Numerical analysis of compressive deformation process of aggregates with bi-modal fine particles

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二峰性微粒子凝集体の圧縮変形過程の数値解析

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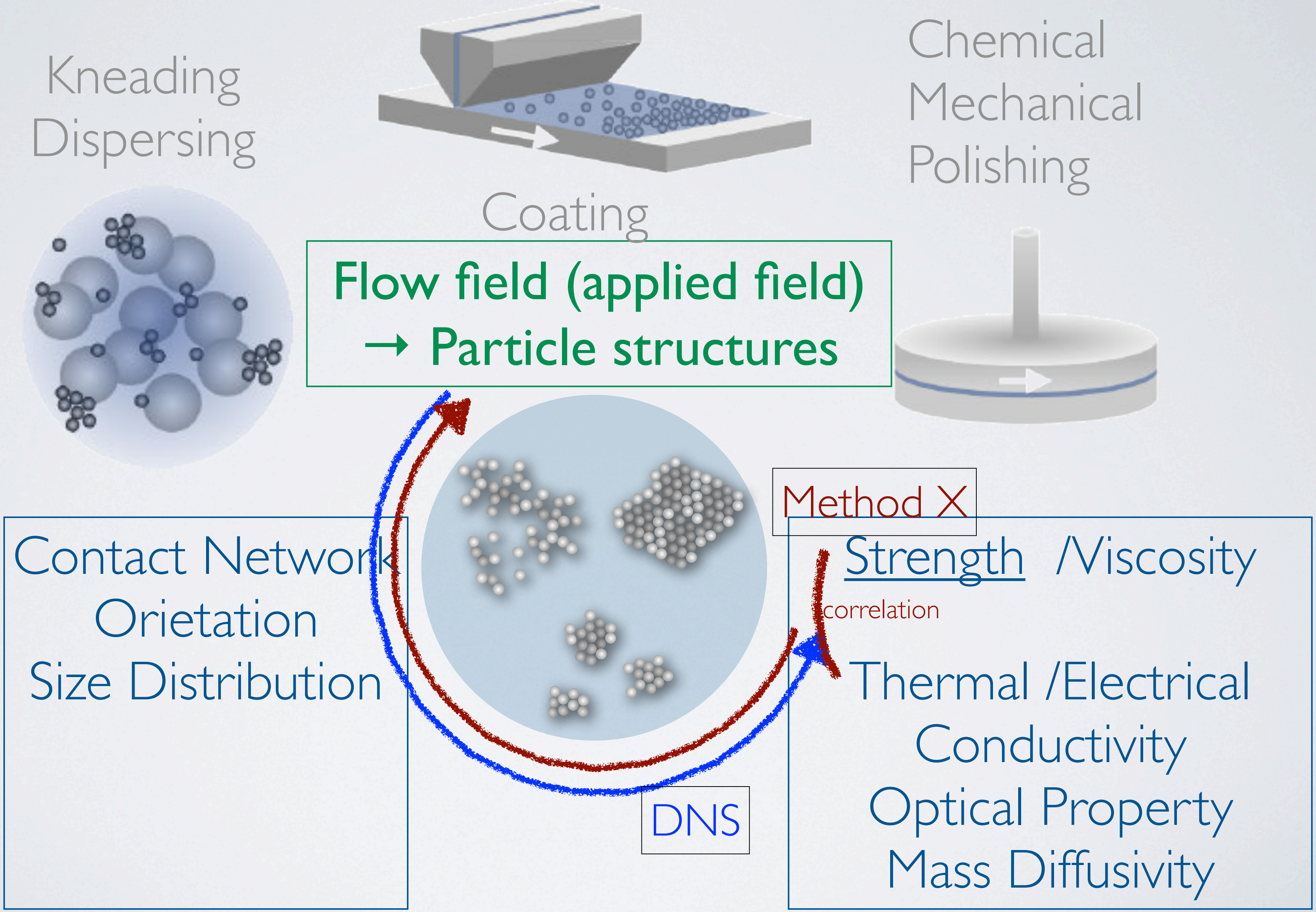
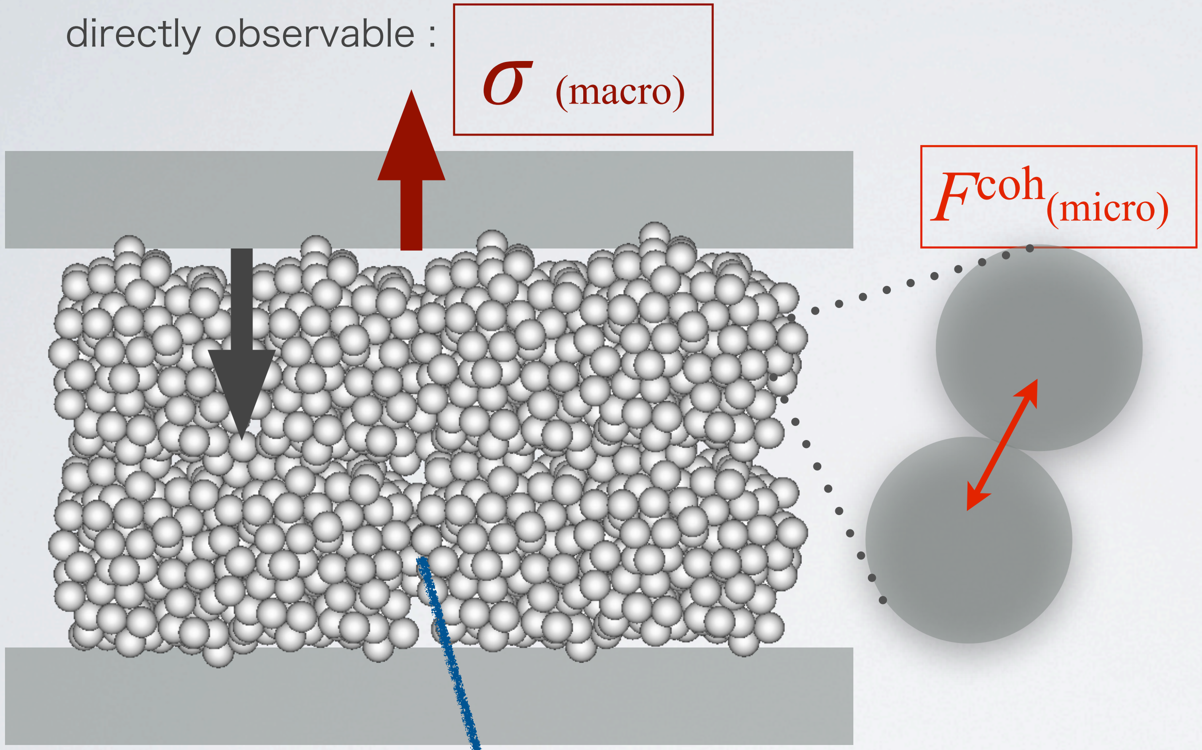
Colloidal Suspensions in Industrial Use



Tensile Strength of Granular Bed



Rumpf's formula

$$\sigma = \frac{\varphi_{\mathrm{p}} n_{\mathrm{c}} F^{\mathrm{coh}}}{\pi d^2}$$

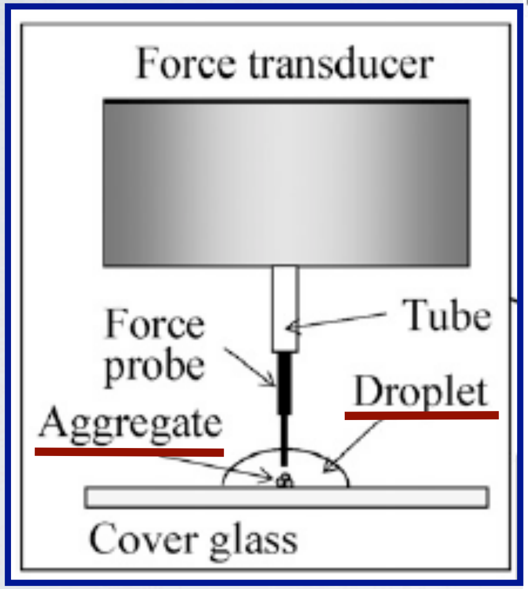
$\sigma \propto d^{-1}$ if $F^{\mathrm{coh}} \propto d$.

