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Micro-Macro Transition for Weakly Wet Granular Materials

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Motivation

How does material behave

subject to external shear?

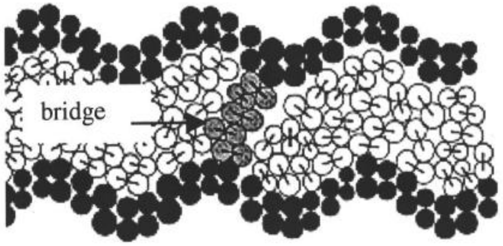
Significant progress in modelling of dry granular materials under shear

for frictionless/ frictional/ cohesive materials

But

Many applications in industrial or agricultural processes involve

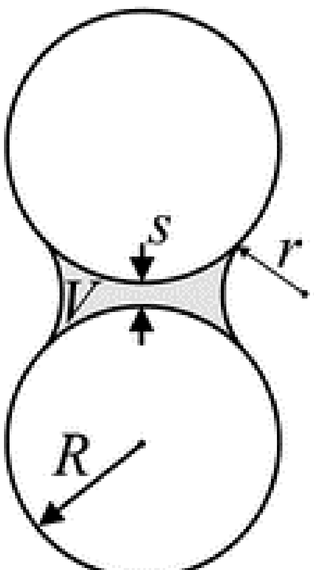
grains and interstitial fluids



Which

May strongly influence the mechanical properties and rheology of flow

Pendular Regime



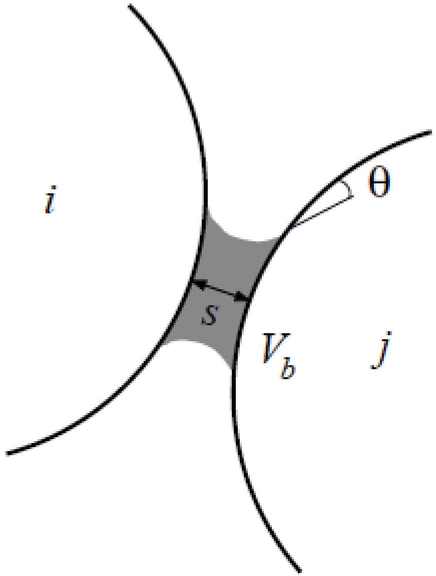
- Liquid Bridge between two spherical particles produces an adhesion force

- Adhesion force arises from the capillary pressure in the bulk of the liquid and due to surface tension at the three phase of contact

- Pendular Regime: Maximum bulk saturation $s^*_{max} \approx 0.3$, corresponding liquid bridge volume $(V_b)_{max} \approx 284$ nl for an average particle radius of 1.1 mm

- Working bridge volumes in the simulation V_b : [0, 4.2, 20, 75, 140, 200] nl < $(V_b)_{max}$

Willett’s Model for Capillary Forces between Spheres



Capillary bridge force between the particles:

