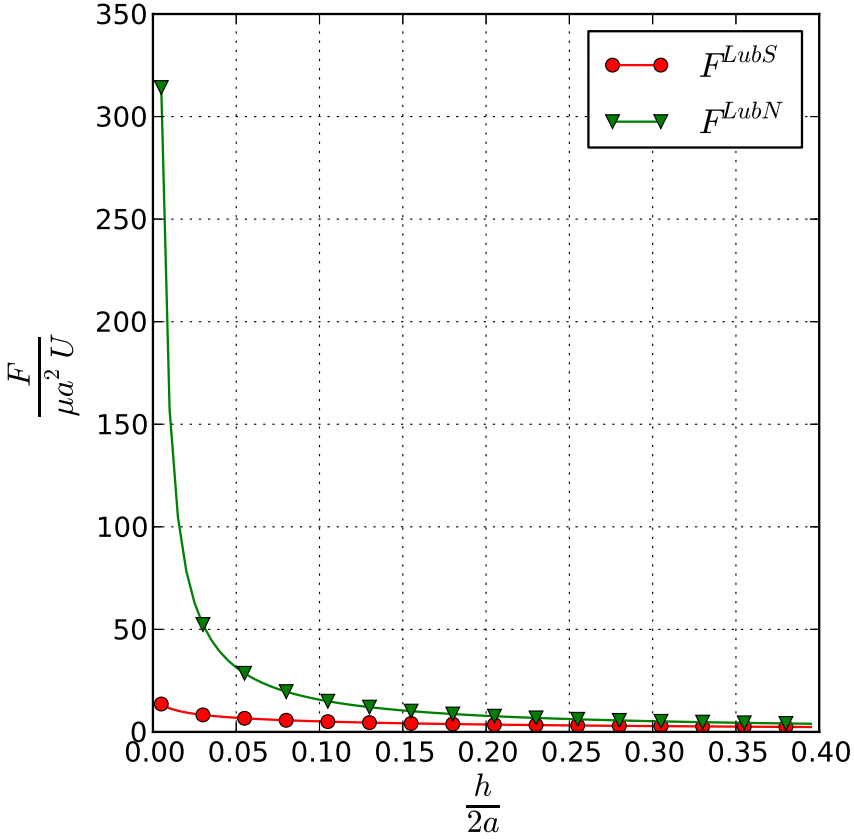


$$C_i^t = -C_j^t = \pi\,\eta\,a^2\,f^t\left(\frac{h}{a}\right)(\omega_i - \omega_j)\cdot\mathbf{n}\,\mathbf{n}$$

$$f^t\left(\frac{h}{a}\right) = \frac{h}{a}\,ln\frac{a}{h}$$



Jeffrey & Onishi (JFM, 1984): Stokesian Dynamics for small gaps between particles



The evolution of F_n^L vs $\frac{h}{2a}$ is faster than that of F_s^L when $h \to 0$.

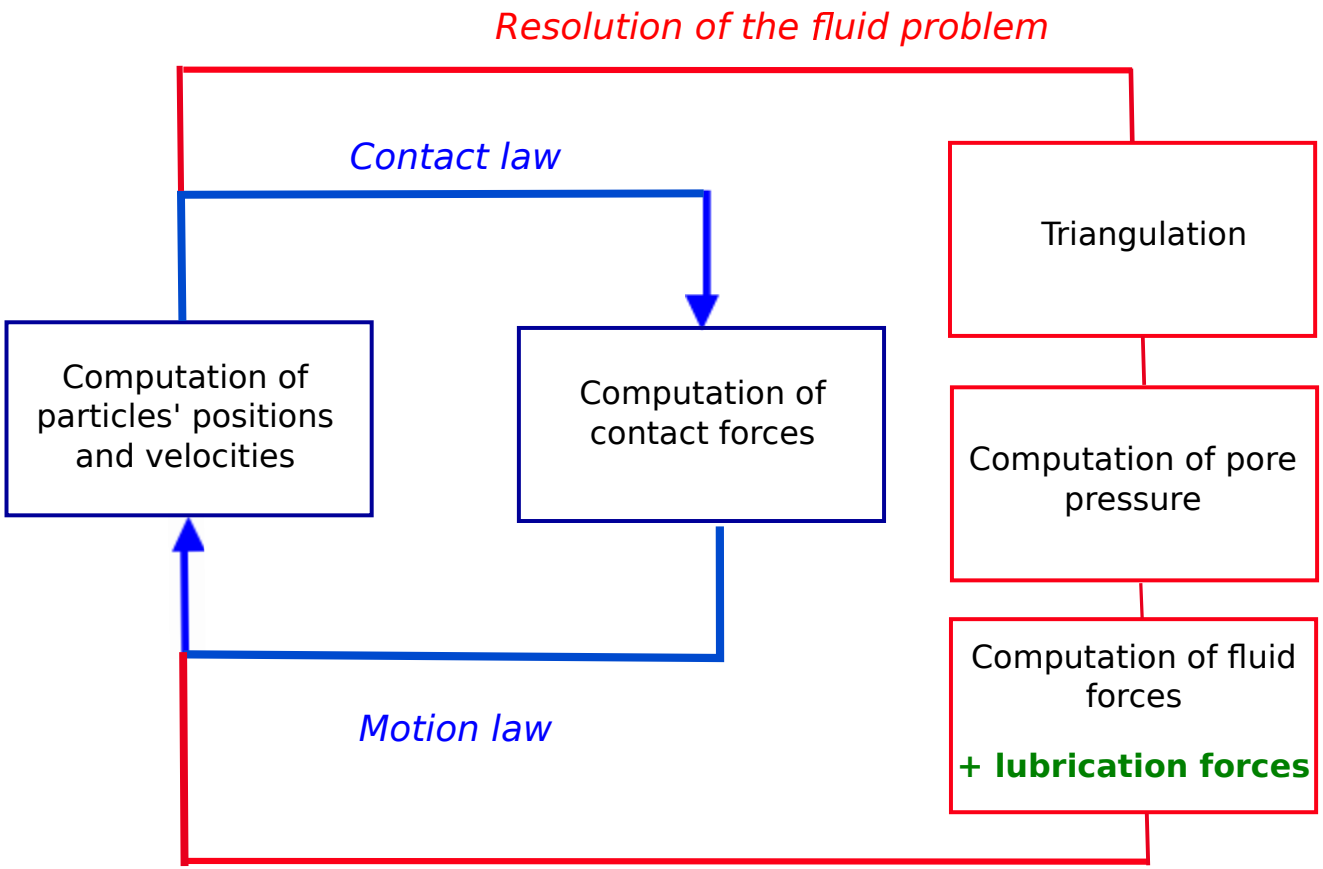
$\Longrightarrow$ F_s^L is usually neglected compared to F_n^L.

Is F_s^L really negligible?

Does it participate to the rheology of the material?

The contribution of the other terms (rolling and twist) will be studied, too.