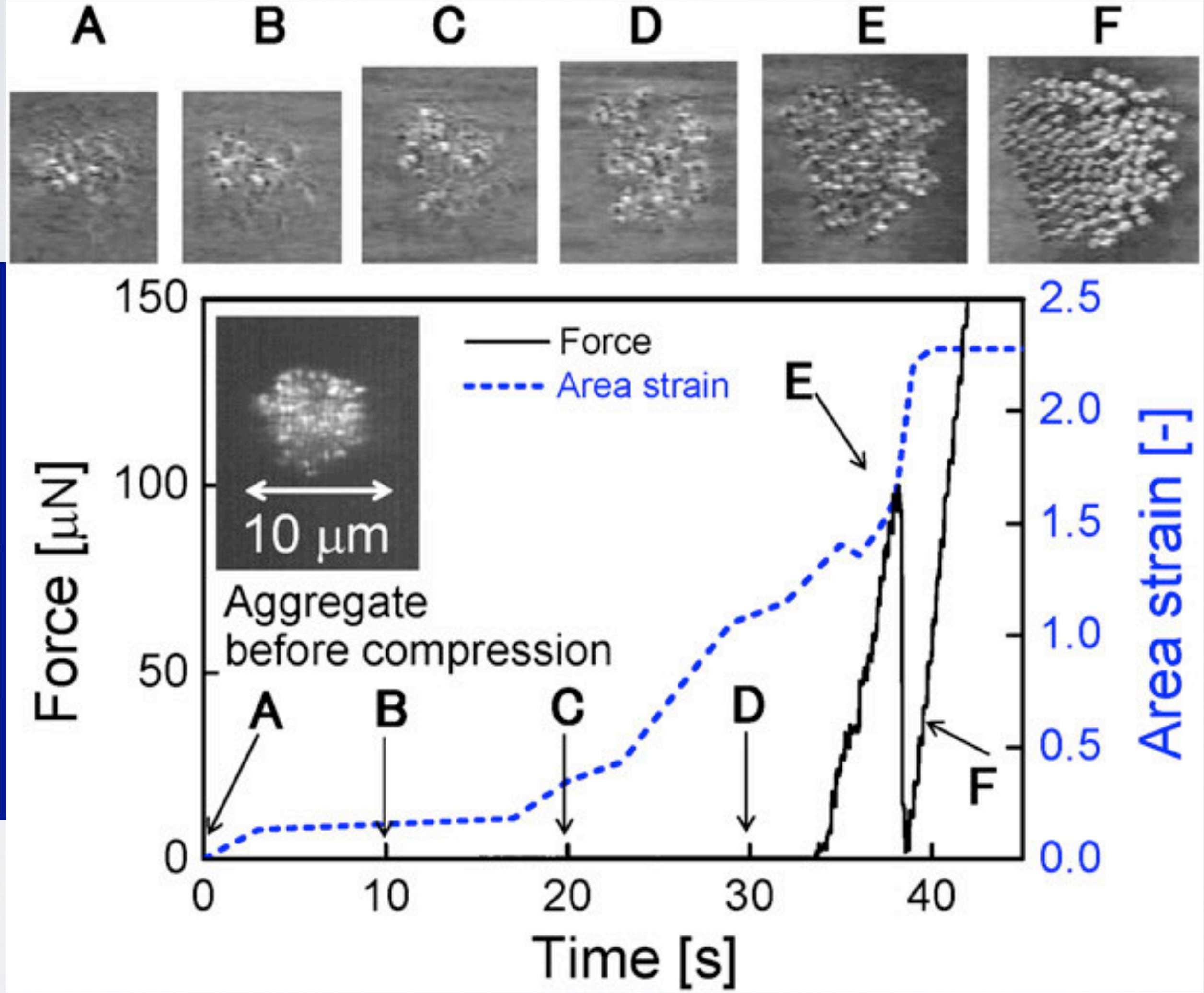
For $d = 1.0$ μm,
$F^{\mathrm{coh}} \sim 0.1$ μN

Conditions
valid for Rumpf's formula:
- Uniform sphere,
- Random packing (isotropic)

Previous Study I
- monomodal particles in liquid -

Exp.



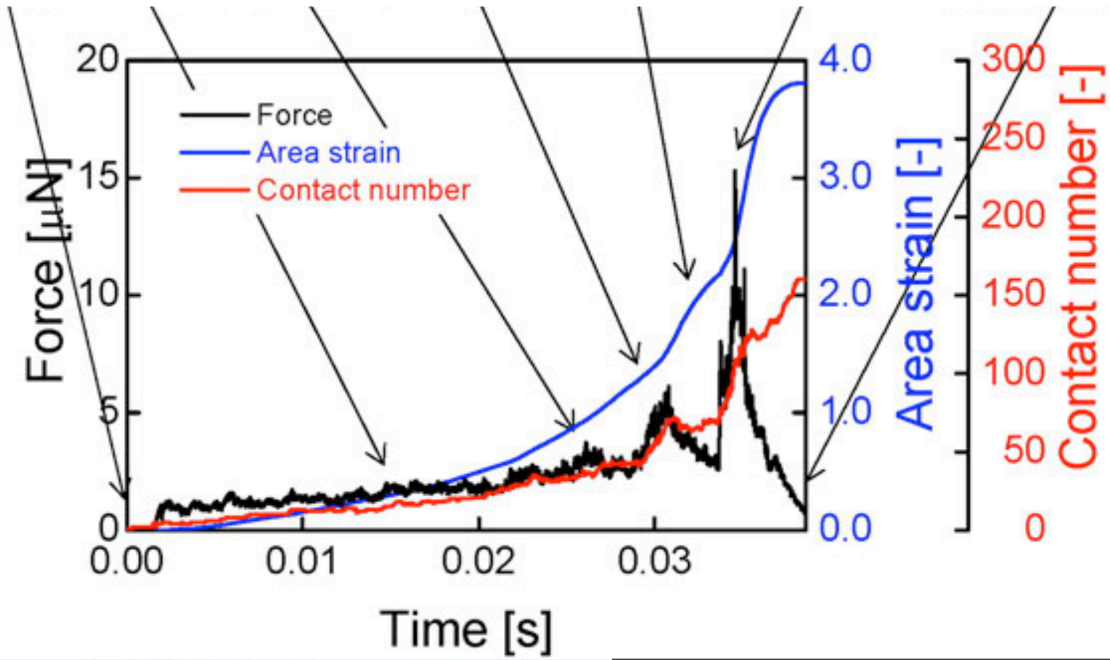


d_p =1 μm

Kubo et al.,
Powder Technology 287 (2016) 431

Previous Study I
- monomodal particles in liquid -

Sim.



