

# Quantifying fabric and considering its effects

Catherine O'Sullivan

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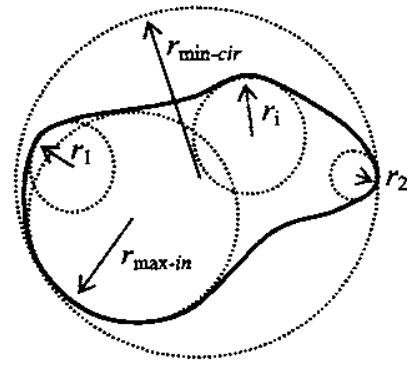
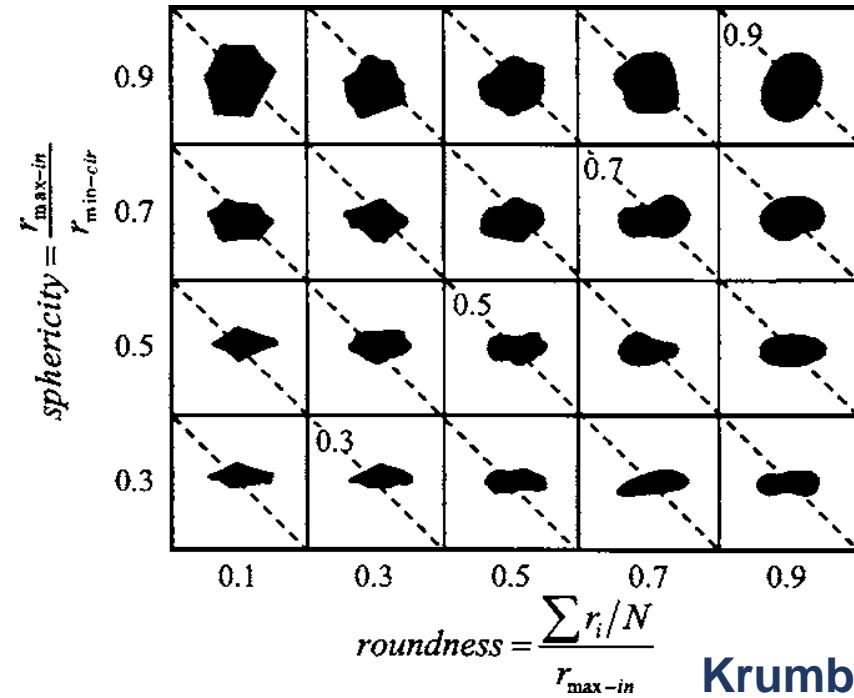
# Soil Fabric

“Particle sizes, shapes and distributions along with arrangements of grains and grain contacts comprise the fabric”

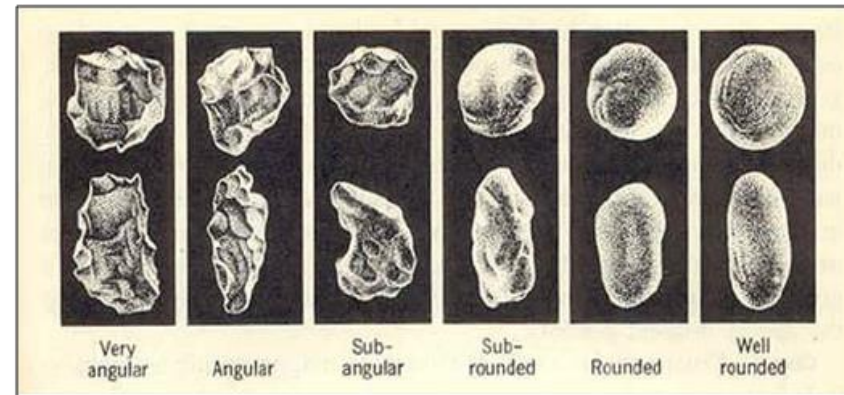
Mitchell and Soga (2005)

**Should fabric encompass particle morphology?**

# Quantifying Soil Fabric – Particle Size & Shape

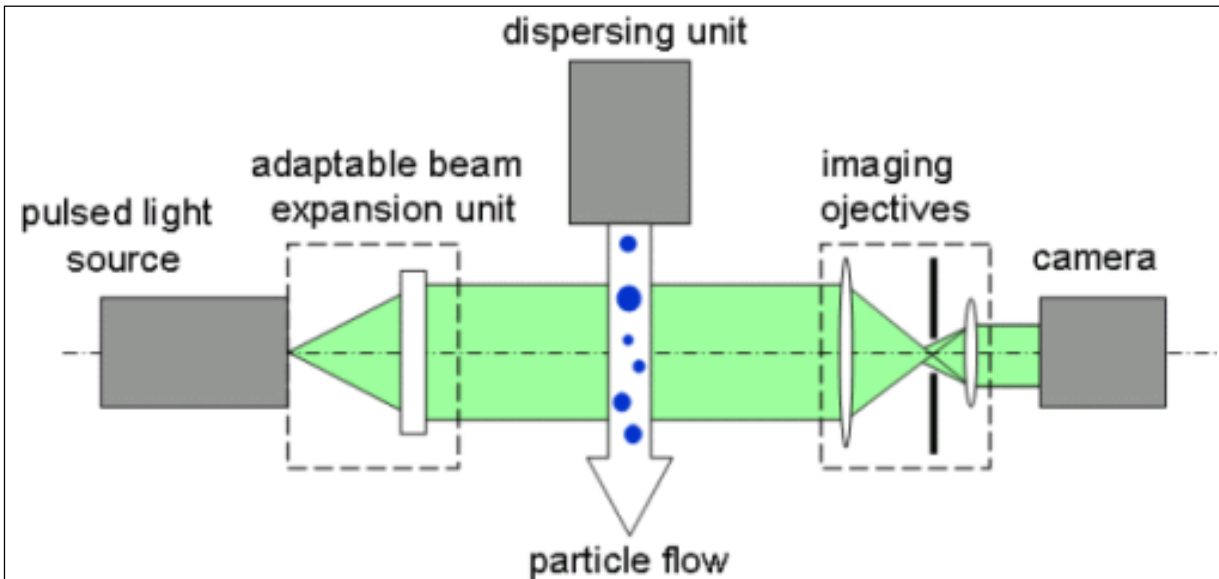
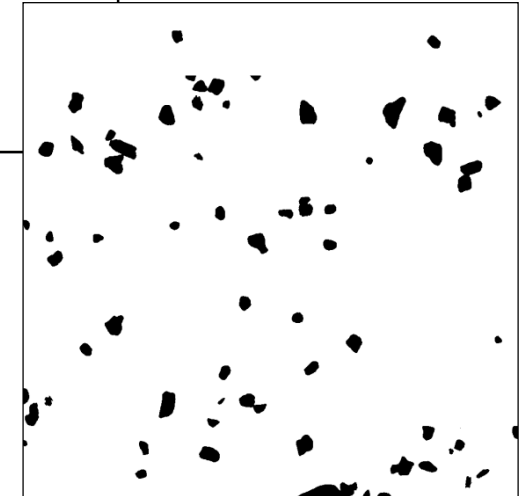
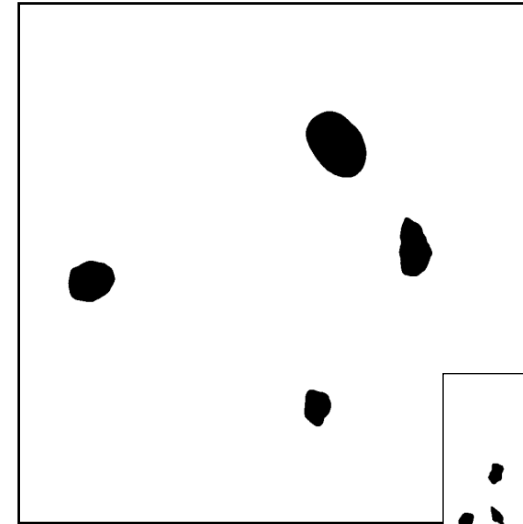


**Krumbein and Sloss (1963)  
& Cho et al (2006)**

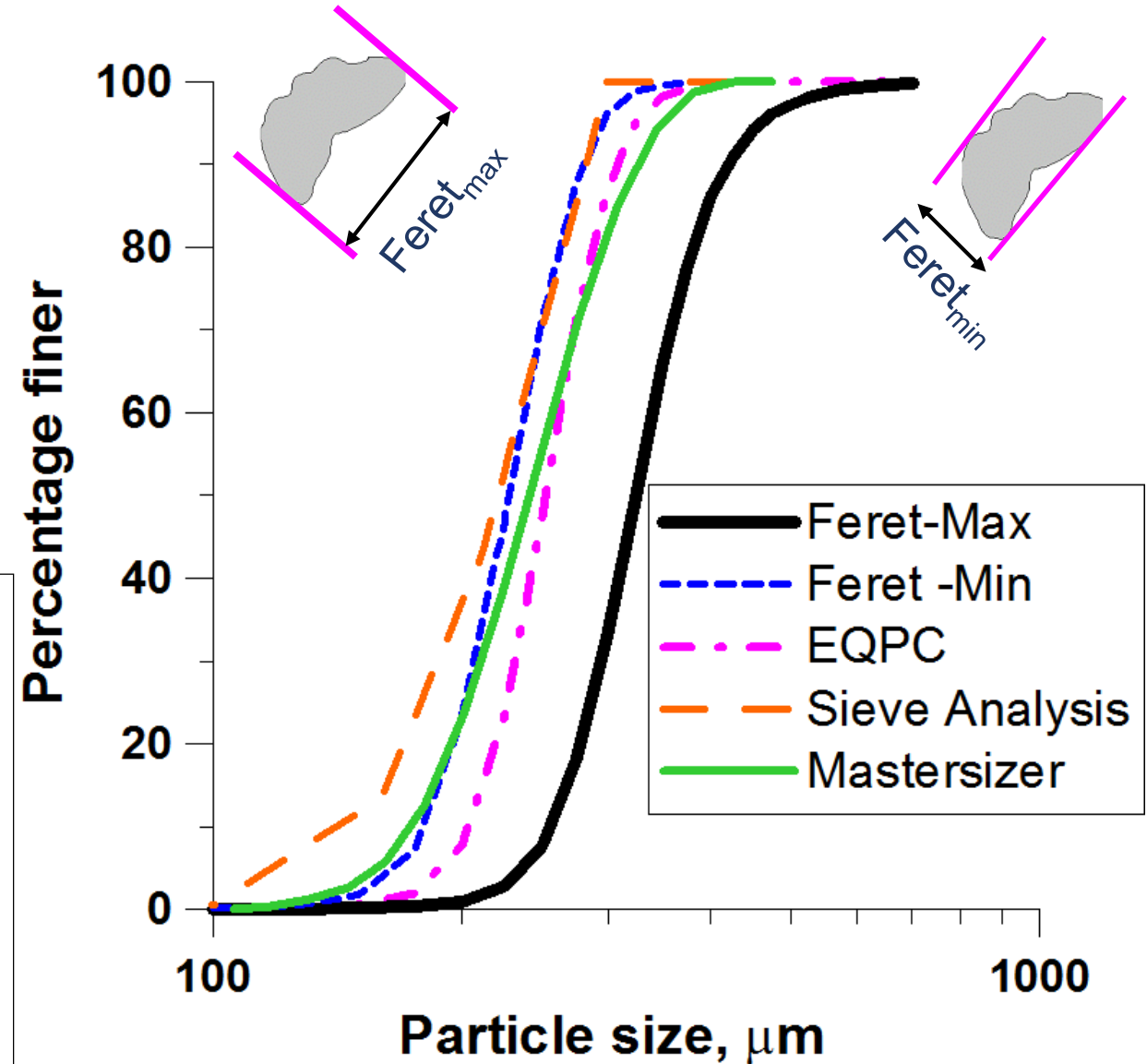
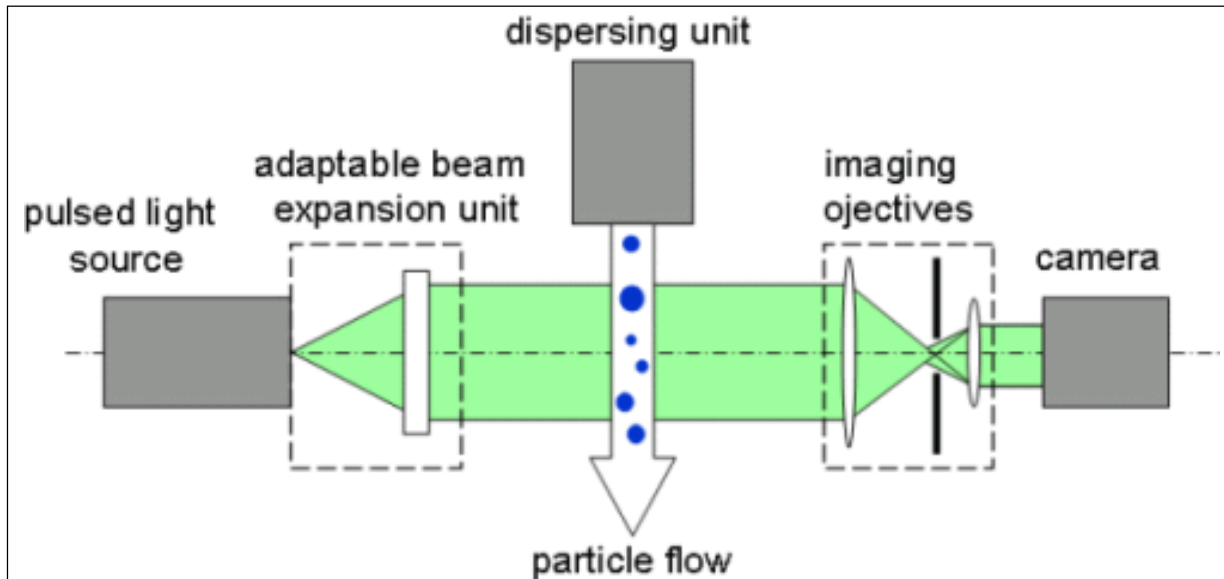


**Powers (1953)**

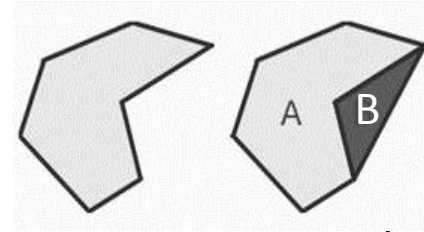
# Quantifying Soil Fabric – Particle Size & Shape



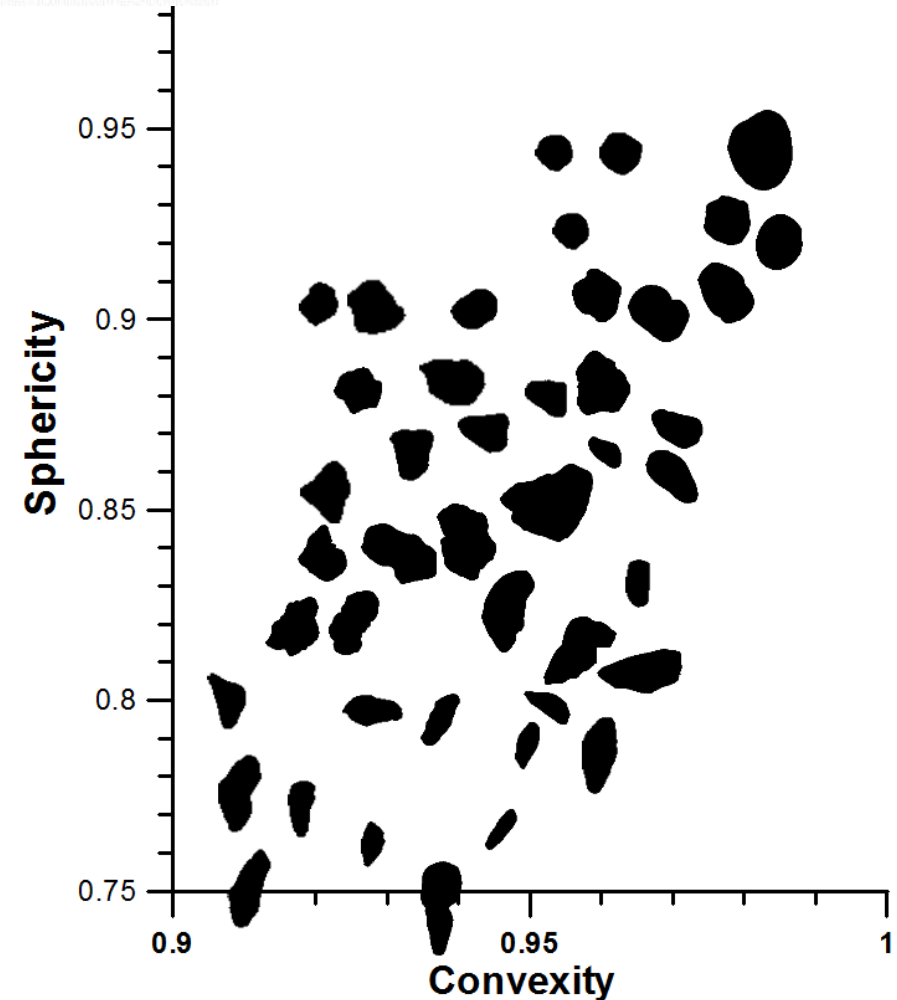
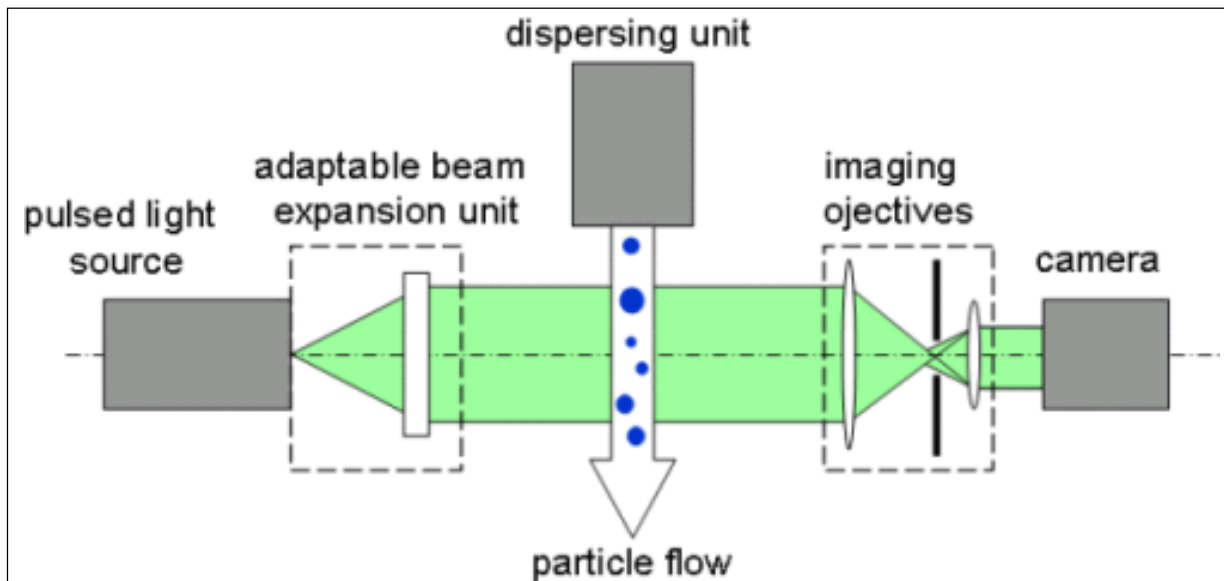
# Quantifying Soil Fabric – Particle Size & Shape