Coupled model

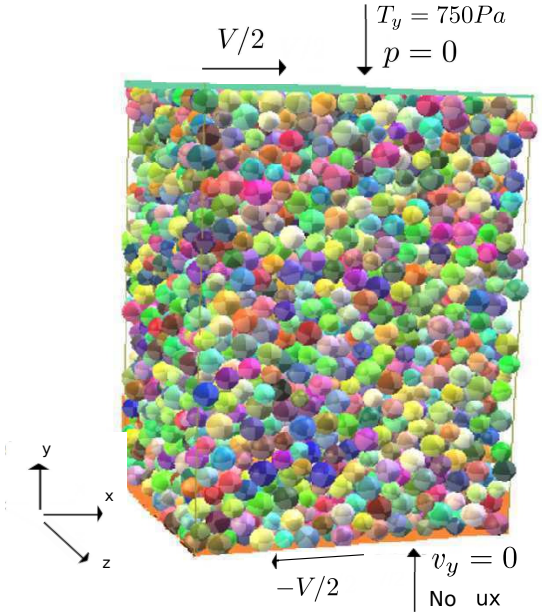


Plan

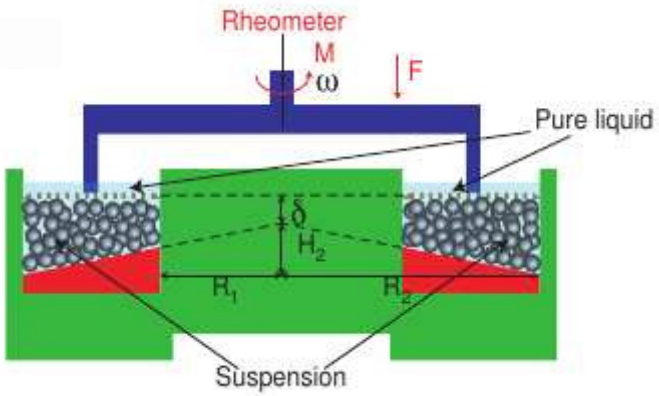
Configuration

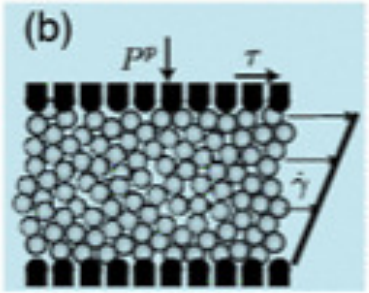
Numerical configuration

shearFlow



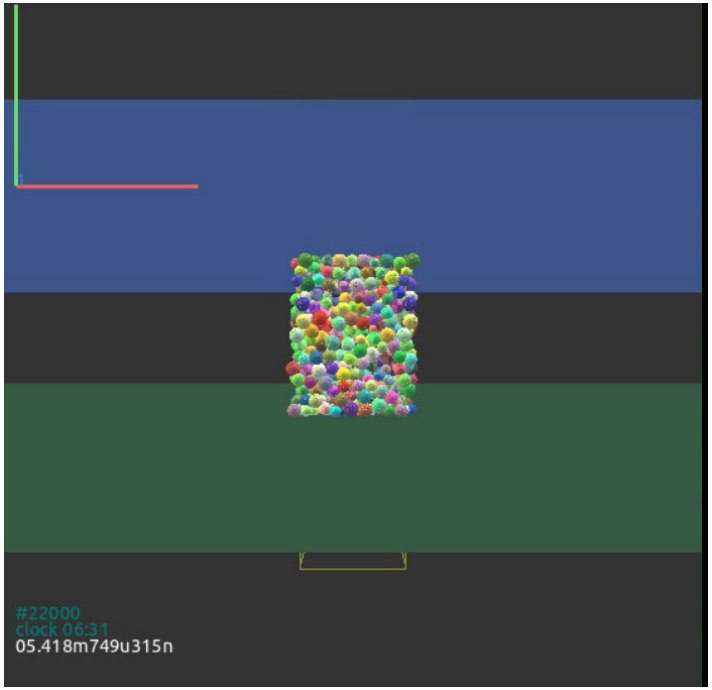
Experimental configuration of Boyer et al



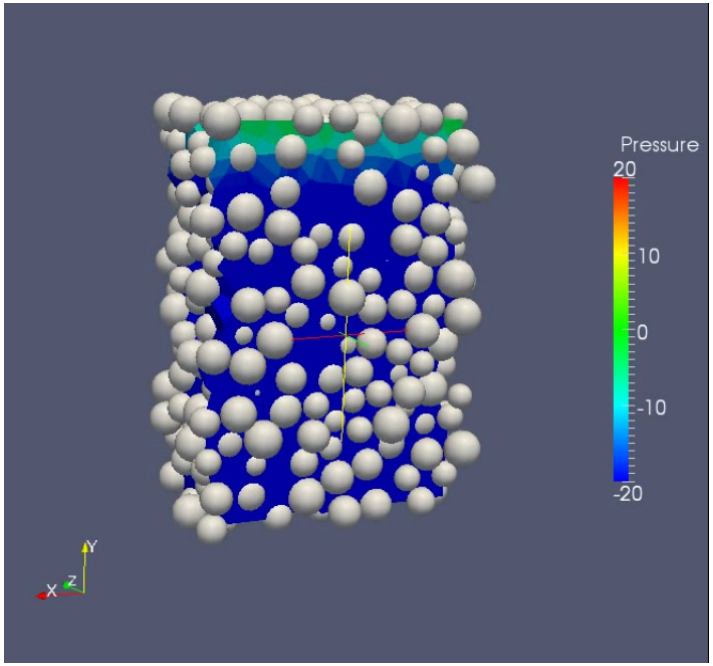


Boyer et al, Physical Review Letters (2011)

shearFlow

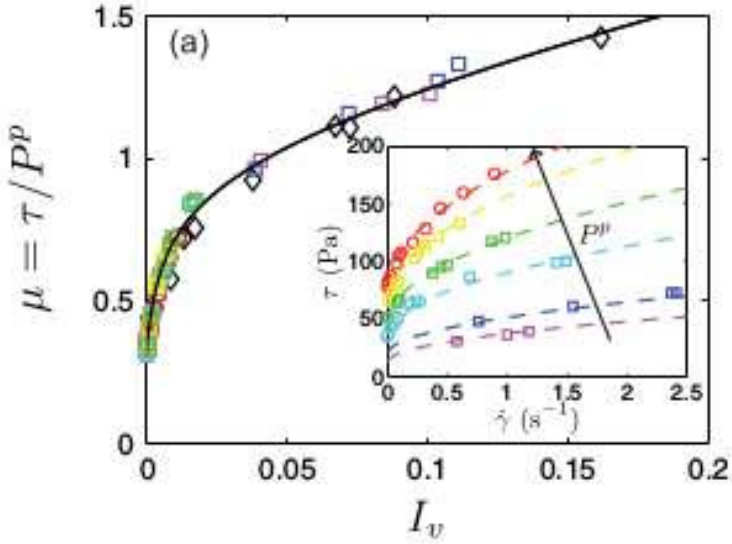


Pressure

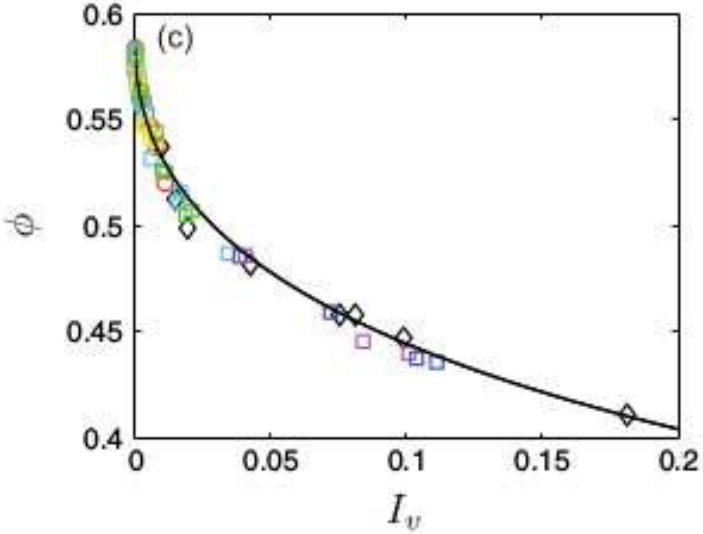


Phenomenological laws from the experiments of Boyer et al.

