Basic mechanical properties of cohesive granular materials
Numerical studies by DEM.

A collaboration with Antonio Castellanos and Francisco Gilbert, 2003-2008

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Navier

- **Simple model in 2D, circular grains, to understand the effects of cohesion.**
- **assembling process, initial state**
- **isotropic compression**
- ***recent developments in 3D models (capillary cohesion)***

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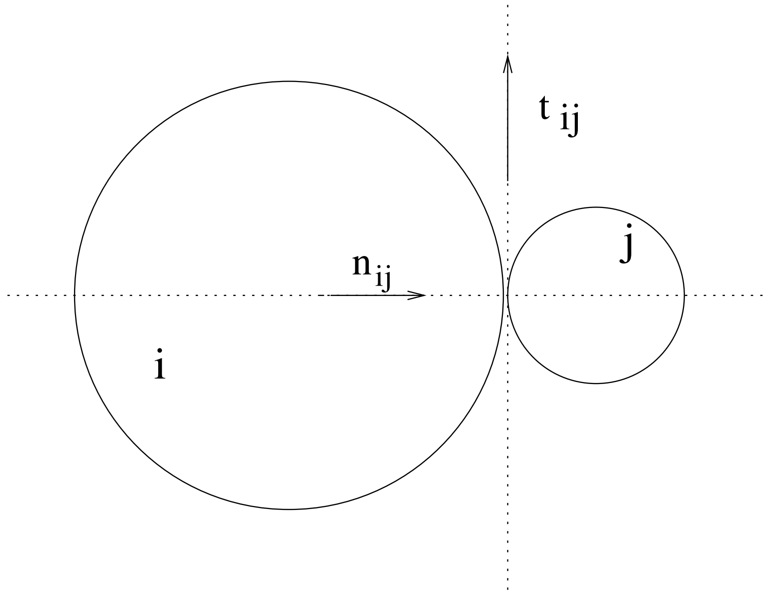
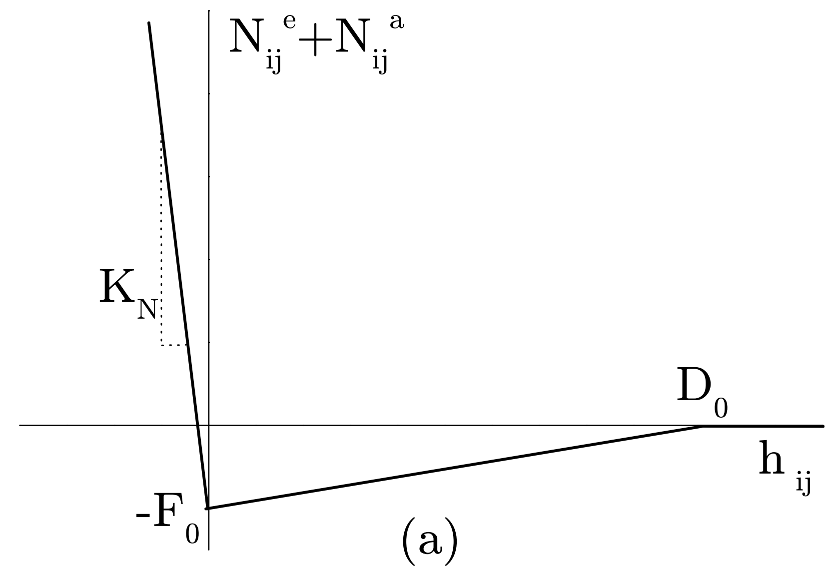
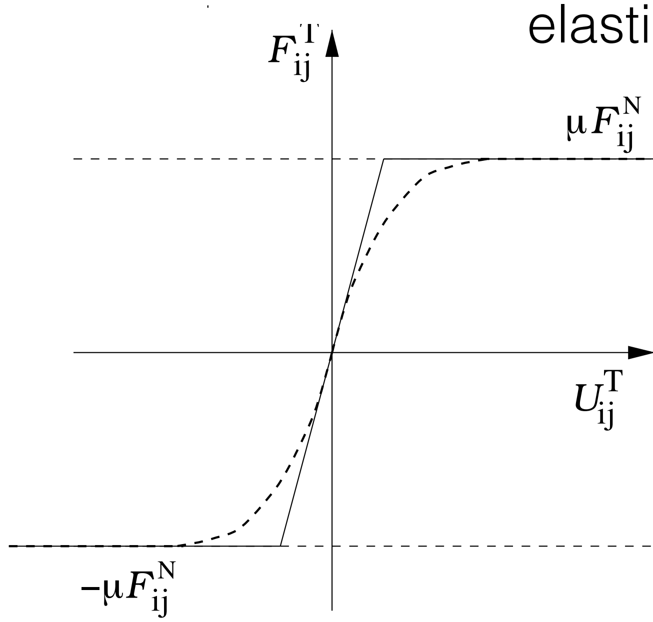
Basic ingredients of the model: contact laws

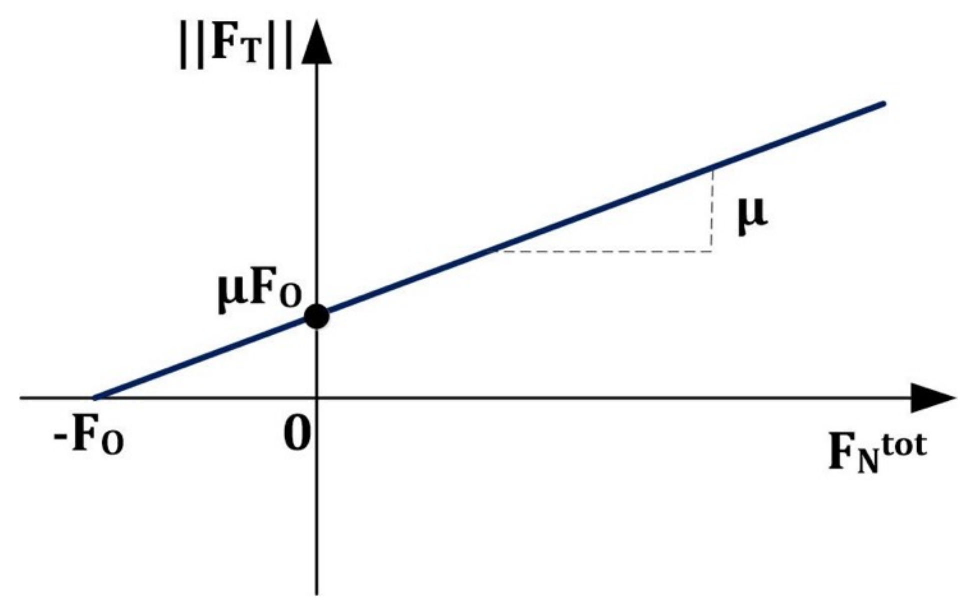


Normal contact force:
elastic + adhesive terms

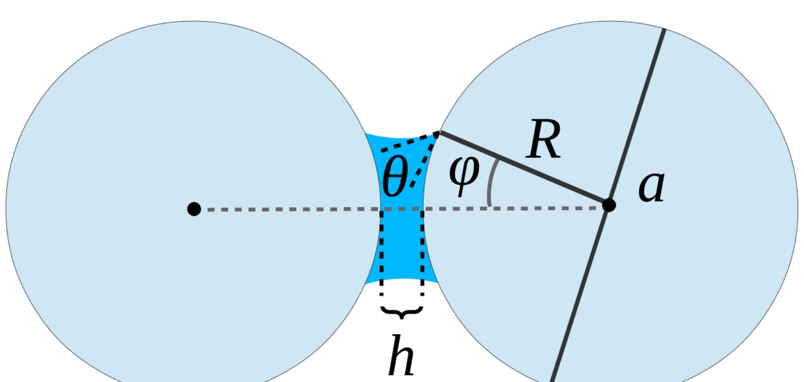


Tangential force:
elasticity + Coulomb friction





3D model for beads with capillary forces caused by liquid menisci

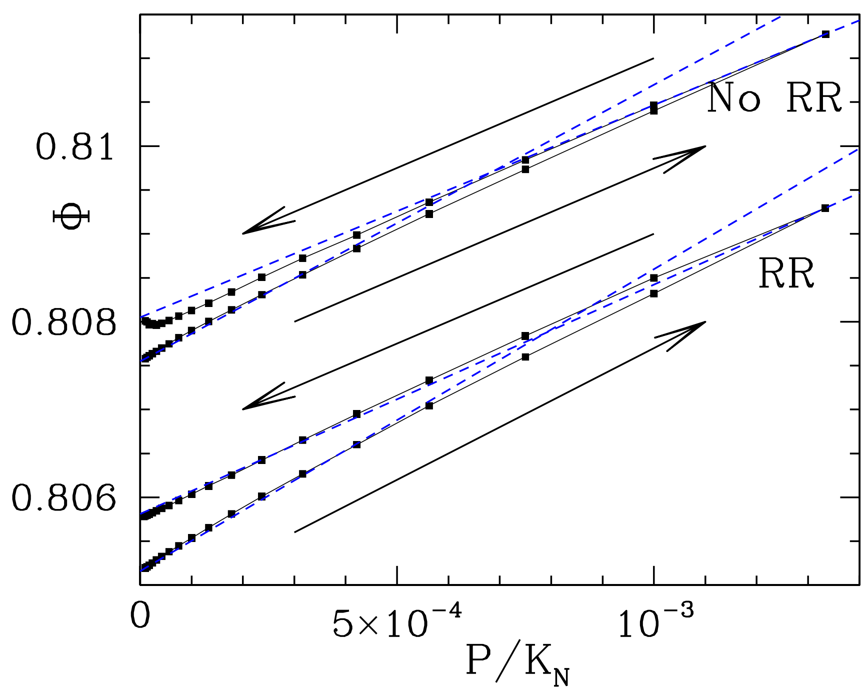


With $F_0 = \pi \Gamma a$ (Γ = surface tension)