$$f_{ij,c} = \frac{2\pi\gamma R\cos\theta}{1 + 1.05\bar{s} + 2.5\bar{s}^2}$$

where

$$\bar{s} = s\sqrt{\frac{R}{V_b}}$$

θ — *Contact angle of the liquid on the spherical particle*

γ — *Surface tension*

R — *Harmonic mean radius of particles*

V_b — *Liquid bridge volume*

s — *Separation distance*

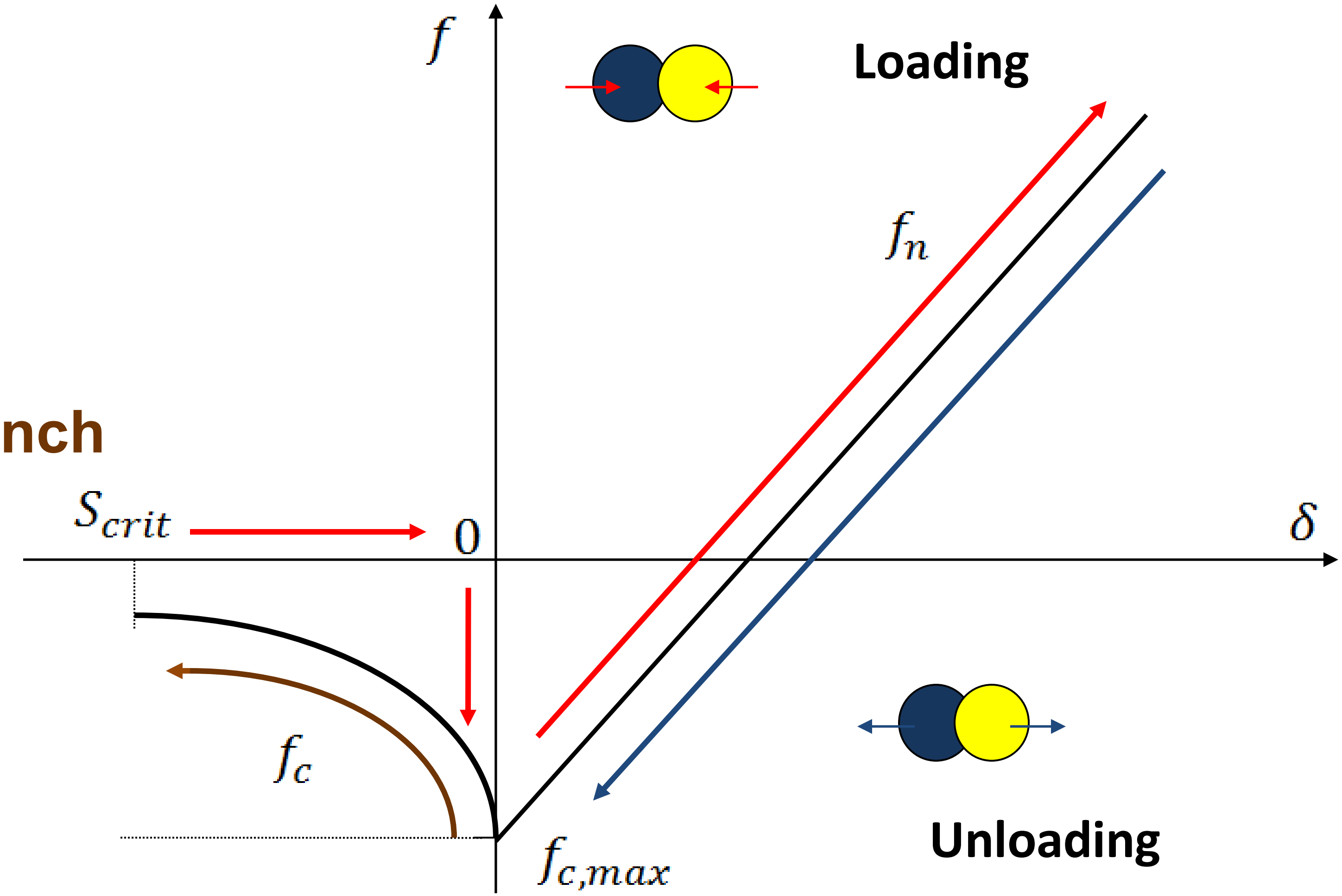
Willett, C.D., Adams, M.J., Johnson S.A. and Seville J.P.K.. 2000. *Capillary Bridges between Two Spherical Bodies.* Langmuir 16.