Boyer et al, Physical Review Letters (2011)



Stress ratio

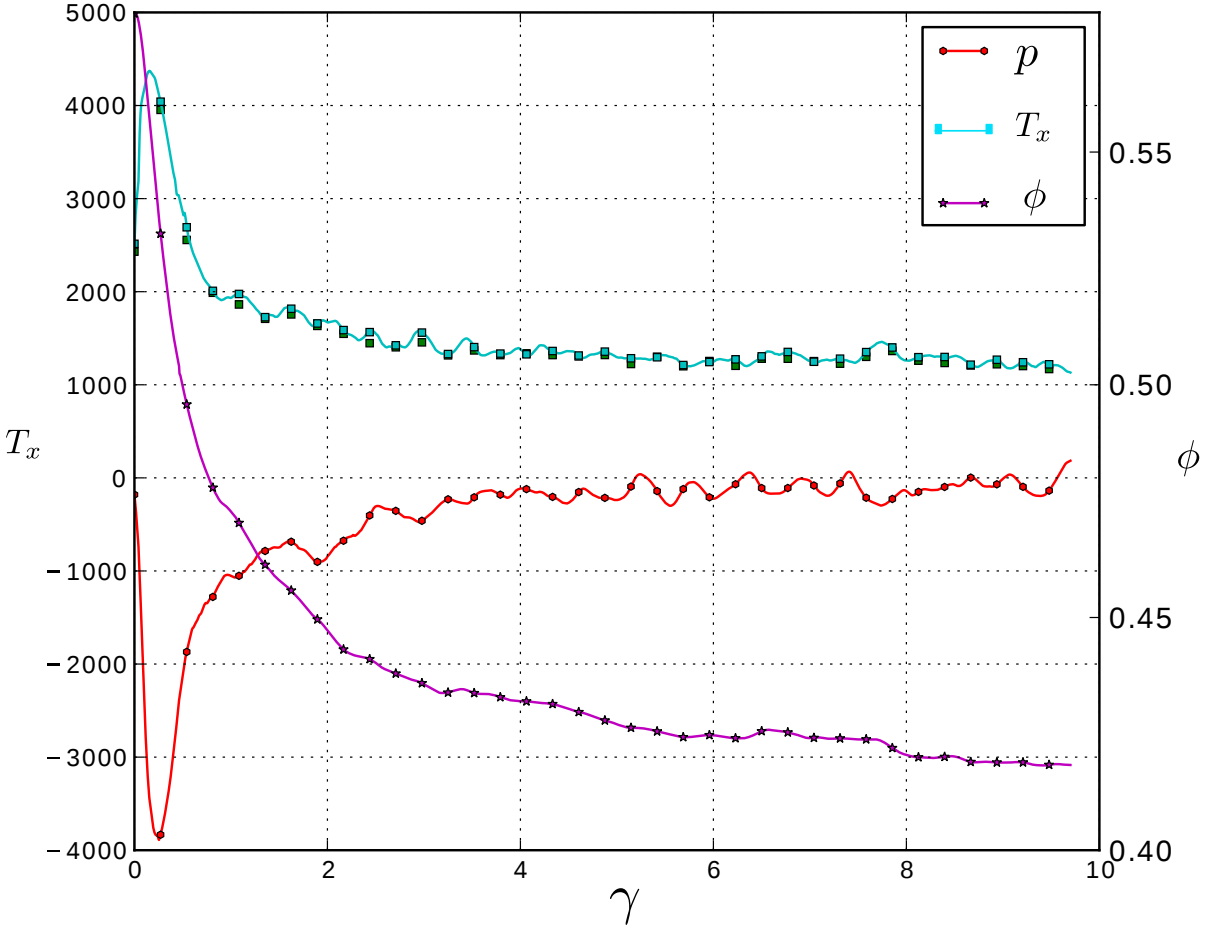


solid fraction

vs

Viscous number $I_v = \frac{\eta \dot{\gamma}}{T_y}$

Shear stress

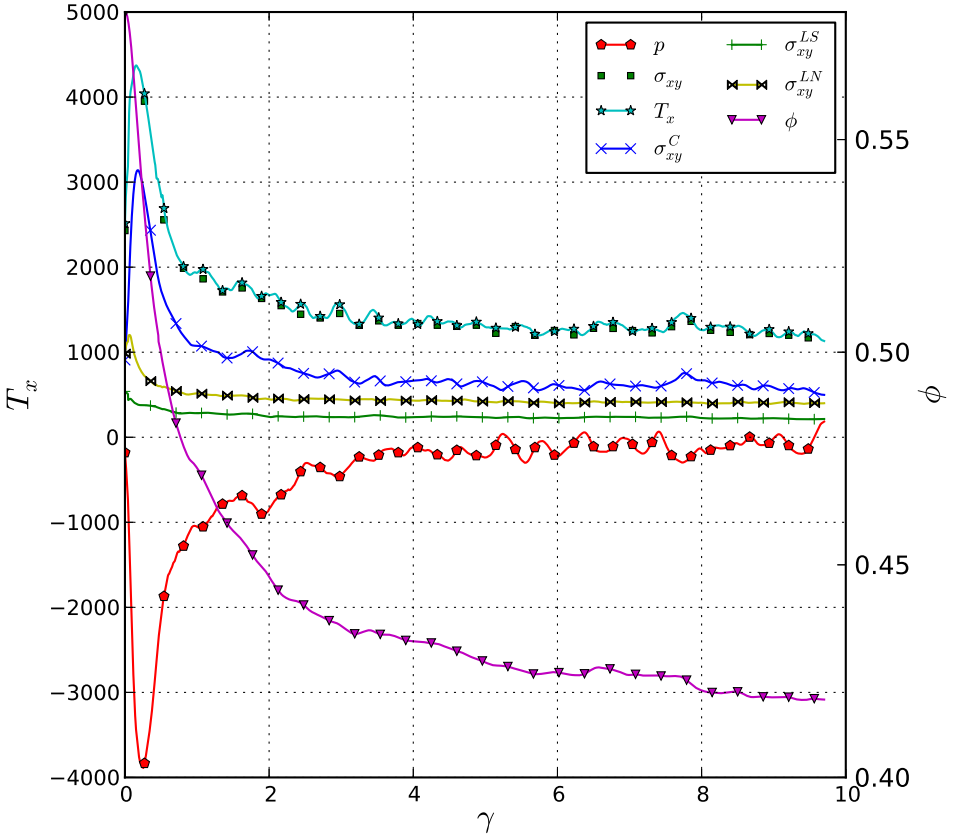


$$I_v = 0.223$$

$$T_x = \frac{F_x}{S}$$

Shear stress

$$T_x = \sigma^C_{xy} + \sigma^{LN}_{xy} + \sigma^{LS}_{xy} + \sigma^I_{xy}$$



For $I_v = 0.223$:

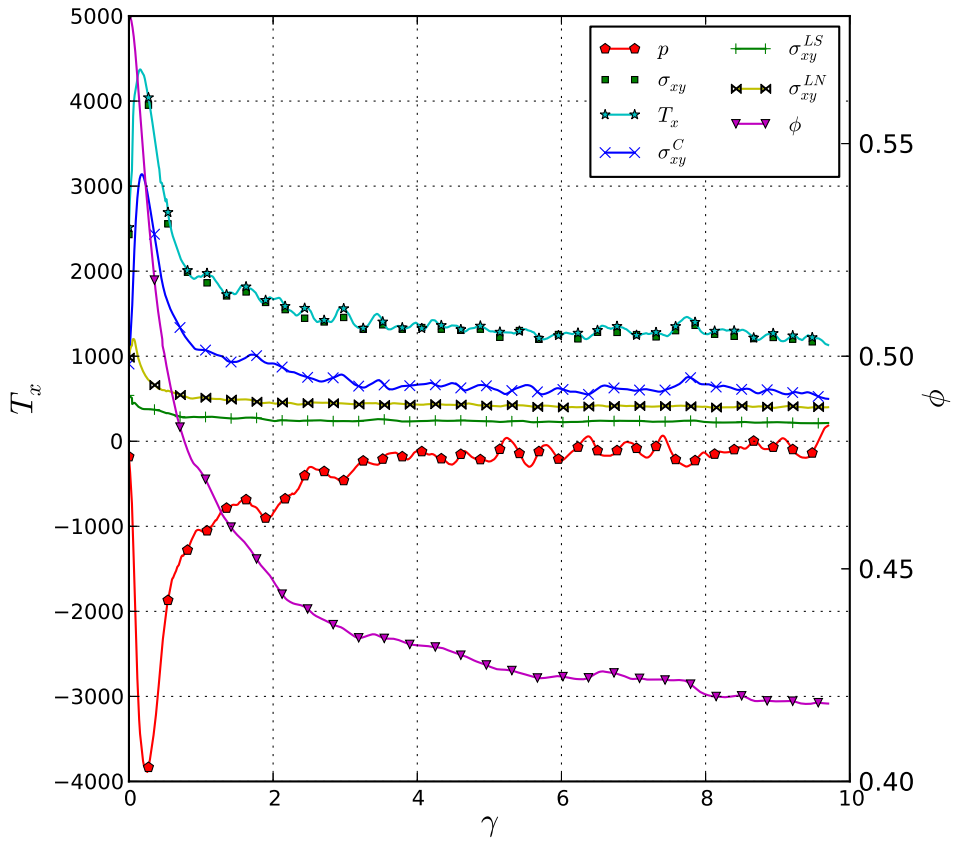
$$\sigma^I = \sum_i m_i \mathbf{v}_i \otimes \mathbf{v}_i$$

$$\sigma^I_{xy} < 2\,\%\ T_x$$

→ Non inertial regime

Shear stress

$$T_x = \sigma^C_{xy} + \sigma^{LN}_{xy} + \sigma^{LS}_{xy} + \sigma^I_{xy}$$



For $I_v = 0.223$:

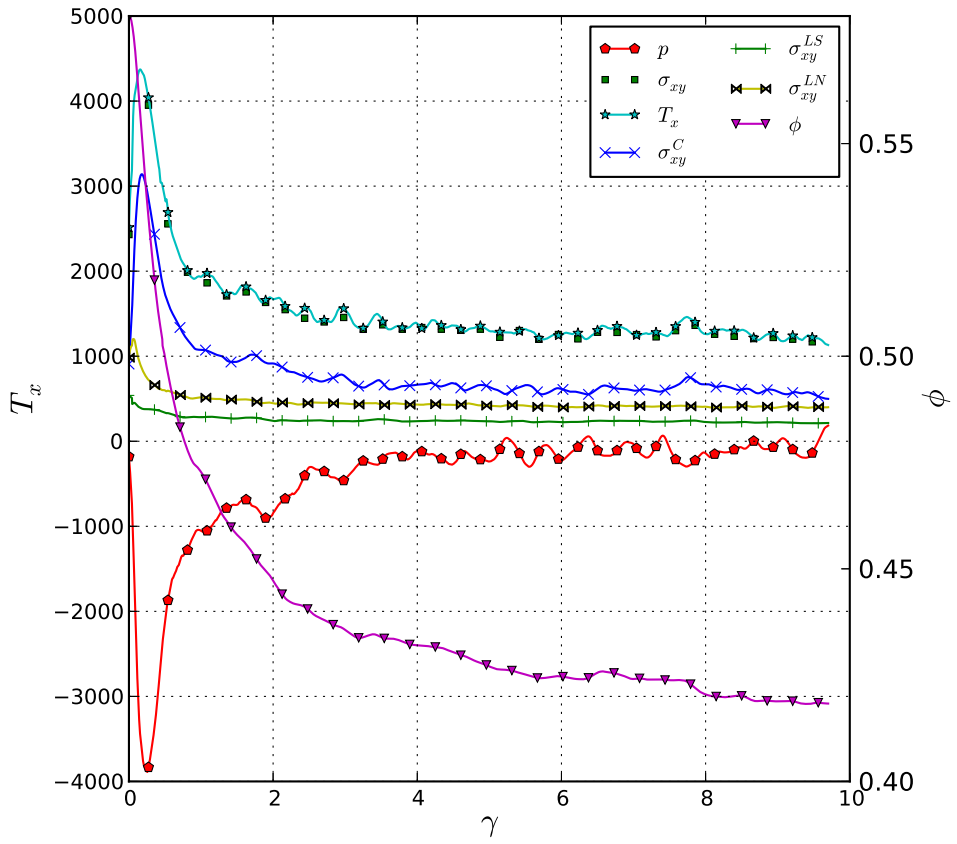
$$\boldsymbol{\sigma}^C = \frac{1}{V} \sum_i \mathbf{F}^C_i \otimes \mathbf{l}_i$$

$$\sigma^C_{xy} \simeq 50\,\%\ T_x$$

→ Contacts are dominant

Shear stress

$$T_x = \sigma_{xy}^{C} + \sigma_{xy}^{LN} + \sigma_{xy}^{LS} + \sigma_{xy}^{I}$$



For $I_v = 0.223$:

$$\boldsymbol{\sigma}^{LN} = \frac{1}{V} \sum_i \mathbf{F}_{i,n}^{L} \otimes \mathbf{l}_i$$

$$\boldsymbol{\sigma}^{LS} = \frac{1}{V} \sum_i \mathbf{F}_{i,s}^{L} \otimes \mathbf{l}_i$$

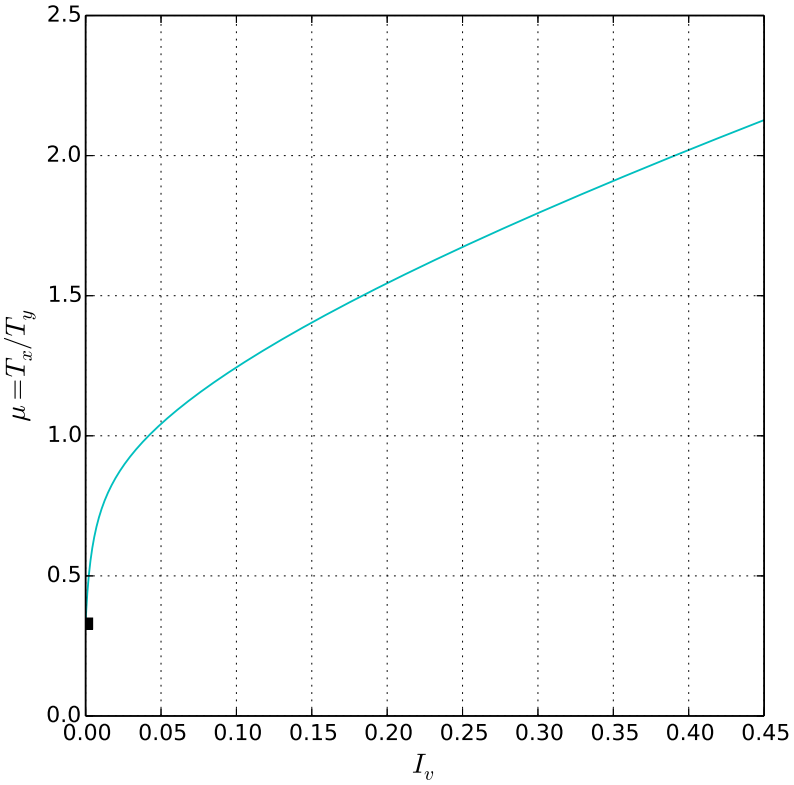
$$\sigma_{xy}^{LN} \simeq 30\,\%\ T_x$$

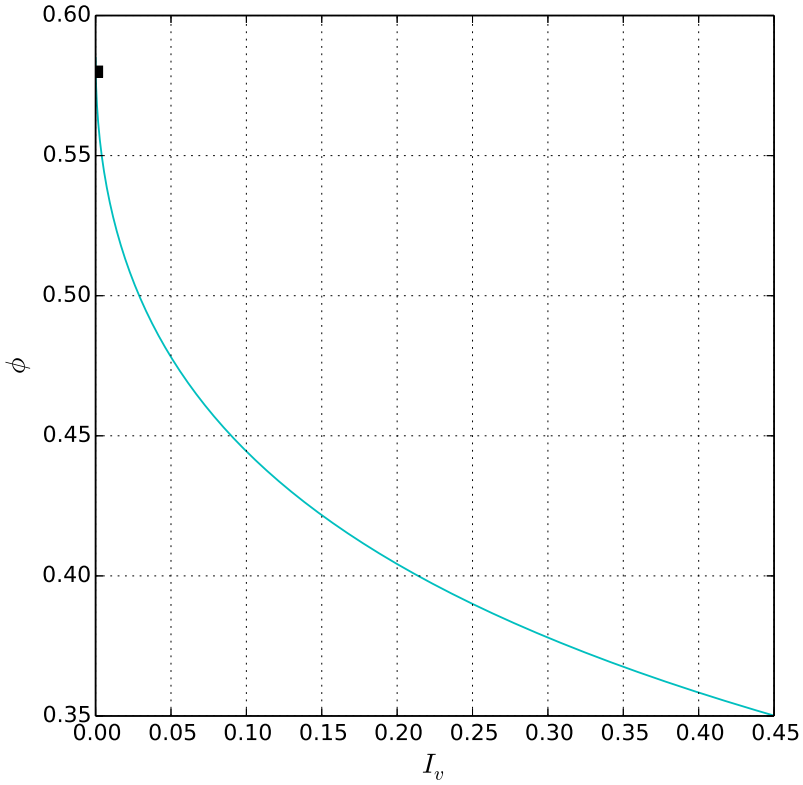
$$\sigma_{xy}^{LS} \simeq 20\,\%\ T_x$$

→ The shear lubrication is not negligible compared to the normal one.

