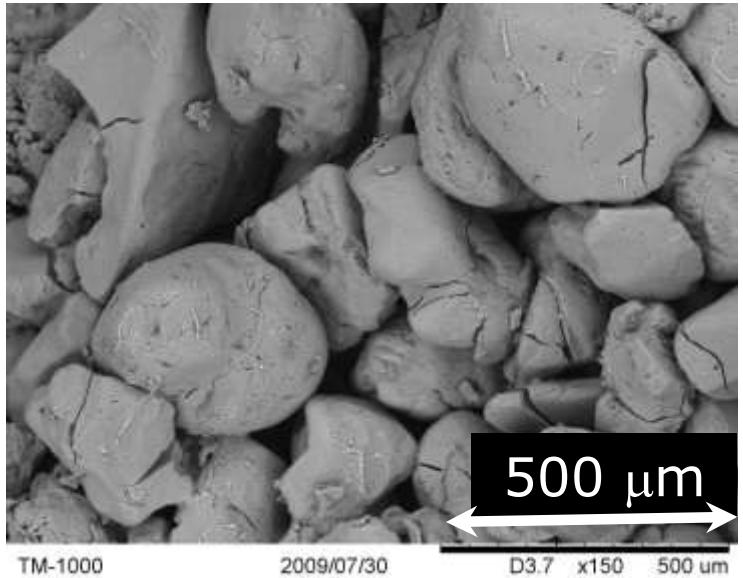


# Engineering sand: From the micro- to the macro-scale

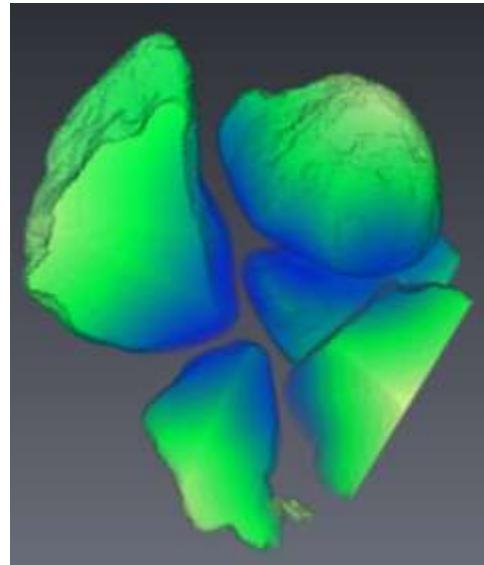
Catherine O'Sullivan

# Overall argument

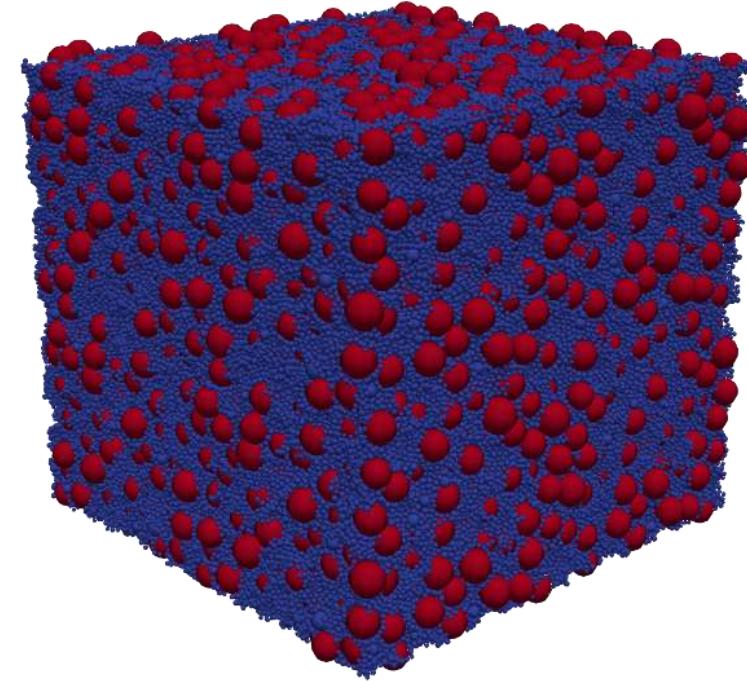
From an engineering perspective, it is worthwhile to look at the behaviour of sand from the perspective of an individual grain



Reigate Sand – PhD Research of  
Dr. Joana Fonseca



Leighton Buzzard Sand – PhD  
Research of Dr. Howard Taylor



DEM simulation of Gap Graded  
Sand  
Dr. A. Sufian & Ms. M. Artigaut

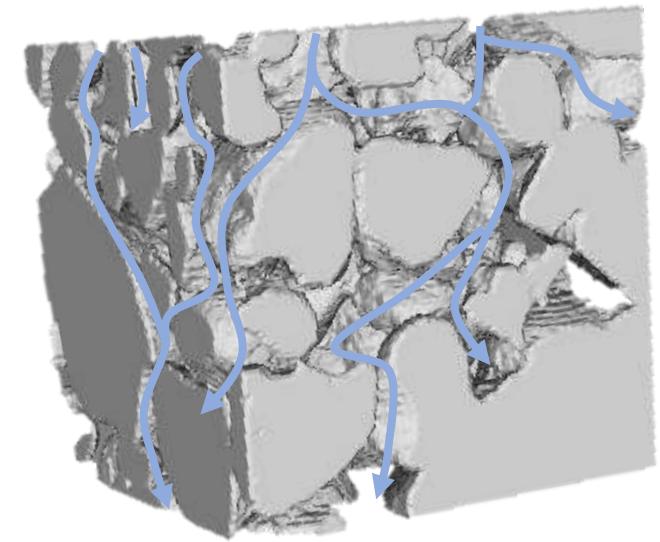
# Sand behaviour



Stiffness

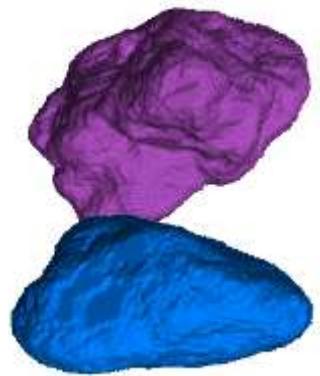
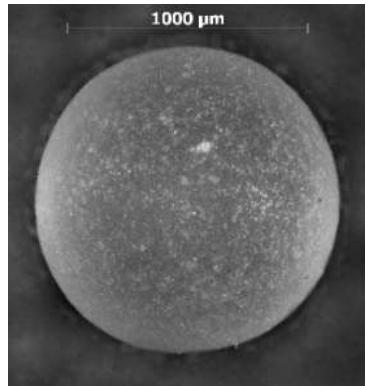


Strength

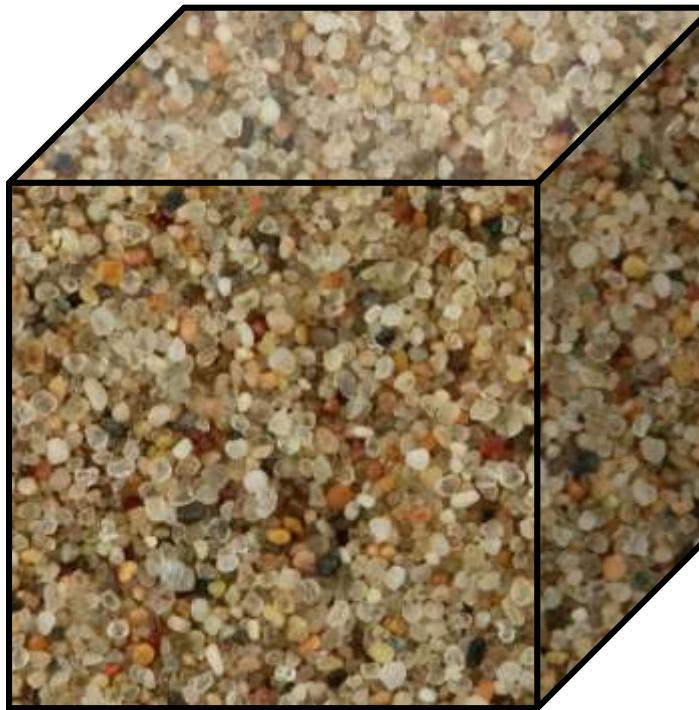


Seepage

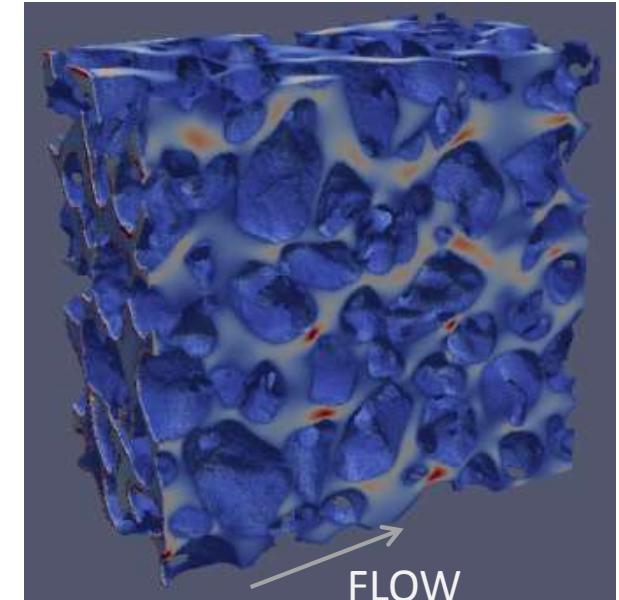
# Sand behaviour



Contact behaviour

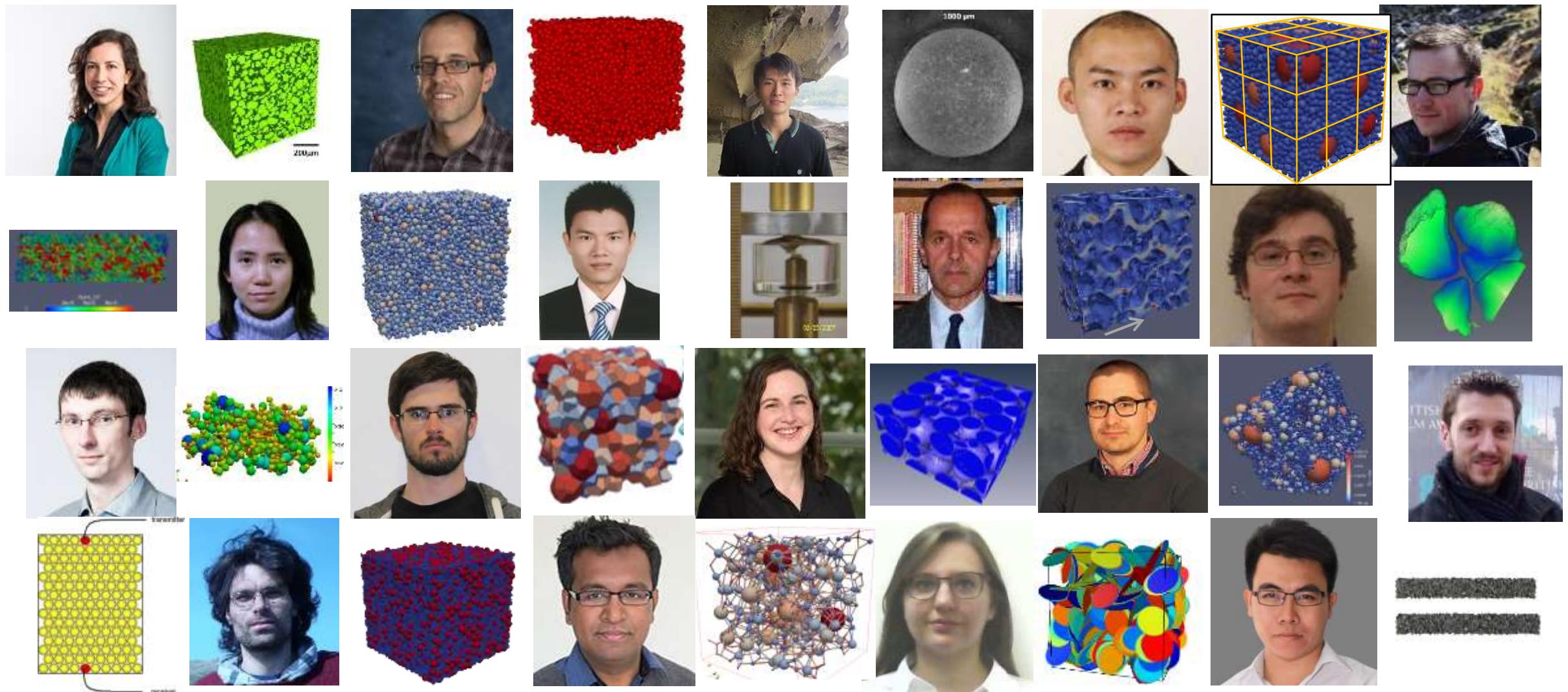


Collective behaviour

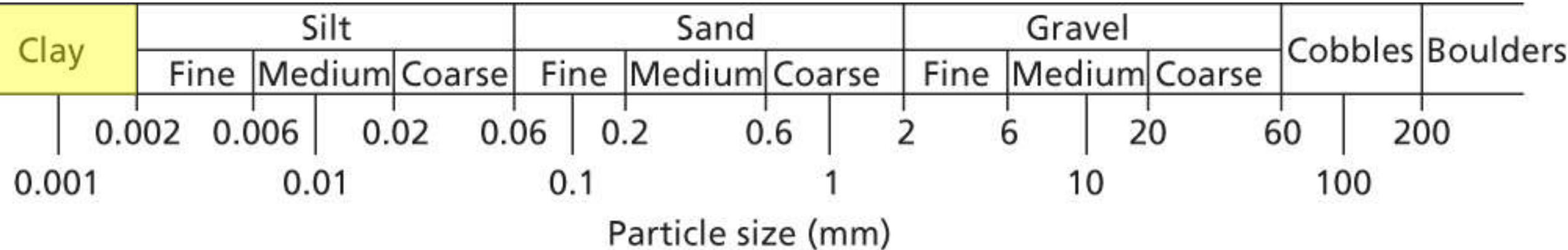


Coupled behaviour

# Supporting research



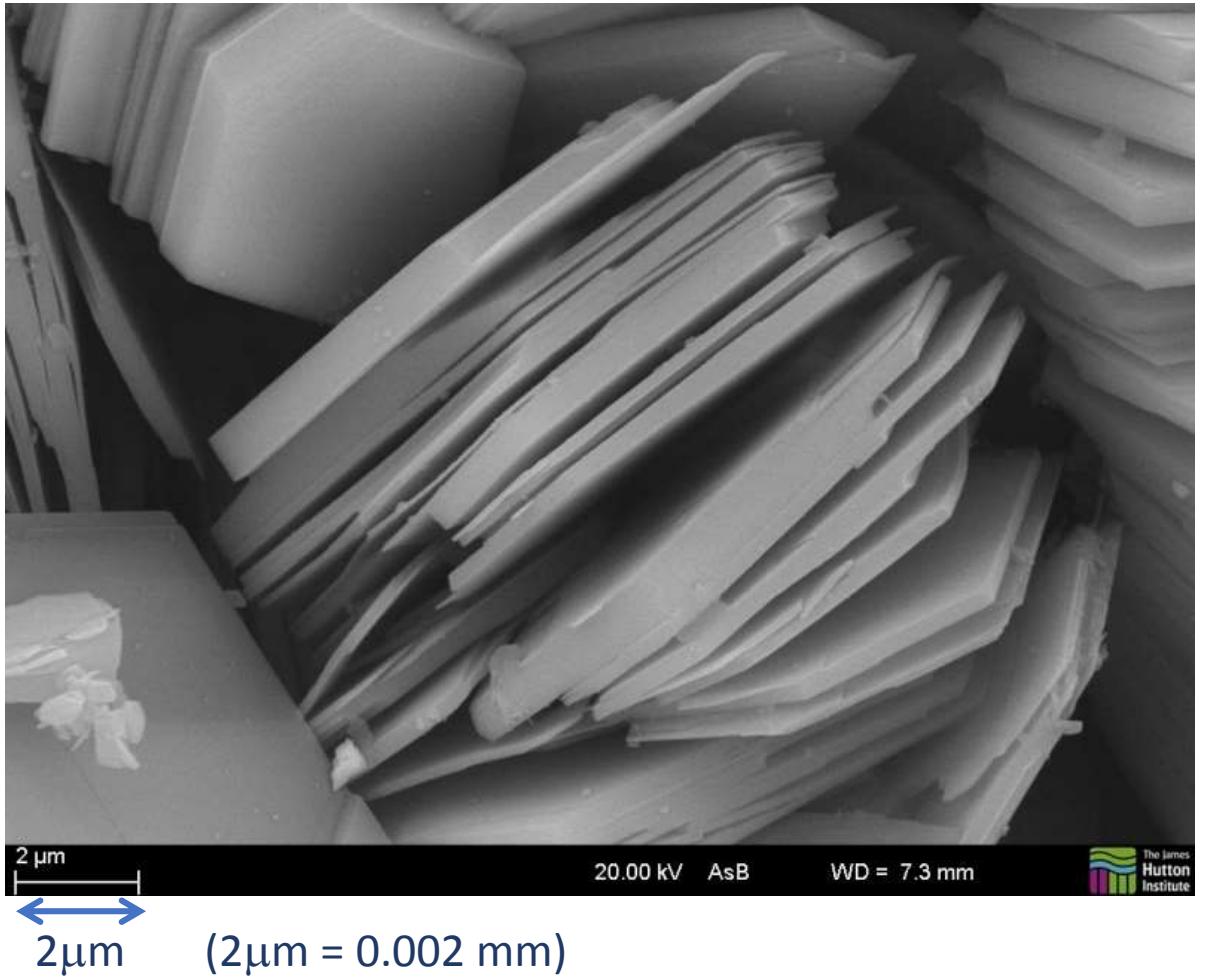
# Size matters in soil classification



- Clay grains smaller than 2 µm (0.002 mm)
- Ratio of surface area to volume is large
- Surface charges influence behaviour

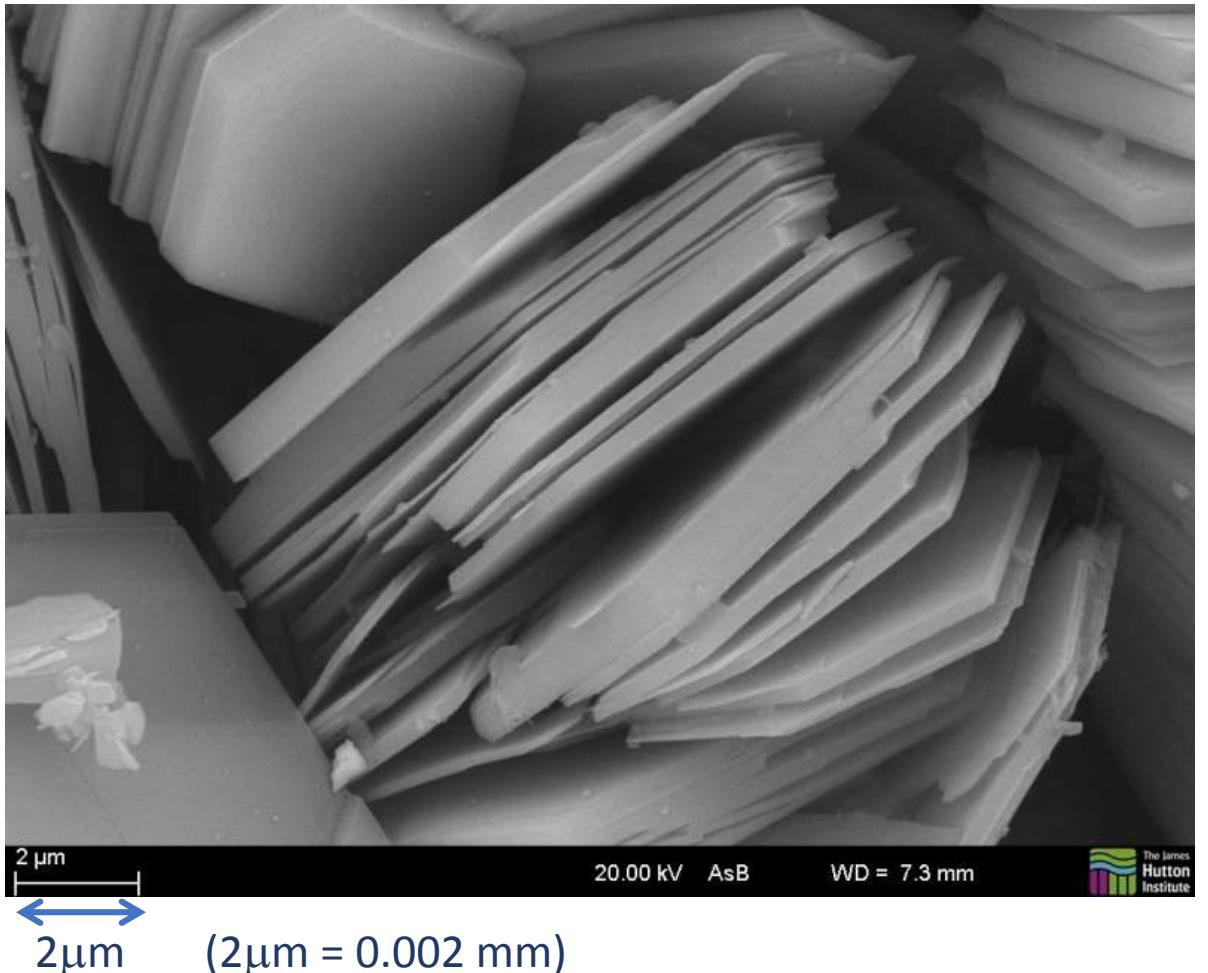
Figure 1.2 Knappett and Craig (2012)

# Clay

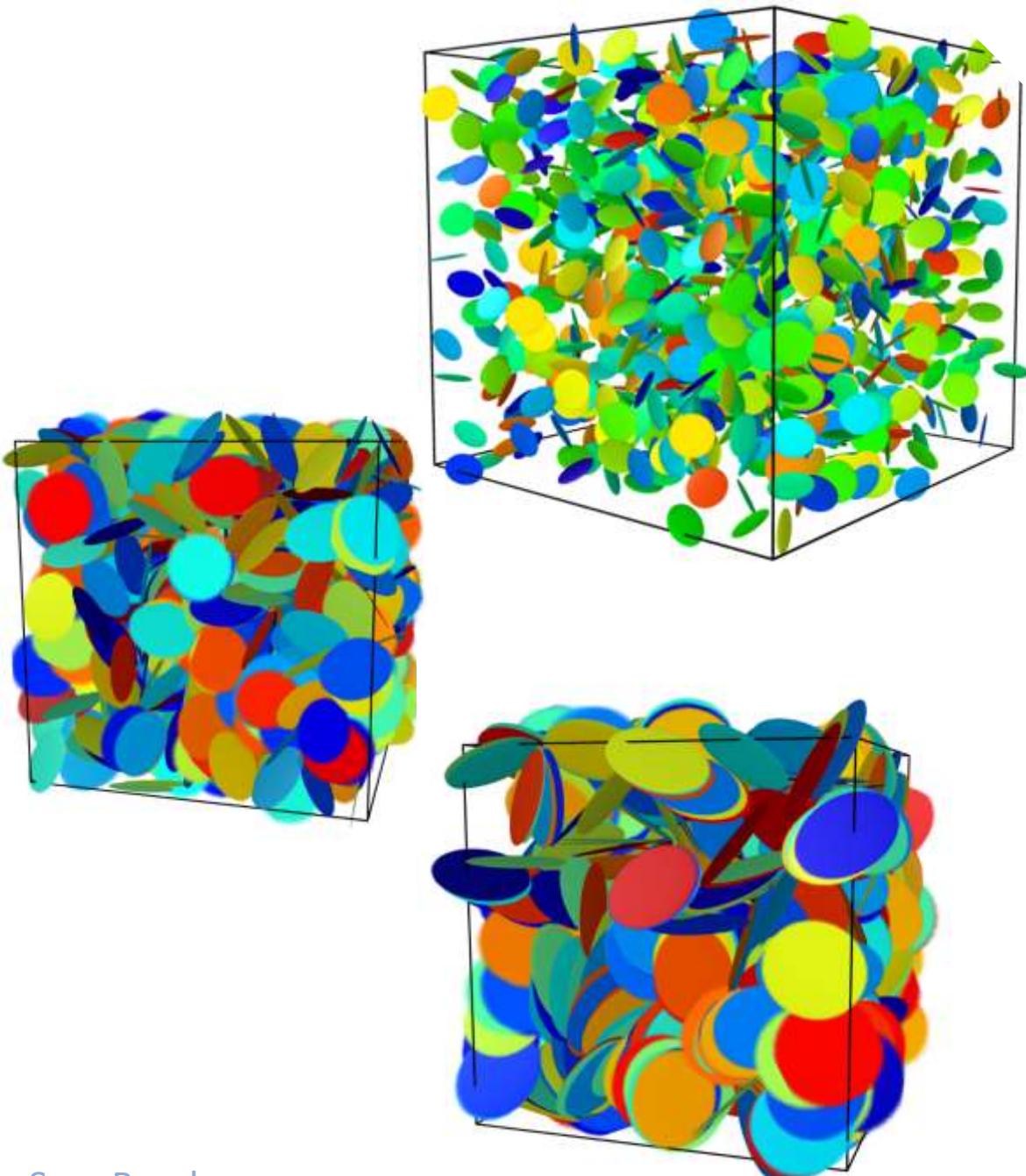


<https://www.minersoc.org/images-of-clay.html>

# Clay

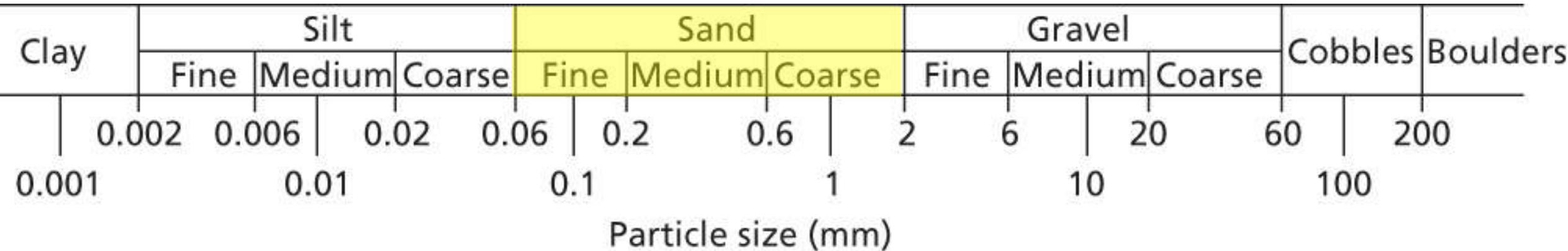


<https://www.minersoc.org/images-of-clay.html>



Sara Bandera

# Size matters in soil classification



- Sand grains exceed 60  $\mu\text{m}$  (0.06 mm)
- Ratio of surface area to volume is small
- Surface charges don't influence behaviour

# Sand



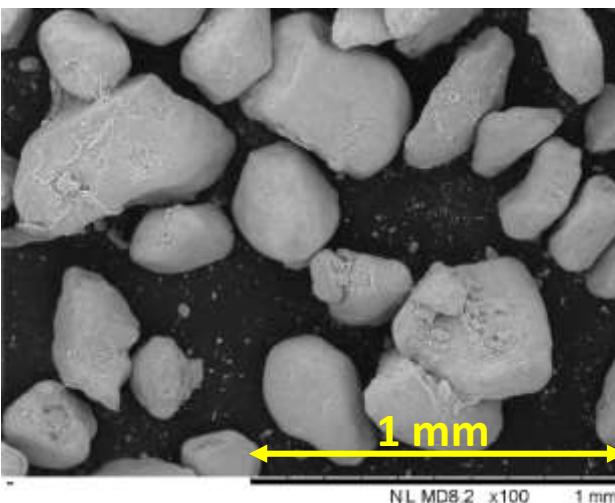
Badger Sand

Image by F. Altuhafi

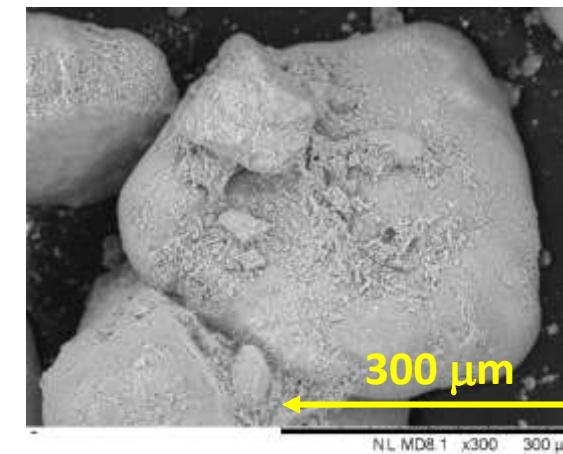


Leighton Buzzard Sand

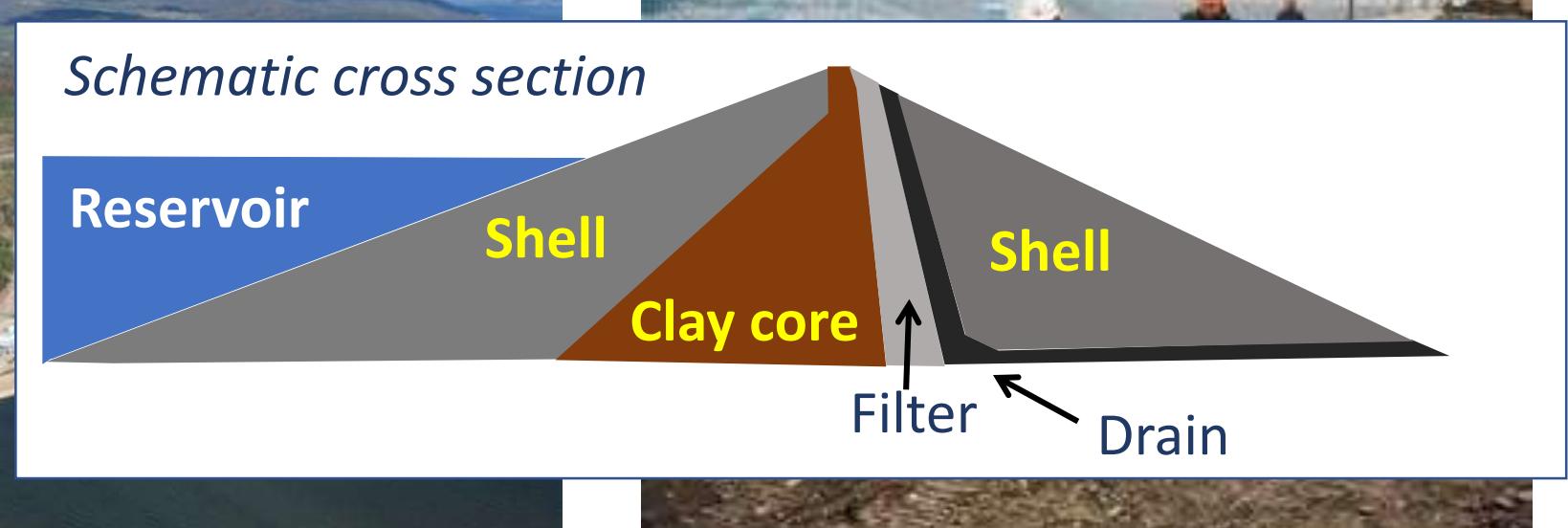
Image by I. Cavarretta



Dunkirk Sand



# Sand behaviour is important



## WAC Bennett Dam

- High as a 60-storey building and two kilometres wide
- Holds back 360 kilometres of Williston Lake, the largest reservoir in North America

1996 Sinkhole at WAC Bennett Dam  
(BC Hydro as cited by Muir Wood, 2007)

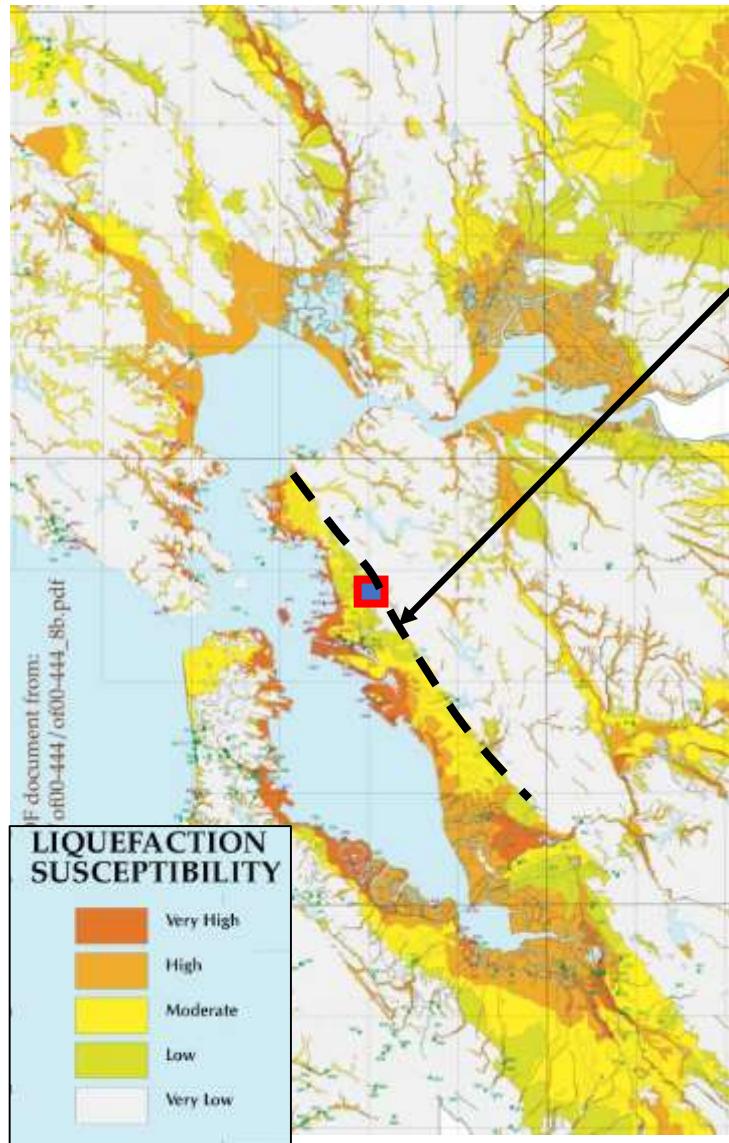
# Sand behaviour is important

Minas Gerais – January 2019

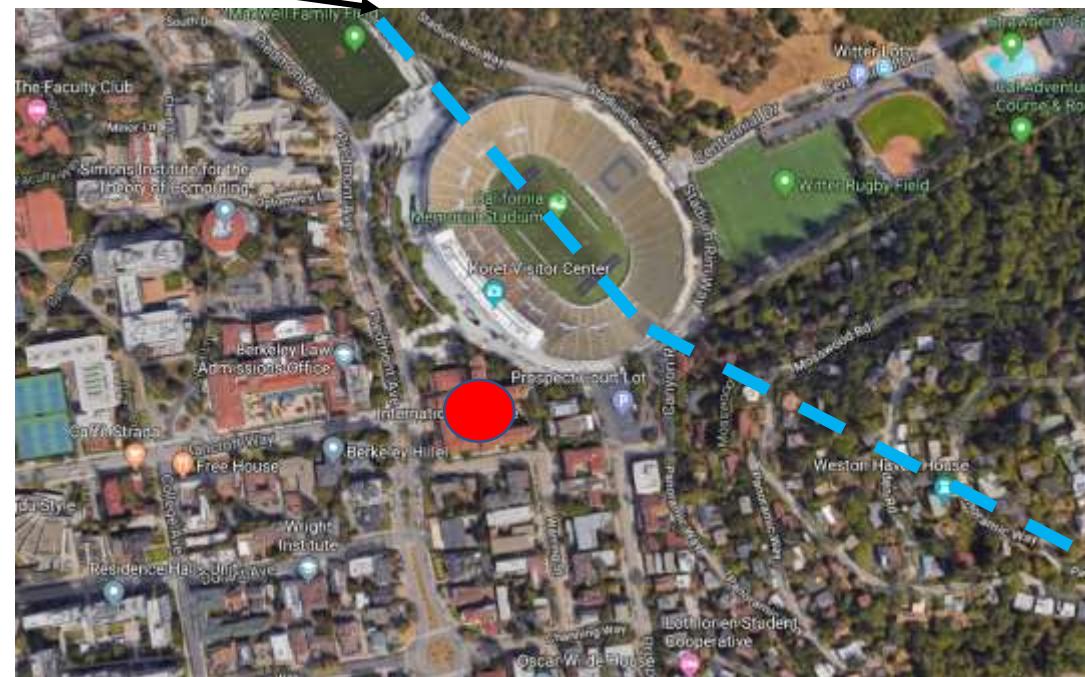
157 fatalities, 182 people unaccounted for



# Sand behaviour is important



Approx. location of the  
Hayward Fault



# Sand behaviour is important



Liquefaction in Maria District, San Francisco  
1989 Loma Prieta Earthquake



Earthquake-induced  
liquefaction at Onahama  
Port, Japan, 2011



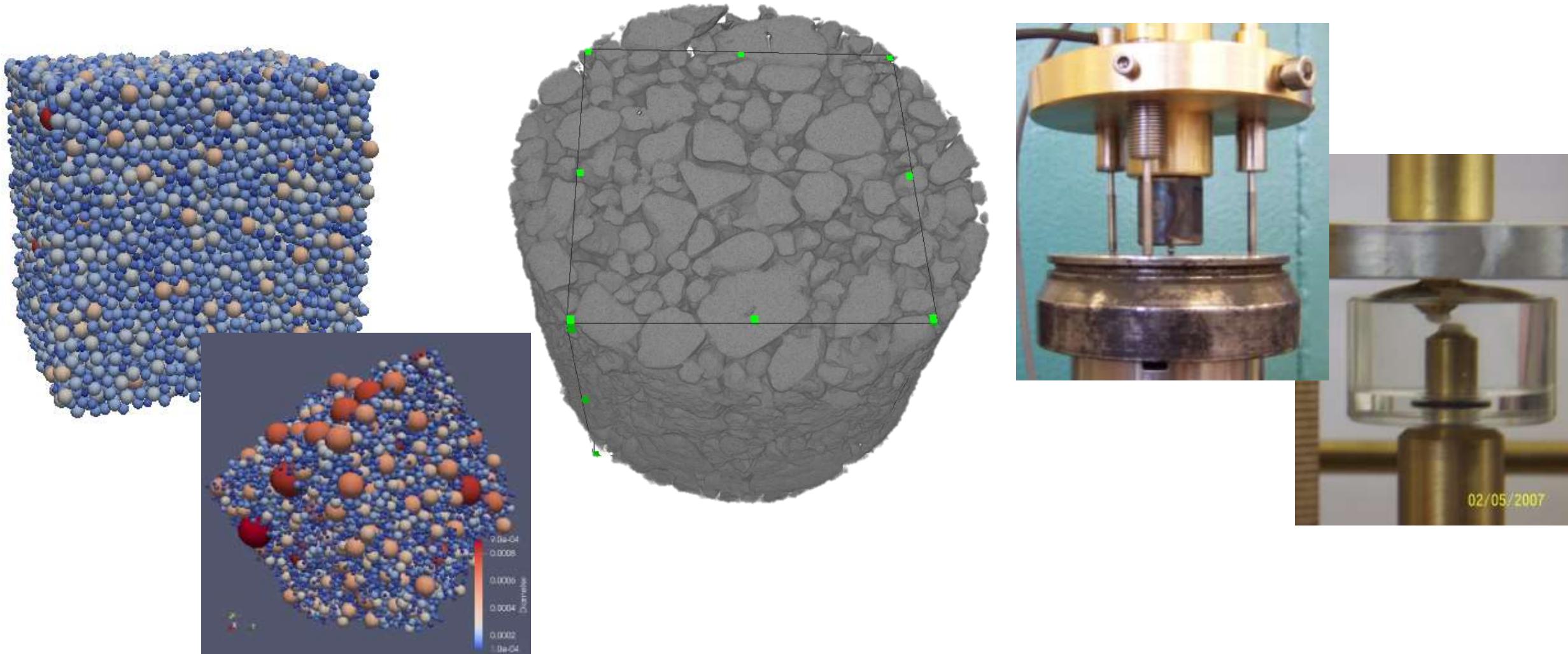
Shortland Street in the  
suburb of Aranui, New  
Zealand, 2011

# Fundamental research into sand behaviour



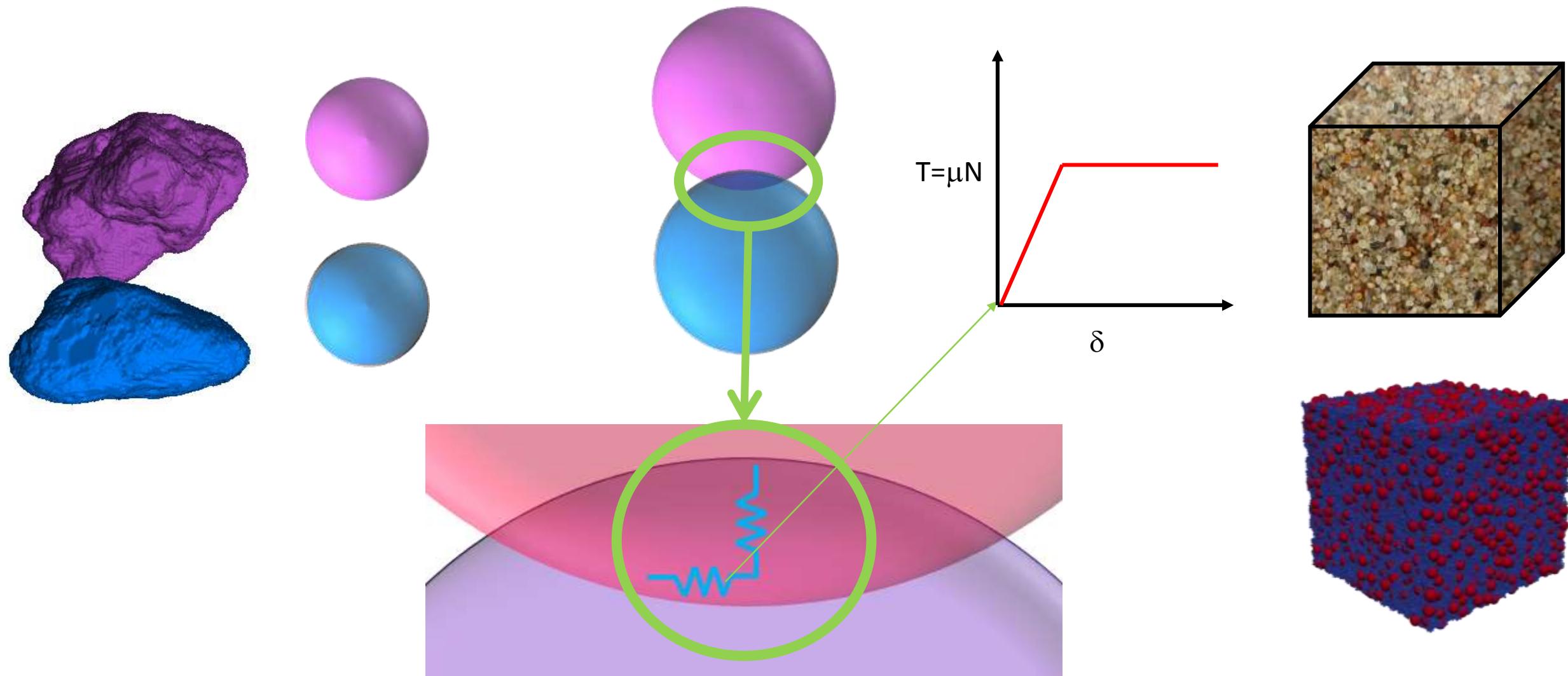
Laboratory element tests → How sand behaves