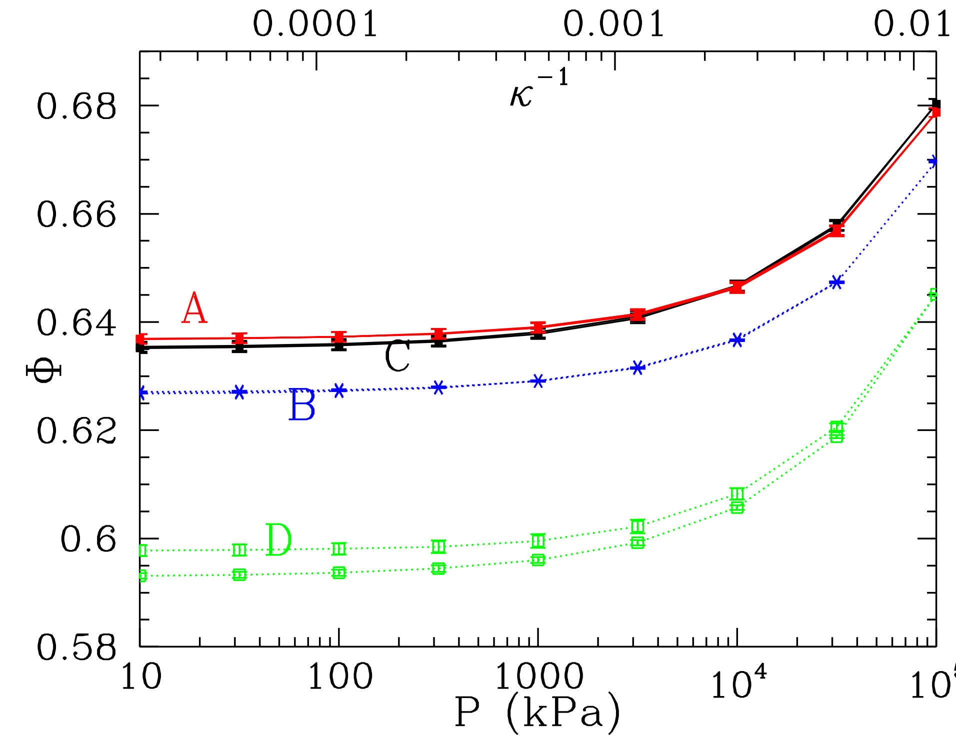
$$F^{cap} = -F_0 \quad \text{if } h < 0 \text{ (contact, deflection } -h)$$

$$F^{cap} = -F_0 \left[1 - \frac{1}{\sqrt{1 + \frac{4V}{\pi a h^2}}} \right] \quad \text{if } 0 \le h \le D_0 \text{ (rupture distance } V^{1/3})$$

Assembling and compressing cohesionless systems

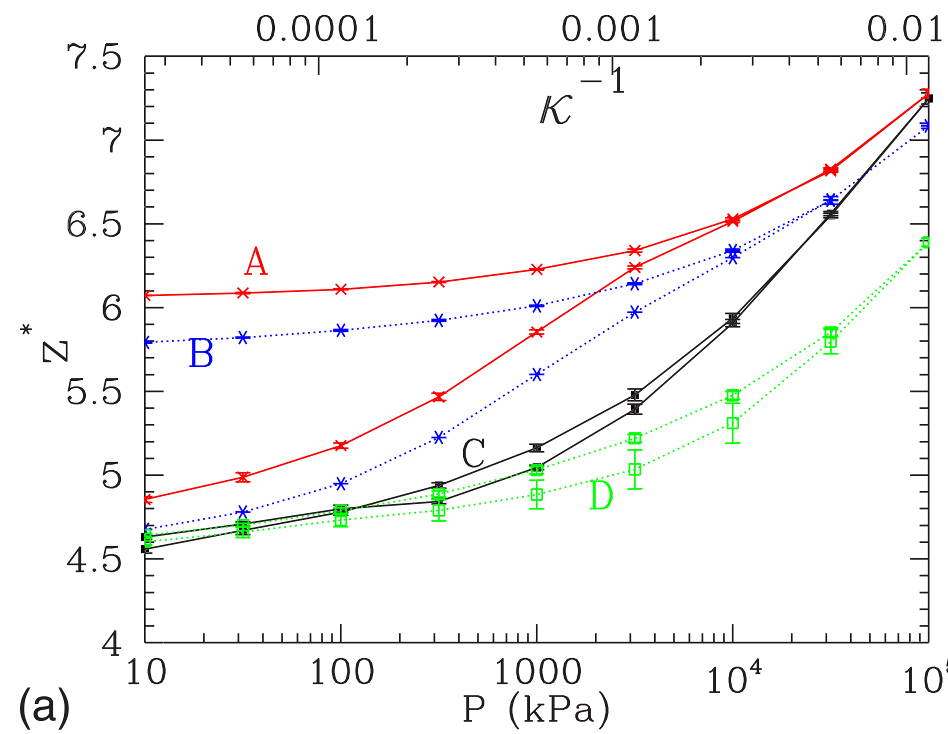


2D model (polydisperse disks)
Solid fraction versus pressure



3D model (monodisperse glass beads)

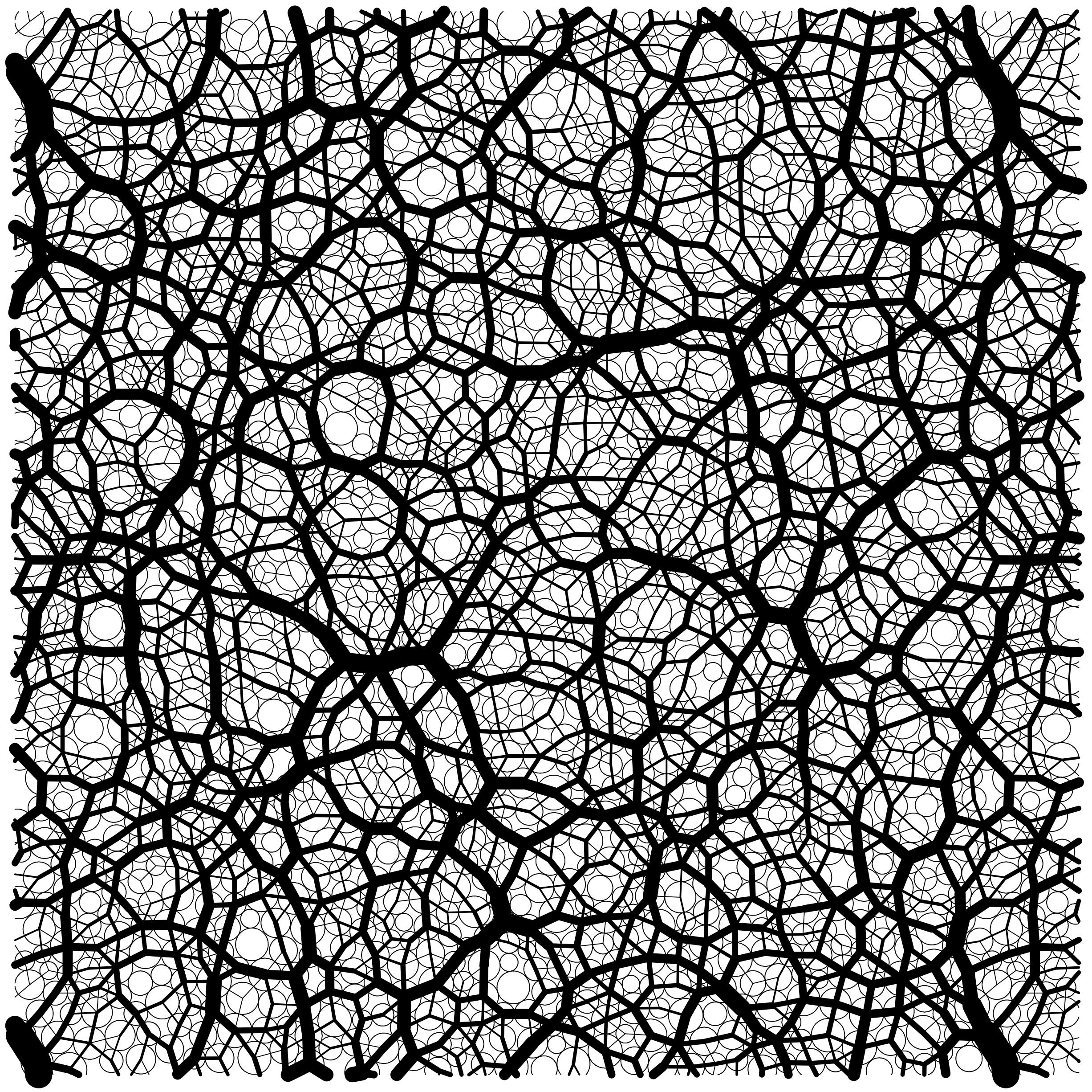
Agnolin & Roux 2007



(a)

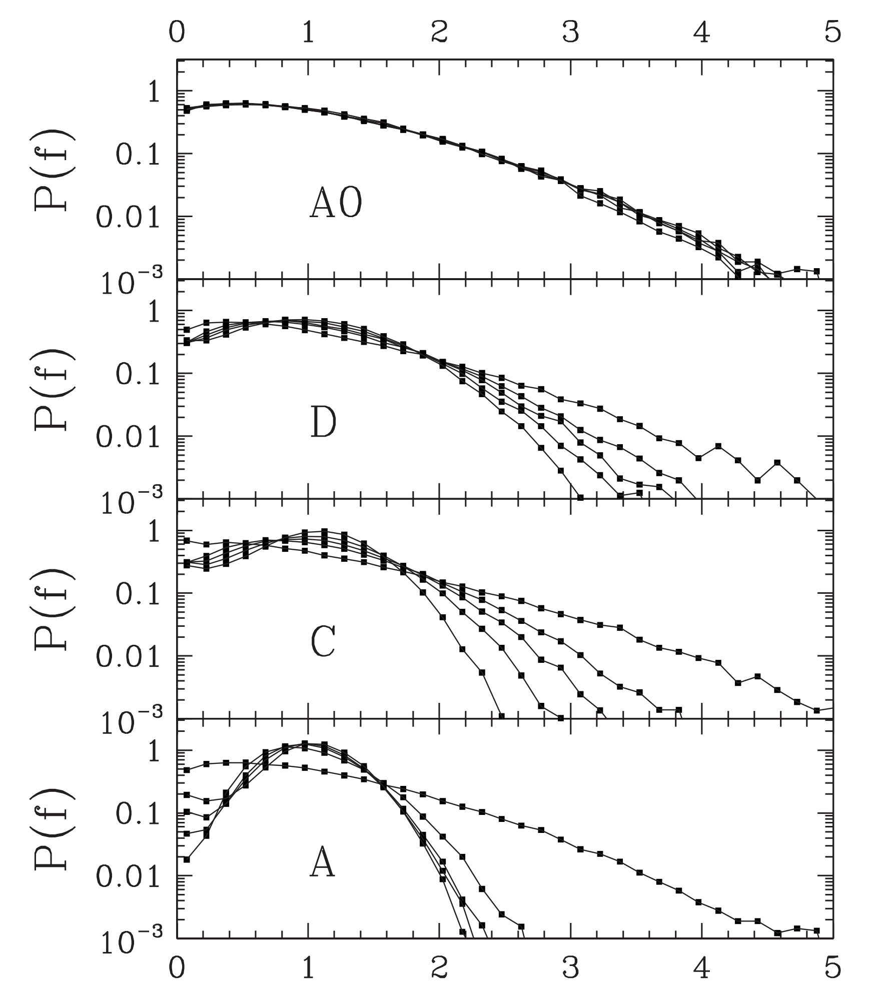
- Possible to assemble different initial states in some density range
- Compression nearly reversible (not quite)
- *Coordination number might change notably in compression cycle*