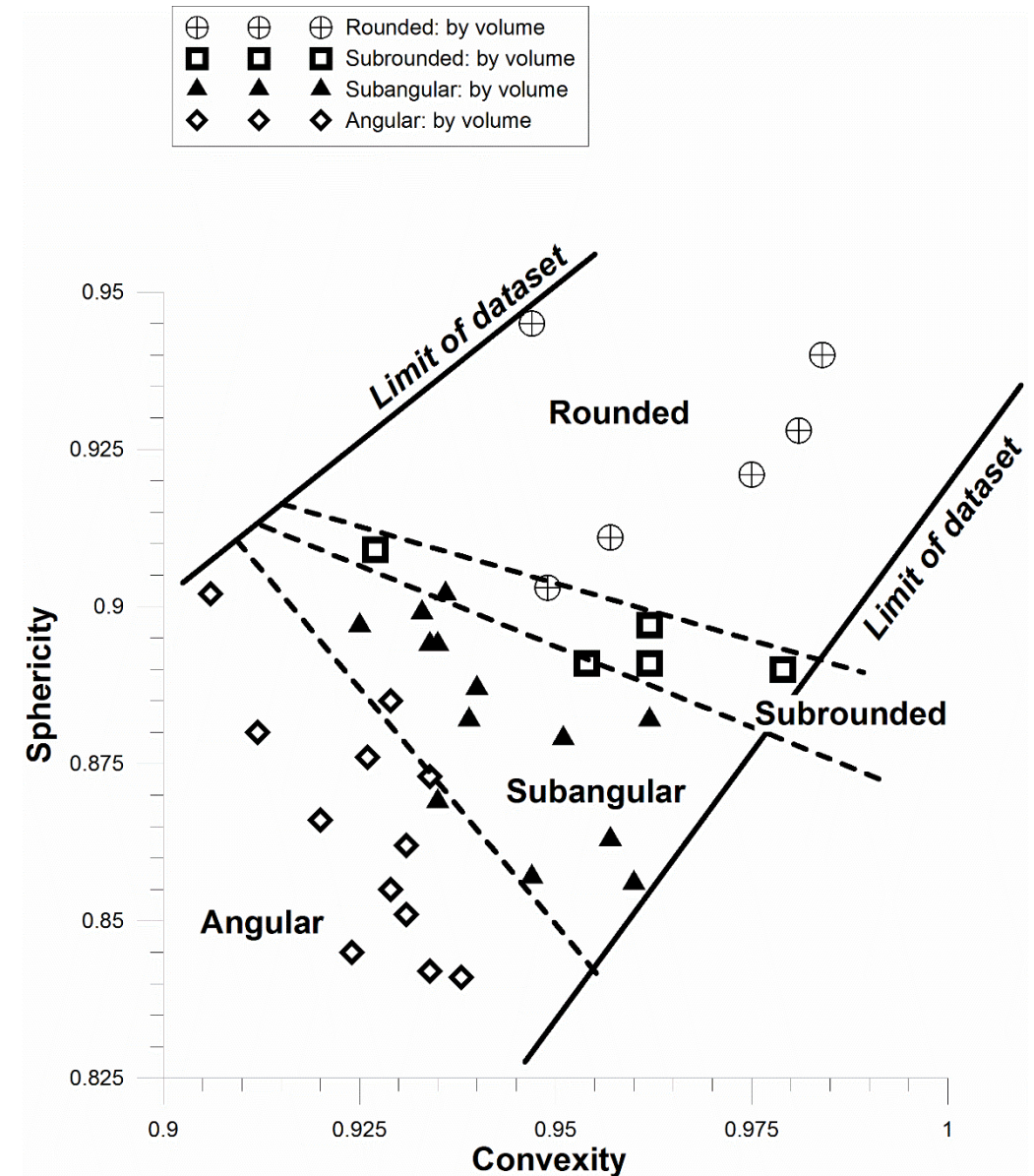
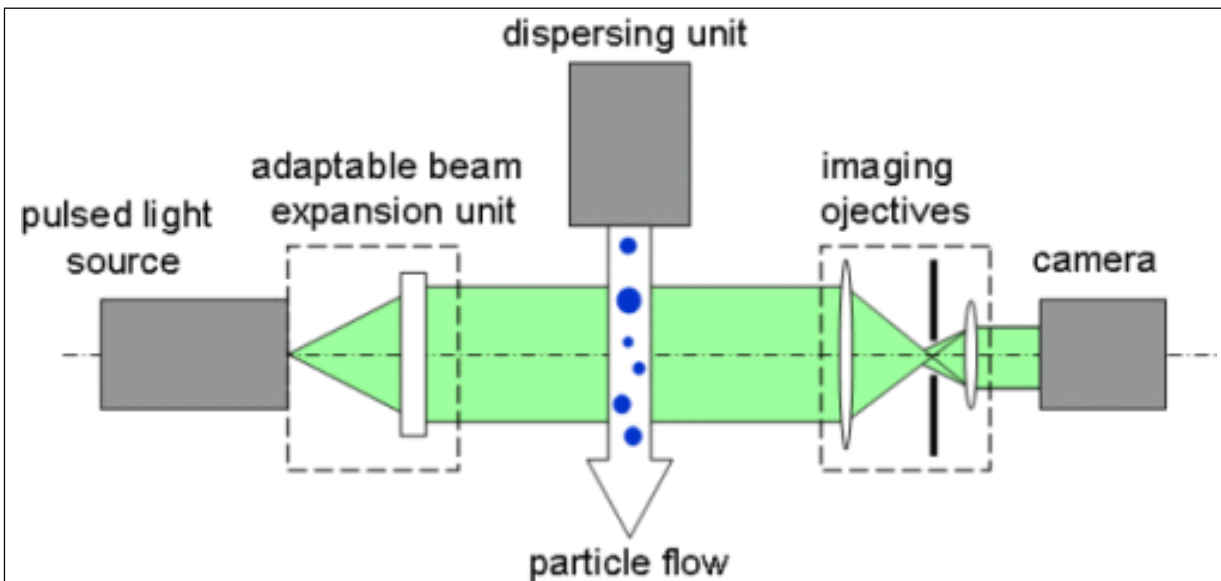
# Quantifying Soil Fabric – Particle Size & Shape



$$\text{Convexity} = \frac{A}{A+B}$$



# Quantifying Soil Fabric – Particle Size & Shape



# Quantifying Soil Fabric – Particle Size & Shape

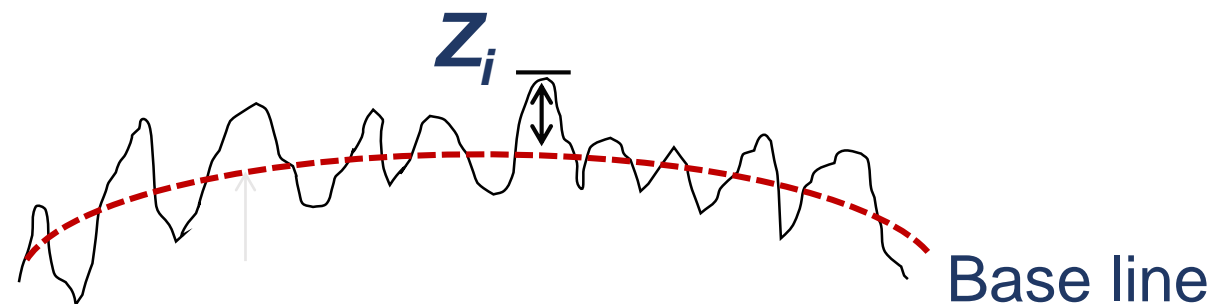
Optical interferometry



Quantify surface roughness

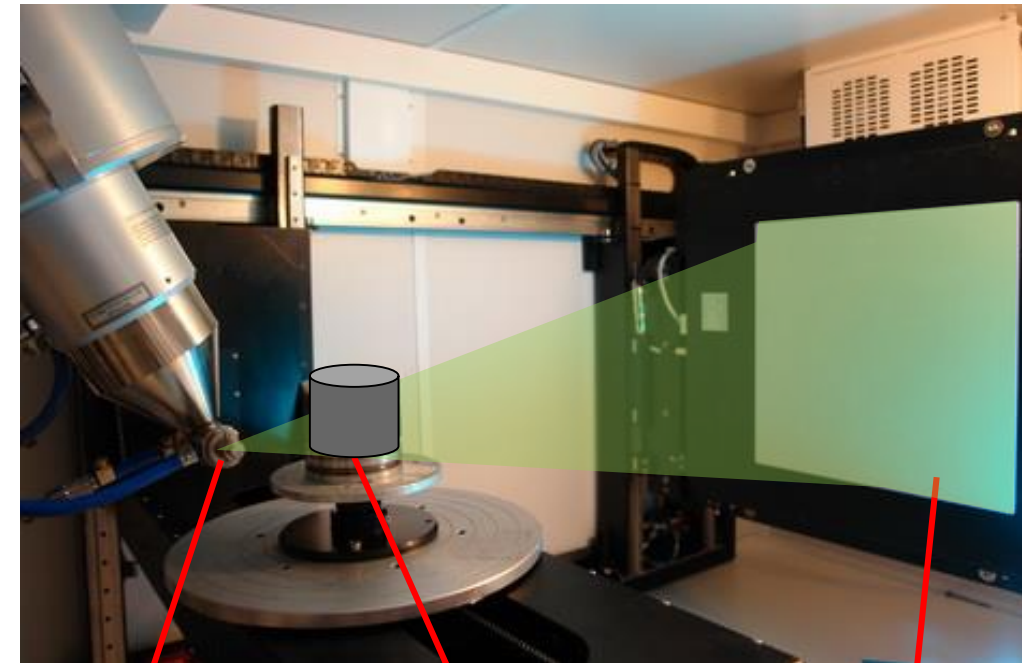
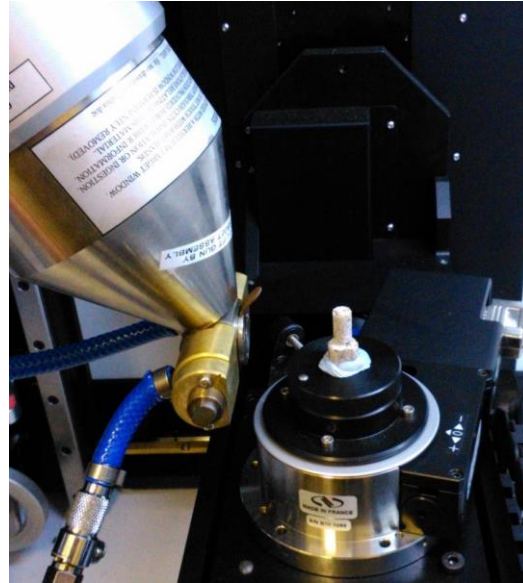
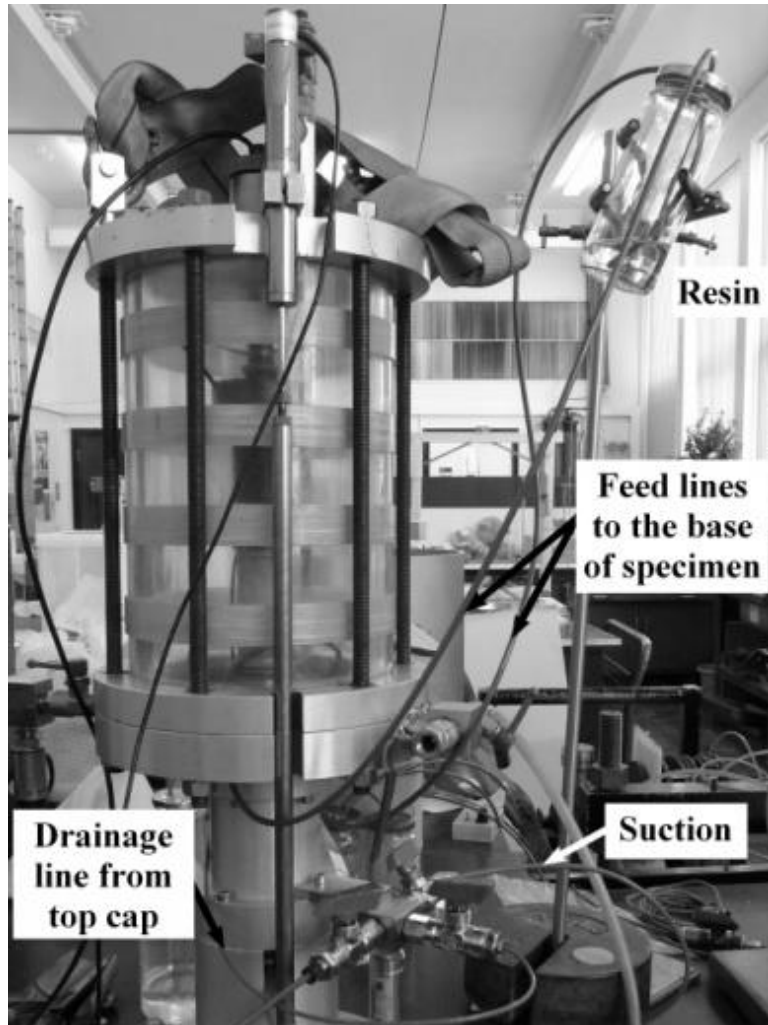
RMS  
roughness

$$S_q = \sqrt{\frac{1}{n} \sum_{i=1}^n Z_i^2}$$



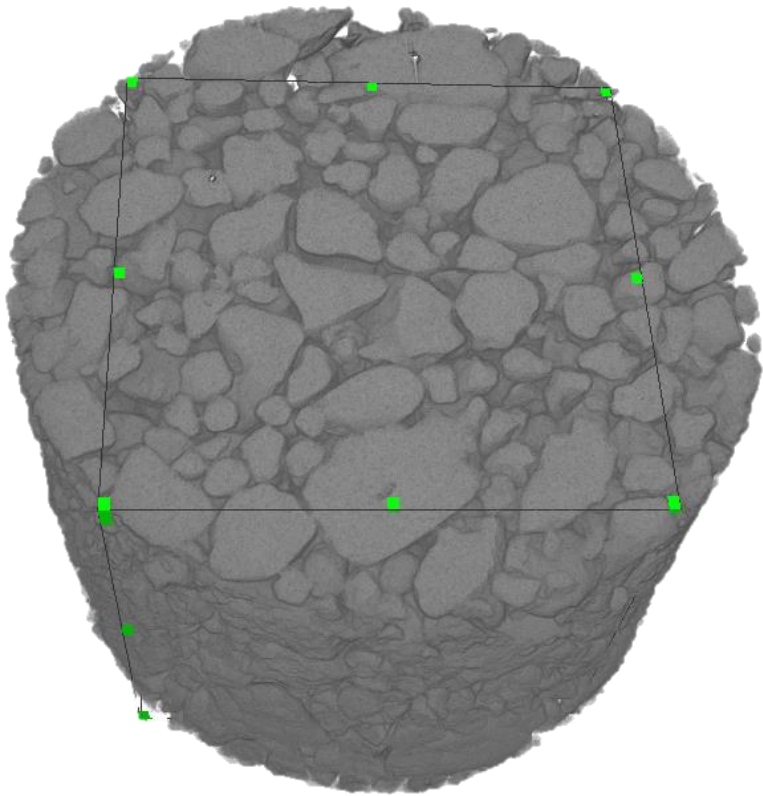


# Quantifying Soil Fabric – Arrangement



Micro Computed Tomography (Micro CT)

# Quantifying Soil Fabric – Arrangement



Micro CT

Raw output – 3D attenuation map

(H. Taylor)

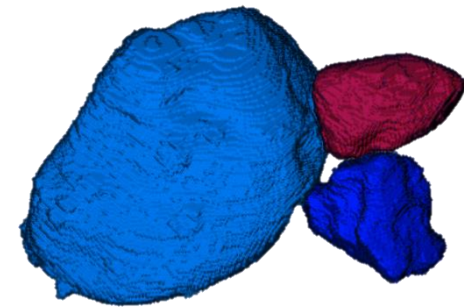
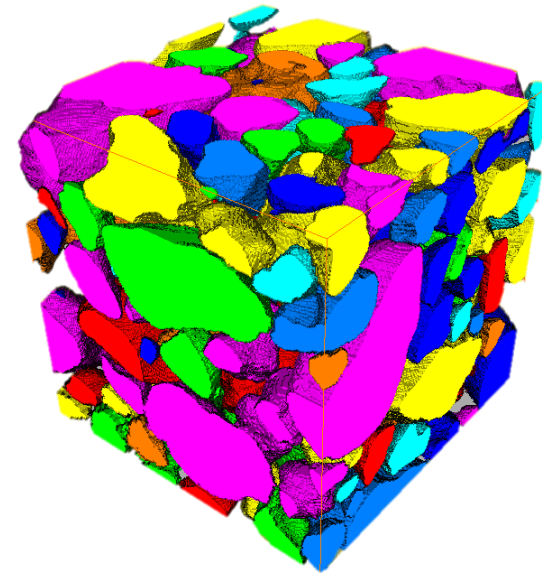
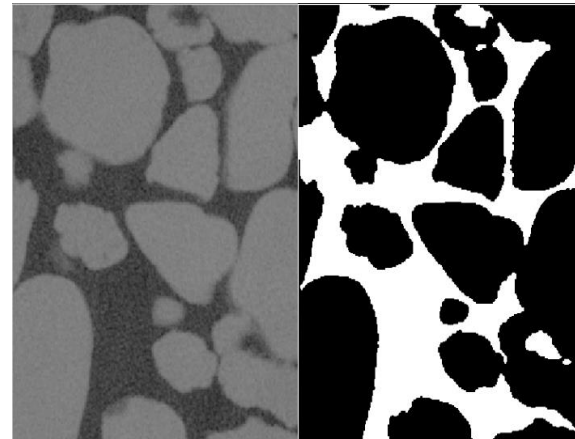
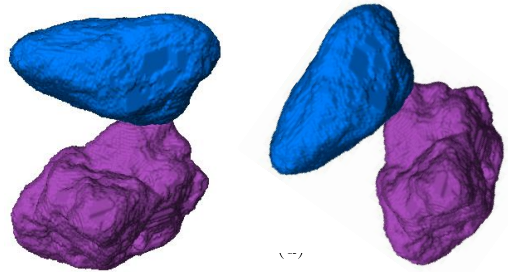


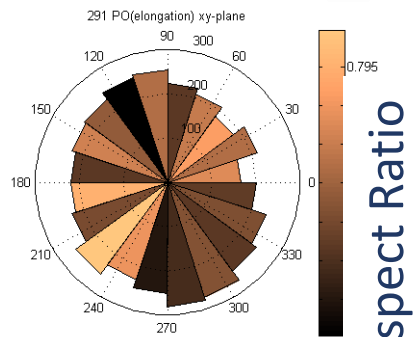
Image processing to identify individual particles

# Quantifying Soil Fabric – Arrangement

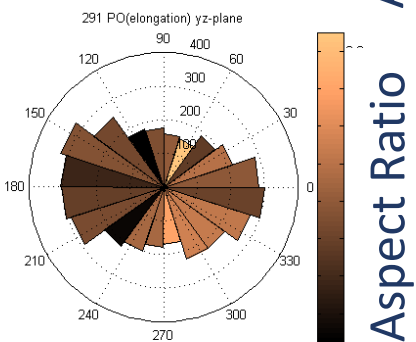
## Particle orientations



xy  
view

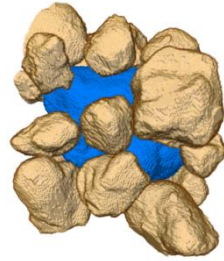


yz  
view

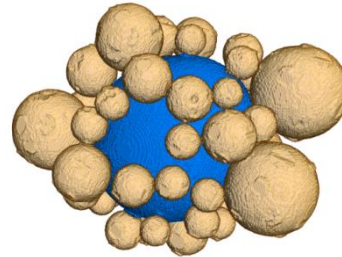


## Coordination Number ( $N_c$ )

Number of contacts per  
particle



Leighton  
Buzzard Sand  
Blue particle  
20 contacts

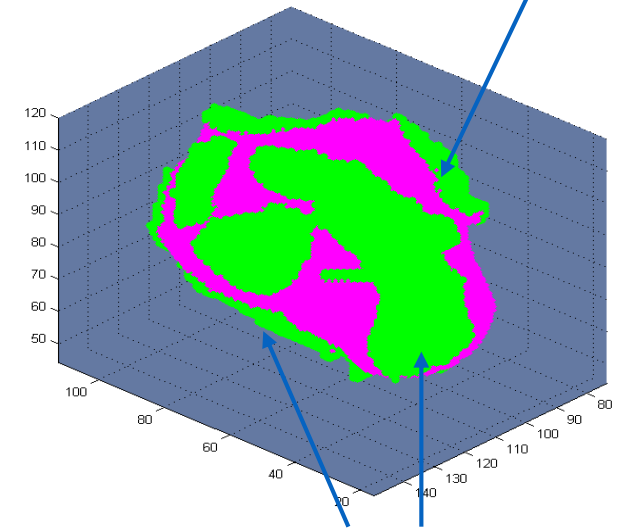


Glass beads  
Blue particle  
50 contacts

## Contact Index

Contact area  
Particle surface area

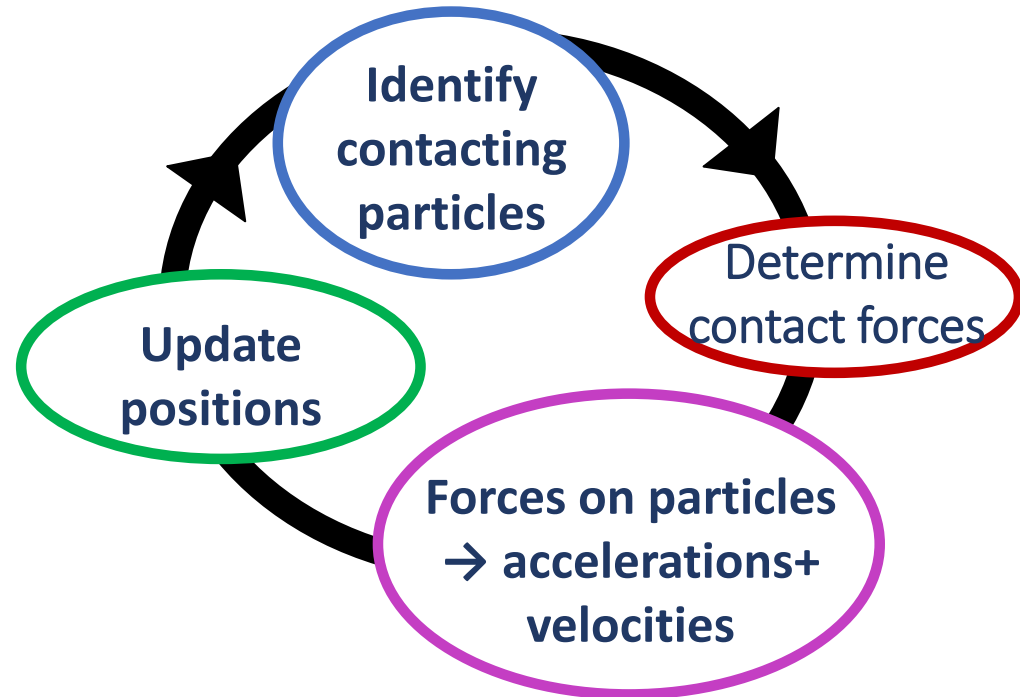
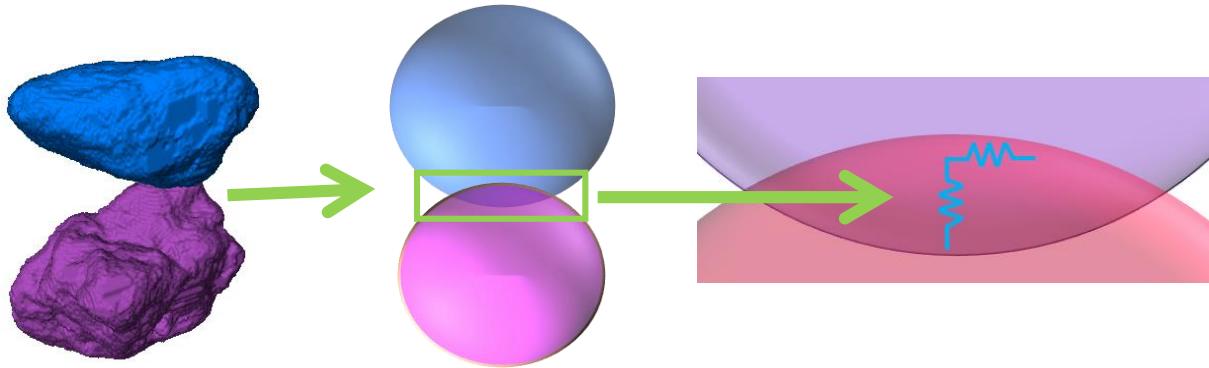
Representative  
Particle