# Fundamental research into sand behaviour



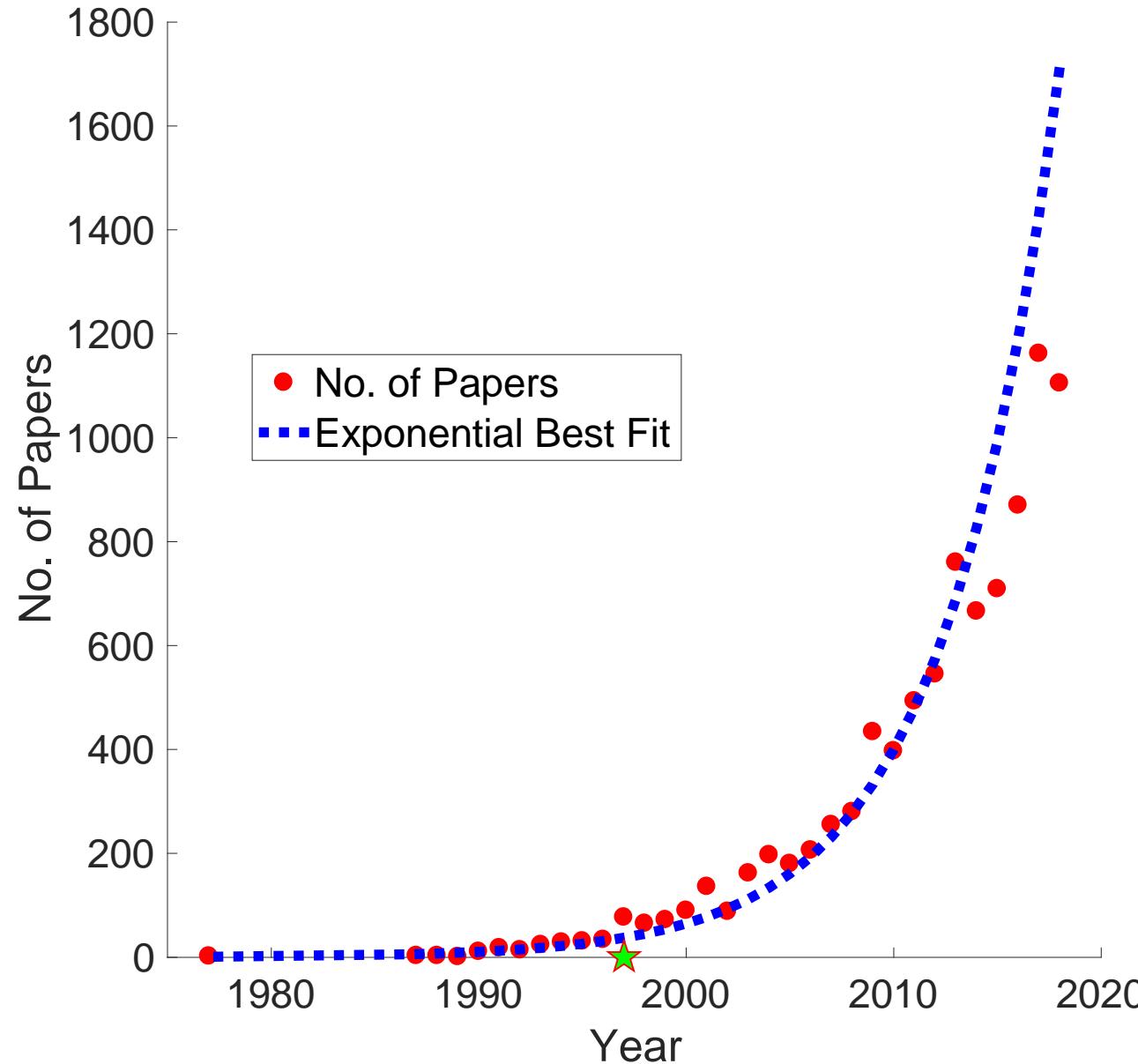
Particle scale simulation and observation → Why sand behaves the way it does

# Discrete Element Method (DEM)

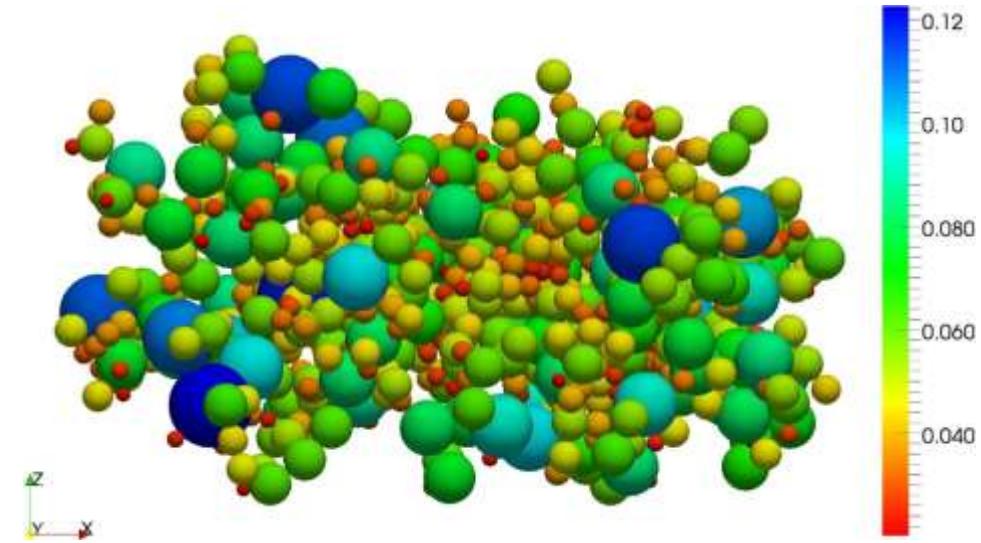
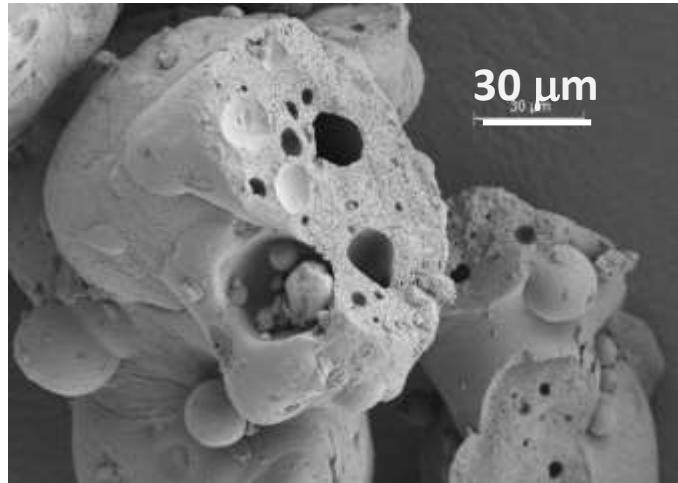
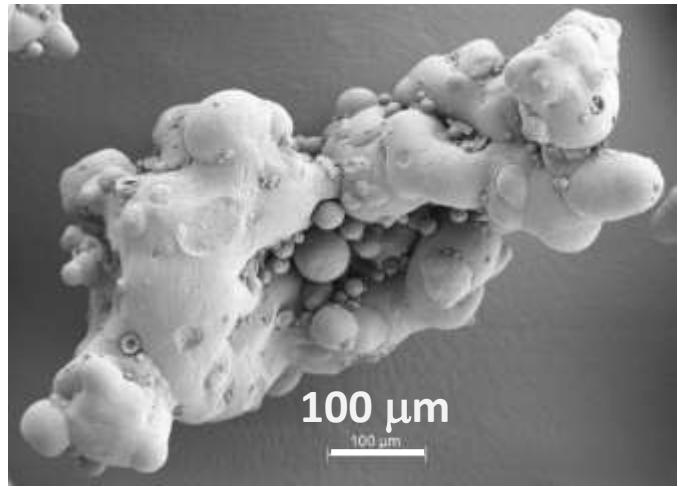


# DEM uptake

All disciplines

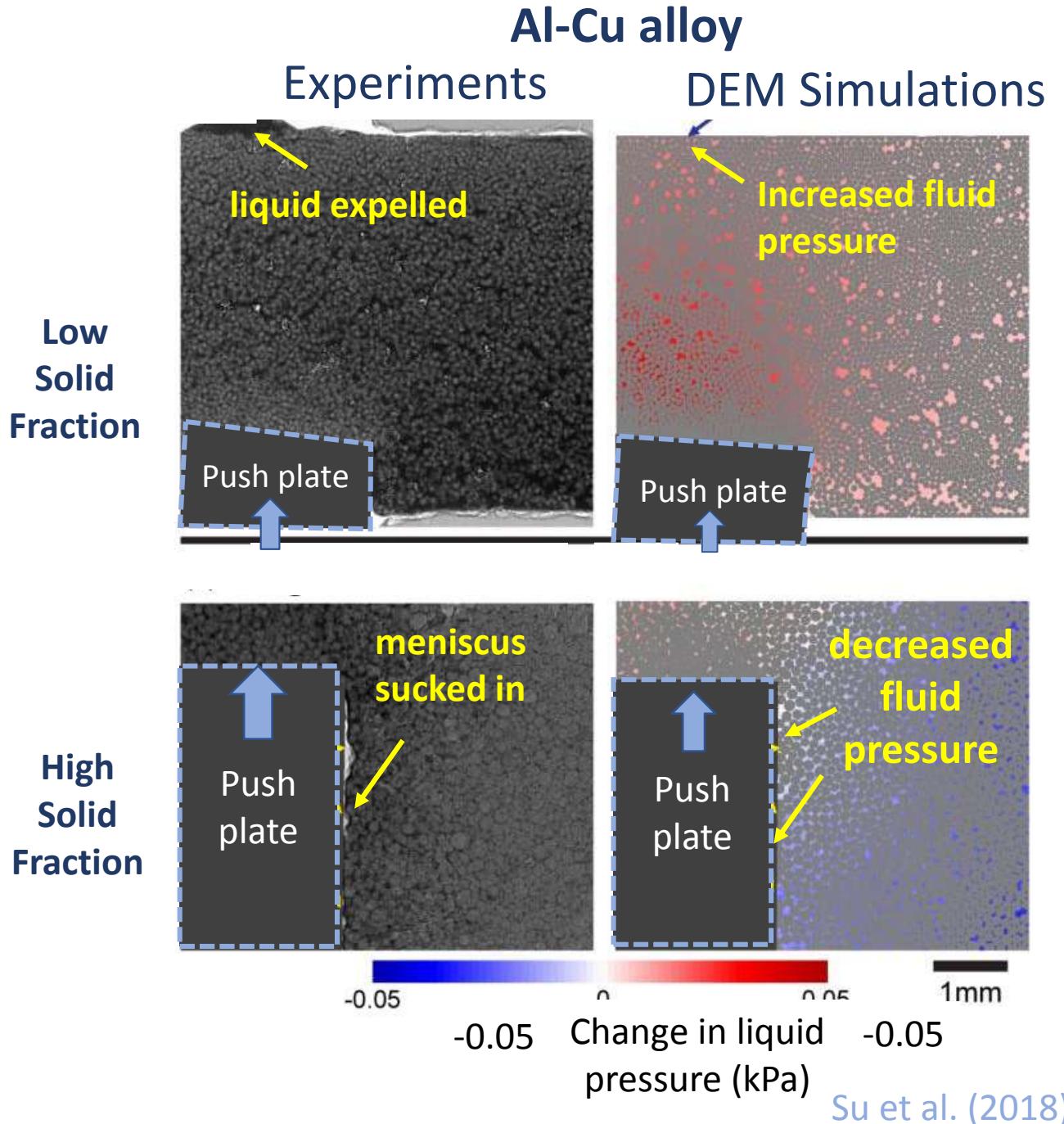


# Application of DEM



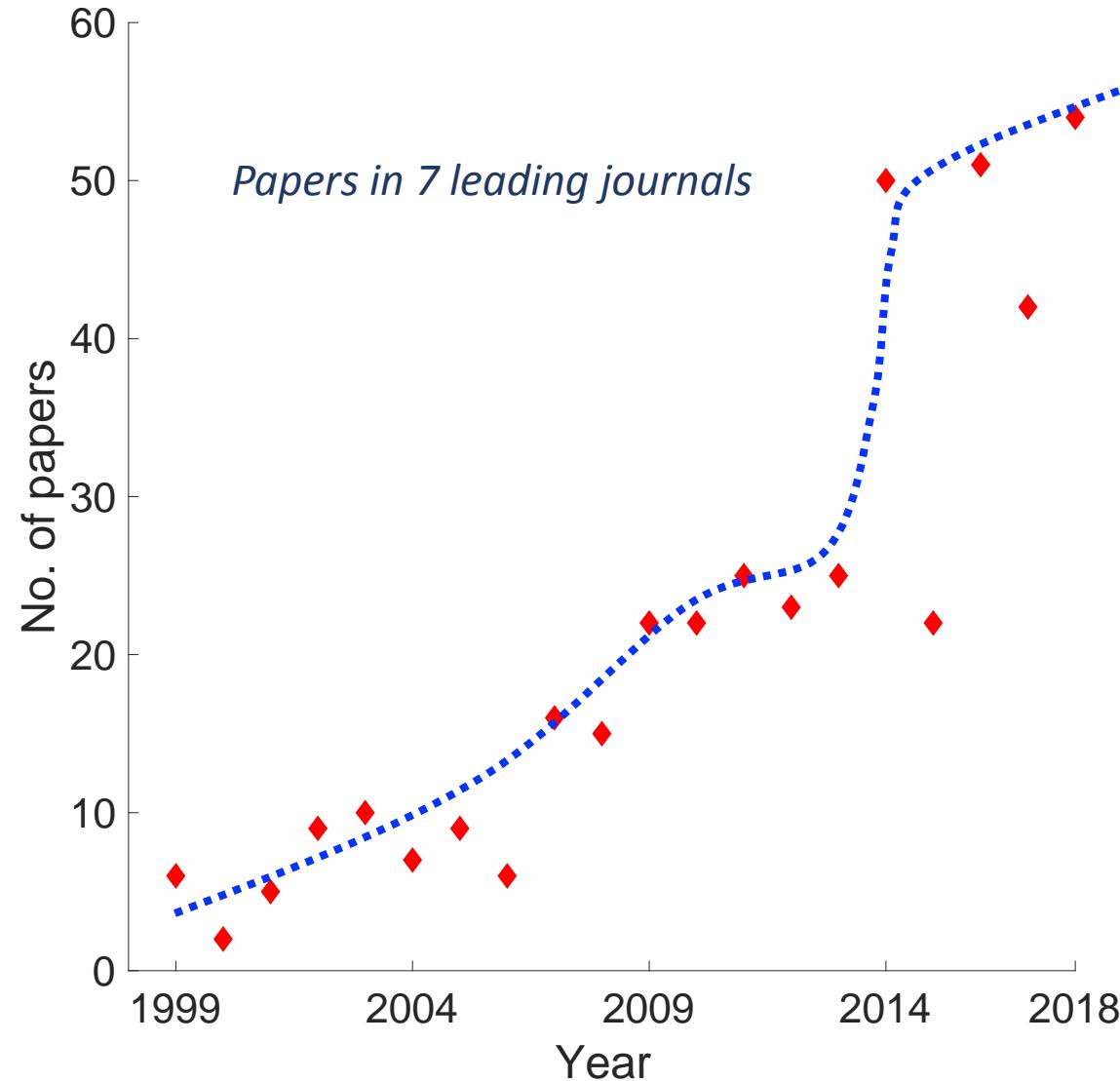
Hanley (2011)

# Application of DEM

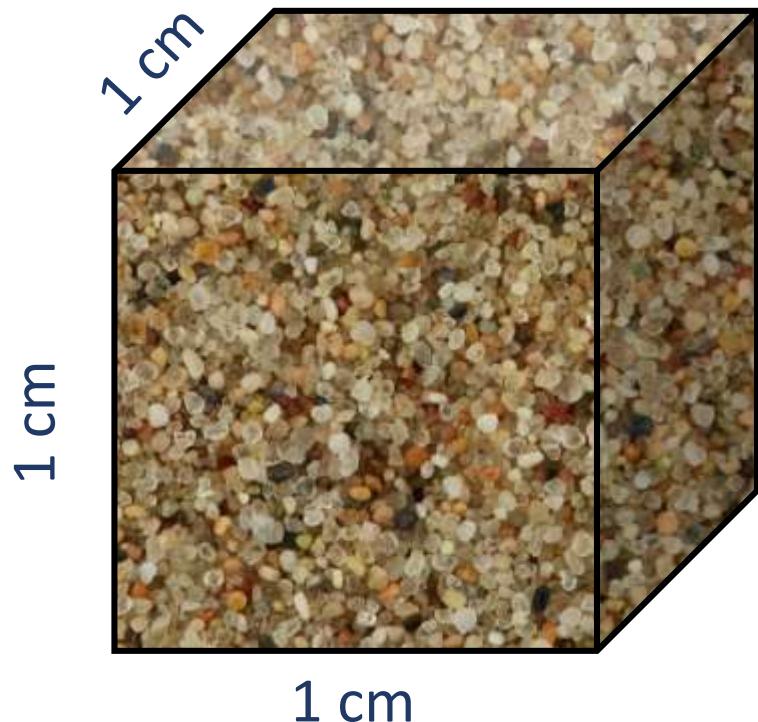


# DEM uptake

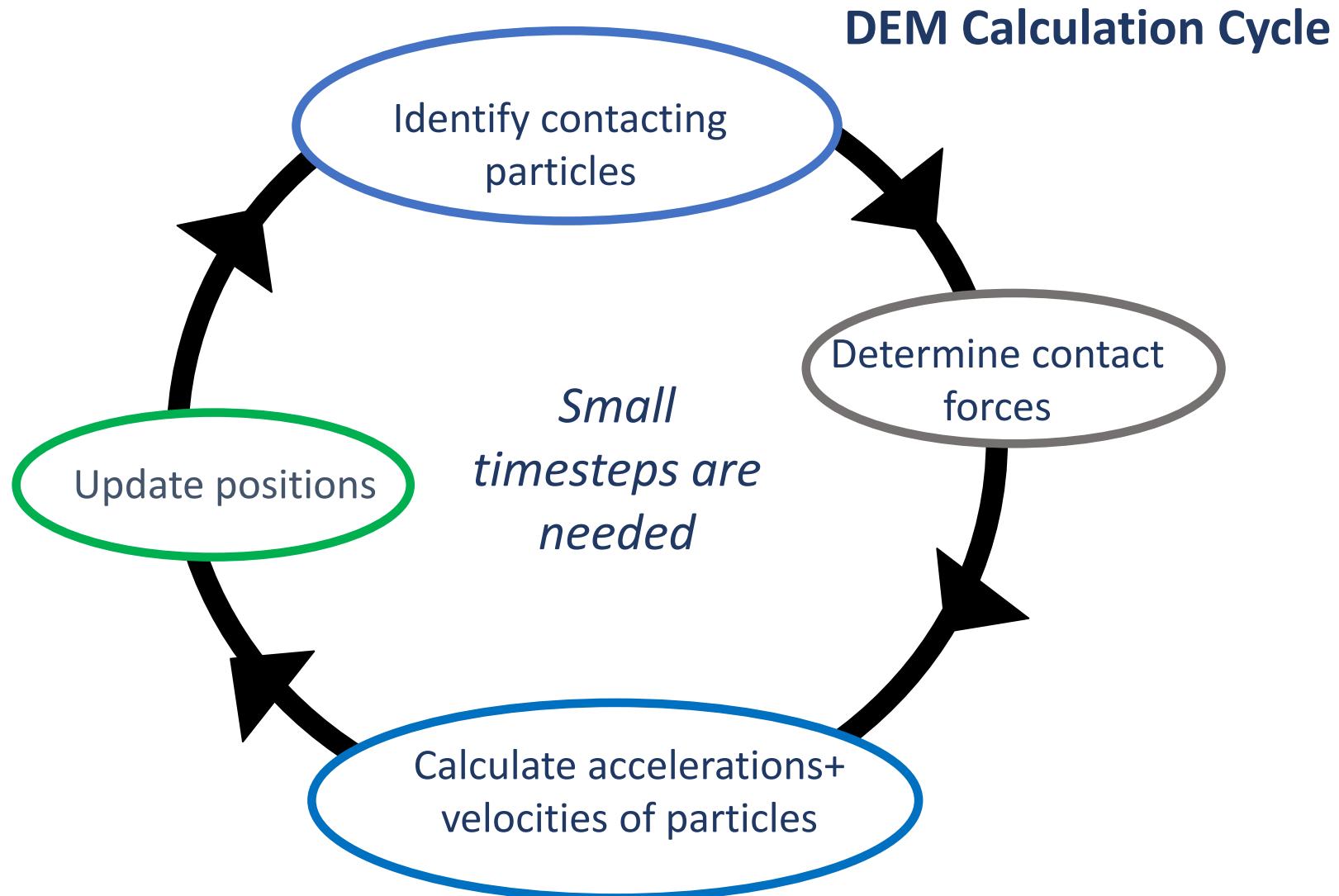
## Geomechanics



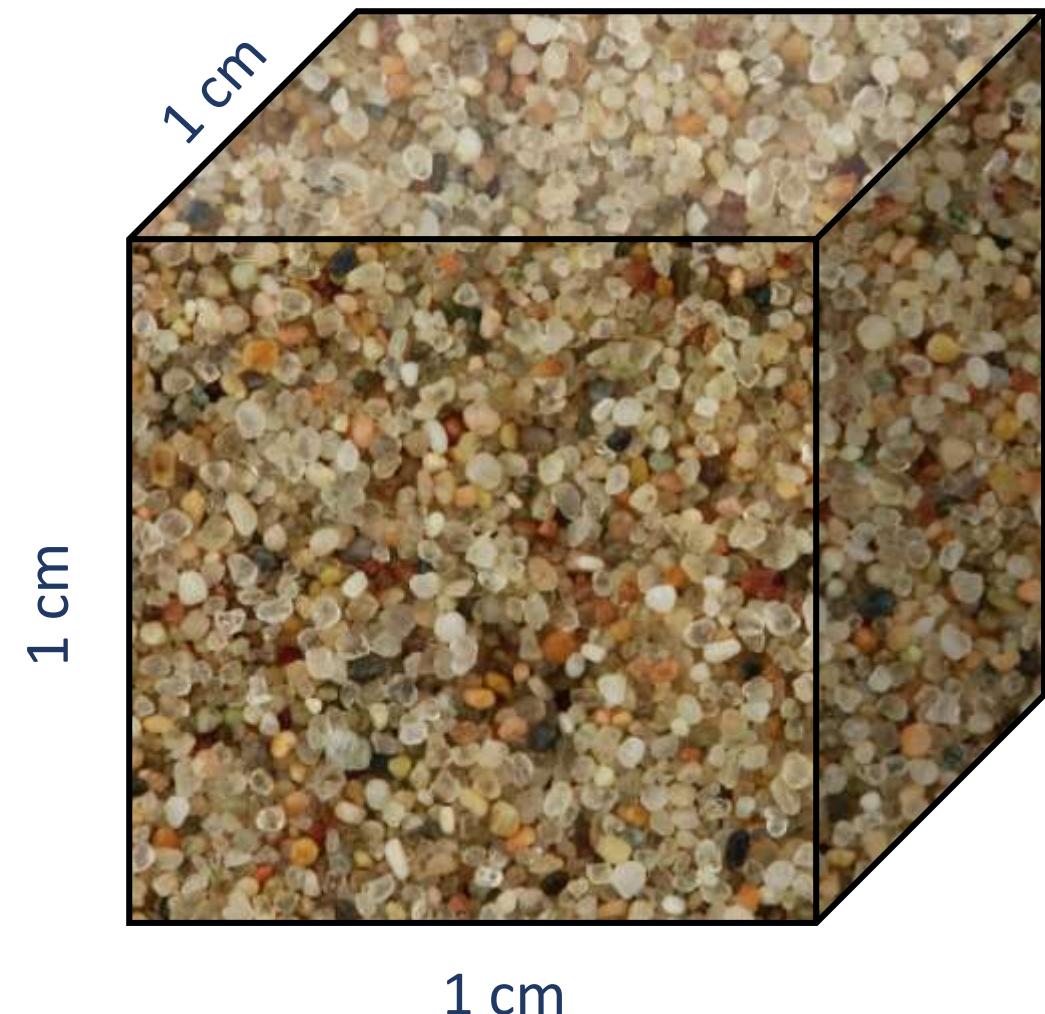
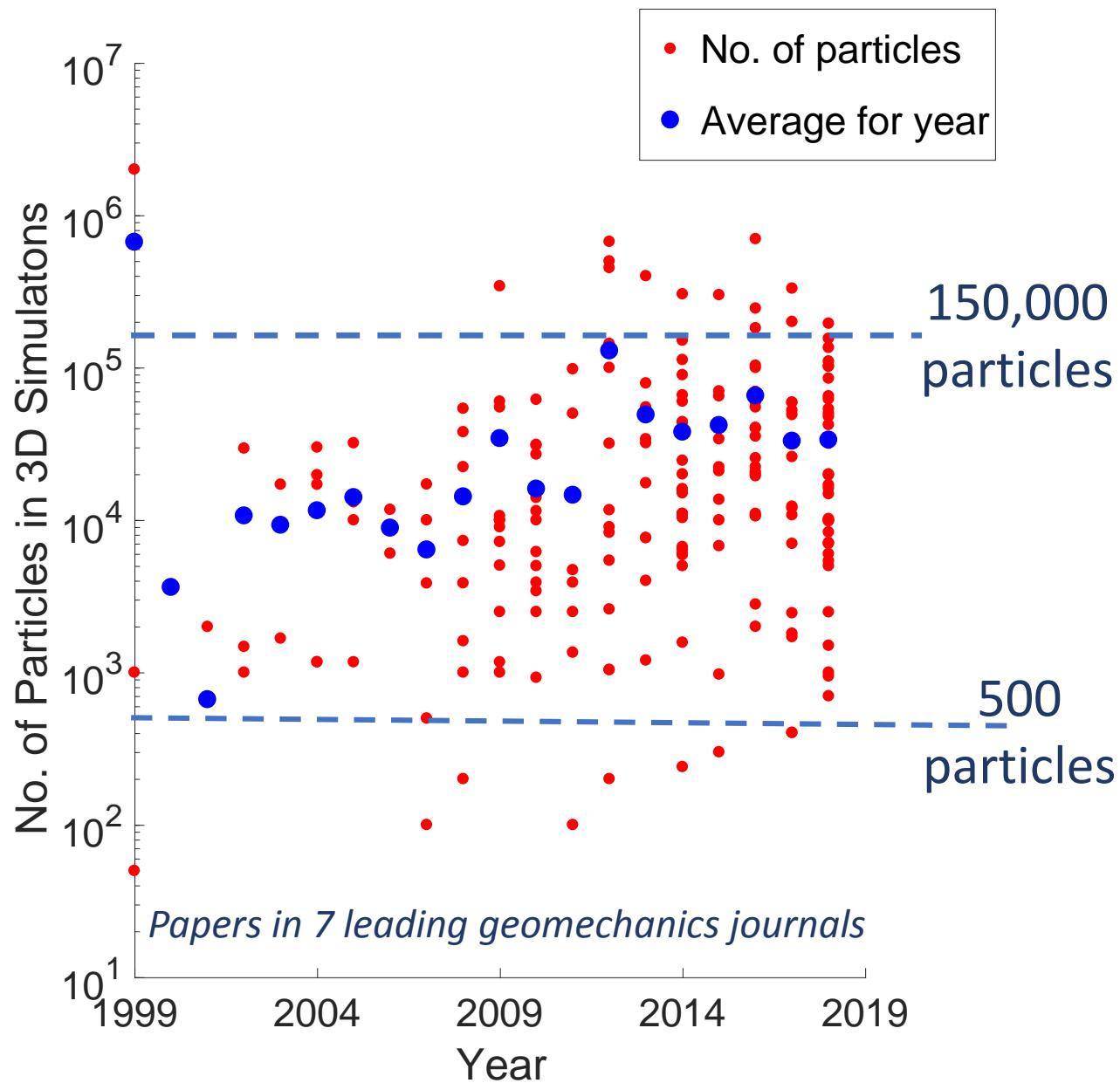
# How many particles in our models?



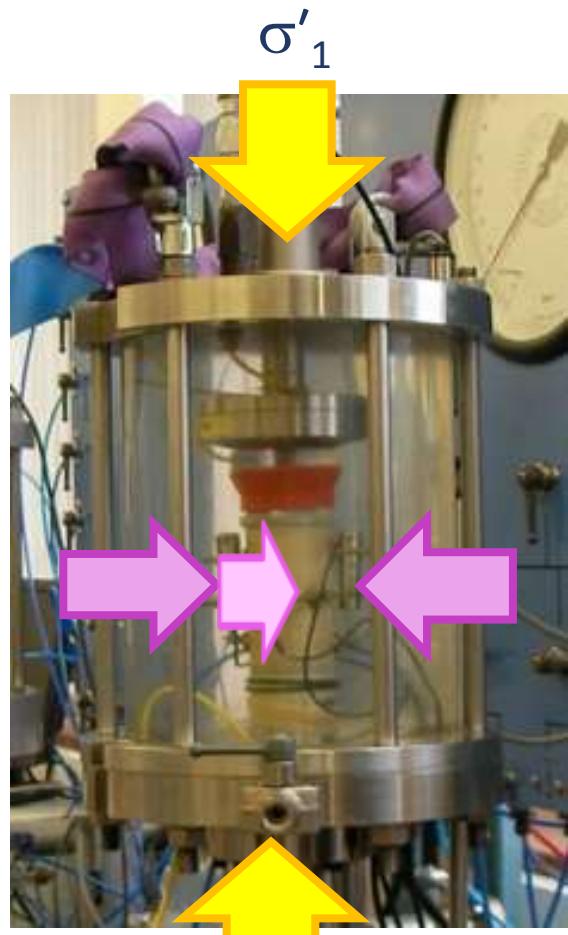
Sand with median particle  
diameter = 0.200 mm:  
>150,000 particles



# How many particles in our models?

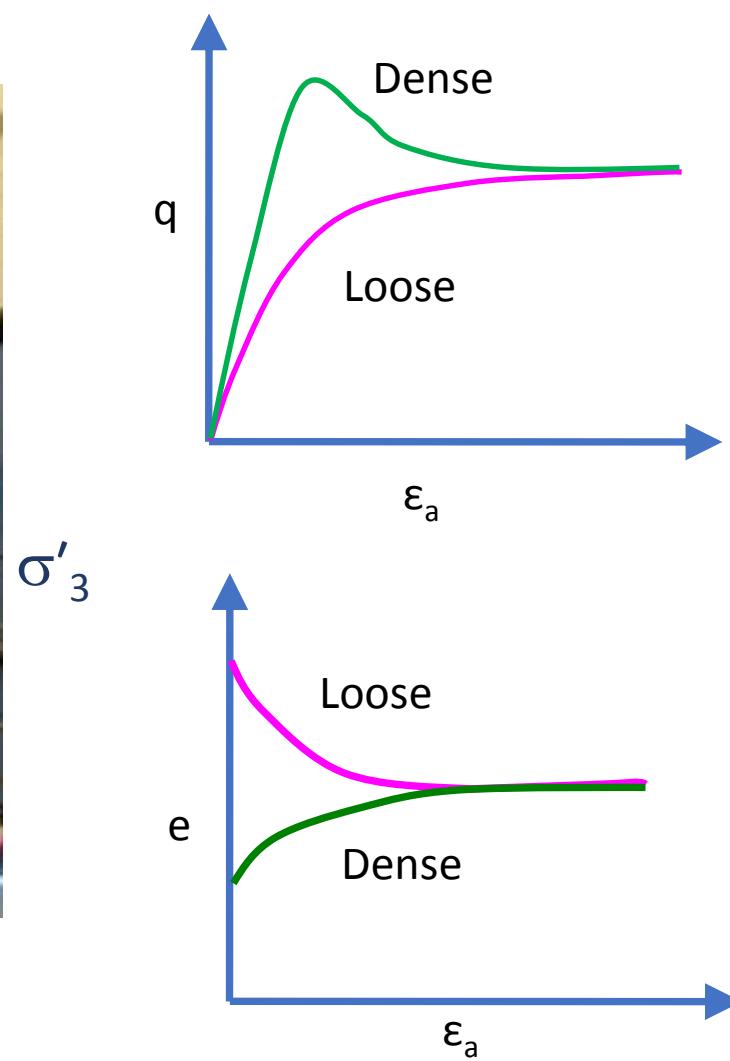


# Density-dependent behaviour



$\sigma'_3$

Triaxial test



$$q = \sigma'_1 - \sigma'_3$$

$q$  = deviatoric stress:

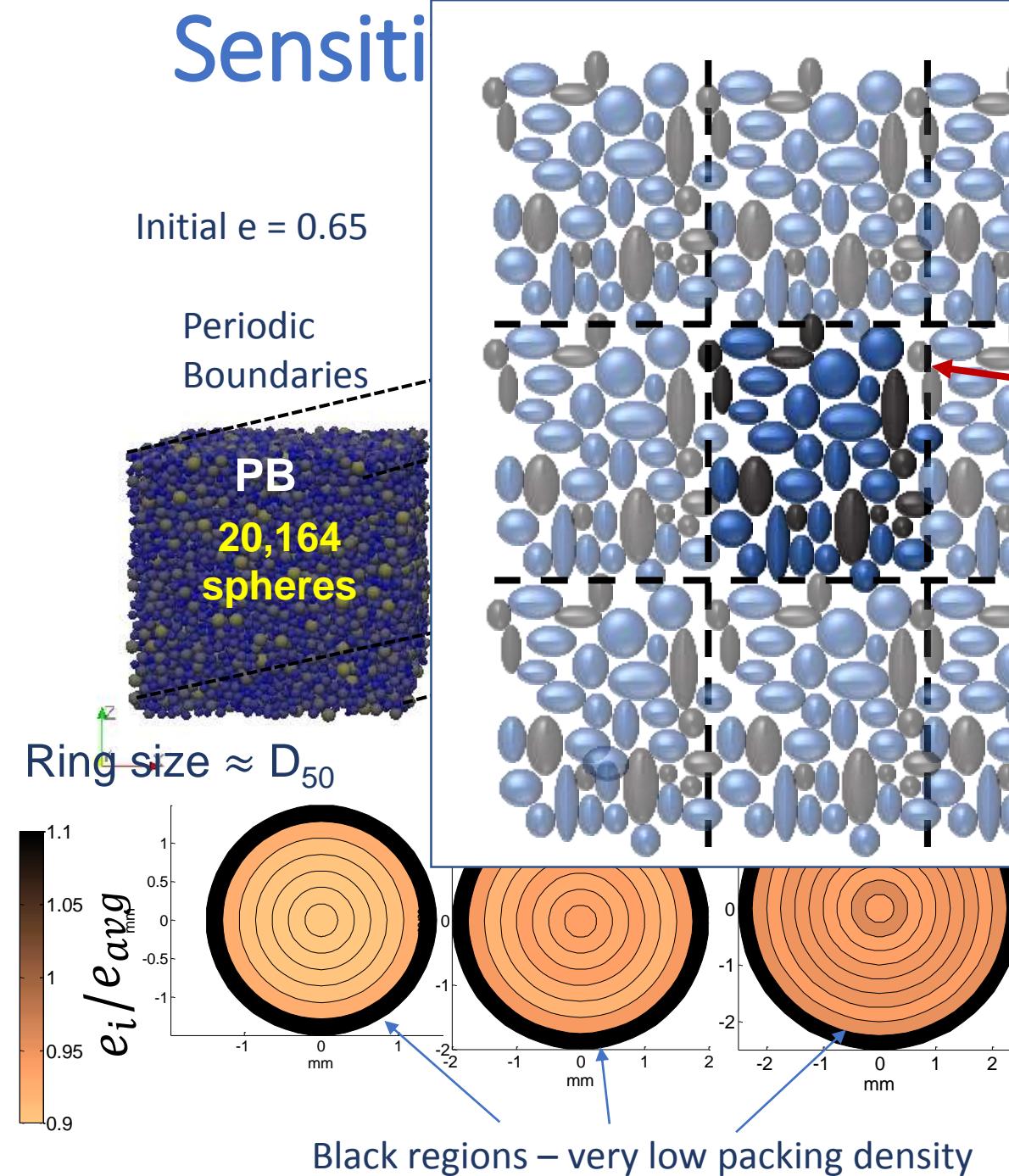
$$\varepsilon_a = \text{axial strain } (\Delta L/L)$$

$$e = \text{void ratio : measure of packing density}$$

Loose sands at risk  
of liquefaction



# Sensitivity



Periodic Boundaries

Cell Simulated

axial strain ( $\Delta L/L$ )

Volume

size

$\varepsilon_a$  = axial strain ( $\Delta L/L$ )