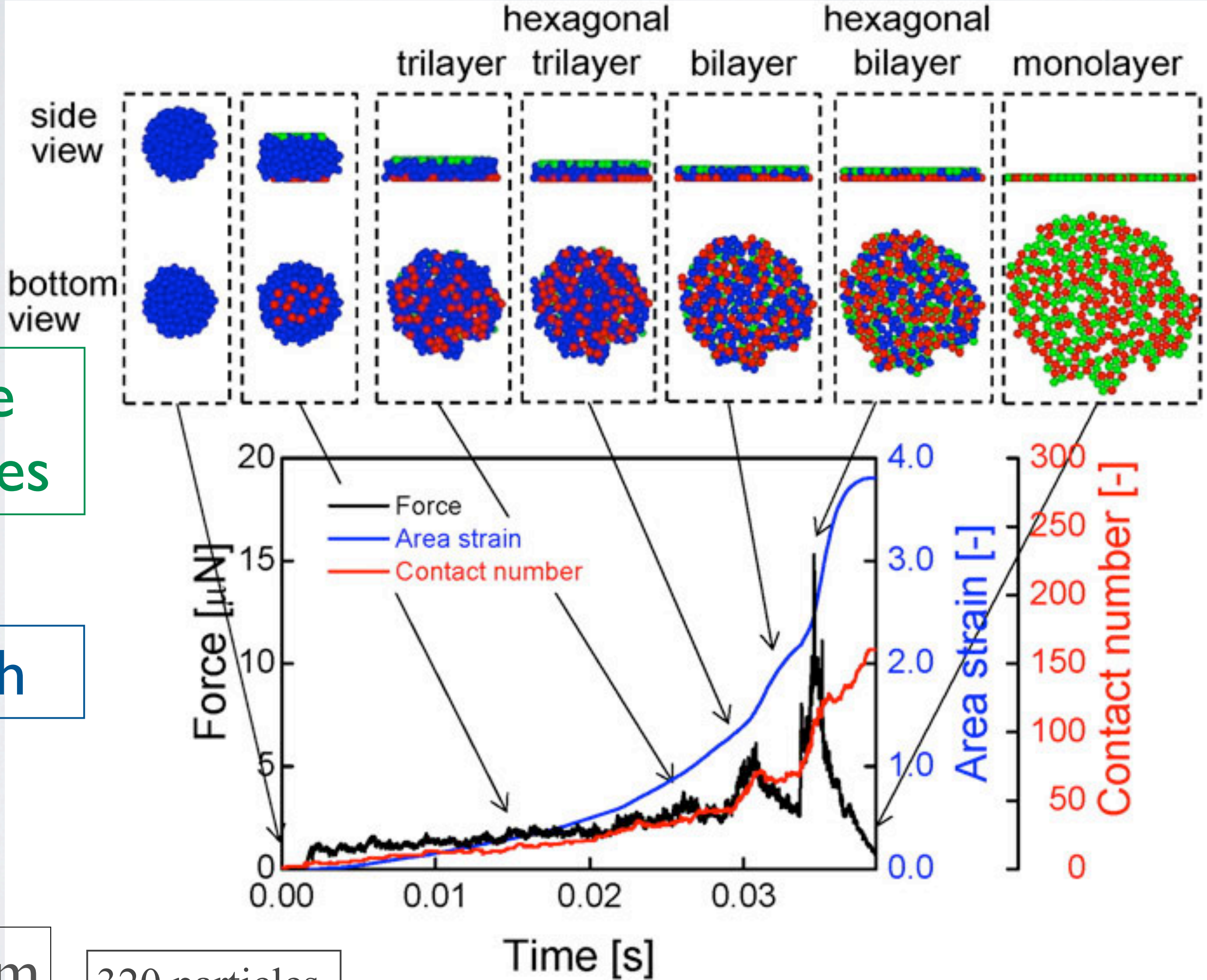
Strength

$d_{\mathrm{p}} = 1\ \mu\mathrm{m}$

Kubo et al.,
Powder Technology 287 (2016) 431

Previous Study I
- monomodal particles in liquid -

Sim.



Particle structures

↓

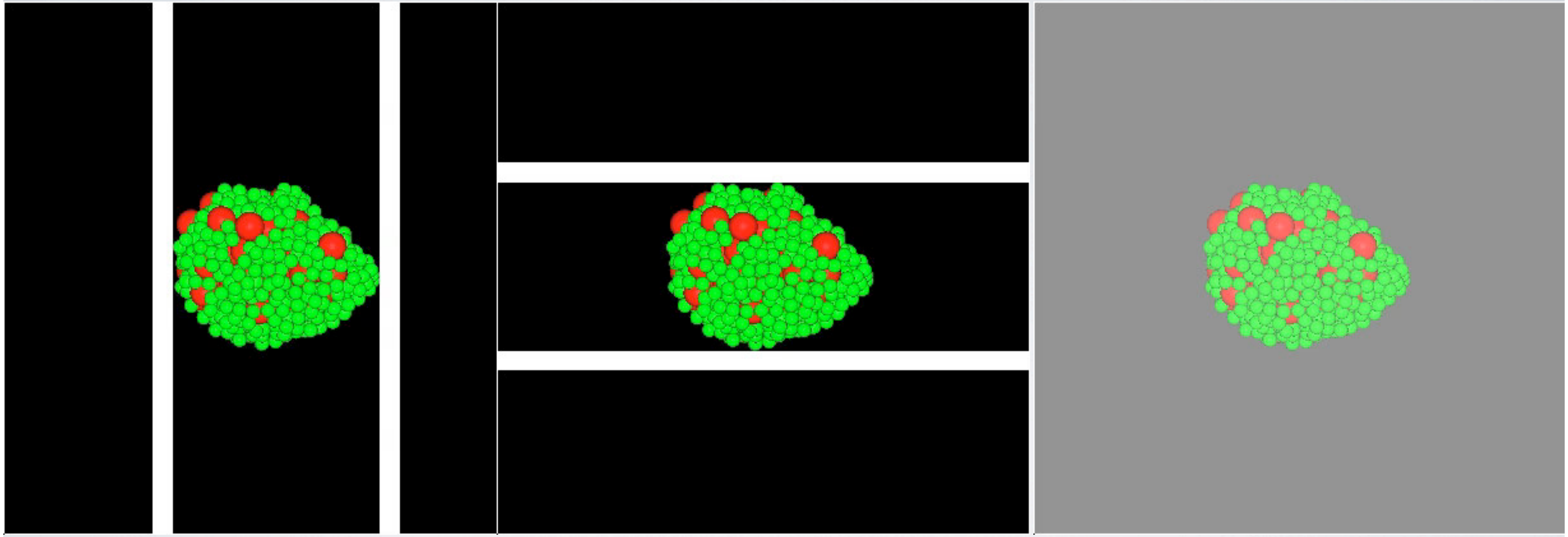
Strength

$d_p = 1\ \mu m$

320 particles

Kubo et al.,
Powder Technology 287 (2016) 431

Previous Study II
- bimodal particles in gas -



Wall - *x*　　Wall - *y*　　Wall - *z*

$d_{\mathrm{L}} = 1.0\ \mu\mathrm{m}$

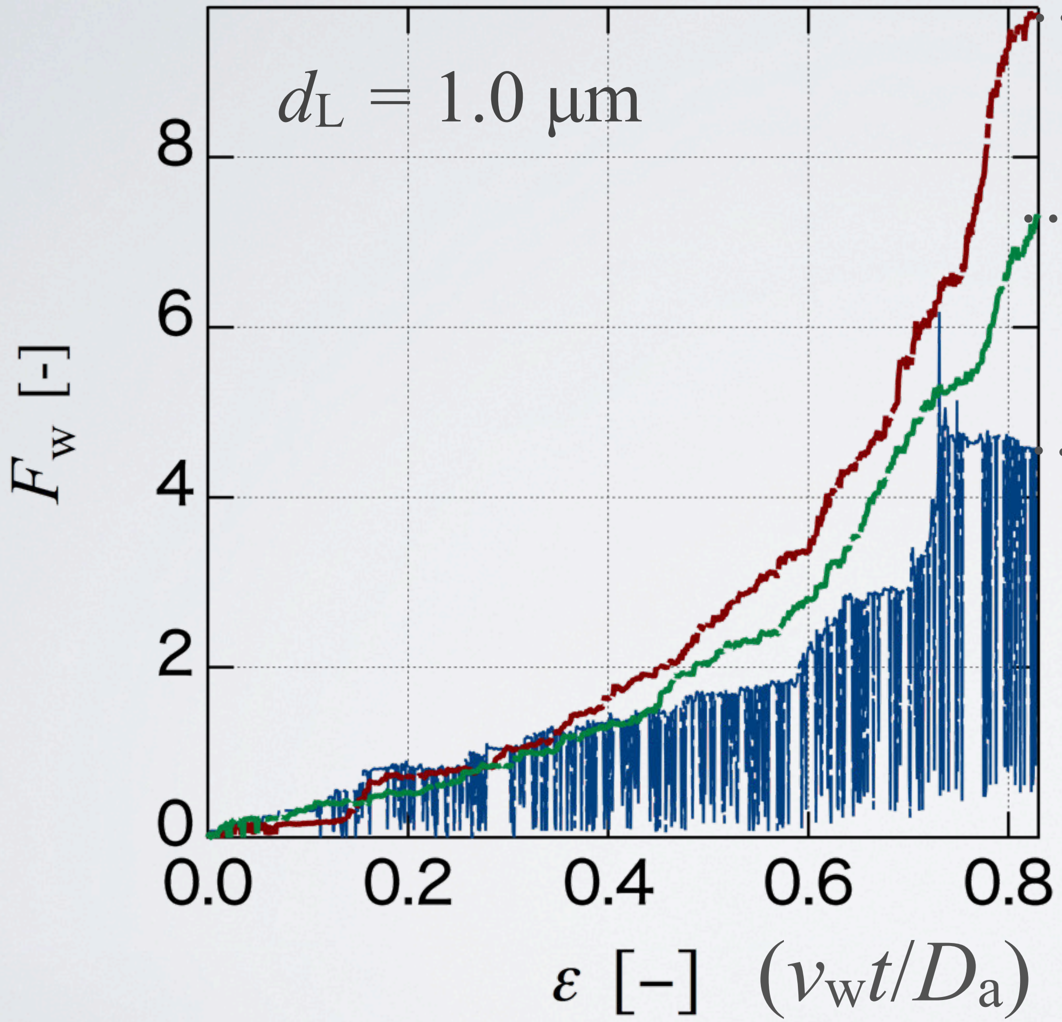
$d_{\mathrm{L}} / d_{\mathrm{S}} = 2.0,\qquad X_{\mathrm{s}} = 0.5$