$I_v = 0$: dry case

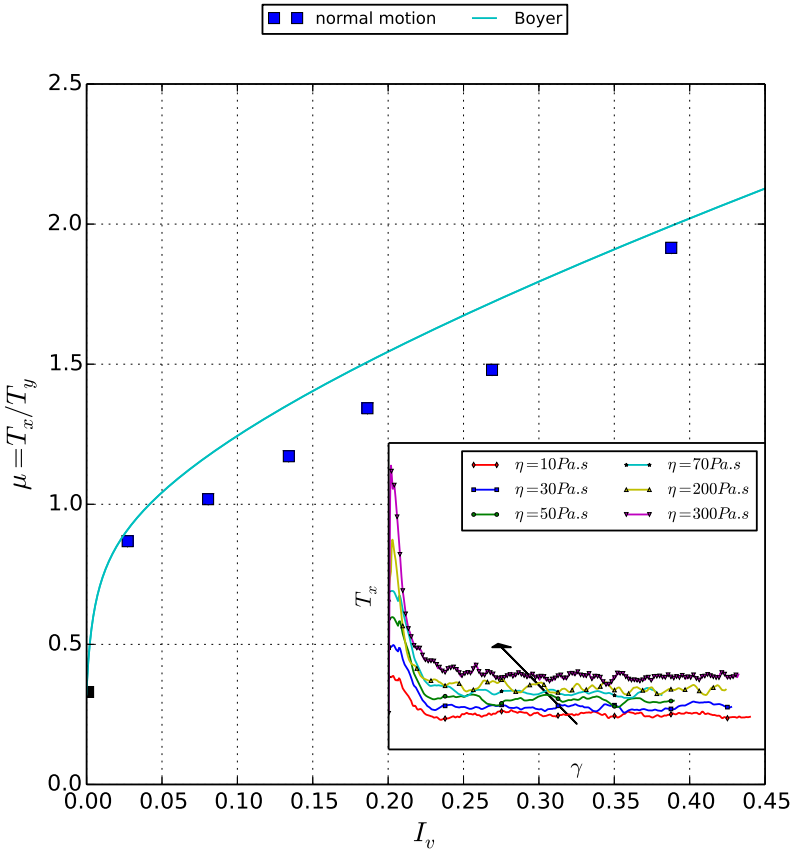
Comparaison with the phenomenological laws from the experiments of Boyer et al:

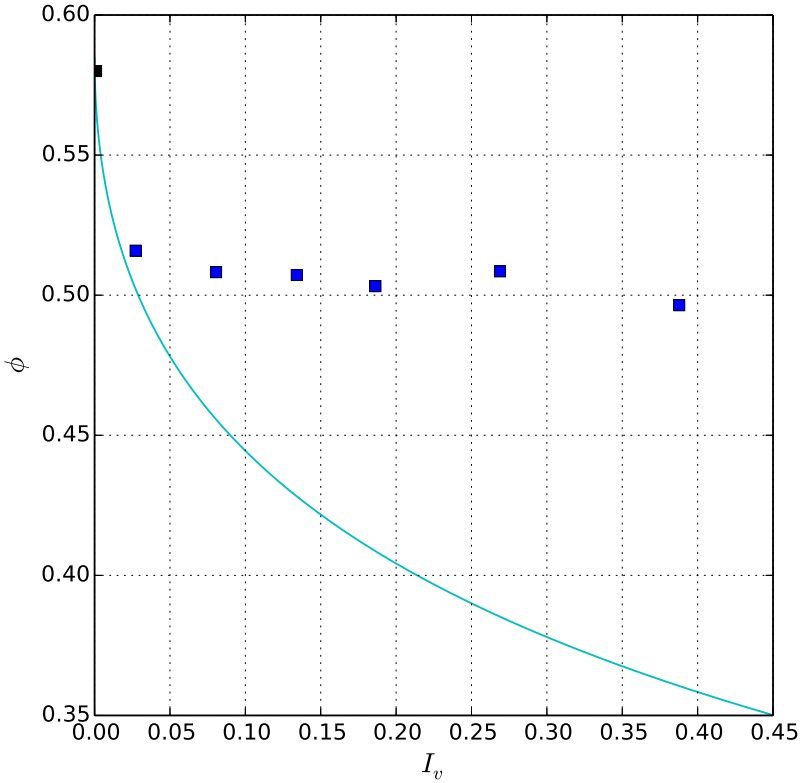




* For $I_v = 0$, the result is that of the dry case.
* $\mu = 0.31$ and $\phi = 0.585$: the results match those measured experimentally on glass beads without any fit.

Normal motion

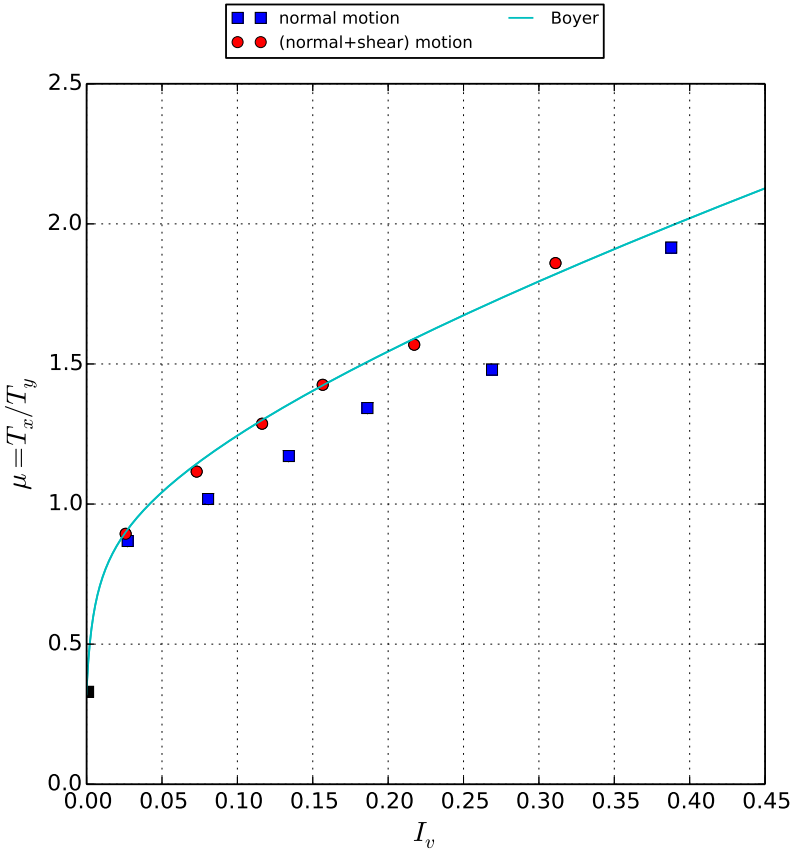


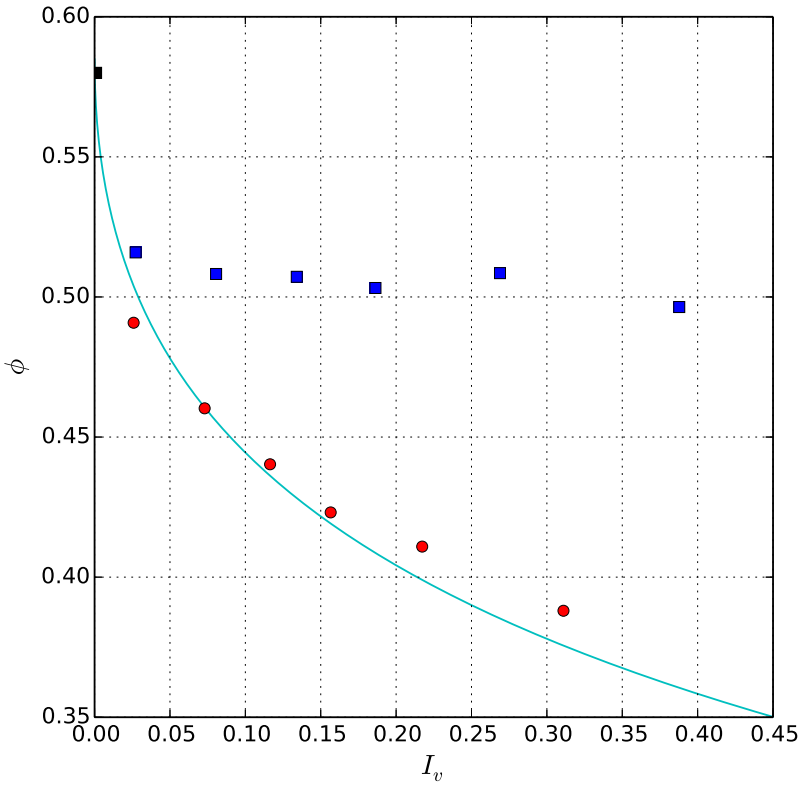


* σ^{LN} contributes to the shear stress.