Contacts

# Quantifying Soil Fabric – Arrangement

DEM Simulations



High performance computers



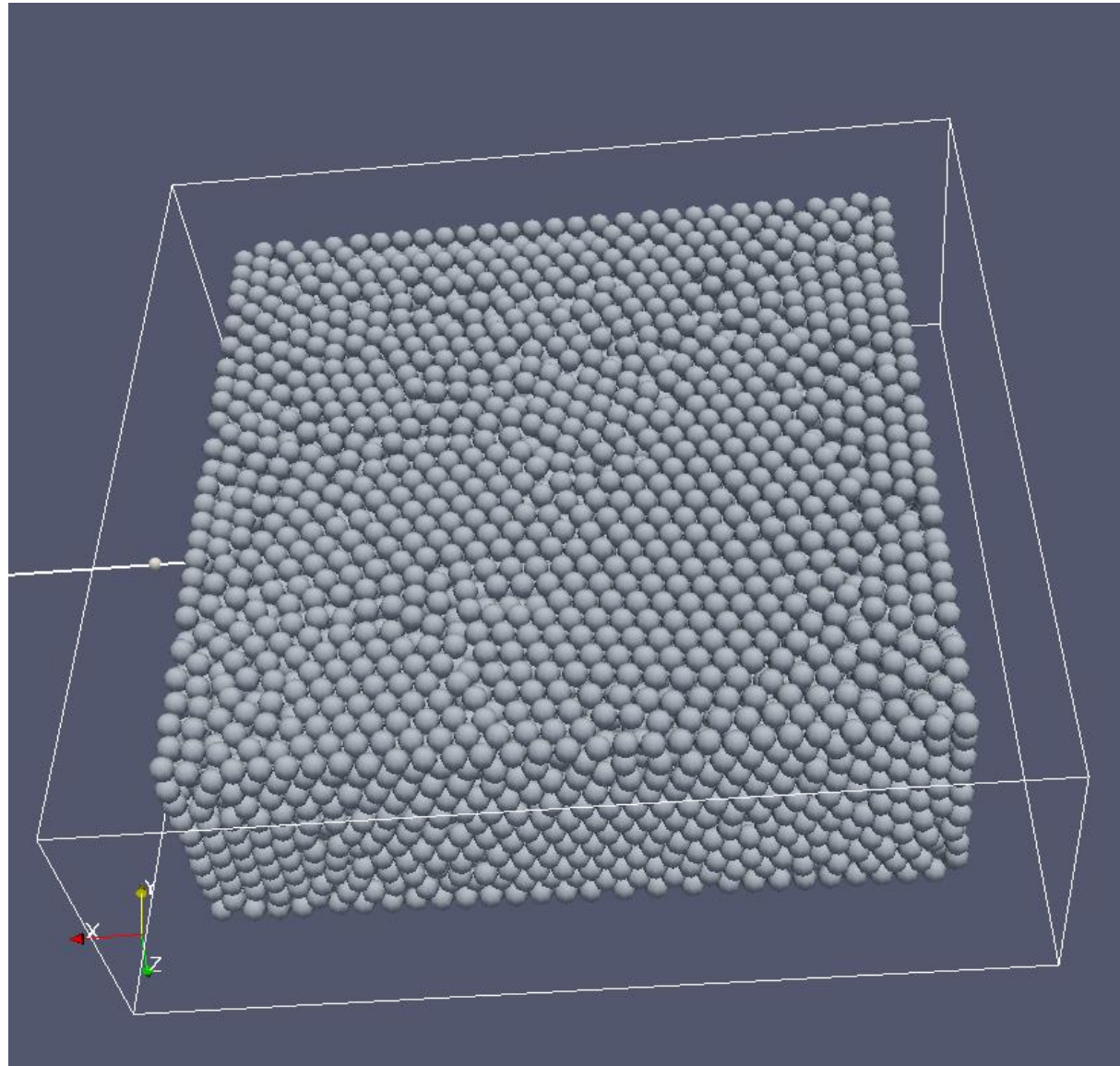
ARCHER (UK national facility)

HPC at Imperial College

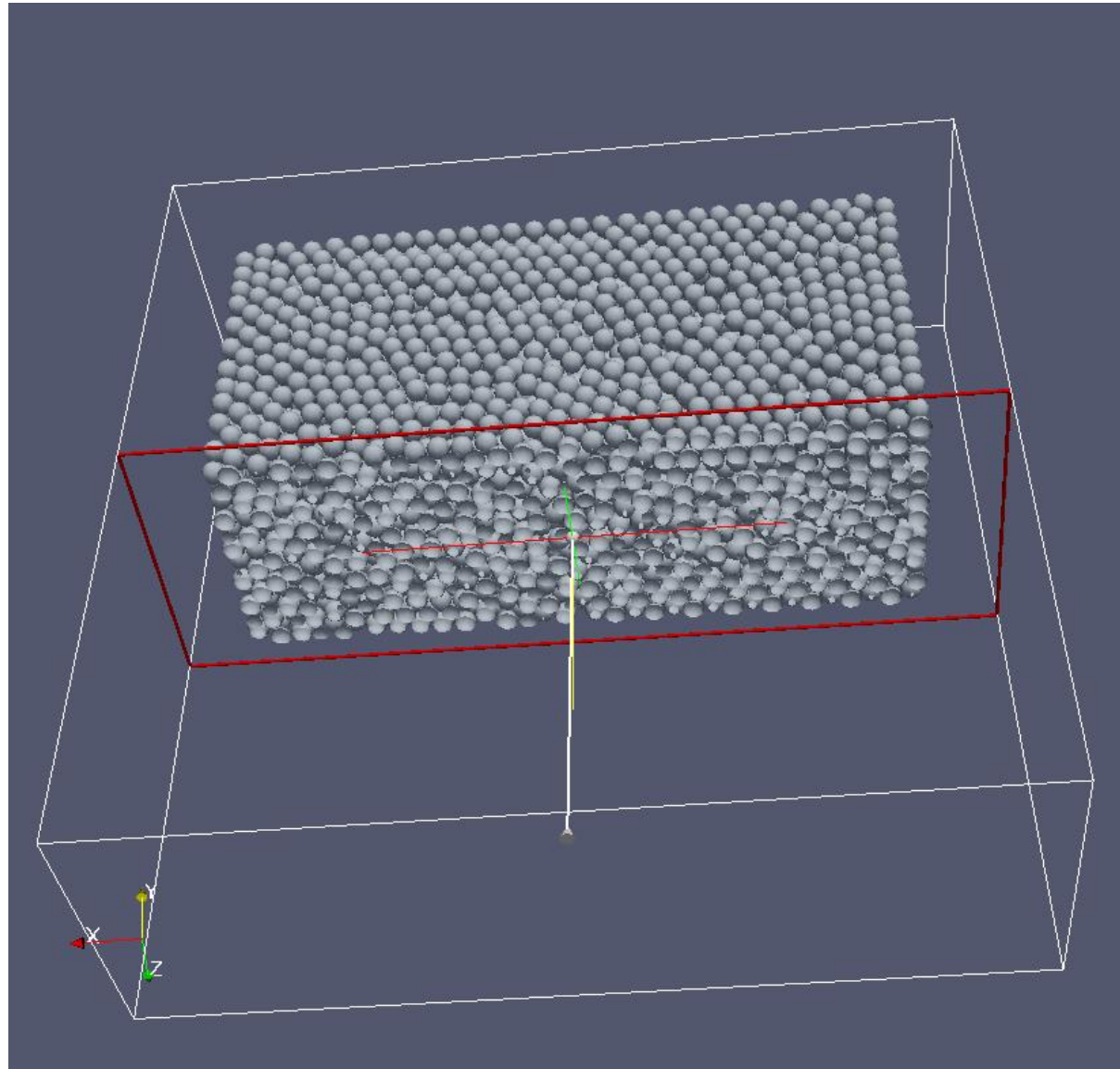


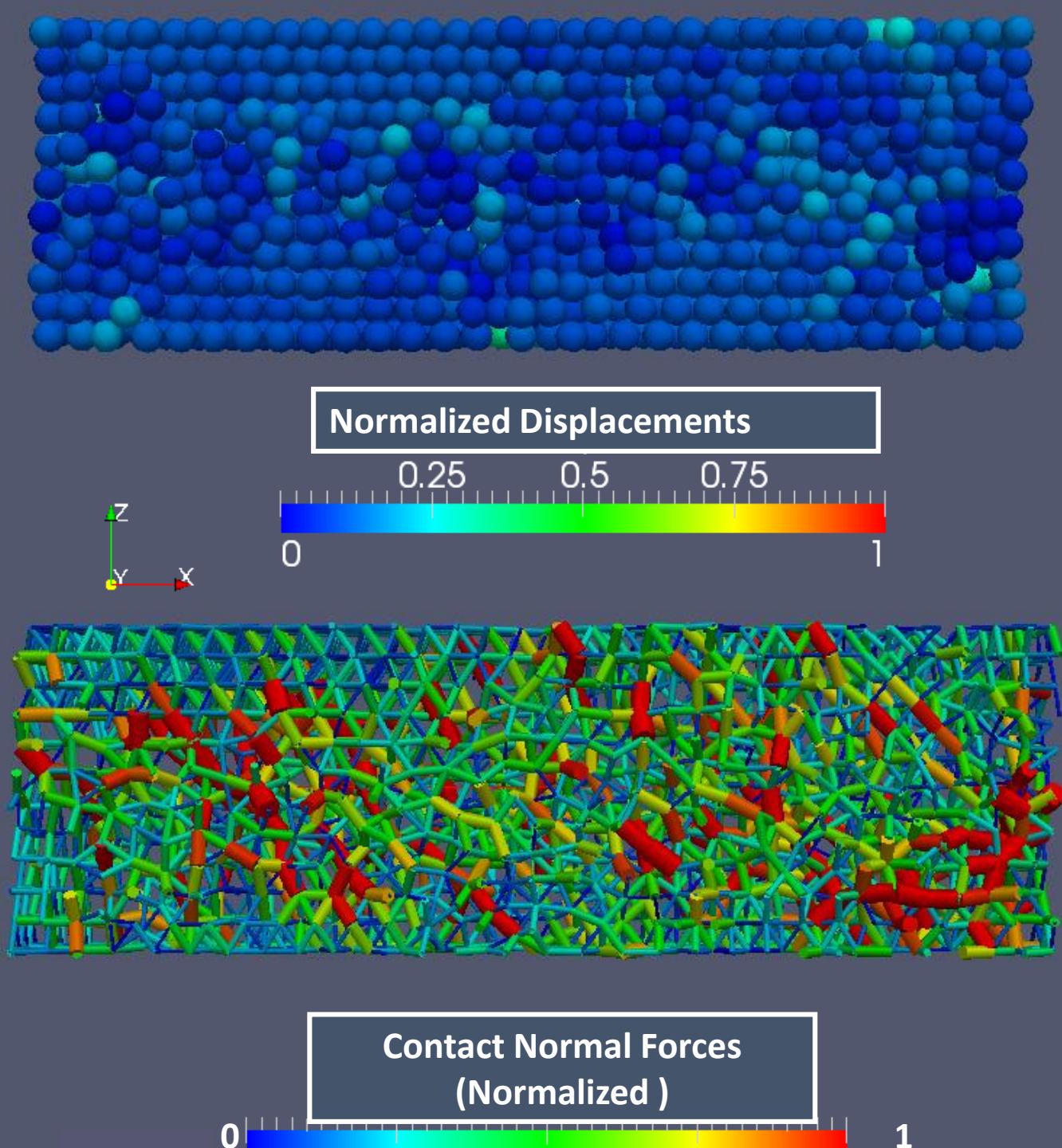
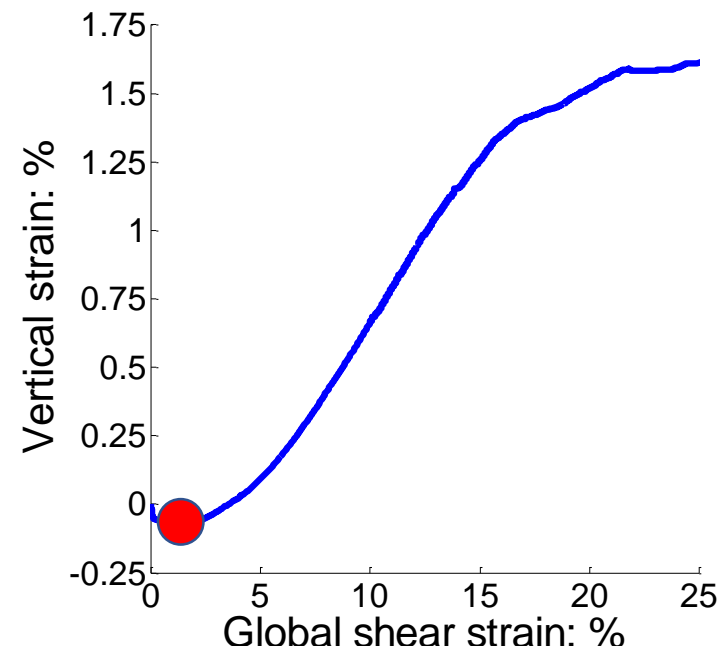
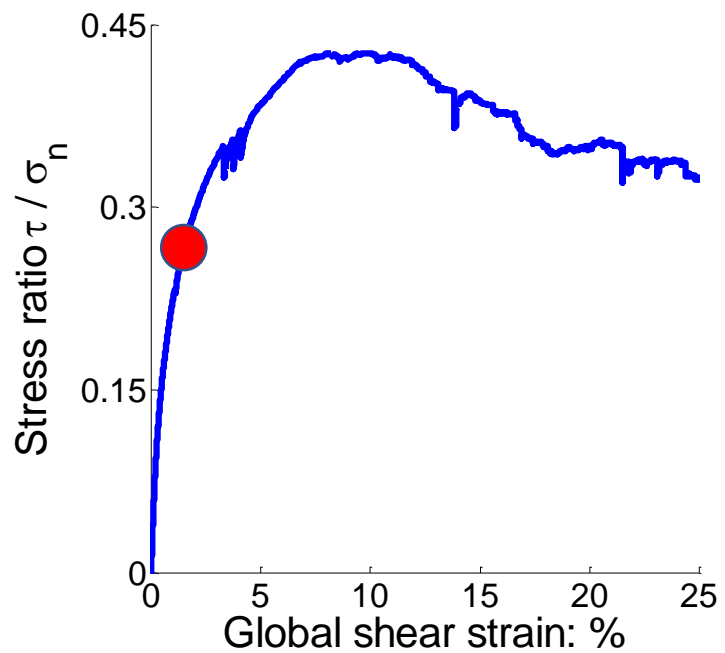
HPC Computer Room

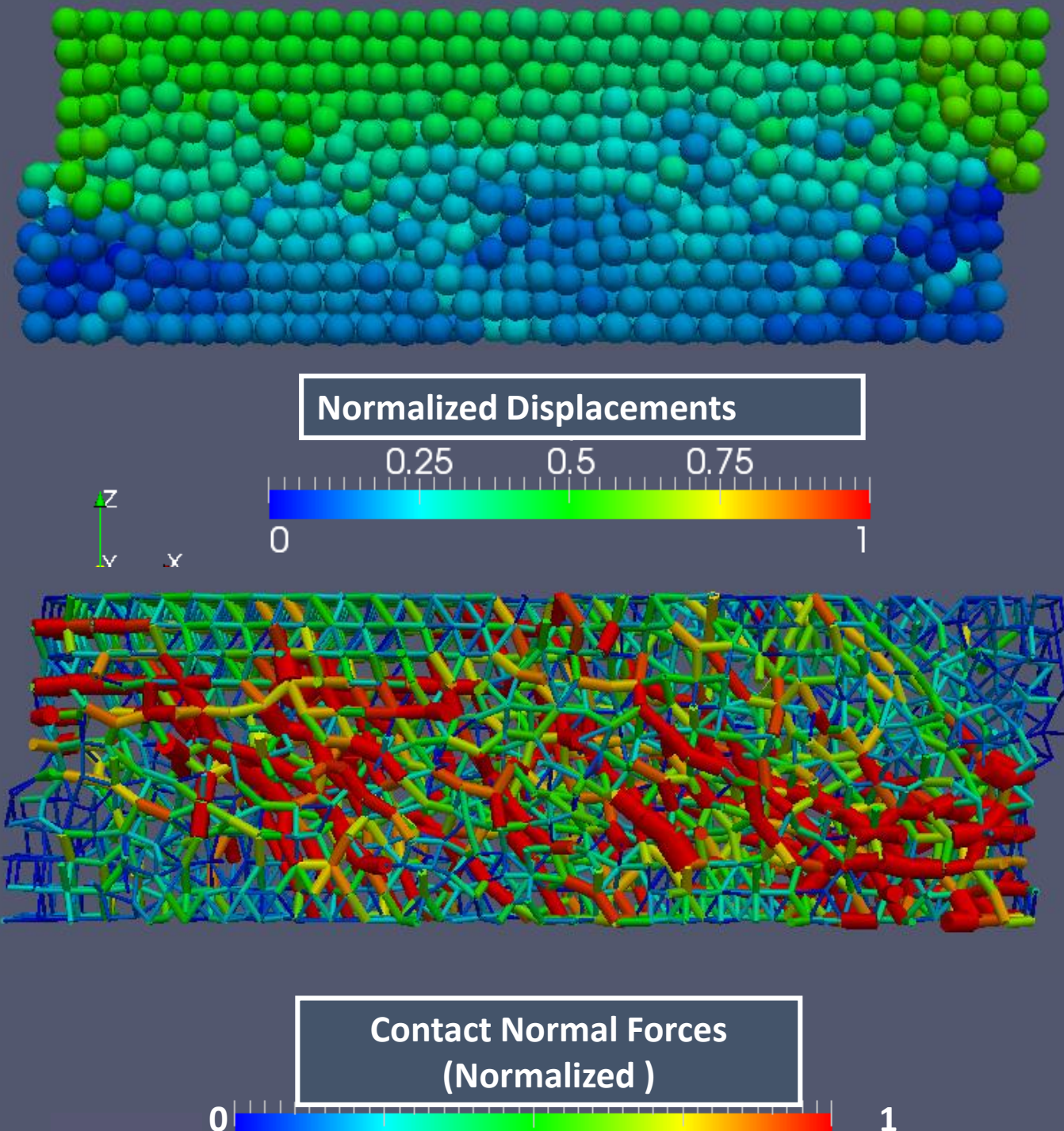
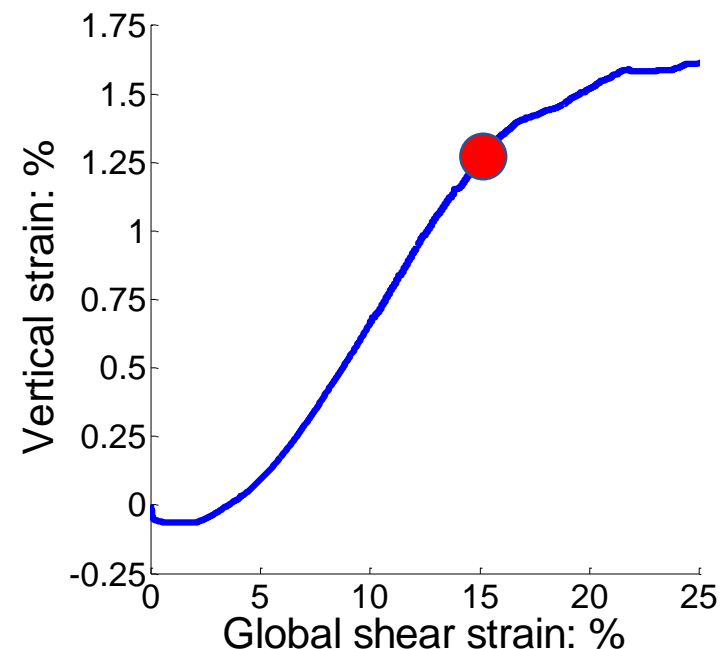
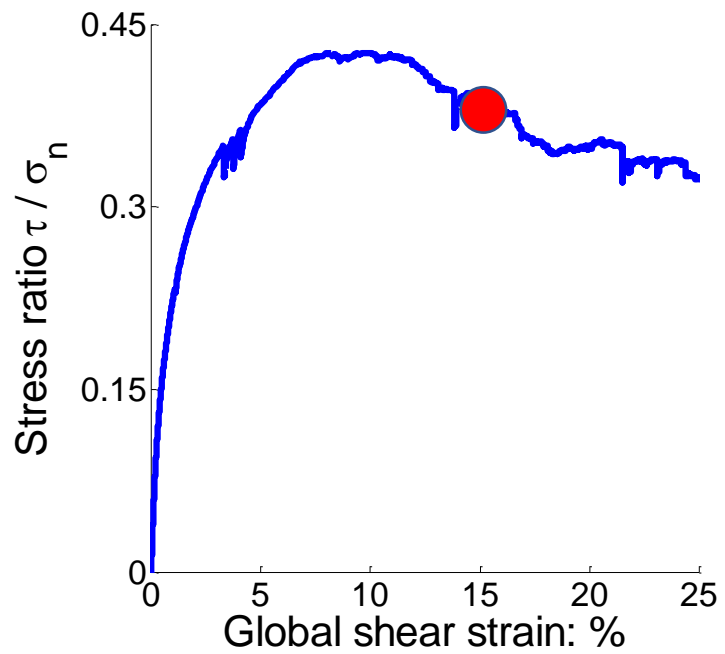
# Quantifying Soil Fabric – Arrangement