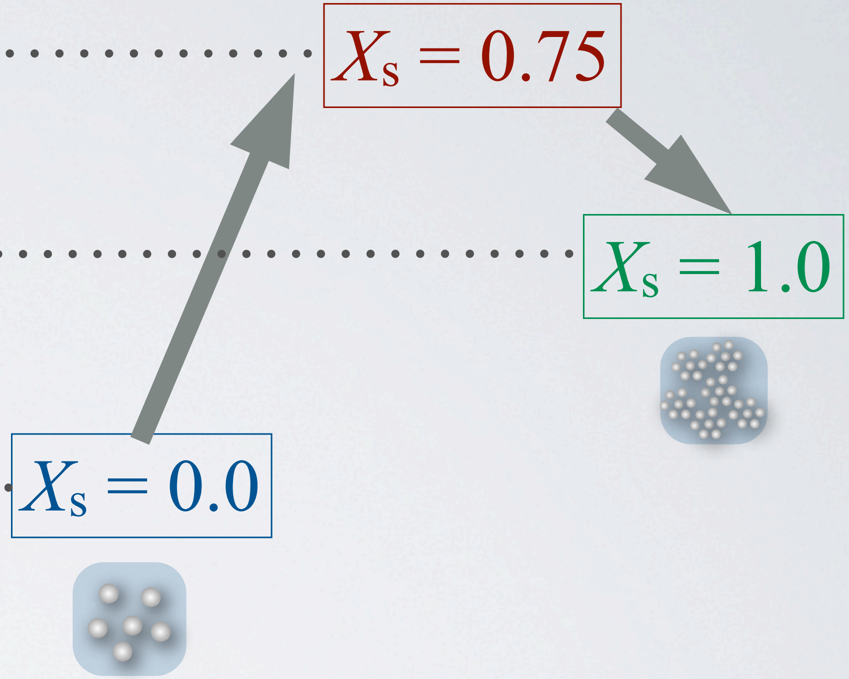
1000 particles
for $X\mathrm{s} = 1.0$

$D_{\mathrm{a}} \sim 6 d_{\mathrm{L}}$

Koike et al.,
2017 SCEJ 82th Annual Meeting

Previous Study II
- bimodal particles in gas -





rough guess :