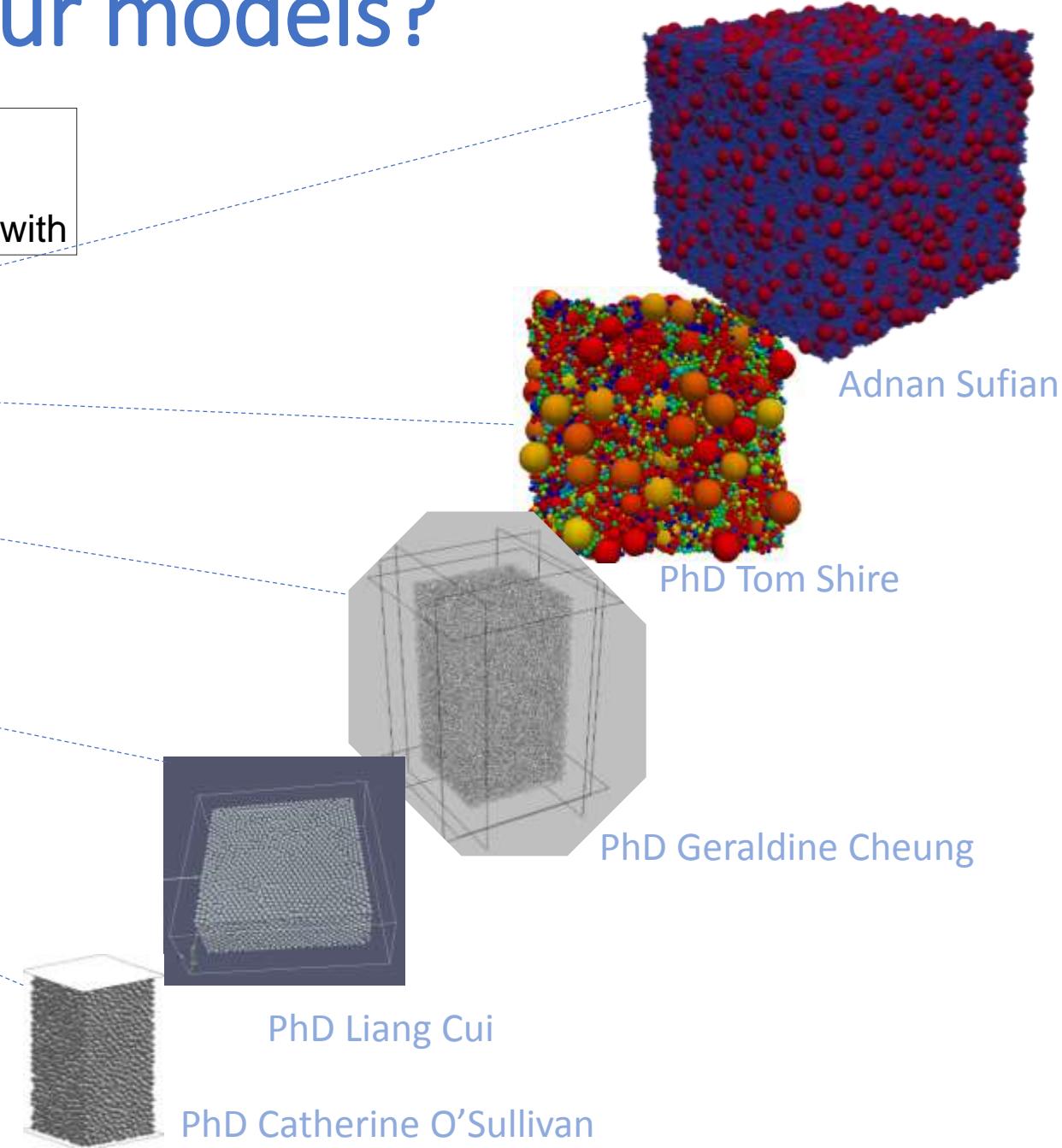
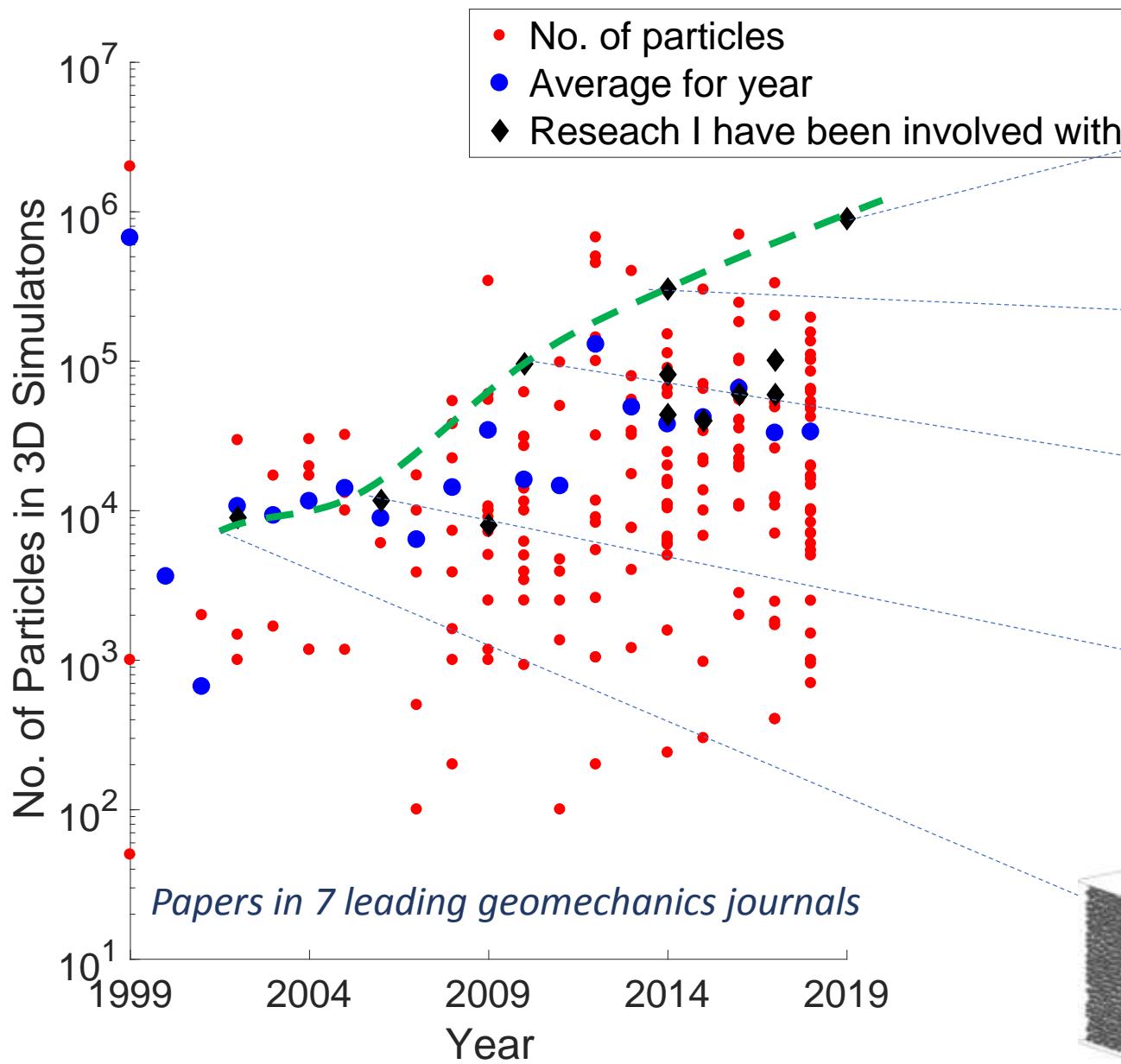
RW-S  
RW-M  
RW-L  
PB

contraction

dilation

RW-S  
RW-M  
RW-L  
PB

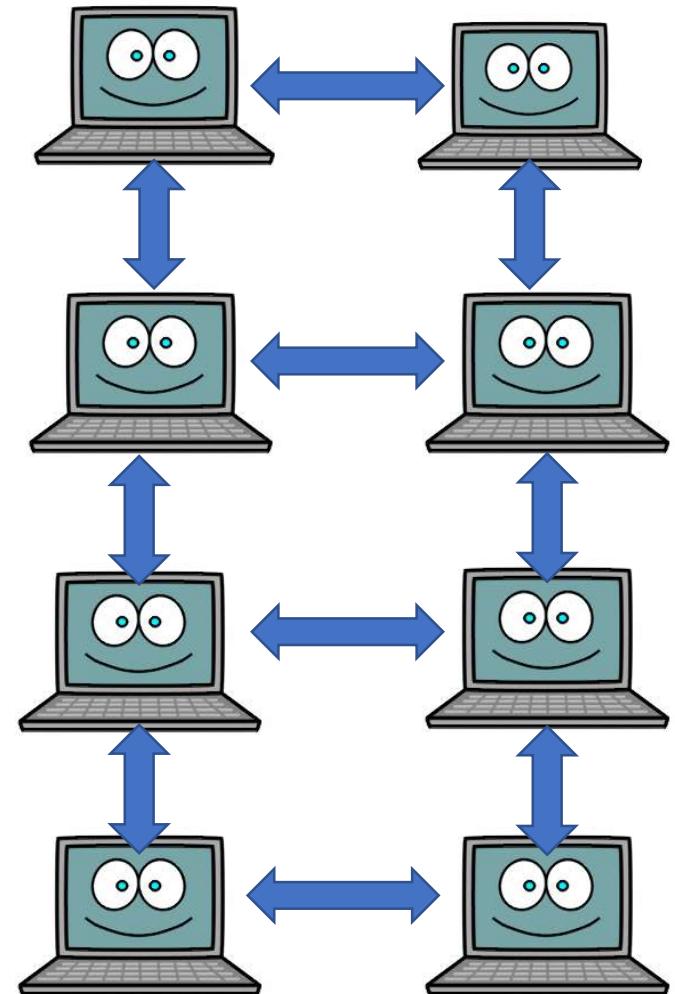
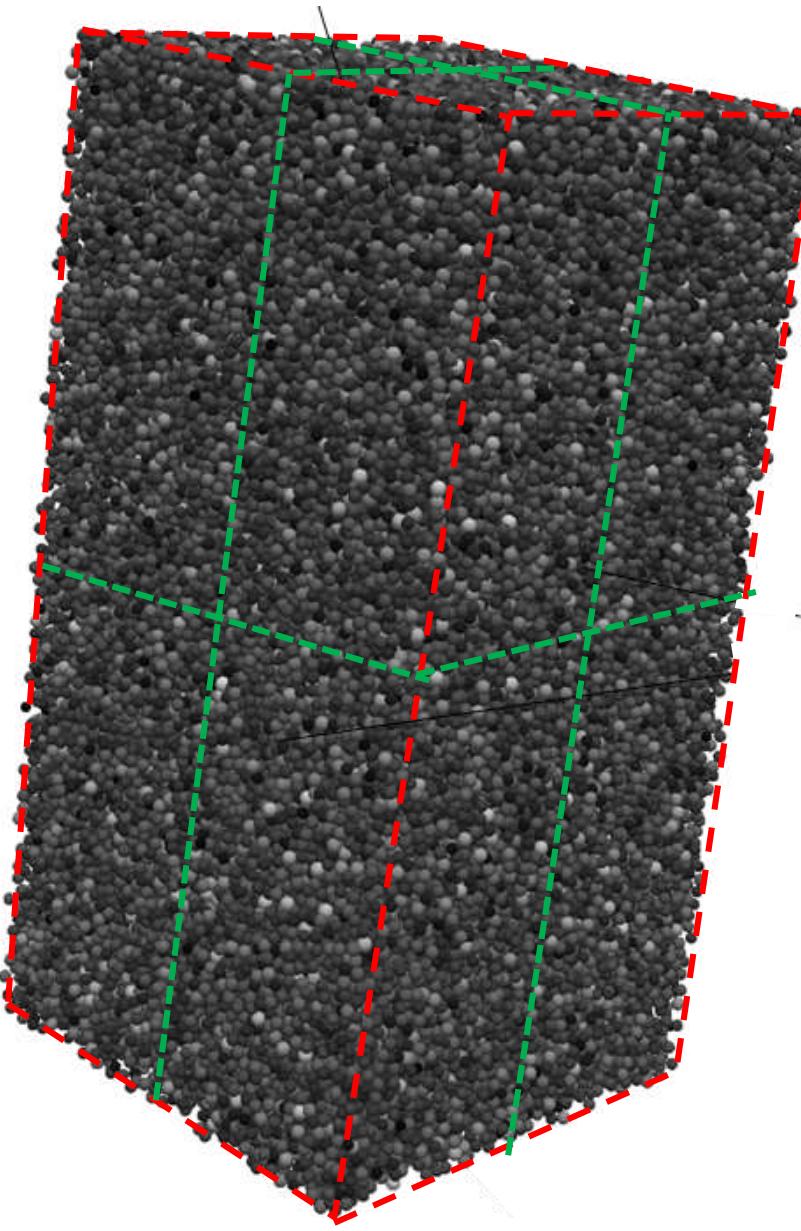
# How many particles in our models?



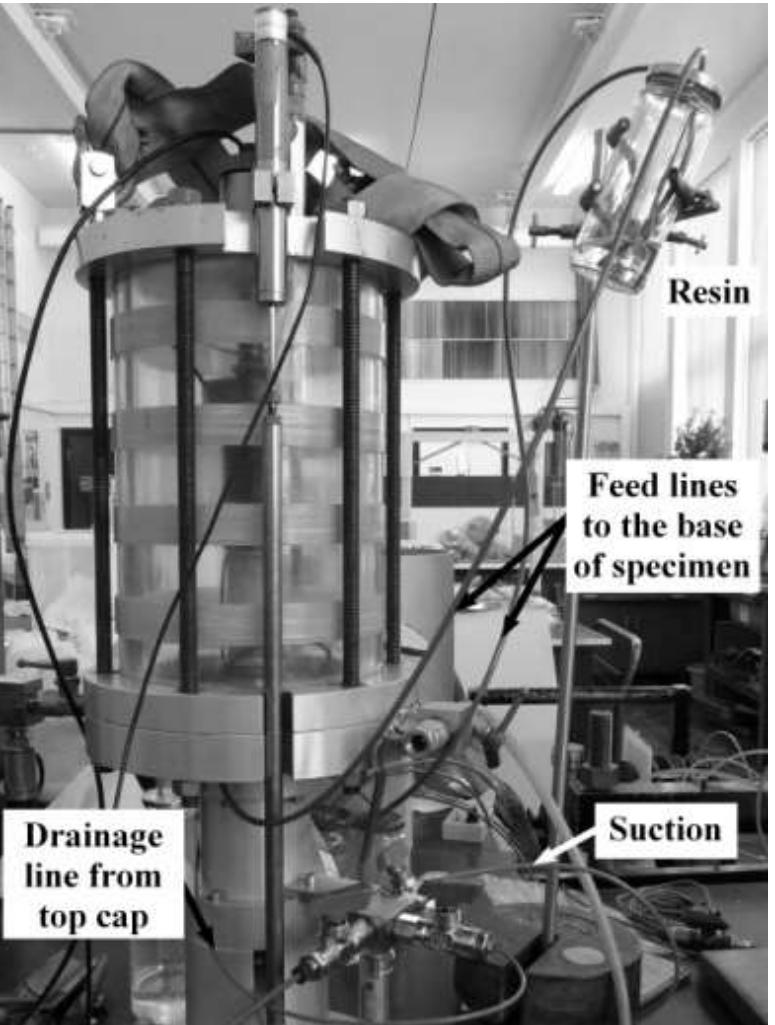
# High performance computers



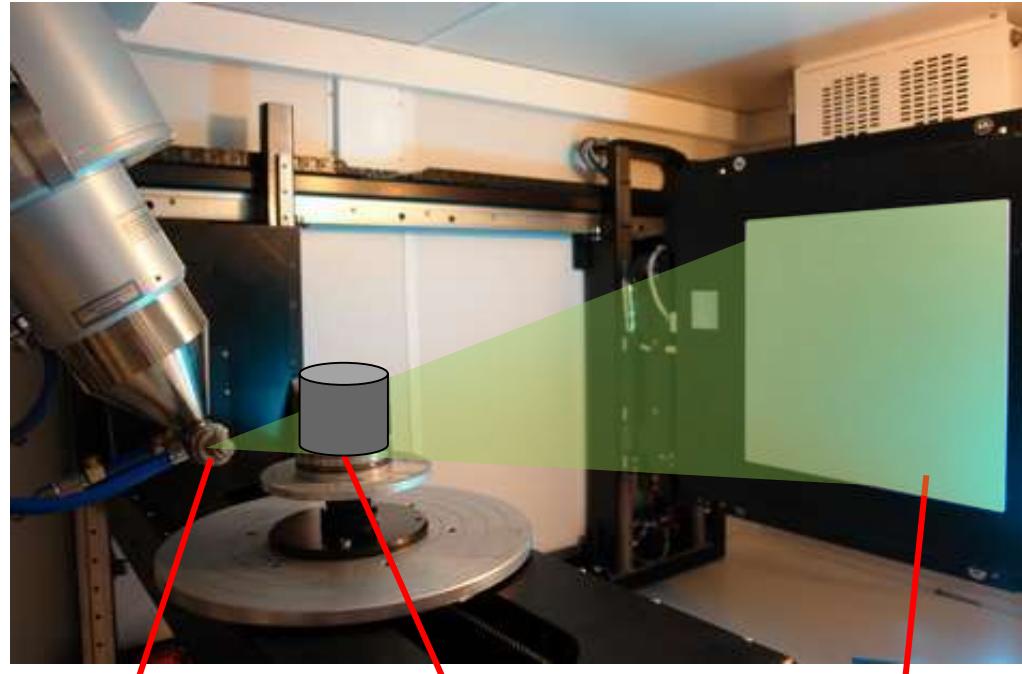
HPC Computer Room



# Microcomputed Tomography



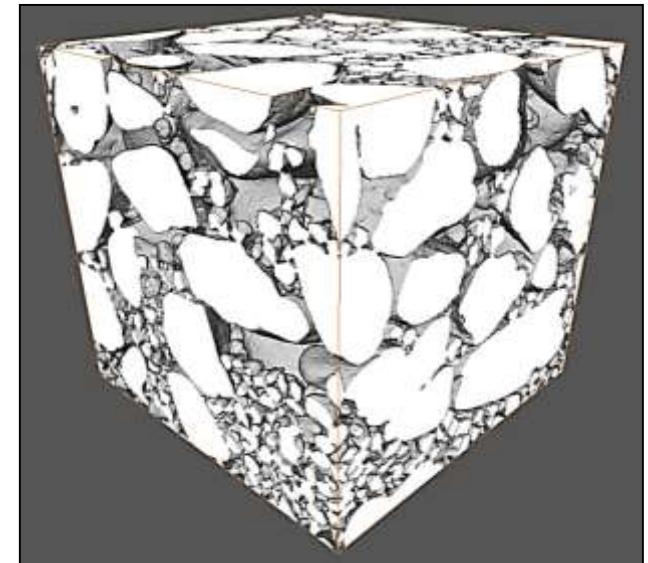
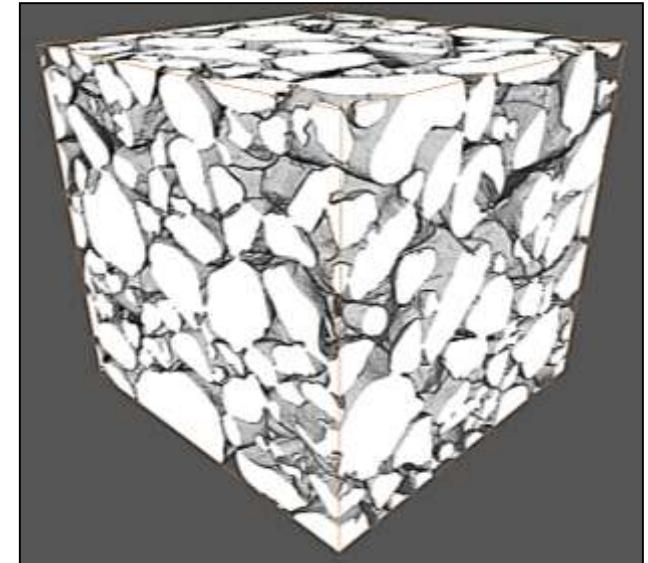
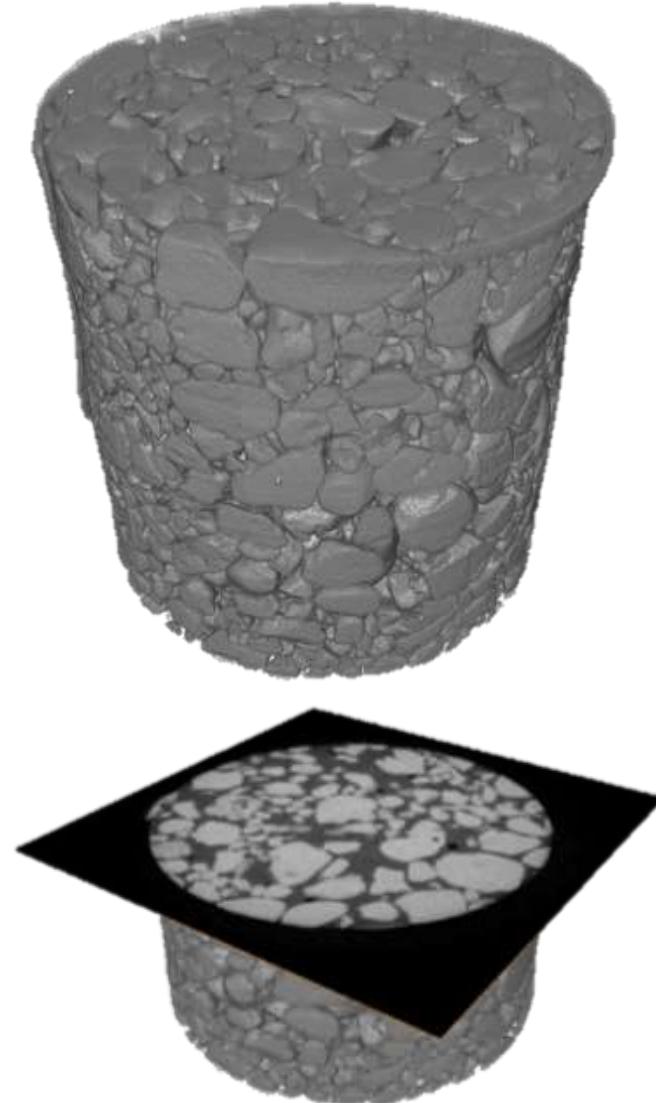
# Microcomputed Tomography



X-ray  
source

Sample

Detector



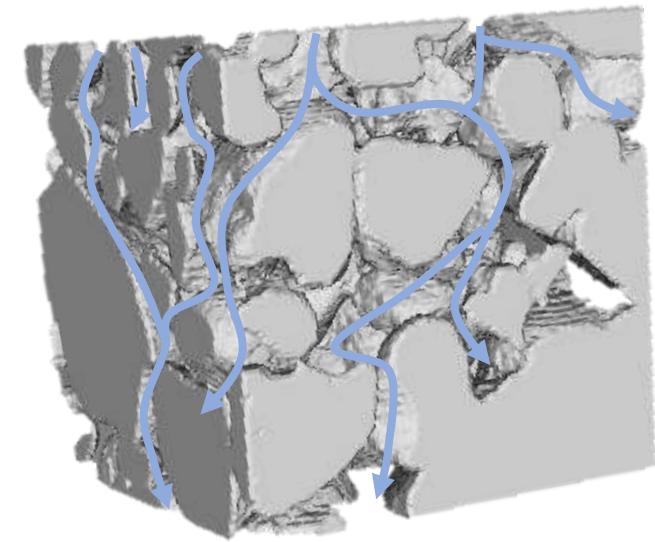
# Sand behaviour



**Stiffness**

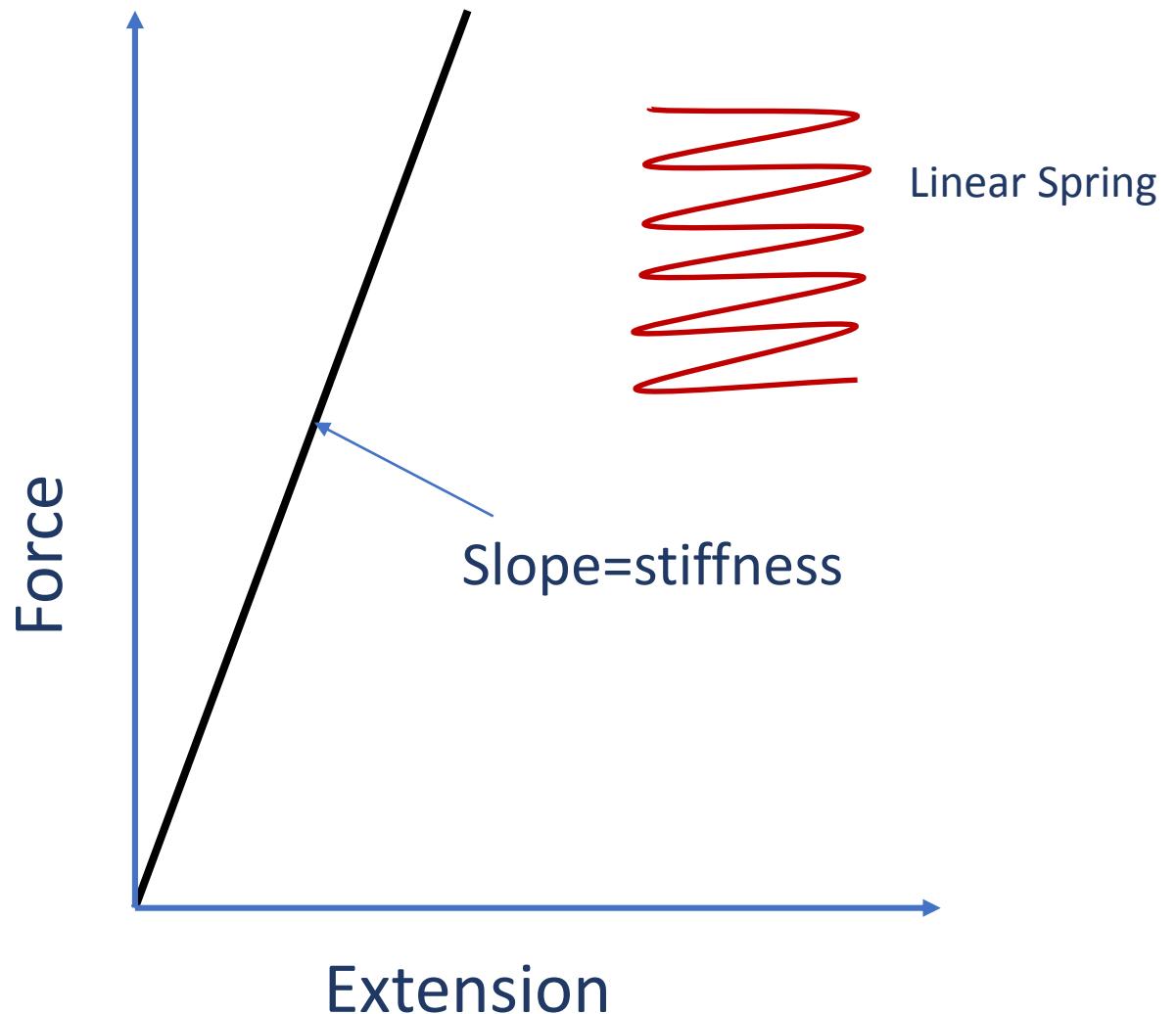
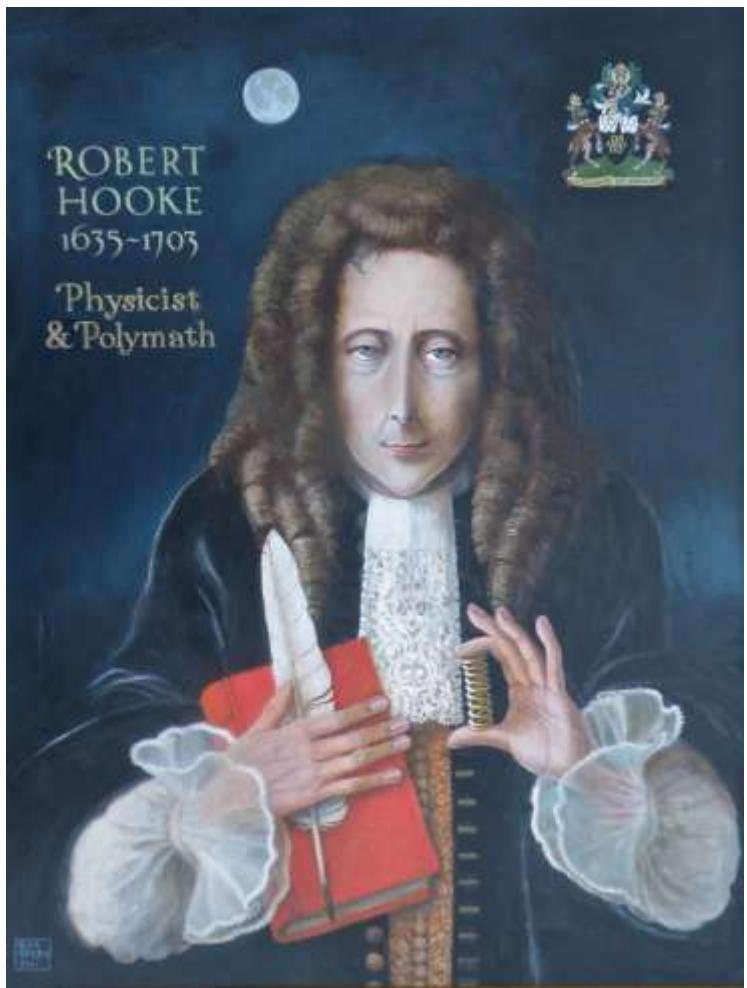


**Strength**



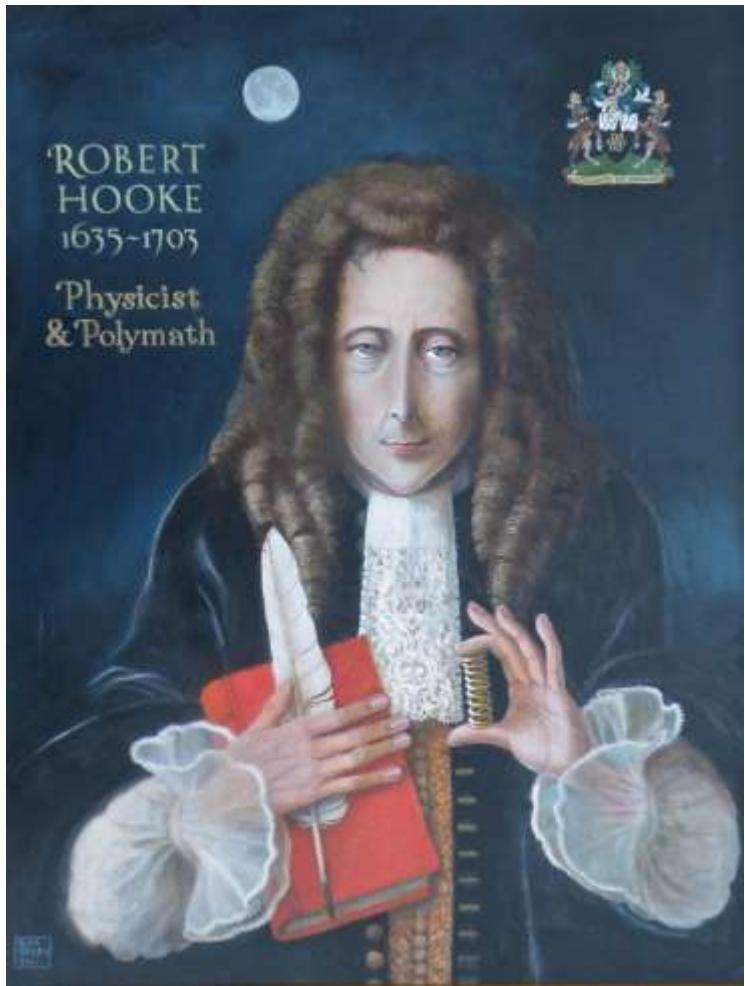
**Seepage**

# Stiffness



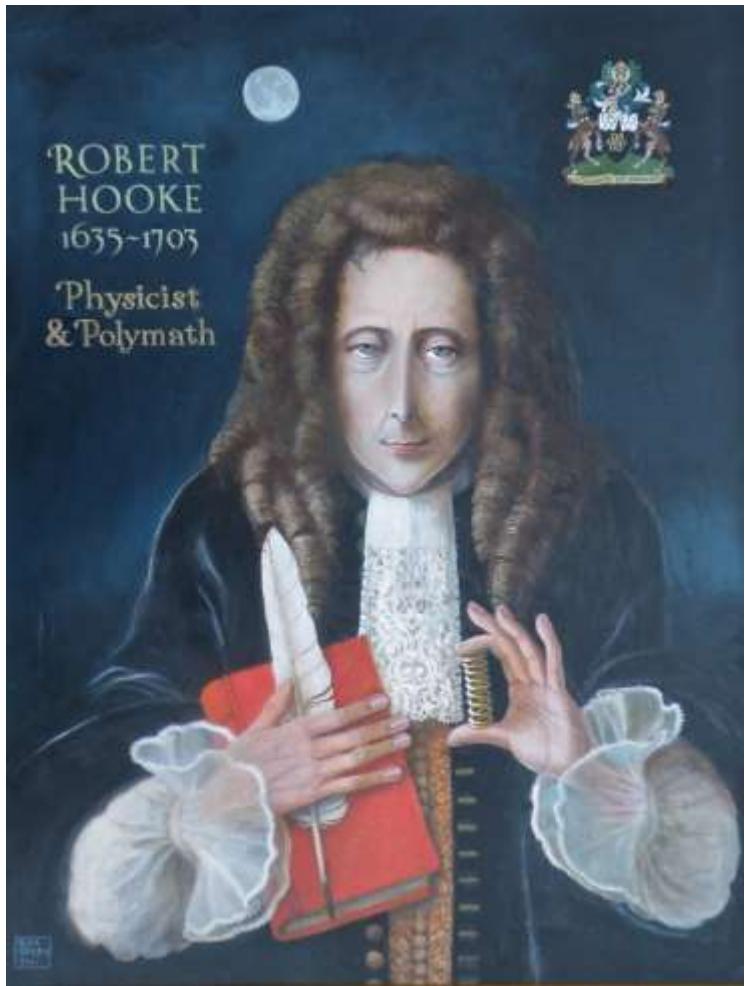
Memorial portrait of Robert Hooke, presented to the Institute of Physics, London by Rita Greer, history painter, 2011

# Stiffness



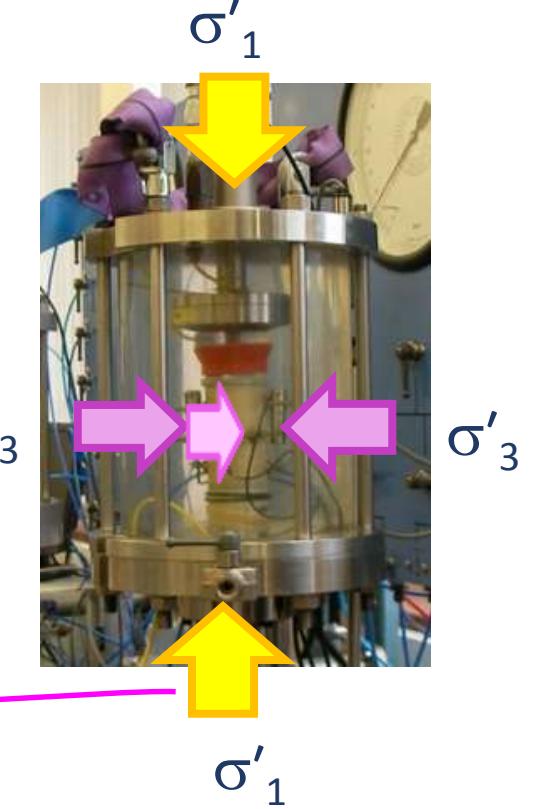
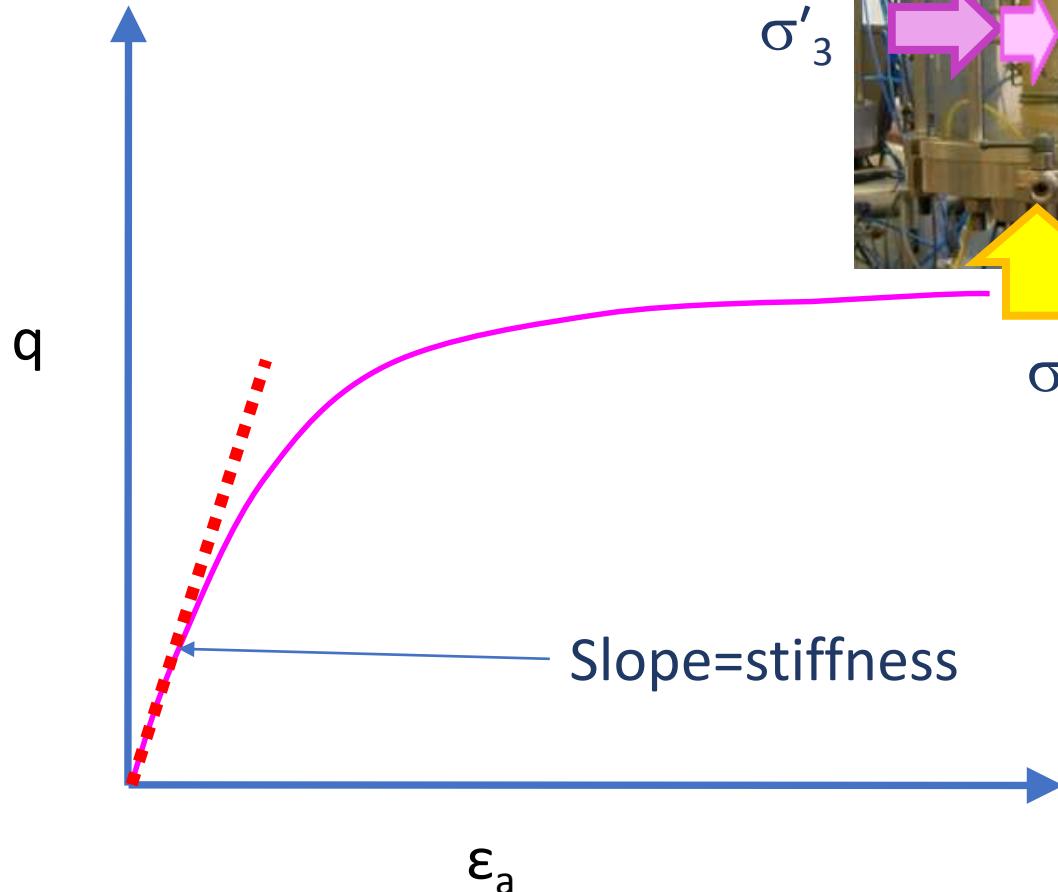
Memorial portrait of Robert Hooke, presented to the Institute of Physics, London by Rita Greer, history painter, 2011

# Stiffness



$$q = \sigma'_1 - \sigma'_3$$

$$\varepsilon_a = \text{axial strain } (\Delta L/L)$$

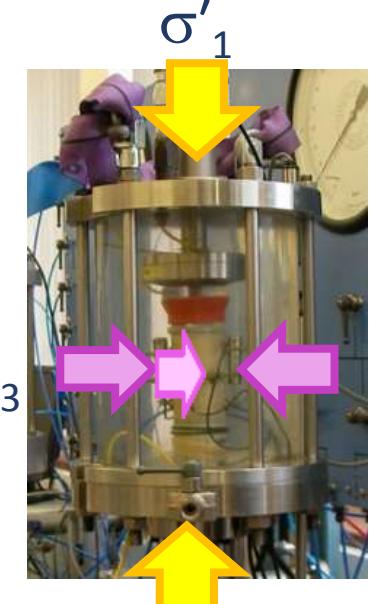
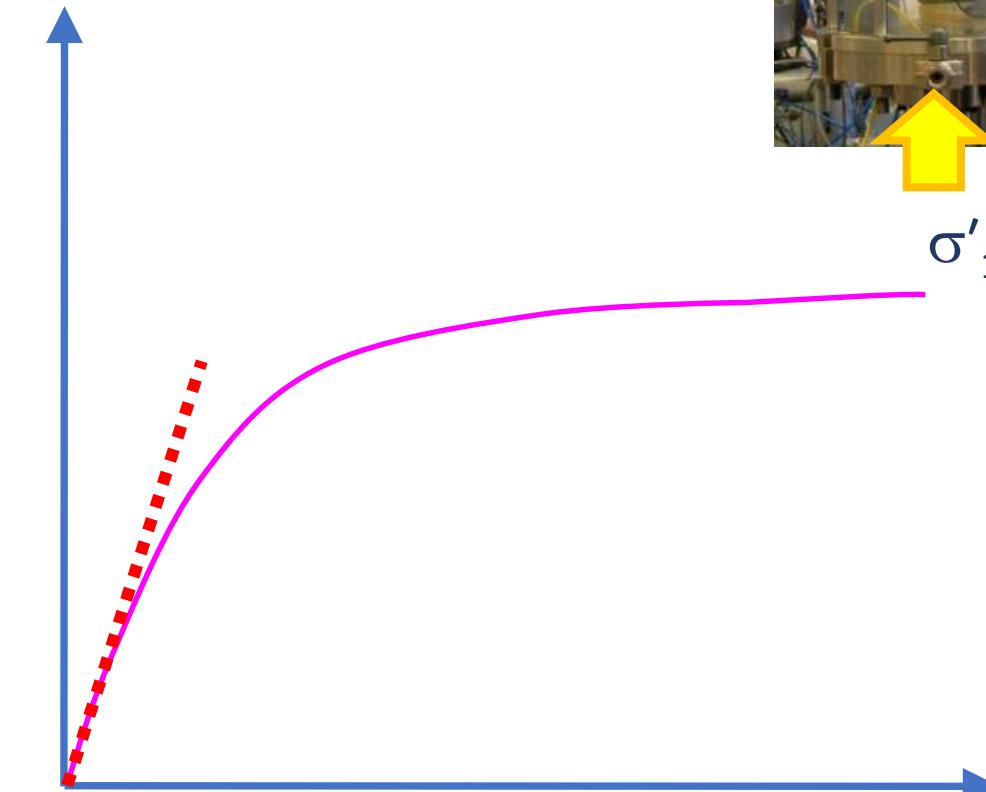
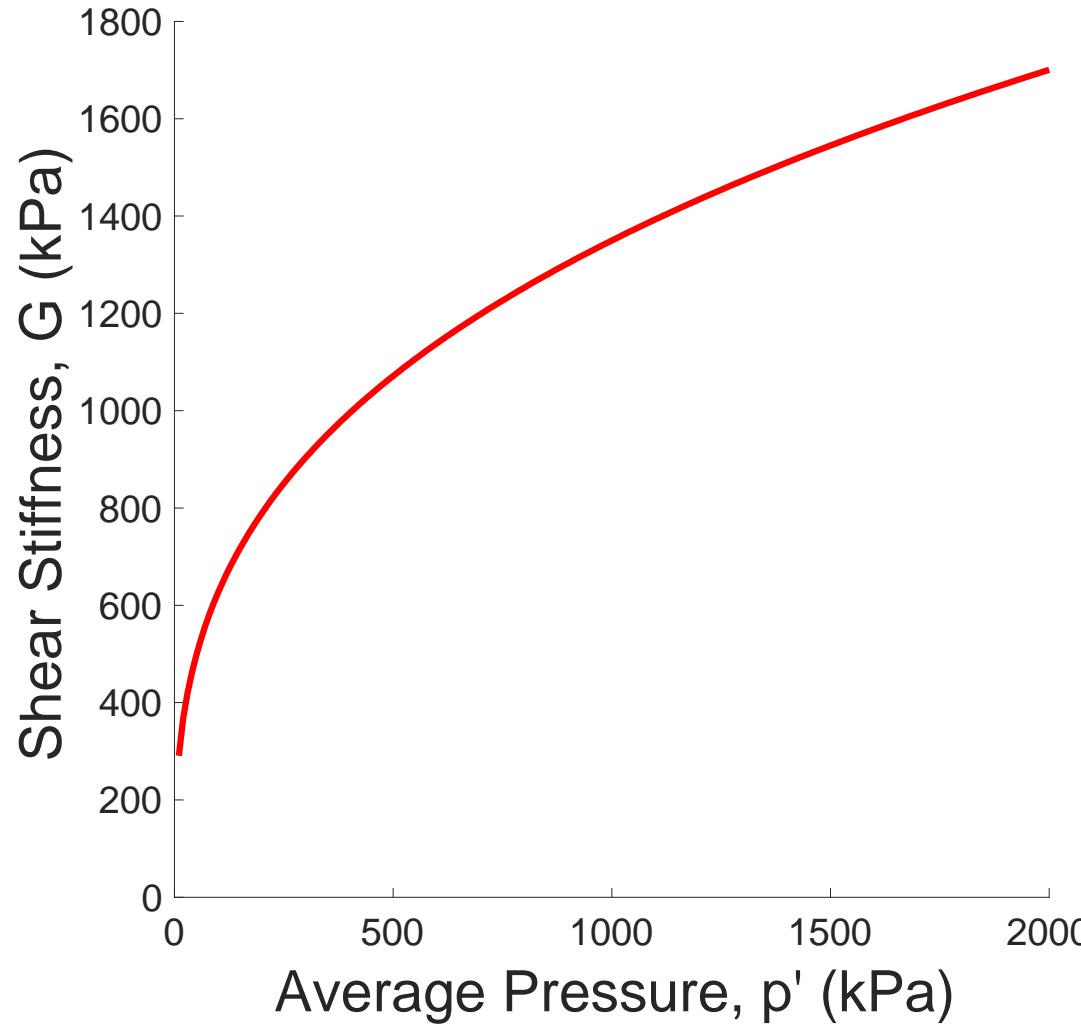


Memorial portrait of Robert Hooke, presented to the Institute of Physics, London by Rita Greer, history painter, 2011