Force transmission in cohesionless packings



'force chain' patterns

(normalized) force distributions
under growing P



New control parameter in cohesive system: reduced pressure P*

$$P^* = \frac{Pa^{D-1}}{F_0} \quad \text{in D dimensions, for grain diameter } a$$

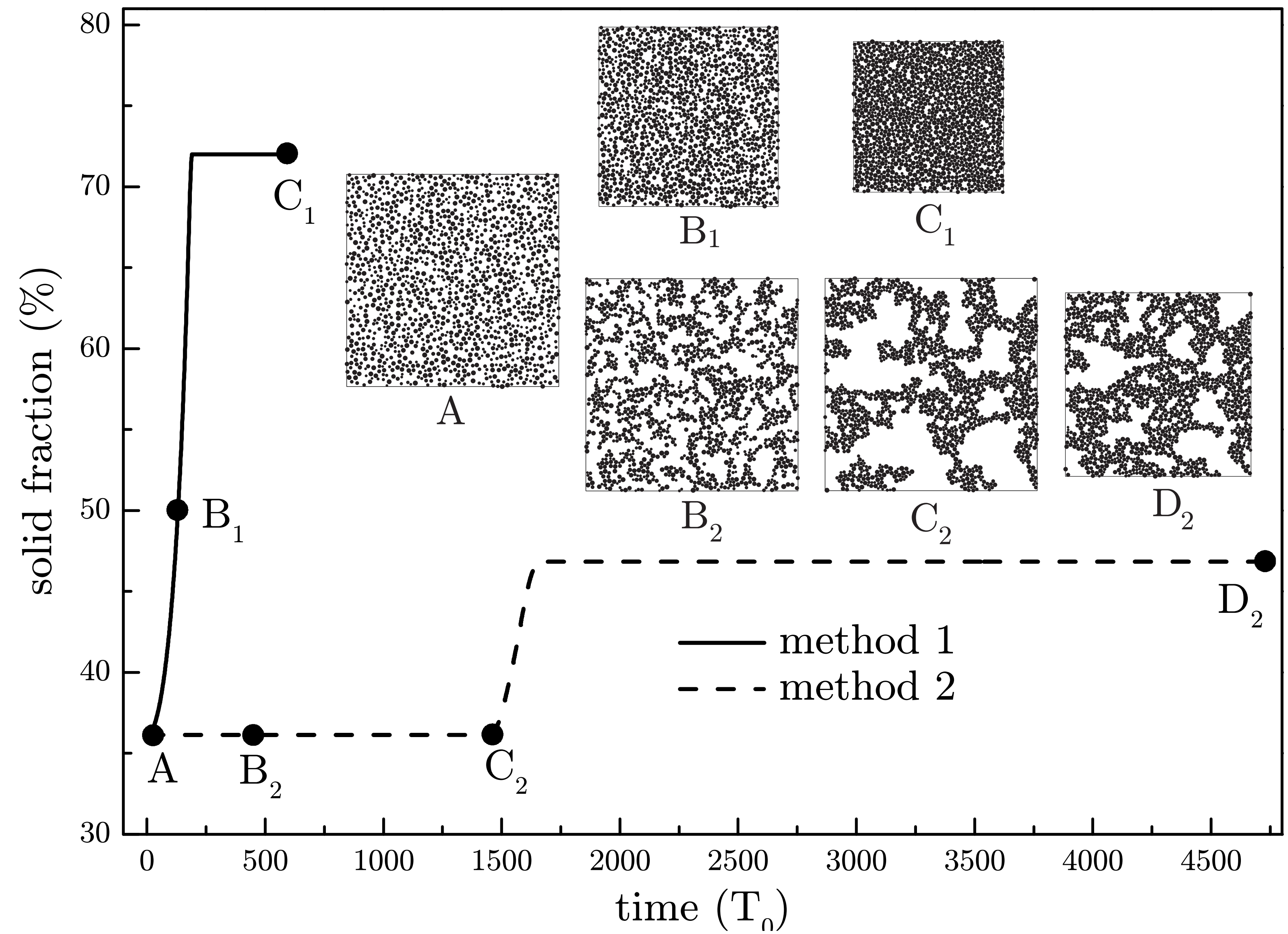
- For P*<< 1, cohesion dominates
- At P*>>1, confining stress dominates

Assembling and compressing initially loose states

Adhesive forces may stabilize loose structures if left to act in ***aggregation stage***
Use ideal numerical procedure: **assemble cohesive aggregates before compressing**:

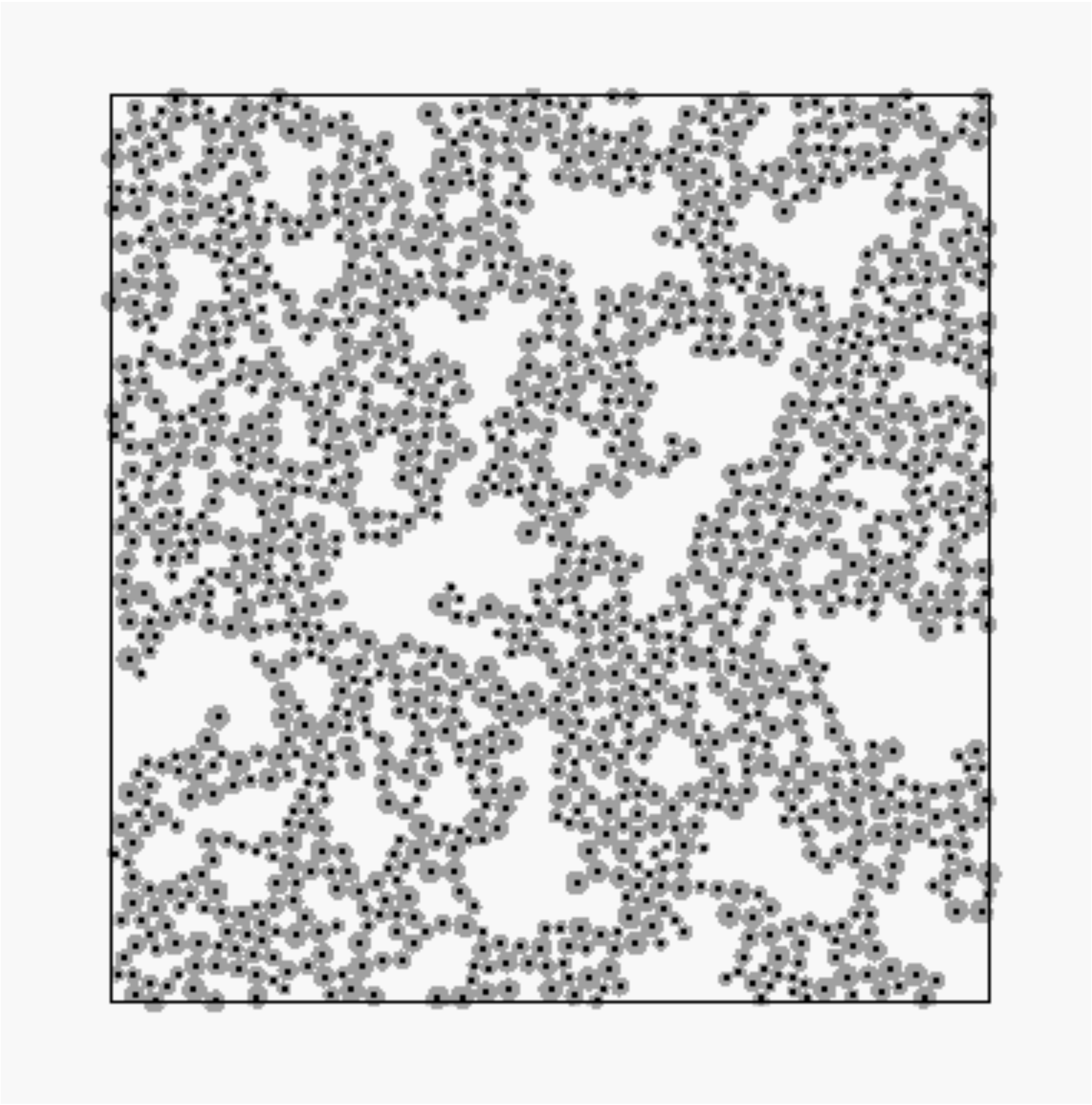
1. Dispersion. Prepare disordered 'granular gas' configuration at low solid fraction Φ_0
2. Aggregation. Give random velocities to grains (Maxwell distribution variance V_0^2), form connected aggregate structure at constant volume. Compare V_0 to $V^* = \frac{1}{m}\sqrt{F_0 D_0}$ (escape attractive potential)
3. Compression. Increase isotropic pressure P, wait for equilibrium at each pressure step.