Liquid - Bridge + Linear Contact Model

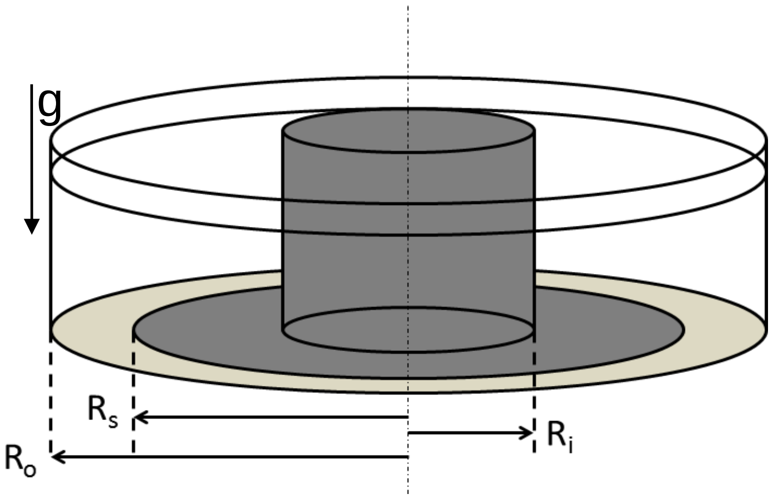
Loading

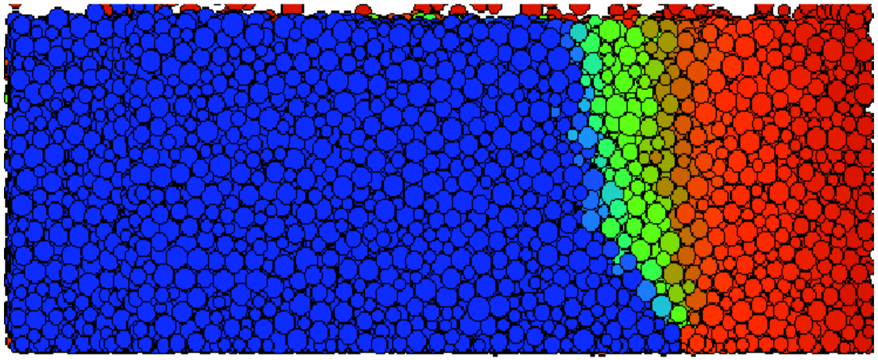
Unloading

Unloading
Adhesive branch



Split Bottom Shear Cell: Simulation Setup

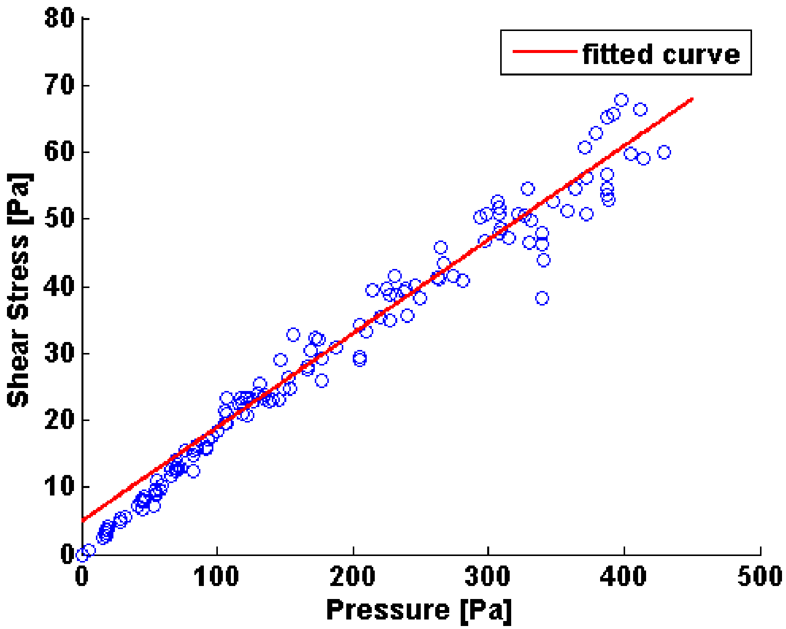




- Polydisperse particles of average size distribution 1.1 mm radius and a range of 0.1892
- Wide and stable shear band
- No side wall effect

Fenistein, D. and Hecke, M. V. 2003. Kinematics – wide shear zones in granular bulk flow. Nature , 425.

Effect on Shear Stress: Macroscopic Cohesion



For 75 nl liquid bridge volume, inside shear band region, at every height of shear cell, strain rate

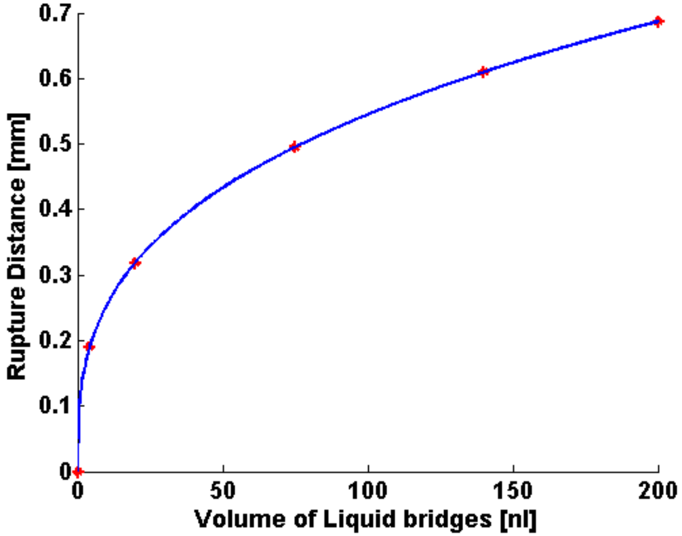
$$\dot{\gamma} > 0.8\,\dot{\gamma}_{\mathrm{max}}$$