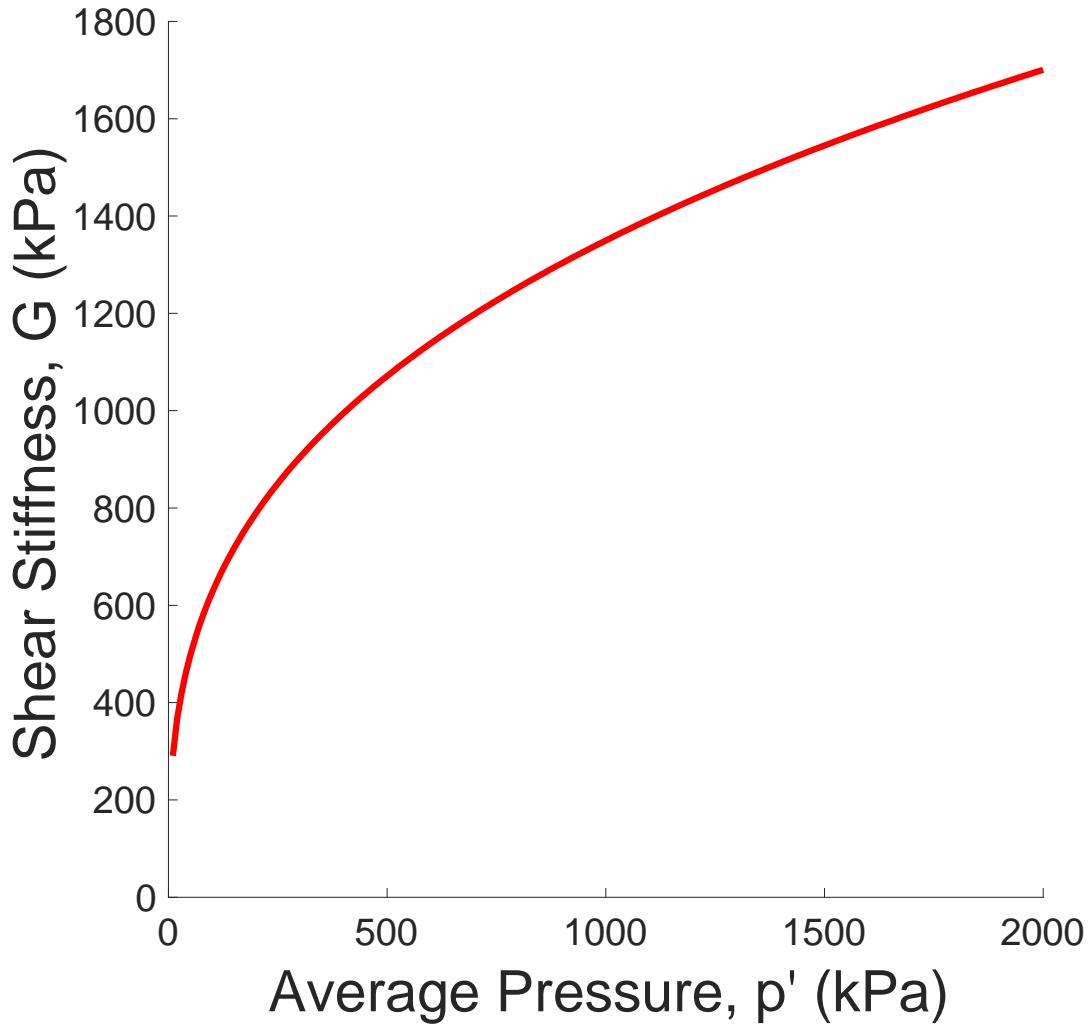
# Stiffness

$$q = \sigma'_1 - \sigma'_3$$

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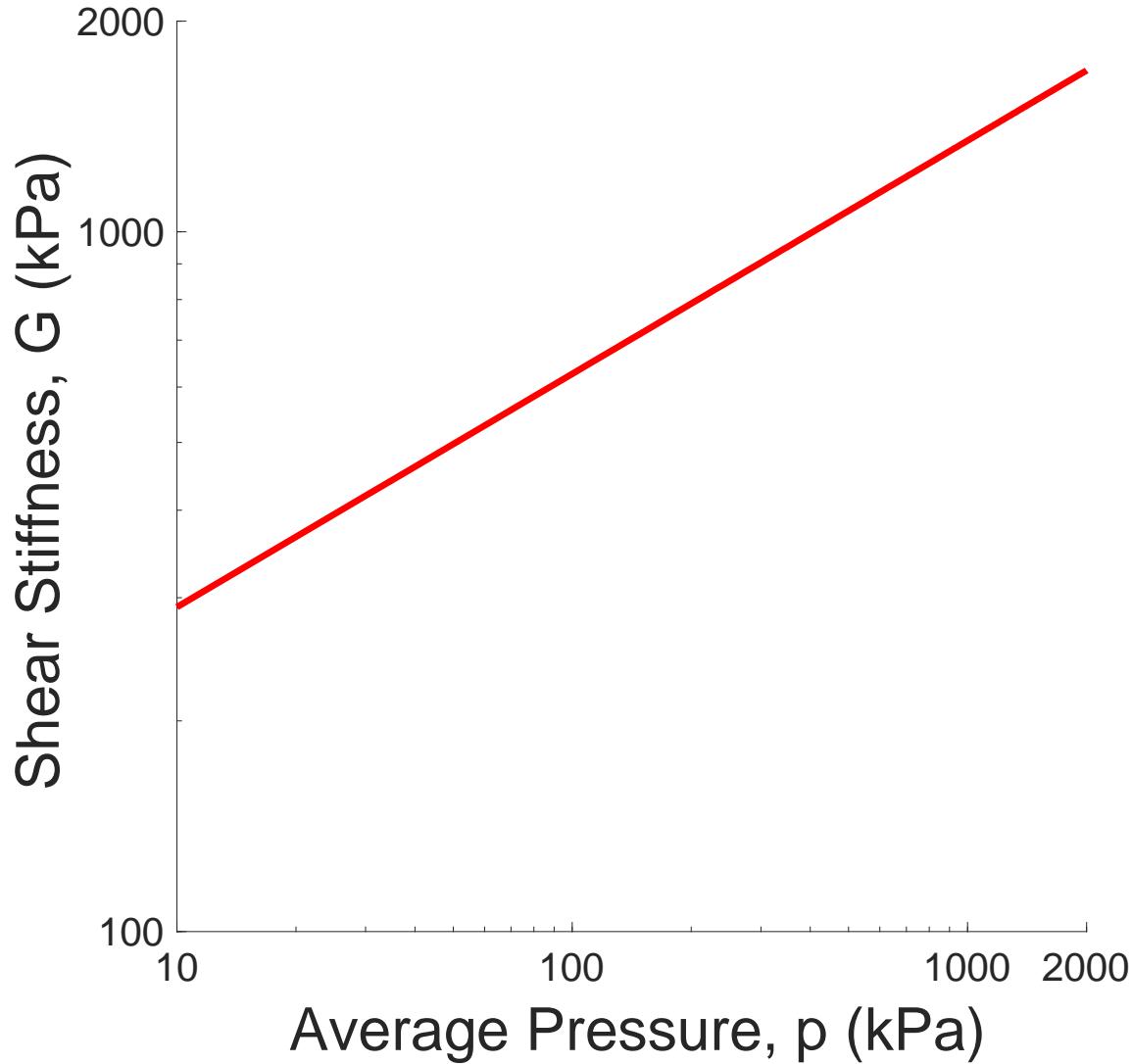
 $\sigma'$

# Stiffness



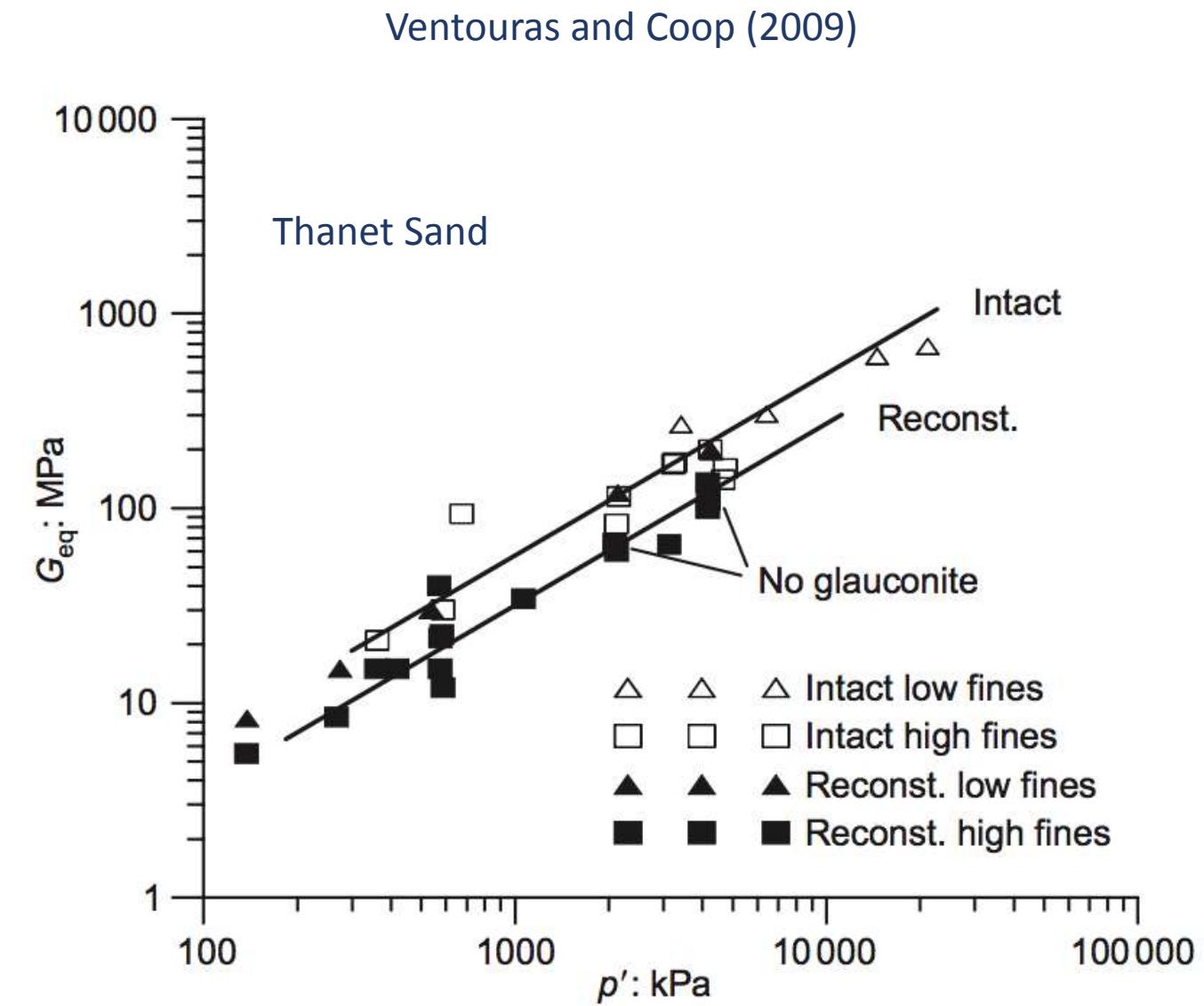
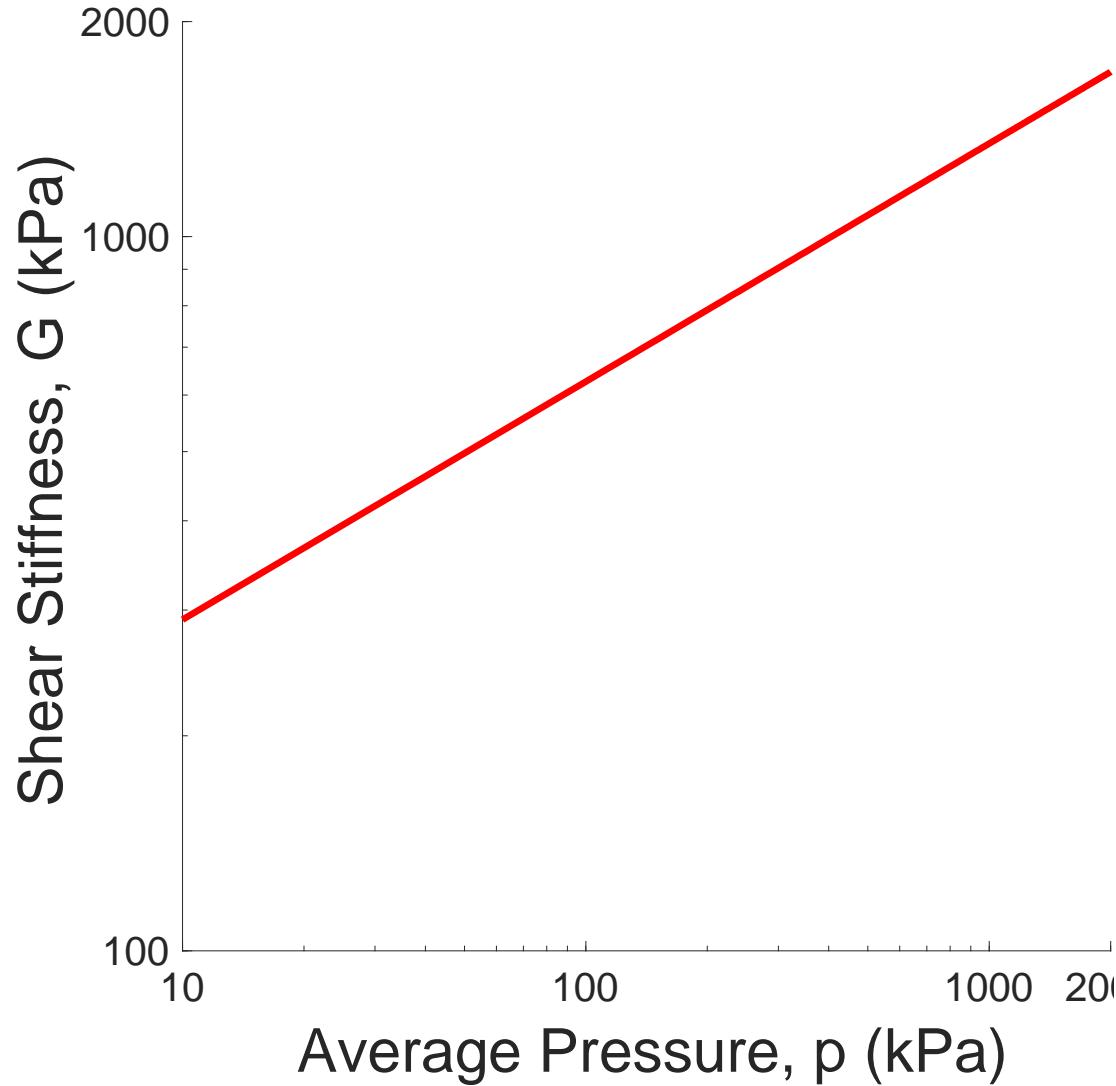
<https://centralpiling.com/case-studies/harbour-central-isle-of-dogs-london/>

# Stiffness

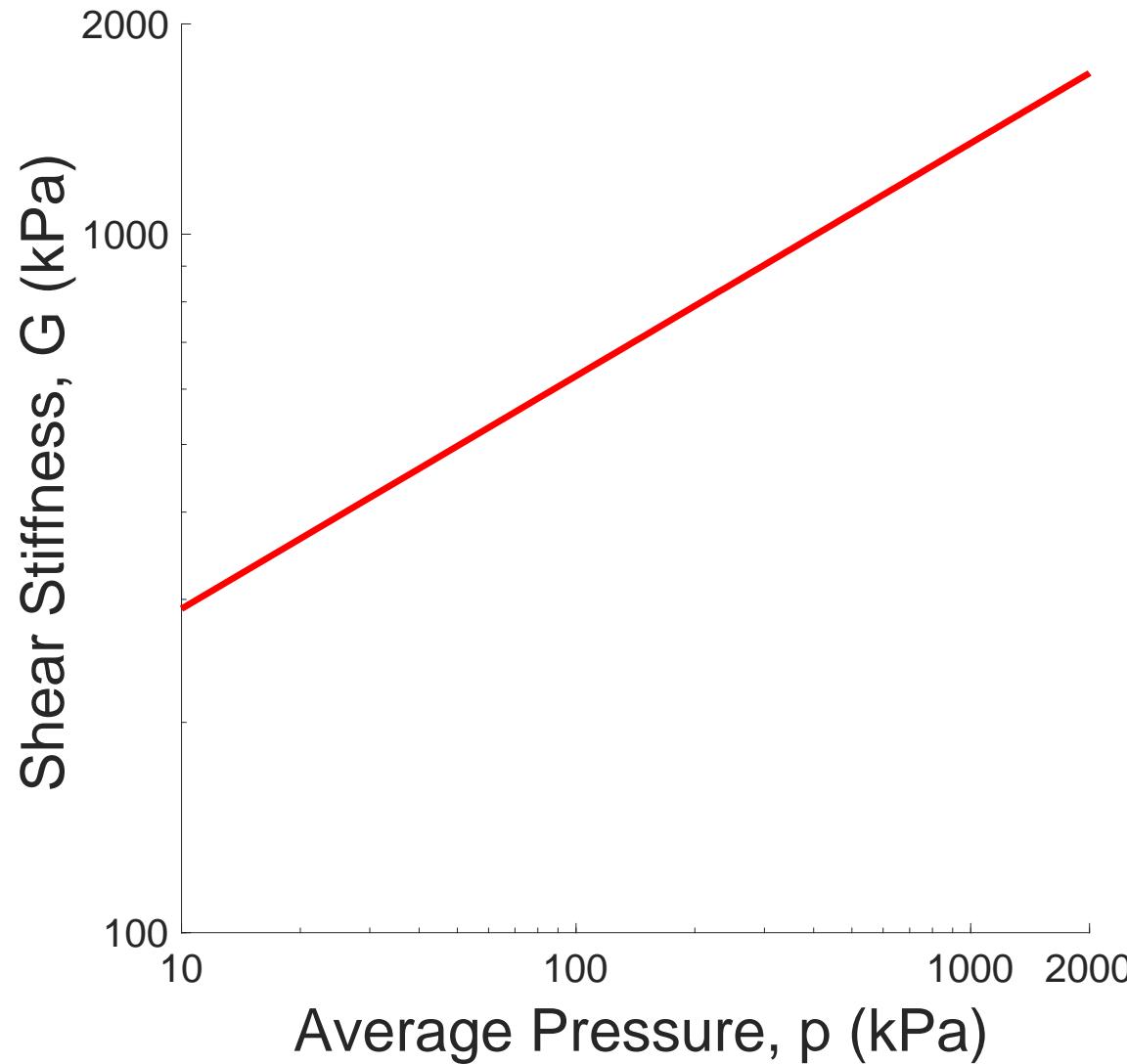


<https://centralpiling.com/case-studies/harbour-central-isle-of-dogs-london/>

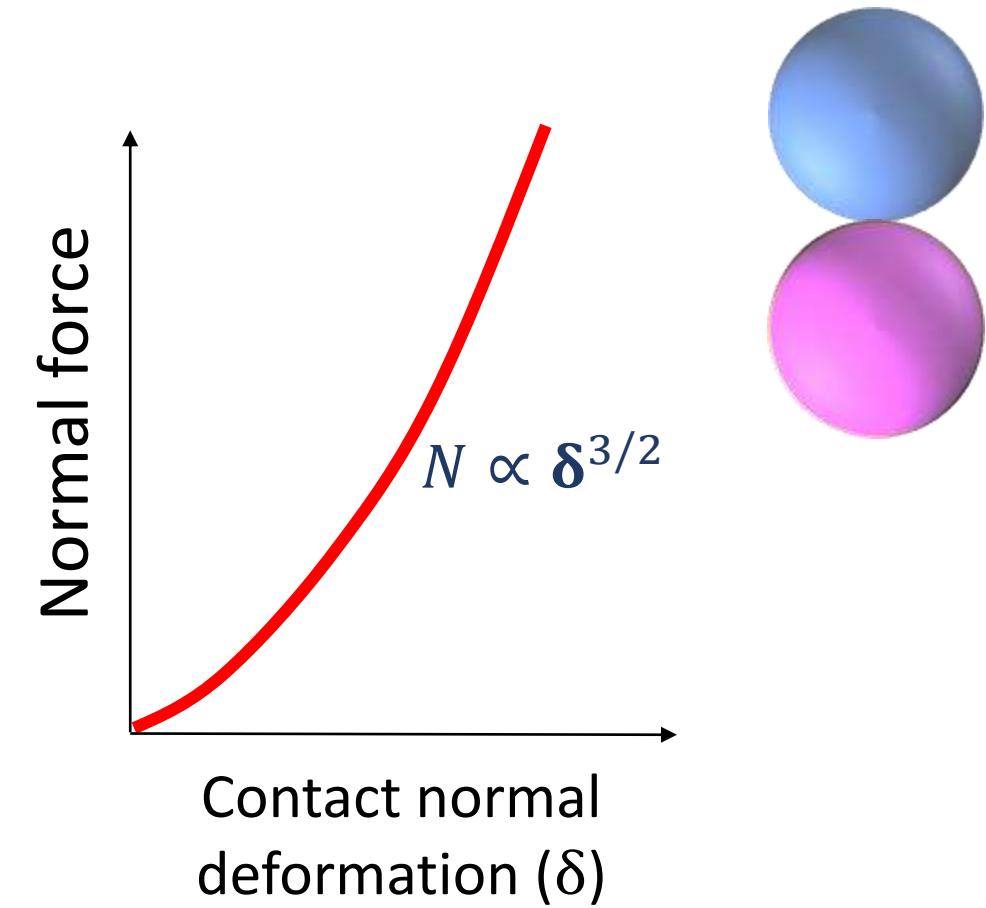
# Stiffness



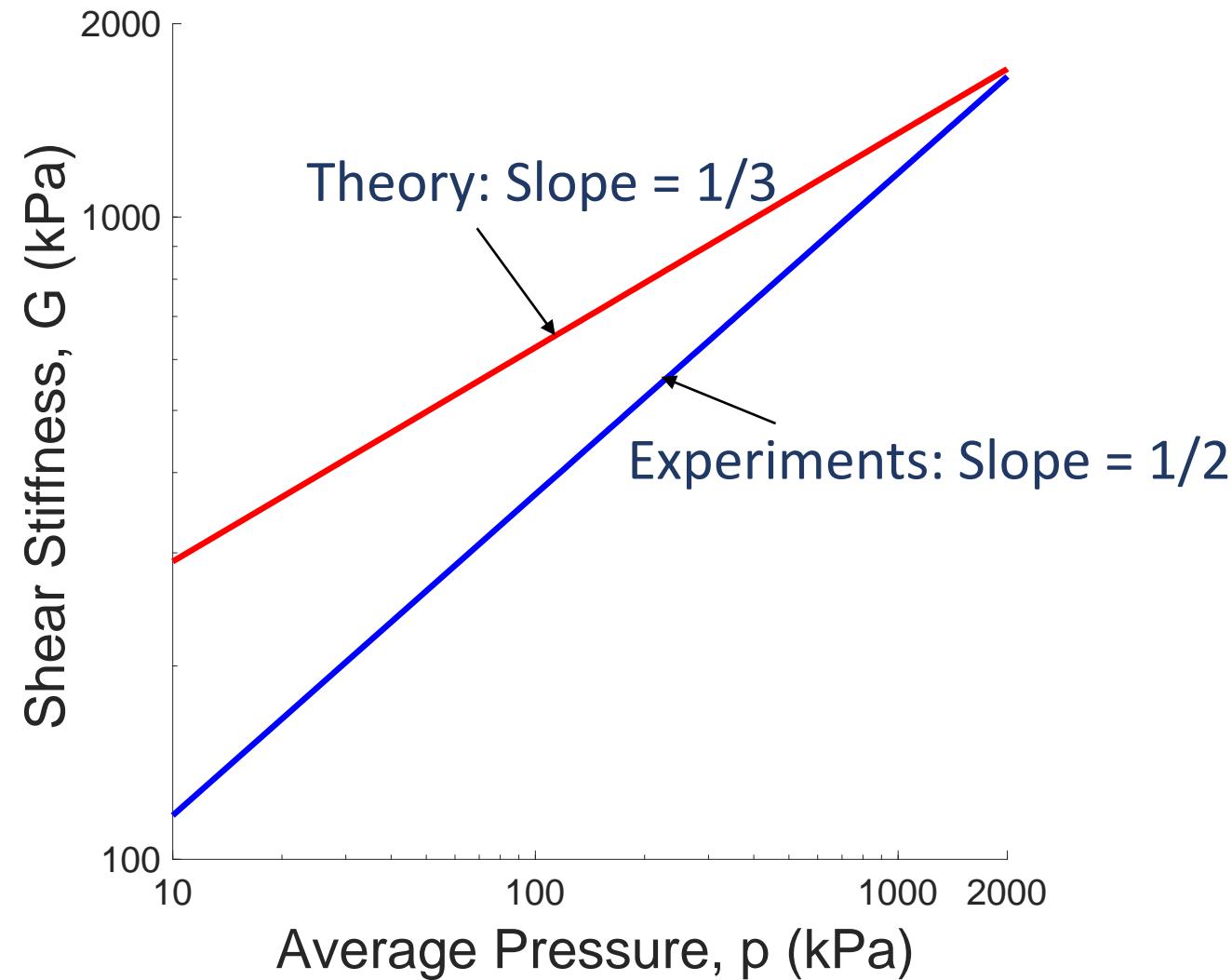
# Stiffness



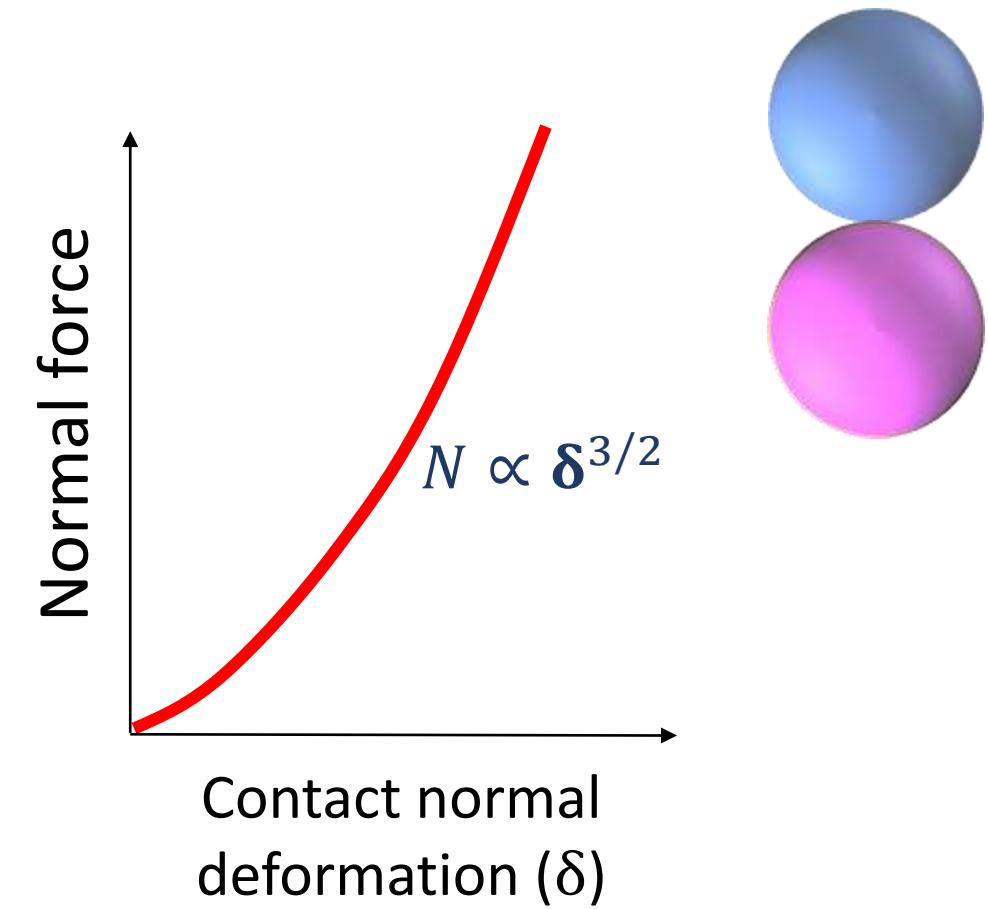
Contact for  
smooth spheres



# Stiffness

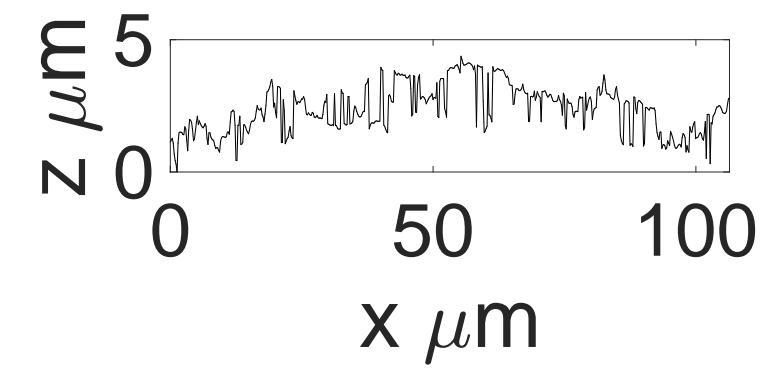
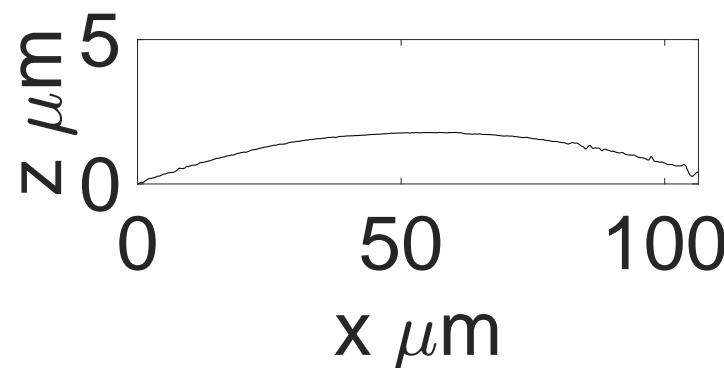
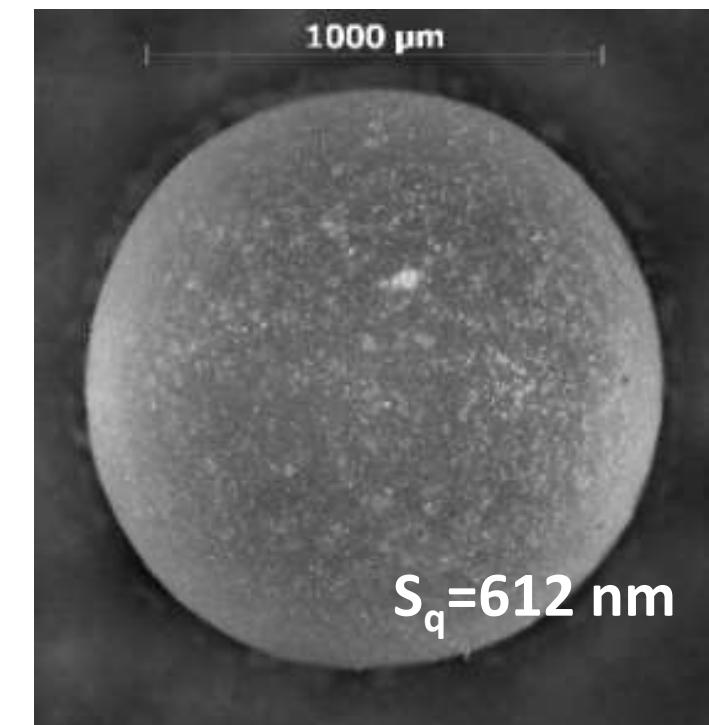
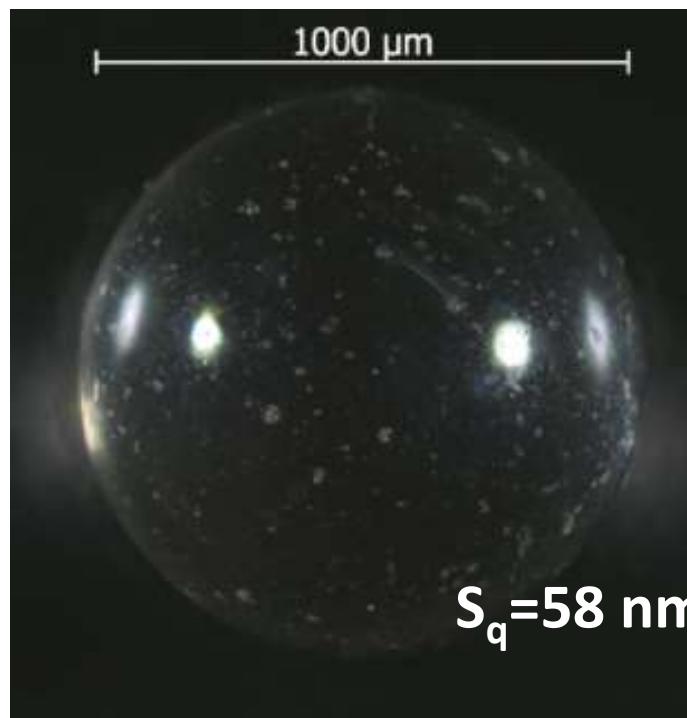
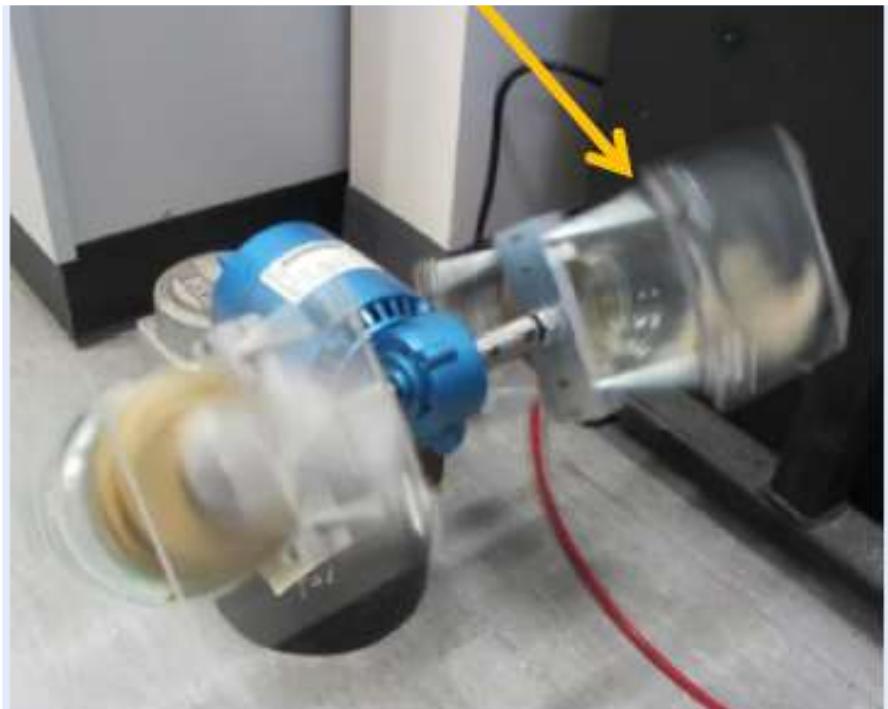


Contact for  
smooth spheres



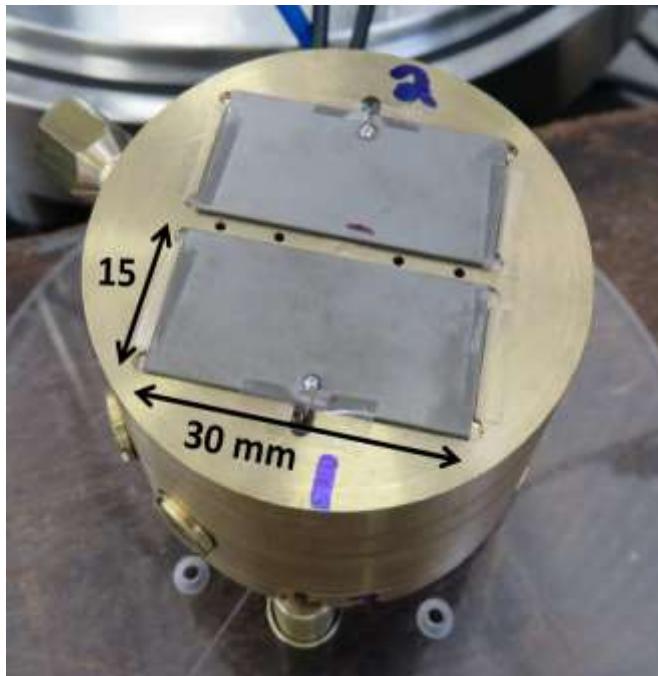
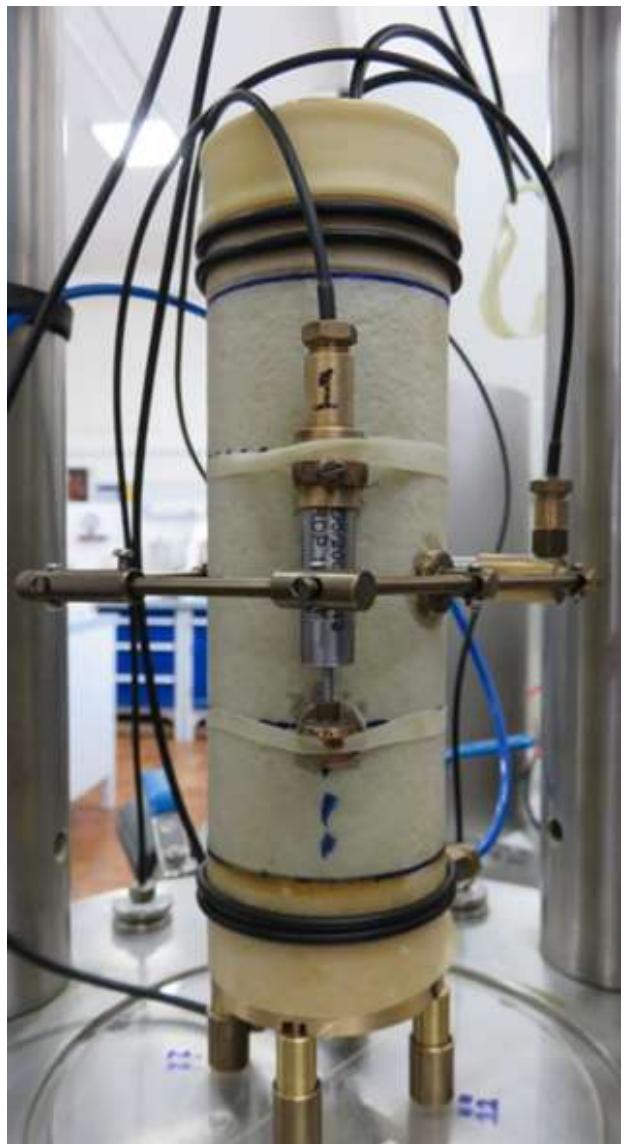
# Surface roughness effects on stiffness

Ballotini + Toyoura Sand

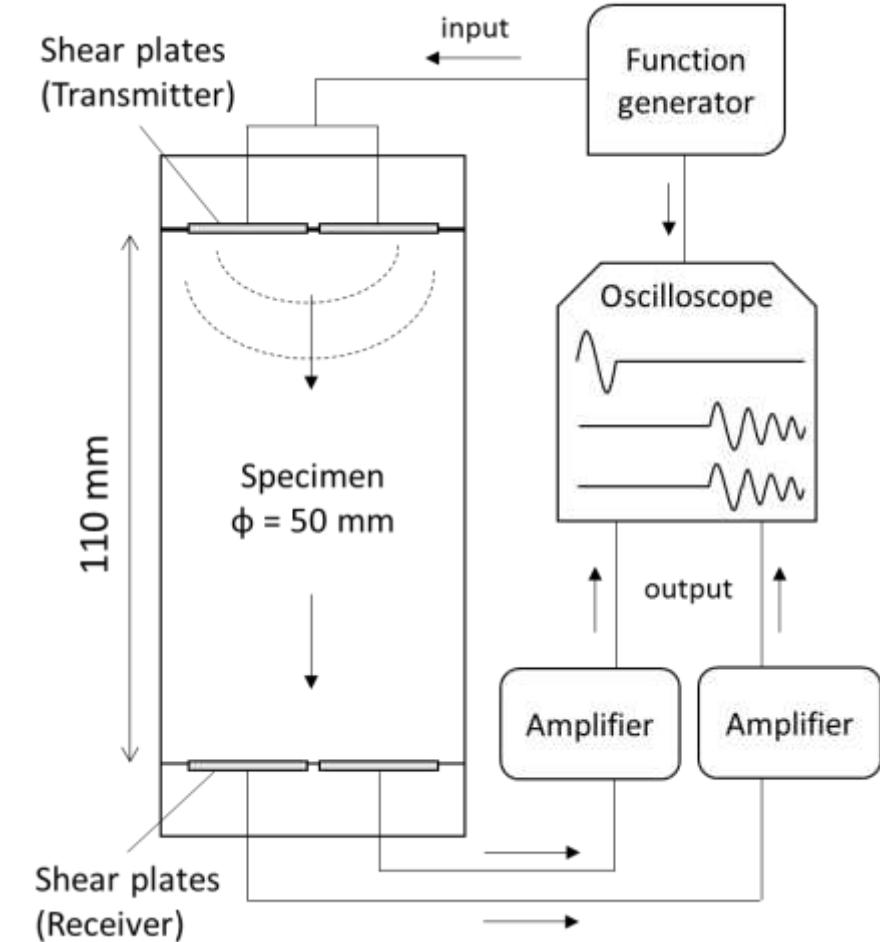


(Otsubo, 2017)

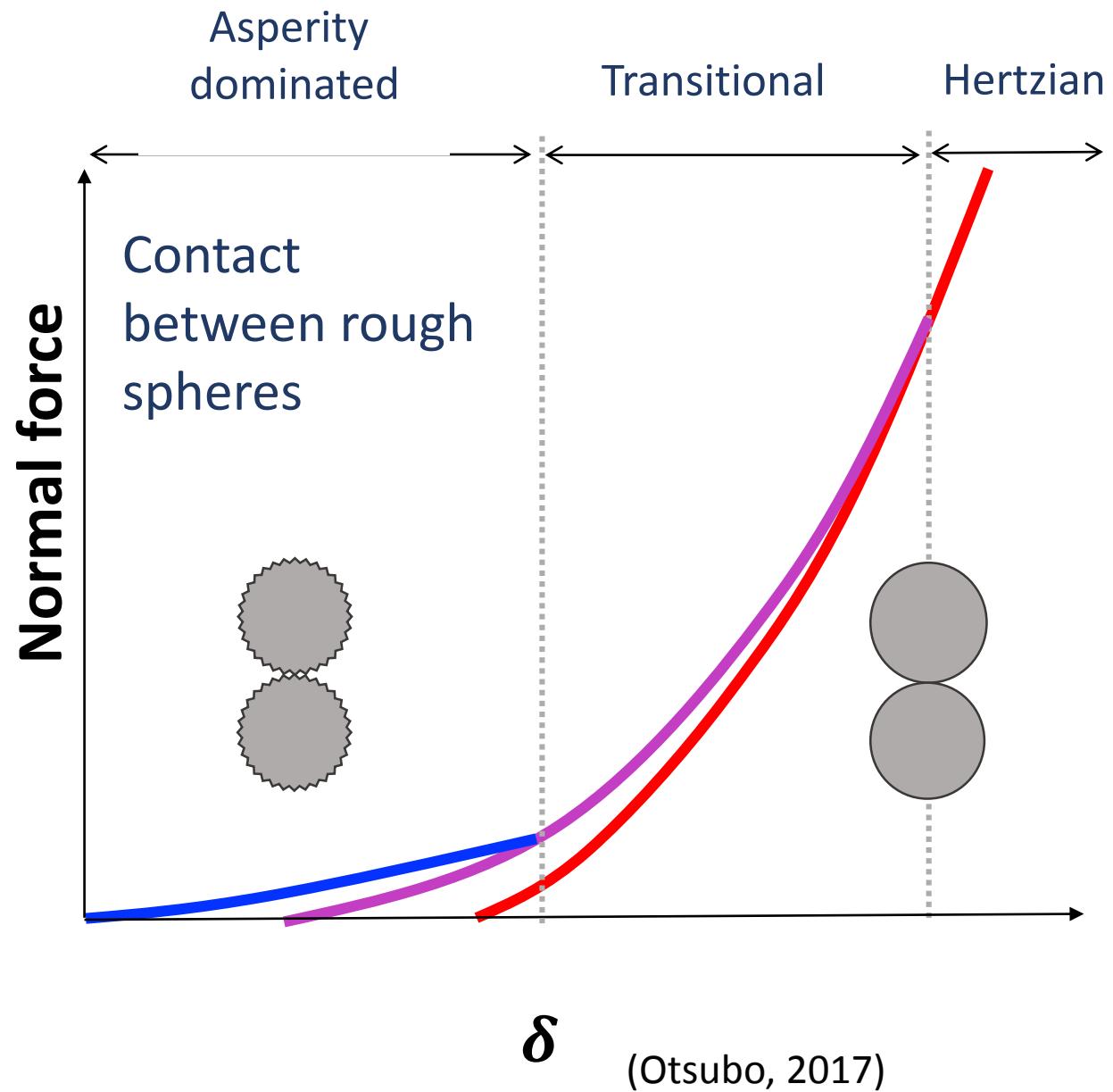
# Quantifying stiffness via wave propagation