$F_W \propto S_{con}, \quad V = S_{con}\, h$

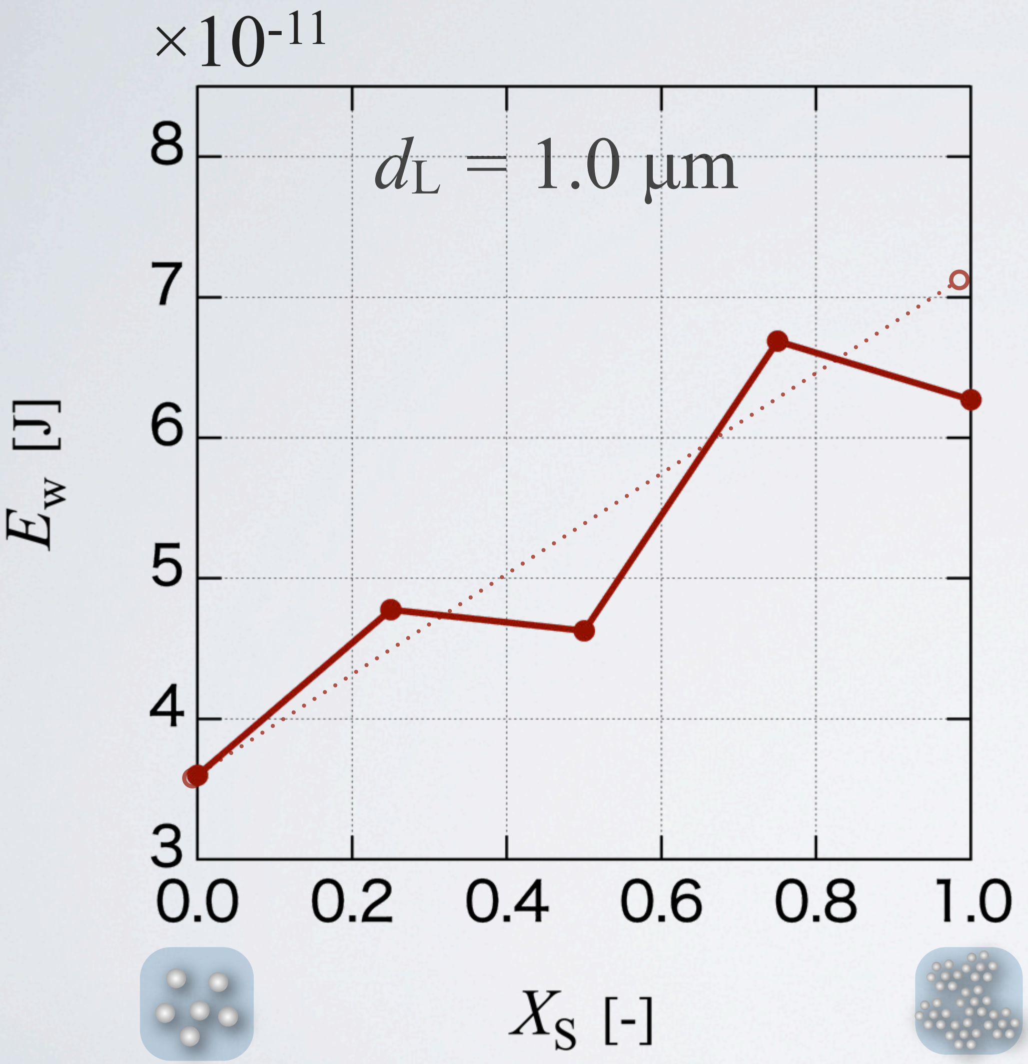
$F_W \sim V / (h_0 - v_W\, t)$

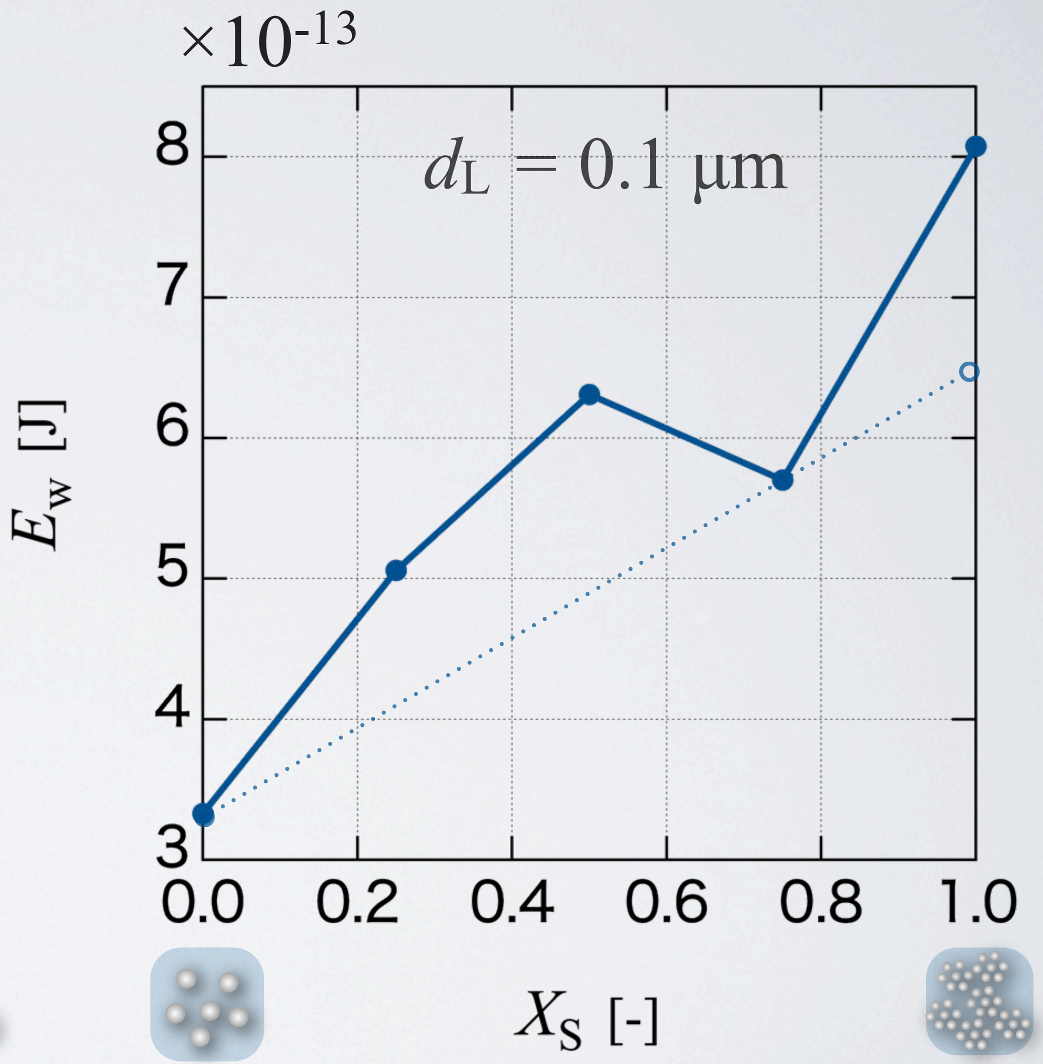
→ concave line

F_W : total contact force on wall

Previous Study II

- bimodal particles in gas -





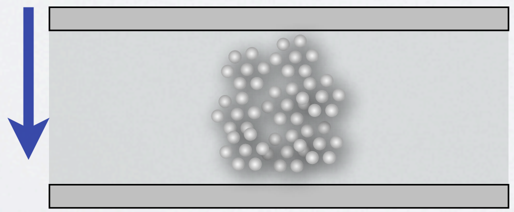
E_w : average work done by wall,
ε : $0 \rightarrow 0.83$; $\delta \sim 5 d_L$

Objective

- Analyse deformation process of aggregates composed of bimodal fine particles by DEM (numerical simulation)

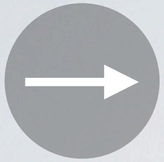
Method

- Based on Discrete Element Method (SNAP-L)
- Compress aggregates by moving plane-parallel walls



Equation of Motion for Particle

D.O.F



$$m\frac{d\boldsymbol{v}_{\mathrm{p}}}{dt} = \boldsymbol{F}^{\mathrm{co}} + \boldsymbol{F}^{\mathrm{v}} + \boldsymbol{F}^{\mathrm{cb}}$$

$$I\frac{d\boldsymbol{\omega}_{\mathrm{p}}}{dt} = \boldsymbol{T}^{\mathrm{co}}$$

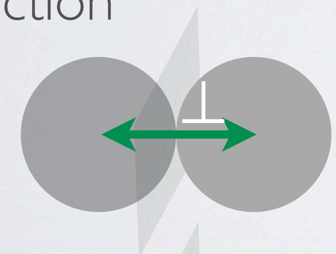
Cohesive force:
- van der Waals force
- capillary bridge force

$F^{\mathrm{coh}} \propto d$

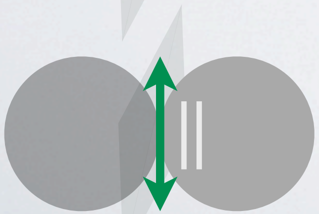
Contact force:
- Visco-elastic type
- Coulomb's friction

$$\left|\boldsymbol{F}_{\mathrm{t}}^{\mathrm{co}}\right| = \min\left(\left|\boldsymbol{F}_{\mathrm{t}}^{\mathrm{co}}\right|, \mu\left|\boldsymbol{F}_{n}^{\mathrm{co}}\right|\right)$$

Direction



: $F_{\mathrm{n}}^{\mathrm{co}}$ $F_{\mathrm{n}}^{\mathrm{v}}$ $F_{\mathrm{n}}^{\mathrm{cb}}$



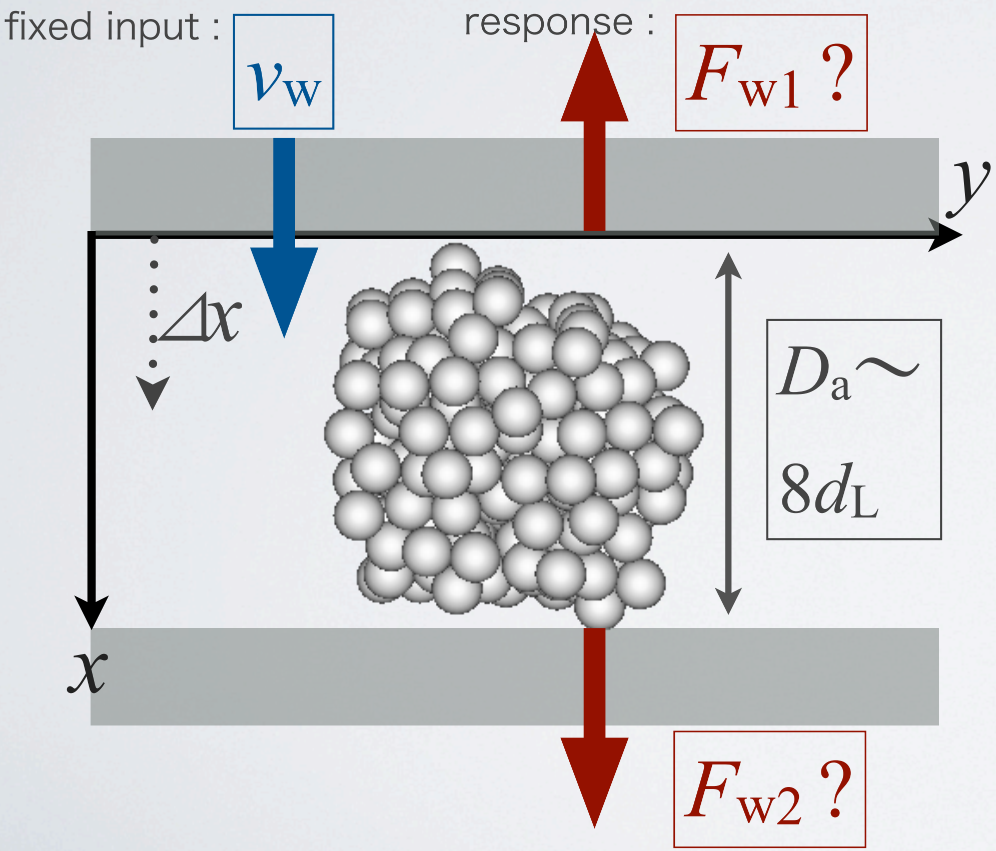
: $F_{\mathrm{t}}^{\mathrm{co}}$

Simulation Condition

Wall

v_w [m/s] : 2.5×10^{-3}

Δx , Δy , Δz $=7d_L=\delta$



Particle

		1/10 →	
d_L [μm]	:	1.0	0.1
d_S [μm]	:	0.5	0.05

(1/2 ↓)