# Quantifying Soil Fabric – Arrangement









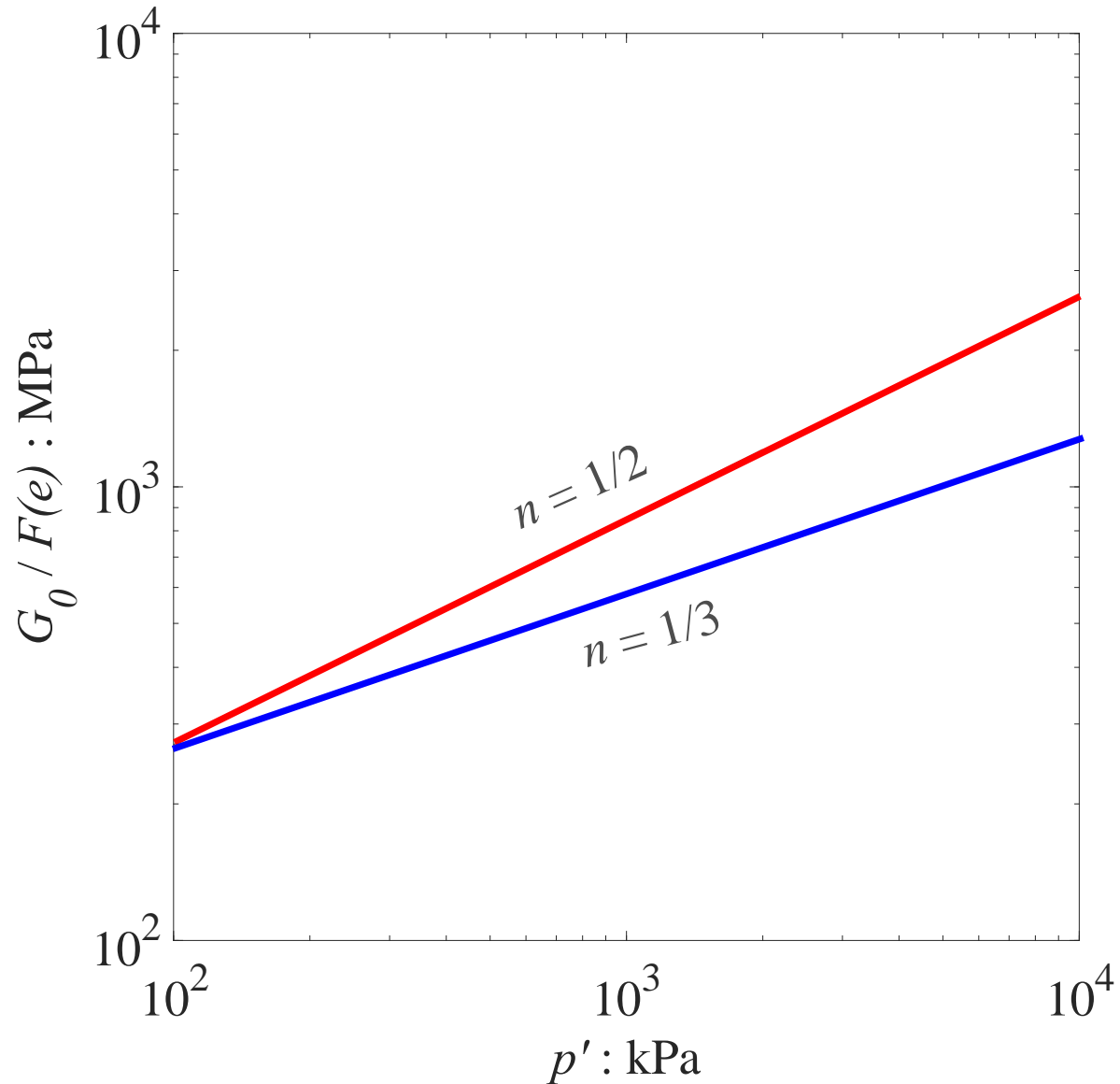
# Soil Fabric Effects

**Question**

**What determines the small strain stiffness ( $G_0$ ) -pressure ( $p'$ ) relationship?**

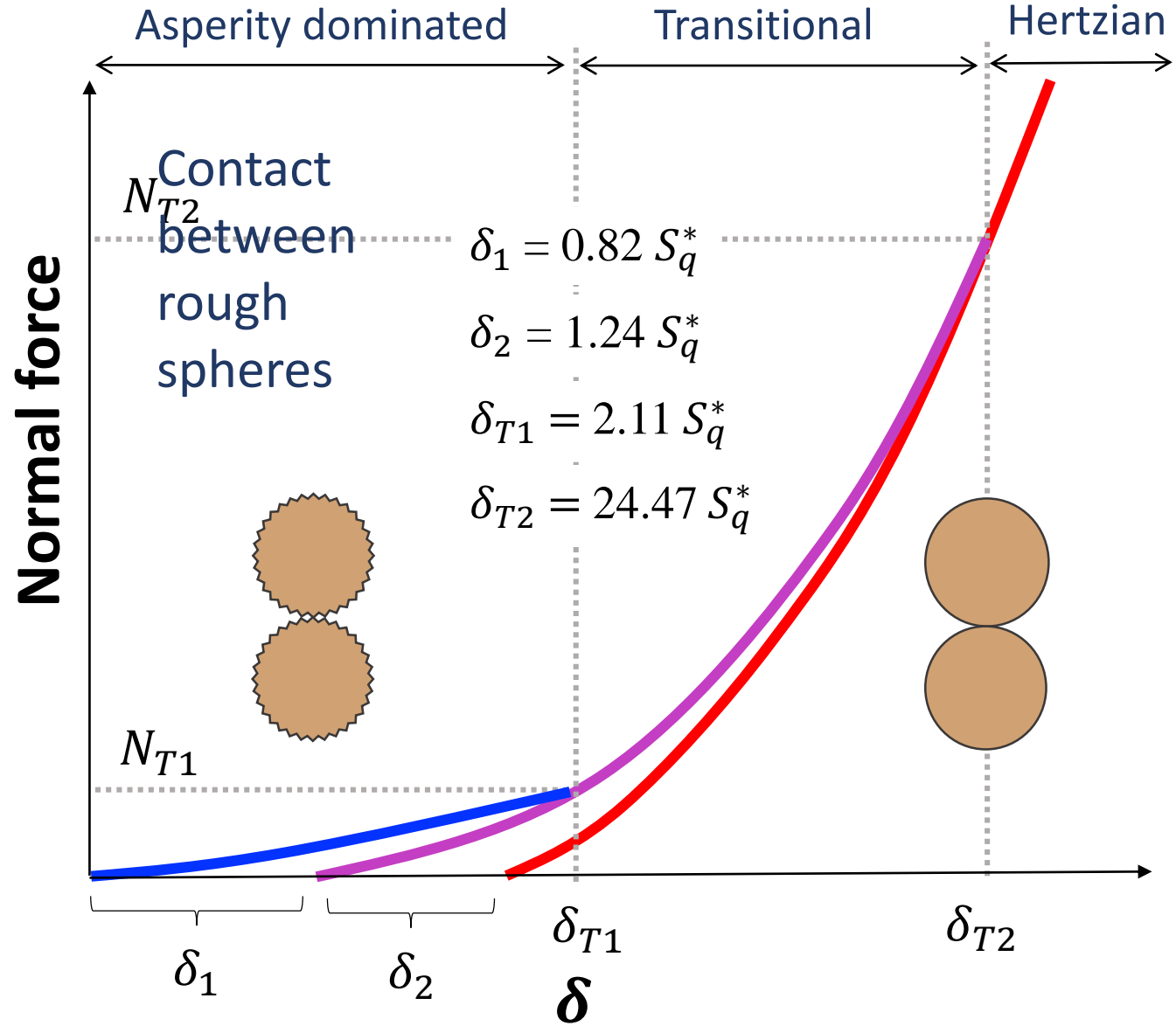
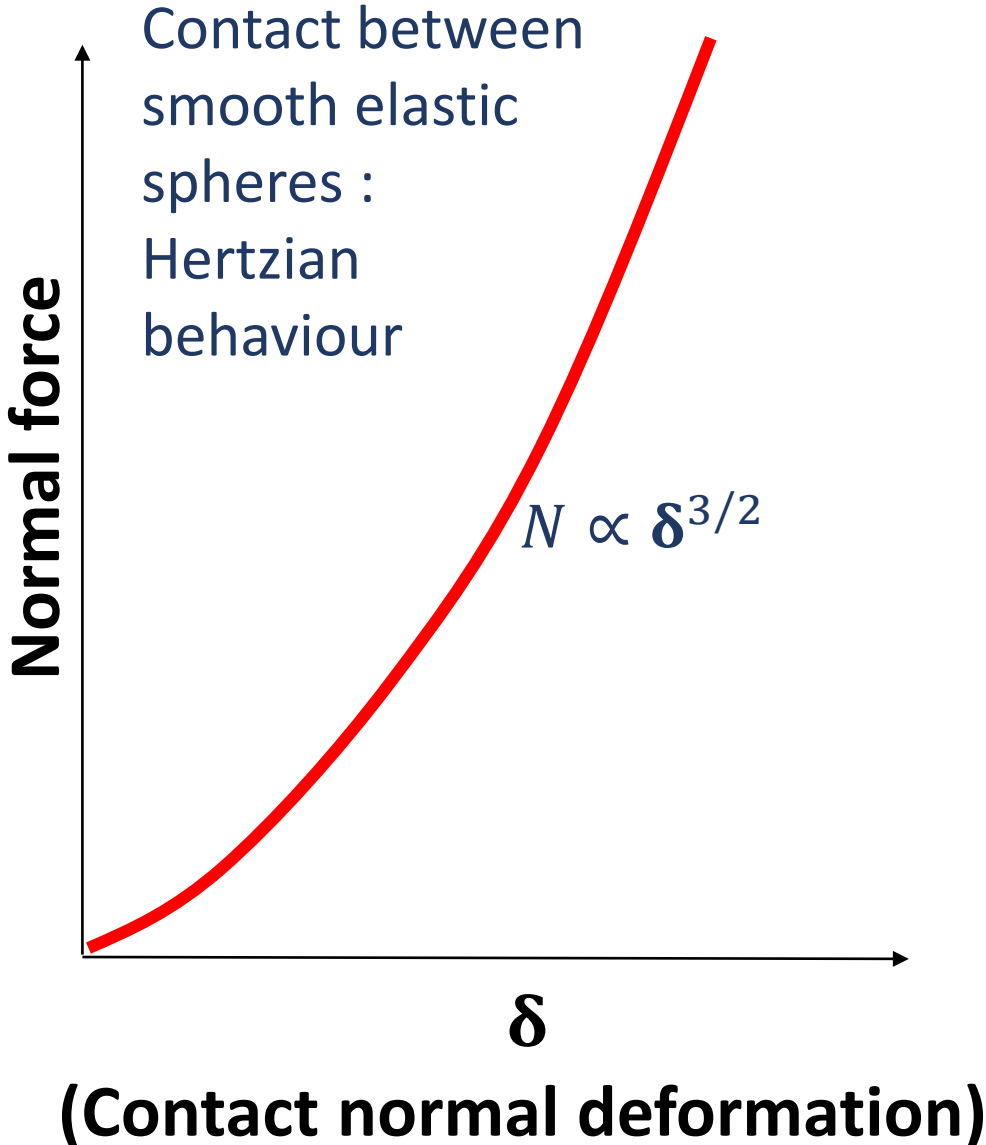
**Should the particle size distribution  $D_{15}$  determine filter design?**

# Pressure-Stiffness Relationship



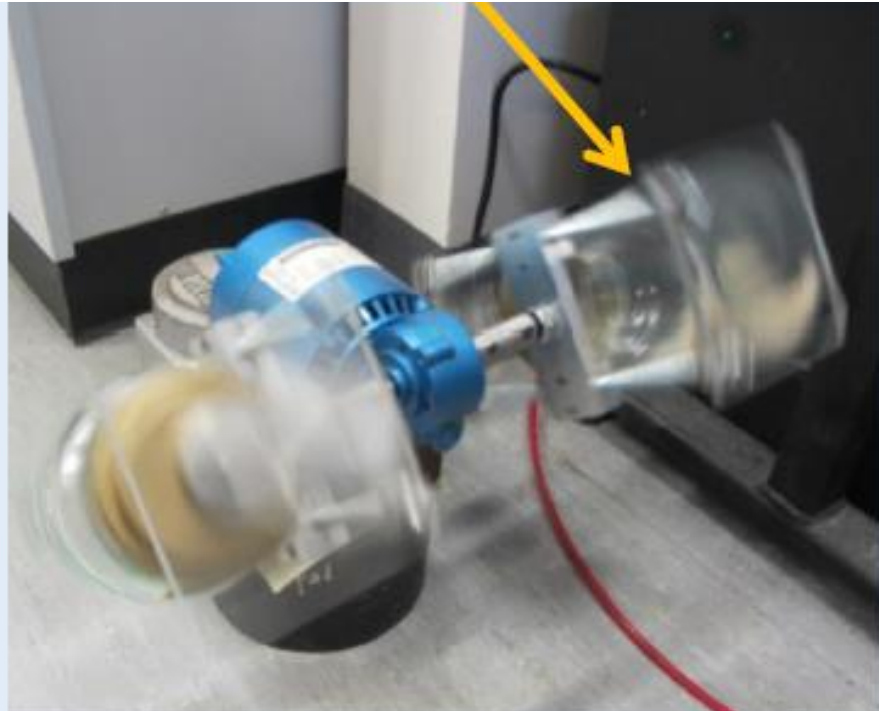
- Elastic theory explains pressure dependency: contact area increases as pressure increases – larger area gives a larger stiffness
- Elastic theory predicts that  $G_0 \propto (p')^{1/3}$
- Experimental data for sand gives  $G_0 \propto (p')^{1/2}$

# Roughness-dependant contact behaviour

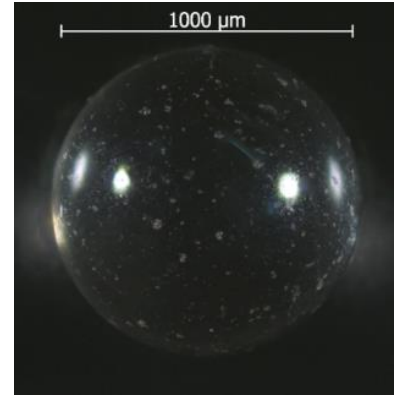


# Controlling and Surface Roughness

## Ballotini + Toyoura Sand



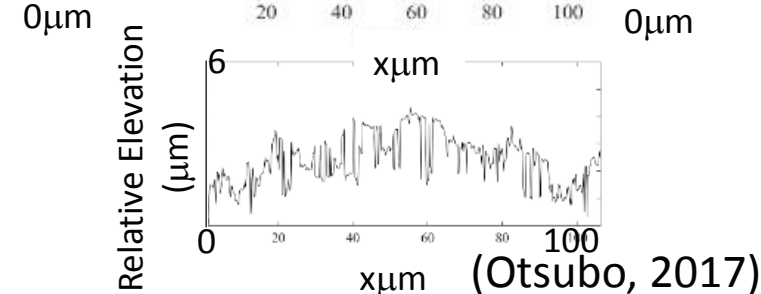
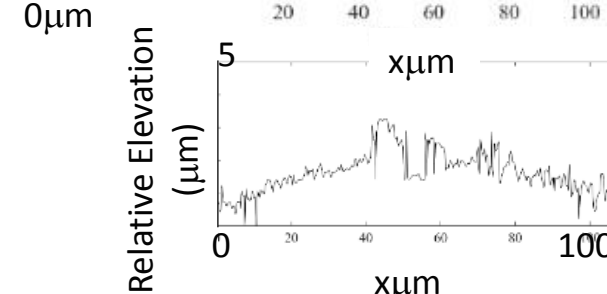
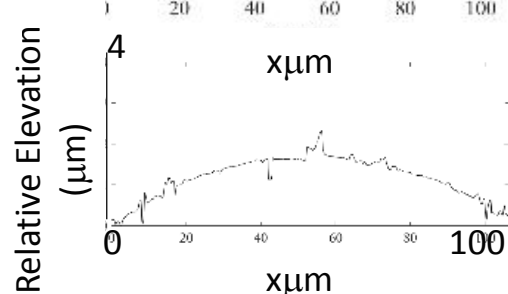
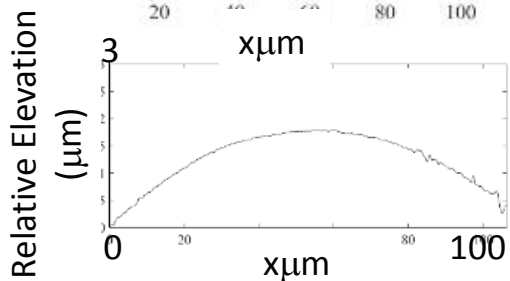
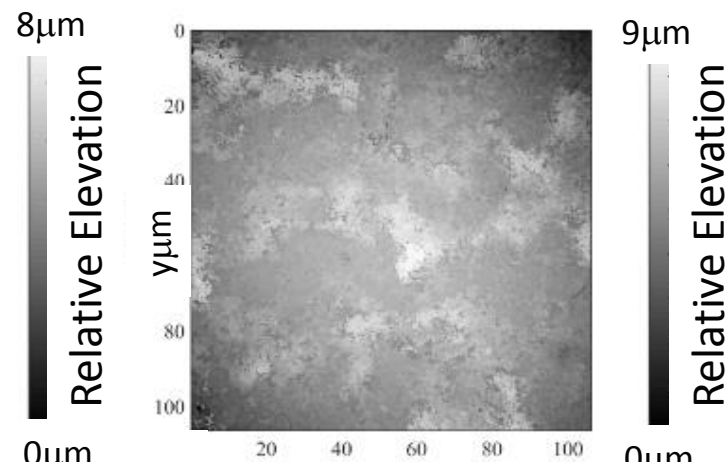
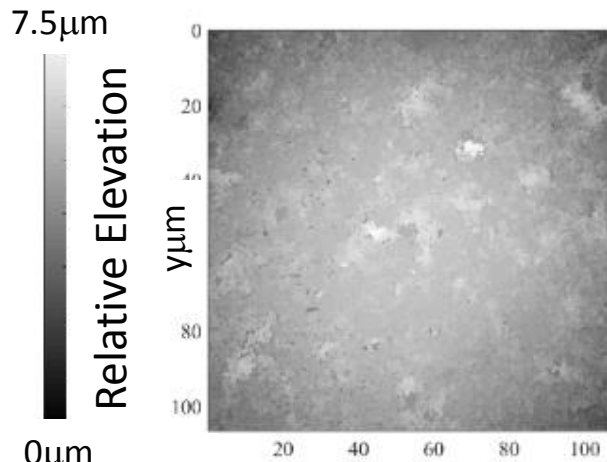
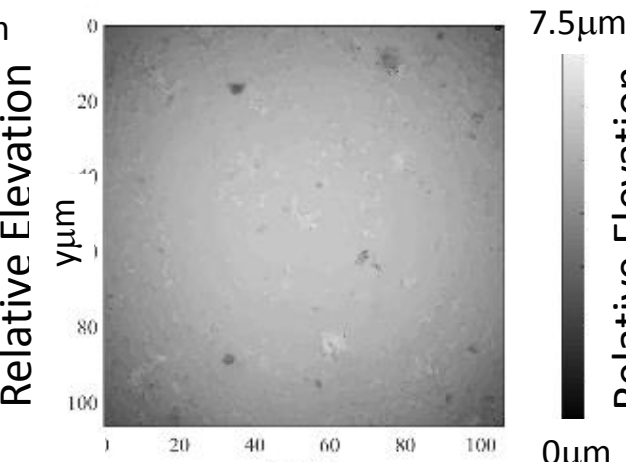
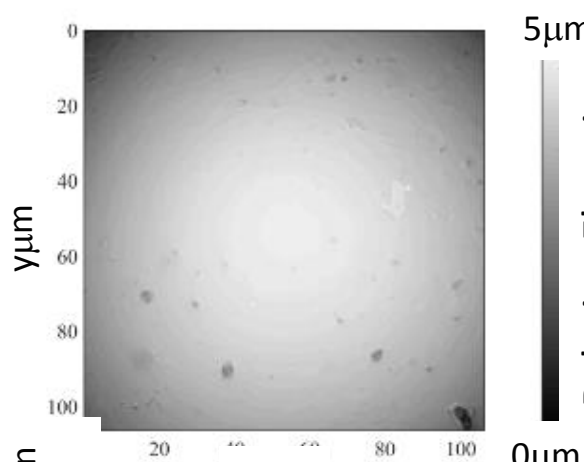
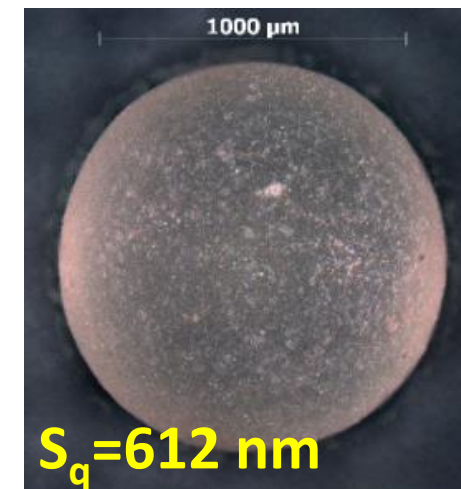
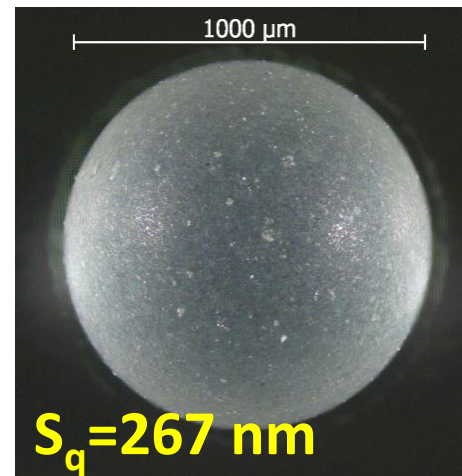
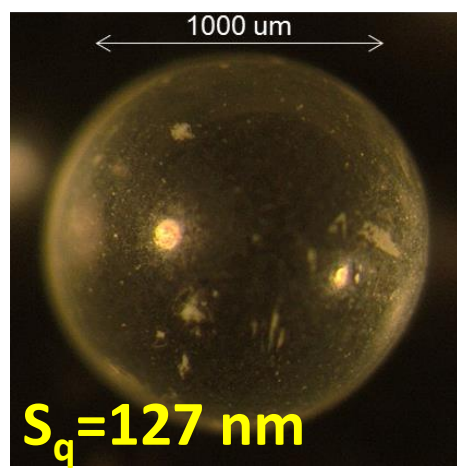
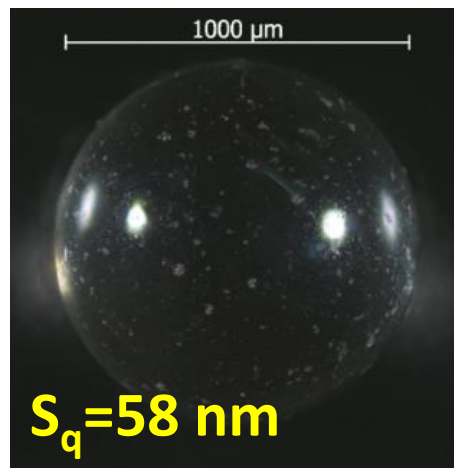
Used spherical glass beads to isolate roughness from shape (form) effects



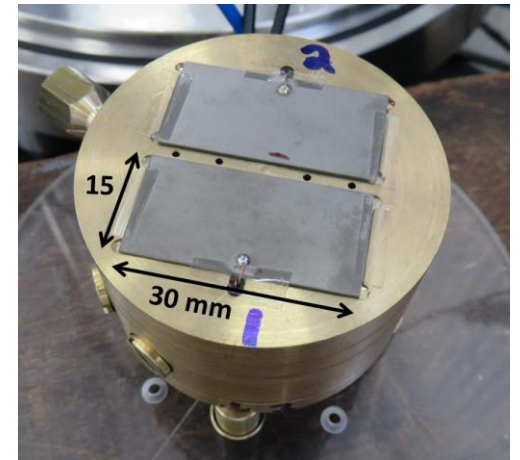
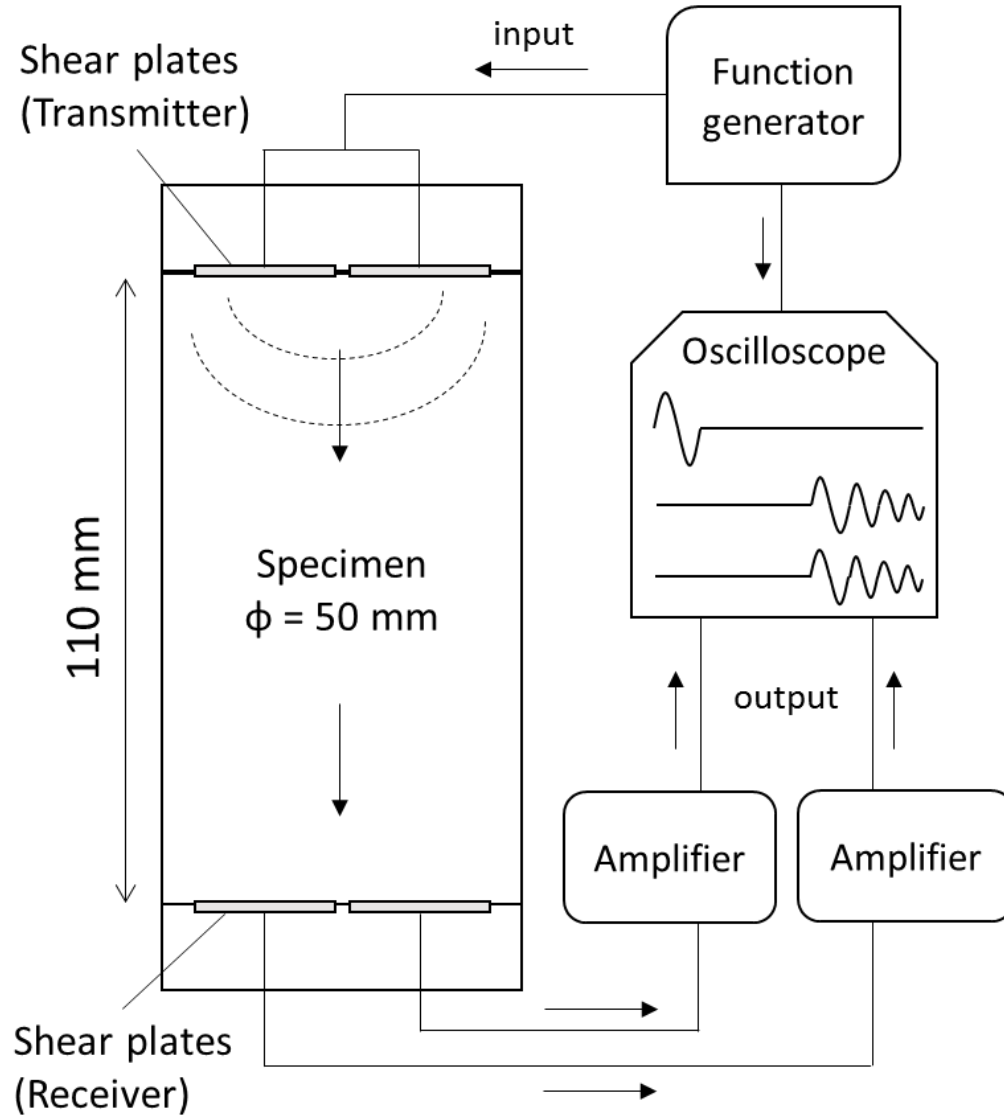
Measured roughness using interferometry



