Investigating Cohesion in Wet Particles Systems

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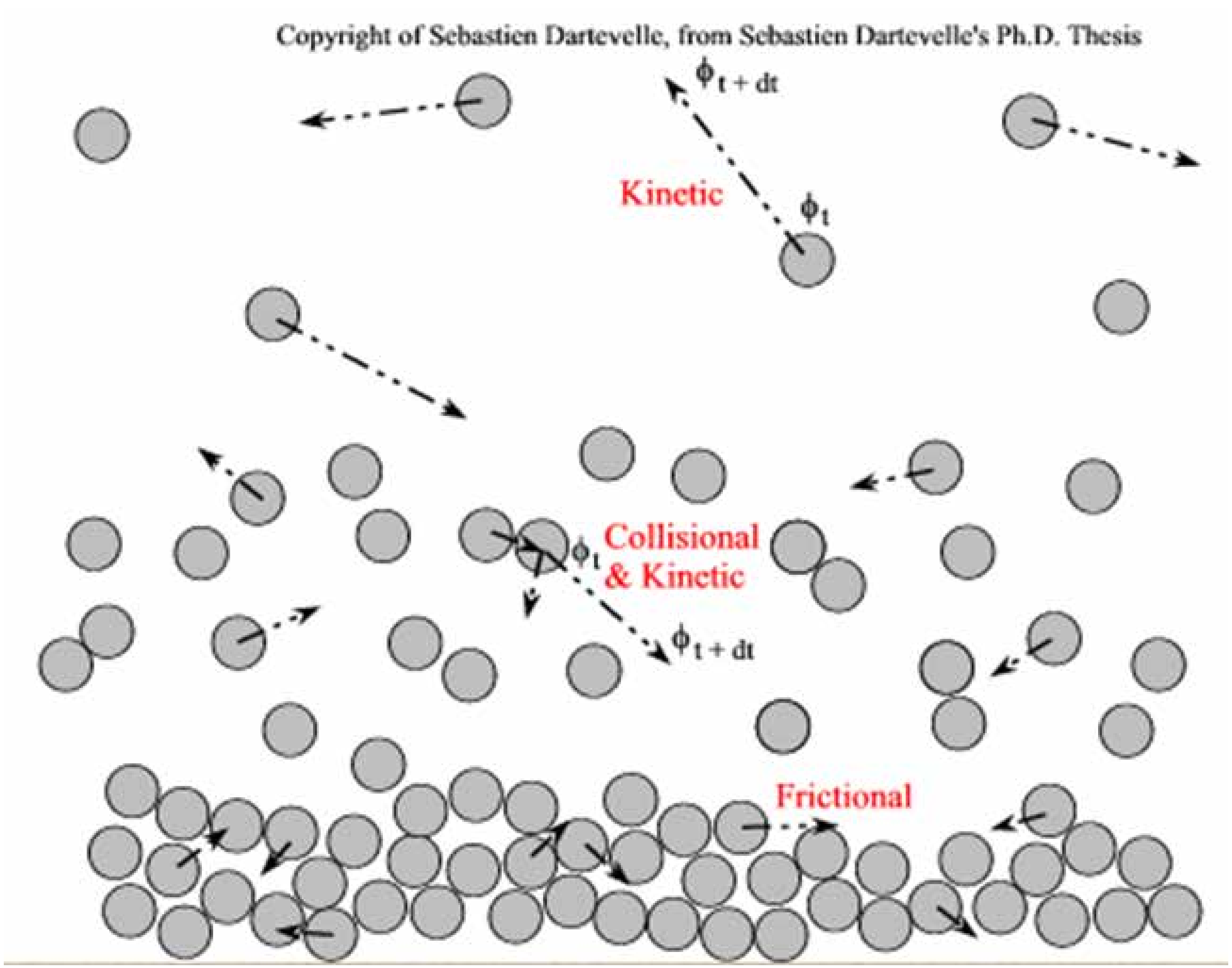
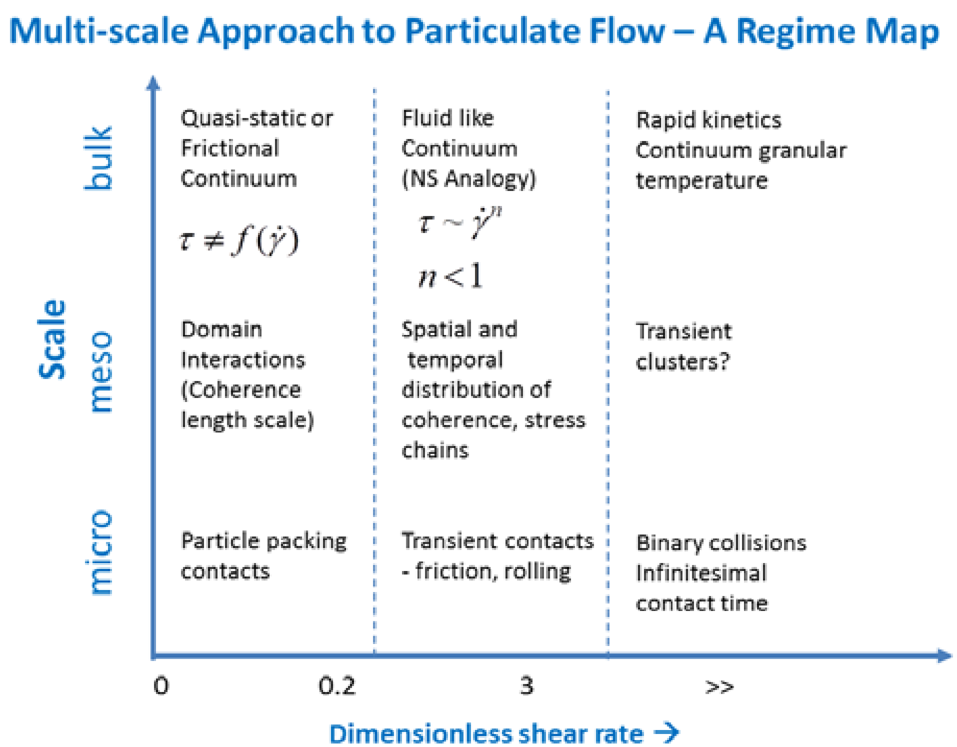
Regime Map for Particle-Particle Interactions



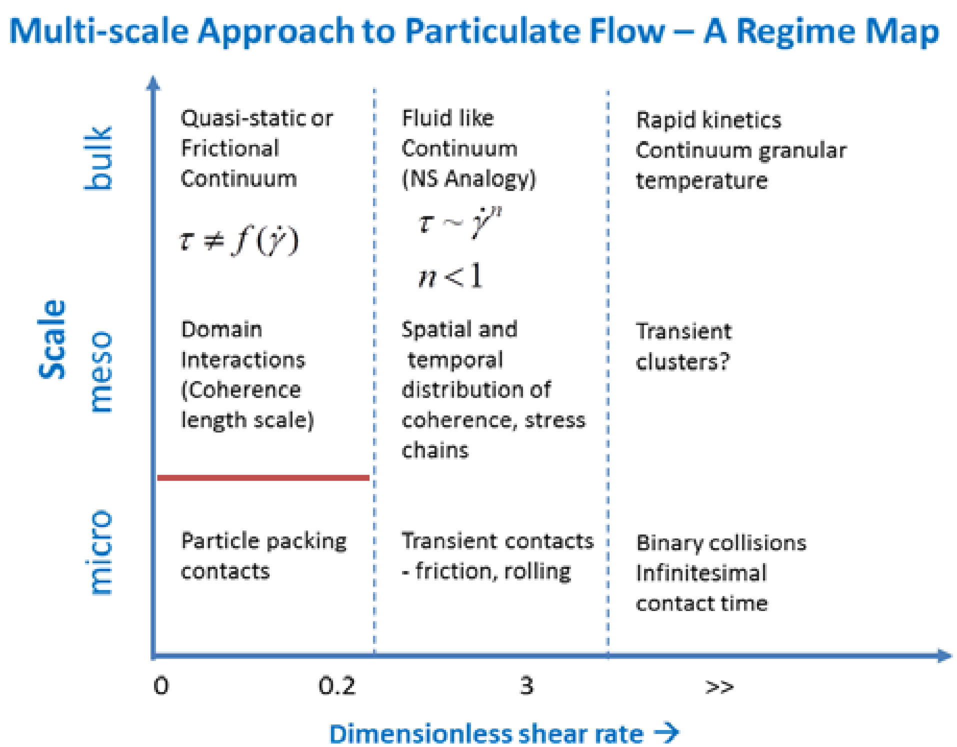
- **Rapid flow regime**
  Binary-collisions
  Fluid-like behaviour
  KTGF (kinetic theory of granular flow)
- **Intermediate regime**
  Coexistence of frictional and collisional stress
- **Slow, friction regime**
  Solid-like behaviour
  Particle packing
  Enduring contact
  Coulomb frictional law

The Classification of Flow Regimes depends on the Applications



[courtesy of P Mort]

The Classification of Flow Regimes depends on the Applications



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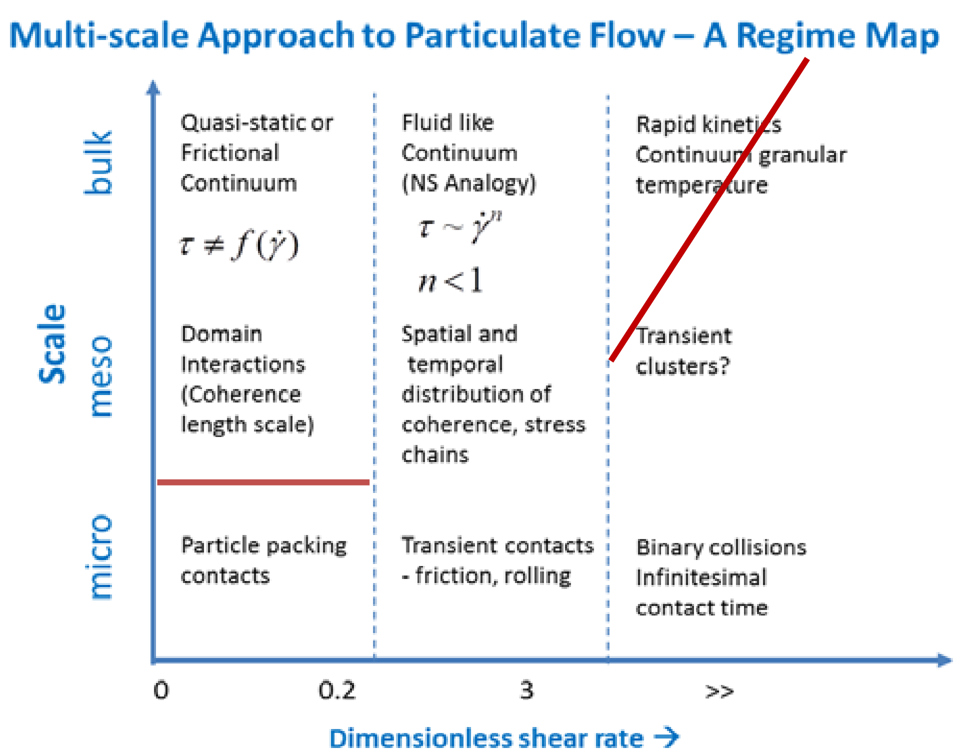

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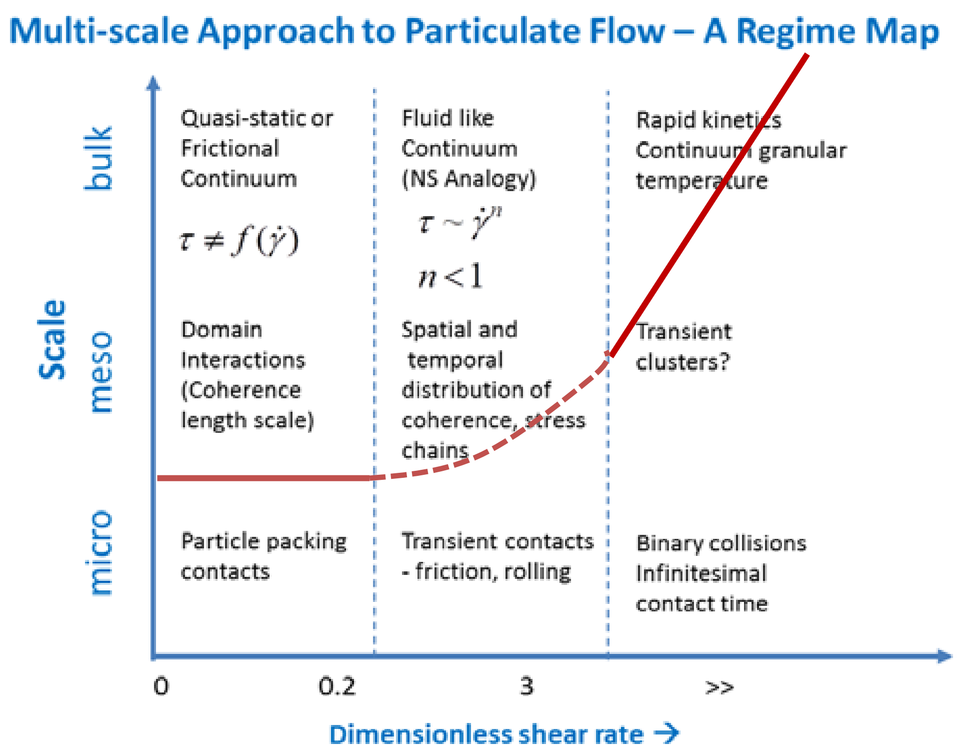
The Classification of Flow Regimes depends on the Applications