* The simulation of only the normal motion overestimates the solid fraction: ϕ is almost constant for increasing I_v

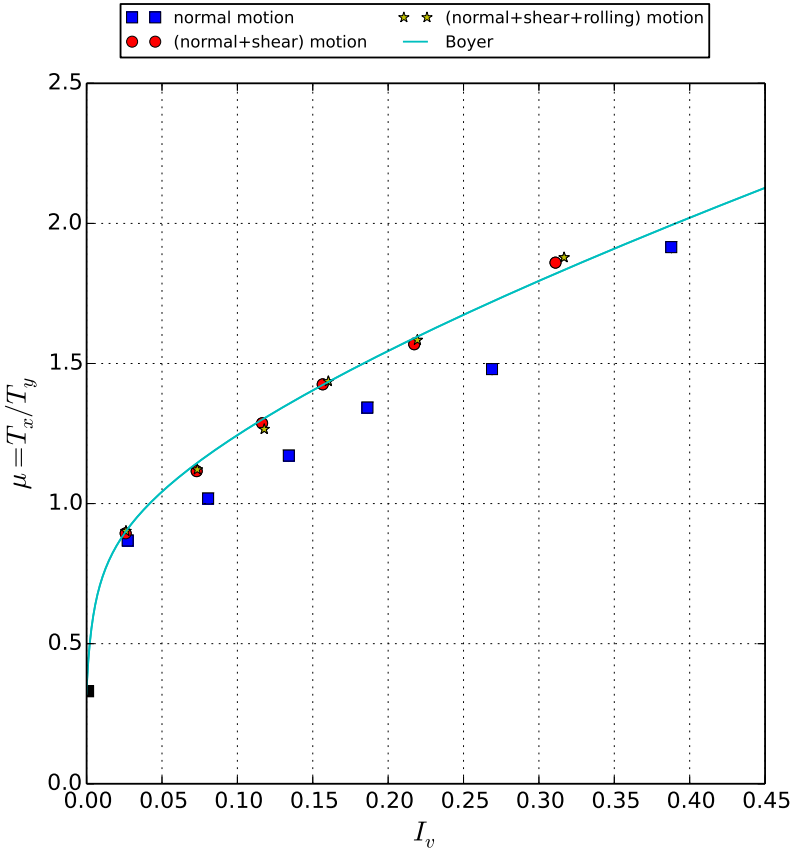
Normal + shear motion

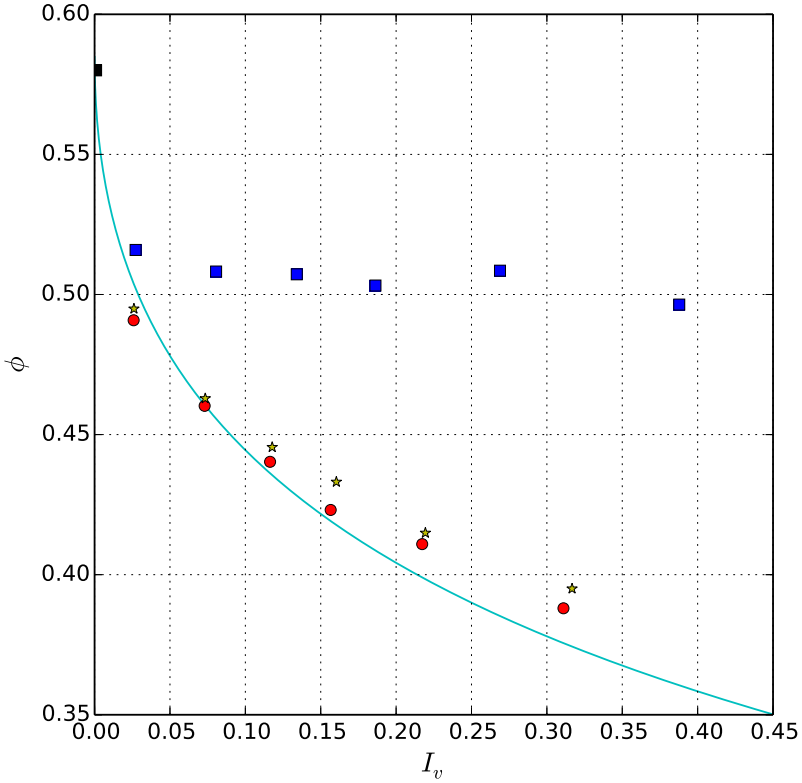




* σ^{LS} ontributes to the shear stress.
* σ^{LS} plays a key role to the dilatancy.
* By combining σ^{LS} and σ^{LN}, the behavior get colser to that of the phenomenological laws from the experiments of Boyer.