Assembling initially loose states



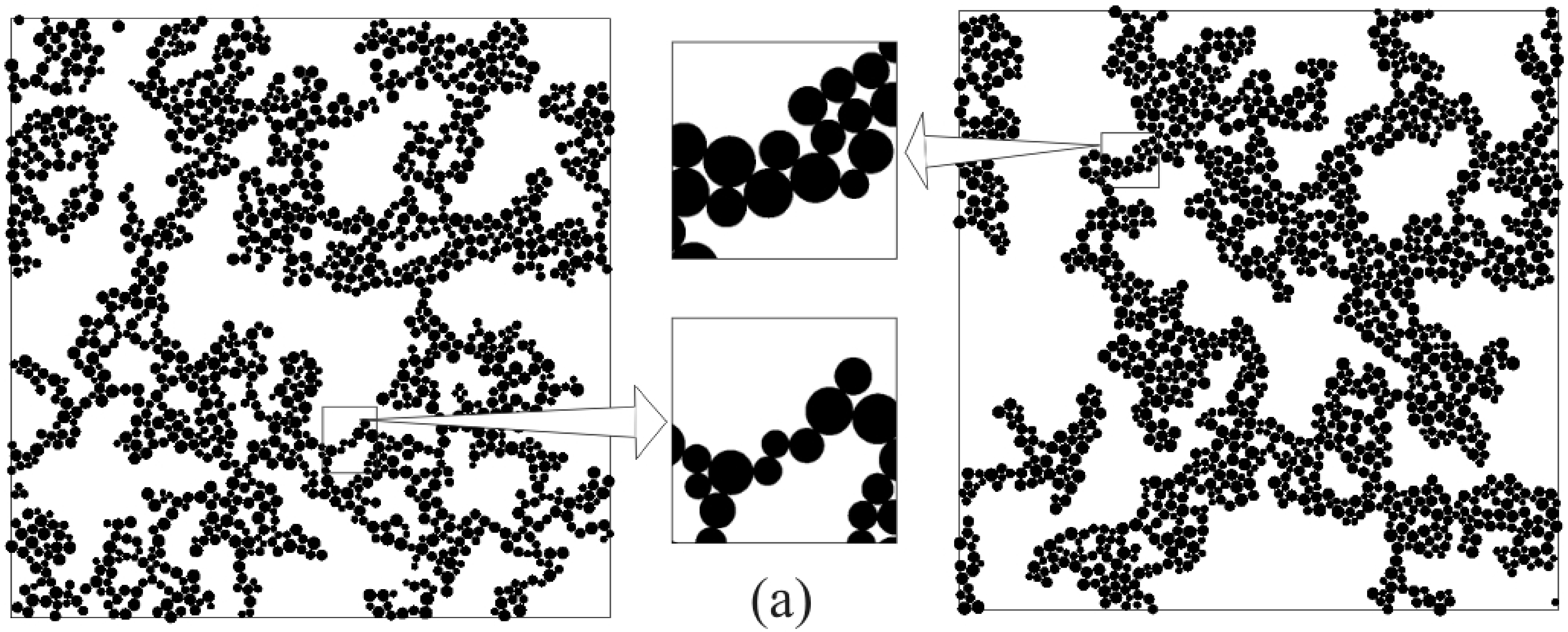
Direct compression (method 1) —> dense states.
Loose states stabilized by aggregation step
First compression to P*=0.01

Aggregation and first pressure step (to P*=0.01)



Reminiscent of colloid aggregation processes
(here, ballistic aggregation)

Role of Rolling Resistance (RR)

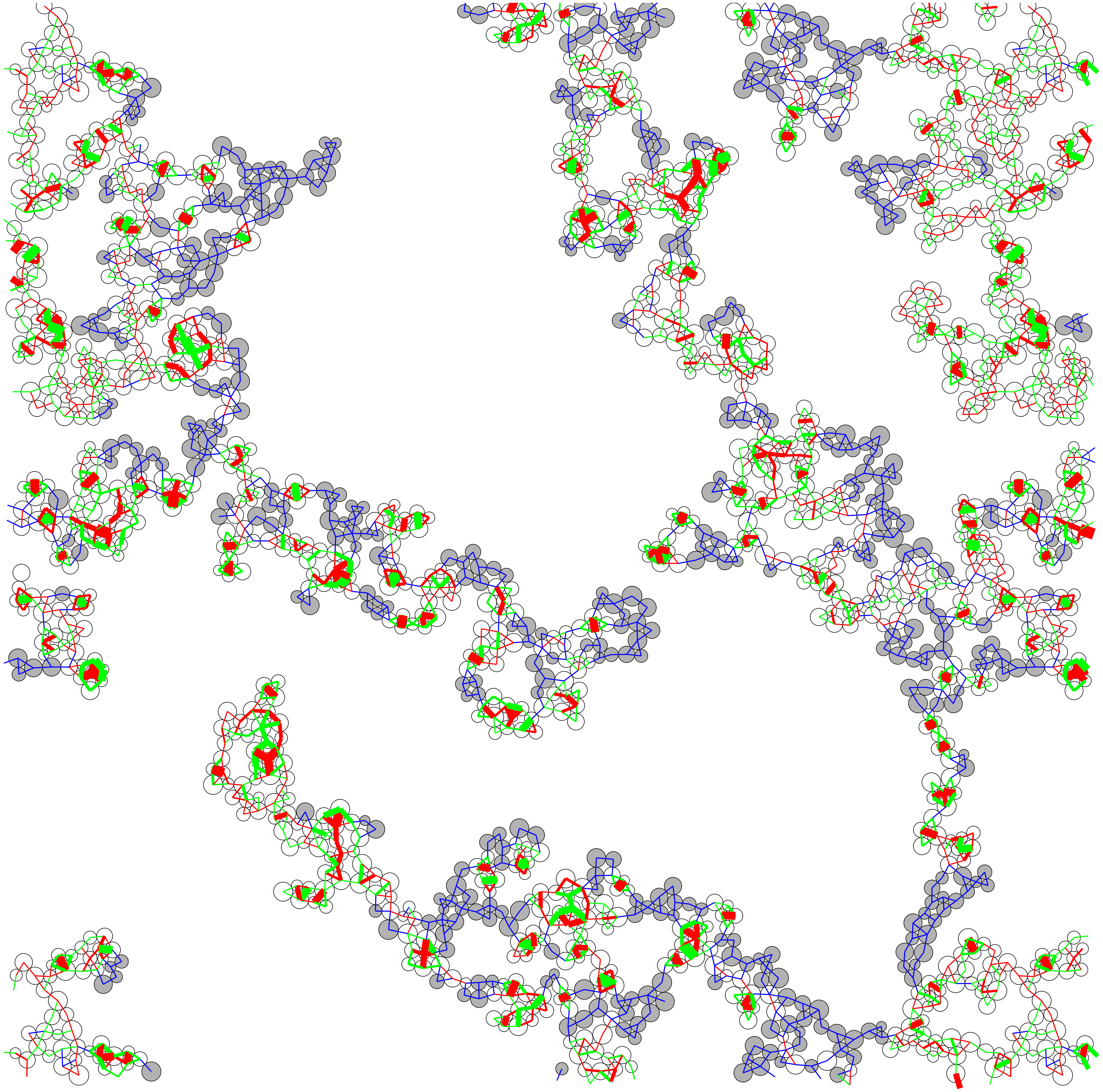

(a)

Analog to Coulomb condition for tangential force, condition on contact rolling moment

$$||\Gamma|| \leq \mu_R F_N$$

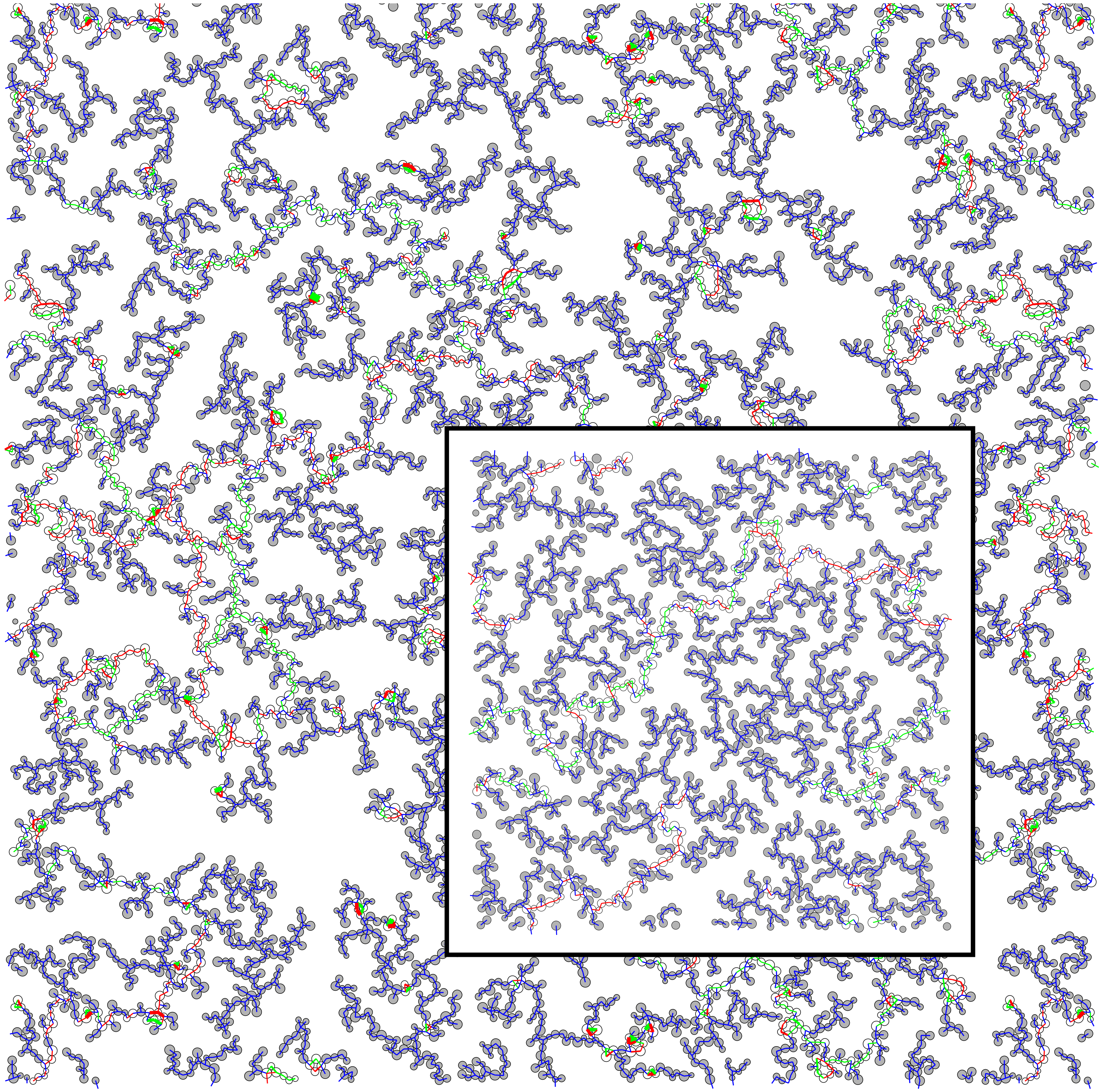
$$\mu_R = \text{length (surface roughness)}$$