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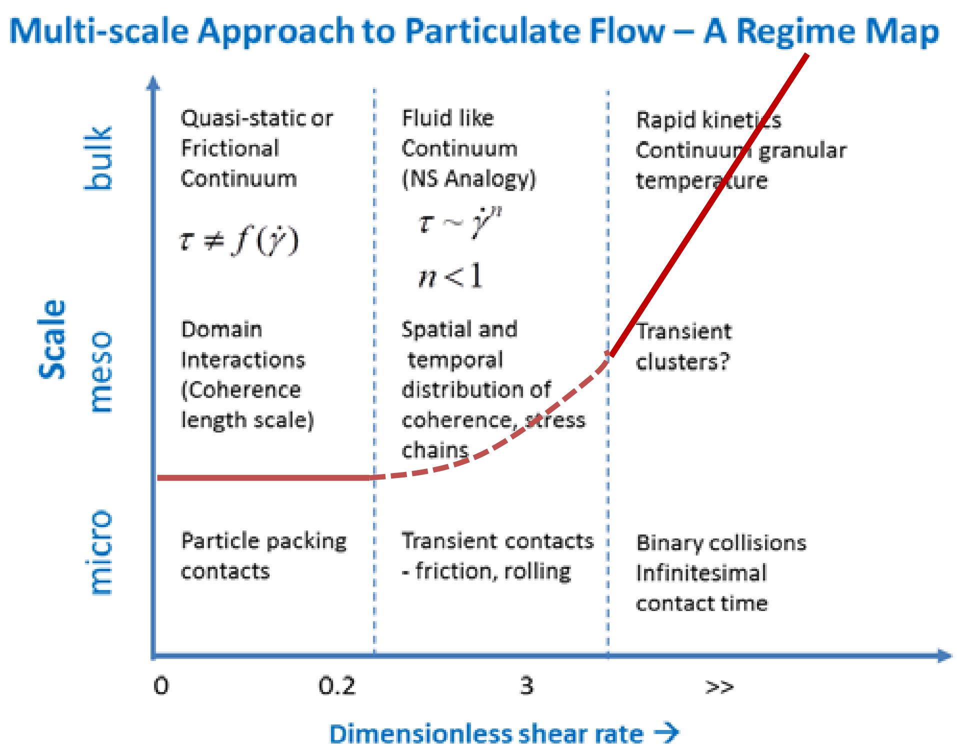
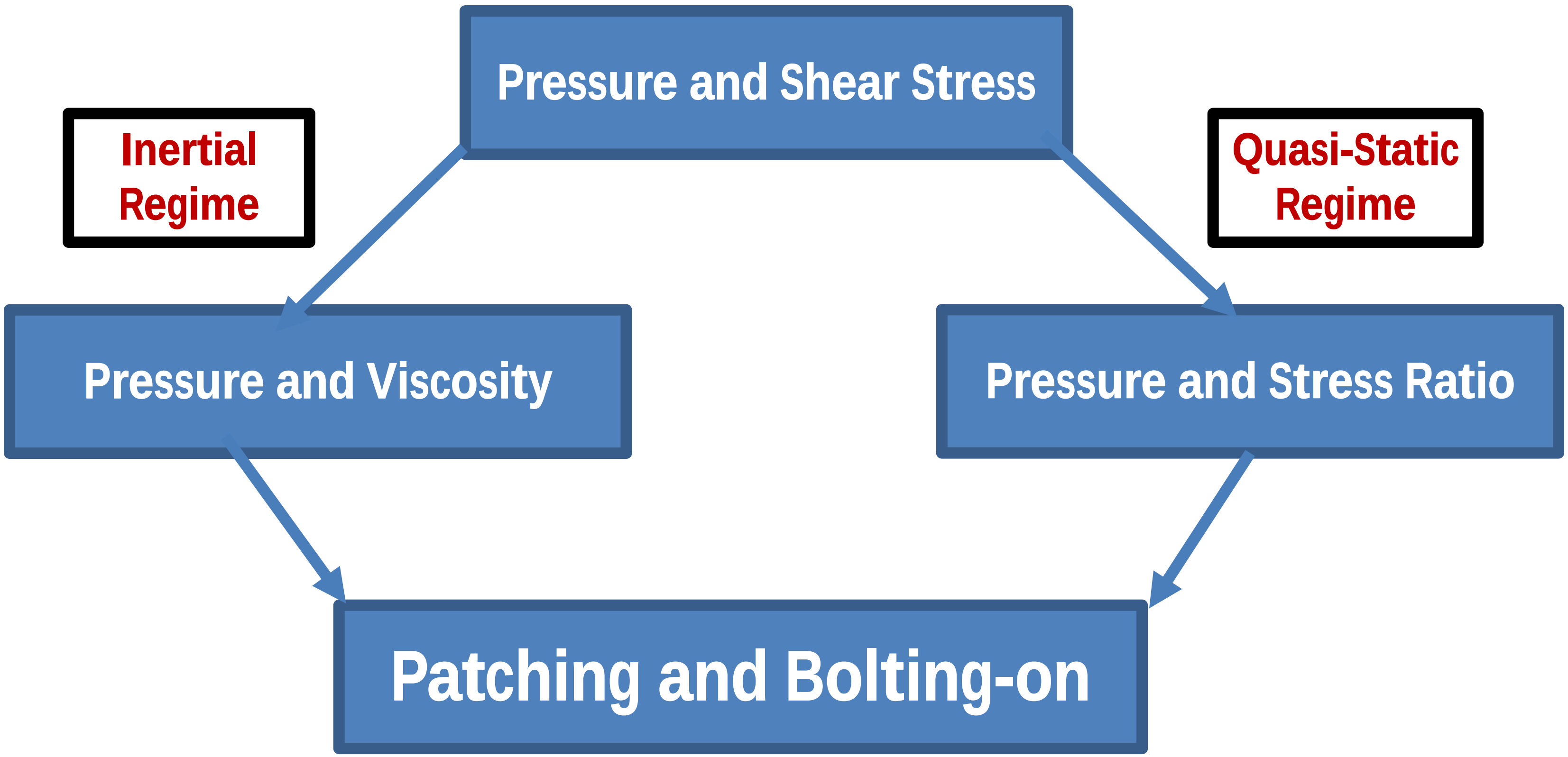
The Classification of Flow Regimes depends on the Applications



[courtesy of P Mort]

To understand the bulk properties (meso-scale) we need **RHEOLOGICAL** measurements

Constitutive Requirements



Multiscale

+

Averaging

Cohesion

- Chemical bonding
- Electric charging
- van der Waals
- Liquid bridges

Cohesion

- Ø Chemical bonding
- Ø Electric charging
- Ø van der Waals
- Ø Liquid bridges

We deal with particles with size ranging from 10^{-3} to 10^{4} mm

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7 orders of magnitude!

Cohesion

Ø Chemical bonding

Ø Electric charging

Ø van der Waals

Ø Liquid bridges

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7 orders of magnitude!

Wet Particles

- When particles are wet or are in a moisture-rich environment, capillary forces may be important: these forces are generated by condensed moisture on the particle surface

- The behaviour of wet particles differs significantly from that of dry particles

- Capillary forces, brought about by what are often referred to as "liquid bridges", are typically stronger than other type of cohesive forces

Inertial Regime

In collaboration with:

Xi Yu and Yassir Makkawi

Proposed Inter-Particle "Cohesive" Model

[Ocone et al, 2000]

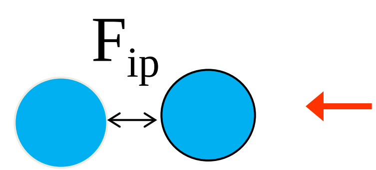
The radial component of the cohesion force is derived:

$$P_c = C_o \frac{6\sqrt{2}F_{ip}\sqrt{T}}{u_t d}\left|\nabla \varepsilon_s\right|$$

Based on experimental data on Group A/B particles, we are taking an average value of F_{ip}=0.2X10^{-8} N

The tangential cohesion force is given by a modified formula of Molerus (1982):

$$\tau_c = P_c \frac{\pi}{6(1-\varepsilon_s)}$$



Two isolated particles in contact

where C_o is a factor introduced due to uncertainty about the exact value of F_{ip} and F_{ip} is the cohesive force

Proposed Inter-Particle "Cohesive" Model

[Ocone et al, 2000]

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BOLTED ON

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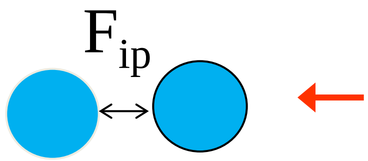
$$t_c = P_c \quad \ldots \quad 6(1 - e_s)$$



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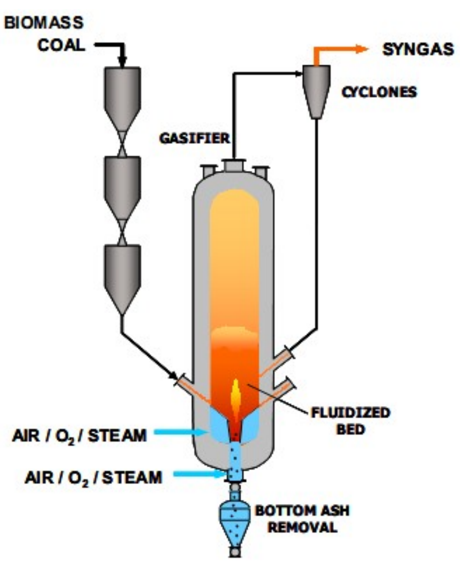
Examples of Wet Fluidised Beds

Coal/biomass gasification

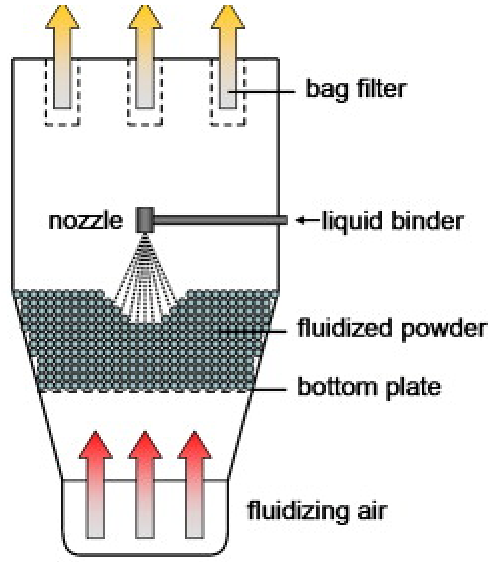
Surface oil/tar leading to
agglomeration and sever
Degradation and fluidisation



Simple Gasification Process Graphic
(Gas Technology Institute, Illinois, US)

Fluidized bed coating

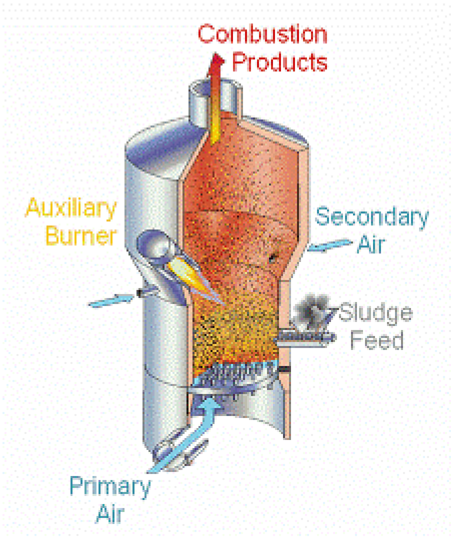
Liquid presence leading to
undesired Agglomeration
and particles segregation



Schemes of fluidized bed spray granulator
(Fries et al, 2011)

Exothermic fluidized reactor

Temperature control by liquid
injection leading to dead zones
And overheating at various
Parts Of the reactor

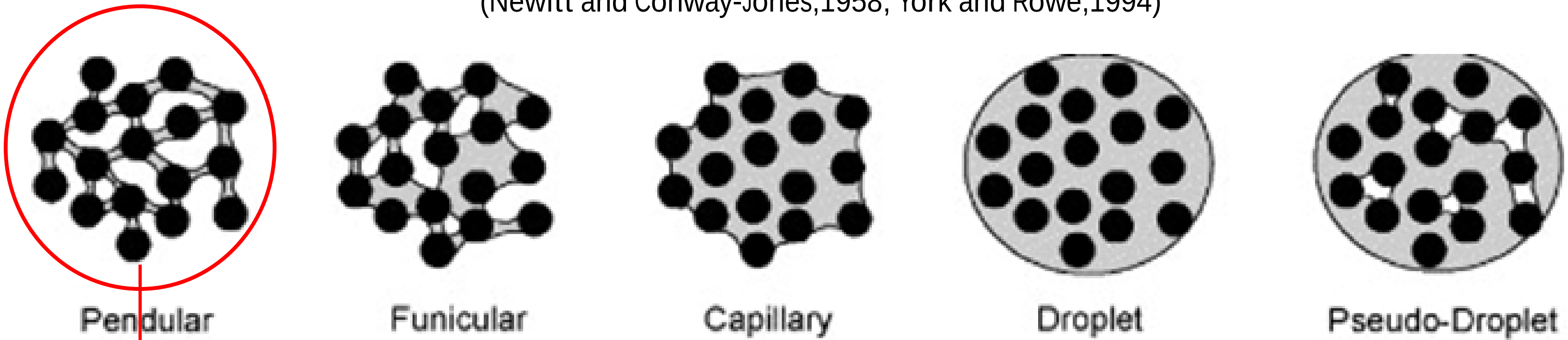


Fluidized Bed Systems, hitachi Zosen
Inova, Switzerland)