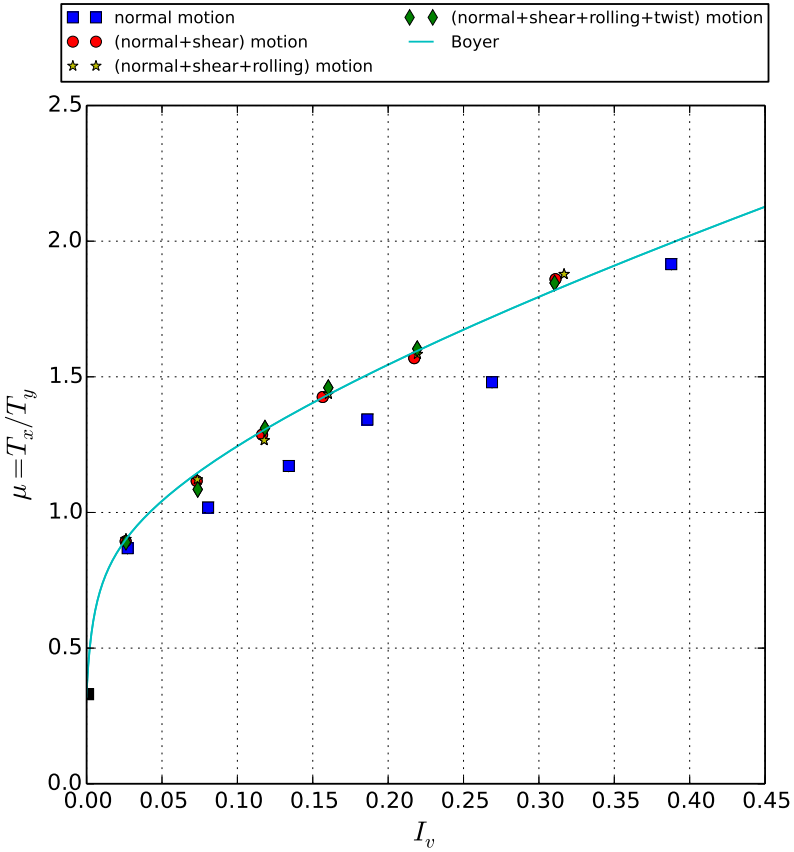
Normal + shear + rolling motion

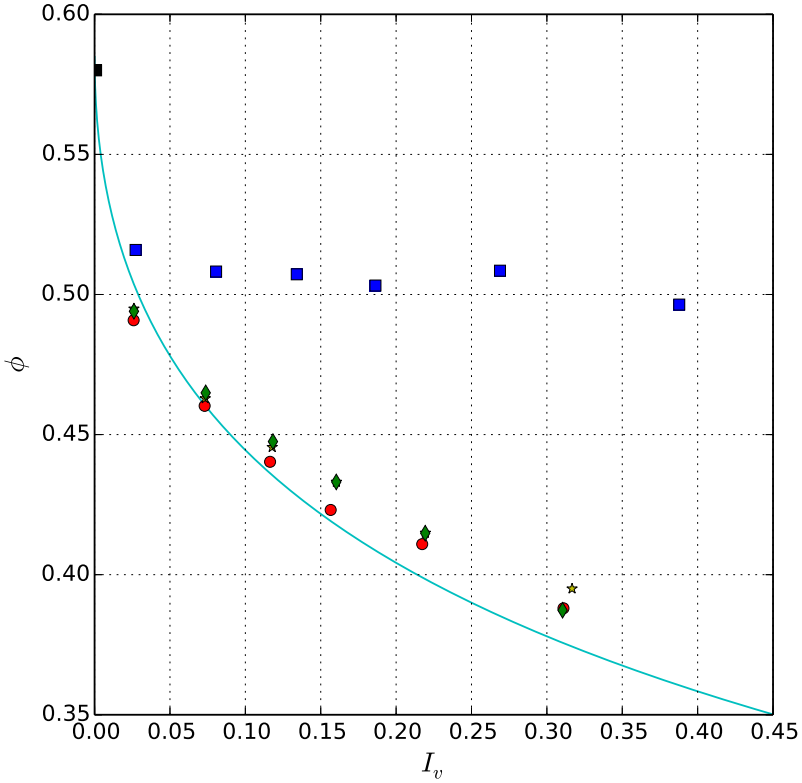




The effect of the rolling motion is very negligible.

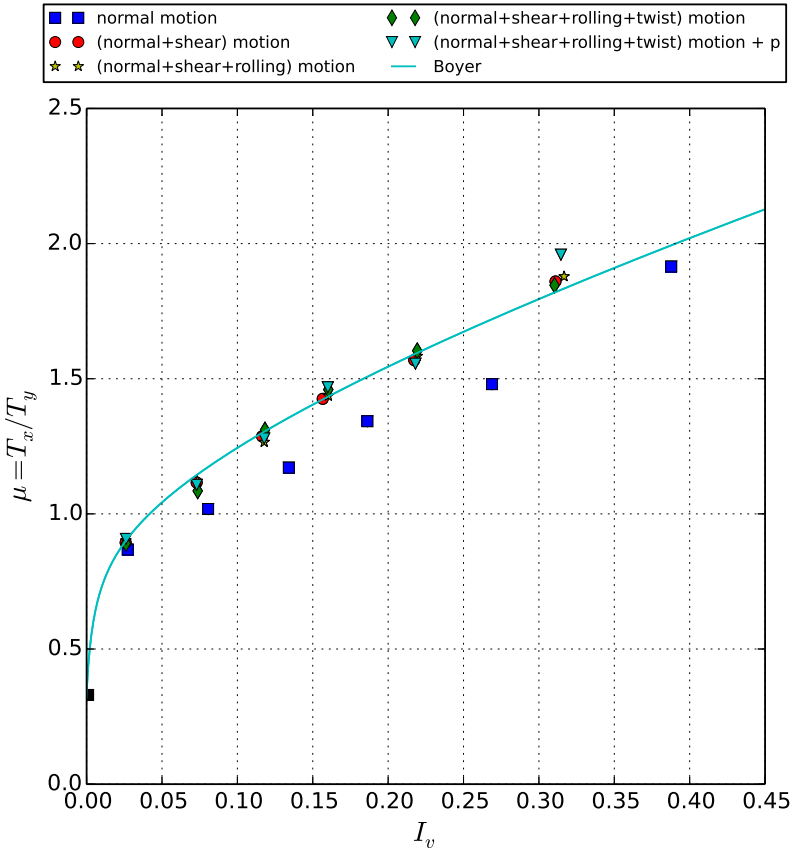
Normal + shear + rolling + twist motion

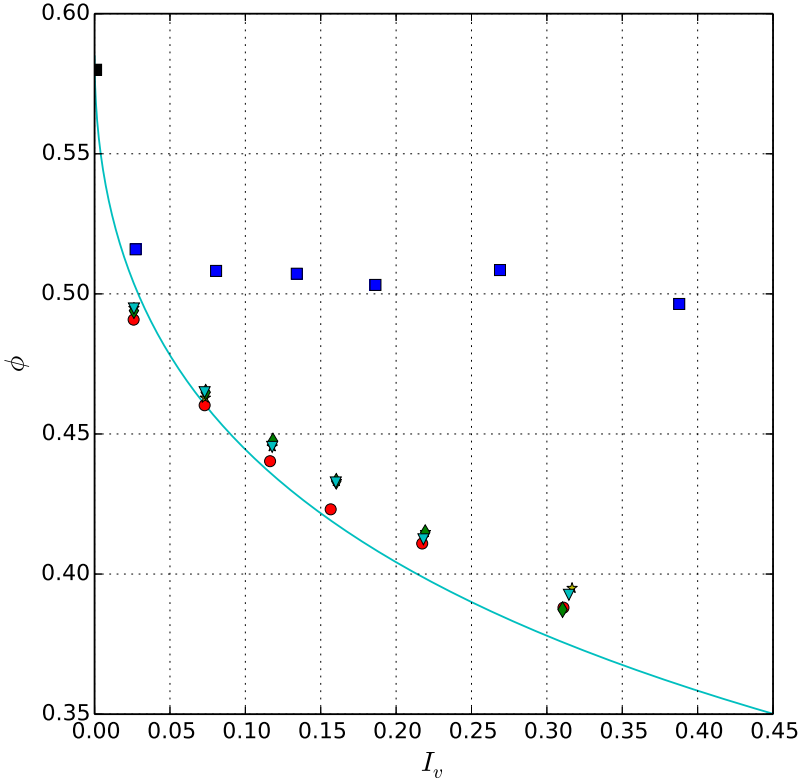




The effect of the twist motion is very negligible.

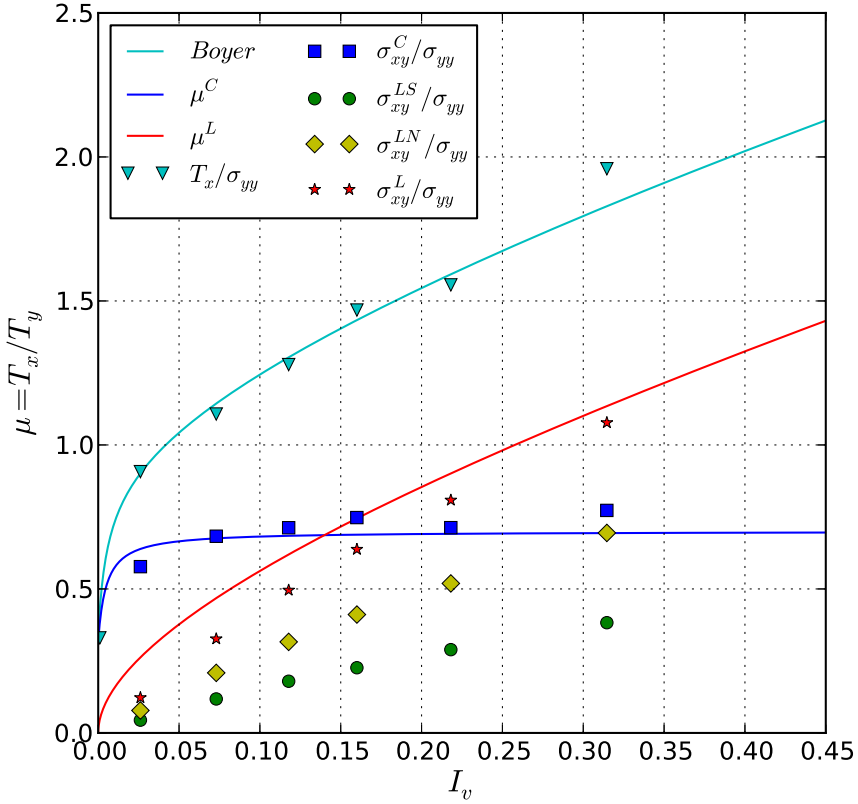
Normal + shear + rolling + twist motion + poromechanical coupling





The poromechanical coupling doesn't contribute to μ and ϕ (in the steady state).

$$T_x = \sigma_{xy}^{C} + \sigma_{xy}^{LN} + \sigma_{xy}^{LS}$$



- Contact forces play a significant role. They saturate for larger I_v.
- Lubrication stress increase linearly. For $I_v > 0.15$, It exceeds the contact stress.