Forces in loose structures (no RR) at P = 0



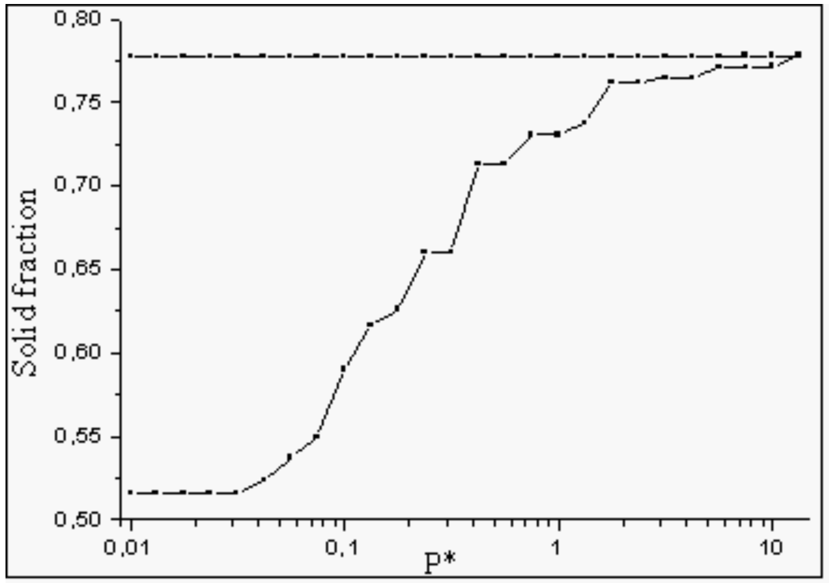
Compensation of repulsive and attractive forces, presence of unstressed grains

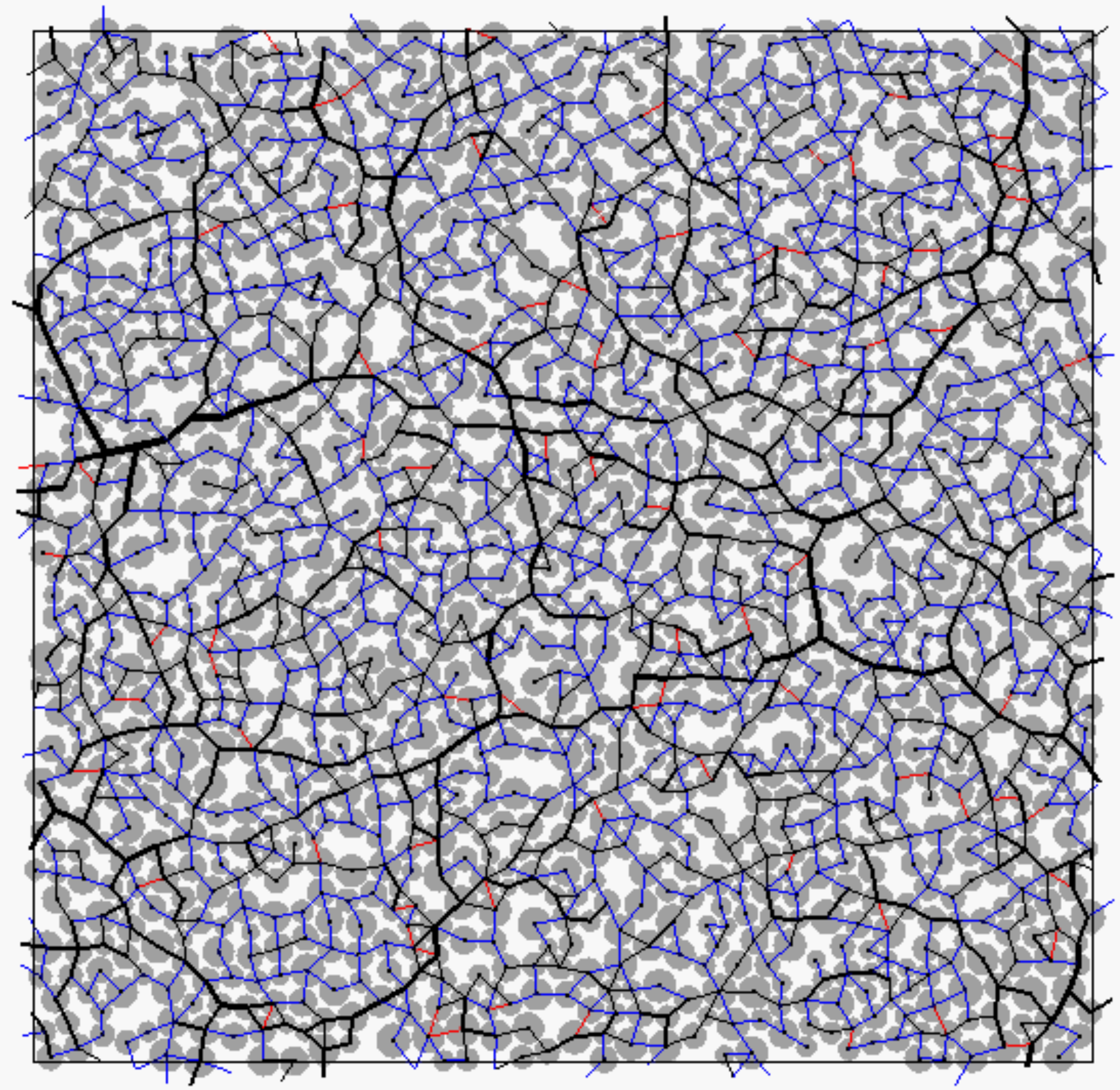
With RR: initial stress

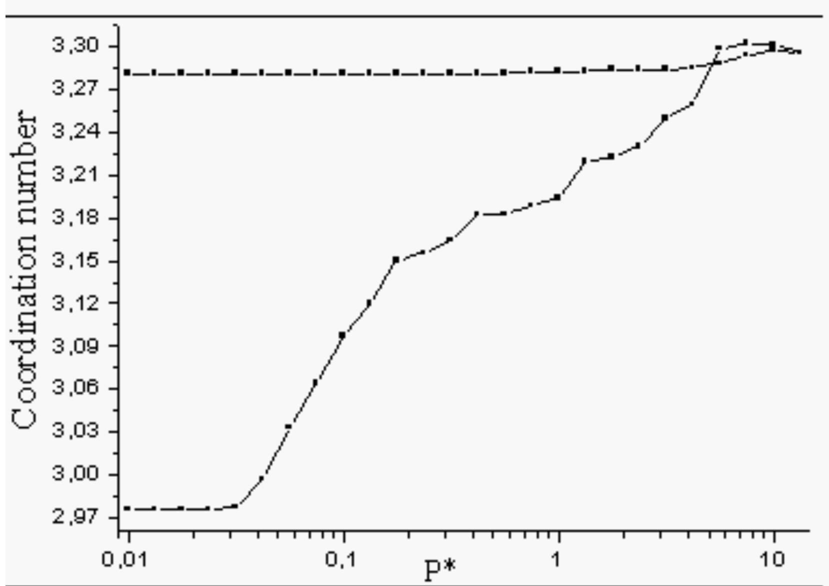


No initial stress for large RR, or very gentle process (low V_0)
Limit of geometric aggregation rule

Quasistatic compression: equilibrium under varying P*







Classically, use void ratio rather than solid fraction

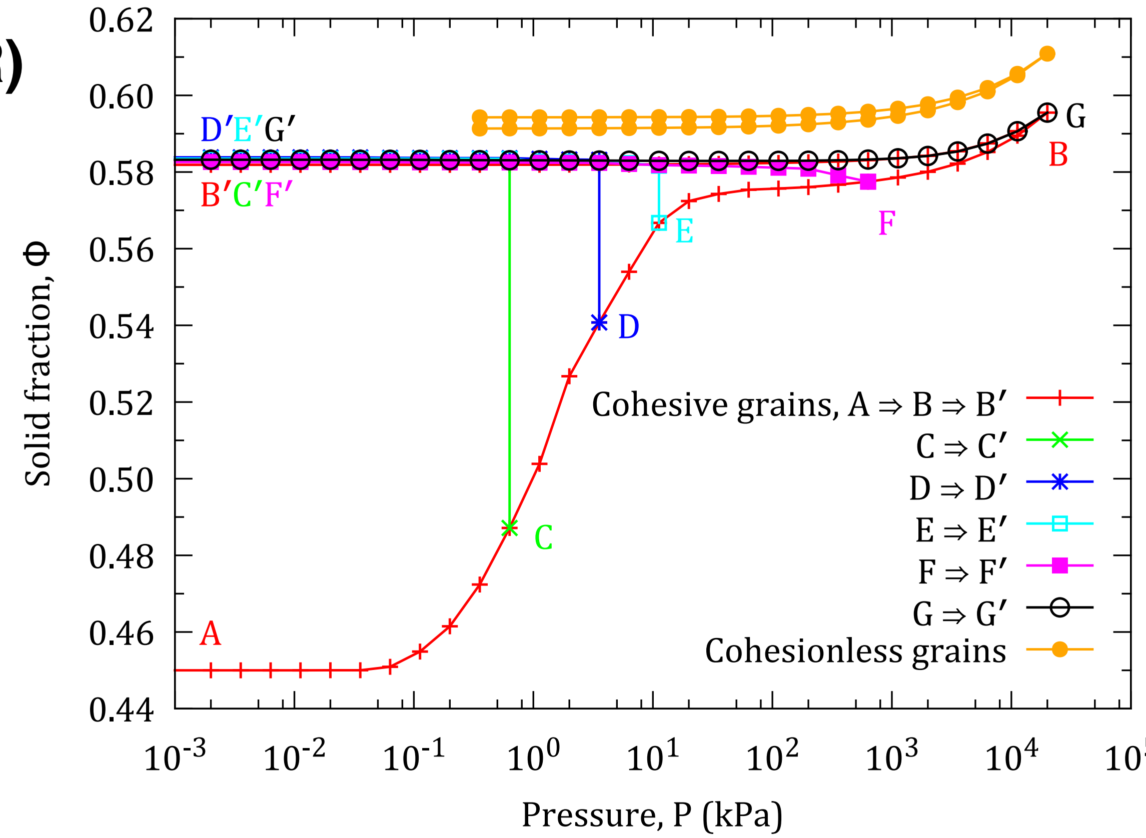
$$e = \frac{1}{\Phi} - 1$$

Macroscopic behaviour: irreversible compression

3D simulation of wet beads (Than, Tang & JNR)