# Roughened Ballotini

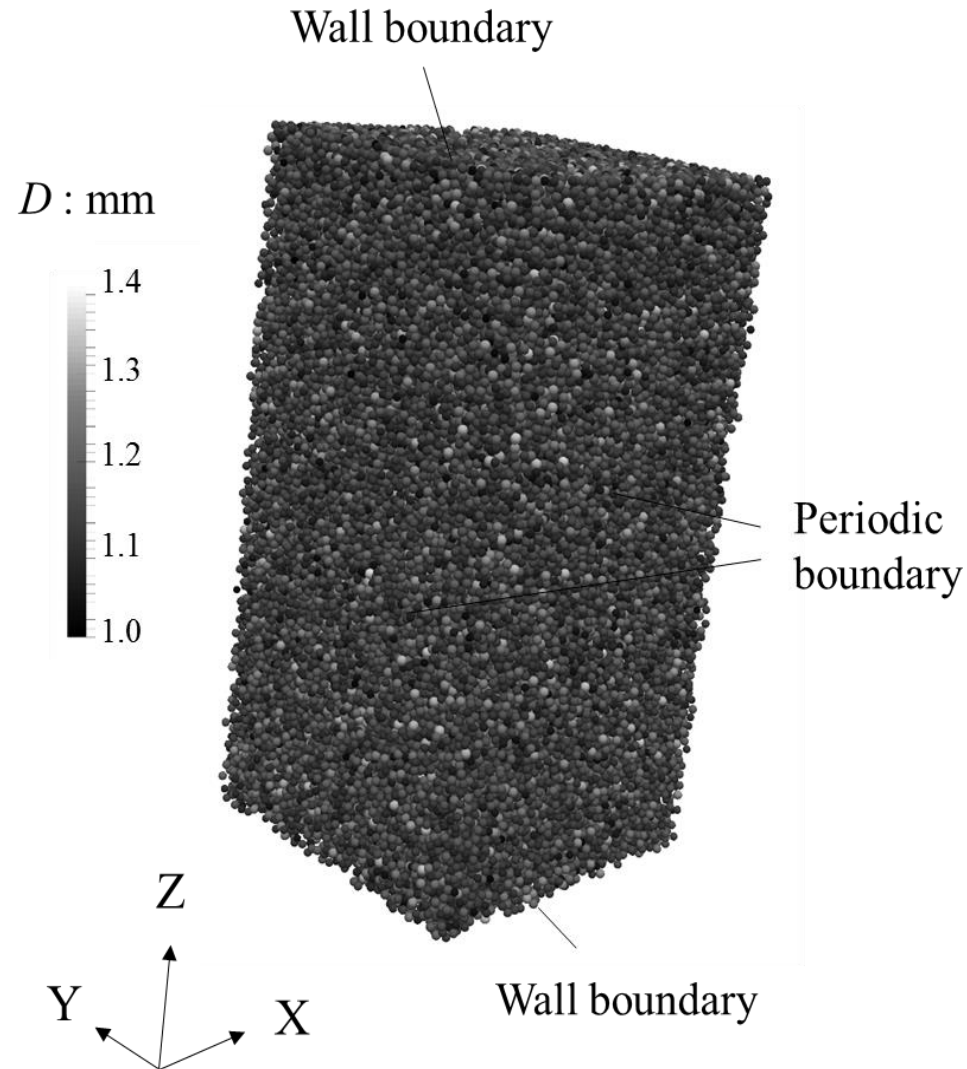


# Quantifying Stiffness in Laboratory



(Otsubo, 2017)

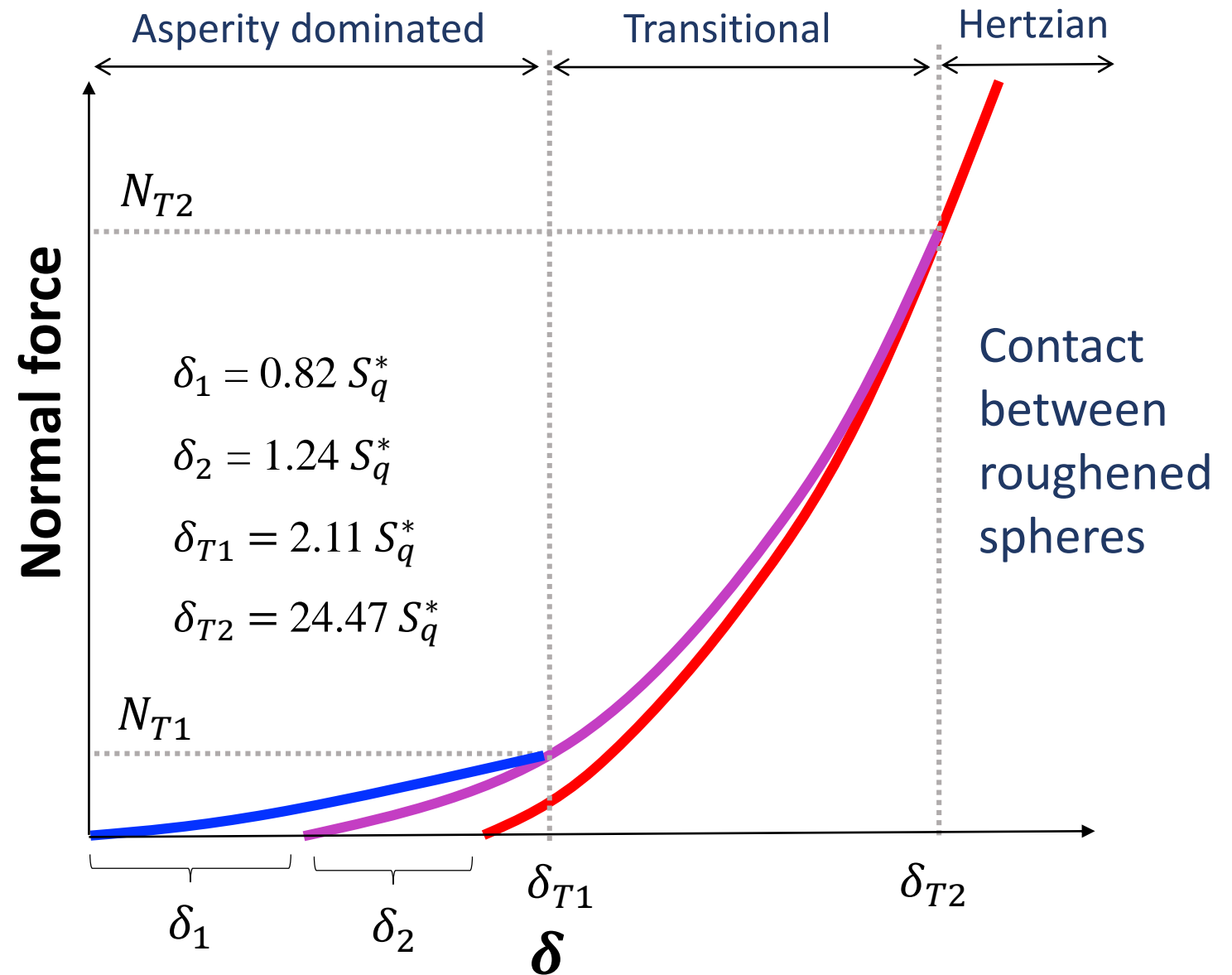
# Simulating Tests using DEM



- DEM code: LAMMPS
- 155,165 particles
- Diameter :  $D = 2.54 \text{ mm}$  (mono-size)
- Particle shear modulus :  $G_p = 25 \text{ GPa}$
- Particle Poisson's ratio :  $\nu_p = 0.2$
- Inter-particle friction :
- $\mu = 0.0$  (dense) 0.15 (loose)
- $p' = 100 \text{ kPa}$  to  $10 \text{ MPa}$
- Planar shear waves

# Roughness-dependant contact behaviour

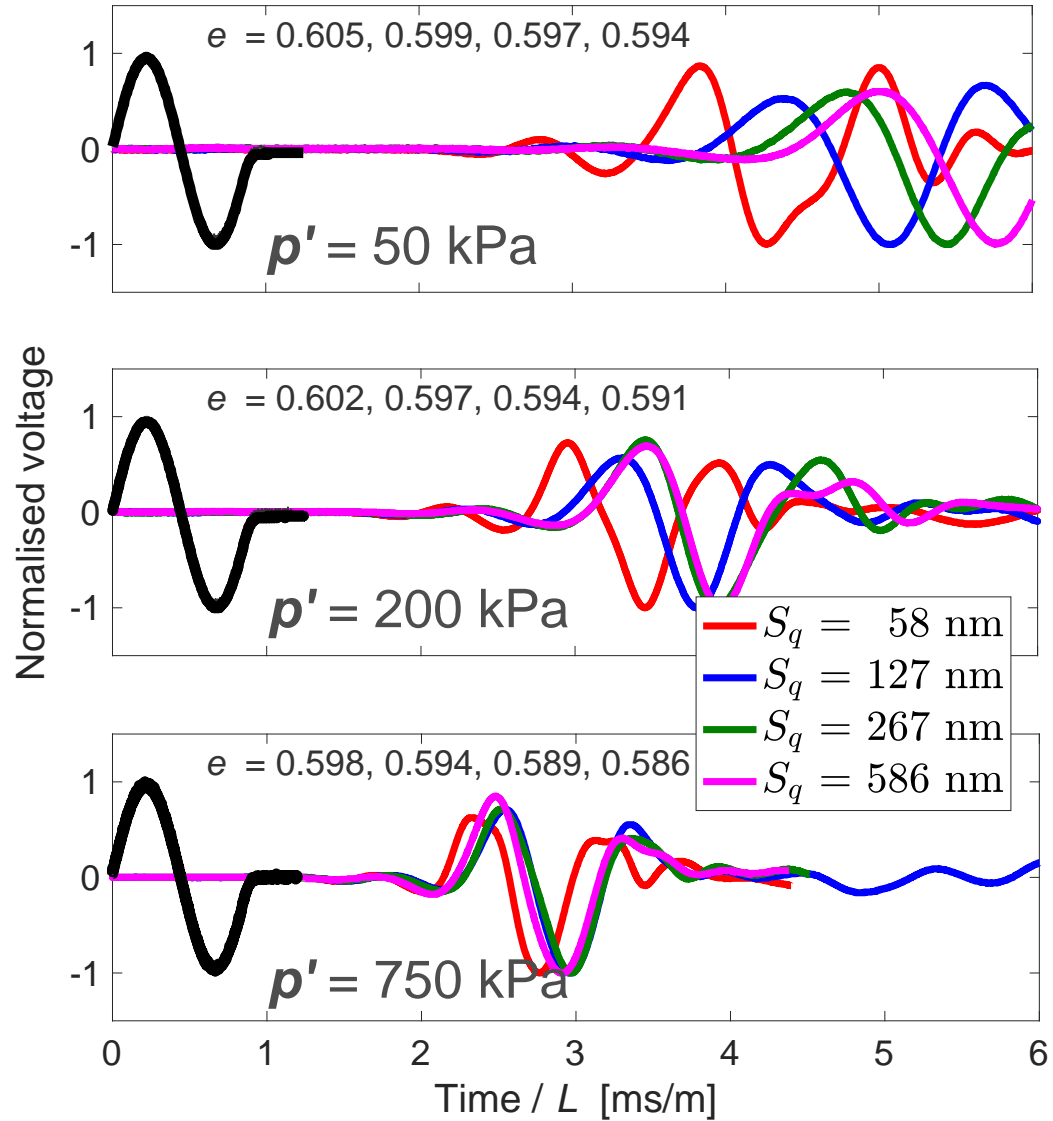
DEM Contact Model



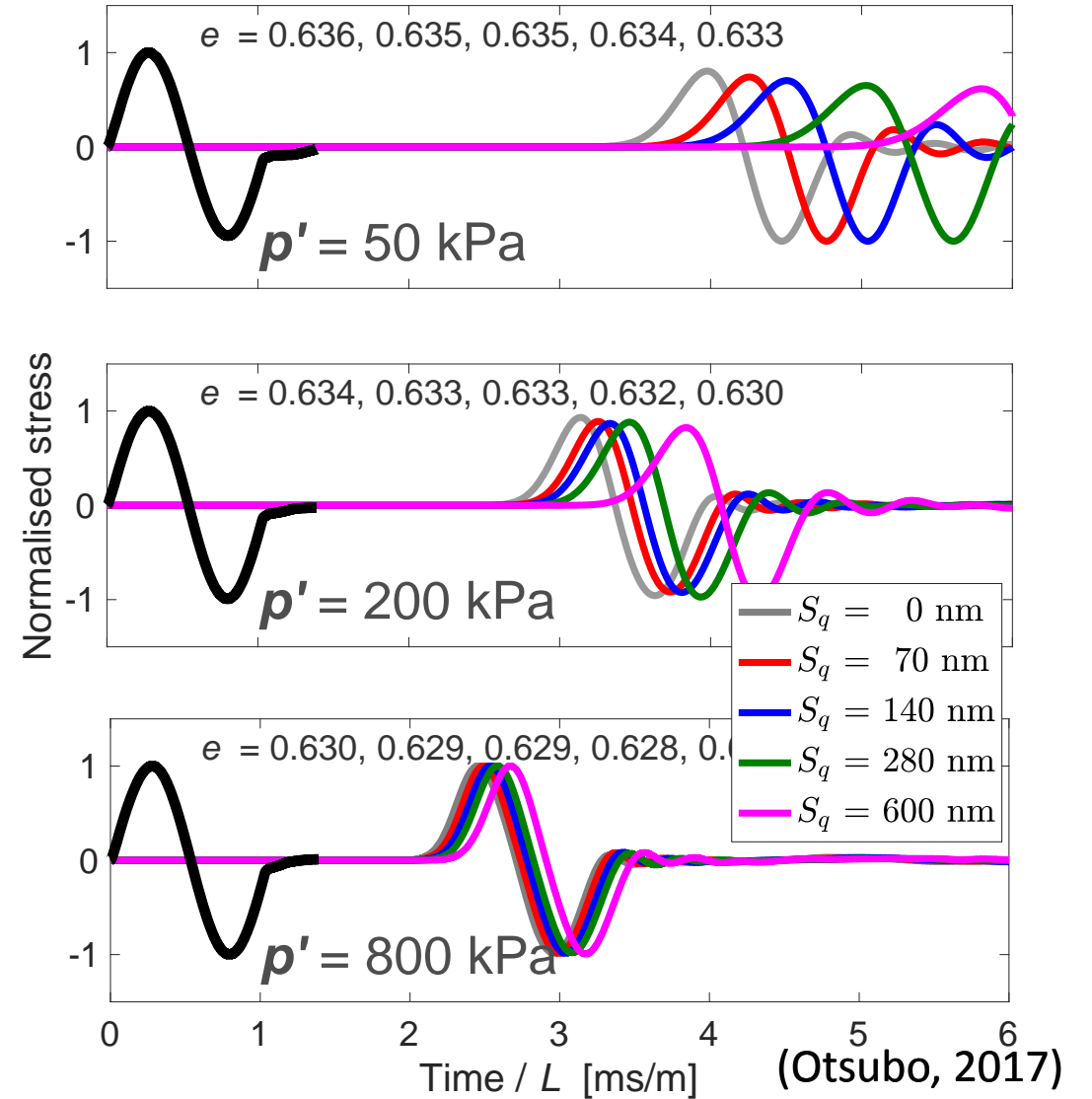


# Surface Roughness and Stiffness

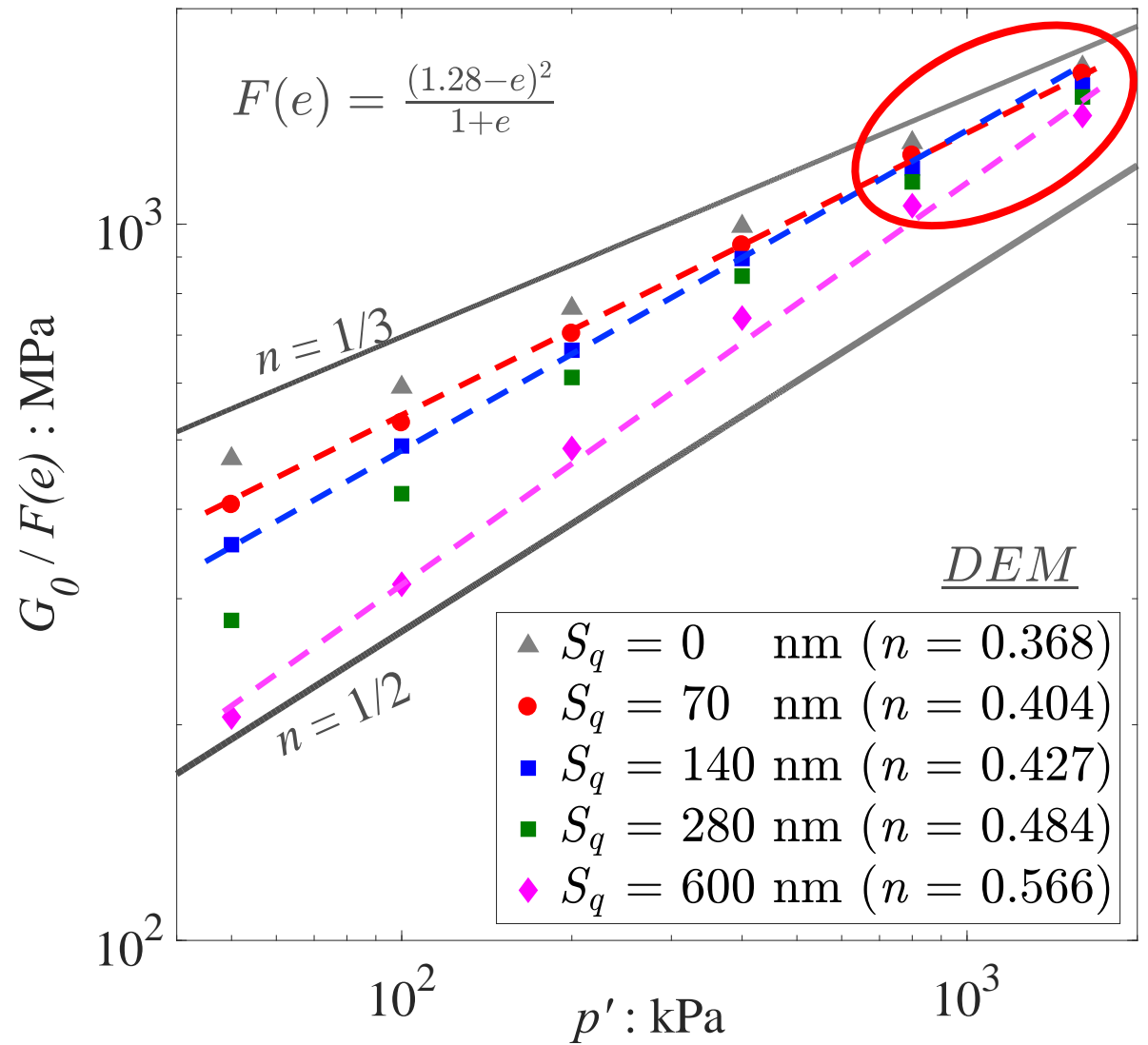
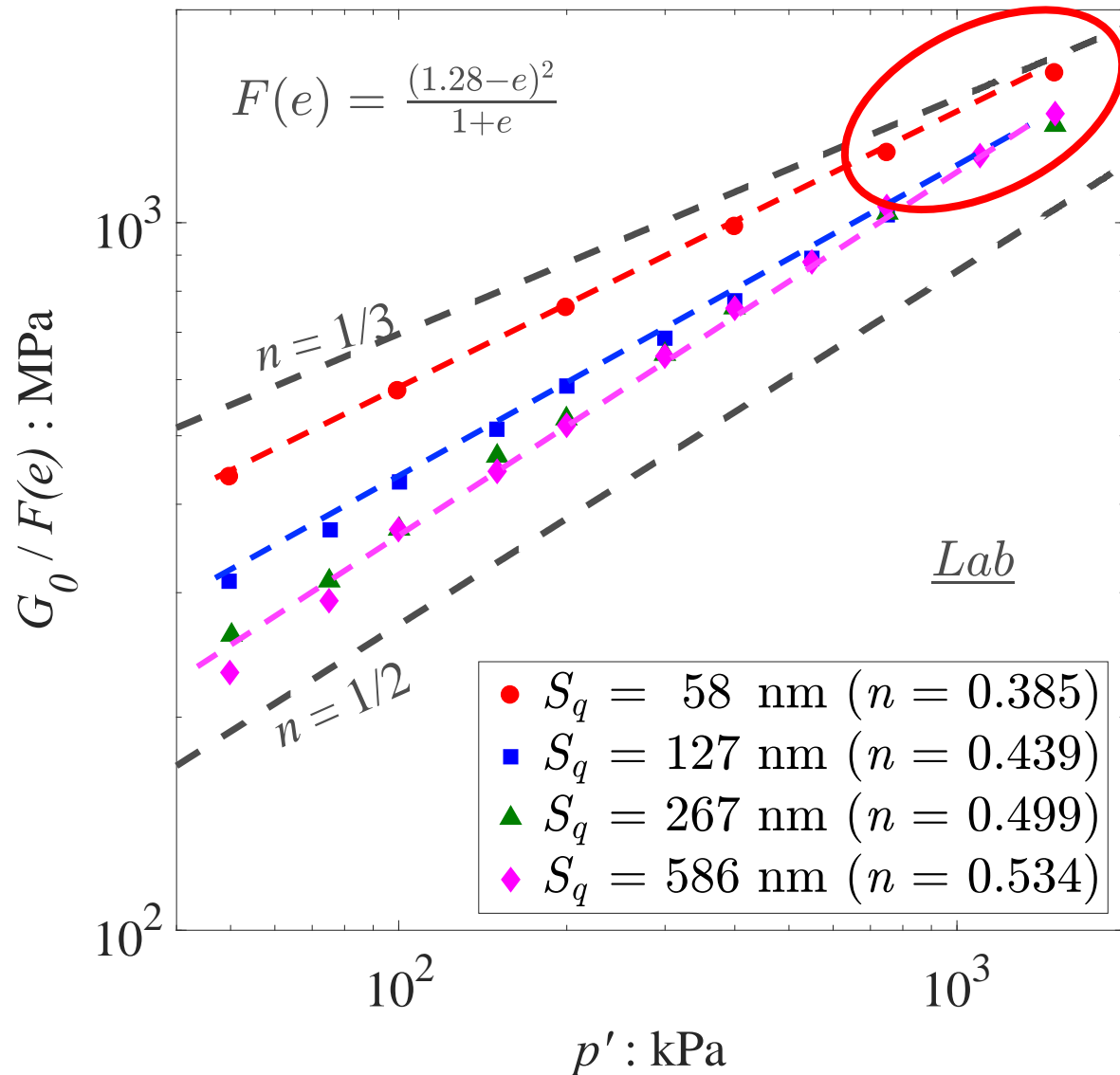
Experiments