Slightly Wet Systems

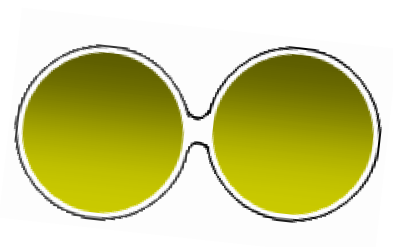
Figure: the different states of saturation of liquid-bound granules

(Newitt and Conway-Jones,1958; York and Rowe,1994)



liquid saturation higher

Liquid bridges —merge→ continuous fluid network



Frictional contact → Fluid shear resistance

Collisional contacts dissipate energy in both the liquid bridges and particles

Particle-Particle Interactions in Slightly Wet Suspensions

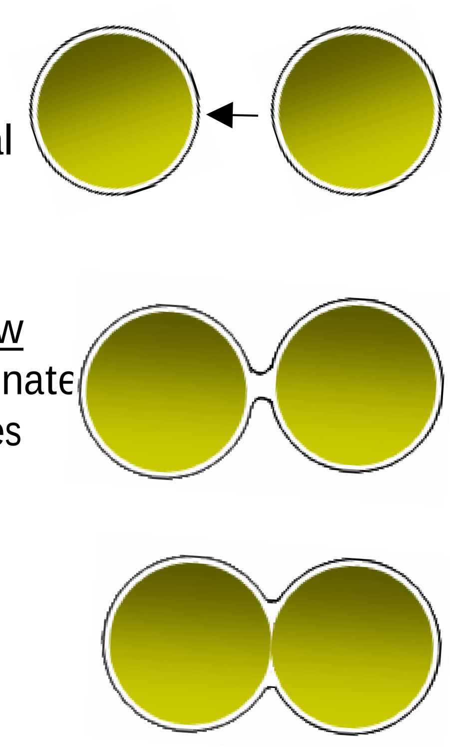
Hypothesis

Solid concentration

Rapid flow
Transient contacts dominated by collisional stresses

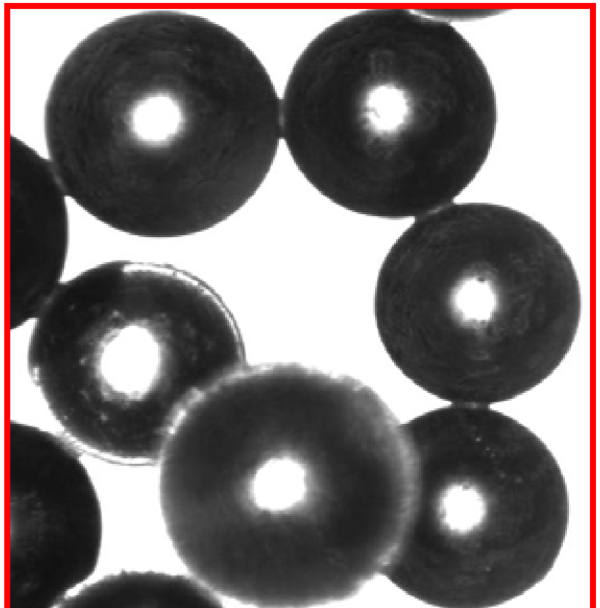
Dense-intermediate flow
Enduring contacts dominate by liquid viscous stresses

Quasi-static flow
Enduring contacts dominated by particle frictional stresses



Particle-Particle Interactions in Slightly Wet Suspensions

- In wet particles flow, direct solid-solid contacts are limited



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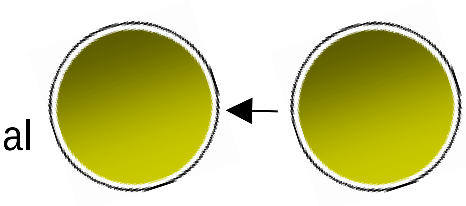
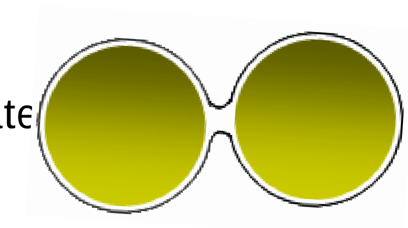


Dense-intermediate flow
Enduring contacts dominate by liquid viscous stresses



Quasi-static flow
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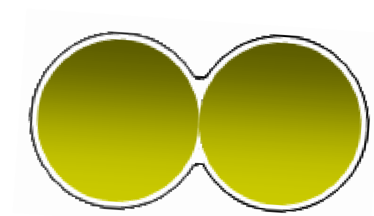


Eulerian Modelling of Dry Granular Flow

Solid phase

continuity equation: $$\frac{\partial(\alpha_s \rho_s)}{\partial t} + \nabla(\alpha_s \rho_s \vec{u}_s) = 0$$

momentum: $$\frac{\partial(\alpha_s \rho_s \vec{u}_s)}{\partial t} + \nabla(\alpha_s \rho_s \vec{u}_s \vec{u}_s) = -\alpha_s \nabla P - \nabla P_s + \nabla\left(\bar{\bar{\tau}}_s\right) + \beta\left(u_g - u_s\right) + F$$

Gas phase

continuity equation: $$\frac{\partial(\alpha_g \rho_g)}{\partial t} + \nabla\left(\alpha_g \rho_g \vec{u}_g\right) = 0$$

momentum: $$\frac{\partial\left(\alpha_g \rho_g \vec{u}_g\right)}{\partial t} + \nabla\left(\alpha_g \rho_g \vec{u}_g \vec{u}_g\right) = -\alpha_g \nabla P + \nabla\left(\bar{\bar{\tau}}_g\right) - \beta\left(u_g - u_s\right) + F$$

Energy equation (granular temperature):

$$\frac{3}{2}\left[\frac{\partial(\alpha_s \rho_s T)}{\partial t} + \nabla(\alpha_s \rho_s T)\vec{u}_s\right] = \left(-P_s \bar{\bar{I}} + \bar{\bar{\tau}}_s\right) : \nabla \vec{u}_s - \nabla(\kappa_T \nabla T) - \gamma_T - J_T$$

Well developed KTGF (kinetic theory of granular flow)

Shear Stress in Particle-Particle Interaction

$$\bar{\bar{\tau}}_s = \left(\lambda_s - \frac{2}{3}\mu_s\right)(\nabla \cdot \vec{u}_s)\bar{\bar{I}} + 2\mu_s \bar{\bar{S}}_s$$

solids shear viscosity $\mu_S = \mu_{S,col} + \mu_{S,kin} + \mu_{S,fr}$

$\mu_{S,fr} = 0$ $\quad 0 < \alpha_s < 0.5$ No friction

$\mu_{S,fr} = \dfrac{P_S \sin\phi}{2\sqrt{I_{2D}}}$ $\quad 0.5 < \alpha_s < 0.63$ Particle packing-enduring contact

How to present friction shear stress in slightly wet granular flow?

$$\mu_S = \mu_{S,col} + \mu_{S,kin} + \mu_{S,fr} + \mu_{wet}$$

Wet shear viscosity
(fluid shear resistance)

How to Modify Solid Stress Model

Solid phase momentum

$$\frac{\partial(\alpha_s \rho_s \vec{u}_s)}{\partial t} + \nabla(\alpha_s \rho_s \vec{u}_s \vec{u}_s) = -\alpha_s \nabla P - \nabla P_s + \nabla\left(\bar{\bar{\tau}}_s\right) + \beta\left(u_g - u_s\right) + F$$

Energy equation (granular temperature):

$$\frac{3}{2}\left[\frac{\partial(\alpha_s \rho_s \Theta_S)}{\partial t} + \nabla(\alpha_s \rho_s \Theta_S)\vec{u}_s\right] = \left(-P_s \bar{\bar{I}} + \bar{\bar{\tau}}_s\right) : \nabla \vec{u}_s - \nabla\left(\kappa_{\Theta_S} \nabla \Theta_S\right) - \gamma_{\Theta_S} - J_{\Theta_S}$$

User Defined Function written in C language

Big Picture

How to incorporate shear stress (based on liquid bridge) in slightly wet particle flow?

Formula → User Defined Function (UDF)

ANSYS Fluent (platform)

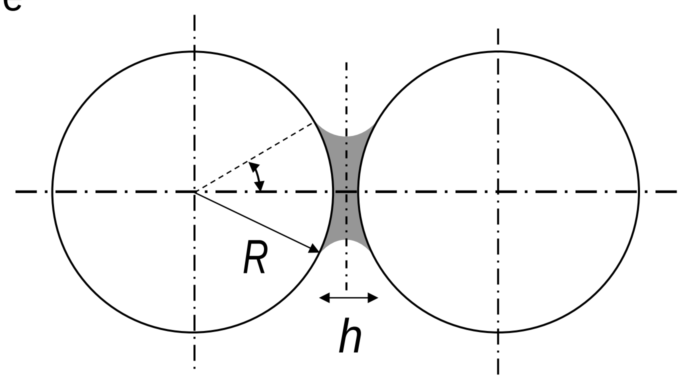
↓

Experimental observation ECT → Validate → Predicted flow behavior (flow pattern, Solid concentration distribution)

Liquid Bridge Stresses

q For this, we may start from the interparticle force at single particle level:

$$\dot{F}_{liquid} = \frac{3}{8}\pi\mu_{liquid}d_p^2\frac{\dot{u}}{h}$$



q Interparticle approach velocity can be estimated from granular temperature:

$$\dot{u}_s = \frac{3}{2}\sqrt{\pi\theta_s}$$

Normal stress

q For this, it is required to determine the force per unit area:

$$P_{liquid} = \frac{9}{16h}\pi\mu_{liquid}\sqrt{\pi\theta_s}\left(\frac{6\alpha_s}{\pi}\right)^{2/3}$$

Equivalent shear viscosity

q Analogue to Coulomb friction law

$$\mu_{wet} = \frac{\sqrt{2}P_{liquid}\eta}{\left|\bar{\bar{S}}\right|}$$

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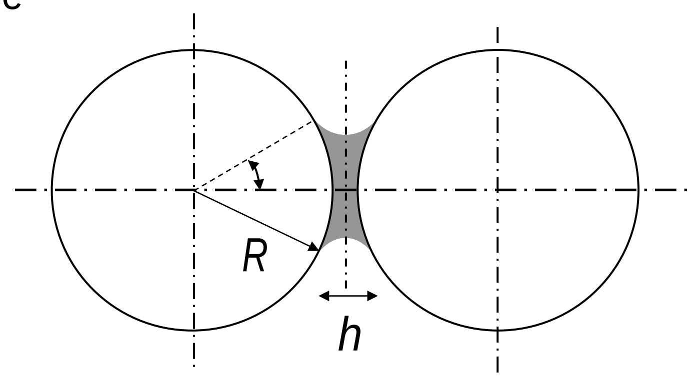
Approach velocity

Interparticle gap



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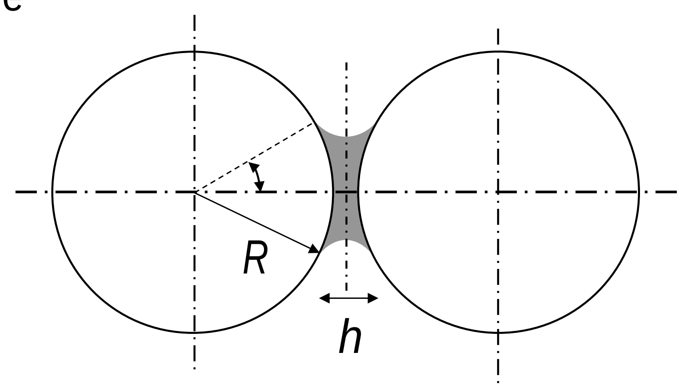
Approach velocity ($\dot{u}$)

Interparticle gap (h)



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$$\mu_{wet} = \frac{\sqrt{2}P_{liquid}\eta}{|\bar{\bar{S}}|}$$

"lubrication" coefficient (η)