Inside shear band region

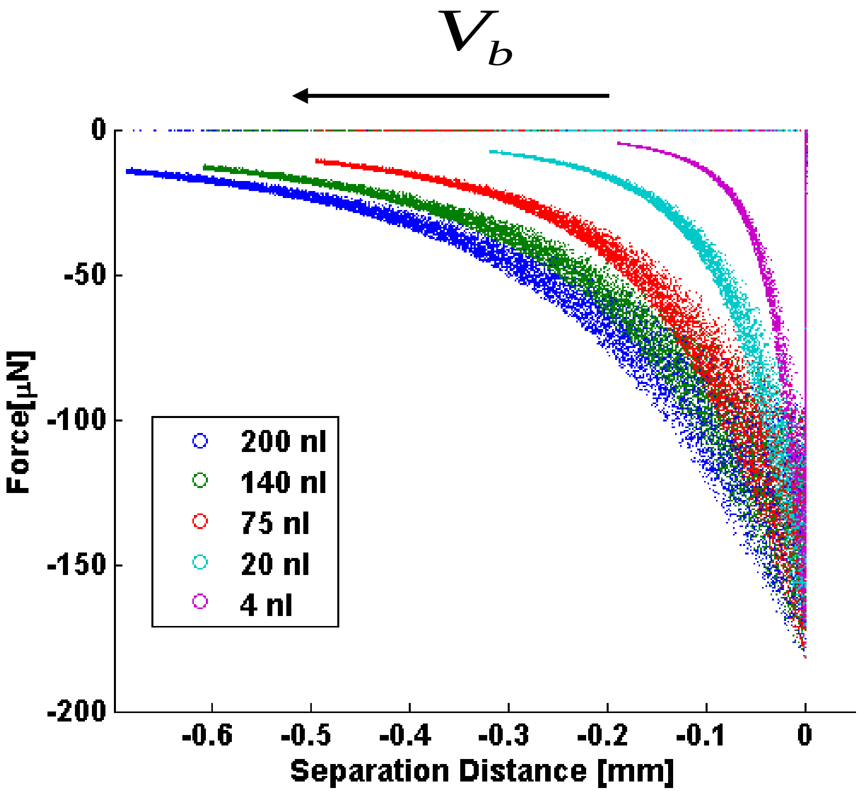
$$\tau = \mu_m P + c$$

$$c = f(V_b, \gamma)$$

Liquid – bridges with different bridge volumes



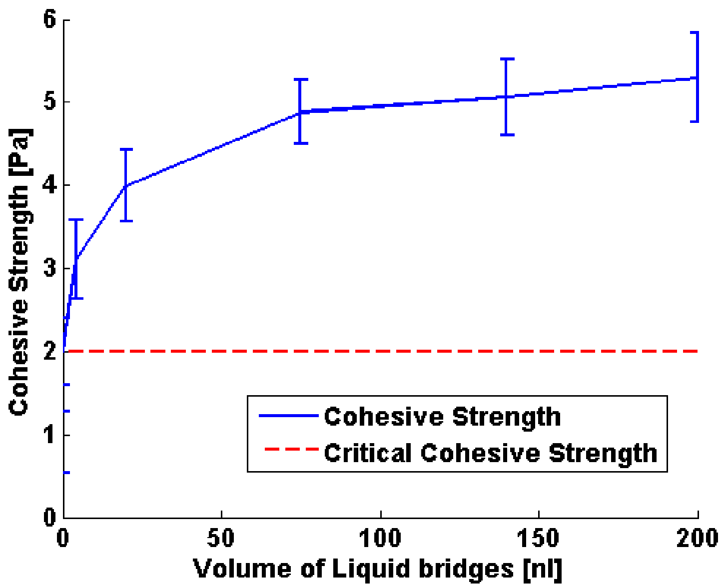
$$S_c = V_b^{1/3}(1+\frac{\theta}{2})$$

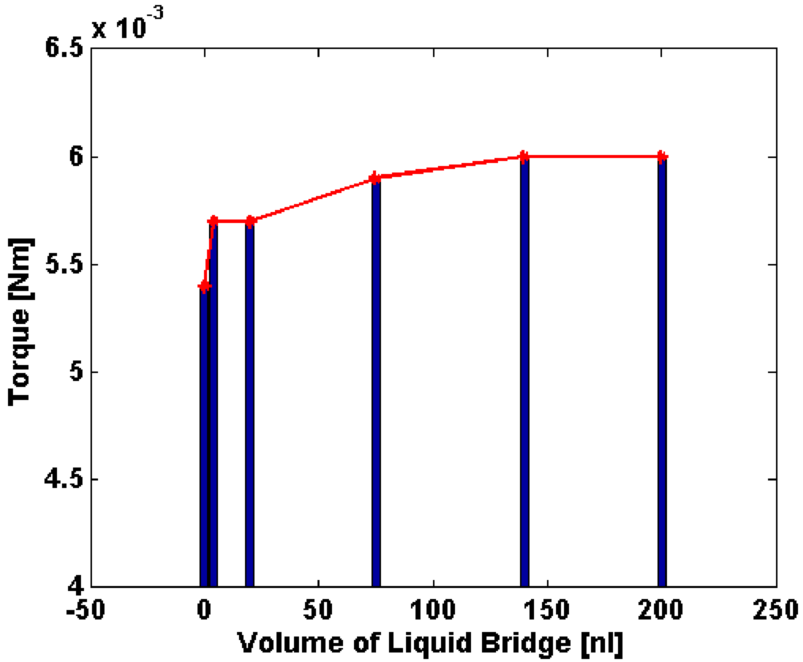


- Maximum force at s = 0 is independent of the liquid bridge volume
- Interaction distance increases with increase in liquid bridge volume