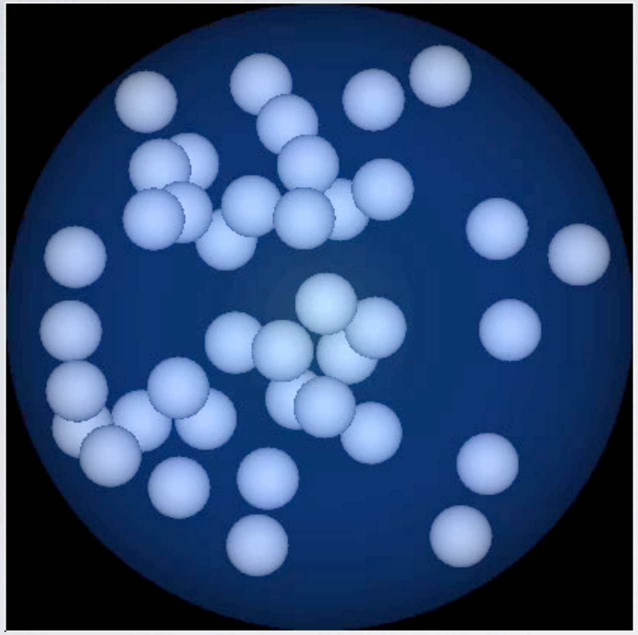
$X_S = V_S/V$: 0.0 - 1.0

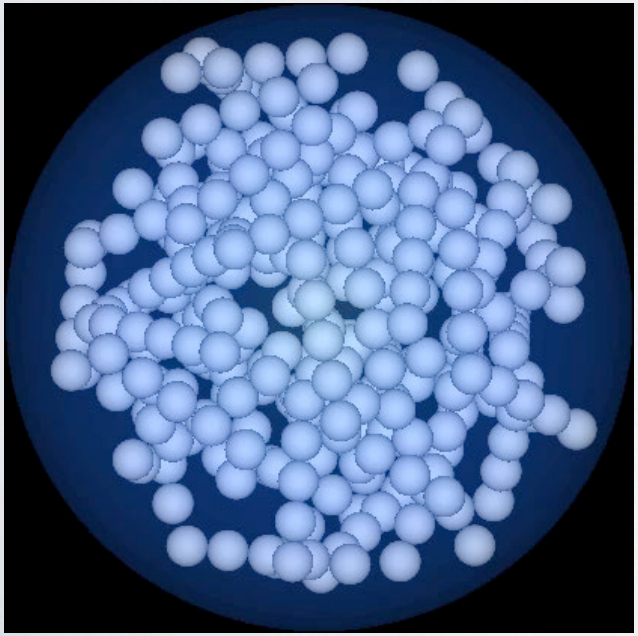
For X_S = 1.0,
2.0×10^3 small particles

A [J] : 3.0×10^{-20}

Particle is same as wall
in memchanical properties

How to Make Single Aggregate





- Confine particles in a droplet
- Shrink the droplet during drying
- Push particles into the center of droplet by capillary force

- Simple and efficient method
- It is hard to control the fractal dimension as in DLCA

Gyration radius of an aggregate

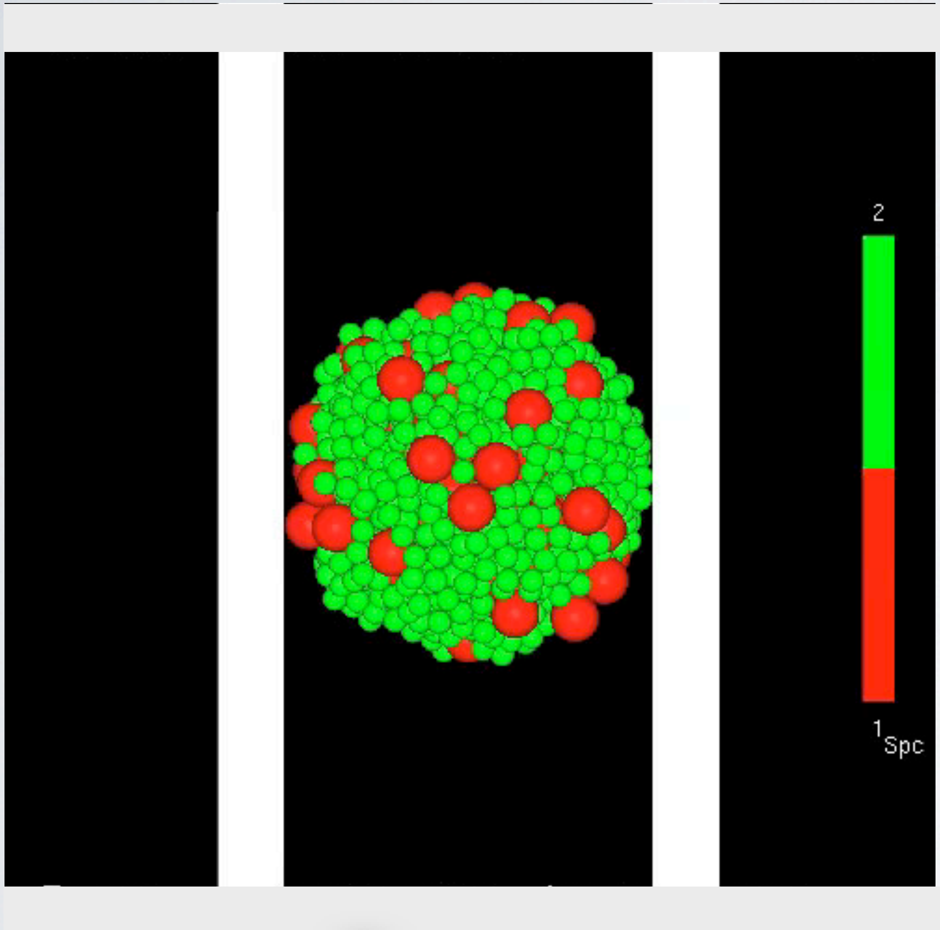
$$\left(\frac{R_g}{a}\right) \propto N^{1/d_f}$$