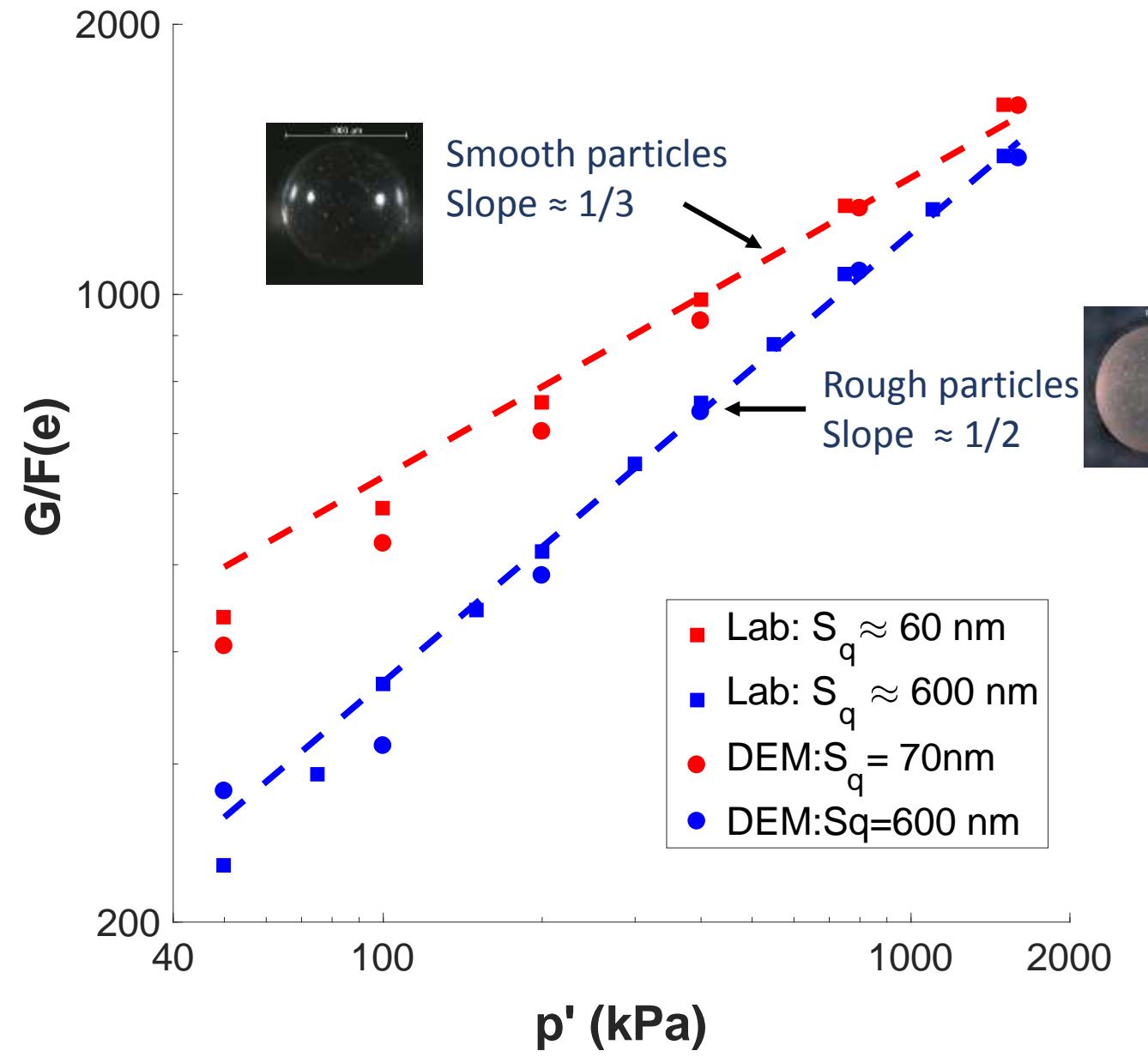
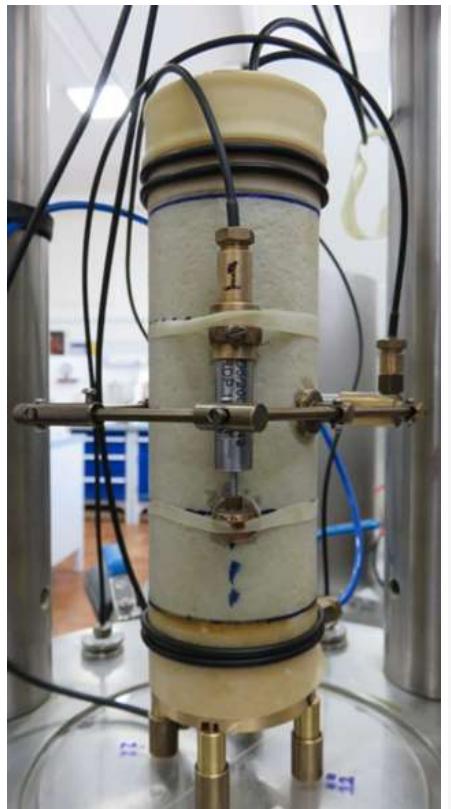
(Otsubo, 2017)



# Quantifying stiffness via wave propagation



# Surface roughness and stiffness



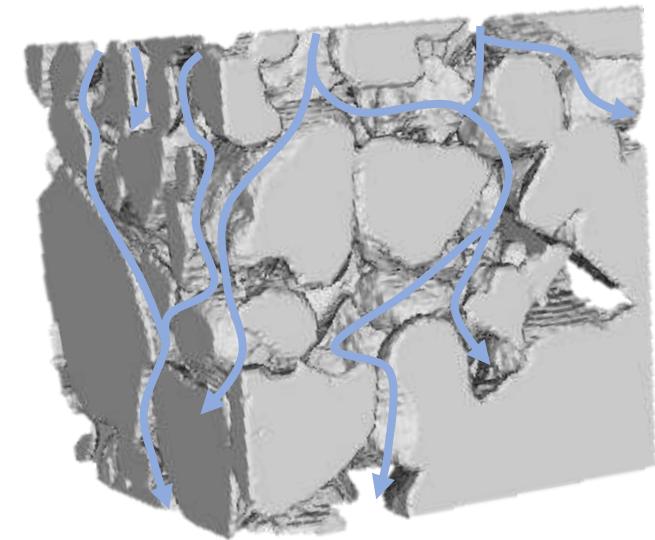
# Sand behaviour



Stiffness



Strength



Seepage

# Strength



Big Sur Landslide – California (2017)



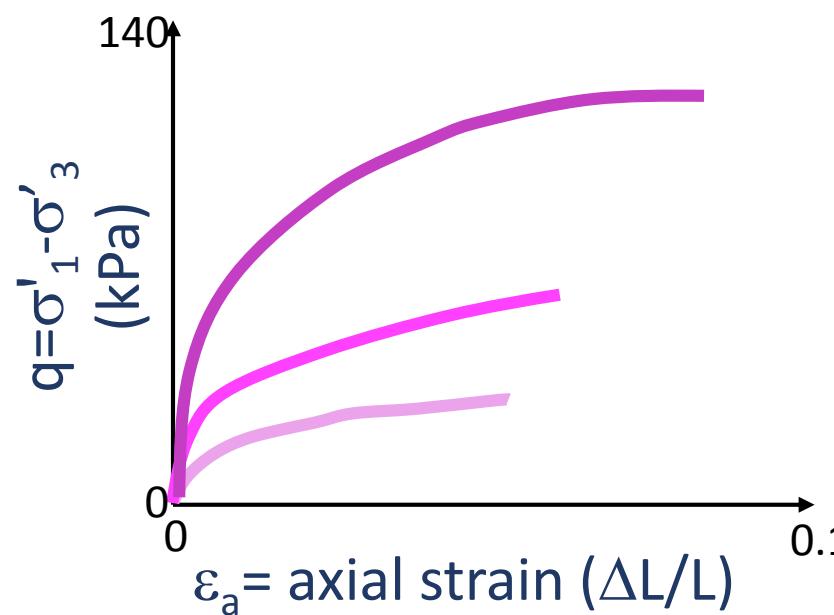
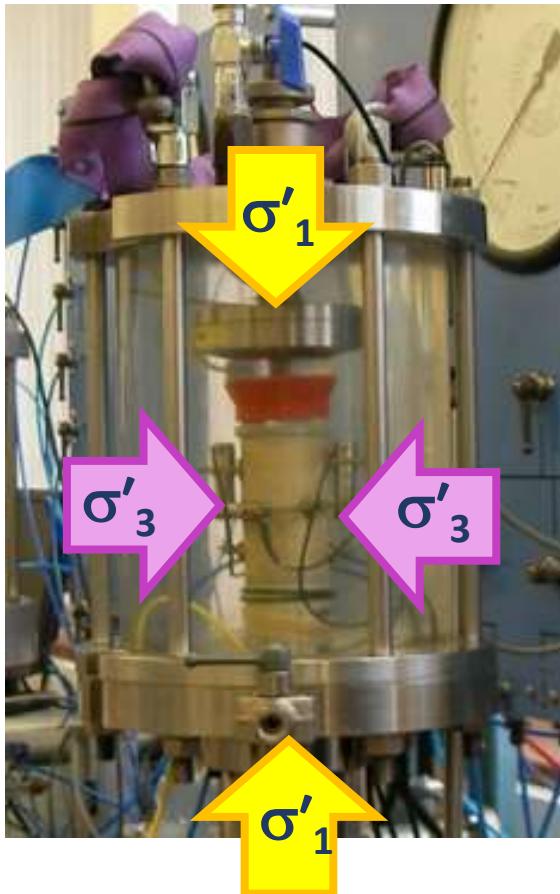
Domestic foundation failure: Rehoboth Beach Delaware, 1962

[https://soundwaves.usgs.gov/2017/10/images/BigSur1\\_May20SlideDES.jpg](https://soundwaves.usgs.gov/2017/10/images/BigSur1_May20SlideDES.jpg)

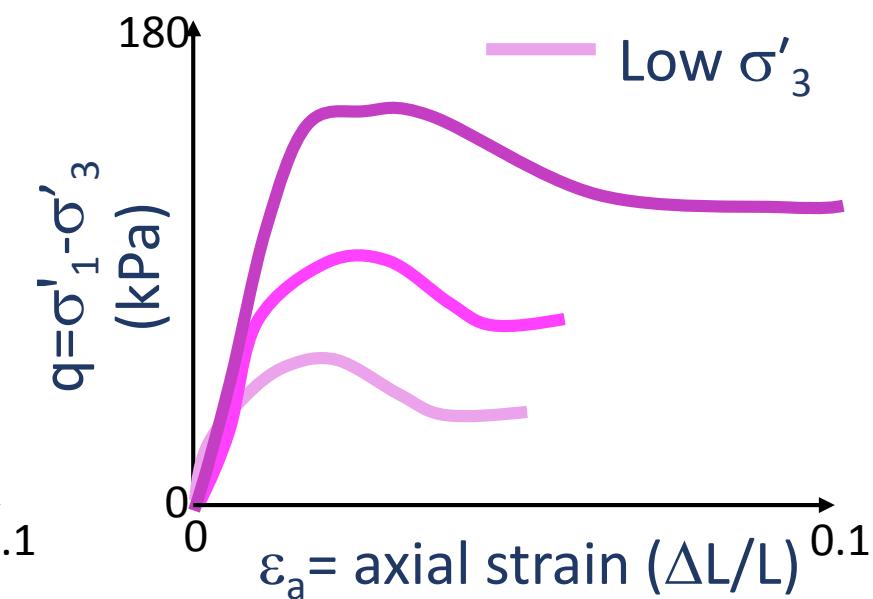
<https://www.capec gazette.com/node/23907#&gid=1&pid=13>

# Soil strength is stress-dependent

Strength = maximum stress or pressure  
that can be applied

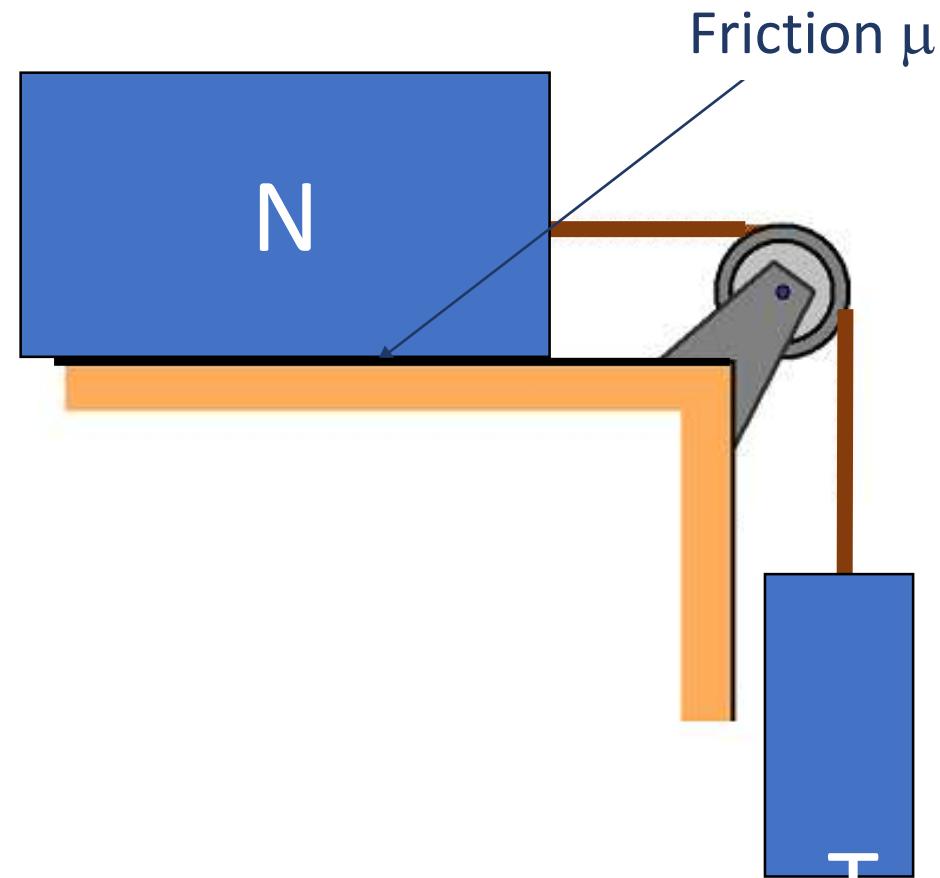
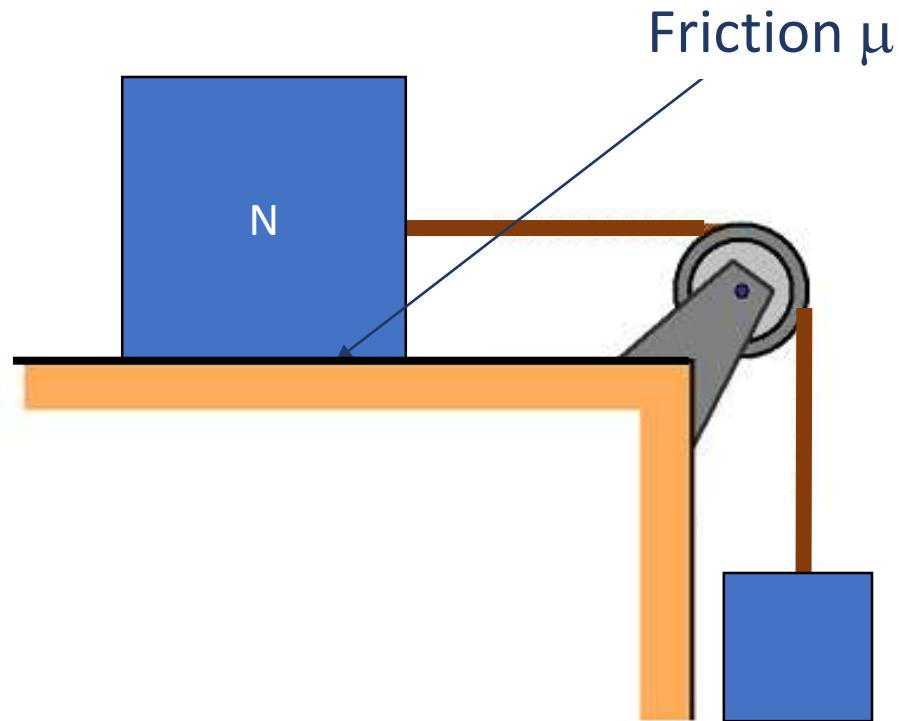


Loose sand

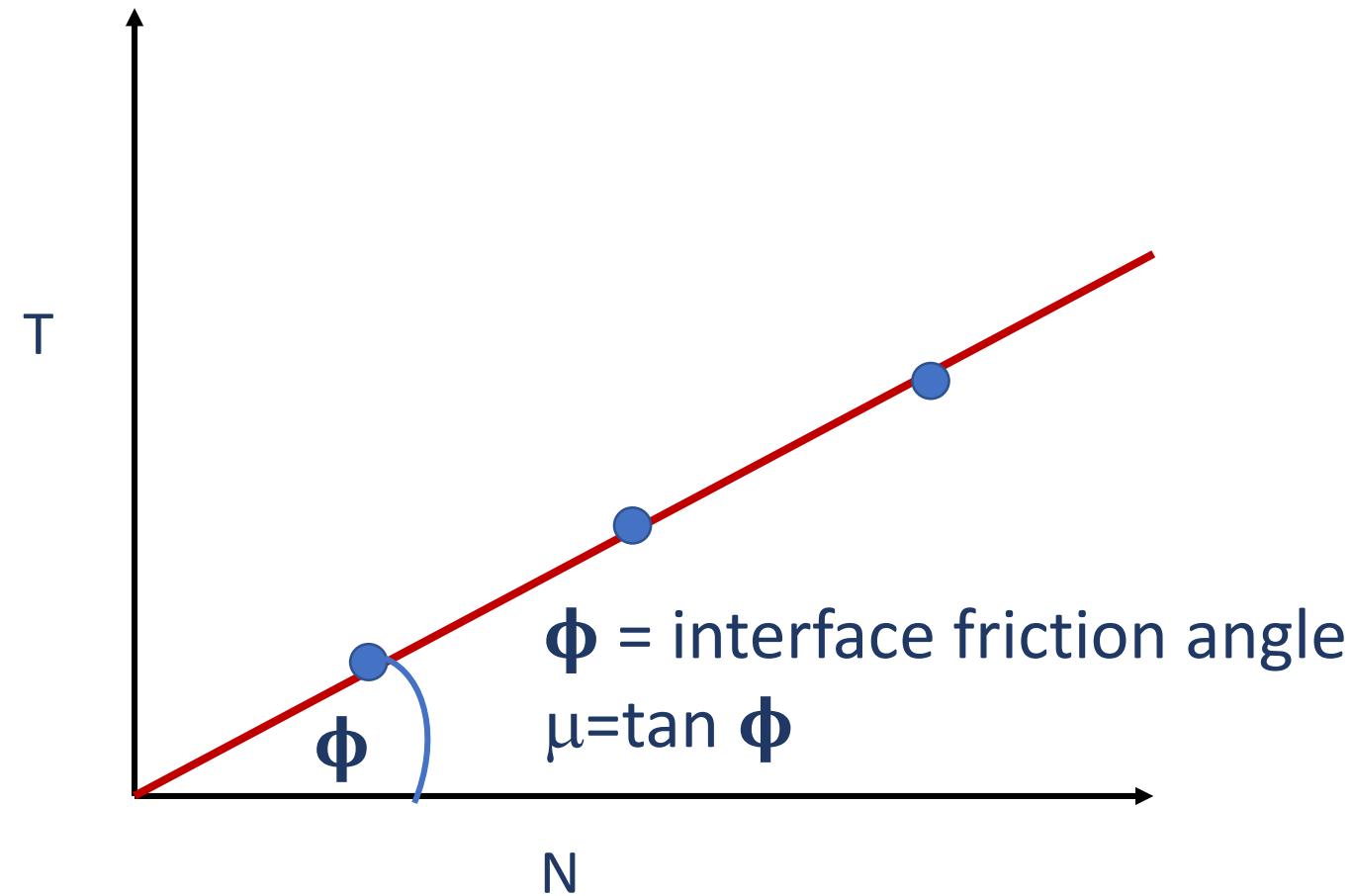
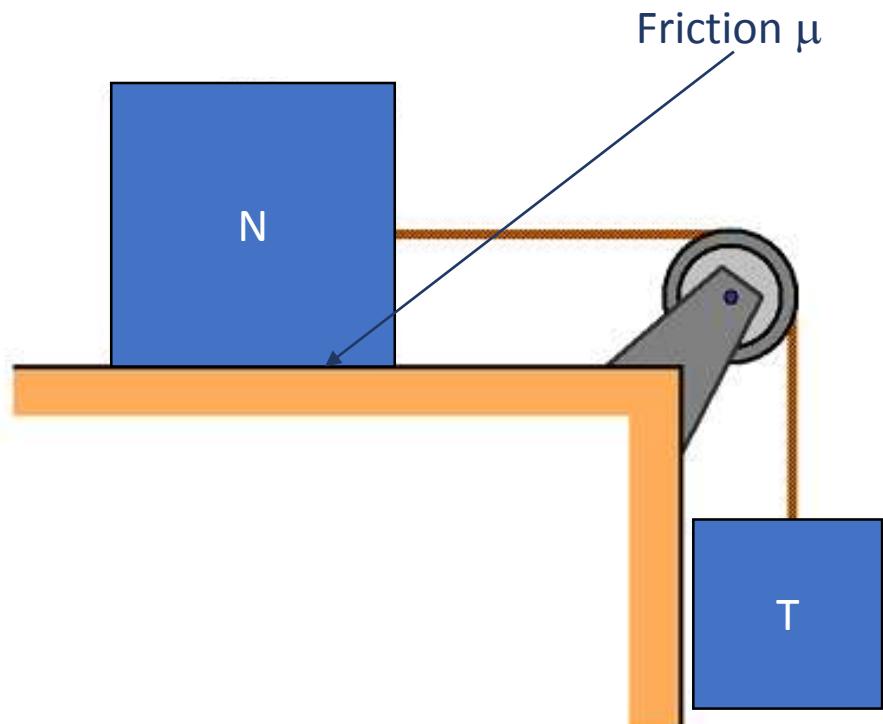


Dense sand

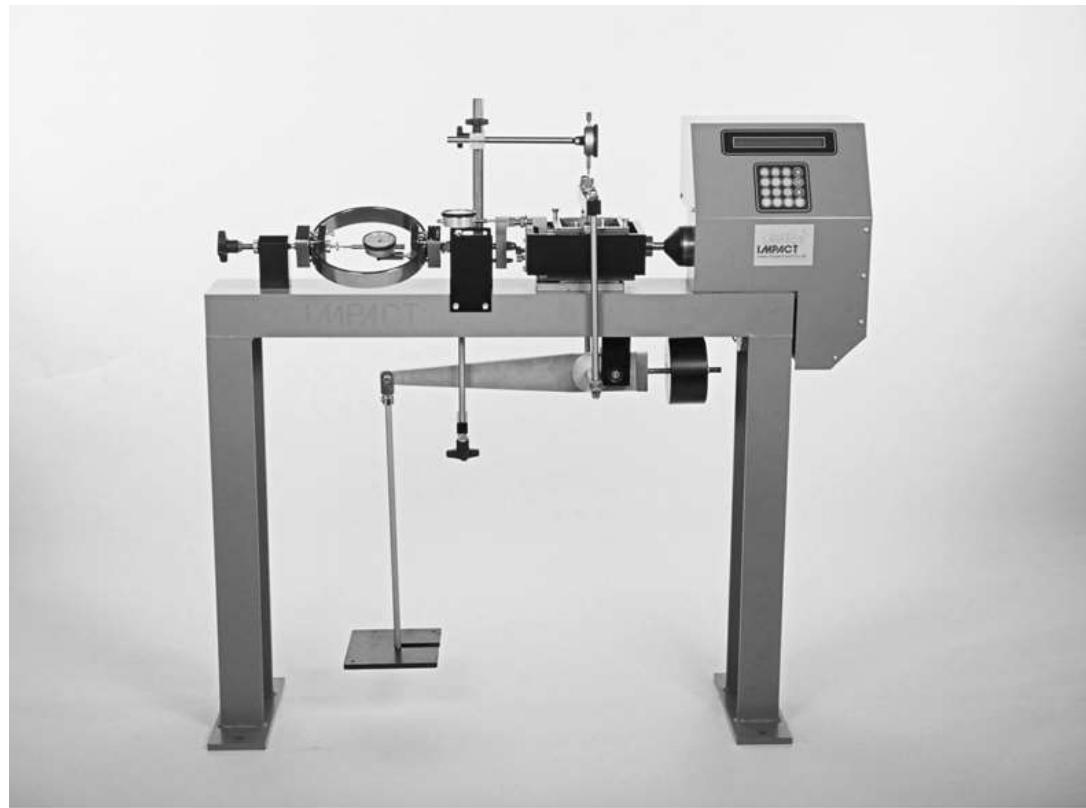
# Stress:strength relationship



# Stress:strength relationship



# Stress:strength relationship



(b)

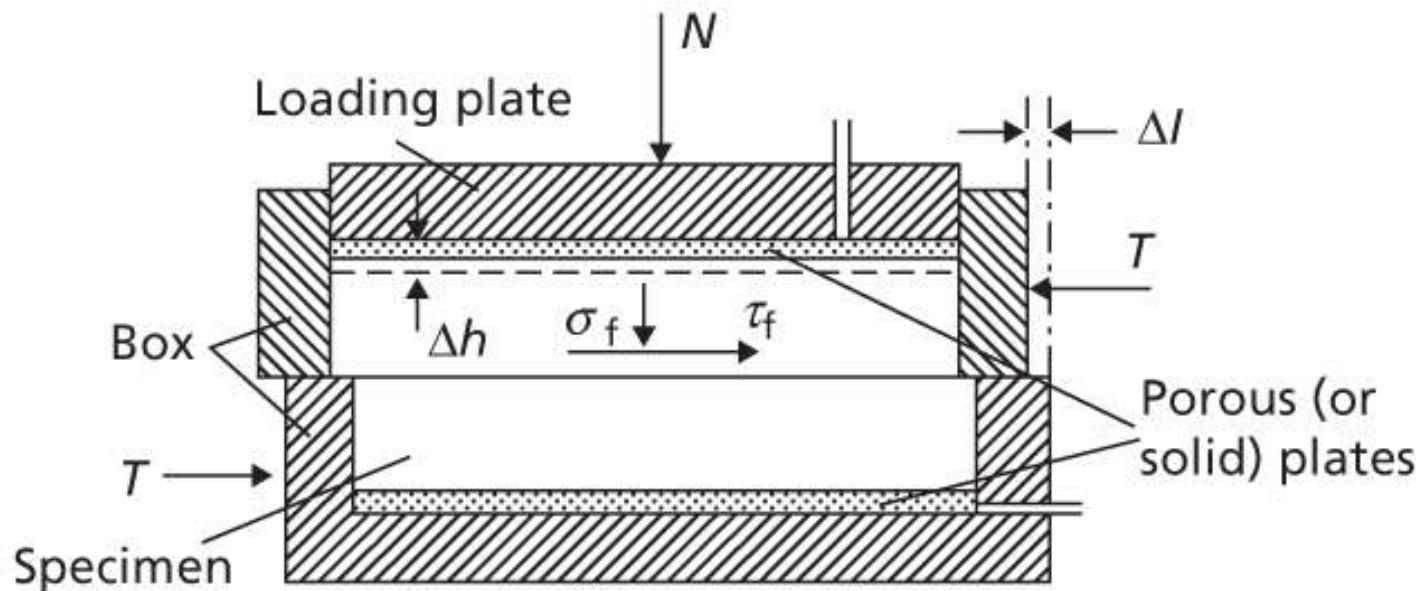


Figure 5.8 Knappett and Craig (2012)

# Stress:strength relationship

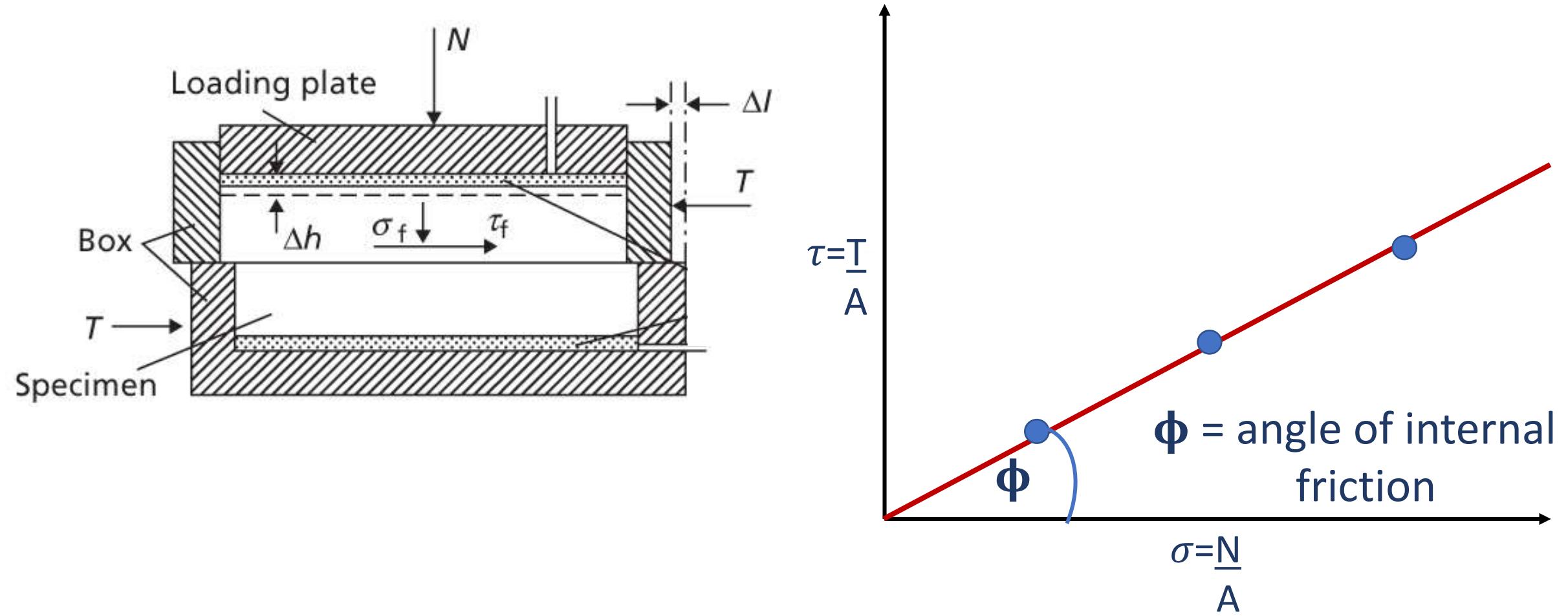


Figure 5.8 Knappett and Craig (2012)

# Stress:strength relationship

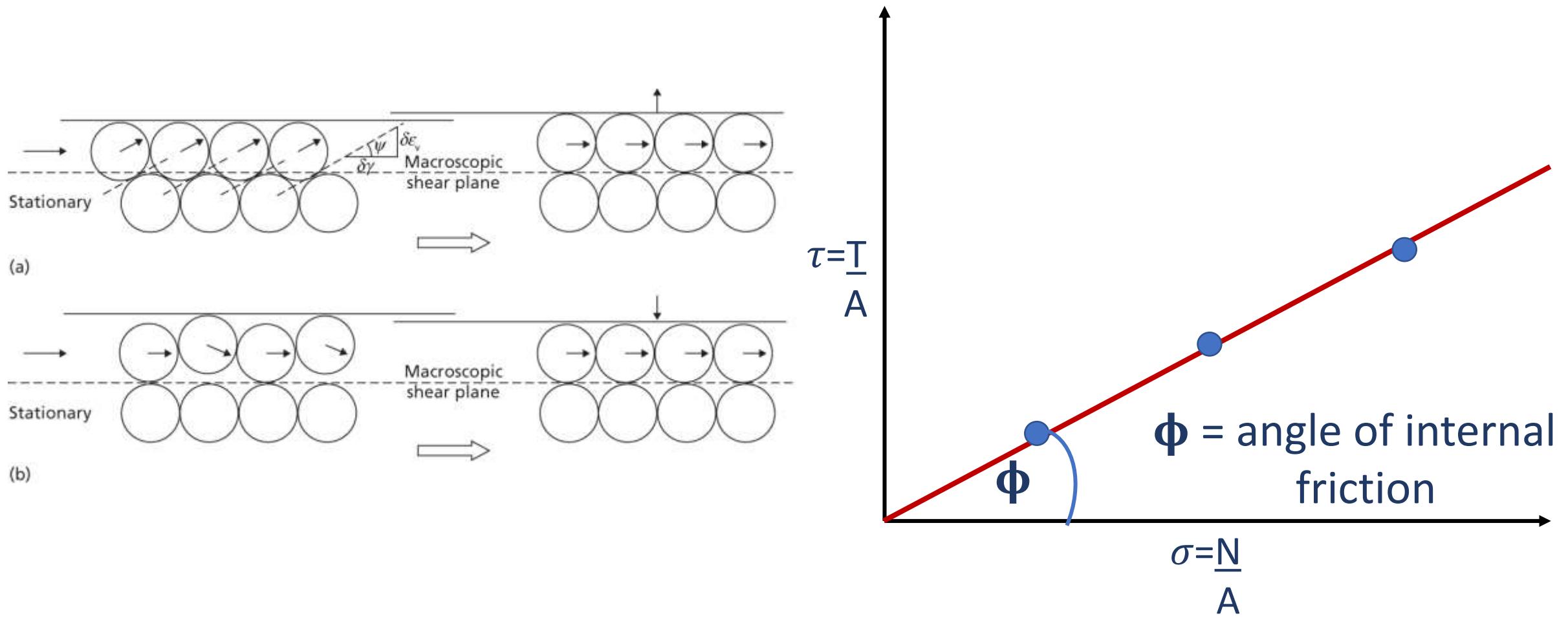
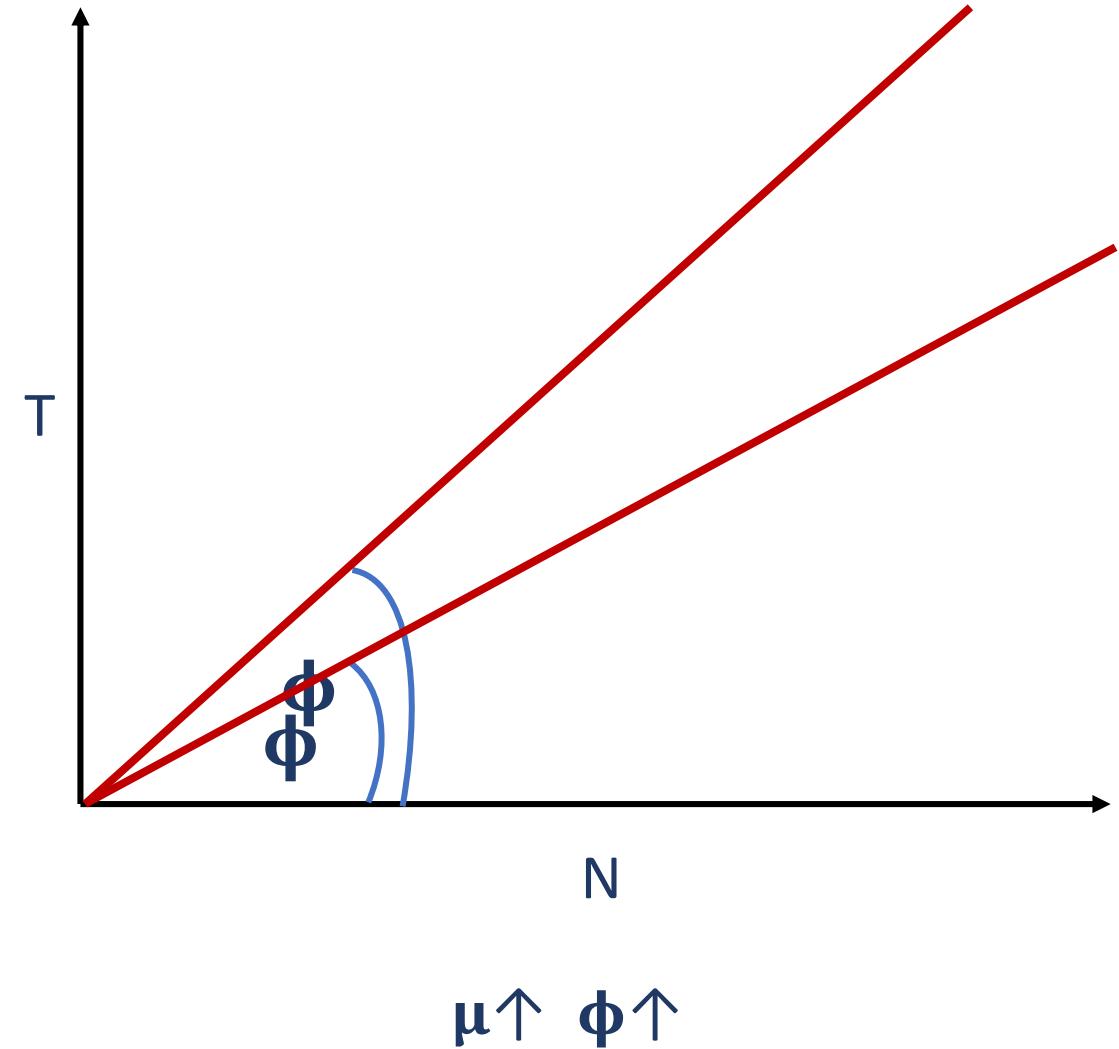
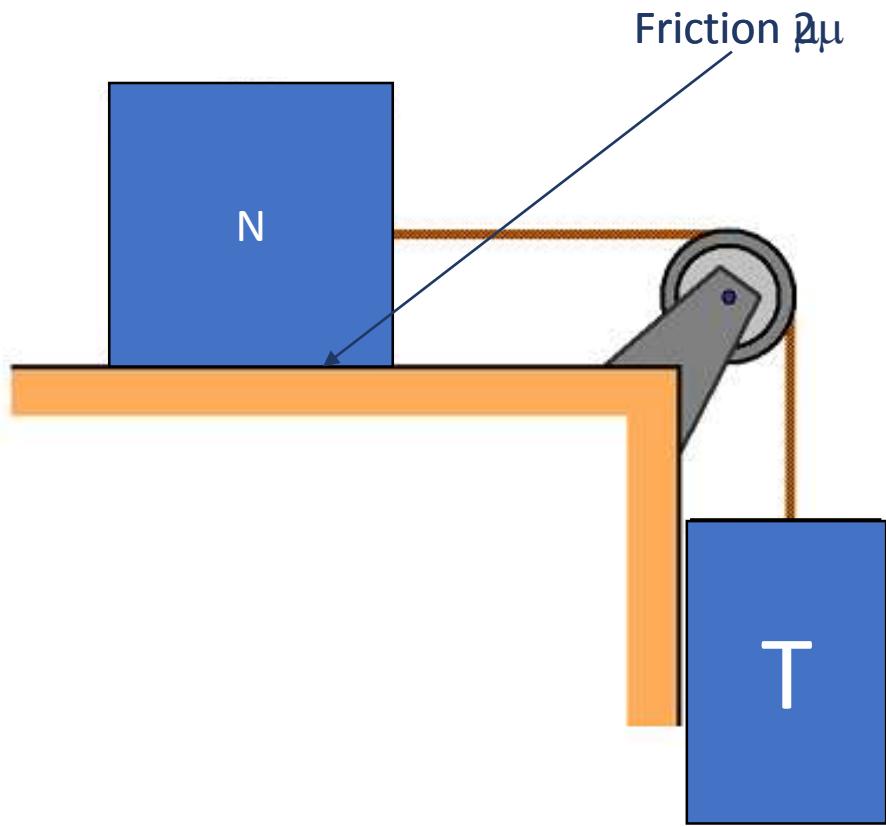
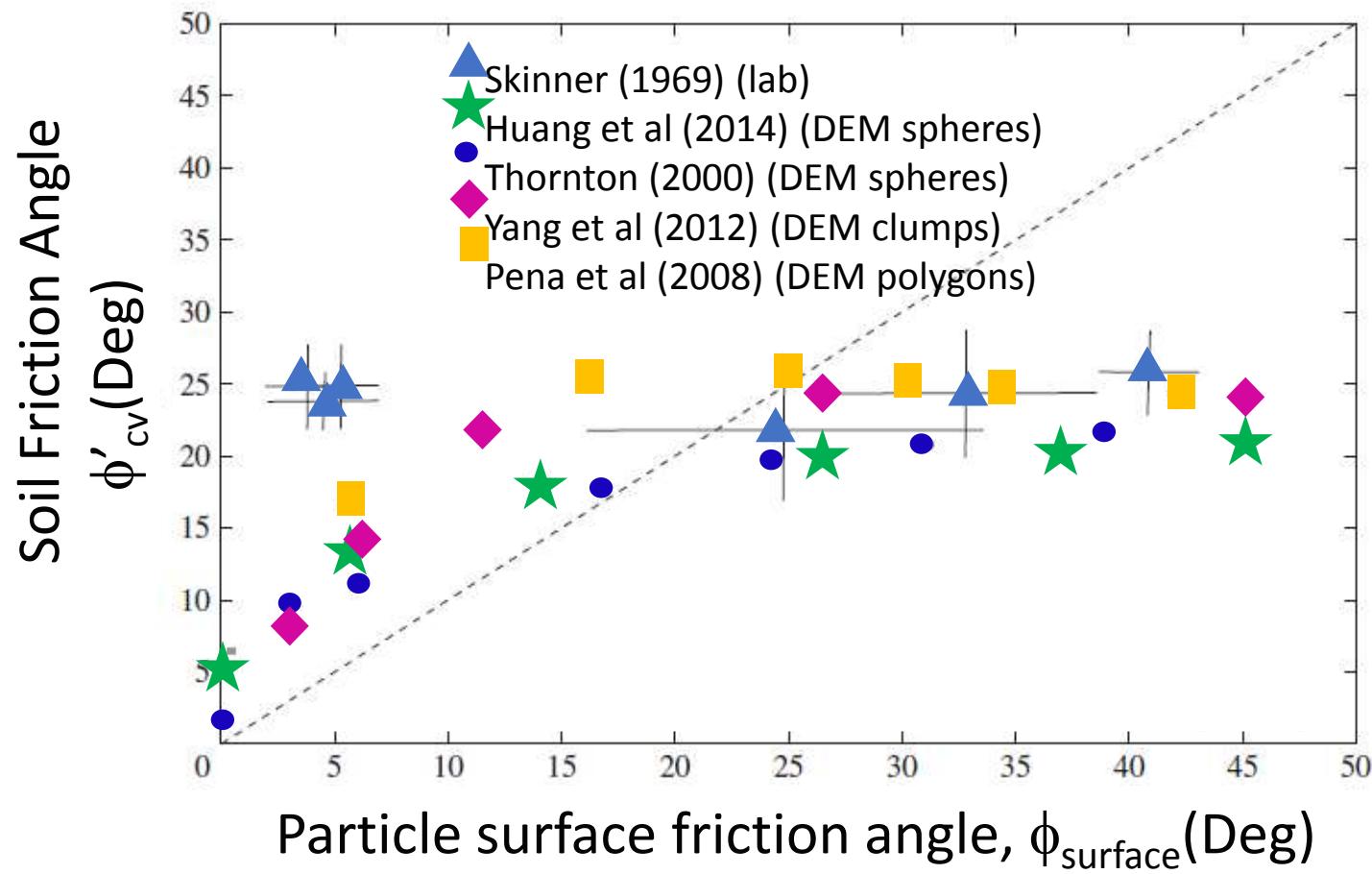
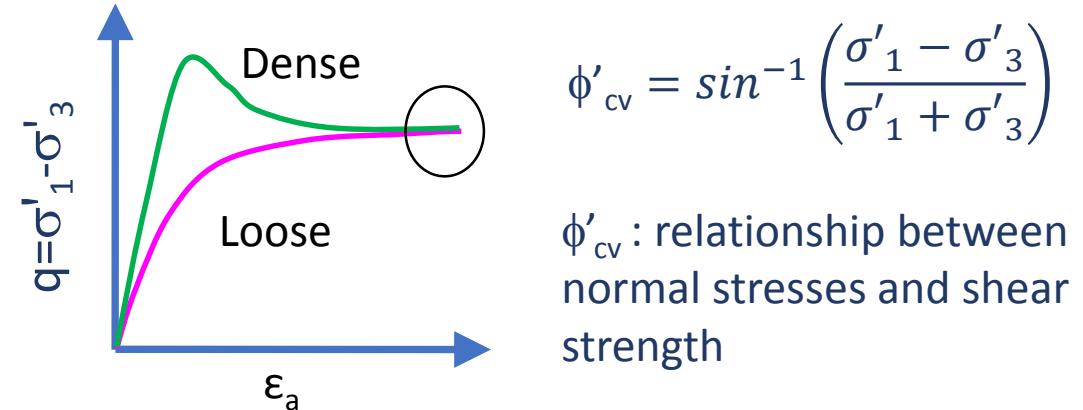
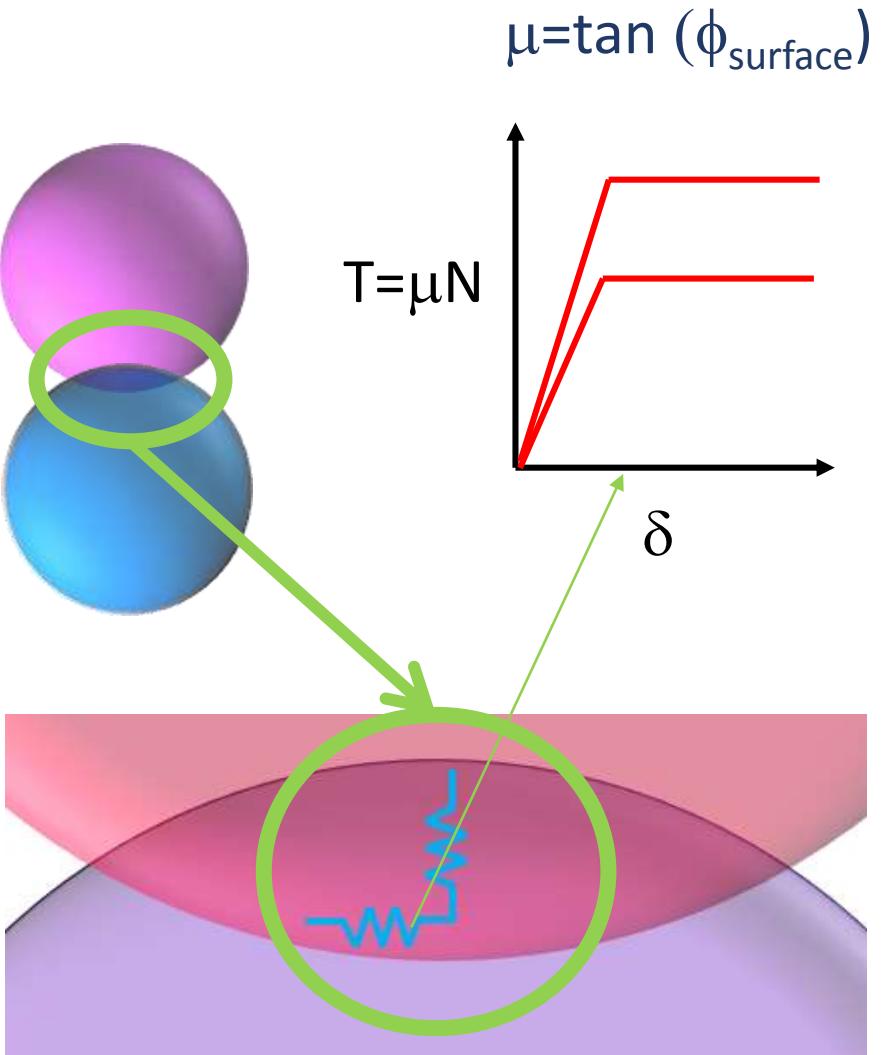