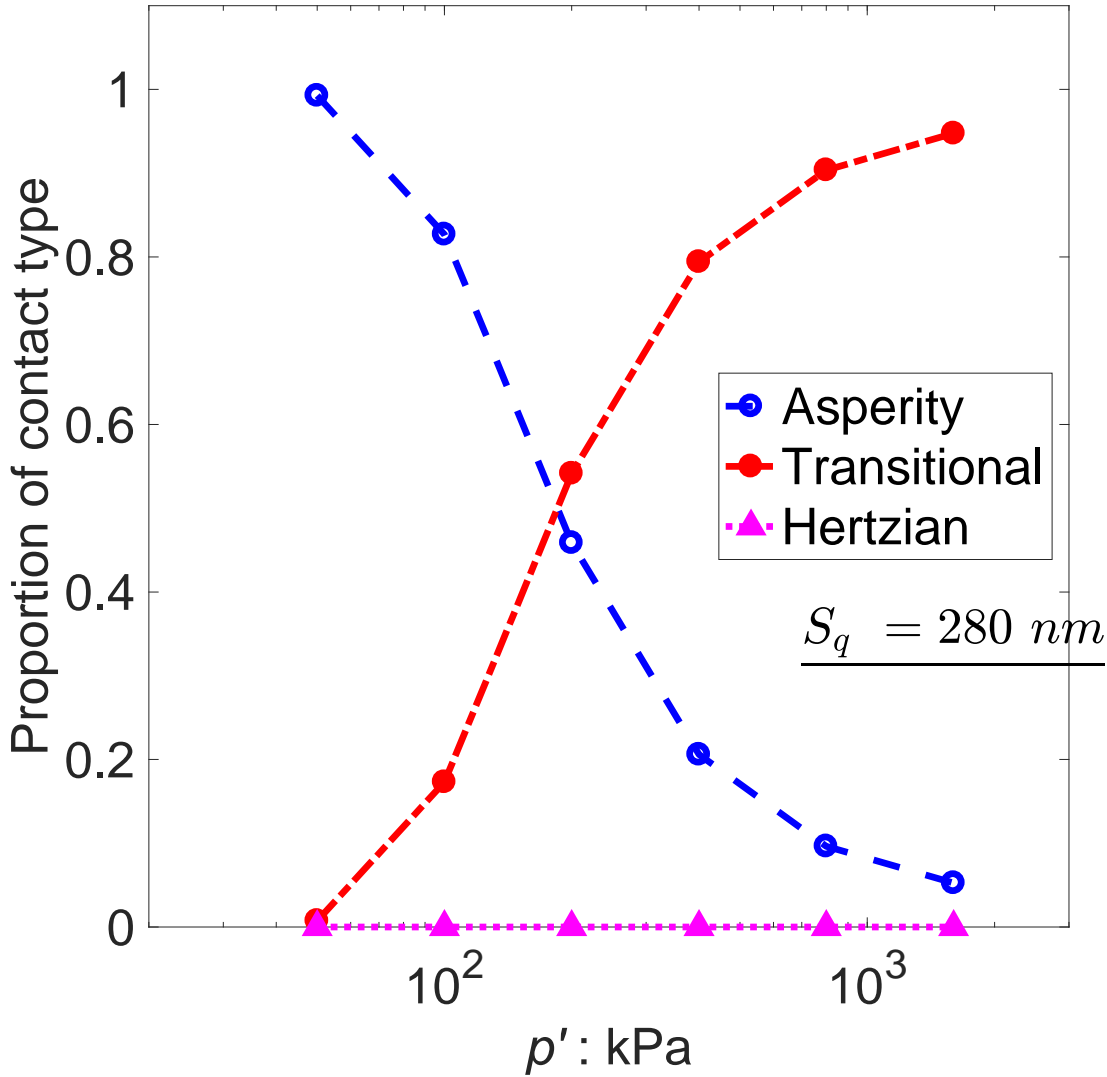
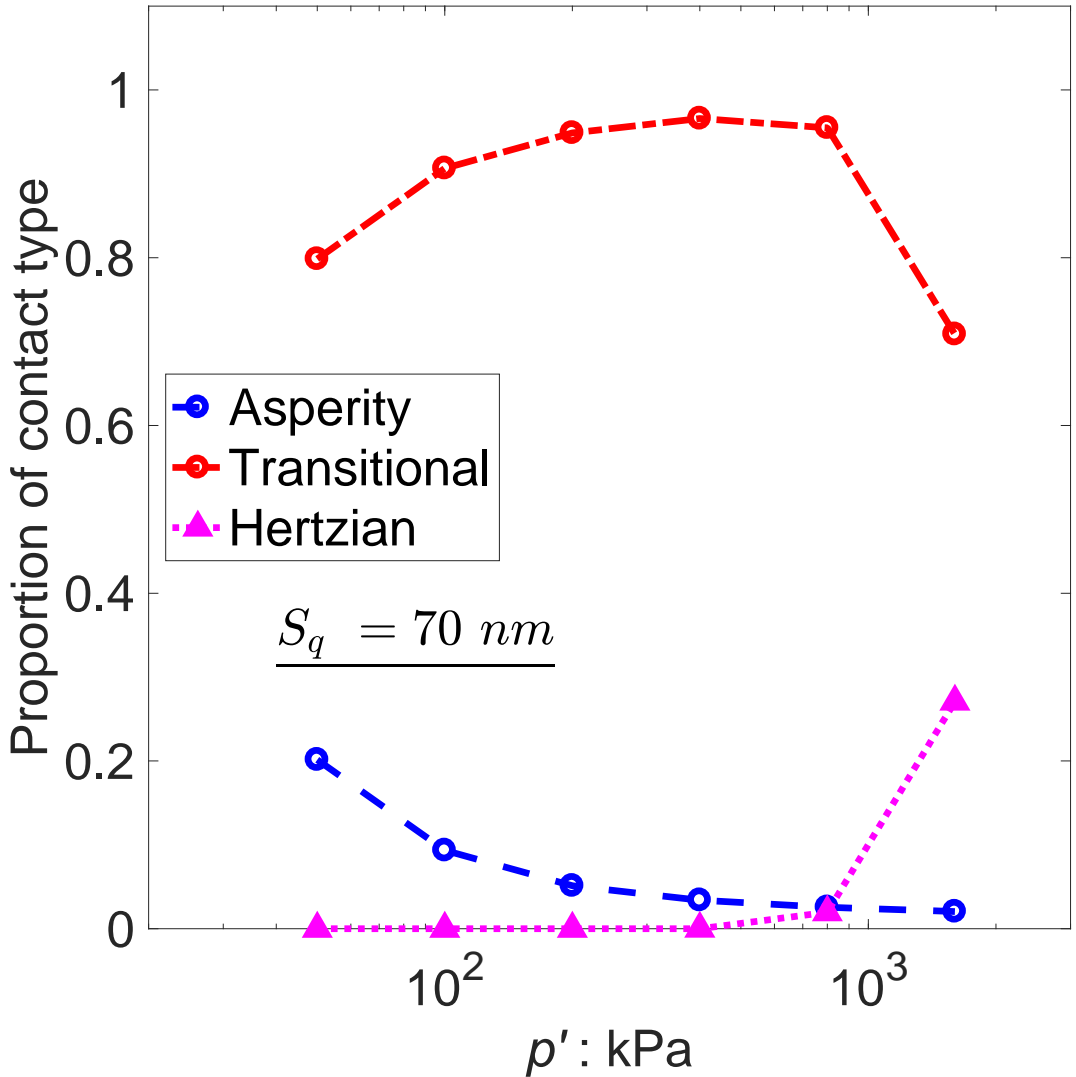
DEM simulations



# Surface Roughness and Stiffness

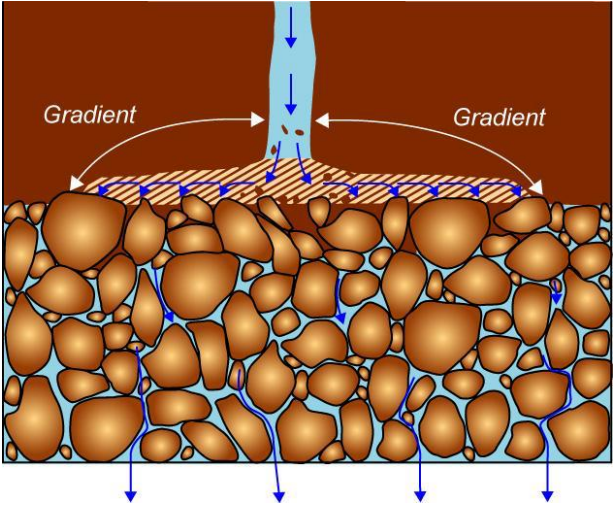
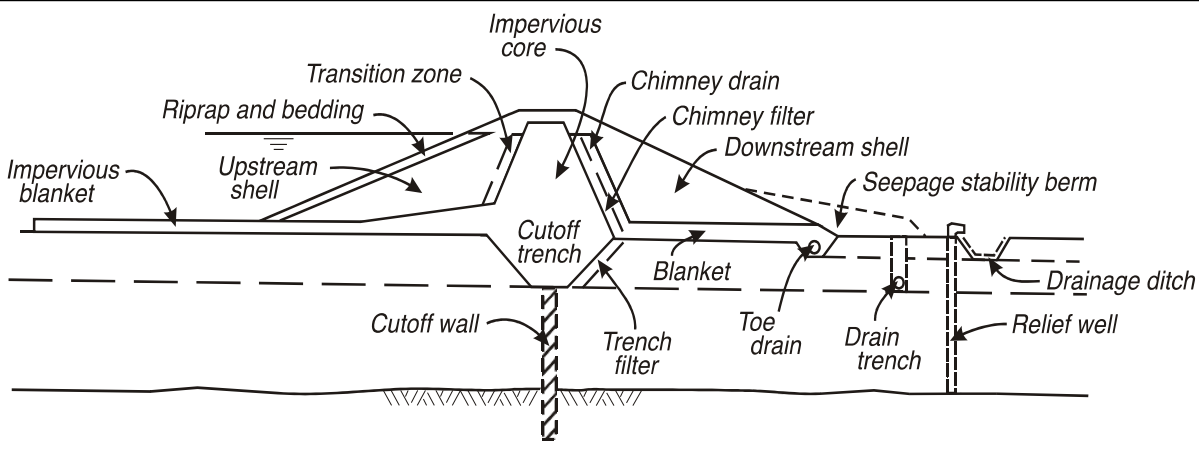


# DEM data on Contact Evolution

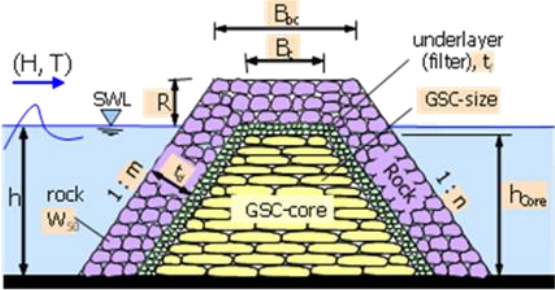


# Filtration

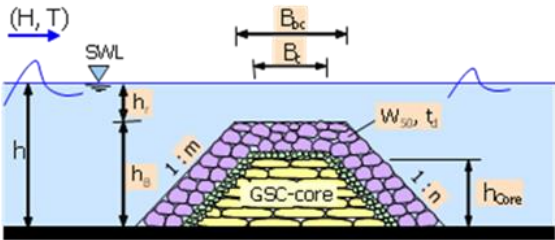
## Embankment dams



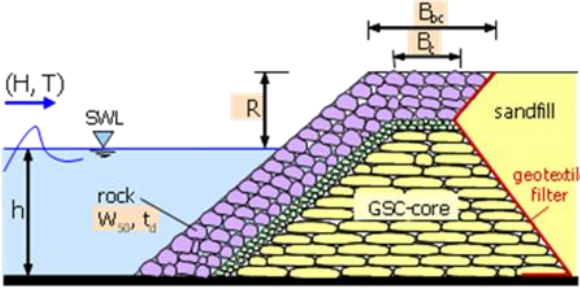
## Rubble Mound Breakwaters



(a1) Rubble mound breakwater with GSCore



(b1) Submerged breakwater with GSCore



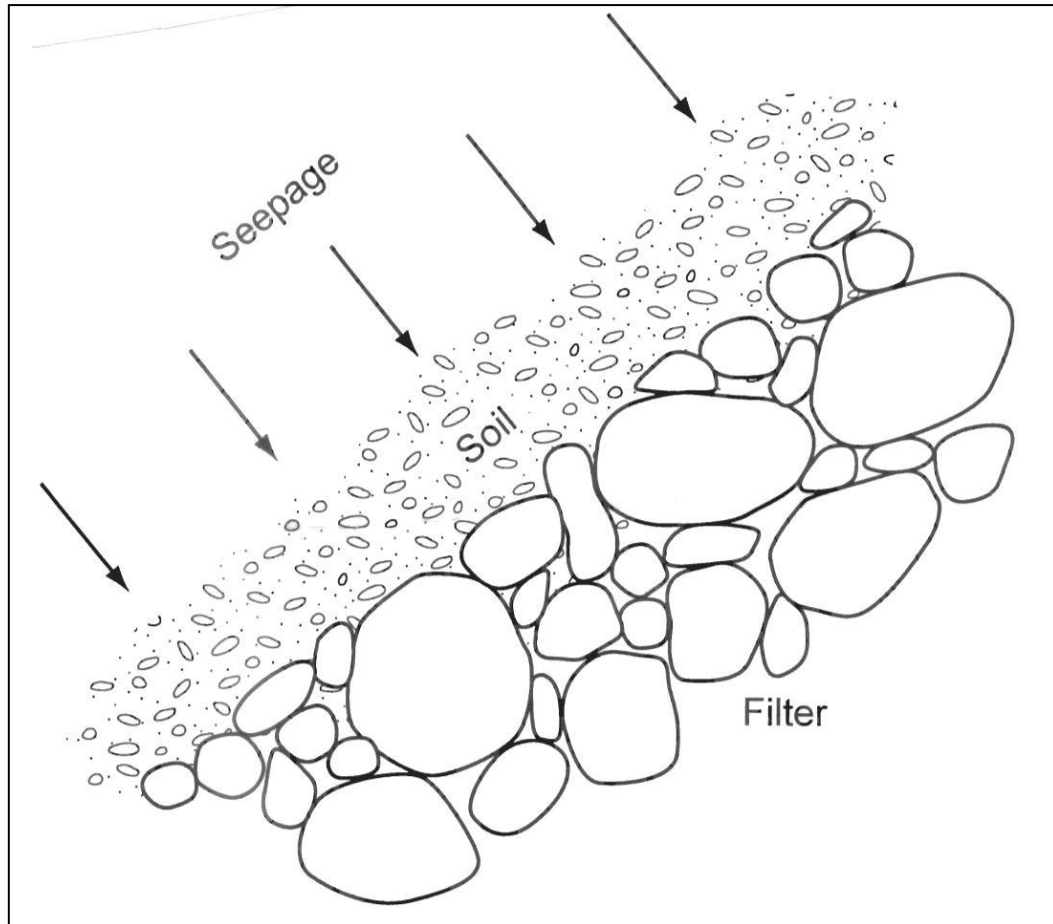
(c1) Seawall with GSCore and backfill  
<https://www.tu-braunschweig.de/Medien-DB/hyku-mi/geocore1.png>



HR Wallingford Images:  
[https://www.innovationresearchfocus.org.uk/Issues/88/IRF88\\_HR1.html](https://www.innovationresearchfocus.org.uk/Issues/88/IRF88_HR1.html)

(FEMA, 2011)

# Filtration

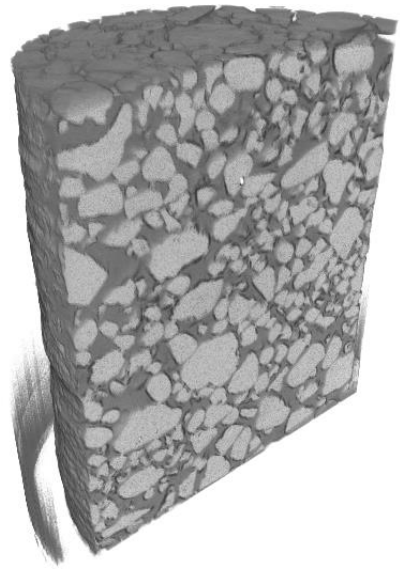


(FEMA, 2011)

- Filter should retain finer base material
- $D_{15}$  often used as a means to infer constriction sizes
- Originates from Terzaghi's filter rule (Sherard & Dunnigan, 1989; ICOLD, 2015)
- Supported by macro-scale filtration experiments (Kenney et al., 1985)

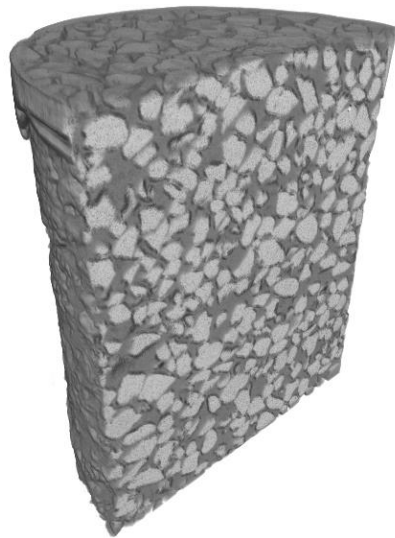
# Filtration – Samples Considered

## Laboratory Experiments

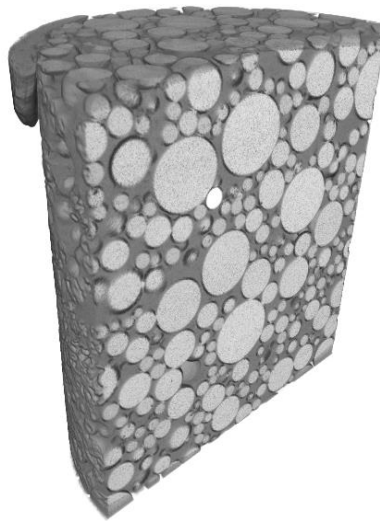


Leighton Buzzard  
Sand  
 $C_u=3$

(Taylor, 2017)

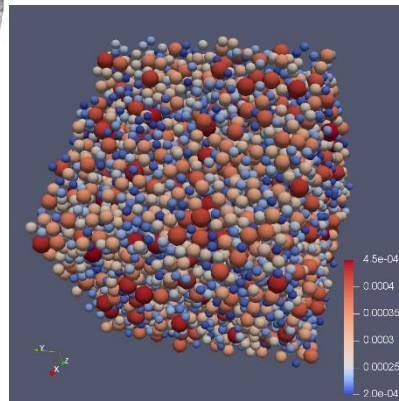


Leighton Buzzard  
Sand  
 $C_u=1.5$



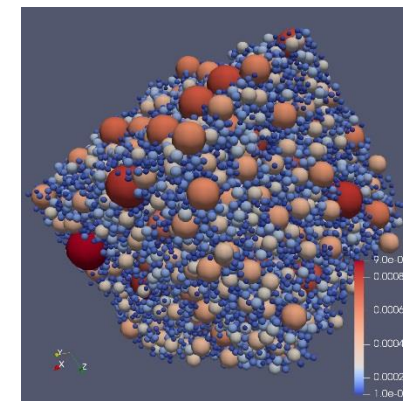
Glass Beads  
 $C_u=3$

## DEM Simulations

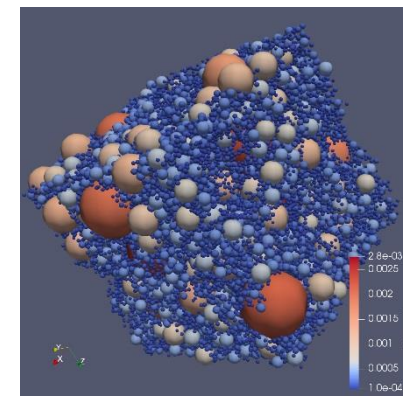


Spheres  
 $C_u=1.2$

(Shire, 2018)