Criteria to Turn on/off the Effect of Liquid Bridges

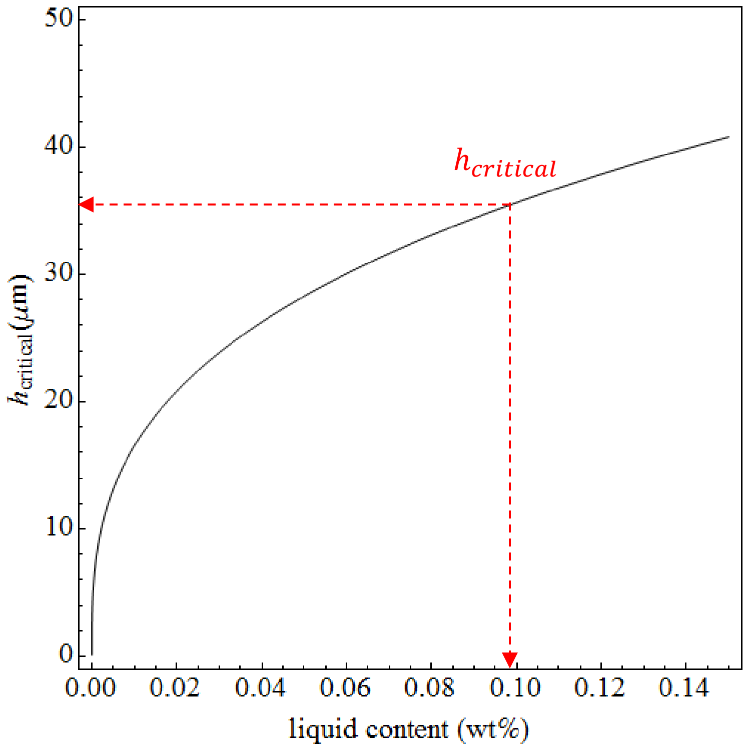
- We need to specify a critical interparticle gap distance at which liquid bridges become dominant:

$$P_{liquid} = \frac{9}{16h}\pi\mu_{liquid}\sqrt{\pi\theta_s}\left(\frac{6\alpha_s}{\pi}\right)^{2/3} \quad \text{if } h_a < h \le h_{critical}$$

$$P_{liquid} = 0 \quad \text{if } h > h_{critical}$$

$$h_{critical} = 0.8d_p\sqrt[3]{\left(\frac{M_L}{M_S}\right)\left(\frac{\rho_S}{\rho_L}\right)}$$ Lian et al. (1992)

$h_a = 2\sim10\mu\text{m}$ particle surface asphericity



$d_p = 350\mu m, \rho_L = 969kg/m^3, \rho_S = 2500kg/m^3,$
$m_s = 4.5kg$

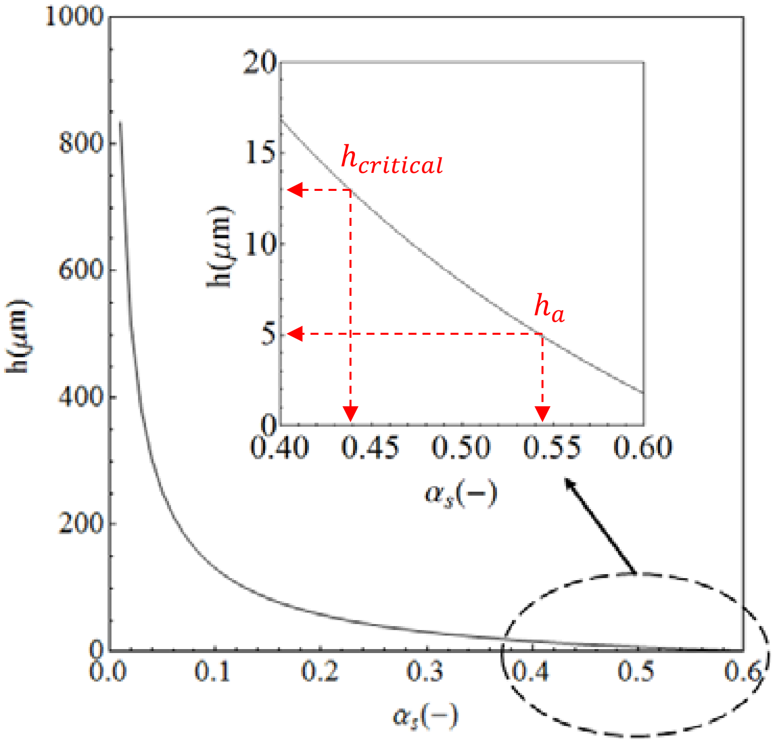
(1) Lian et al.,A theoretical study of the liquid bridge forces between two rigid spherical bodies, Int J. of interface Science,1992

Void and Inter-Particle Gap Distance Relation

- In randomly packed spheres, the gap distance can be expressed in terms of solid volume fraction[1]:

$$h = d_p\left(\sqrt{\frac{1}{3\pi\varepsilon_s}+\frac{5}{6}}-1\right)$$

The critical solid fraction at liquid bridge rupture can be estimated once the rupture distance is known



(1) L.V. Woodcock,in "Proc. of a workshop on glass forming liquids", edited by Z. I. P. Bielefeld (Springer Lecture Series in Physics, 277, 1985) p. 113.

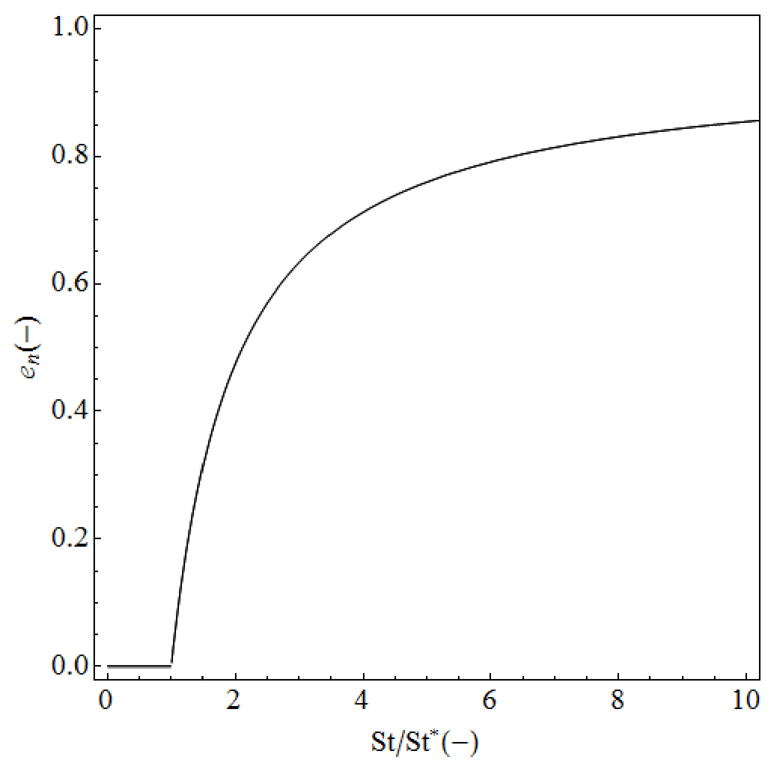
Restitution Coefficient of Wet Particles

$$St = \frac{8m\dot{u}}{3\pi\mu {d_p}^2}$$

$$St^* = \left(1 + \frac{1}{e_{dry}}\right) ln\left(\frac{h}{h_a}\right)$$ critical Stokes number

$$e_{wet} = \begin{cases} e_{dry}\left(1 - \frac{St^*}{St}\right) & if \quad h_a < h \leq h_{critical} \ and \ St > St^* \\ 0 & if \quad St \leq St^* \\ e_{dry} & if \quad h > h_{critical} \ and \ St > St^* \end{cases}$$

$$\gamma_{\Theta_S} = \frac{12(1 - {e_{wet}}^2) g_{0,ss}}{d_S \pi^{1/2}} {\alpha_S}^2 \rho_S {\Theta_S}^{3/2}$$



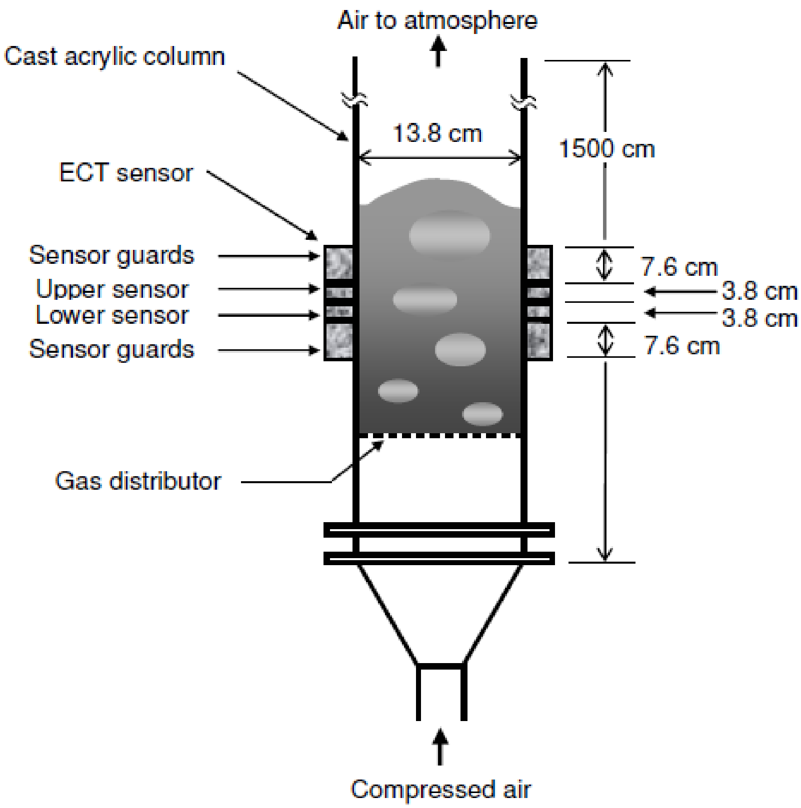
$d_p = 350\mu m$, $\rho_L = 969 kg/m^3$, $\rho_S = 2500 kg/m^3$

$\mu = 0.4945\ kg/(m.s)$

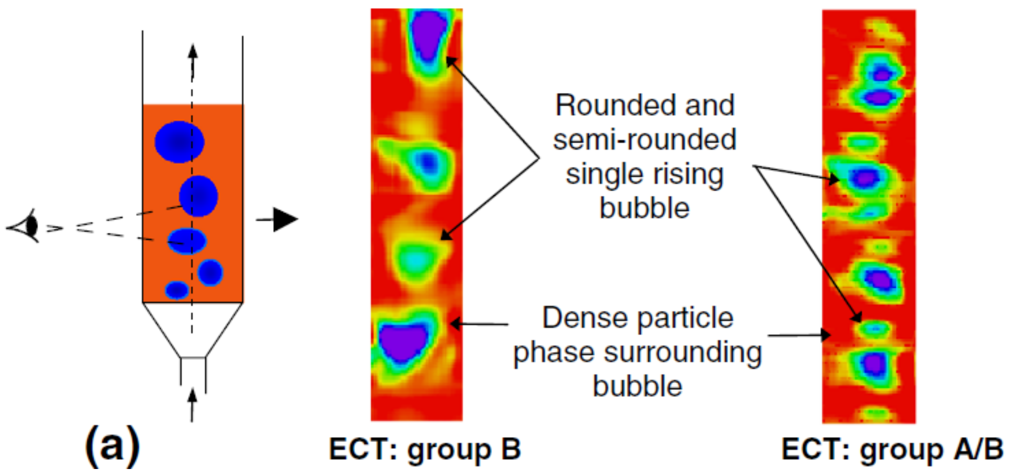
Energy equation (granular temperature):

$$\frac{3}{2}\left[\frac{\partial(\alpha_s \rho_s \Theta_S)}{\partial t} + \nabla(\alpha_s \rho_s \Theta_S)\vec{u}_s\right] = \left(-P_s \bar{\bar{I}} + \bar{\bar{\tau}}_s\right) : \nabla \vec{u}_s - \nabla\left(\kappa_{\Theta_S} \nabla \Theta_S\right) - \gamma_{\Theta_S} - J_{\Theta_S}$$

Experimental Results (ECT) in Dry Particle-Flow



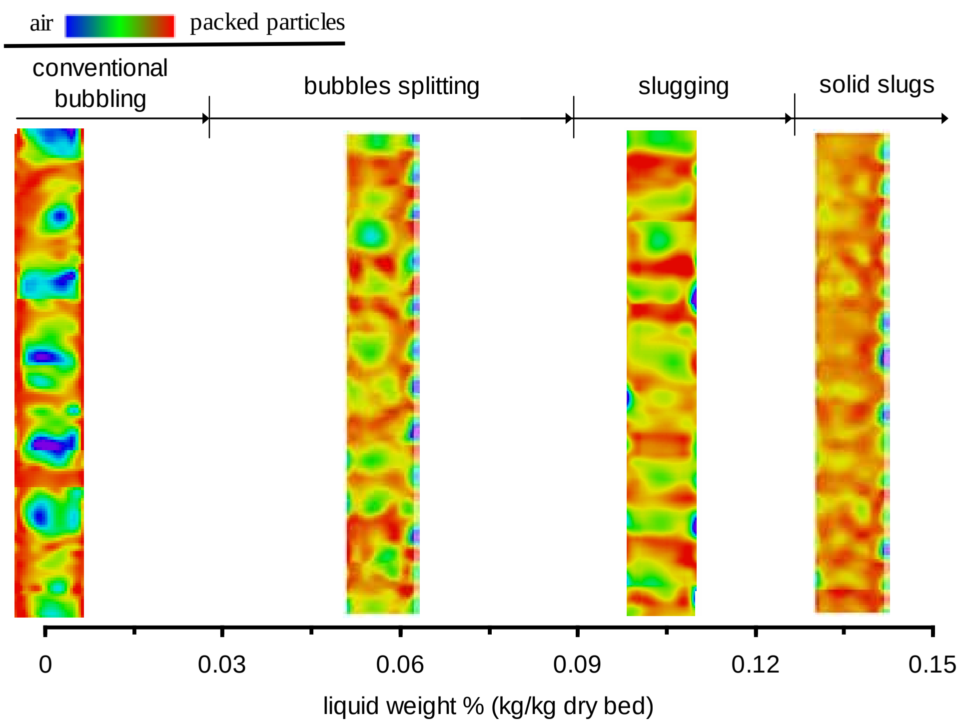
Experimental setup



(Makkawi et al, 2006)
Solid volume fraction

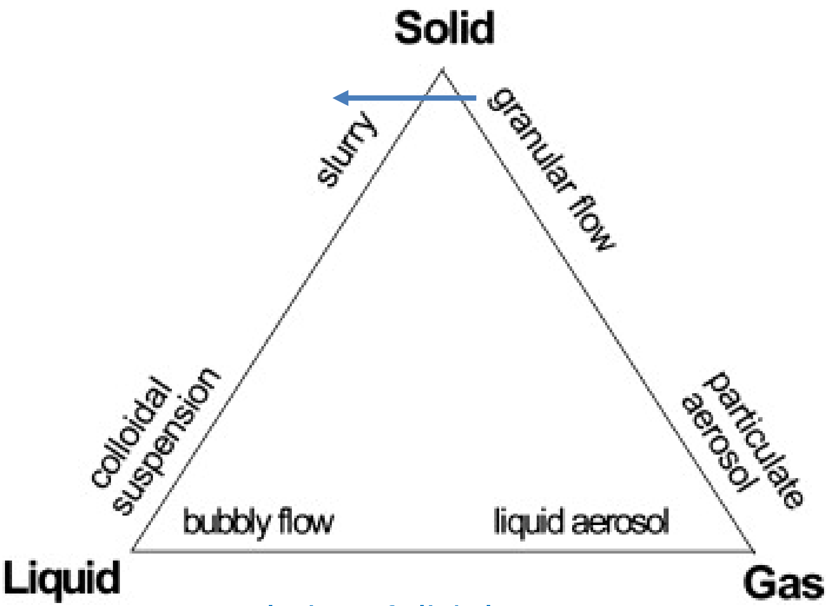
ECT (electrical capacitance tomography) is a diagnostic imaging tool in the medical field