Lian et al. [1993]

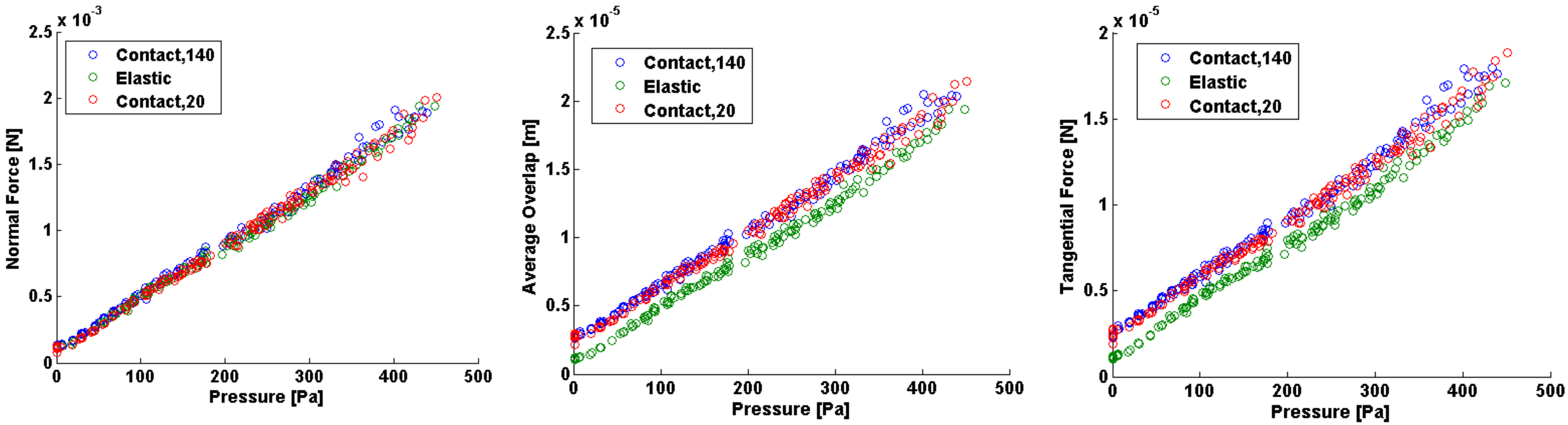
Cohesive strength and torque as a function of liquid volume





- Critical cohesive strength : $c^* = c(V_b = 0)$
- Cohesive strength increases with increase in liquid bridge volume $\longrightarrow$ torque increases

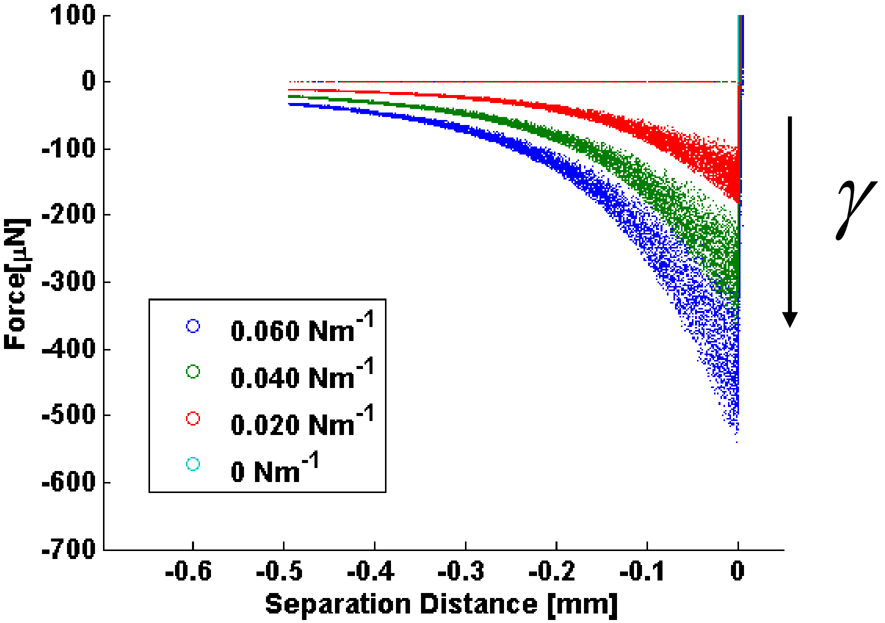
Forces for particles in contact for different liquid bridge volumes



With increase in V_b :

- Average number of contacts increases slightly
- Average normal force remains the same
- Average overlap remains same but higher than non-cohesive system
- Average tangential force same but higher than non-cohesive system