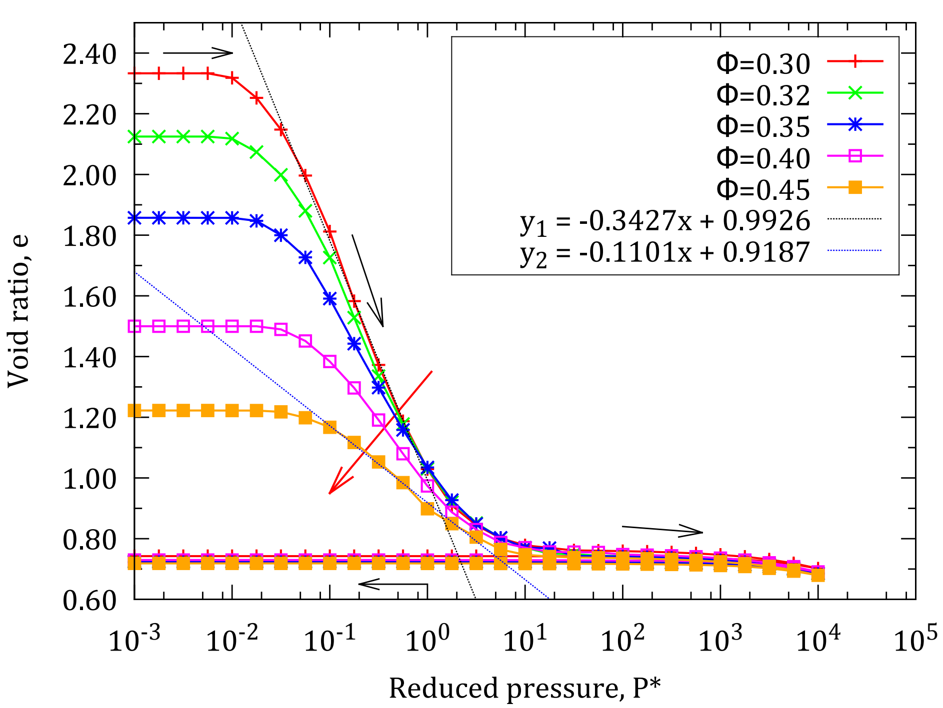
Equilibrated loose configurations under low P*, compression in 3 stages:
(I) stability, (II) collapse,
(III) cohesionless behavior at large P*

Without cohesion: nearly reversible,
small compression due to contact deflections

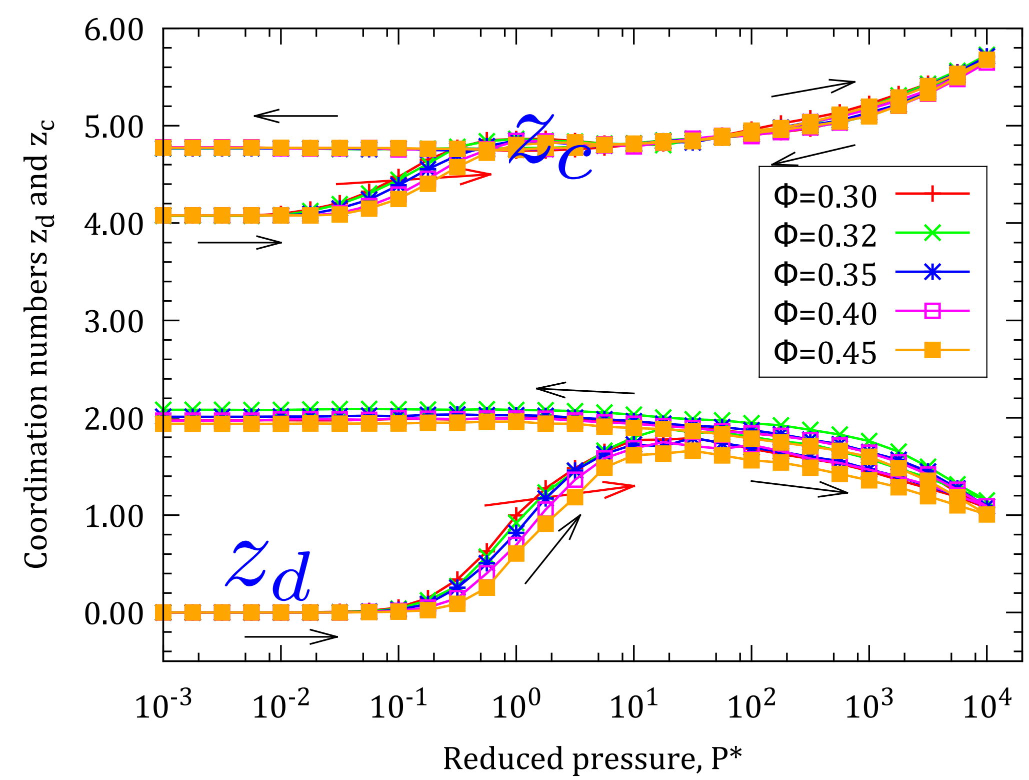


Effect of initial solid fraction

Void ratio versus pressure on log scale



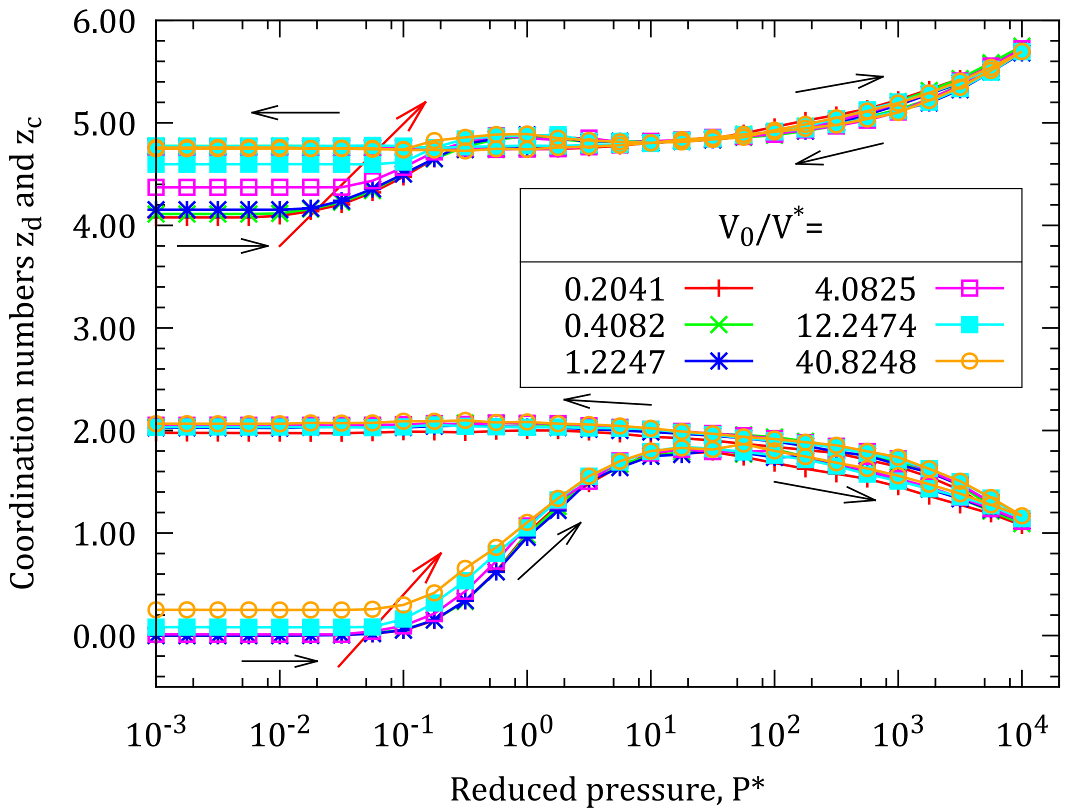
Curves converge to same final states at high P*