Experimental Results (ECT) in Slightly Wet Flow



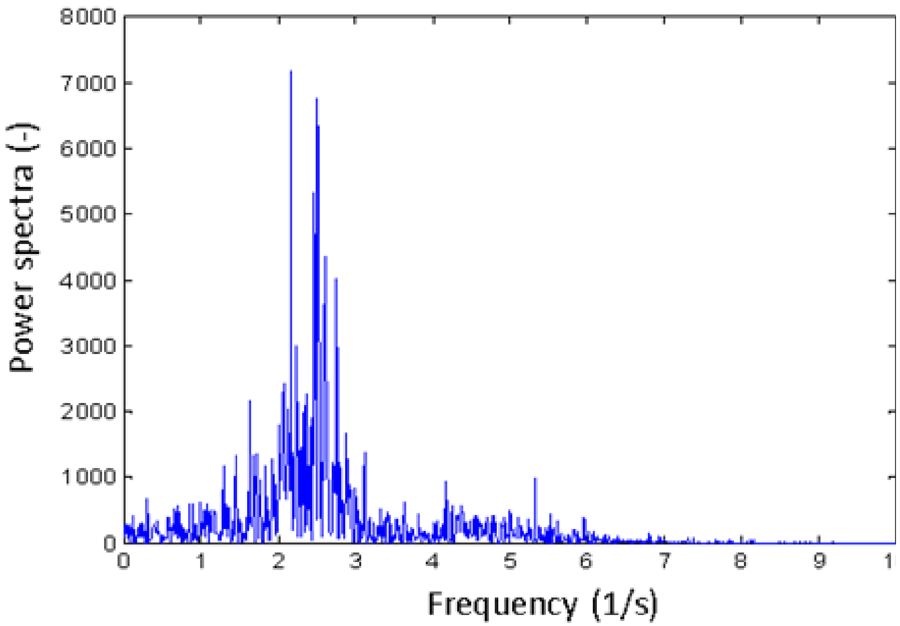
Operating conditions: fluidisation velocity=0.8 m/s, bed of 350 mm diameter glass bead, bed weight=3.5 kg, column diameter=15 cm, liquid used is silicon oil (density=969 kg/m^3, surface tension=0.0165 N/m and dynamic viscosity=0.4945 kg/(m.s))

Lines: Types of two-phase system

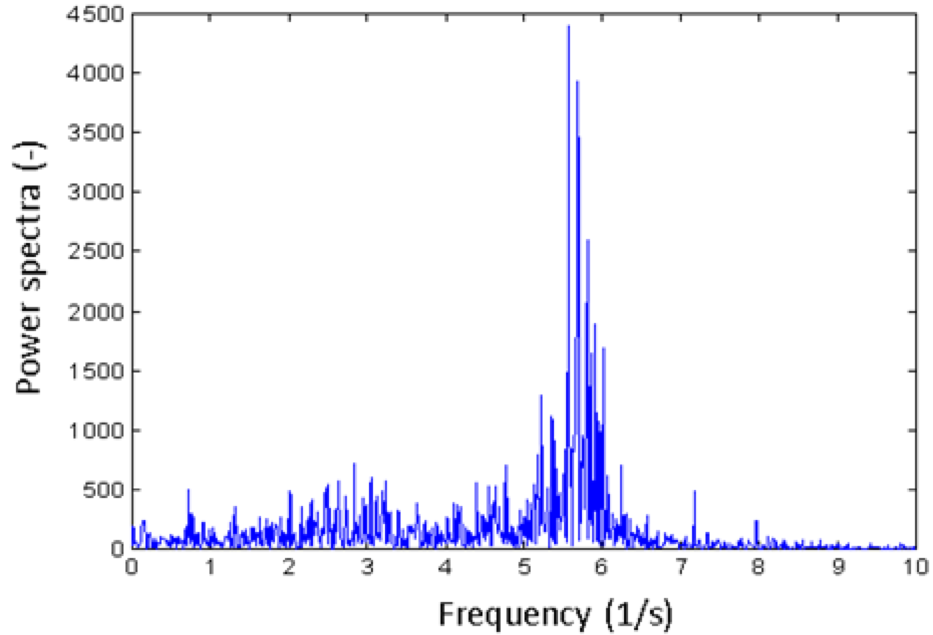


Evolution of slightly wet system
In three-phase diagram

Fast Fourier Transform Analysis



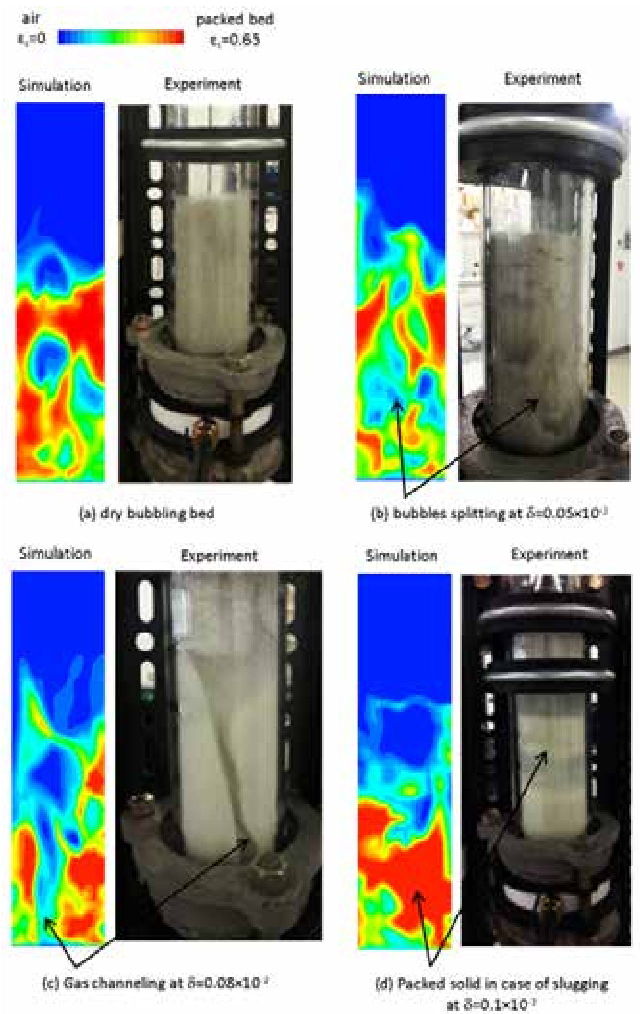
(a) FFT of dry bed

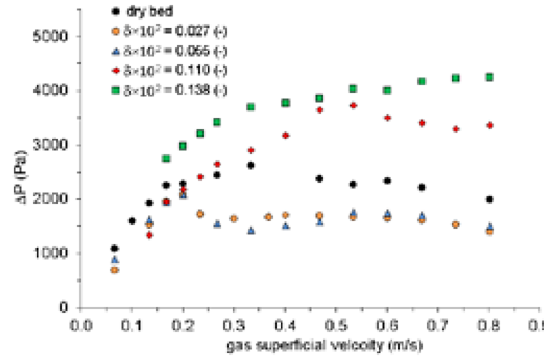


(b) FFT of wet bed

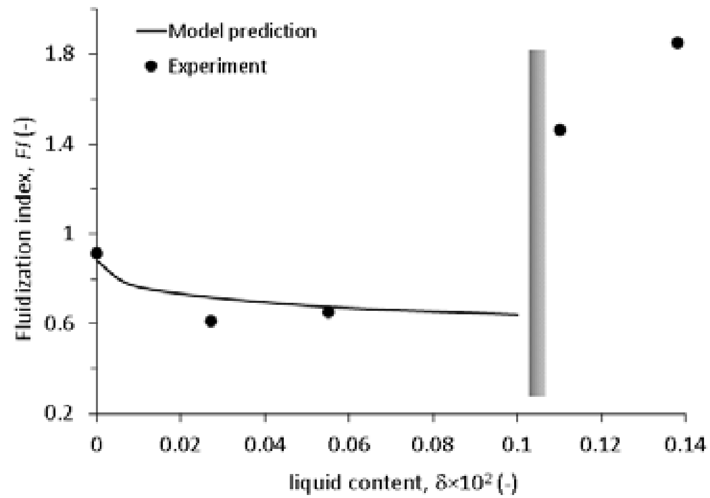
Fast Fourier Transform (FFT) analysis of solid fraction fluctuation obtained by ECT measurement in a bubbling fluidized bed (a) dry (b) wet at $\delta = 0.055 \times 10^{-2}$. The solid fraction data represents the spatial average fluctuations at 7.6 cm above the distributor and was produced in a 15 cm diameter column with the bed material consisting of 3.5 kg glass beads fluidized at the gas velocity of 0.8 m/s.

Fluidisation Analysis





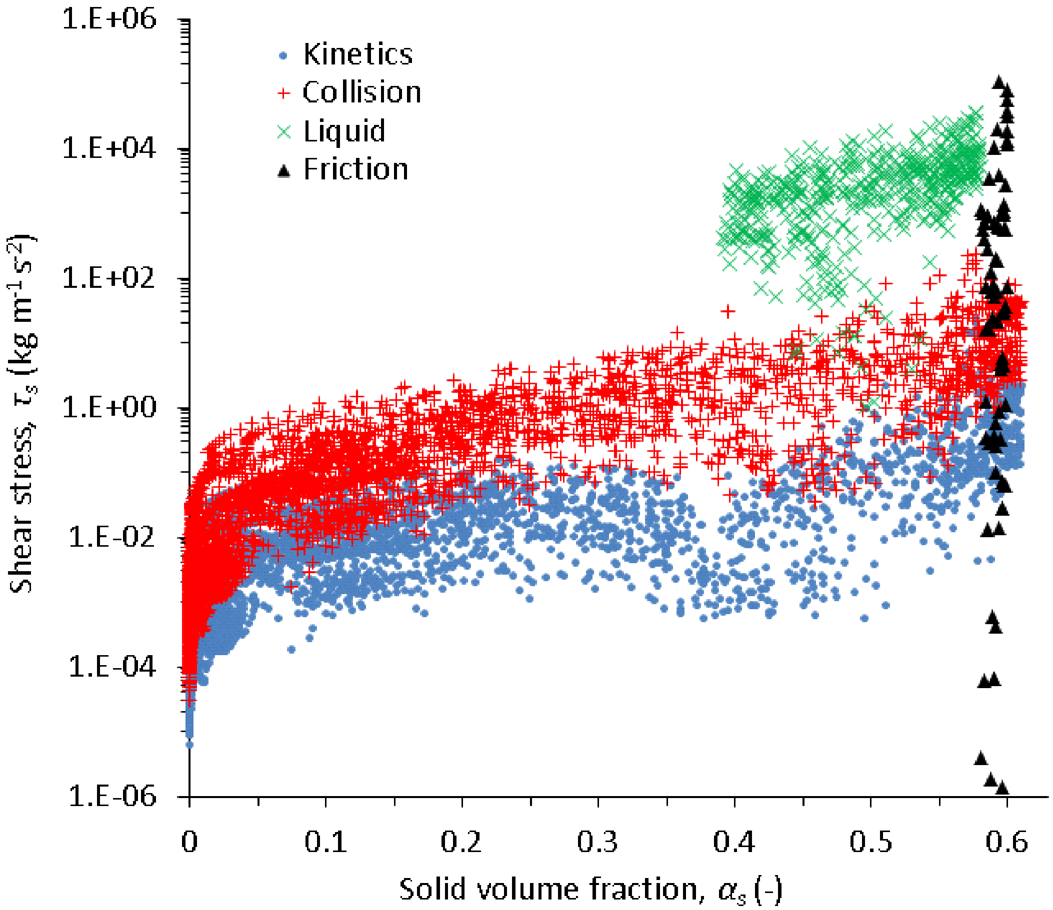
Experimental fluidised bed pressure drop at various gas velocities