$\Downarrow$

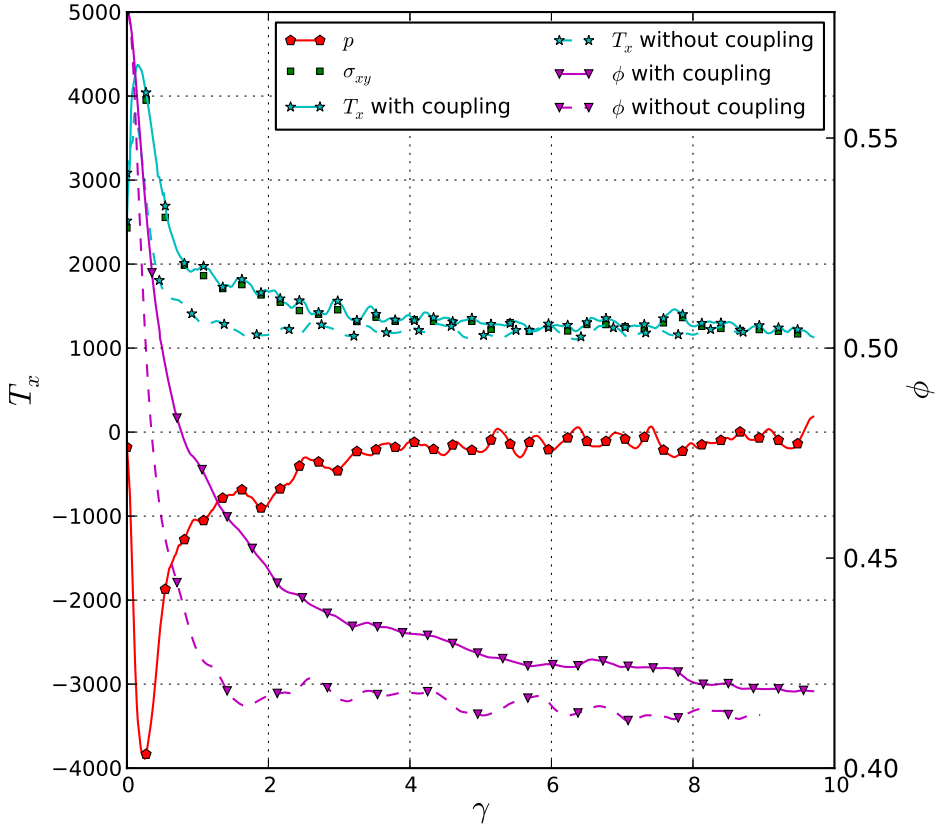
Two regimes are observed:

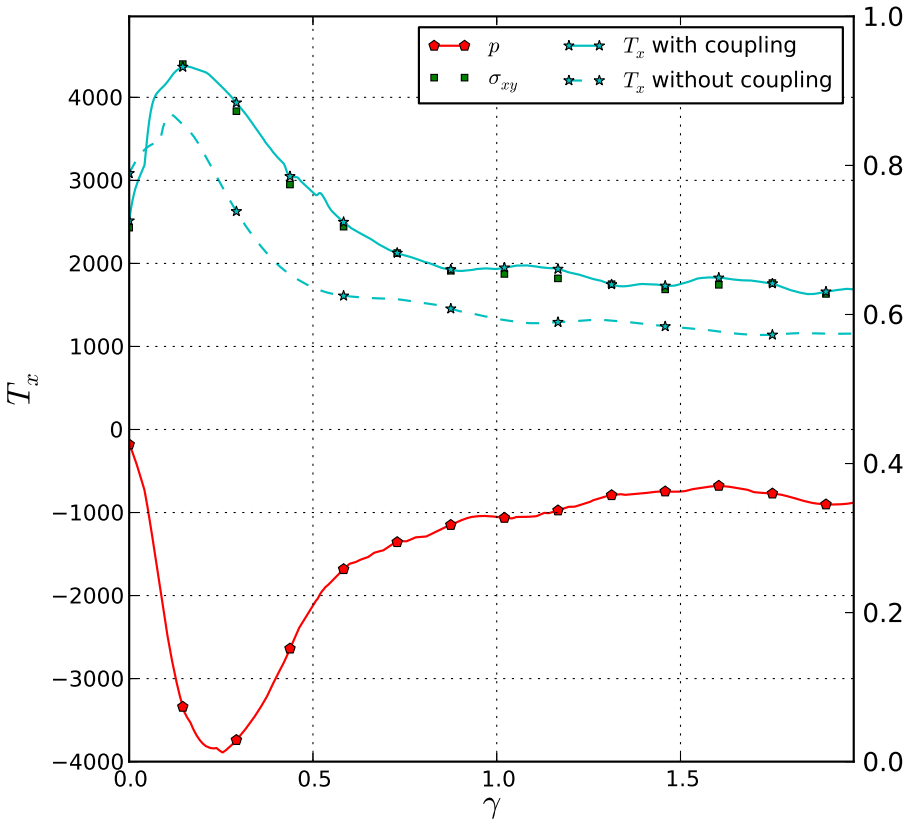
- low I_v, contacts are important.
- At high I_v, lubrication is important.

$\rightarrow$ Consistent with Boyer law:

$$\mu(I_v) = \underbrace{\mu_1 + \frac{\mu_2 - \mu_1}{I_0/I_v + 1}}_{\mu^C} + \underbrace{I_v + \frac{5}{2}\phi_m I_v^{1/2}}_{\mu^H}$$

Shear stress





The poromechanical coupling has an effect on the transient regime and not on the steady regime.

Plan

* A complete micro-hydrodynamical framework has been developed, including solid contact interactions, short range hydrodynamic interactions, and poromechanical couplings.

* The numerical model matches very well rheometer experiments on model materials.

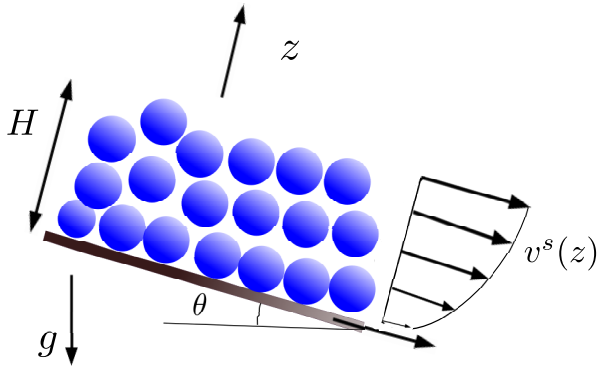
* This framework is general and it lets one analyse, namely:

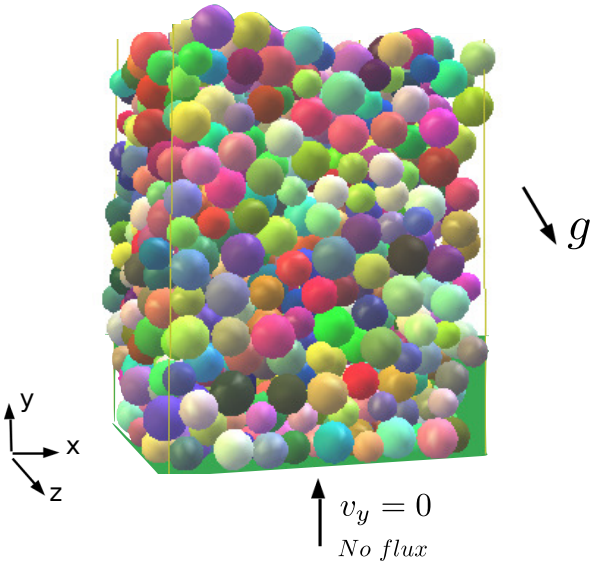
1- the transition between a dense stable material and a flowing material

2- the rheology at very large deformations

* Potential applications range from triggering, runoff, and stabilisation of debris flows, to sediments morphodynamics.

Application to granular avalanches: dependance on the fluid viscosity and the angle of inclination: collaboration with P.Dutto (UPM Madrid)





Thanks for your attention