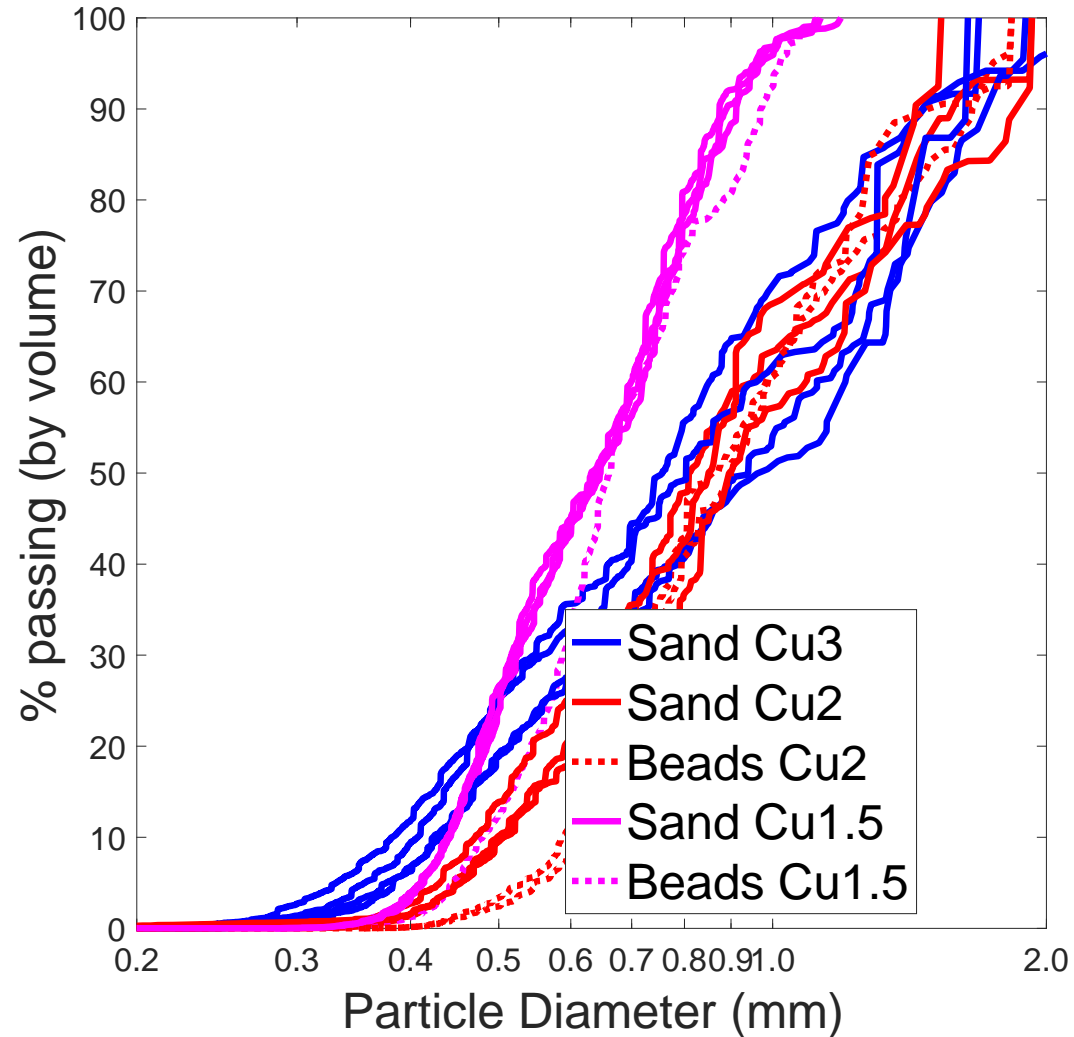
Spheres  
 $C_u=3.0$



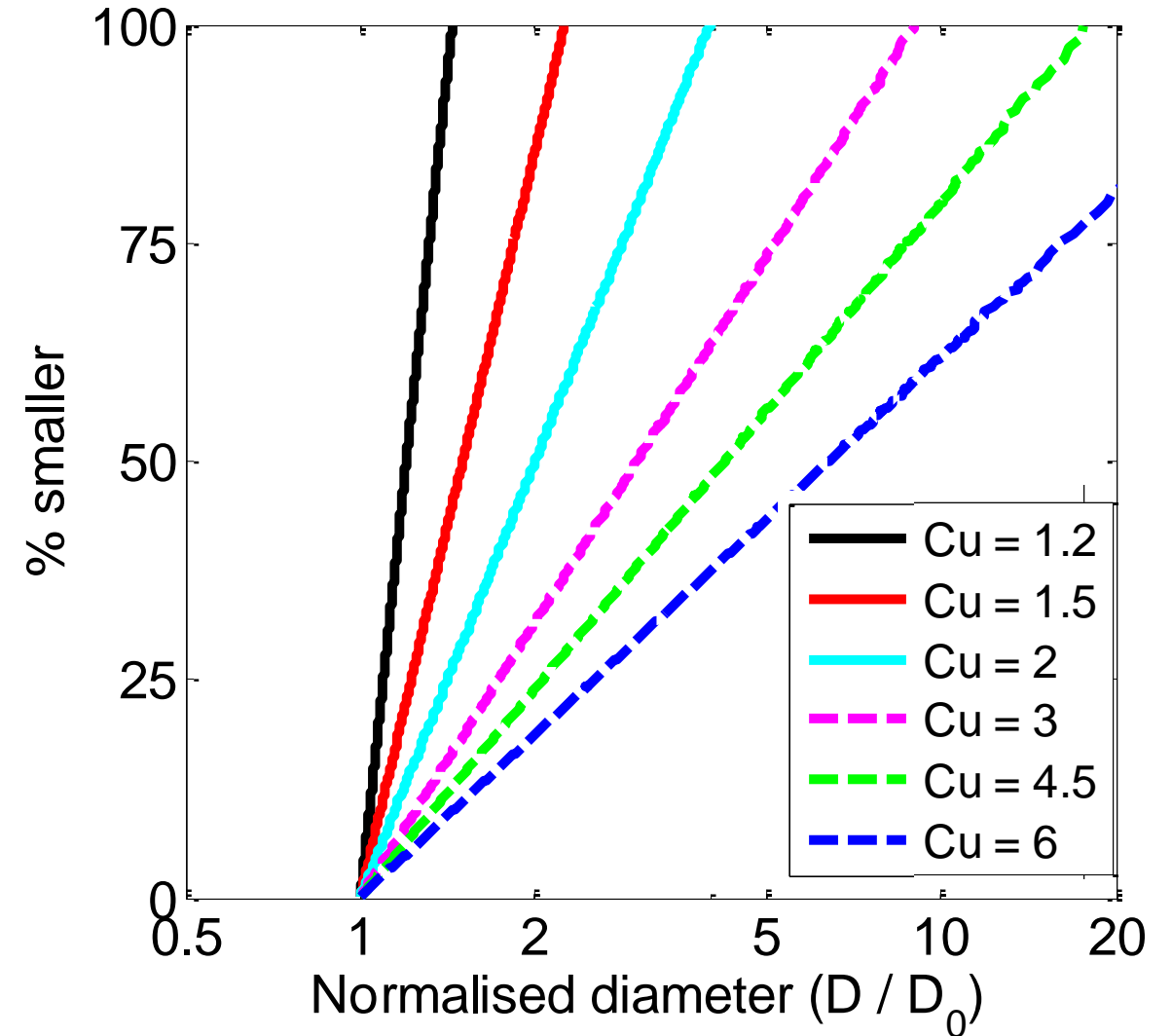
Spheres  
 $C_u=6.0$

# Filtration – Samples Considered

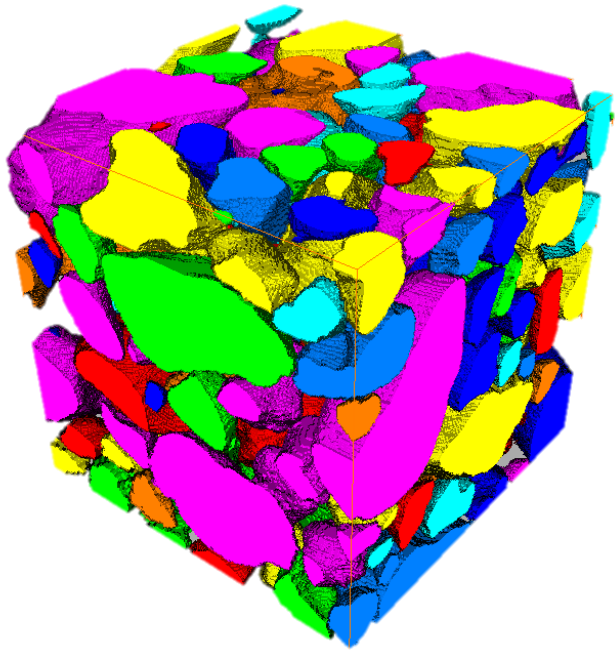
## Laboratory Experiments



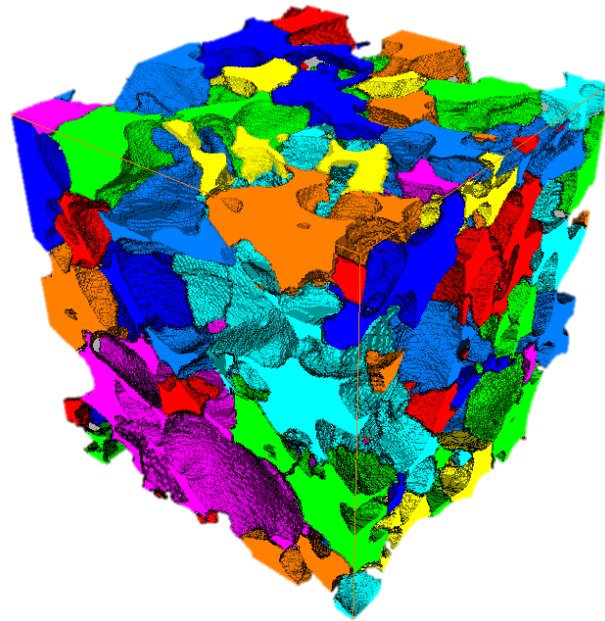
## DEM Simulations



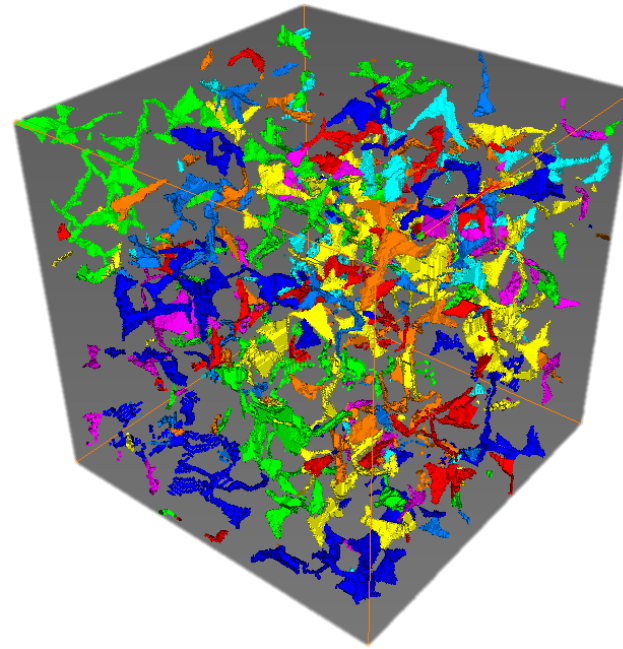
# MicroCT: Void Boundaries



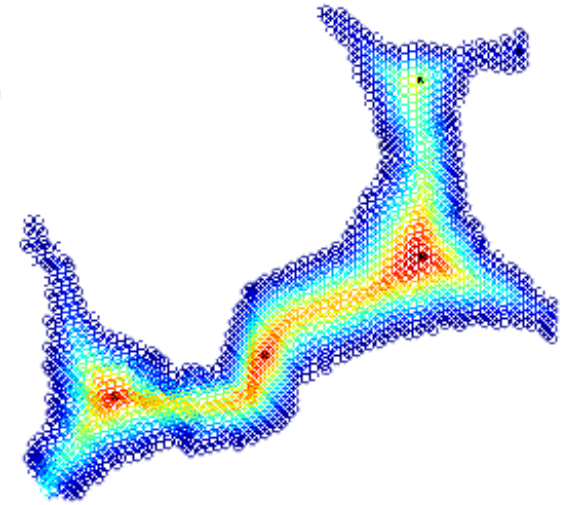
Particles



Voids



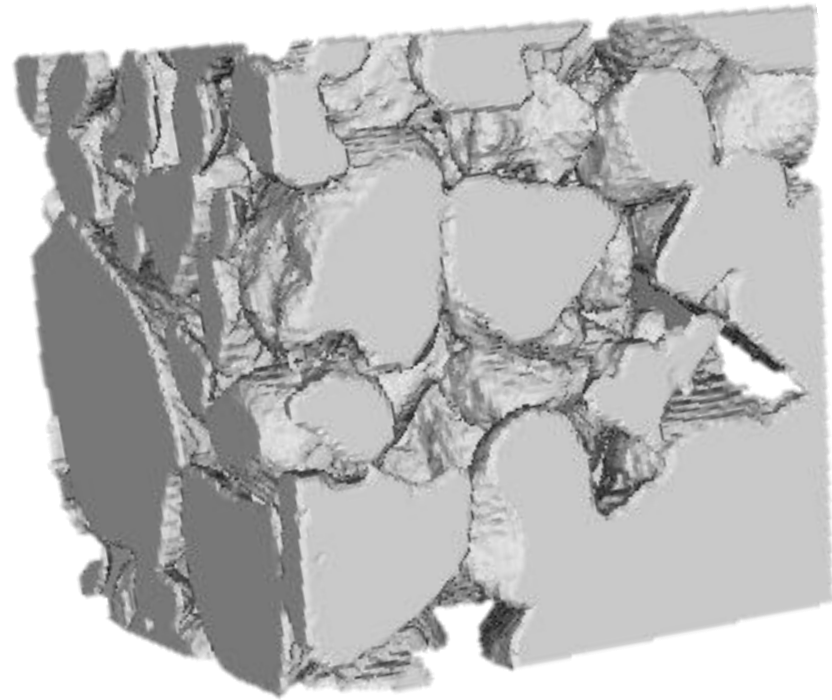
Void Boundaries:  
Surfaces where  
voids meet



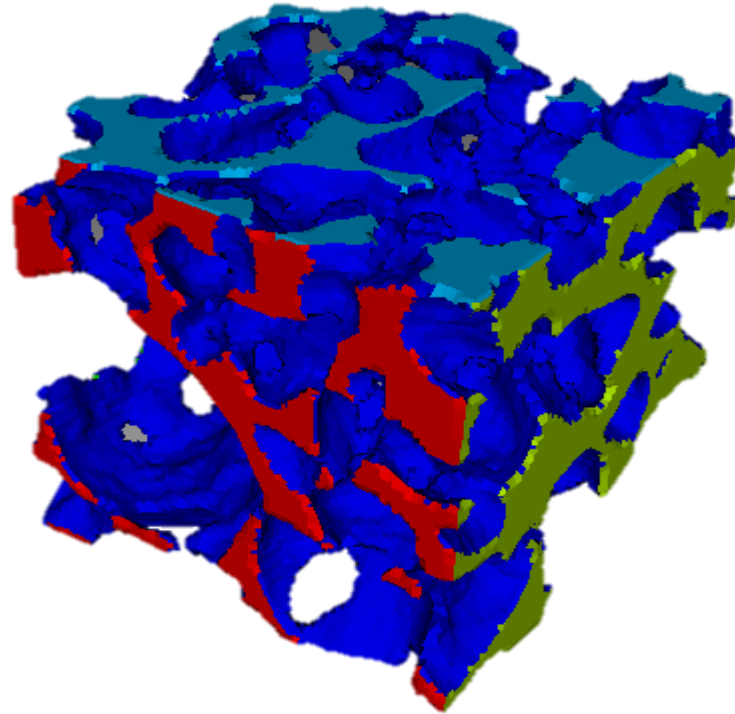
Constrictions: local  
maxima of distances  
to particles along  
void boundary



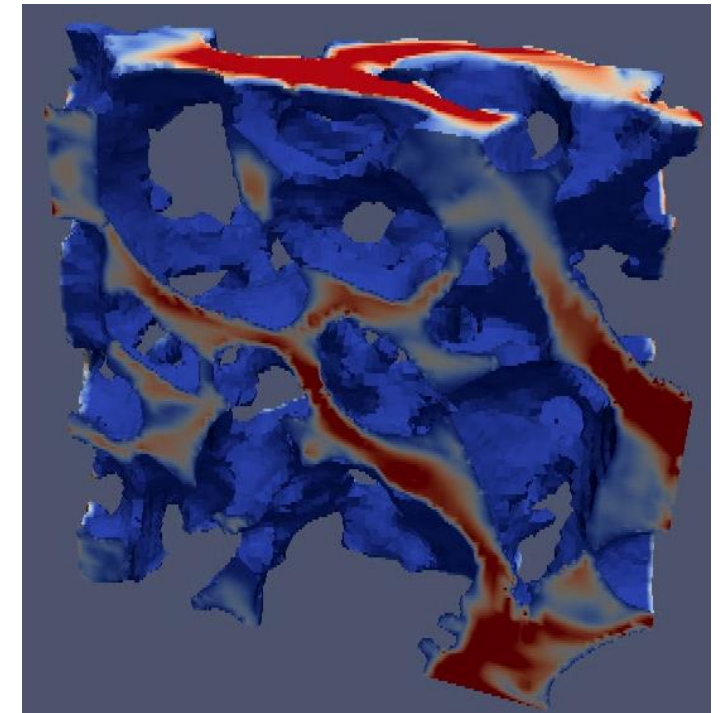
# Filtration - CFD Analysis of Constrictions



Micro CT Data

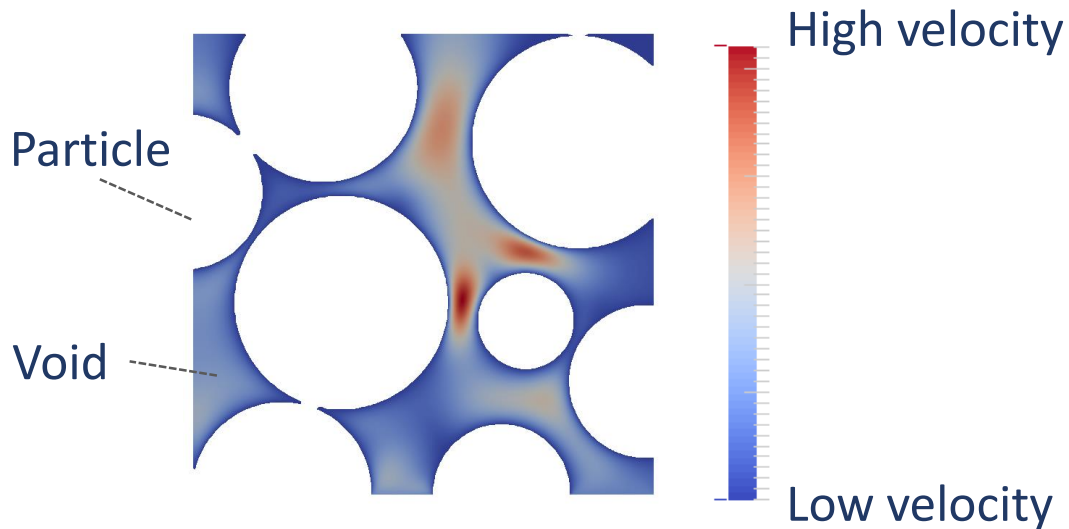


Finite volume mesh

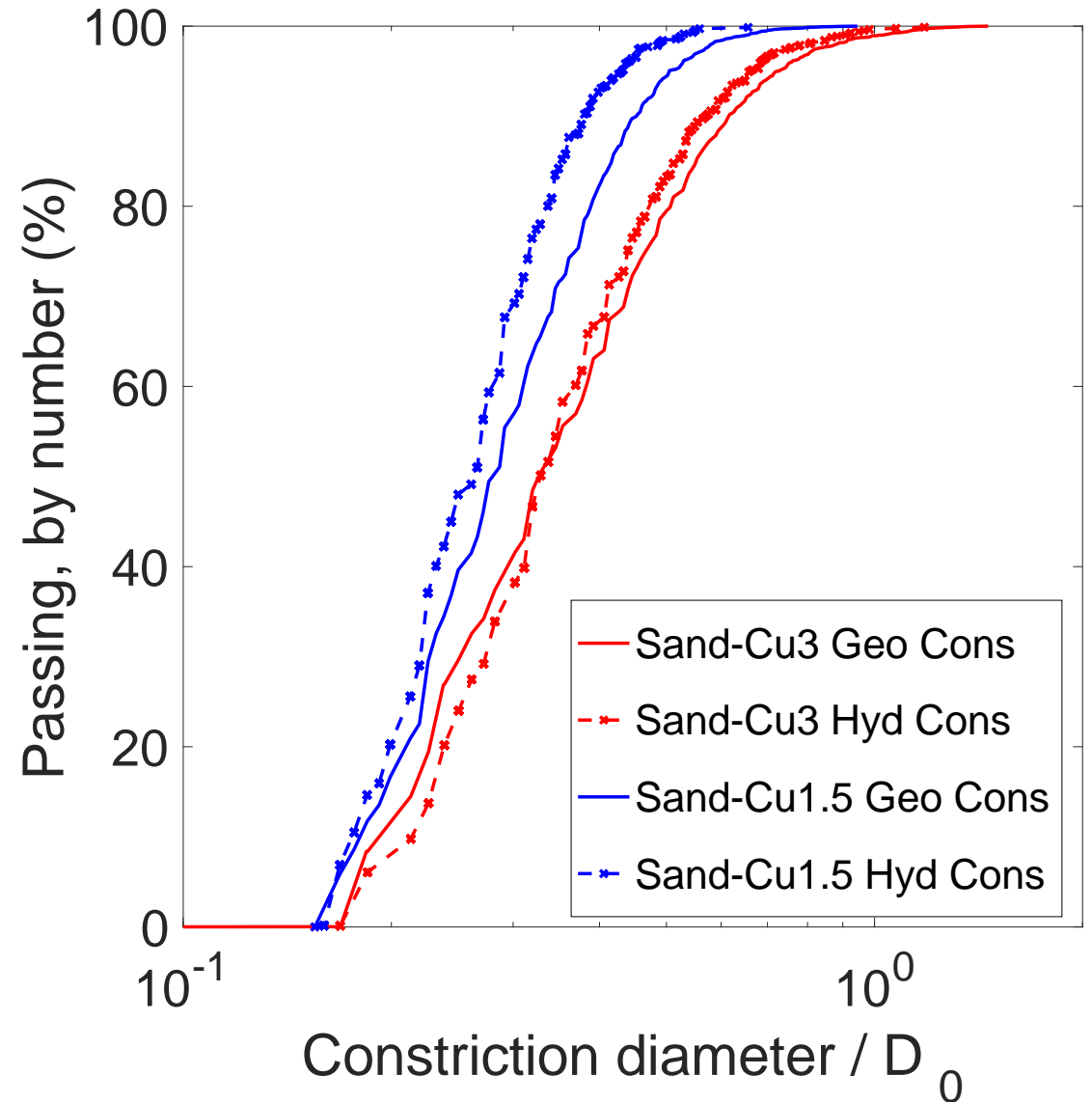
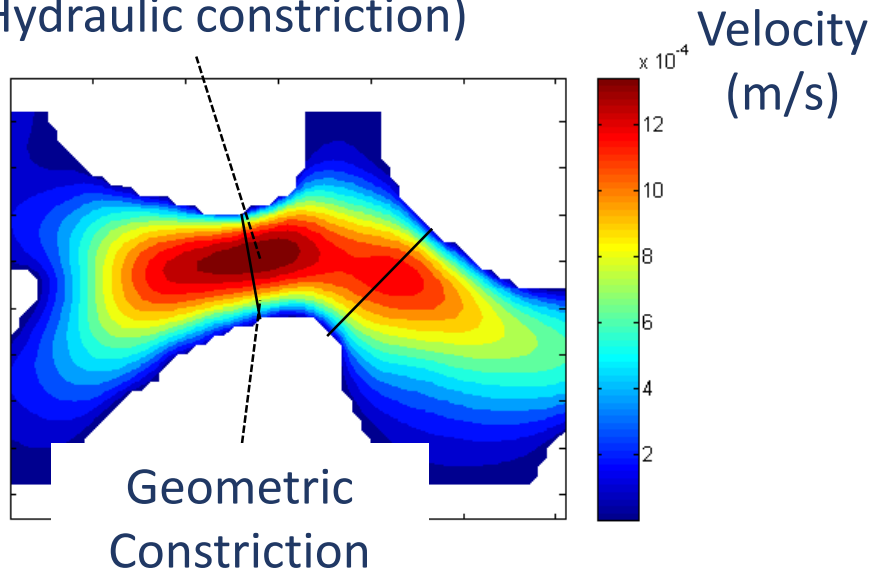