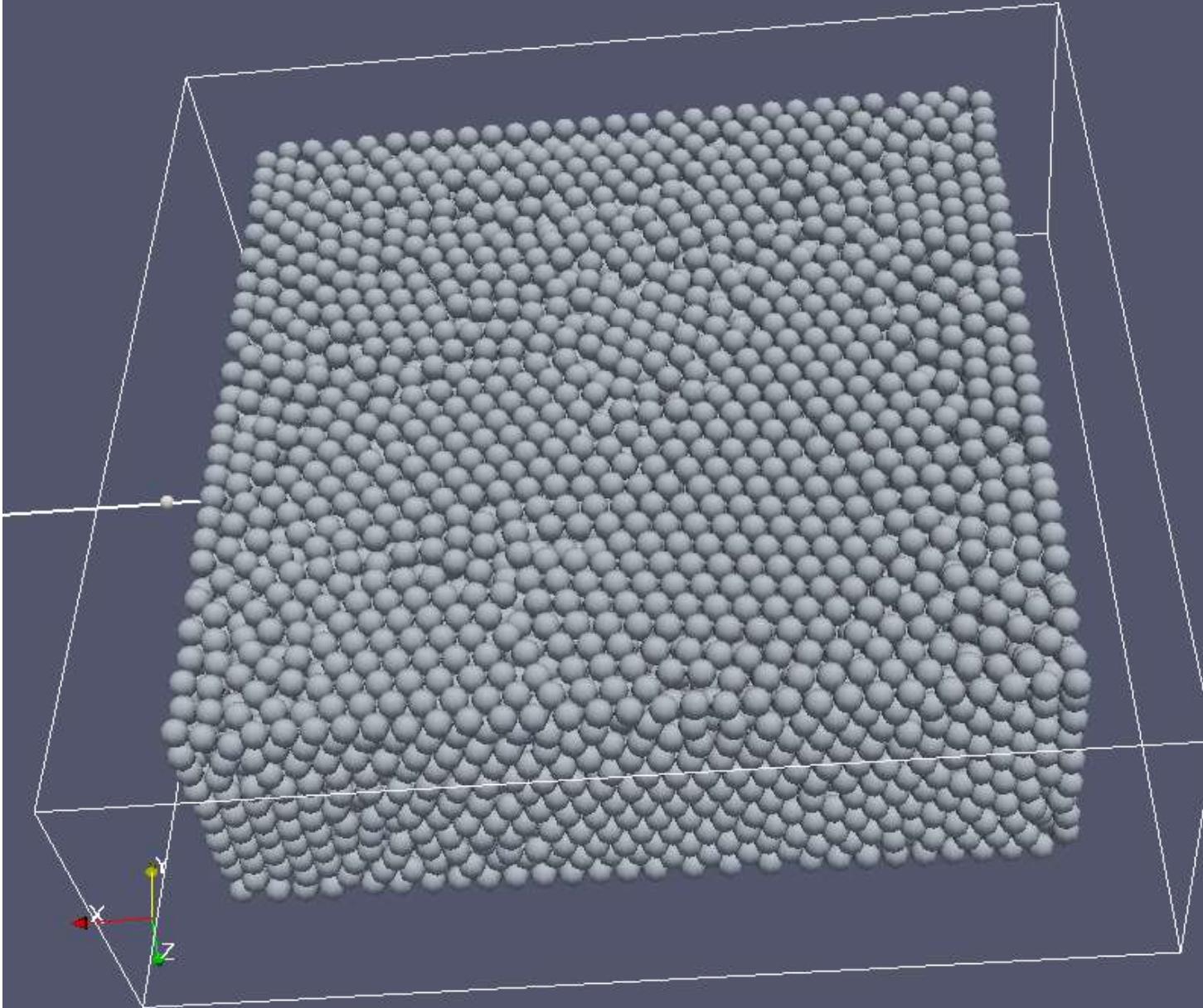
Figure 5.8 Knappett and Craig (2012)

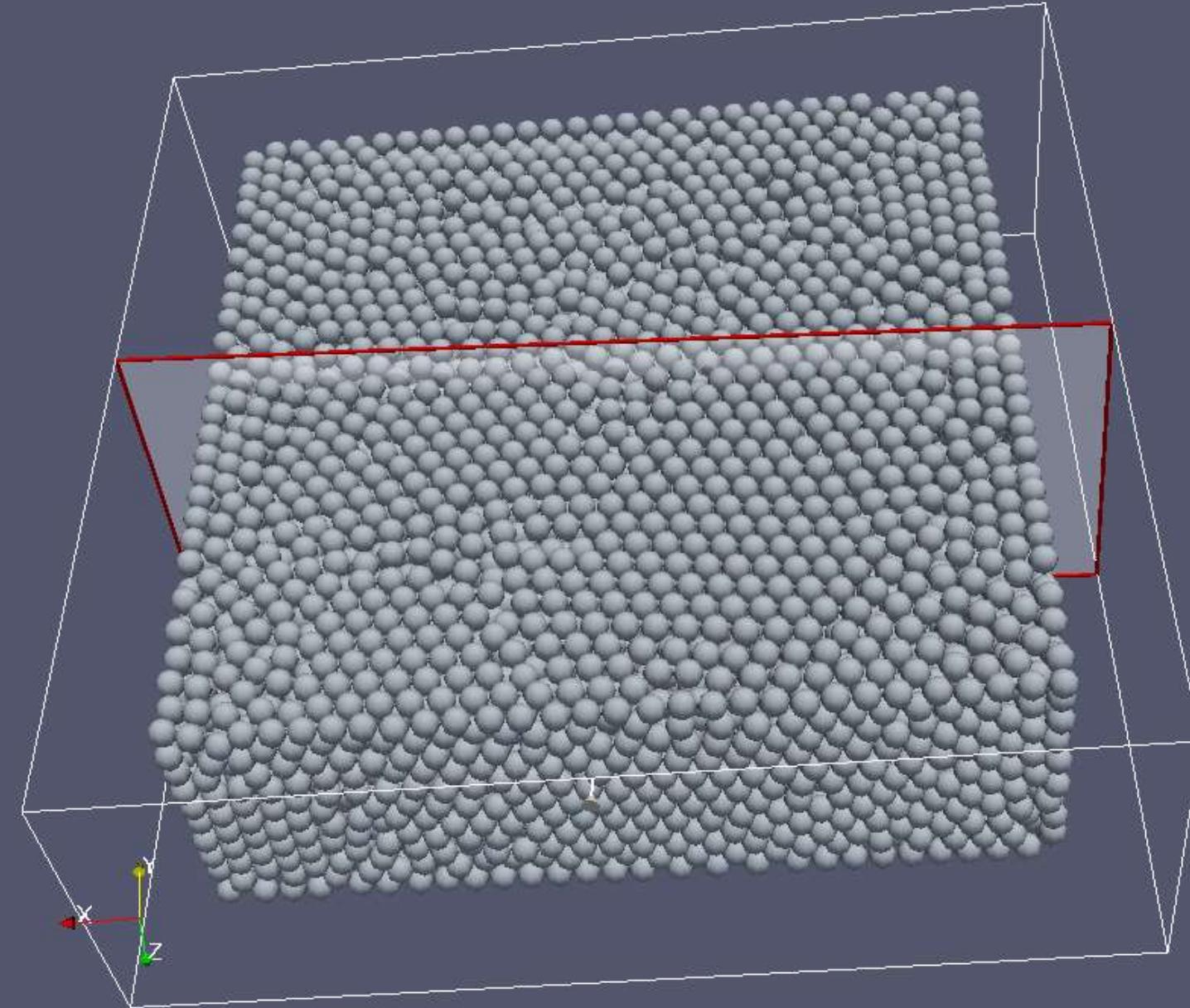
# Stress:strength relationship

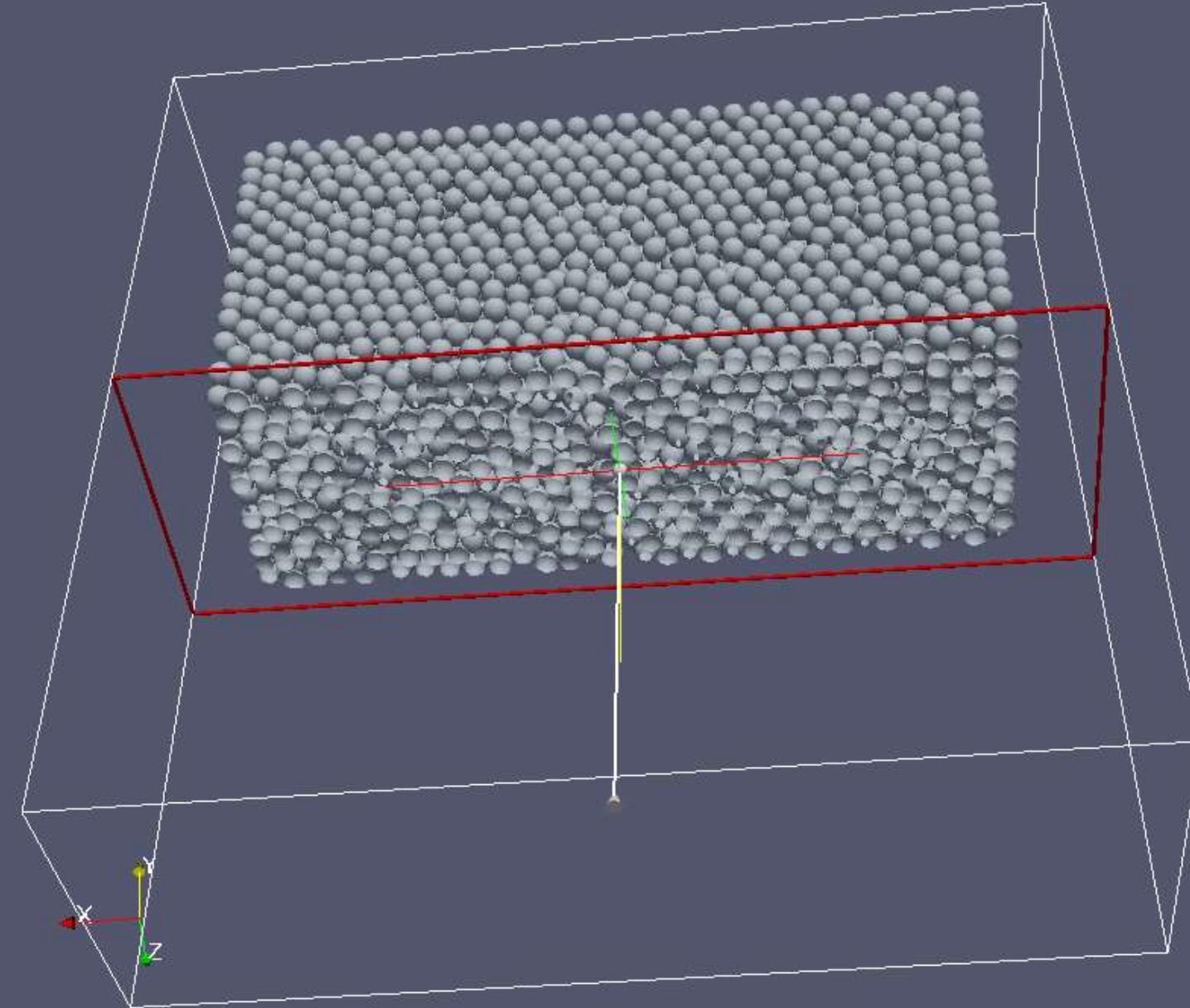


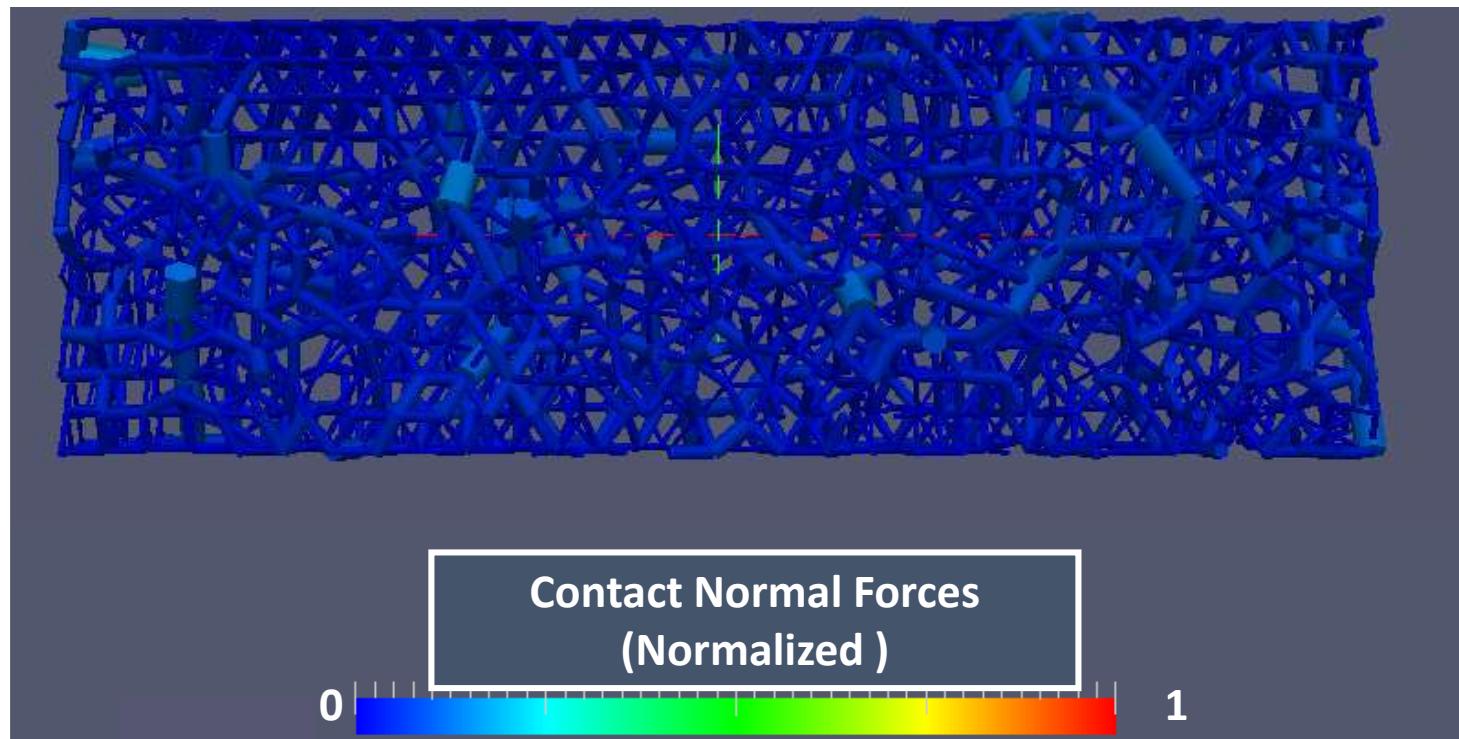
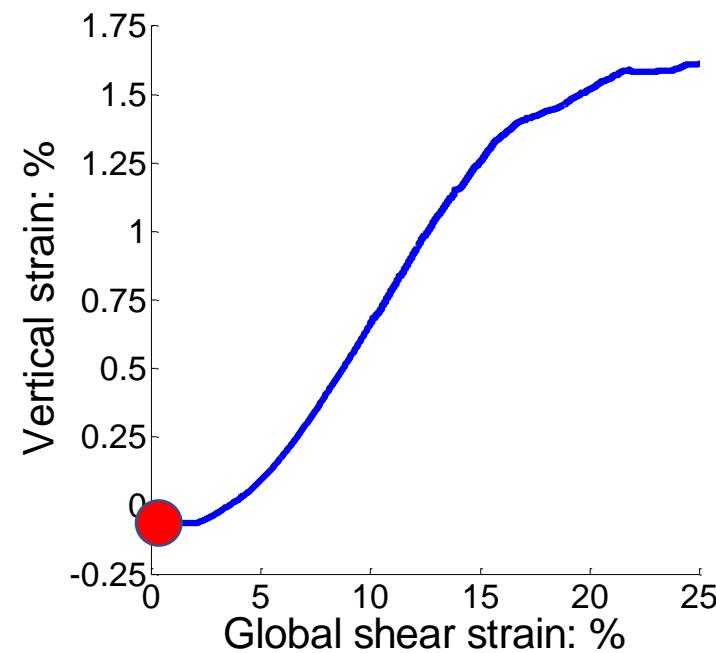
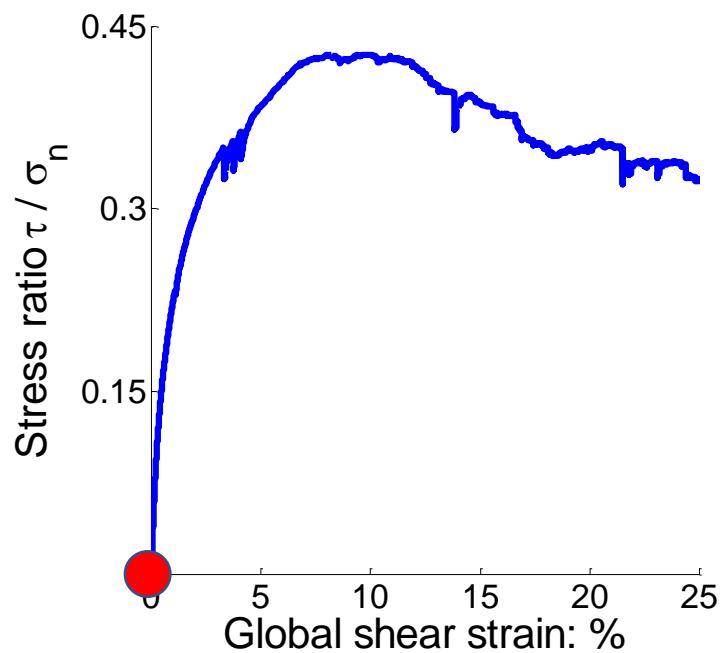
# Effect of particle friction

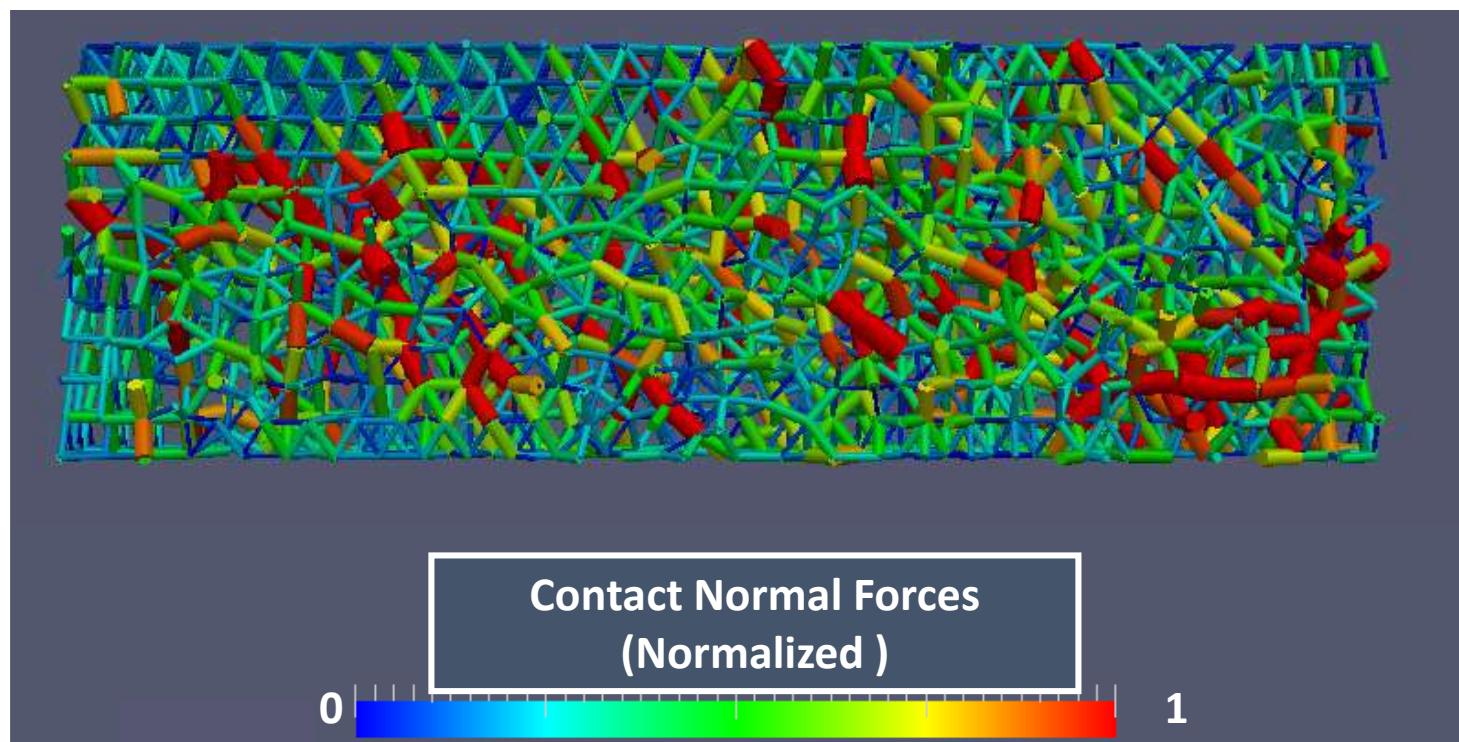
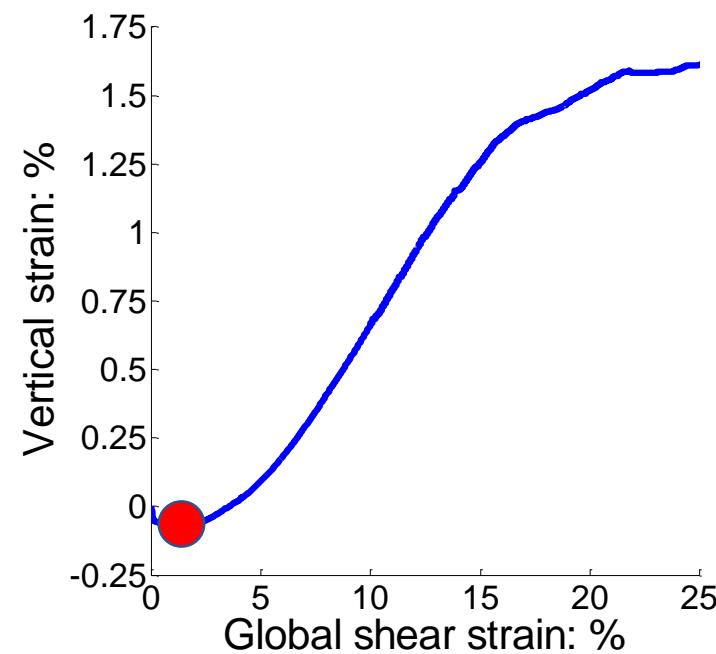
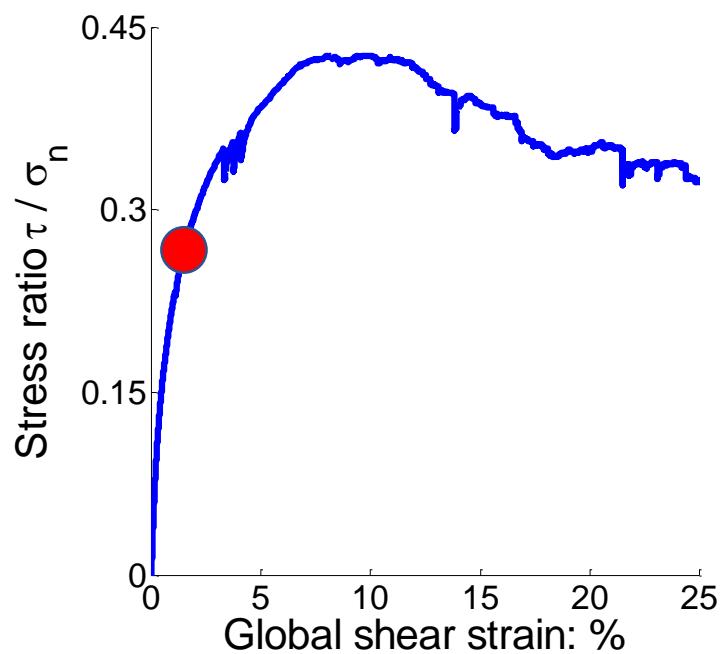


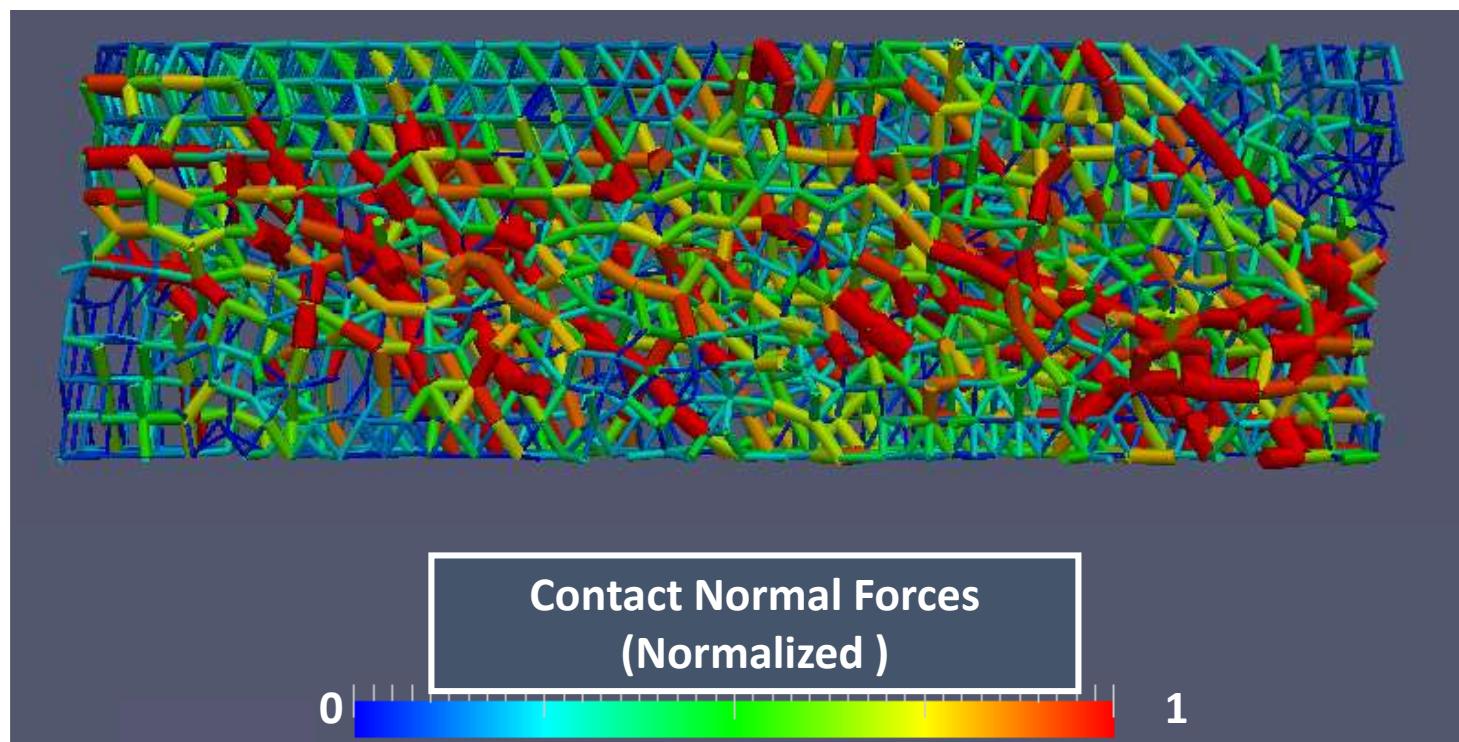
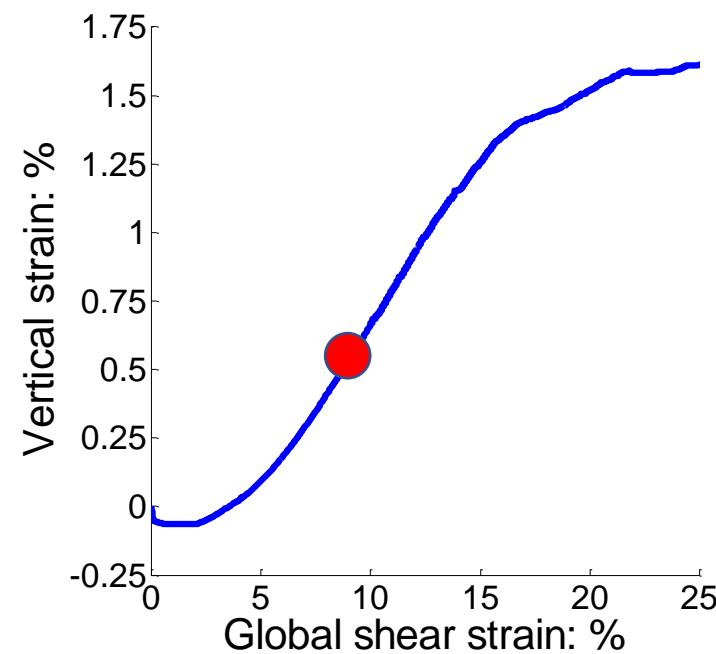
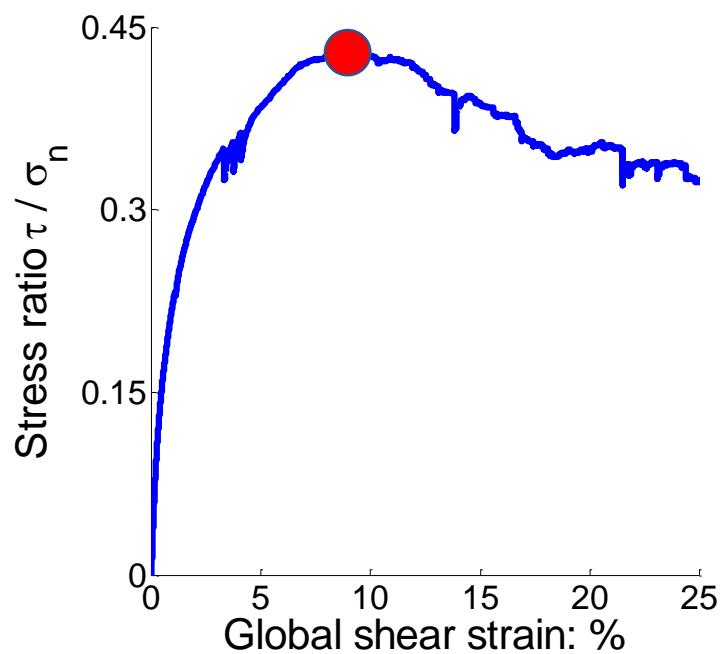


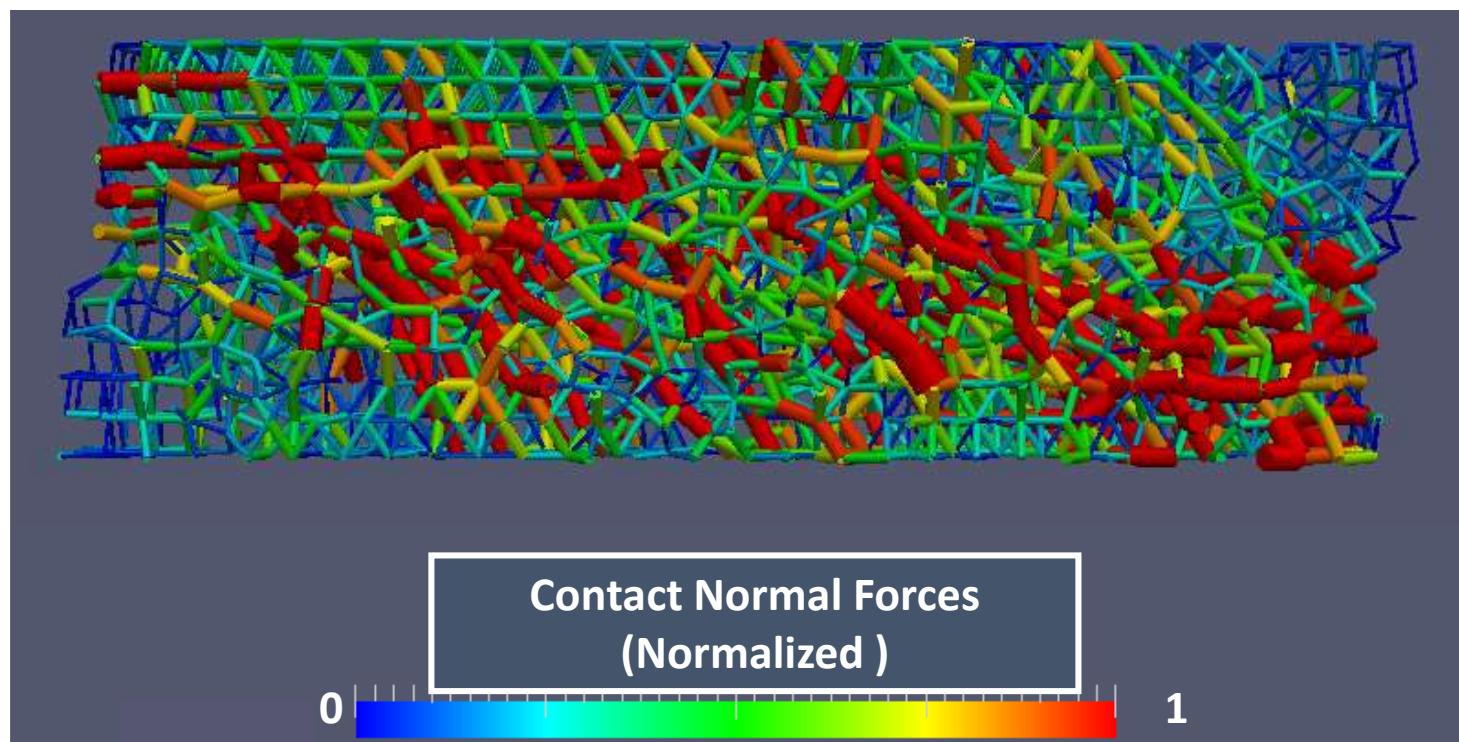
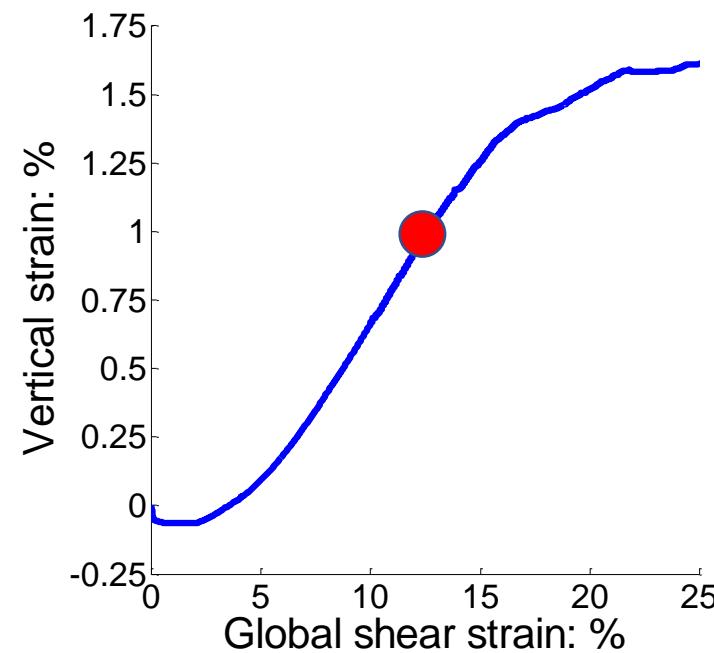
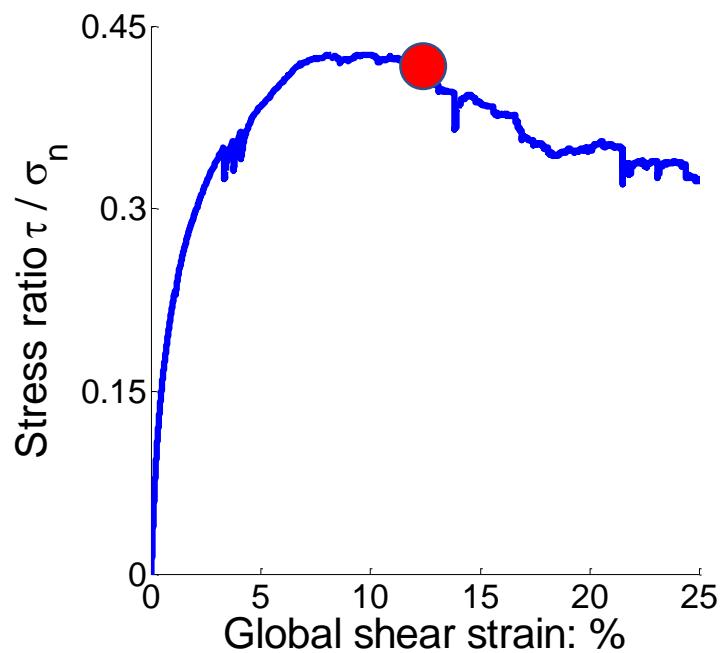