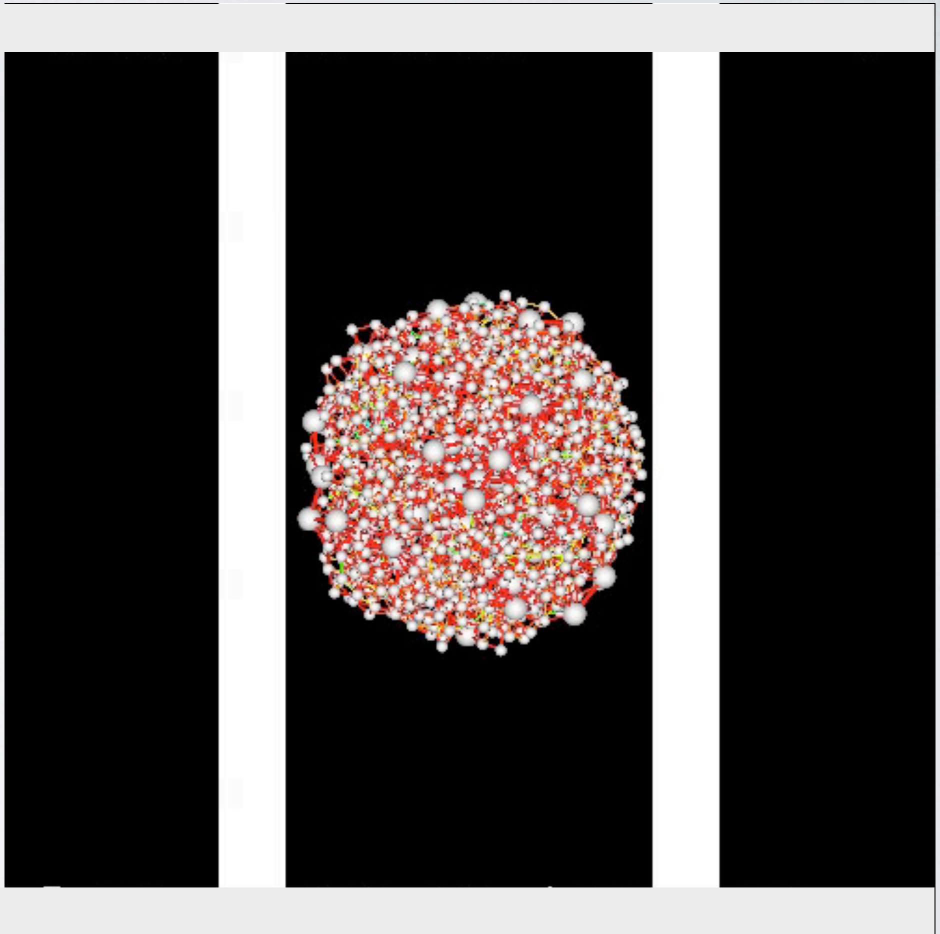
d_f [-] : 2.89

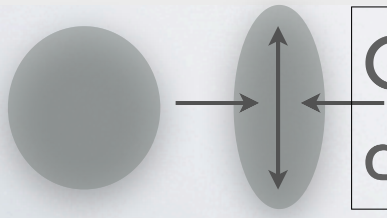
d_f: fractal dimention

Particle Motion & Force Chain

$d_L = 1.0\ \mu m, \quad X_s = 0.5$





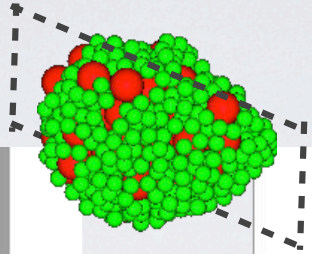


Oblate deformation

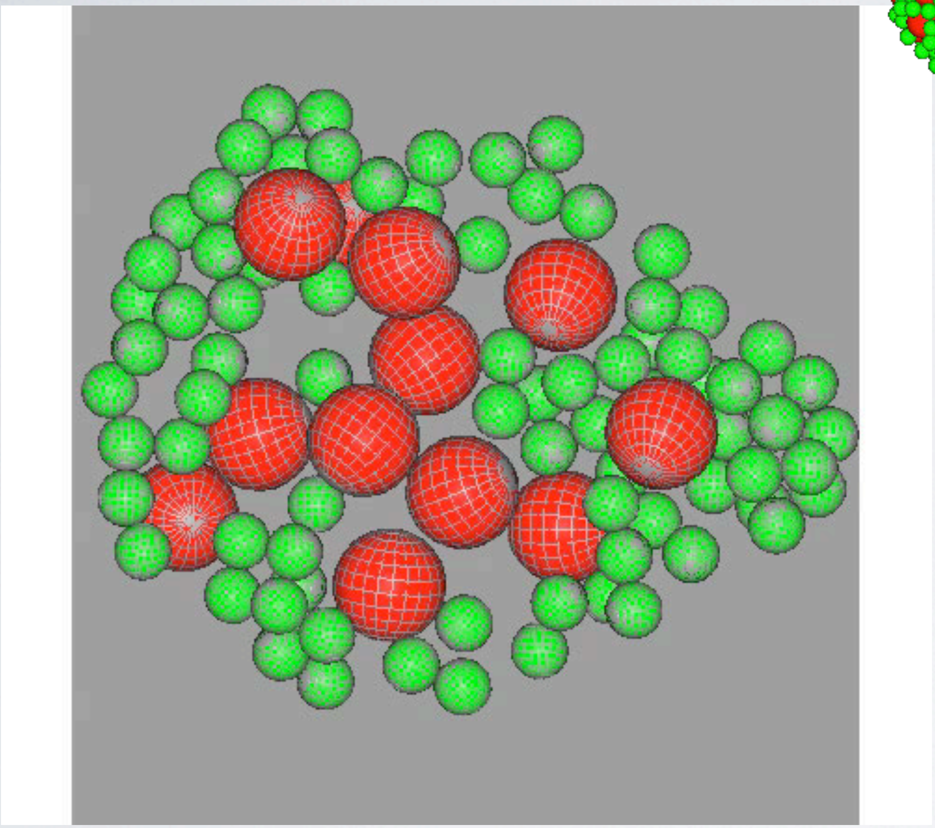
Frequent variation in contact force

Rotation of Particle

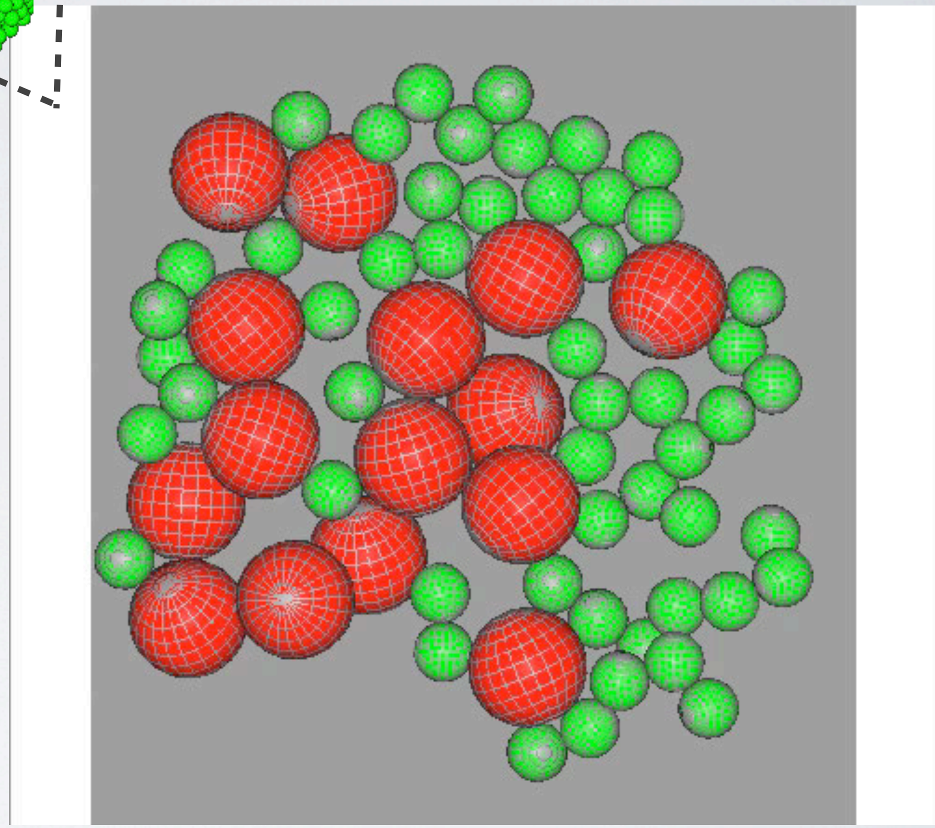
$X_s = 0.5$



$d_L = 1.0\ \mu m$



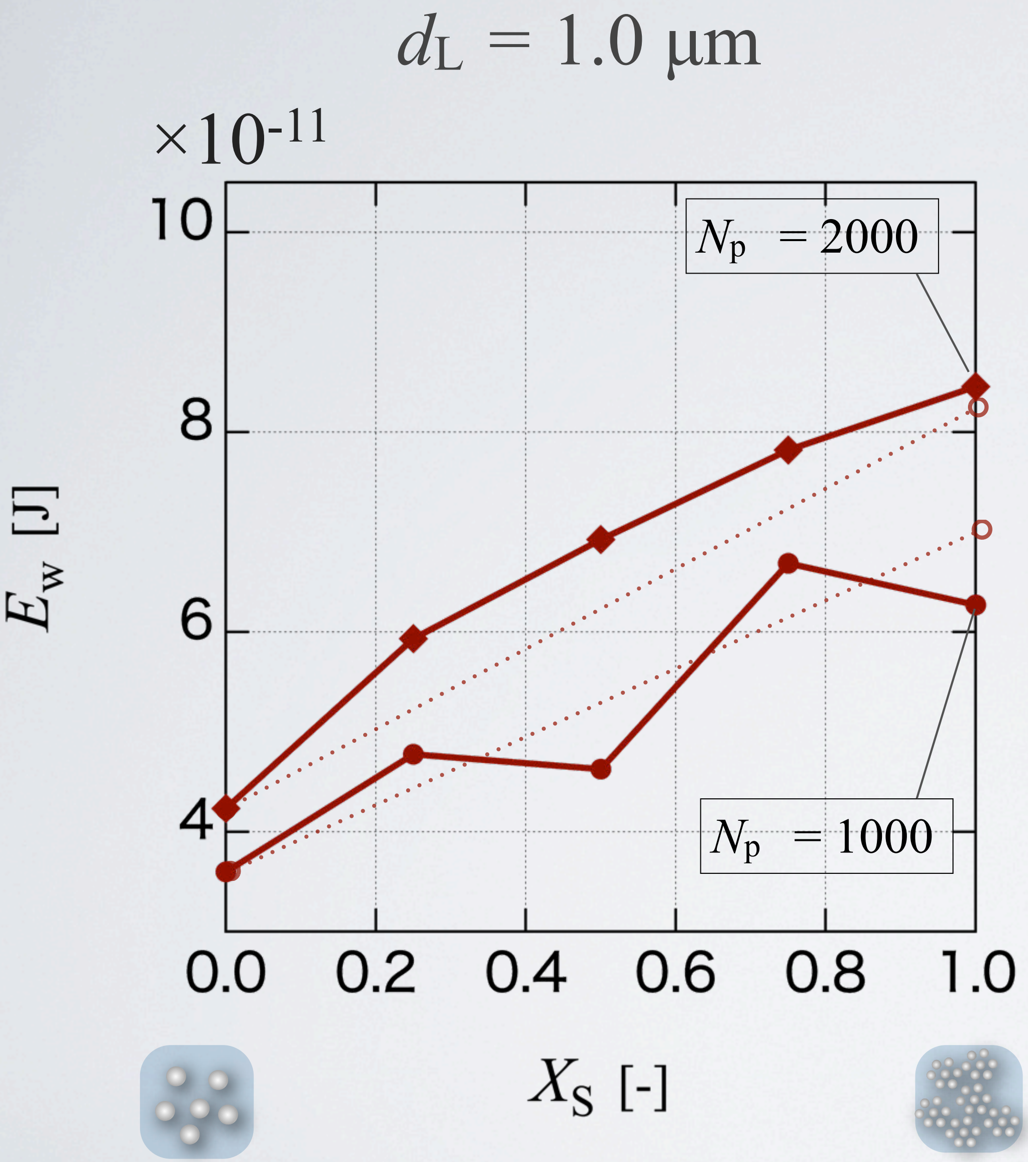