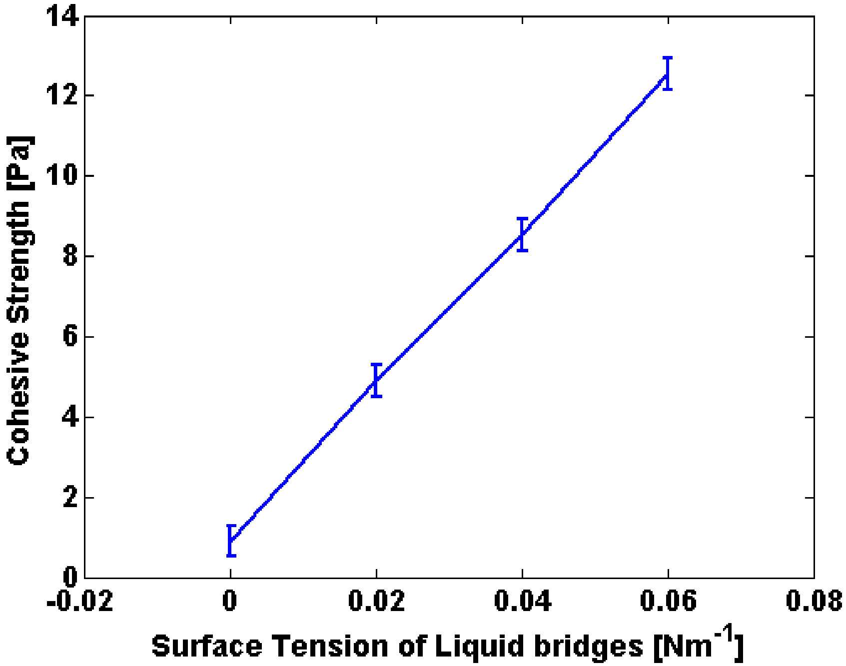
Liquid – bridges with different surface tension of liquid

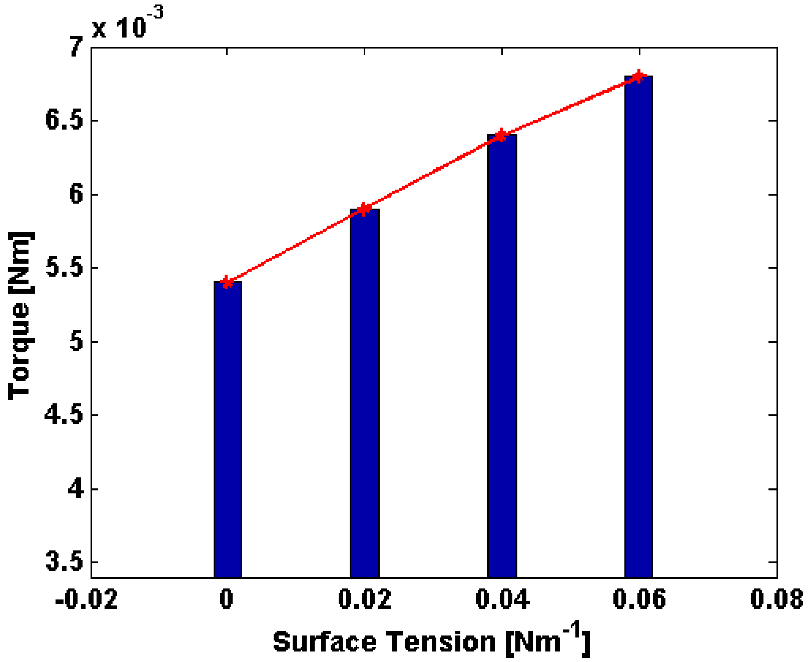


$$f_{\max} = 2\pi\gamma R\cos\theta$$

- Maximum force at s = 0 increases with increase in surface tension
- Interaction distance is independent of surface tension

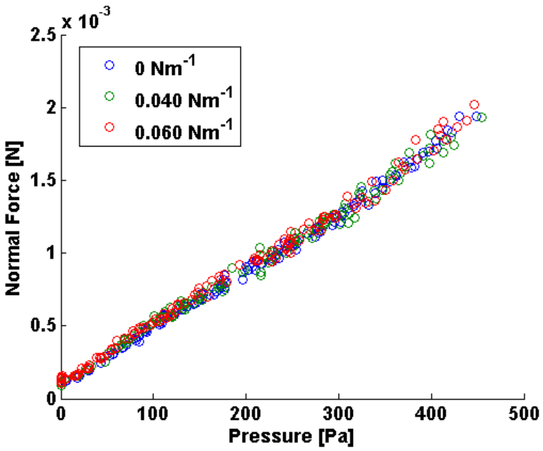
Cohesive strength and torque as a function of surface tension