Computational Fluid Dynamics (CFD)  
Simulation of Fluid Flow

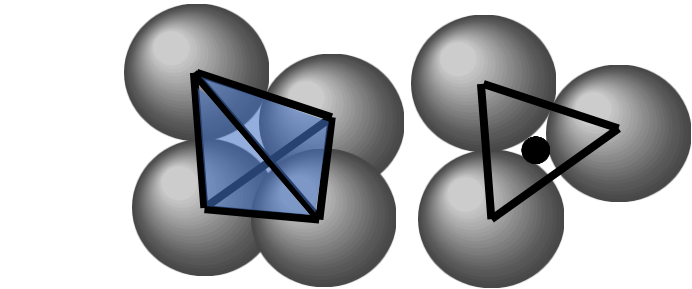
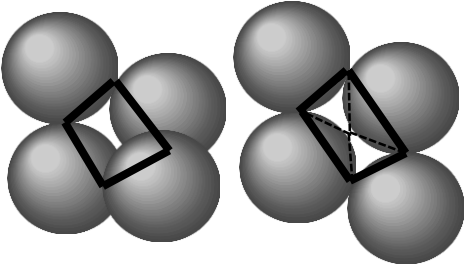
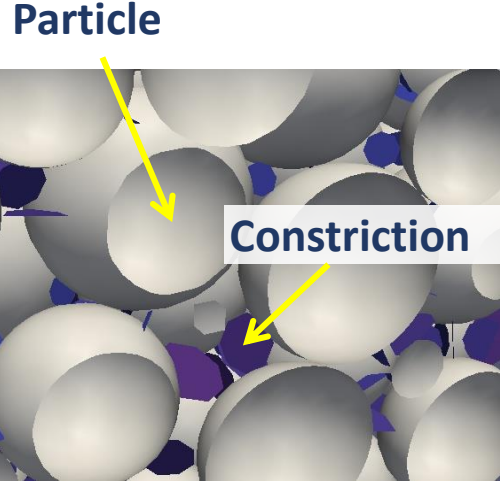
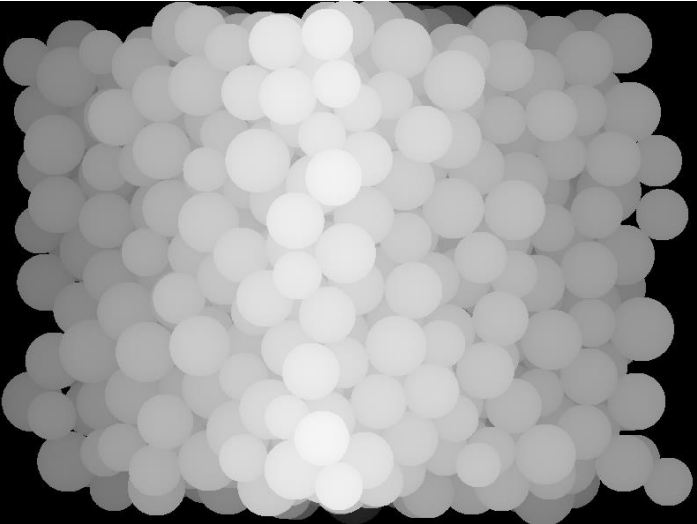
# Filtration - CFD Analysis of Constrictions



Velocity maximum  
(= Hydraulic constriction)

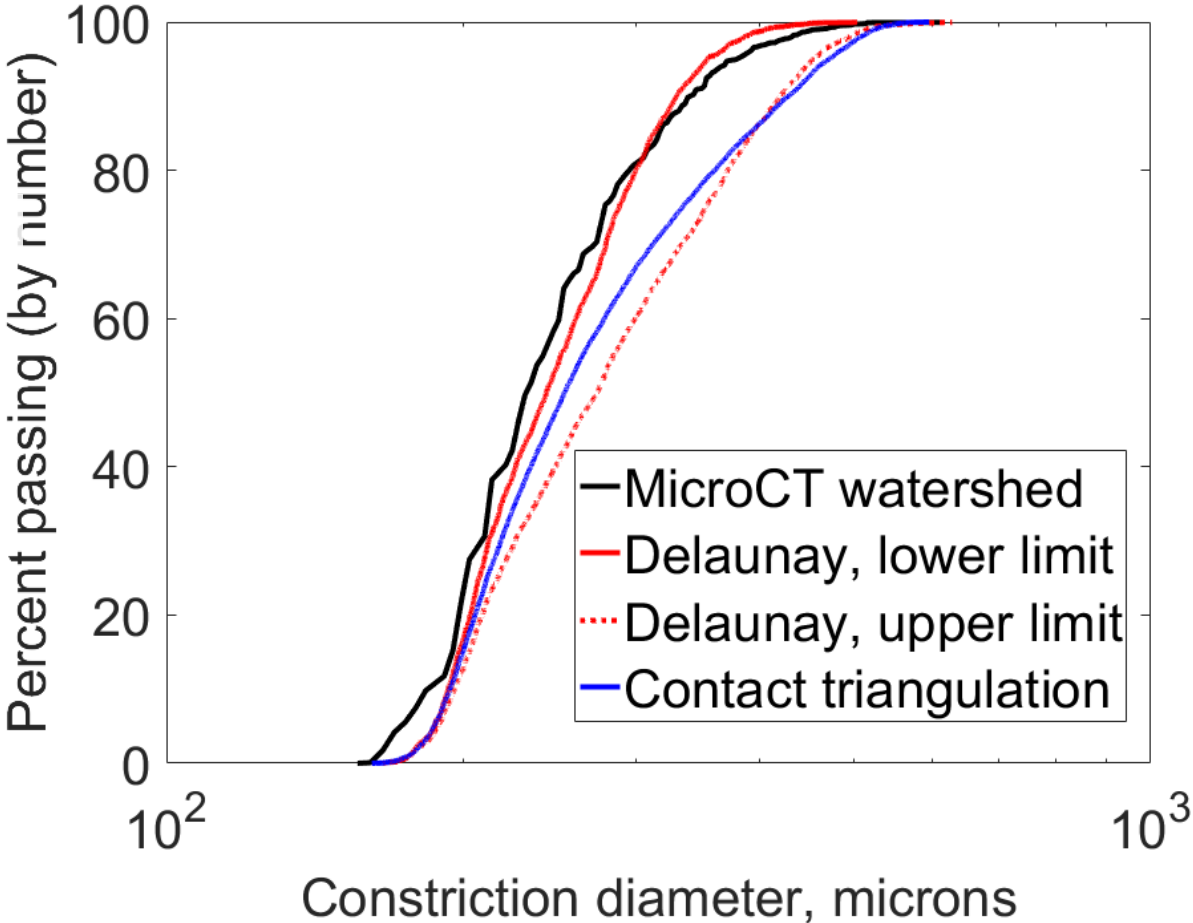


# DEM: Void Boundaries



Contact triangulation

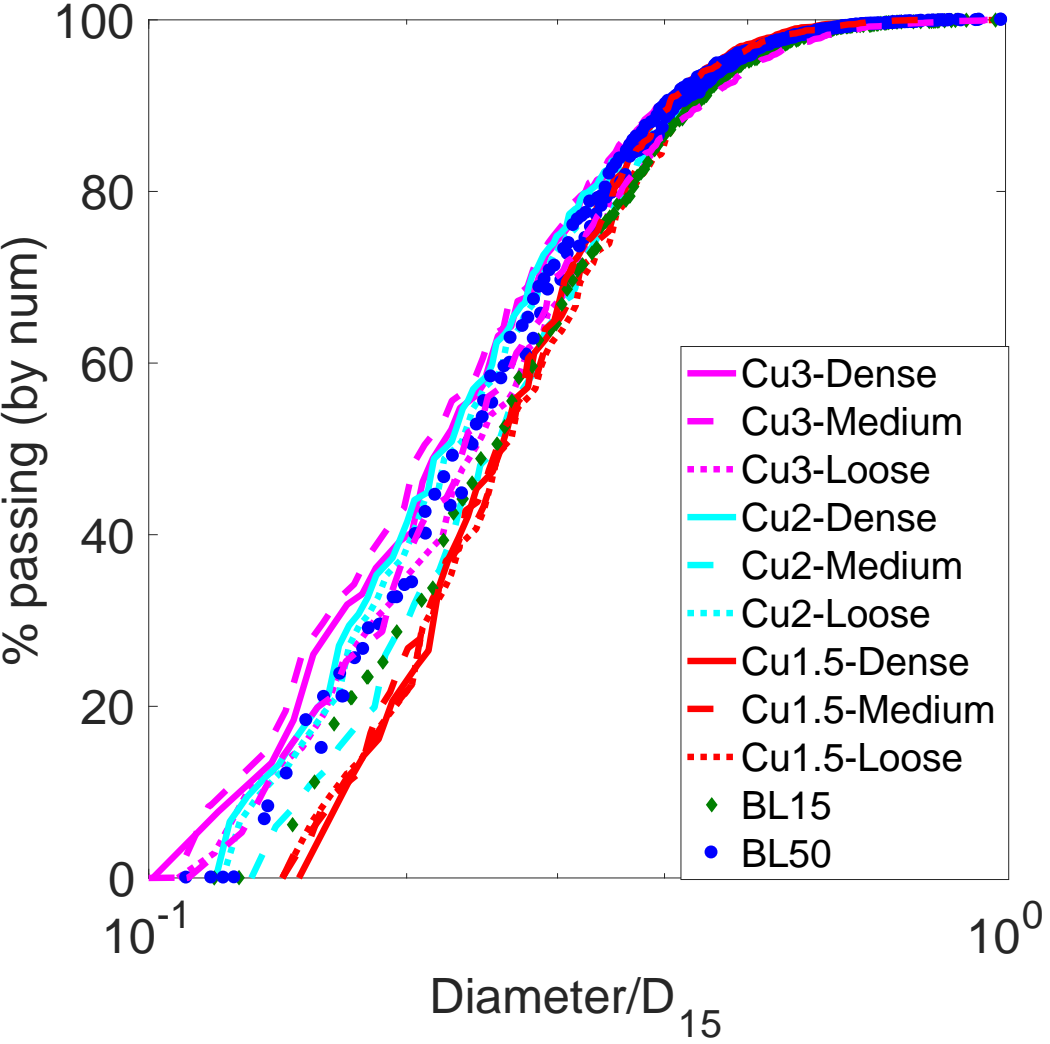
Delaunay triangulation of particles



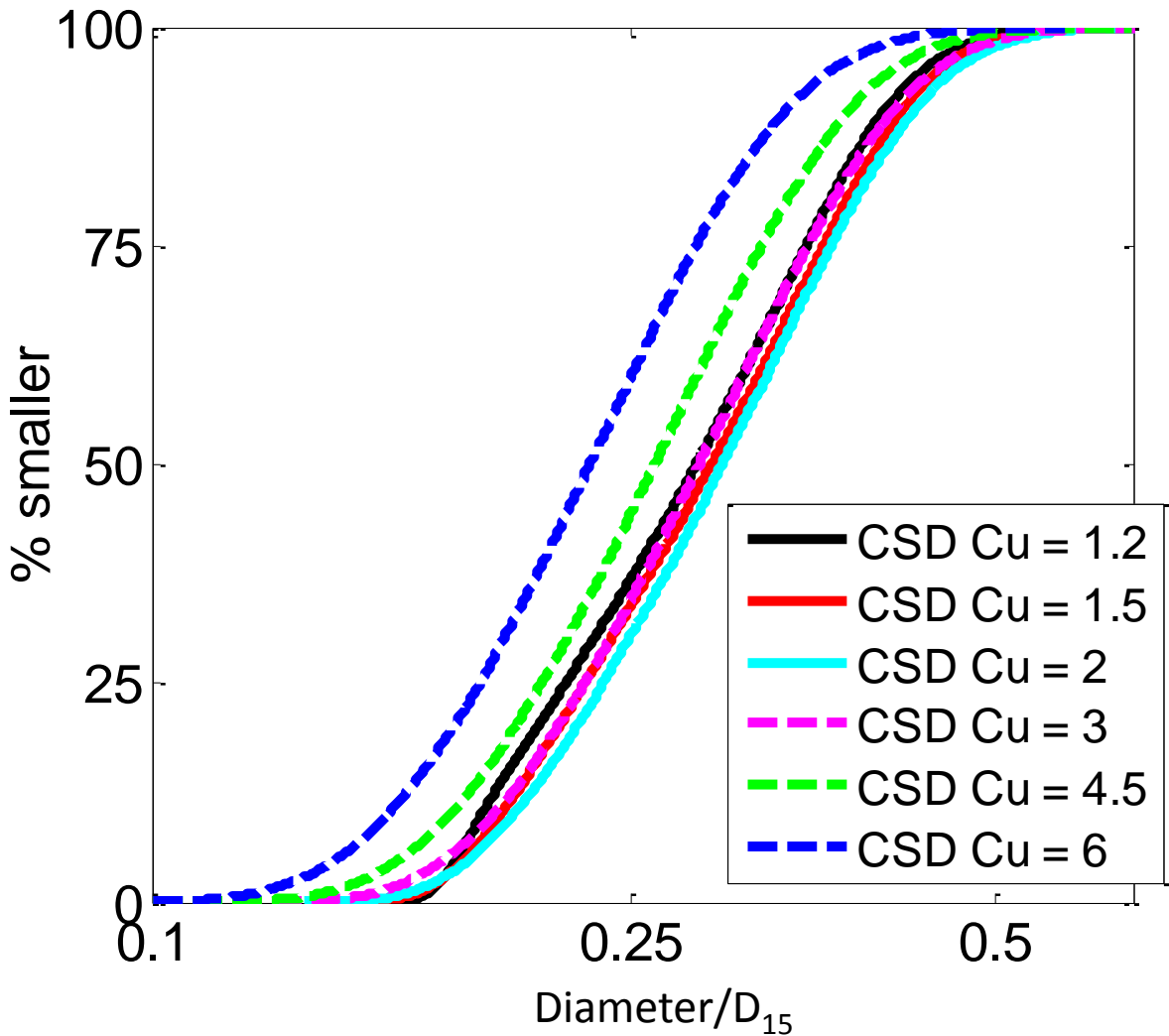
Shire et al. (2016)

# Filtration - Constriction Sizes

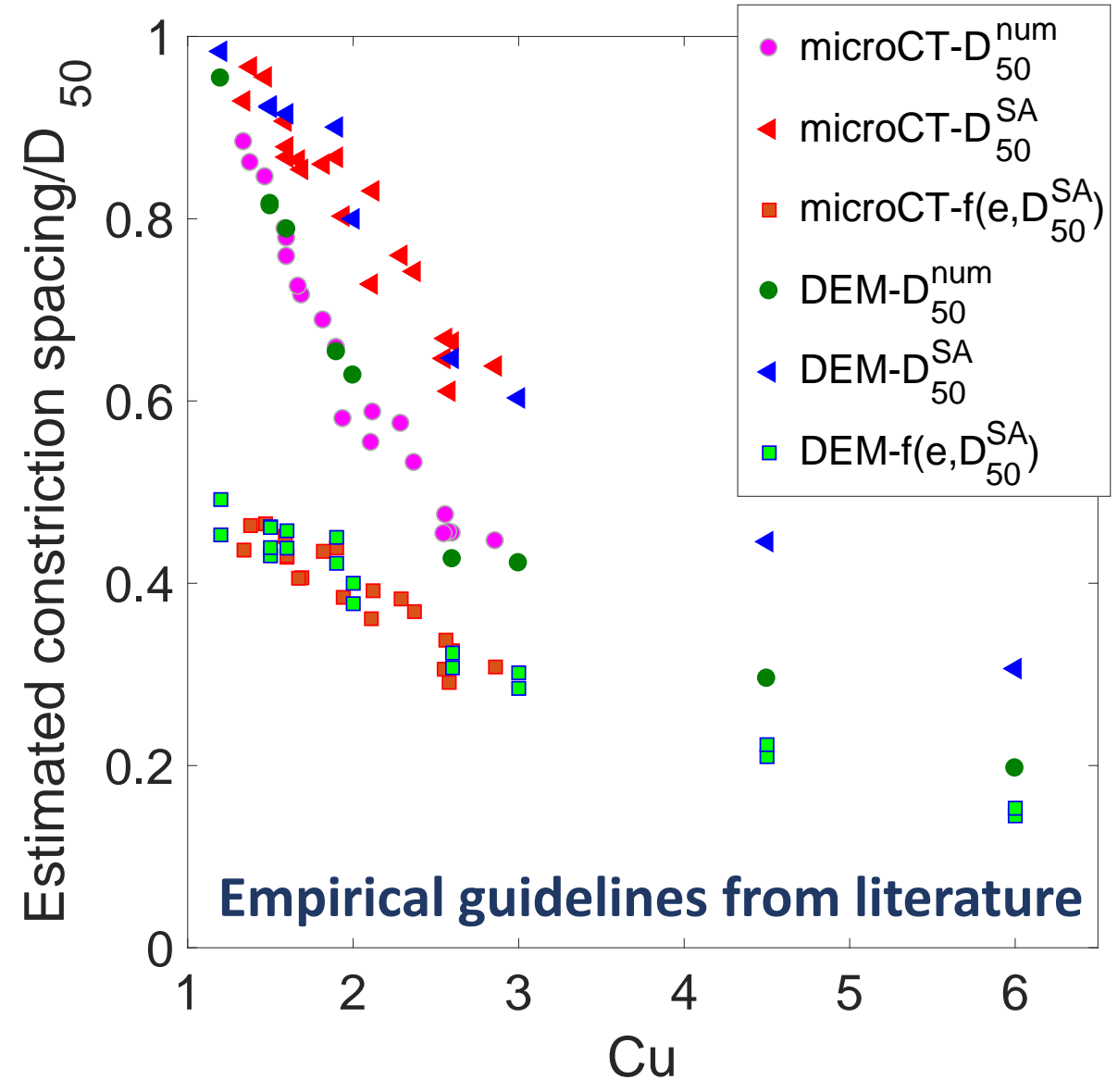
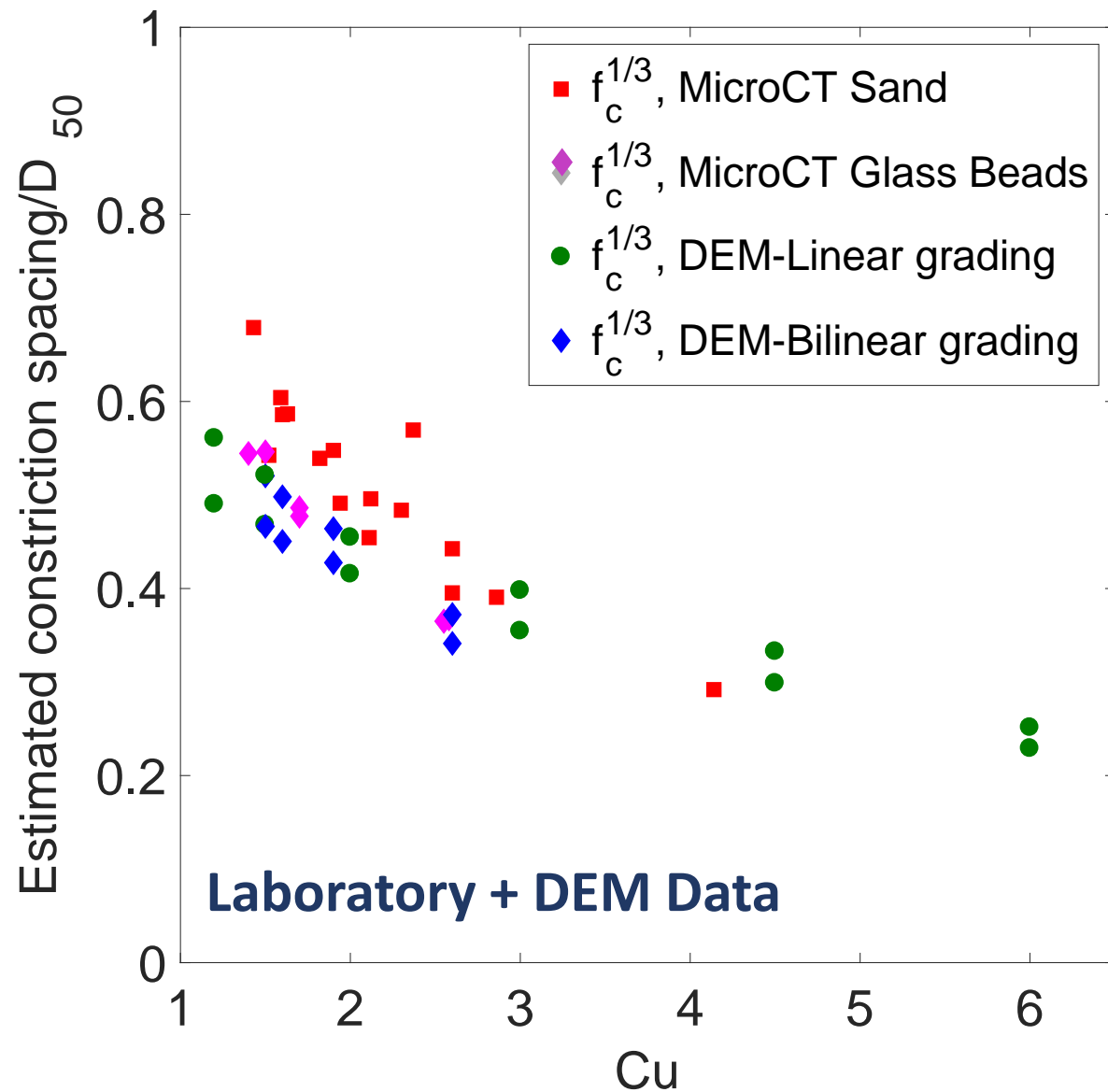
### MicroCT Experimental data



### DEM Simulation data



# Filtration – Constriction Density / Spacing



# Conclusions

- Imaging technologies facilitate detailed particle scale characterization in the laboratory
- DEM enables measurement of forces and avoids resolution issues when looking at contacts in detail in 3D
- DEM + experimental characterization can be used in a complementary manner
- Relationship between  $G_0$  and  $p'$  is influenced by degree of surface roughness
- Measurements of constriction sizes confirm rationale of using  $D_{15}$  to estimate constriction sizes

# Quantifying fabric and considering its effects

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