Comparison of the predicted and experimentally determined fluidisation index $FI = \frac{\Delta P A}{W_{bed} g}$

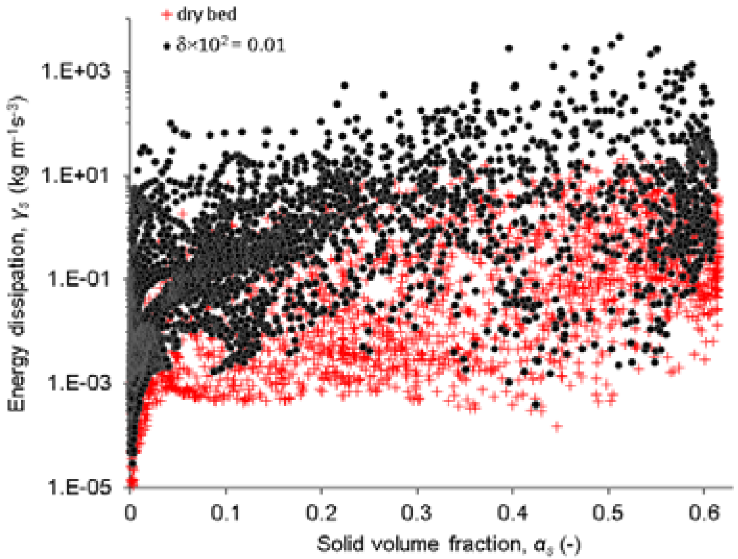
In highly cohesive powders, the experimentally determined FI was found to be greater than 1.4 (*De Jong et al, 1999*). The model failed to provide a stable solution at d>0.1×10^{-2}

Results

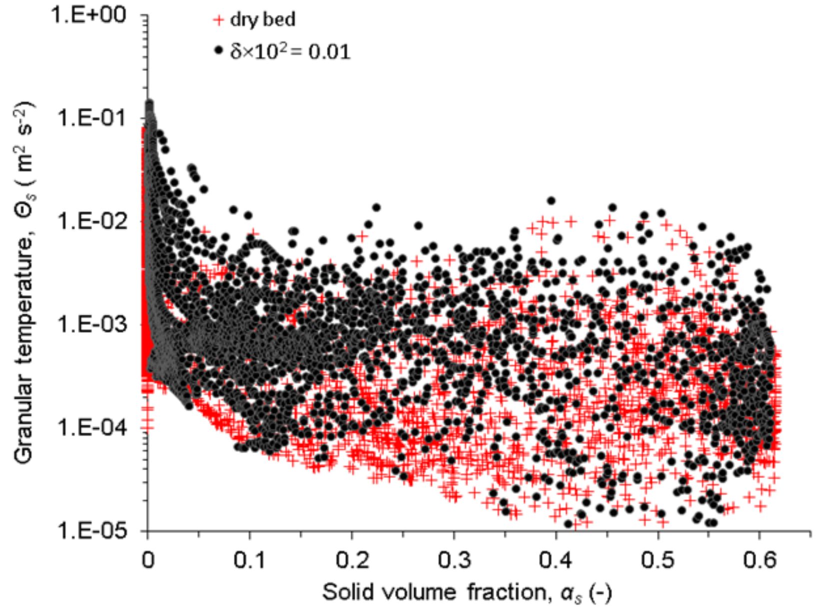


Predicted solid shear stress in a slightly wet fluidised bed of 15 cm diameter at the gas velocity of 0.8 m/s and liquid amount of $\delta = 0.1 \times 10^{-2}$

Results



(a) energy dissipation rate



(b) granular temperature

Predicted (a) energy dissipation rate and (b) granular temperature as function of the solid concentration in dry and a slightly wet fluidized bed of 15 cm diameter at the gas velocity of 0.8 m/s

Conclusions

- The proposed model combines theories of liquid bridge forces with the kinetic theory of granular flow (KTGF)

- The model is capable of predicting characteristic hydrodynamic features of slightly wet, non-porous particles in a bubbling fluidised bed

- The experimental measurement produced by electrical capacitance tomography (ECT) have shown distinct hydrodynamic features characterised by bubbles splitting, gas channelling, slugging and de-fluidisation as the liquid presence in the bed increases

- The proposed model allows, for the first time, continuum modelling of slightly wet solid fluidisation, thus extending the existing classic two-fluid modelling beyond its traditional boundaries.

Quasi-Static Regime

Lyes Ait Ali Yahia, Riccardo Maione and Ali Ozel

HERIOT WATT UNIVERSITY

Shear Test

Evaluation of the stresses needed to generate shear leading to either compaction or dilation states under a given applied normal stress

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- Automated device
- 48mm diameter – shear head
- 18 blads – 2mm height

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Constitutive models combining DEM simulations and experimental results

Shear test procedure

Shear head applies a normal stress (s) by moving downward

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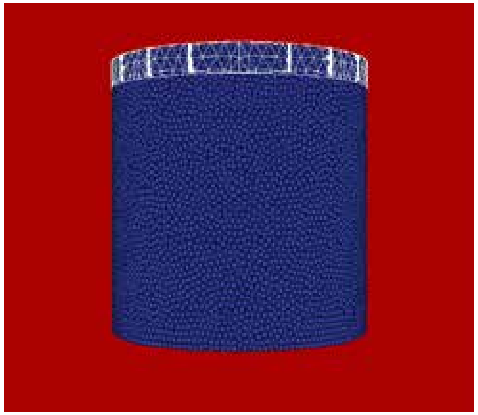
↓

Once the desired normal stress is reached, the shear head induces a shear stress(t)

Shear test procedure



Shear head applies a normal stress (s) by moving downward

↓

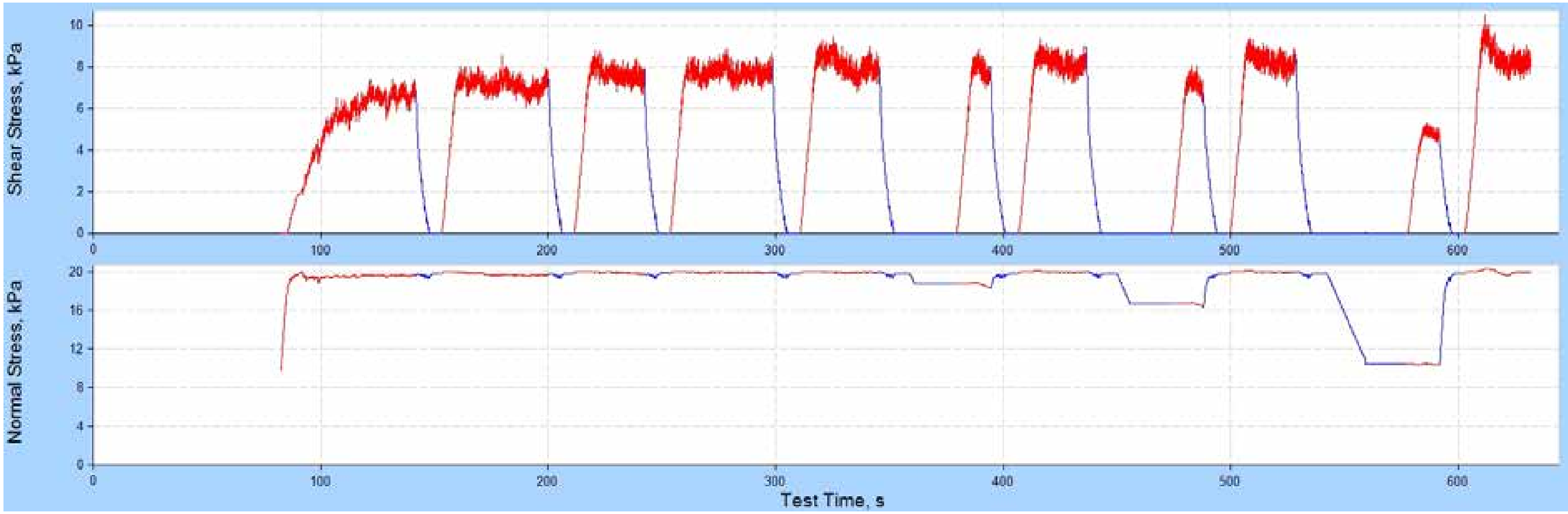
Once the desired normal stress is reached, the shear head induces a shear stress(t)