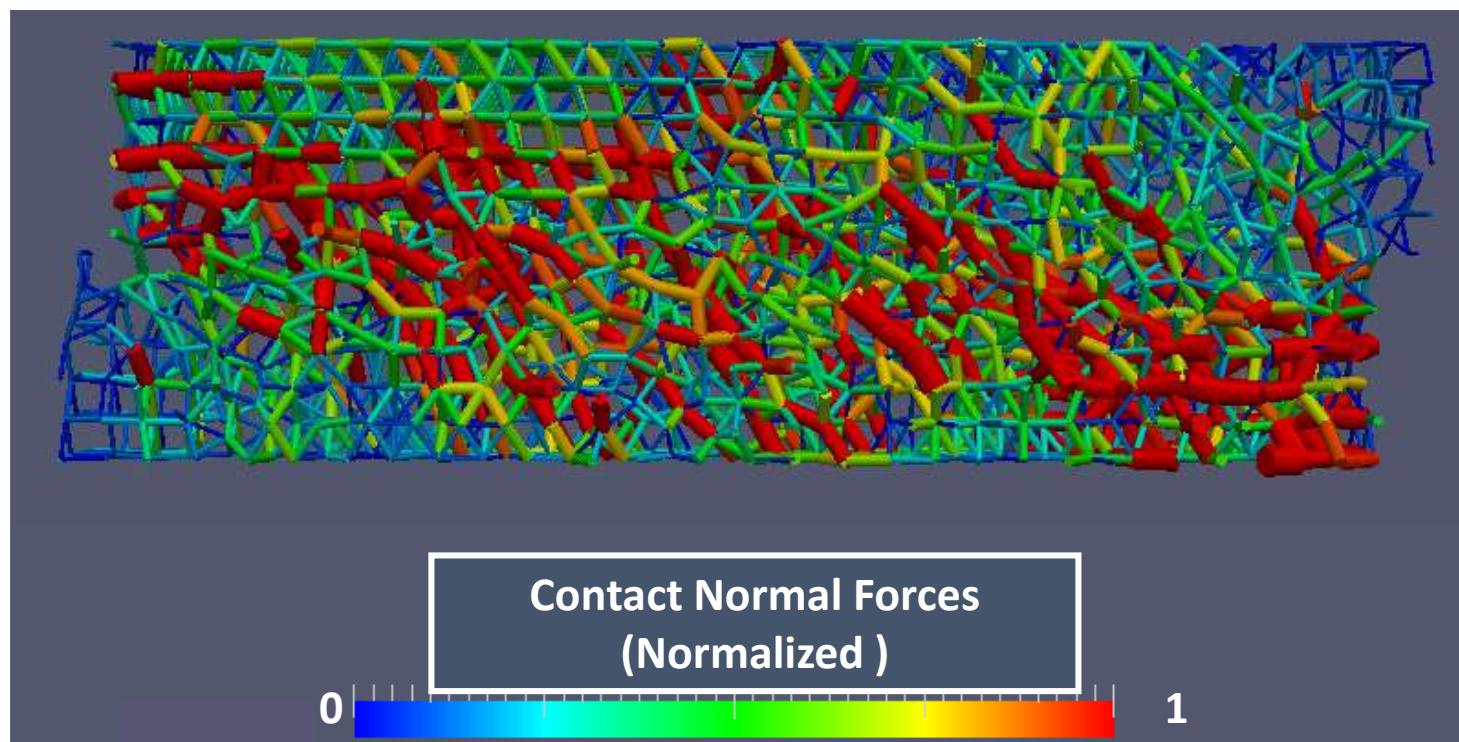
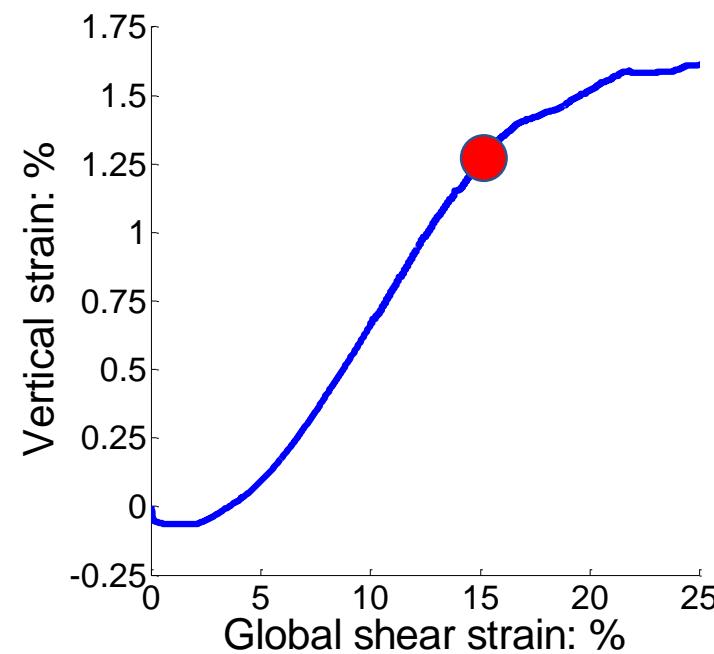
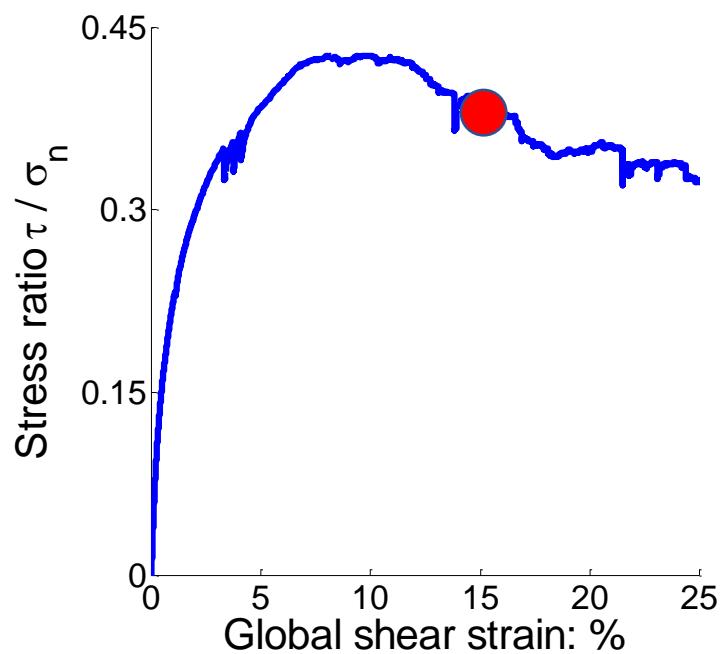


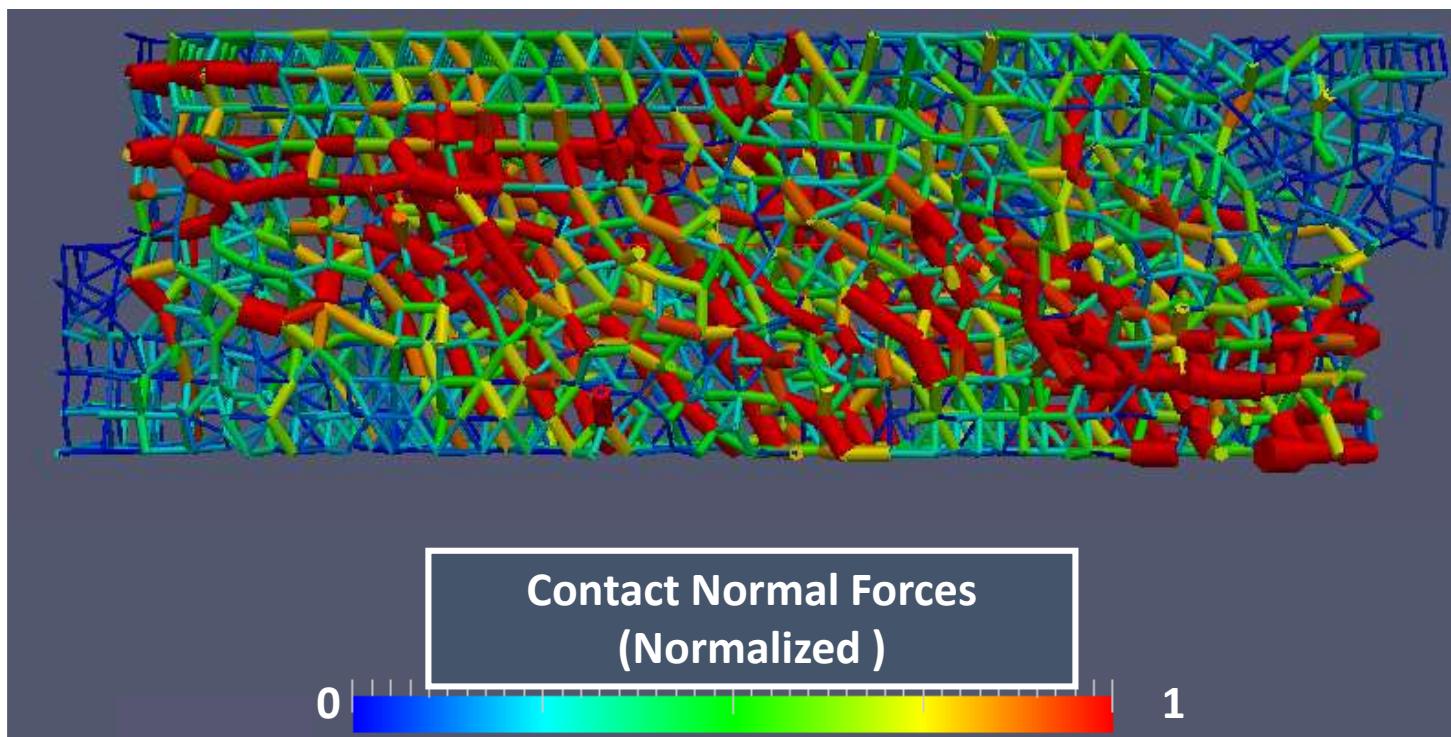
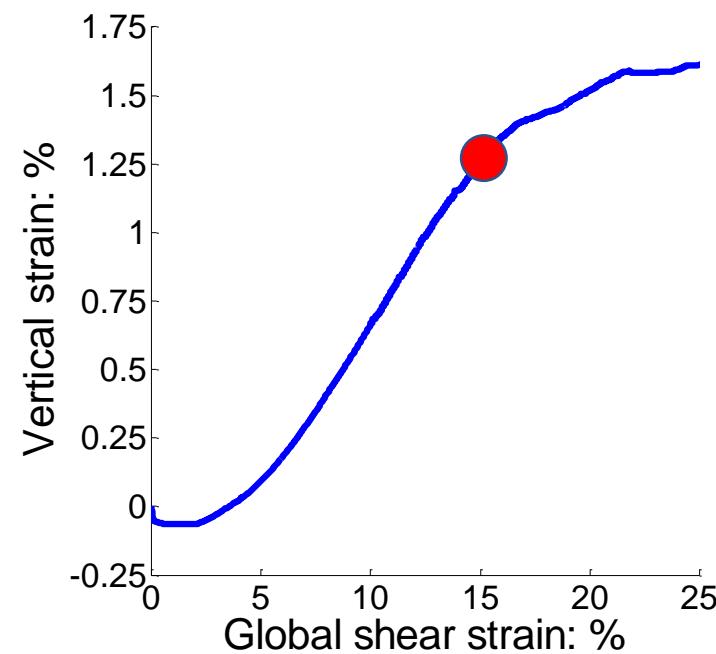
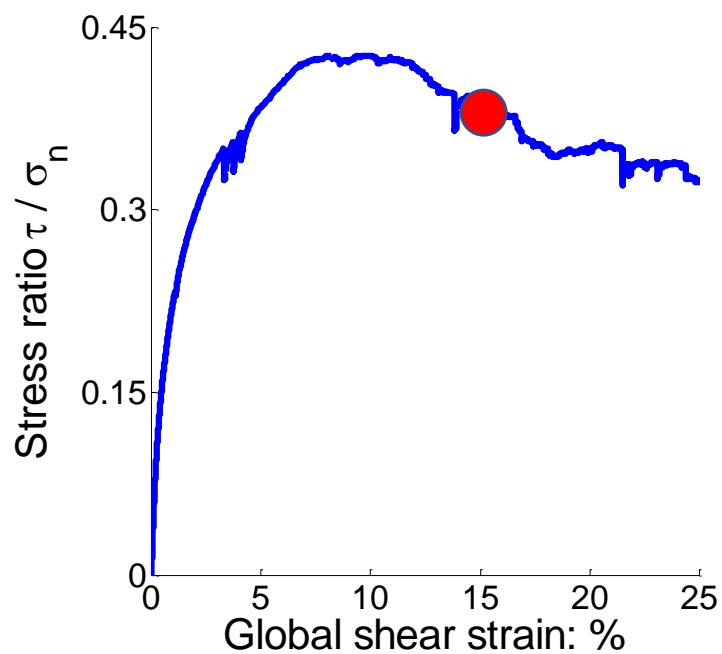


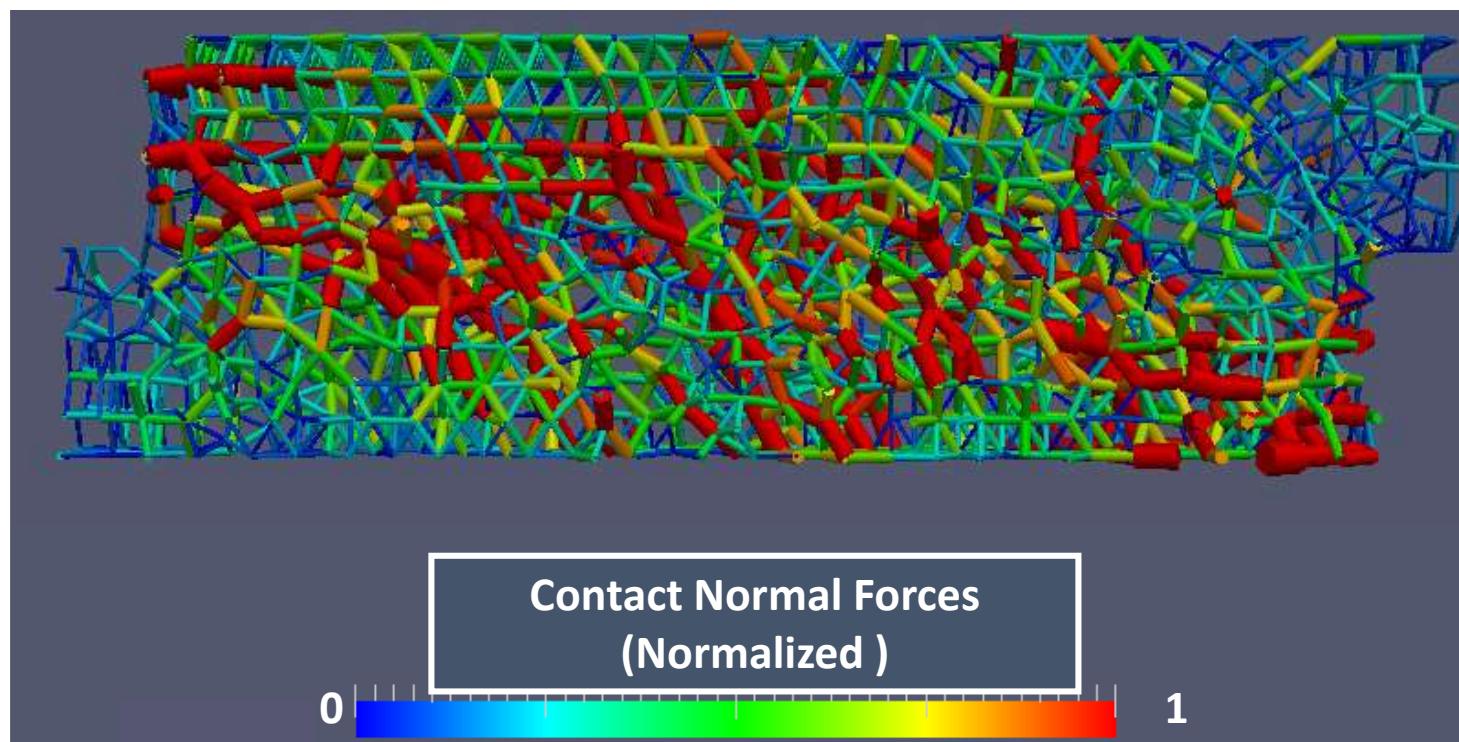
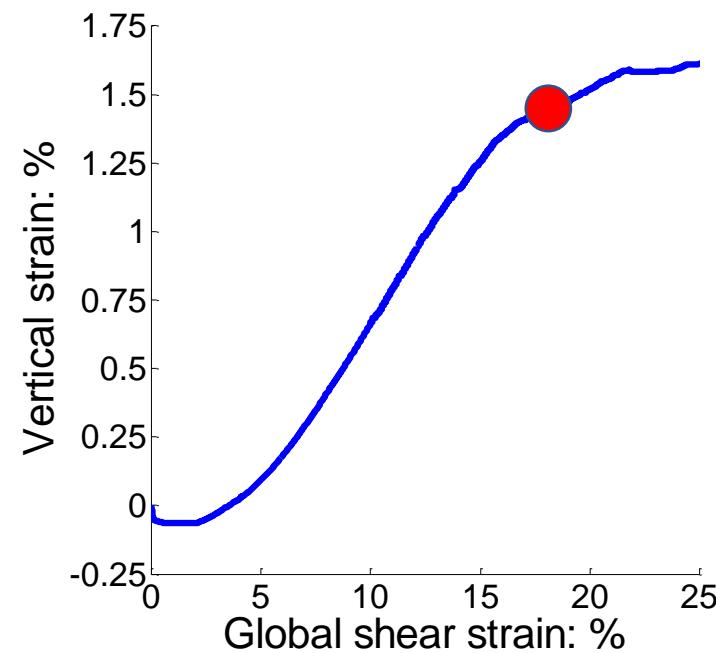
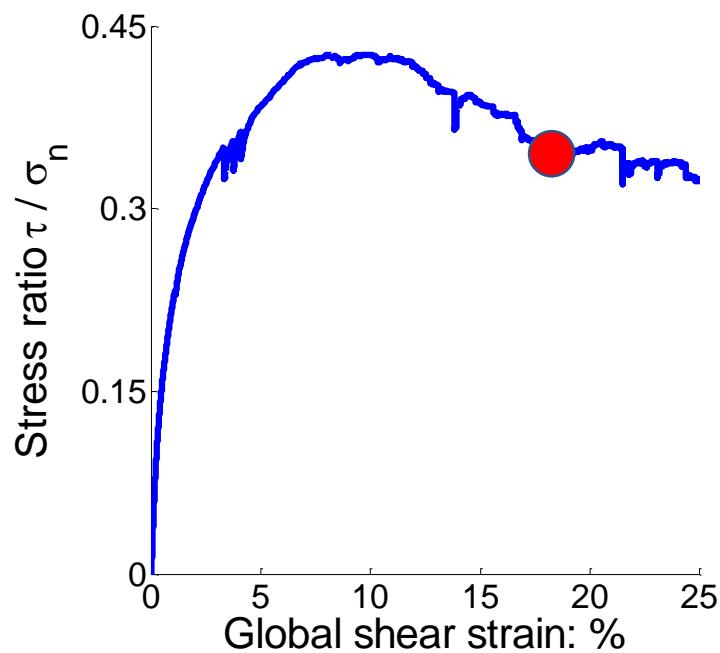


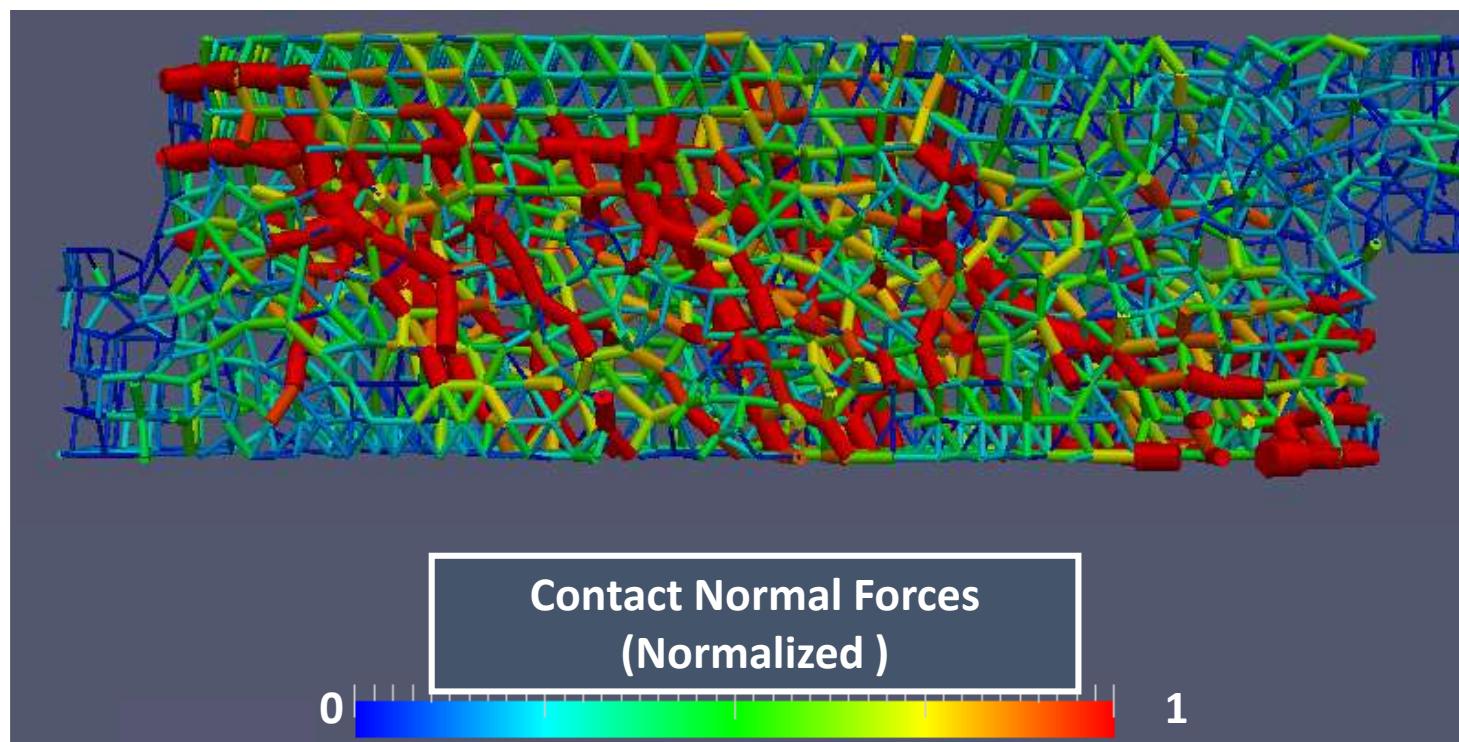
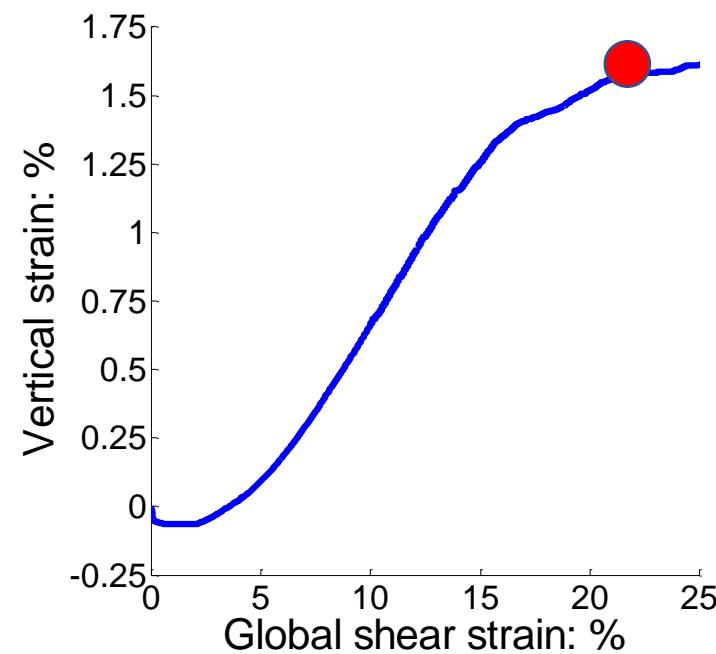
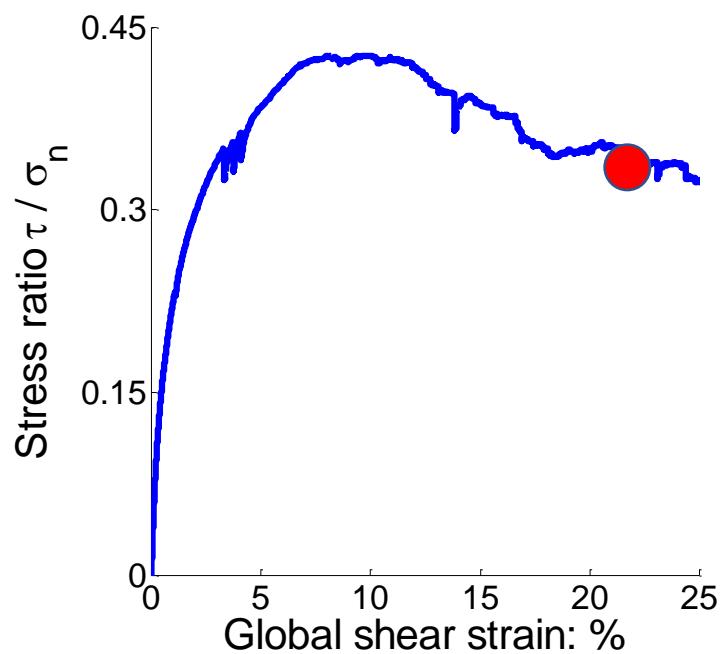


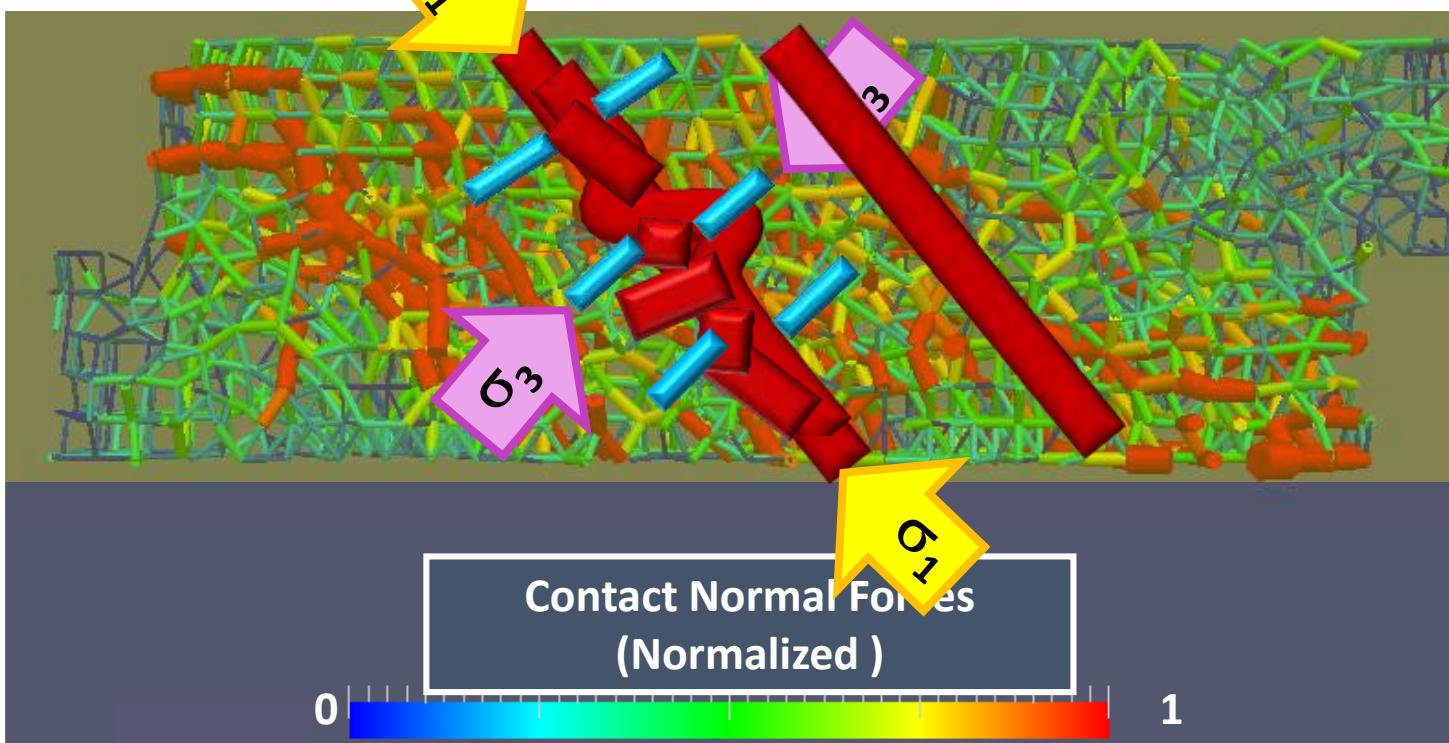
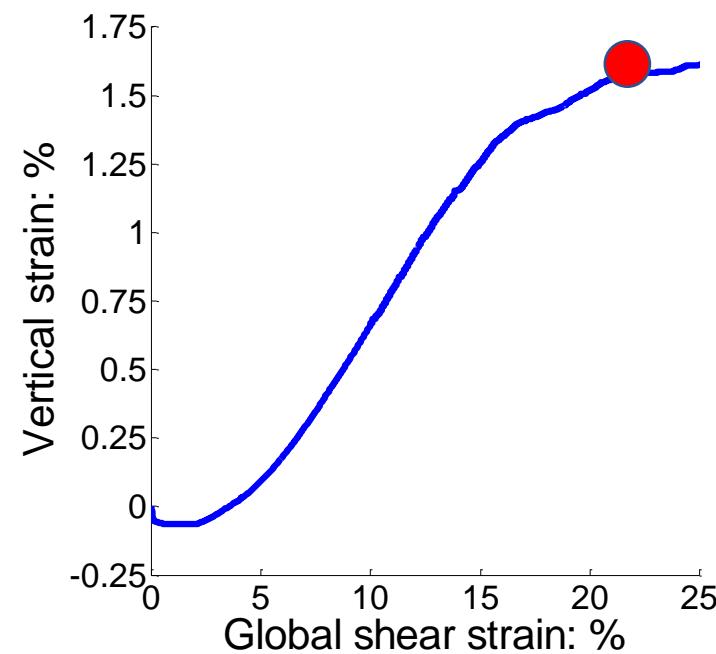
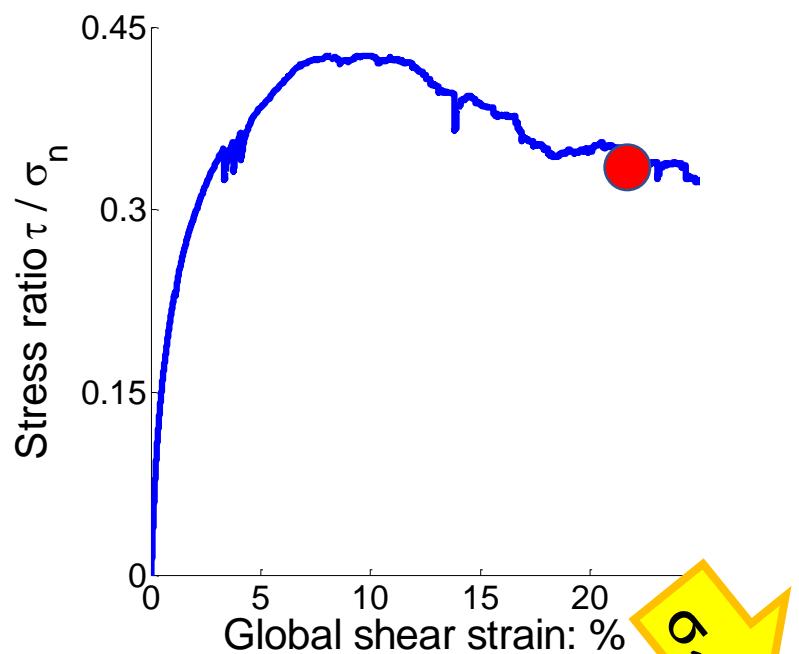




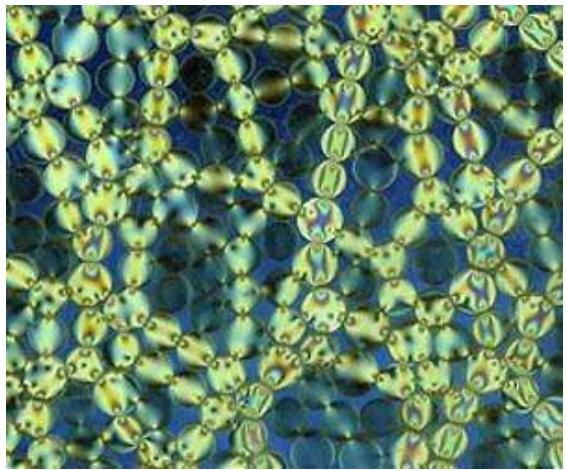






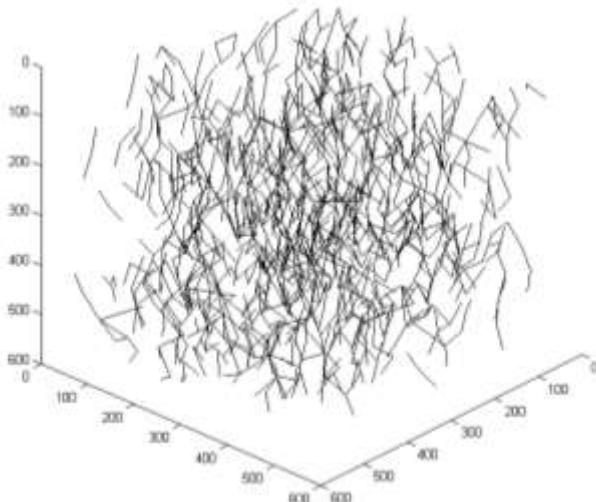
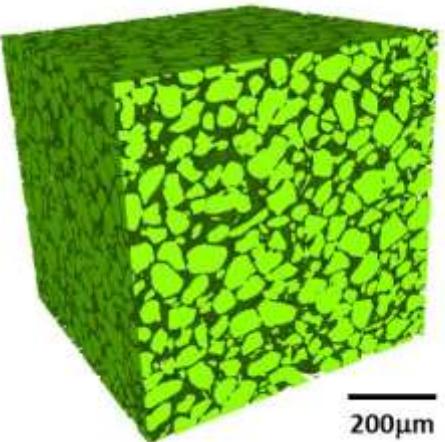


# Force chains

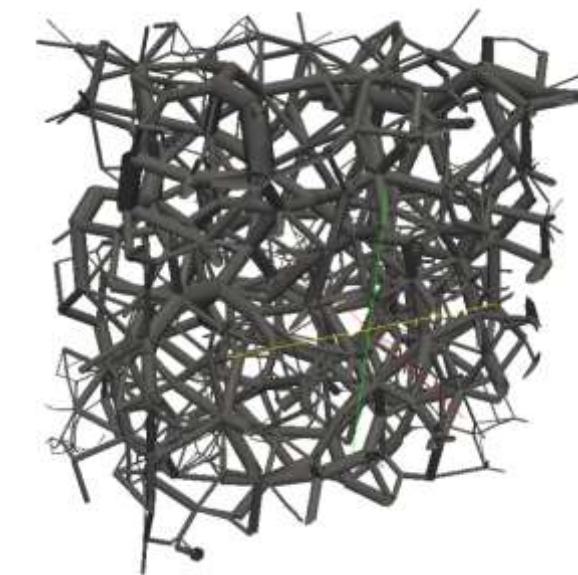
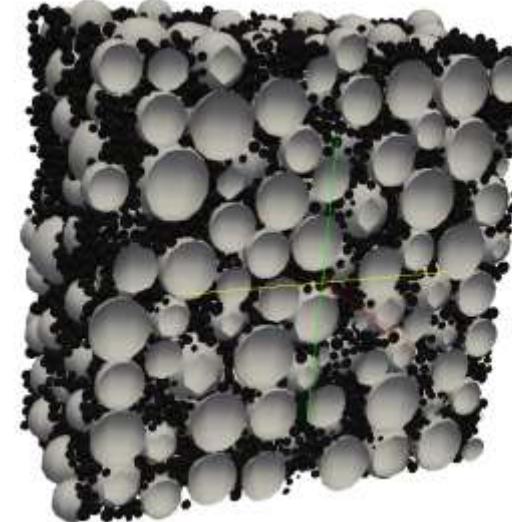


Photoelastic grains under  
shear

Photo/Behringer Group,  
Duke University

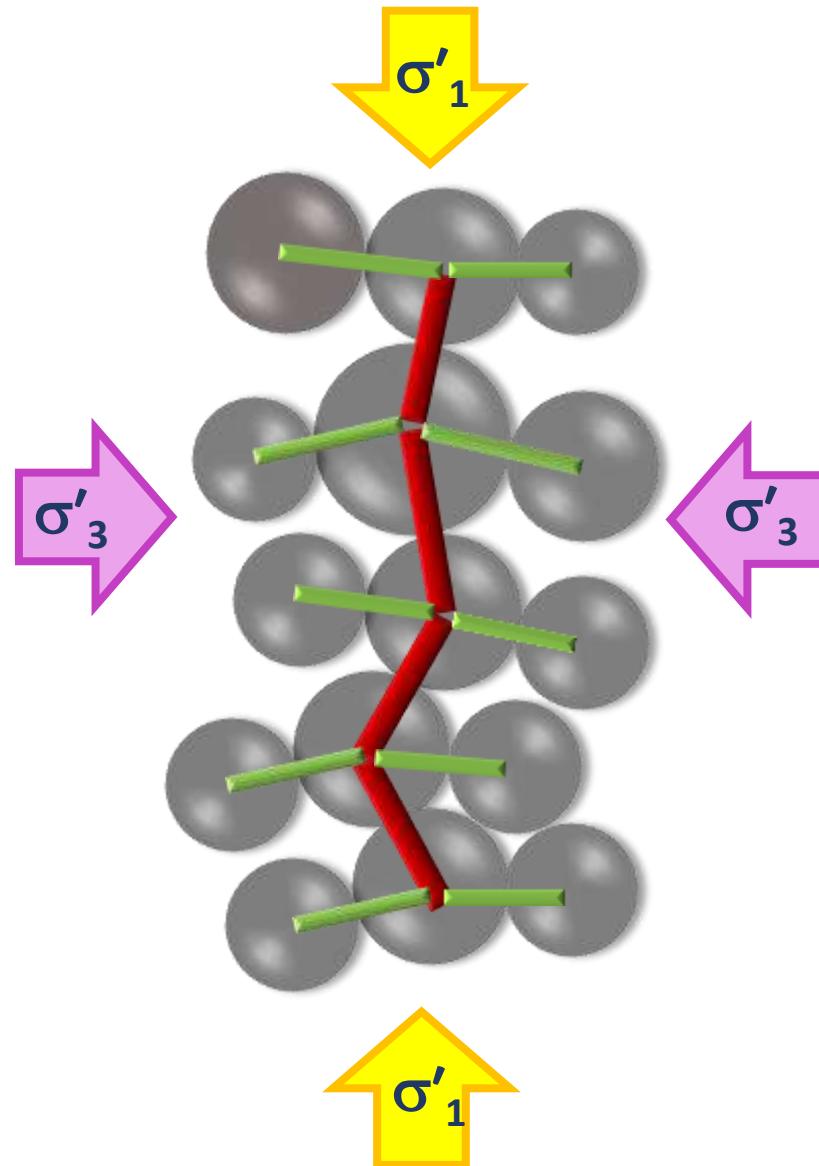
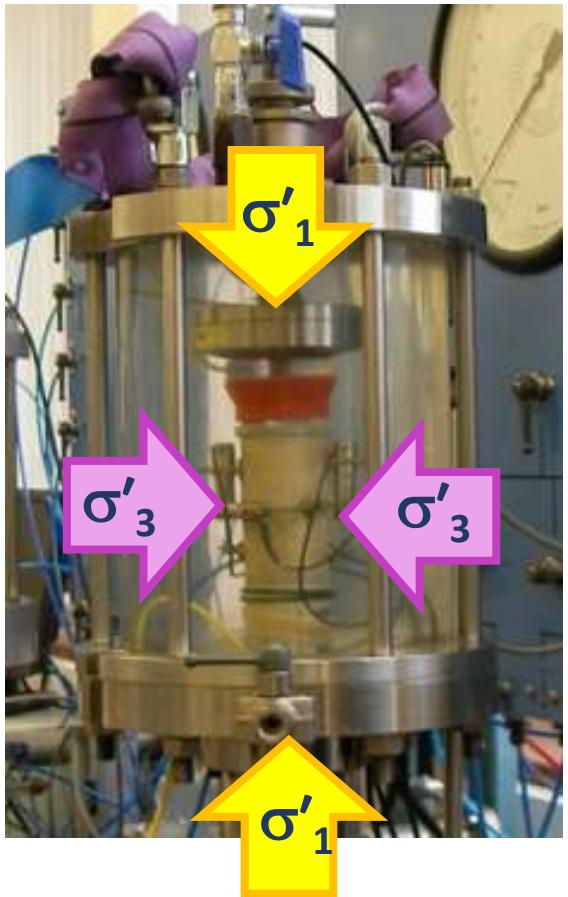


Force chains inferred from  
3D microCT image  
Fonseca et al. ( 2017)

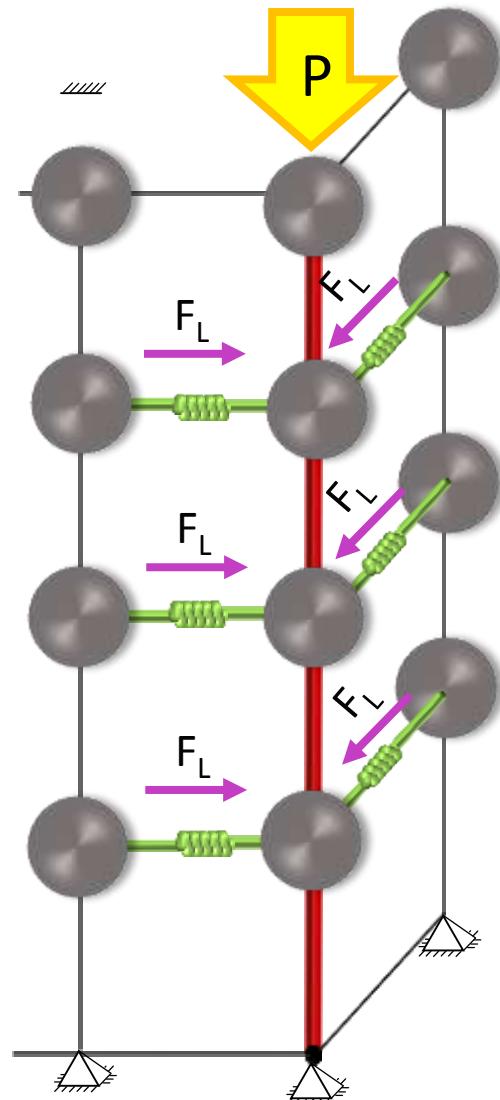
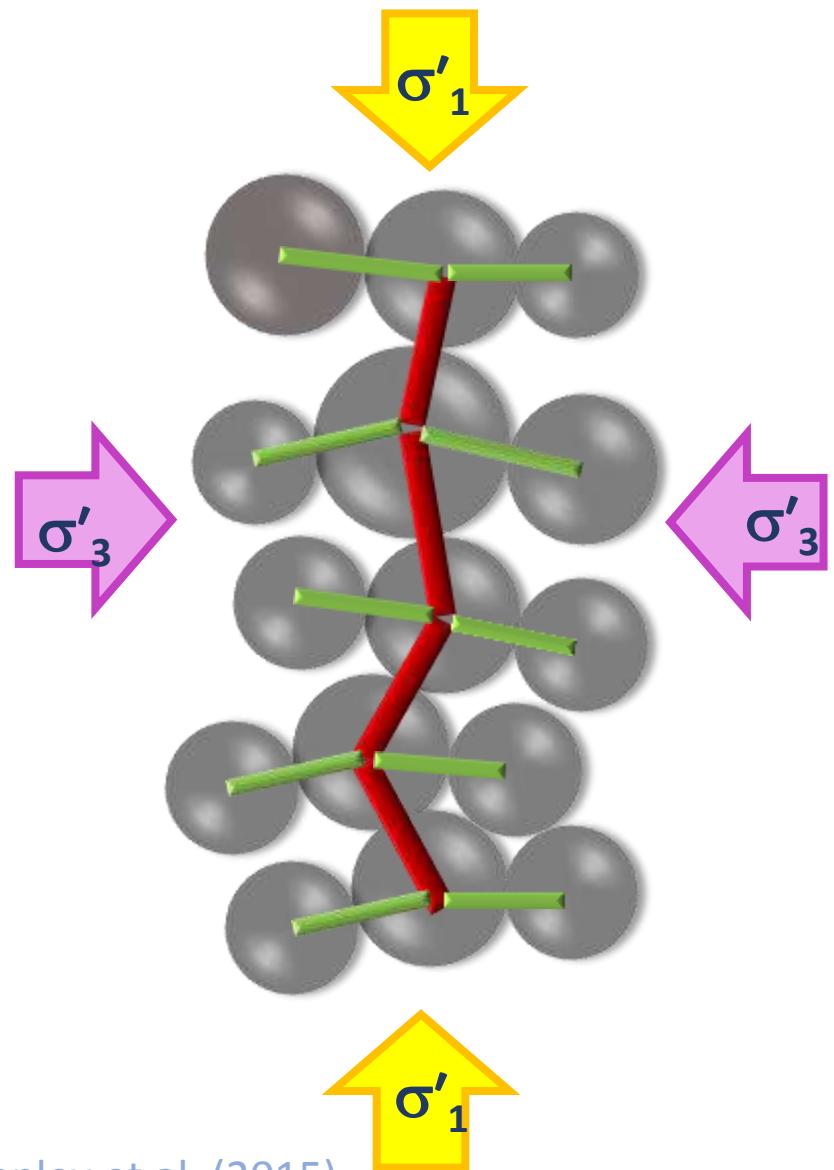