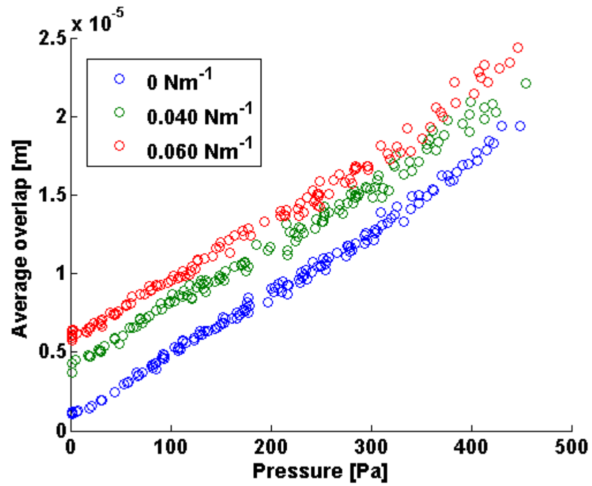


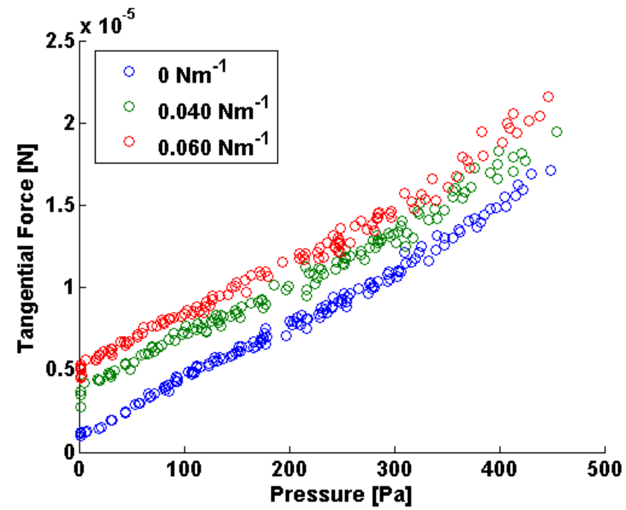


- Cohesive strength increases linearly surface tension ⟶ torque increases

Forces for particles in contact for different surface tension of liquid







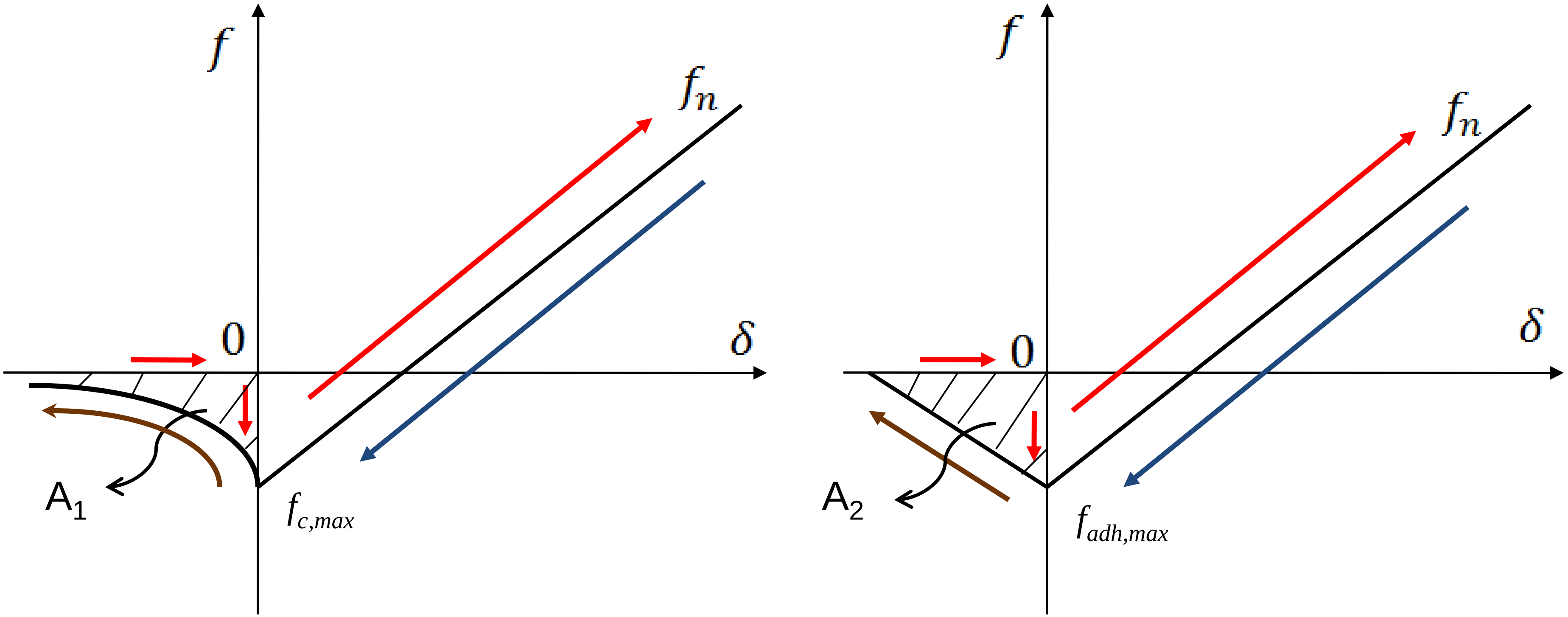
With increase in γ :