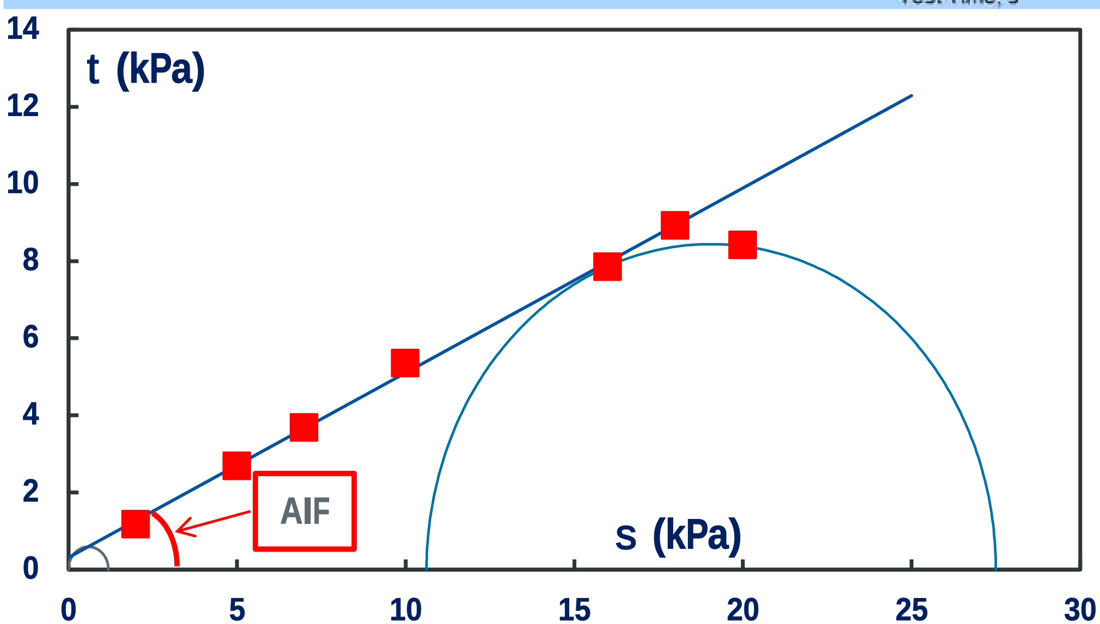
↓

The shear stress (t) increases until the powder bed fails

Shear Test - Experiments

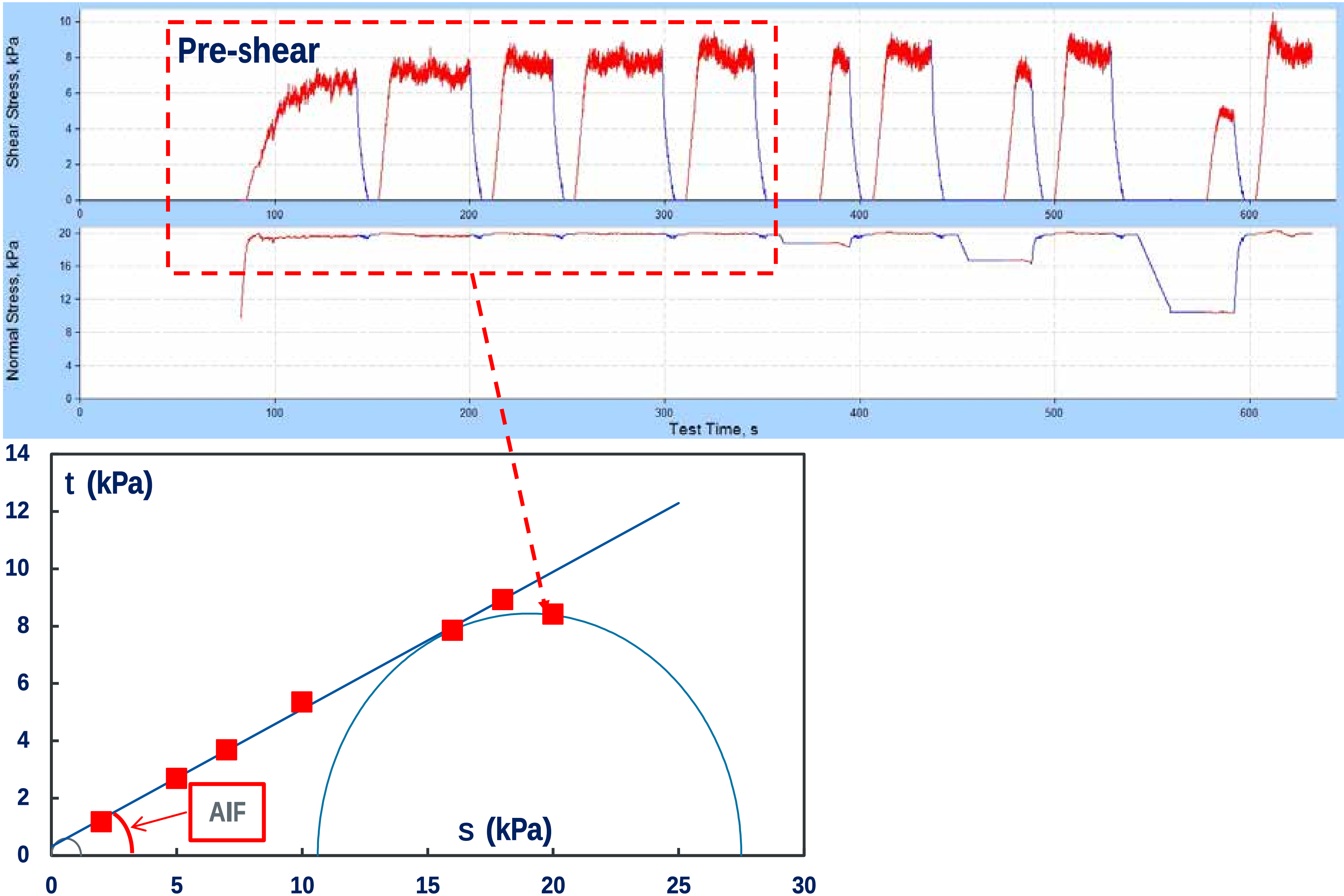
0.5mm diameter dry glass beads





Shear Test - Experiments

0.5mm diameter dry glass beads



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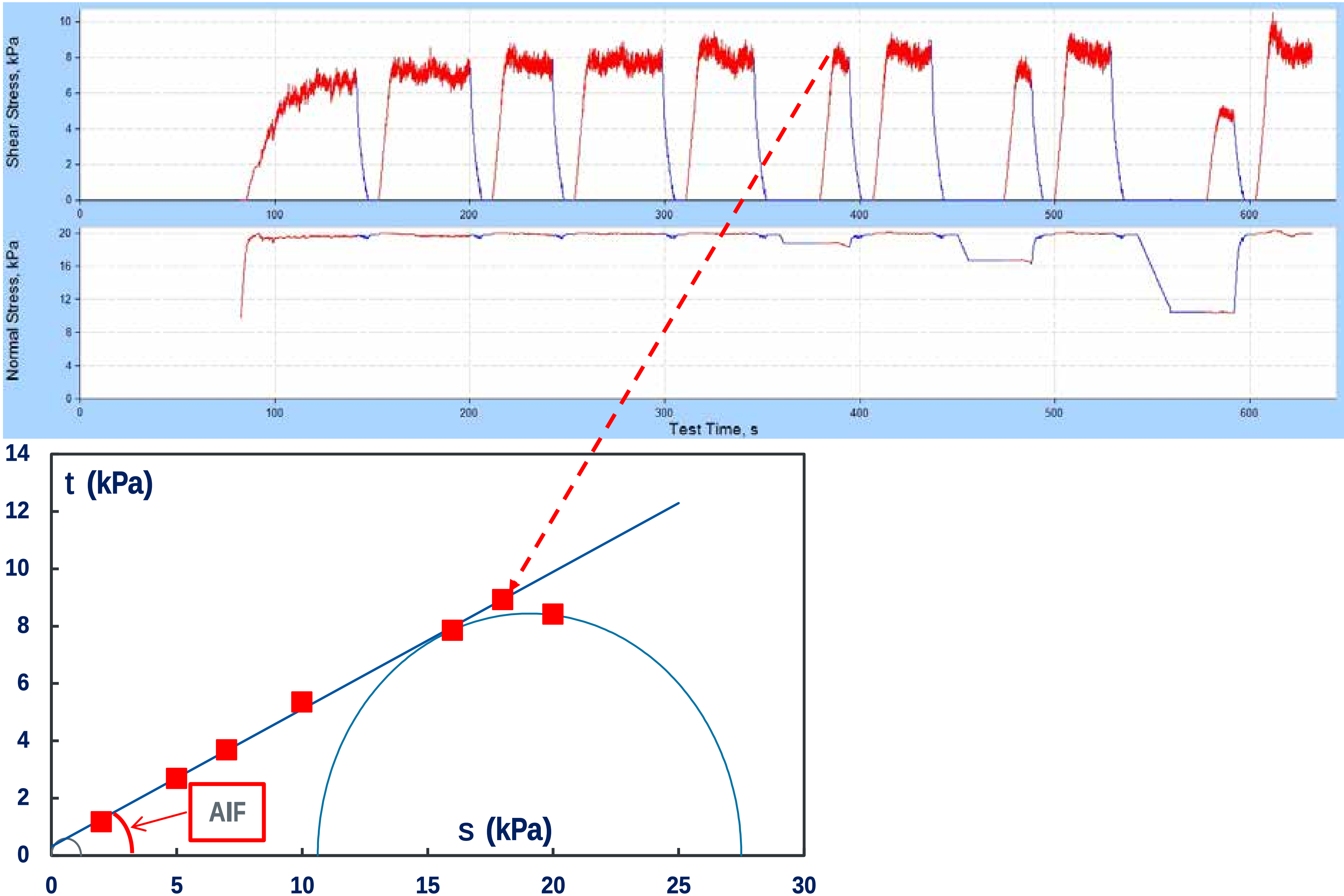

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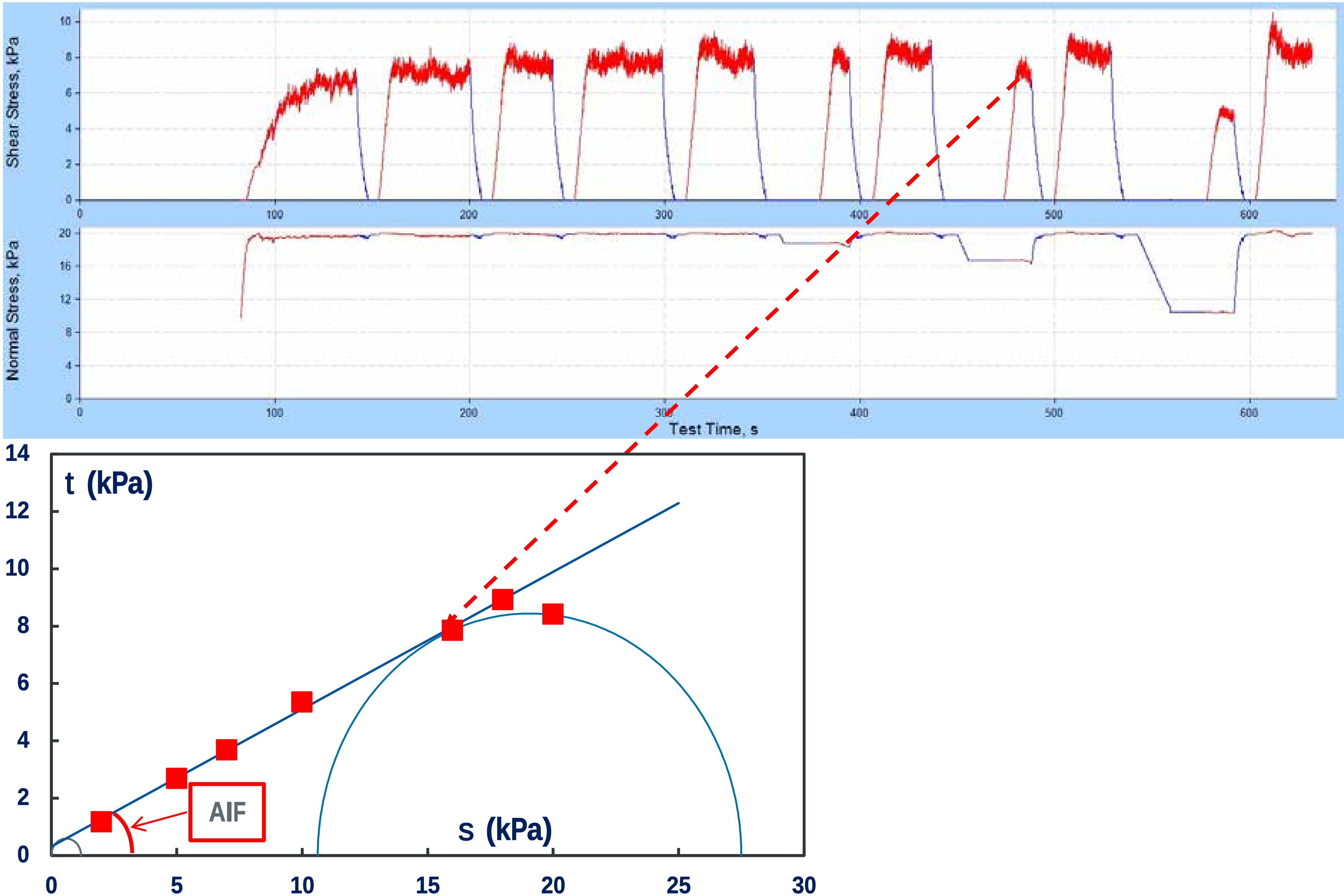

Shear Test - Experiments

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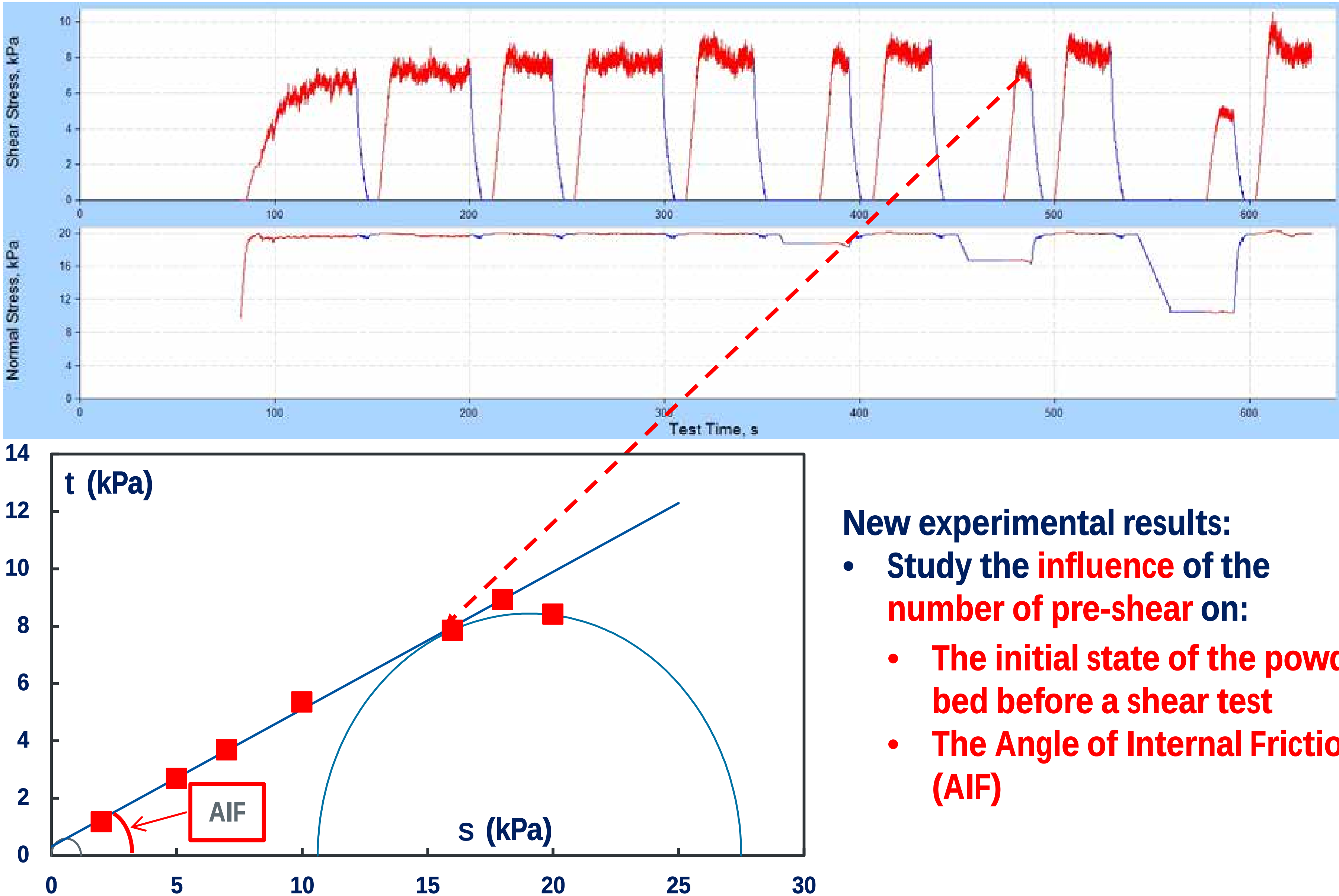
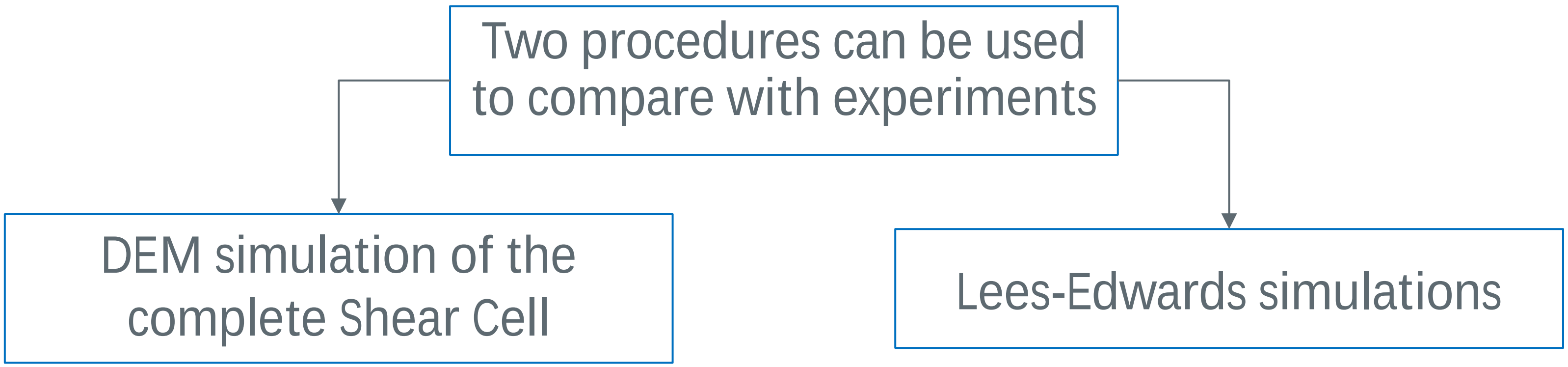