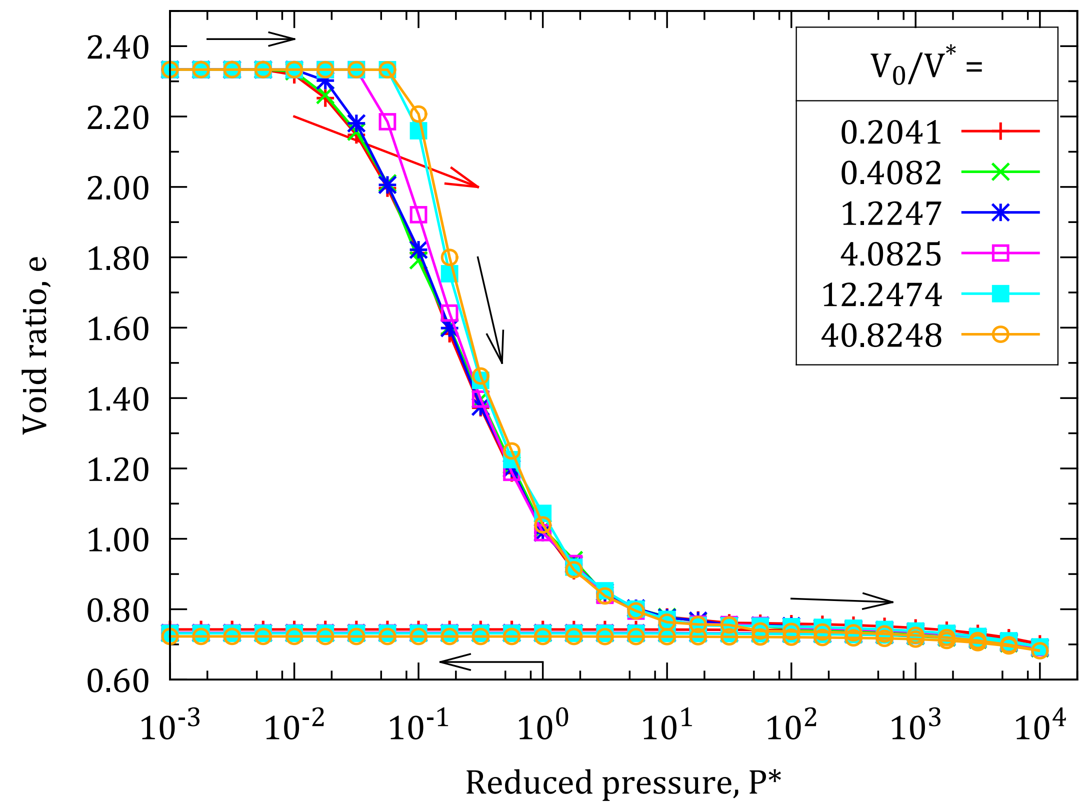


Contact and distant coordination numbers
in compression cycle

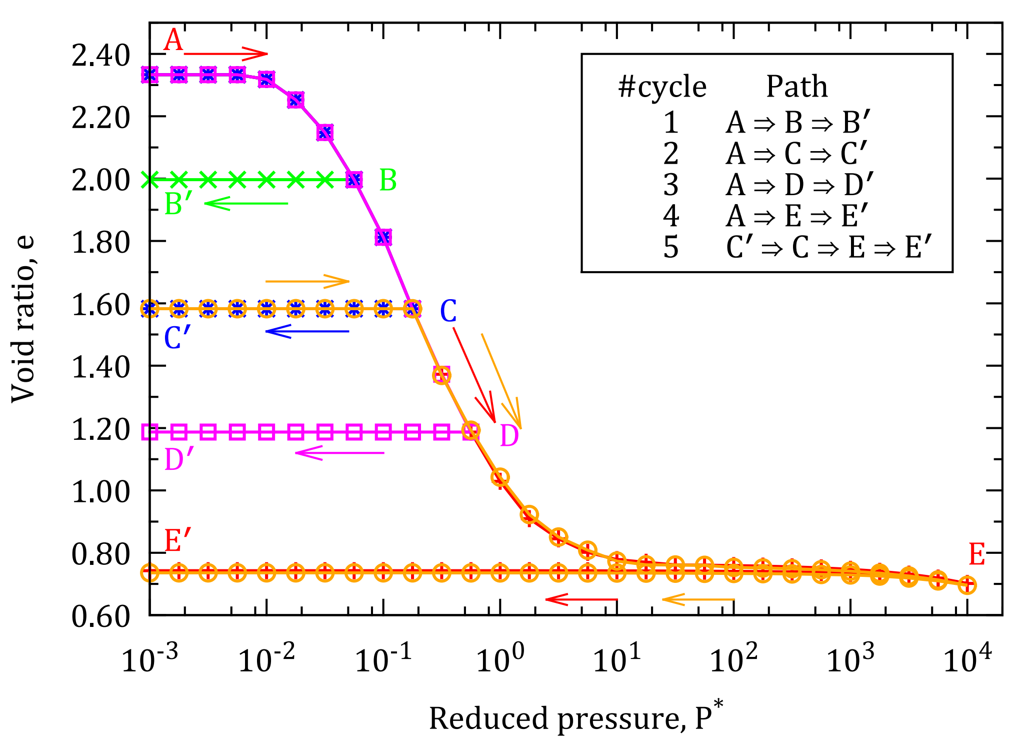
Irreversible compression

Effect of initial coordination number (related to ratio V_0/V^* in aggregation stage)



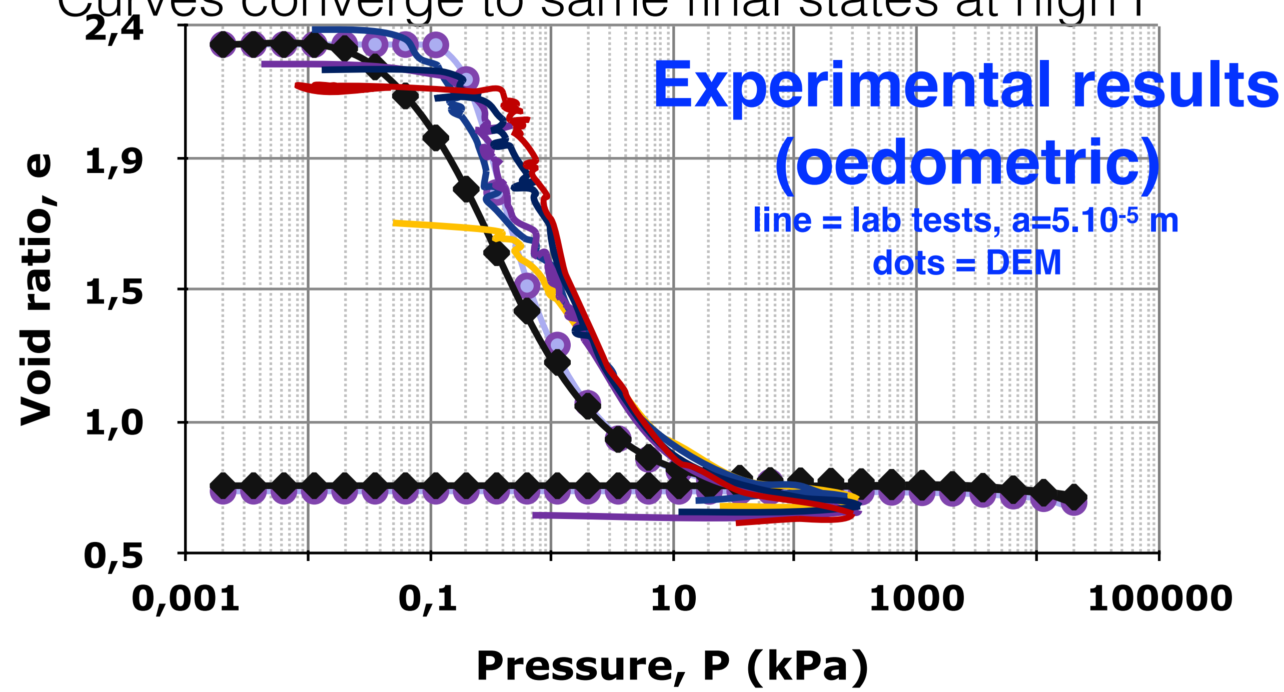


Unloading at intermediate P*

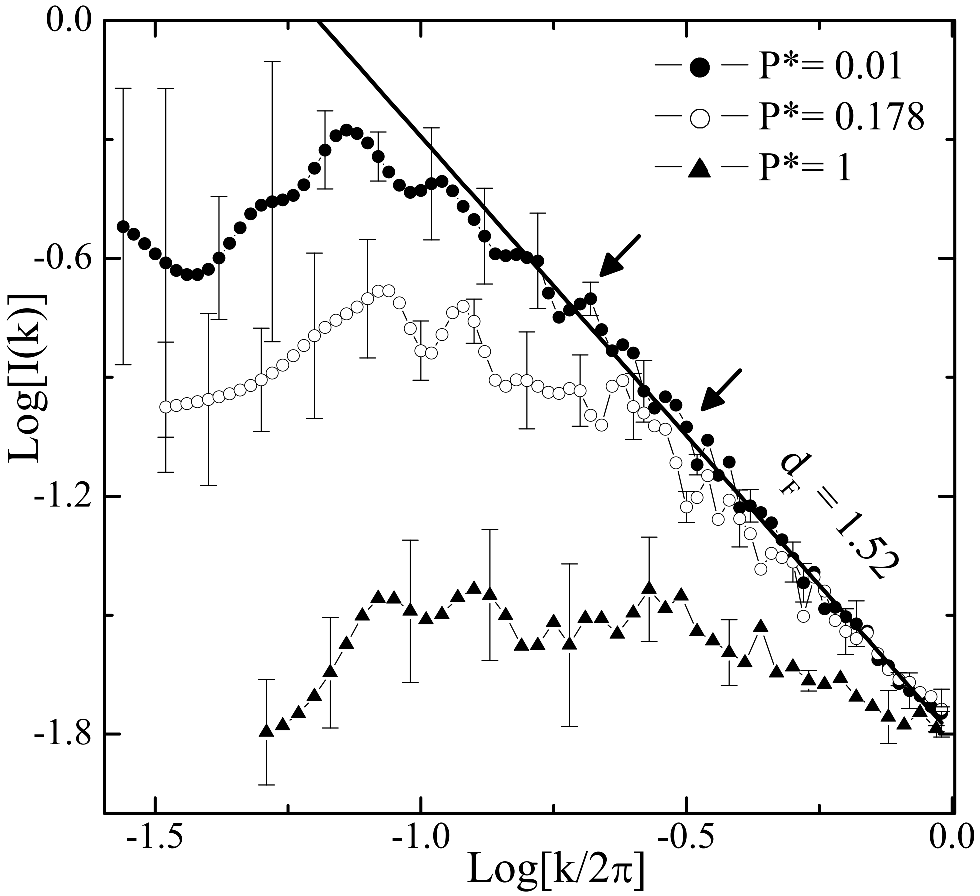


Initial plateau (regime I) wider for larger z

Curves converge to same final states at high P*



Fractal blob at intermediate scale
(fractal dimension corresponds to ballistic aggregation process)

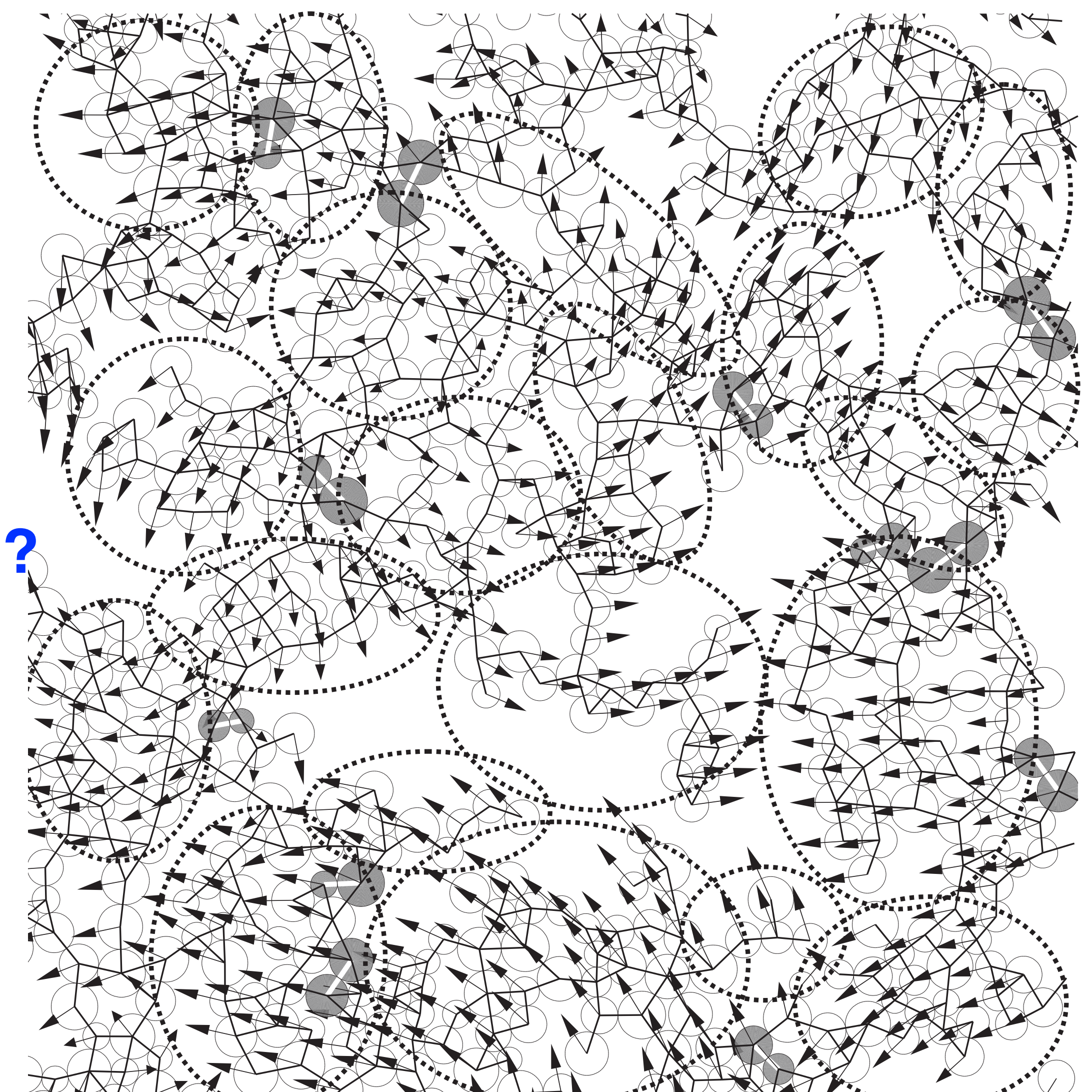


Structure factor I(k)

$$I(k) \propto k^{-d_F} \quad \text{for } a \ll \frac{2\pi}{k} \ll \xi$$

Fractal blob size $\xi \propto \Phi^{\frac{-1}{2-d_F}}$

Mechanism of irreversible compression ?