$d_L = 0.1\mu m$

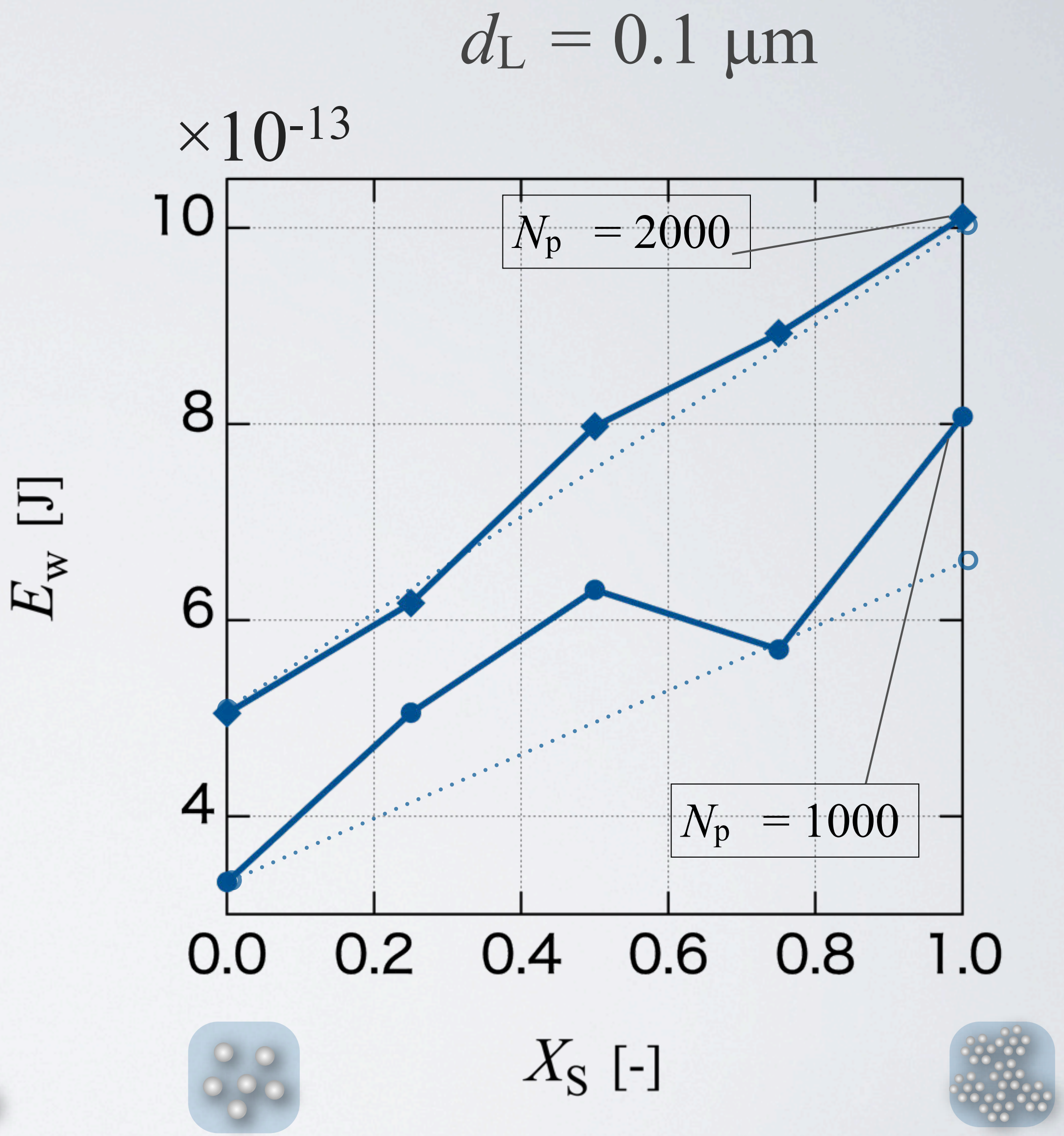


Frequent rotation with slip
for smaller particles

$$I = \frac{2}{5} m a^2 \propto a^5$$

Work vs. Xs





E_w : average work done by wall,
$\delta \sim 5 d_L$

Remarks
- Benefit of DNS -

- Our approach enable us to visulalize the detailed breakup process of the aggregate.

- Our approach leads us to catch a key factor / basic concept affecting compression process / strength of an aggregate.