New experimental results:

- **Study the influence of the number of pre-shear on:**
  - **The initial state of the powder bed before a shear test**
  - **The Angle of Internal Friction (AIF)**

Shear Test – DEM Simulation

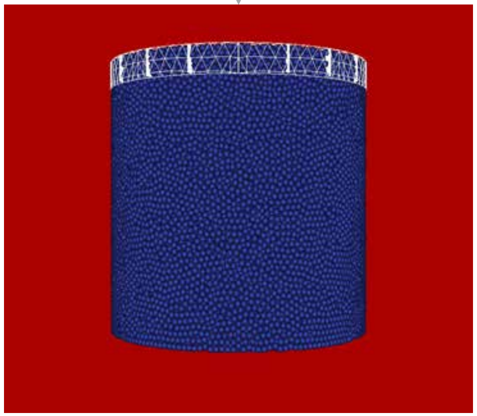


Shear Test – DEM Simulation

Two procedures can be used to compare with experiments

DEM simulation of the complete Shear Cell

Lees-Edwards simulations



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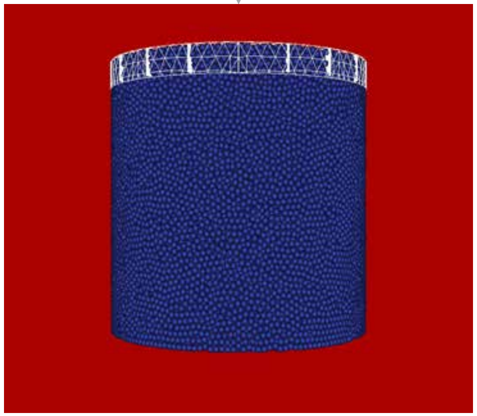
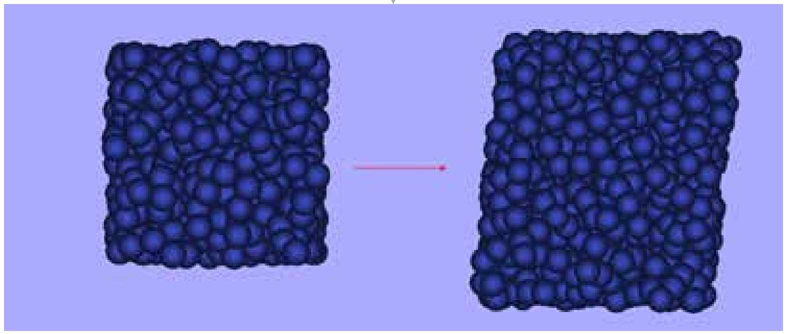


Lees-Edwards simulations

Simulation of the shear zone in a periodic domain by applying Lees Edwards contour conditions



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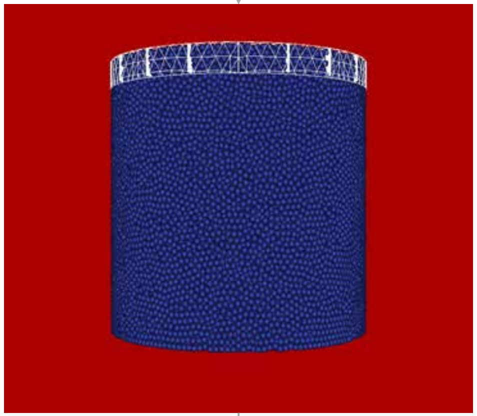
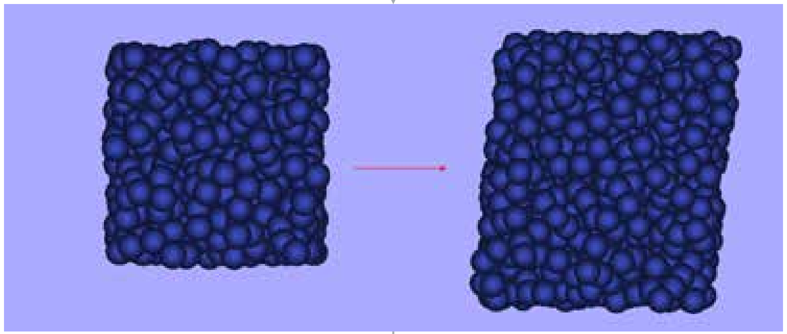


- – Heavy computational load
- + Information on every particle inside the domain

Lees-Edwards simulations

Simulation of the shear zone in a periodic domain by applying Lees Edwards contour conditions



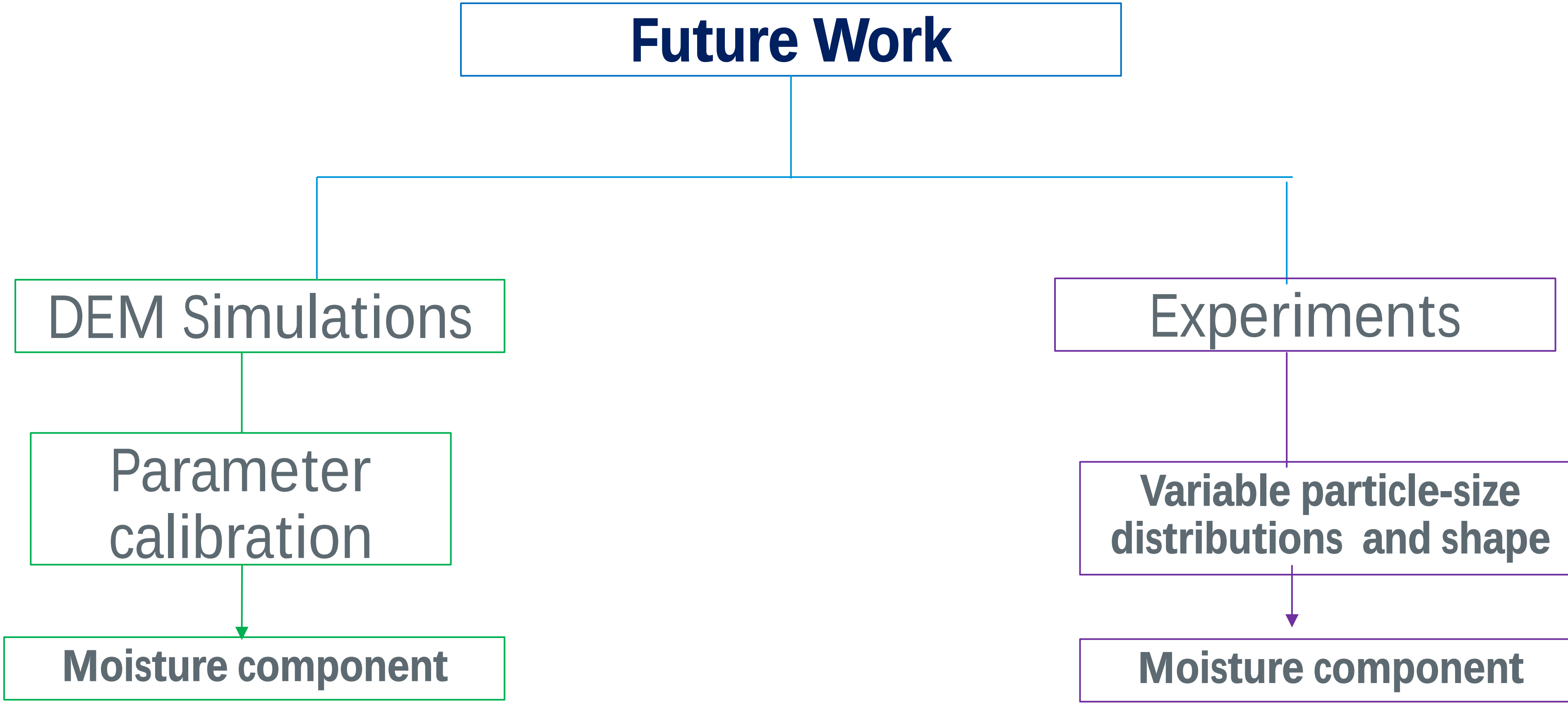
- – Only the shearing zone is simulated
- + Very small particle number

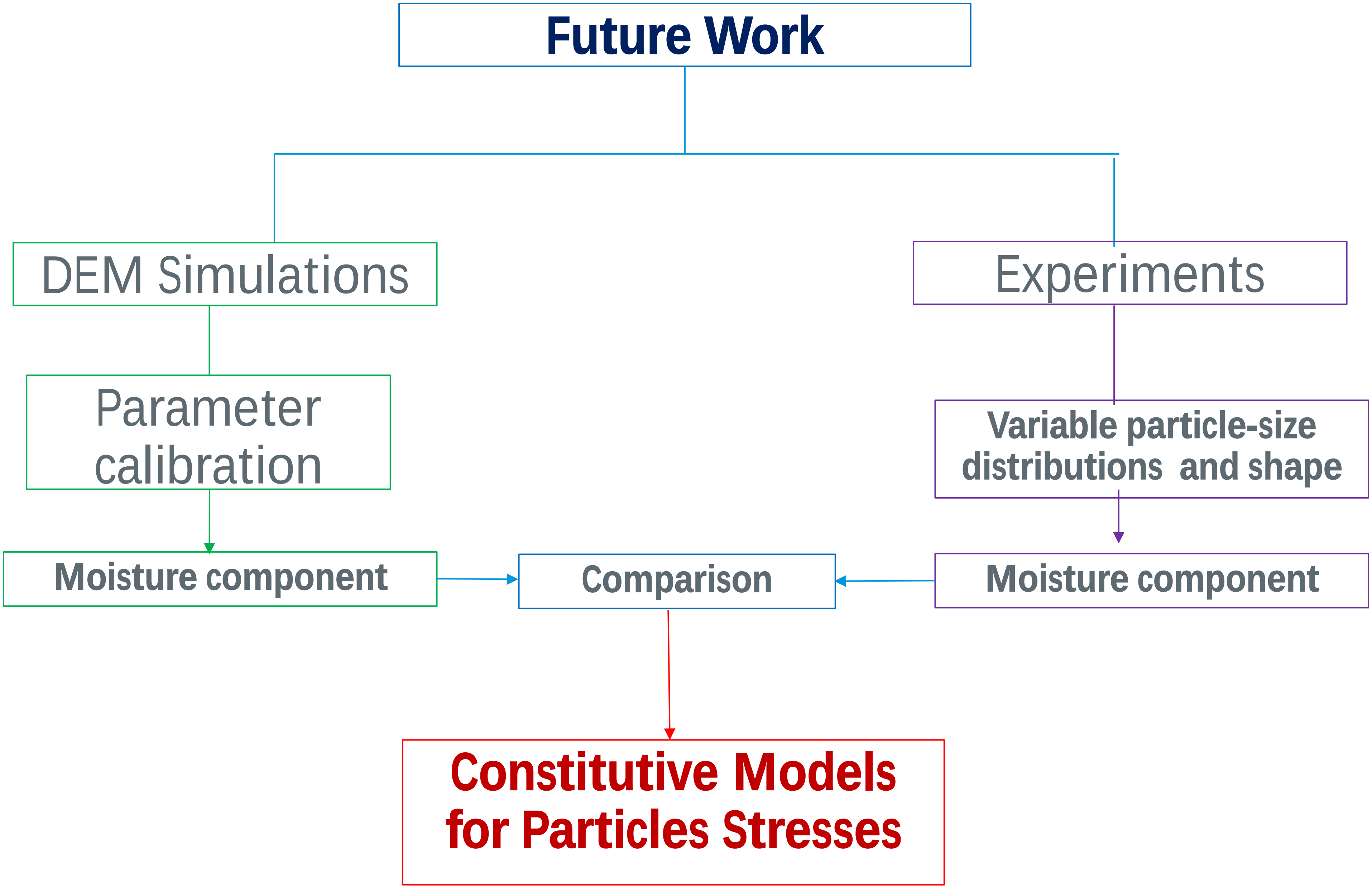
Future Work

- DEM Simulations
- Experiments

Future Work

- DEM Simulations
- Experiments
  - Variable particle-size distributions and shape
  - Moisture component


Future Work
DEM Simulations
Parameter calibration
Moisture component
Experiments
Variable particle-size distributions and shape
Moisture component


Future Work
DEM Simulations
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Moisture component
Comparison
Moisture component
Constitutive Models for Particles Stresses

Thank you for your attention!

Acknowledgement:

The support from the EPSRC (grant no EP/N034066/1) is kindly acknowledged