- Average number of contacts increases slightly
- Average normal force remains the same
- Average overlap increases
- Average tangential force increases

Conclusion

- Macroscopic cohesive strength increases with increase in liquid content and surface tension of liquid
- Validity of the models can be tested by experimentally measuring the average torque required to rotate the system
- Distinguish between the macro properties dependence on maximum force and interaction distance
- Higher microscopic friction coefficient may result in higher shear stress
- Way forward to develop analogy between linear and non-linear adhesive models from the derivations of micro-macro correlations

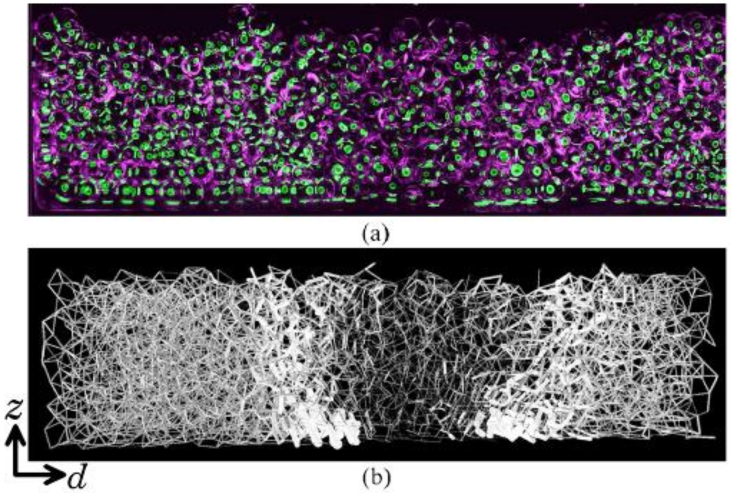
Future work: Analogy between the non-linear and linear adhesive models



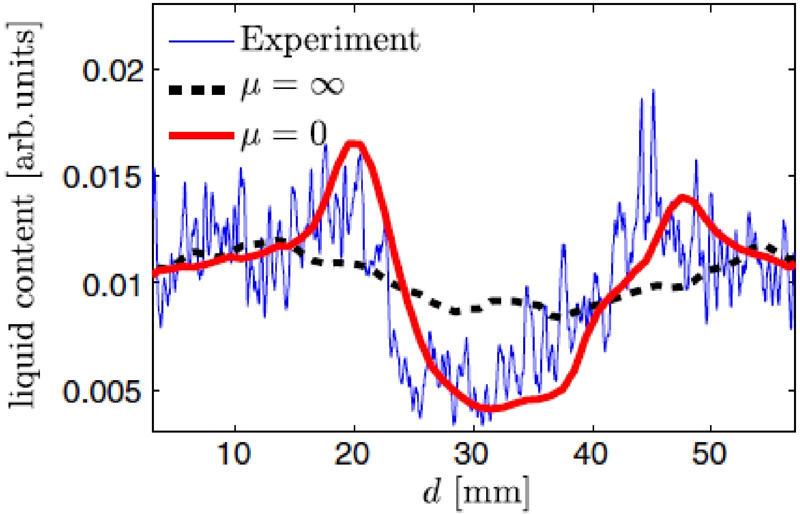
Key Parameters:

- $A_1 = A_2$ (adhesive energy)
- $f_{c,\max} = f_{adh,\max}$ (maximum adhesive force)

Future Plan: Fluid Migration in Sheared granular Media



Shear Band in “Split- Bottom Cell” filled with moist granules a) Experiment b) Simulation



Depletion in humidity inside the shear band

Mani, R., Kadau, D. and Or, D. 2012. Fluid Depletion in Shear Bands. Physical Review Letters 109.

Future Plan: Study the Effect of Liquid Bridge on

- Determining the shear band position and width for different cohesive strength by the least energy dissipation principle
- Probability distribution of normalized force
- Study the analogy between linear and non-linear adhesive models
- Study the effect of fluid migration
- Comparisons with experimental results and CFD simulations

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Thank You