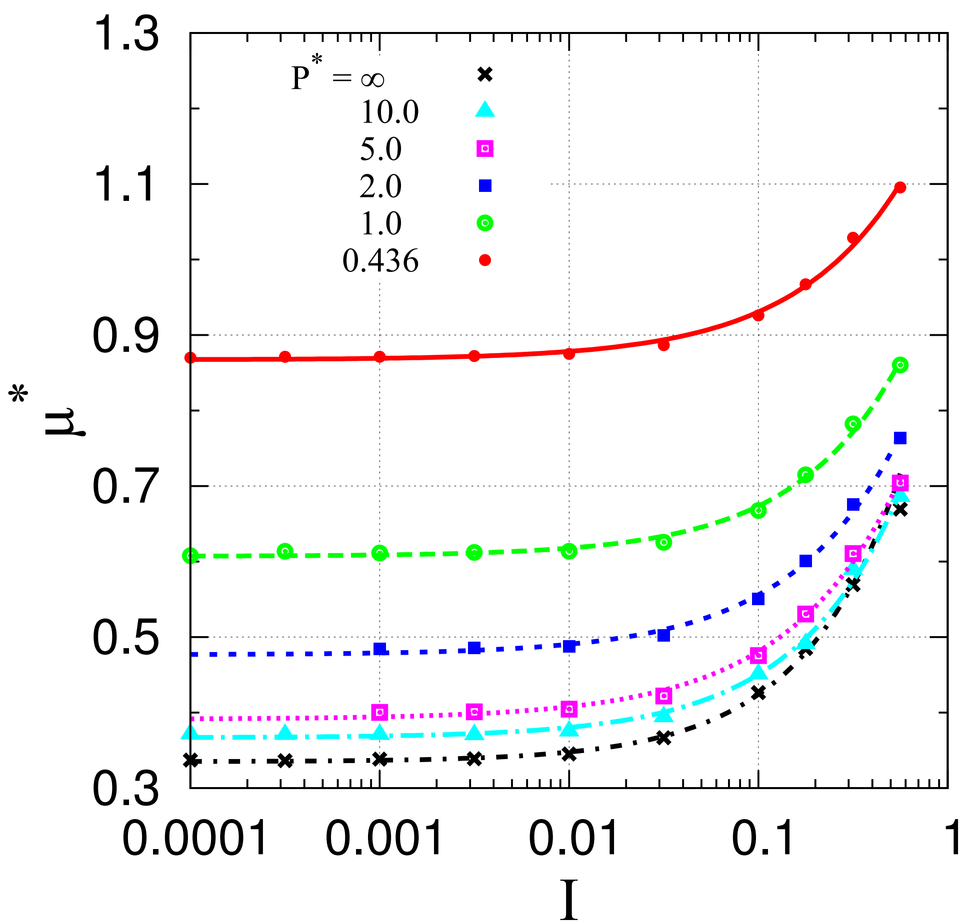
Perspectives

- Explore behavior of loose cohesive structures (beyond simple isotropic compression), from granular systems and powders to colloids

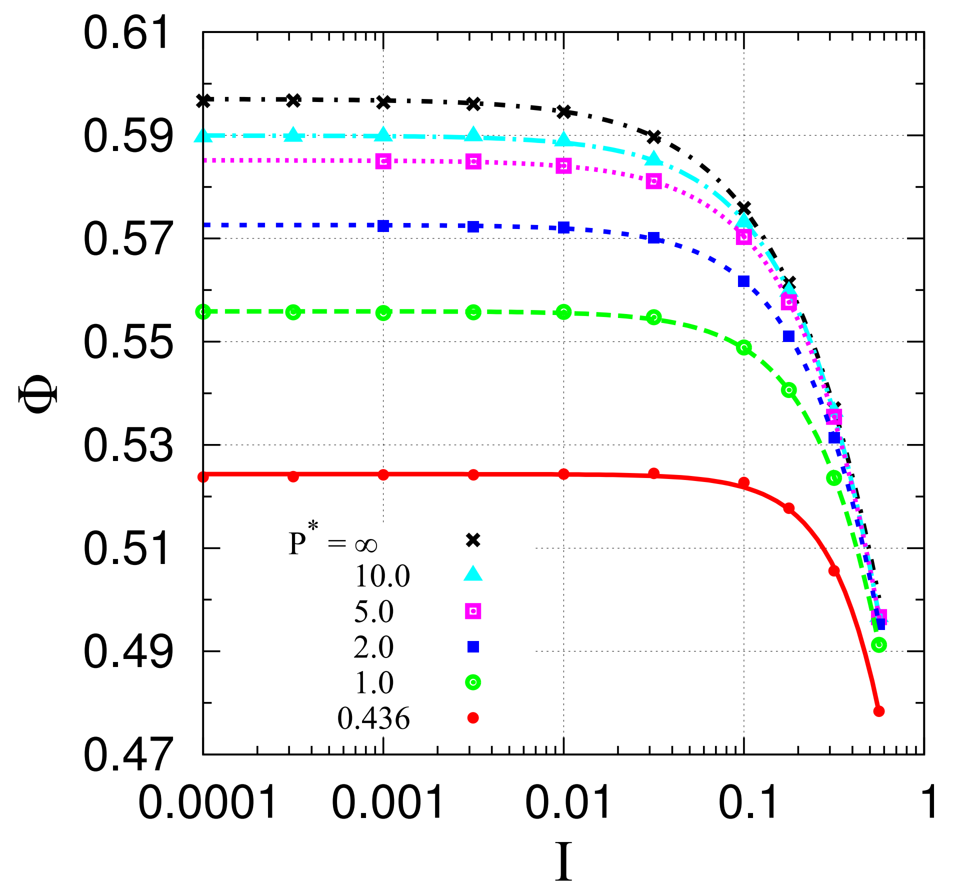
- importance of friction and resistance to rolling… Measurements for small cohesive grains?

Simulation of steady-state shear flow in wet bead assemblies

- Impose shear rate $\dot{\gamma} = \frac{\partial v_1}{\partial x_2}$ while maintaining constant normal stress $\sigma_{22} = P$
- Steady state depends on two parameters, P* and inertial number $I = \dot{\gamma}\sqrt{\frac{m}{aP}}$
- Measure apparent friction coefficient $\mu^* = \frac{\sigma_{12}}{\sigma_{22}}$ and solid fraction Φ



Macroscopic friction coeff. vs. I for different P*



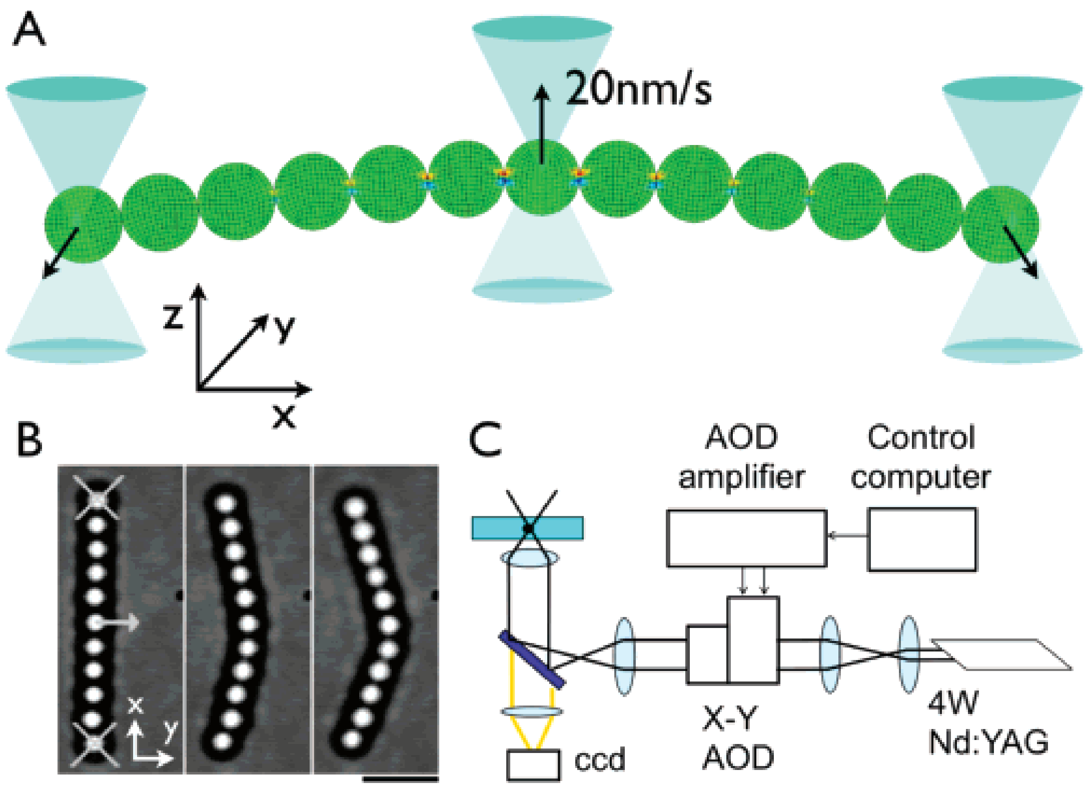
Sold fraction vs. I for different P*

Quasistatic limit of I —> 0 = critical state
Large increase of apparent friction for decreasing P*, while density decreases
Faster approach of quasistatic limit (flat curves)
Systematic shear banding for smaller P* ~ 0.1

Khamseh, Roux & Chevoir PRE 2015

Experimental measurements at grain scale

Pantina& Furst, Langmuir, 2008
'3 point beam bending' experiment
carried out with optical tweezers
on aligned model colloid particles
(PMMA, diameter 1.5 μm)



Resistance to rolling!

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