Force chains in 3D DEM  
simulation  
Shire (2011)

# Stress:strength relationship

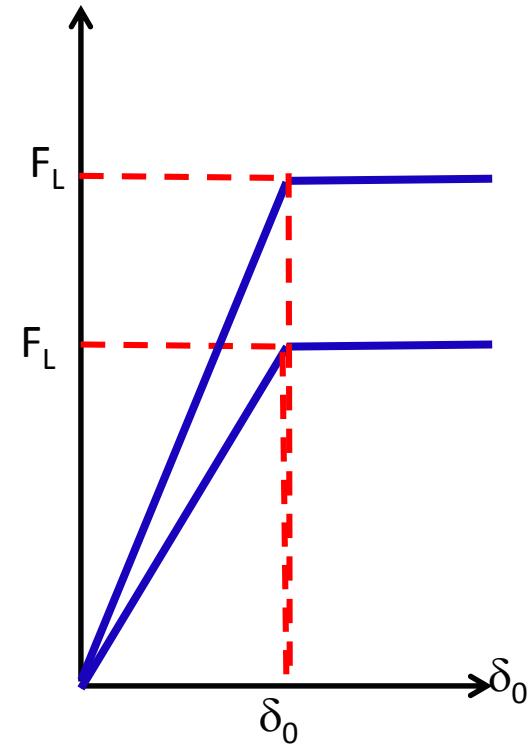


# Stress:strength relationship

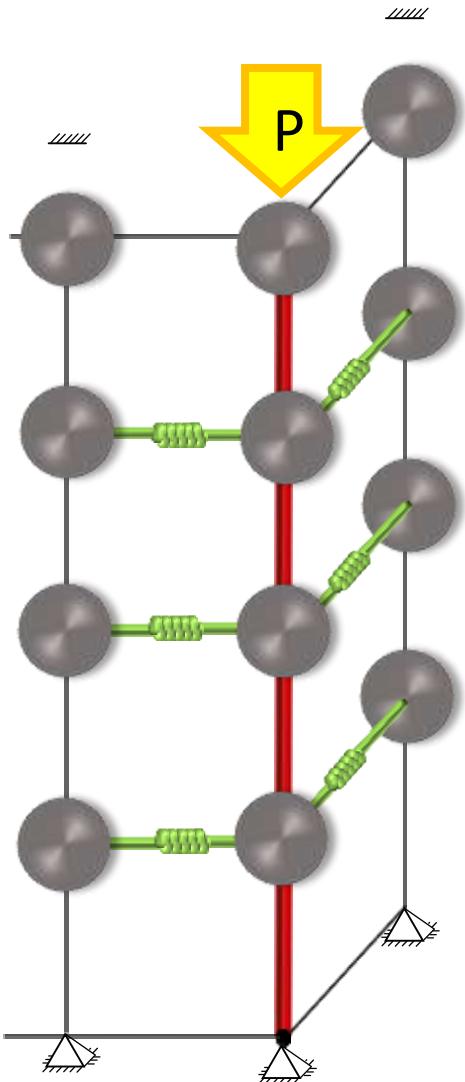


Spring and rigid link model of  
single force chain

Vary FL to model varying  $\sigma'_3$

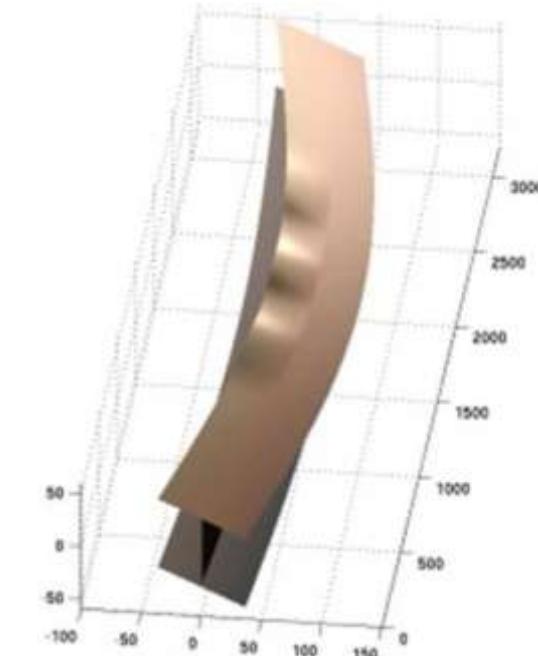


# Stress:strength relationship



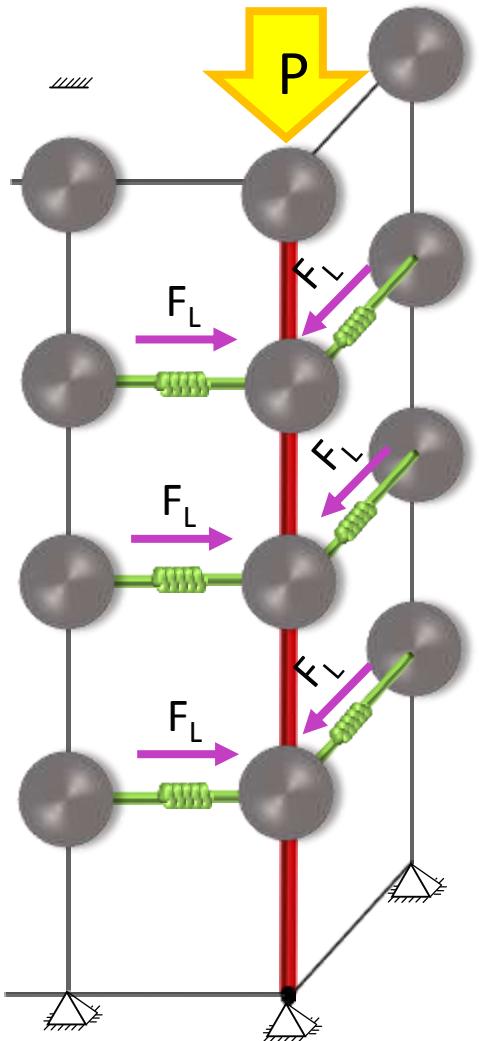
Spring and rigid link model of single force chain

To find  $P$  that causes buckling  
↓  
Minimize potential energy function

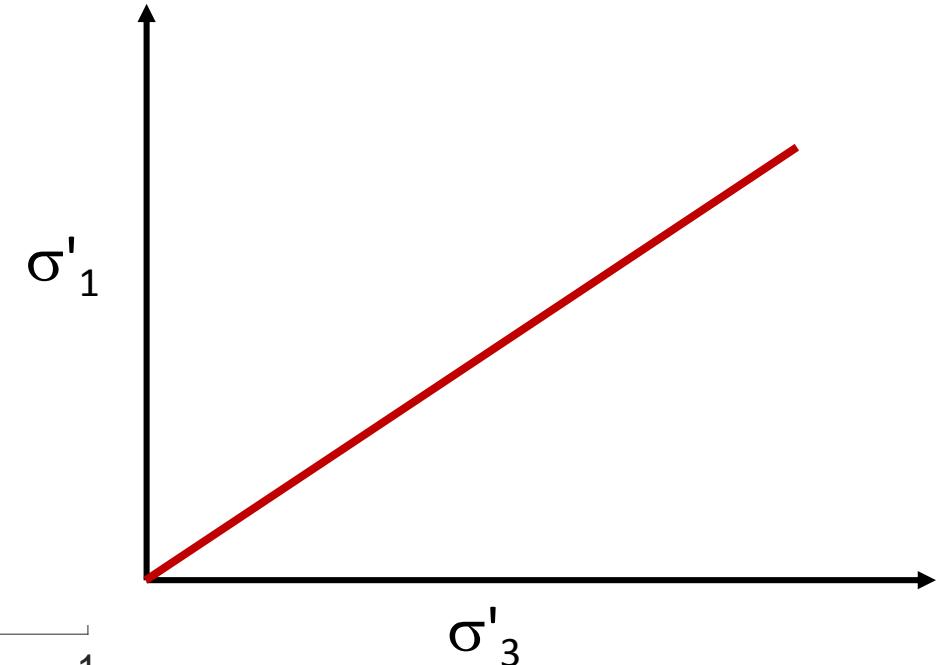
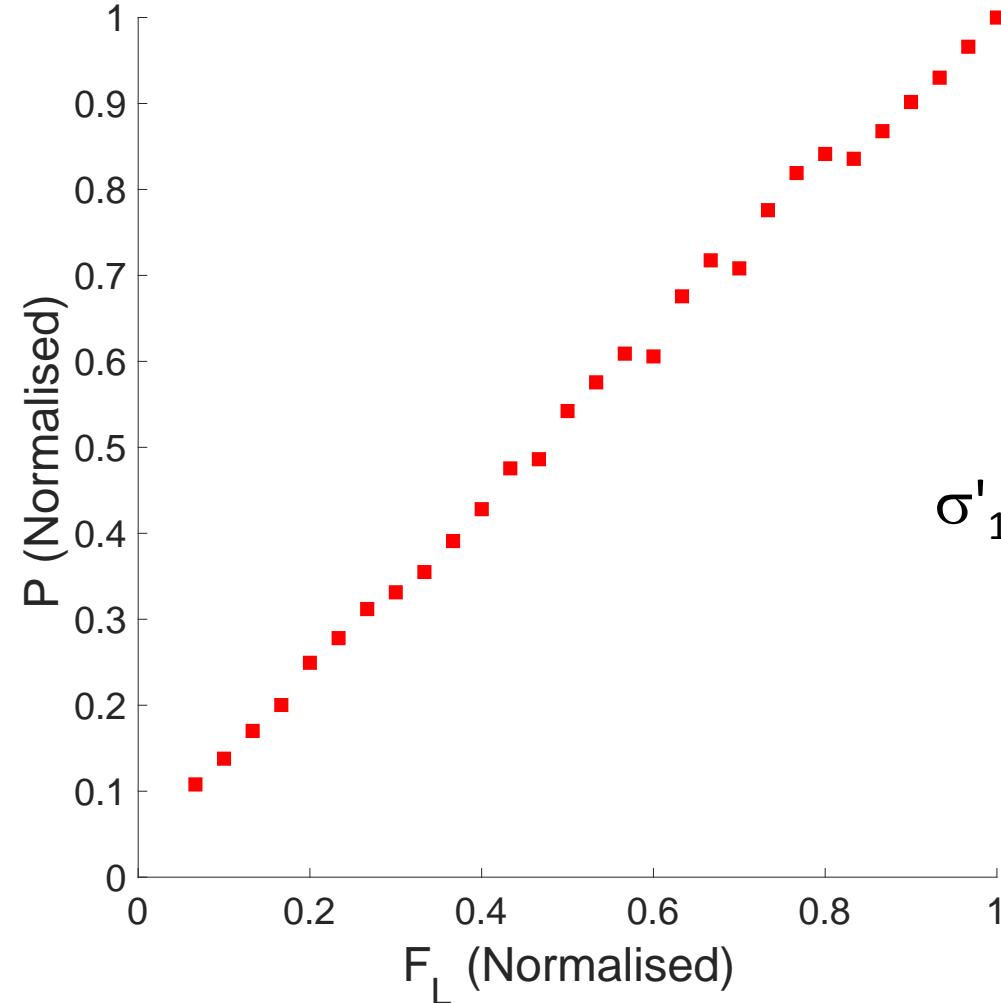


<http://www.imperial.ac.uk/structural-engineering/research/structural-mechanics/nonlinear-structural-stability-group/interactive-buckling-of-thin-walled-structural-components/>

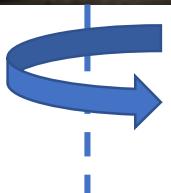
# Stress:strength relationship



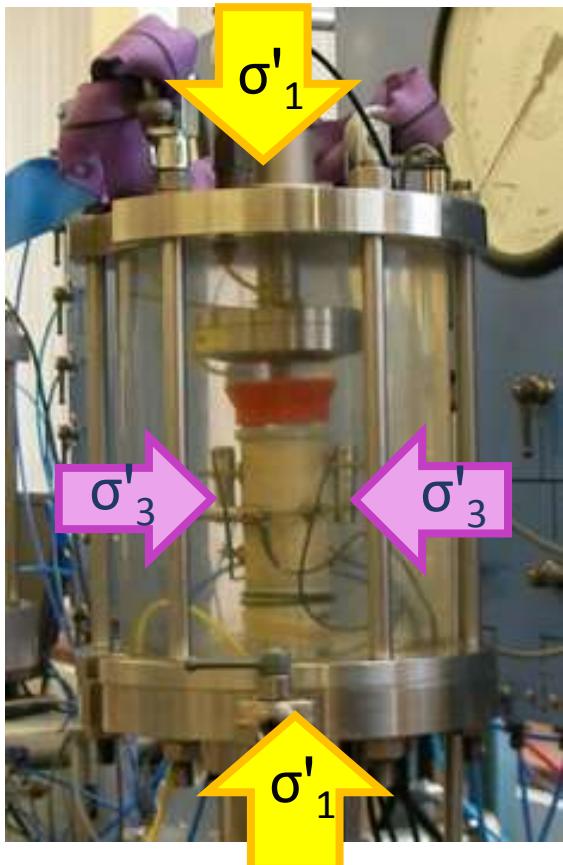
Spring and rigid link model of  
single force chain



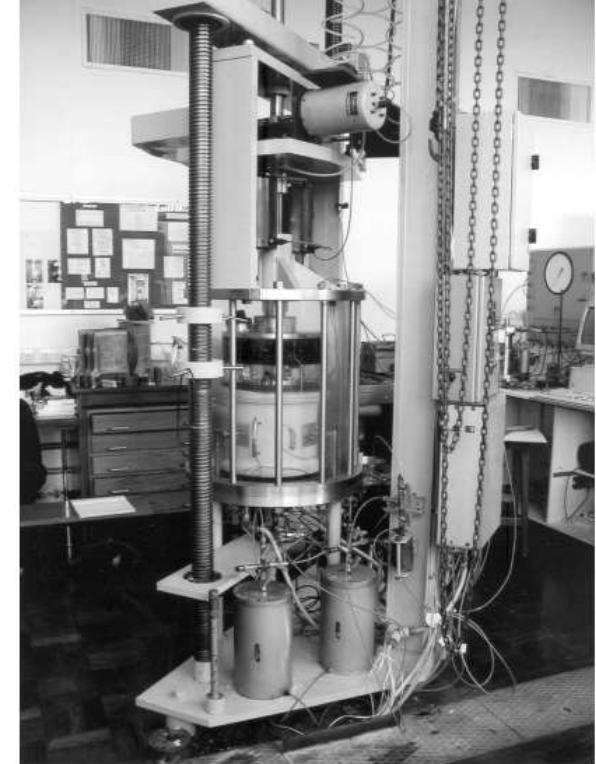
# 3D nature of soil strength



Axisymmetric stress  
conditions

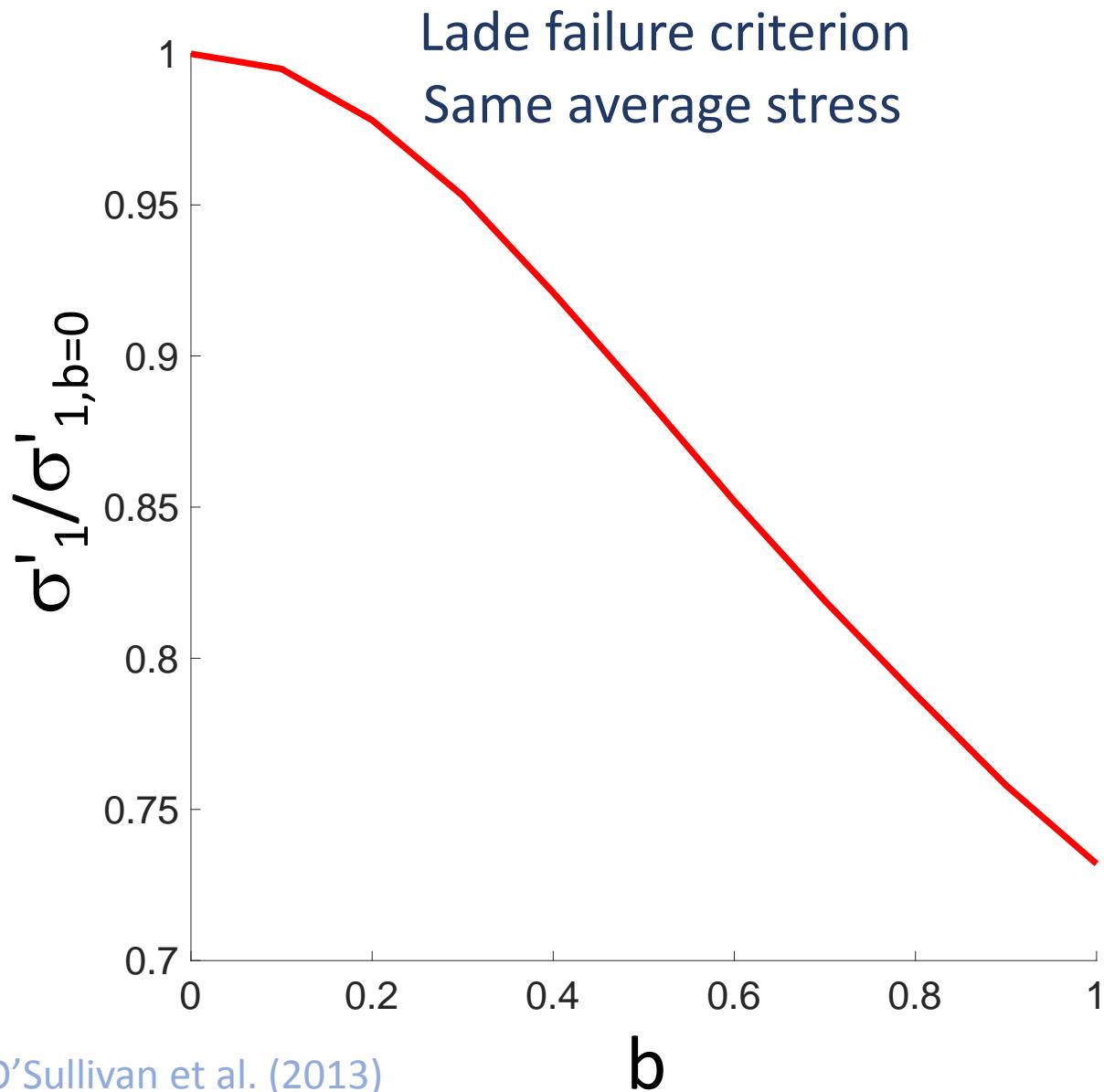


Non-axisymmetric stress  
conditions

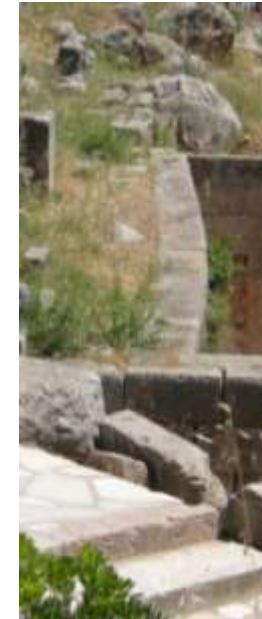


$$\sigma'_1 > \sigma'_2 > \sigma'_3$$

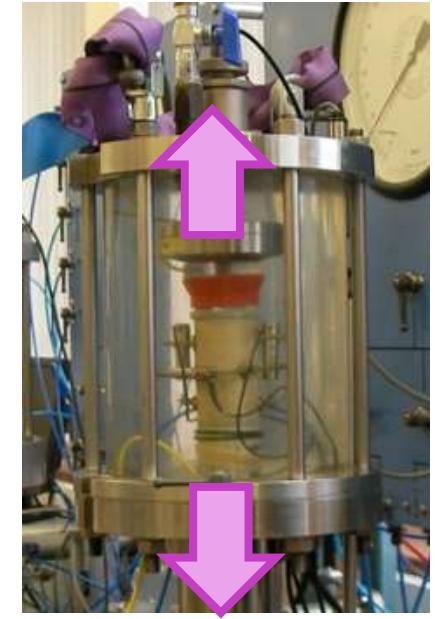
# 3D nature of soil strength



$b=0$

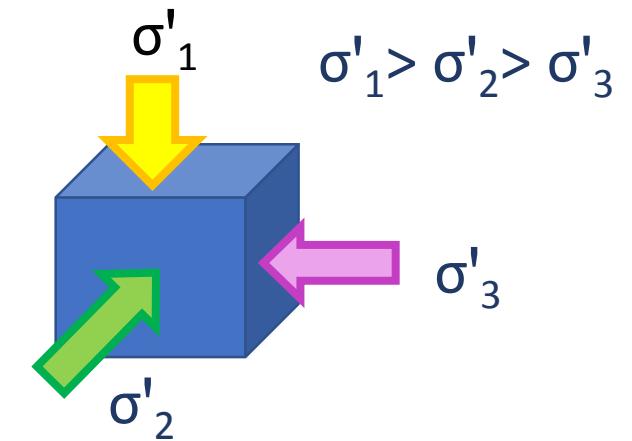


$b \approx 0.5$

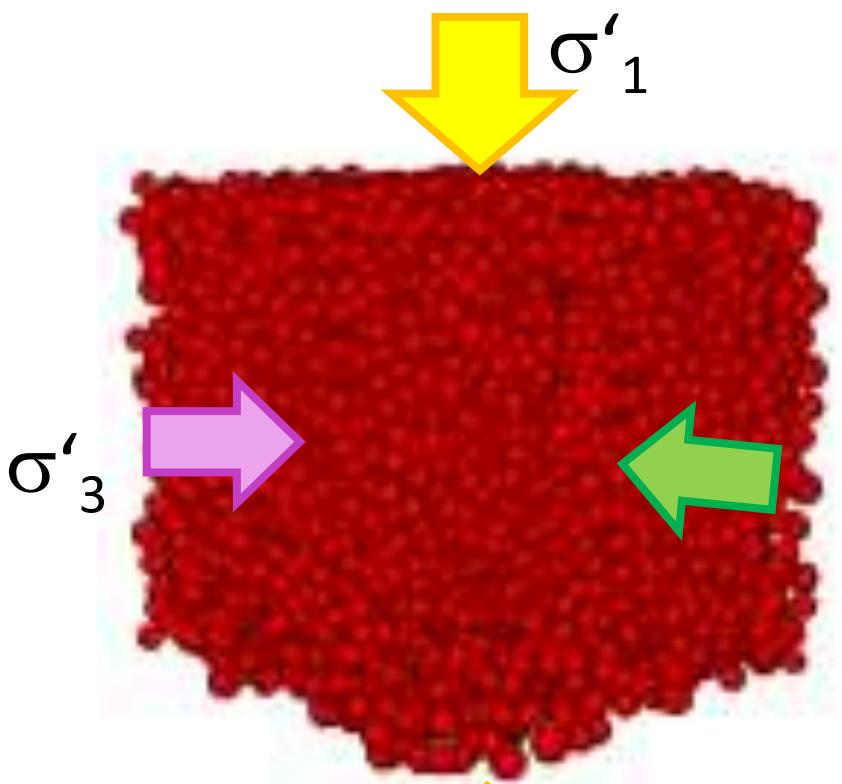


$b=1$

$$b = \frac{\sigma'_2 - \sigma'_3}{\sigma'_1 - \sigma'_3}$$



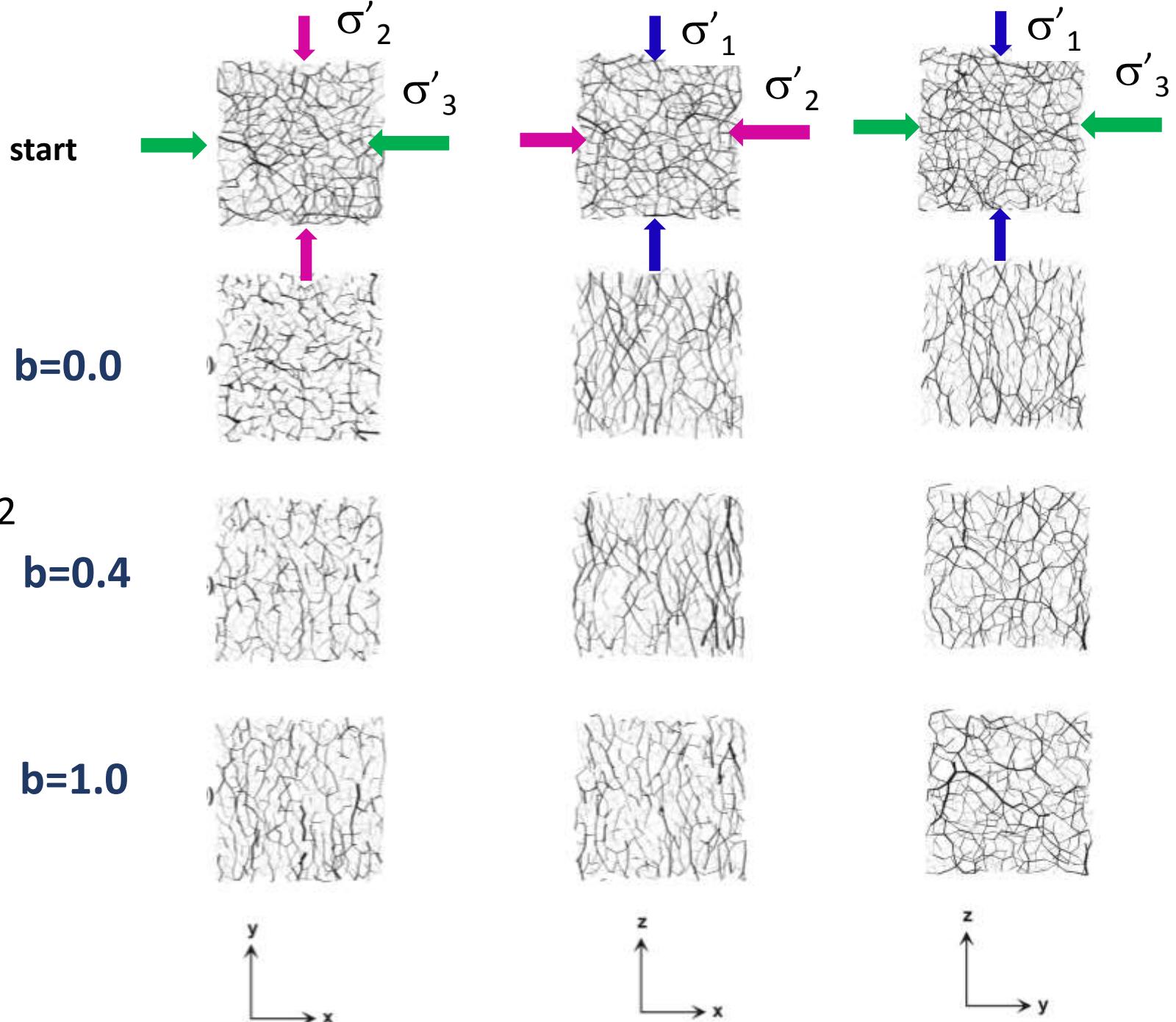
# 3D soil strength



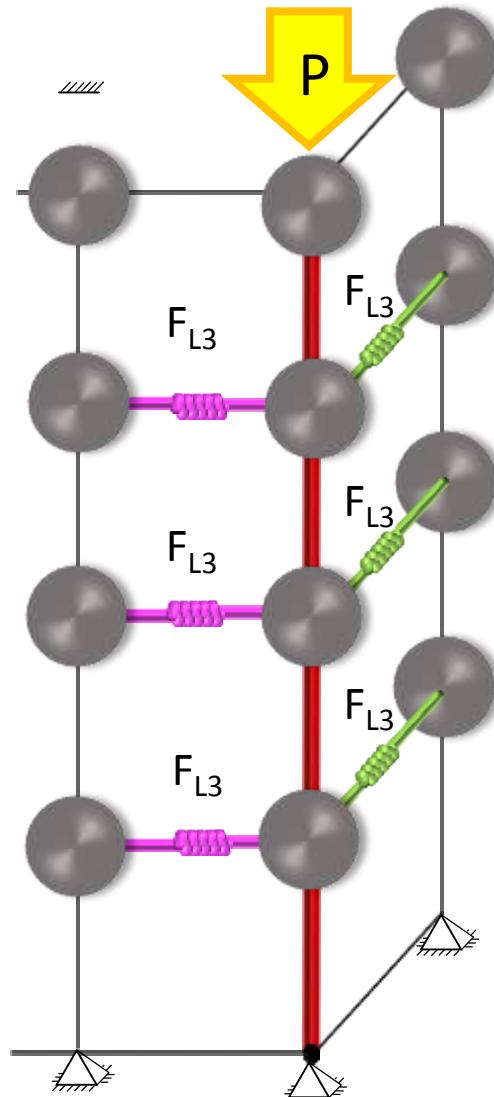
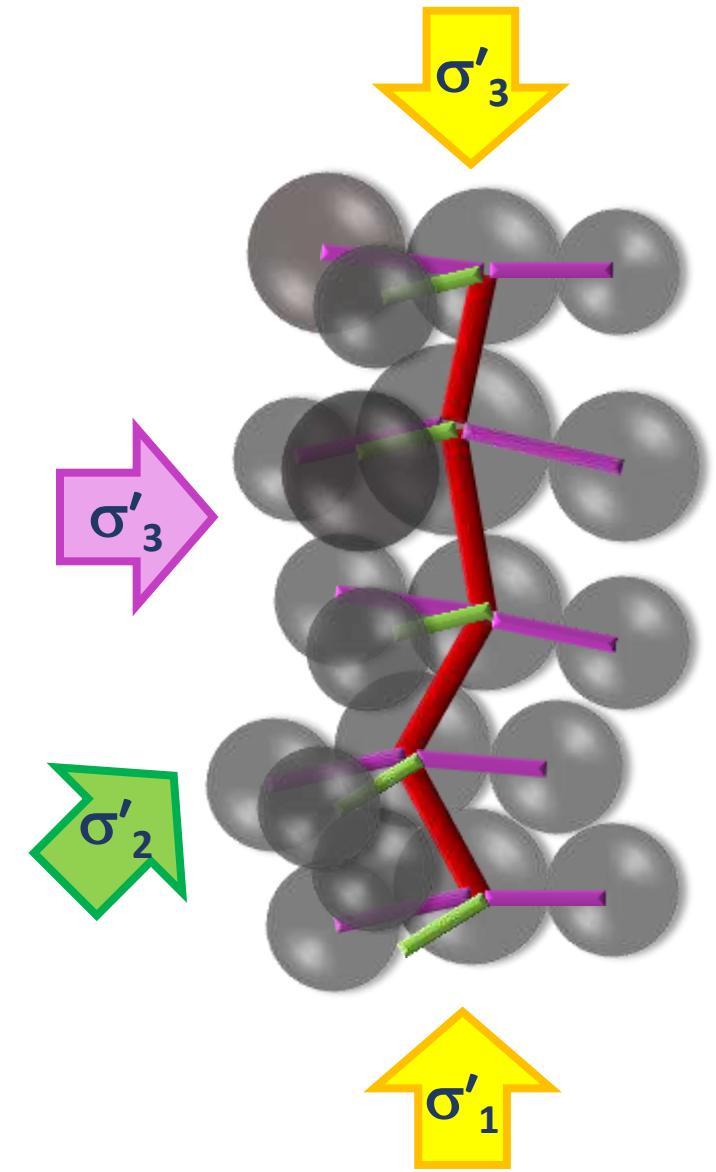
4000 spheres

Narrow size distribution

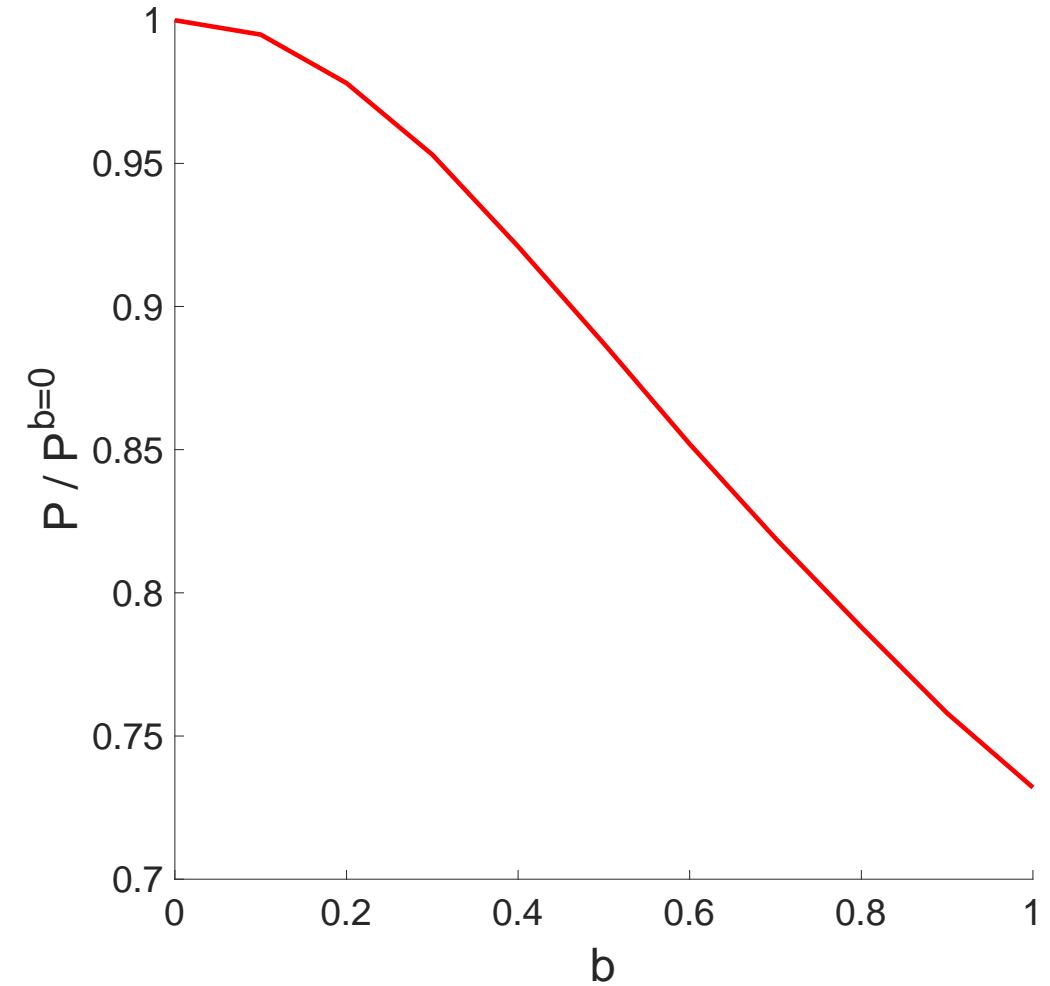
Barreto (2008)



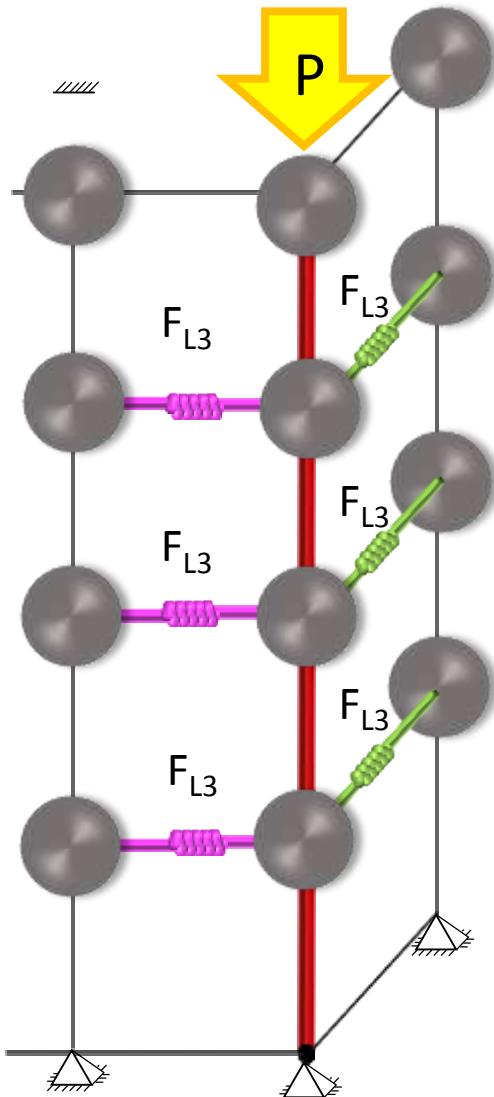
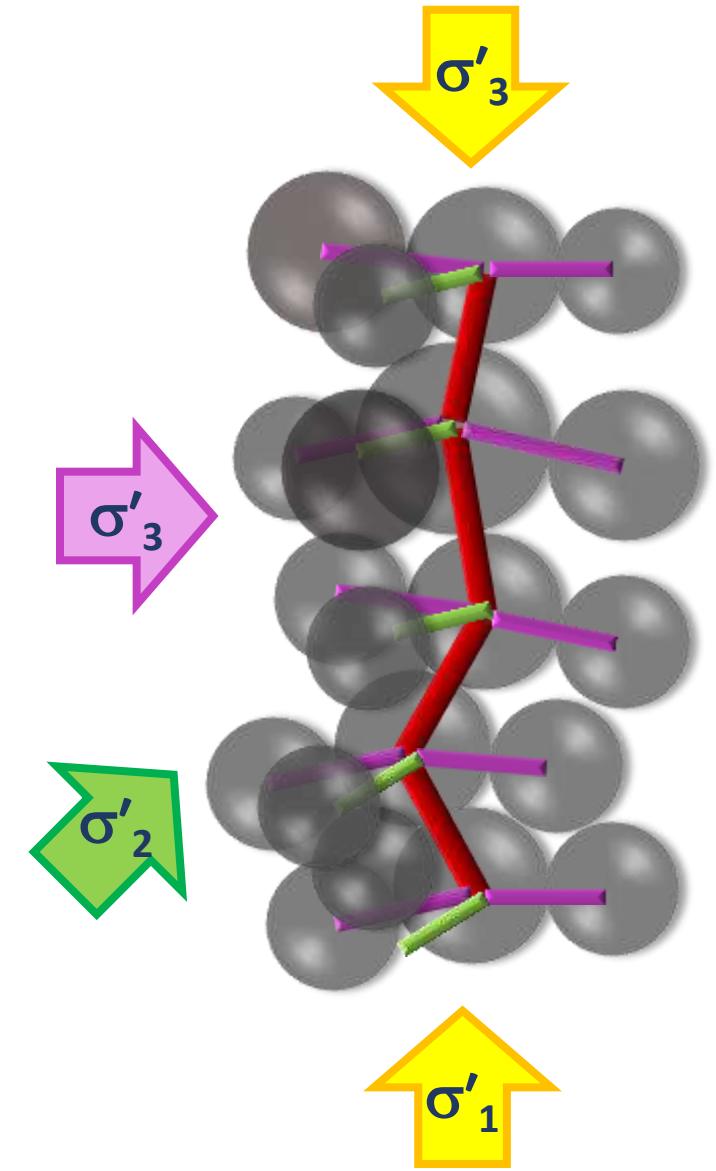
# 3D nature of soil strength



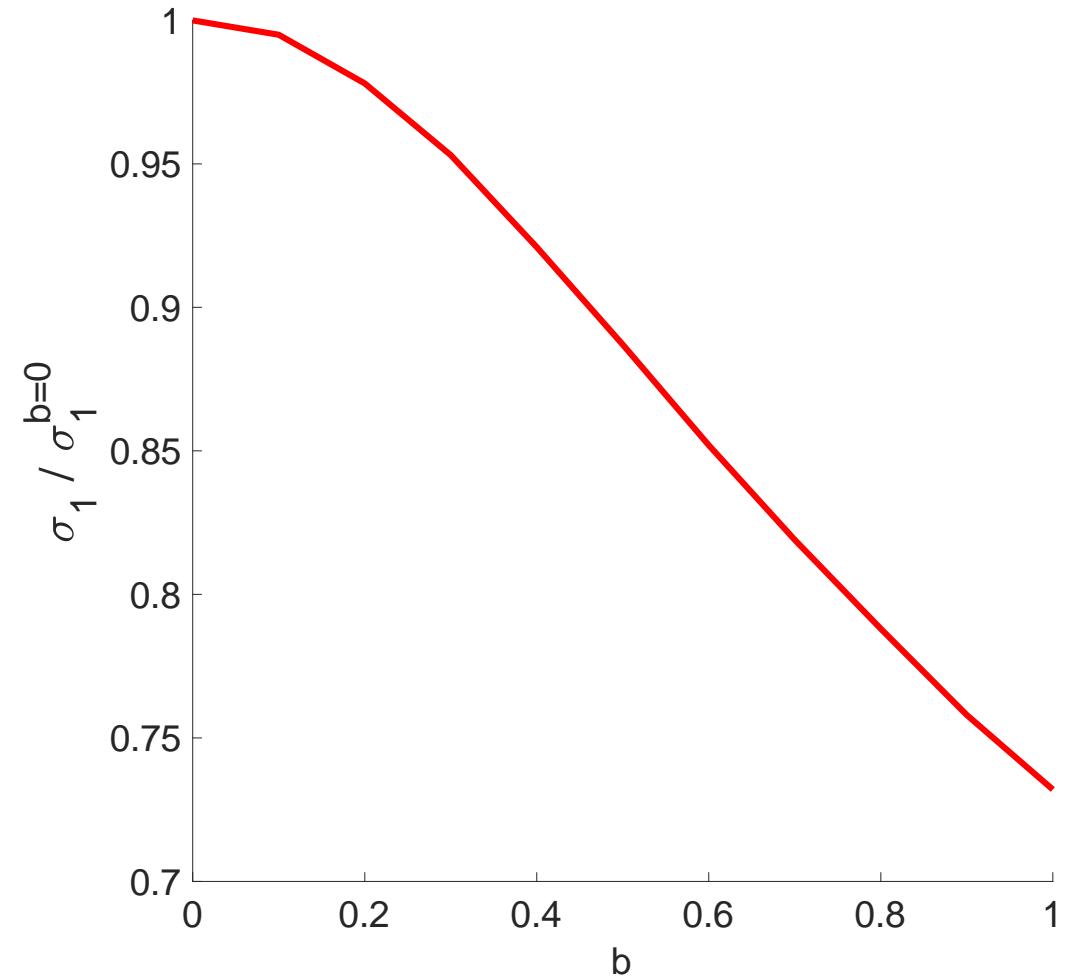
Spring and rigid link model of  
single force chain



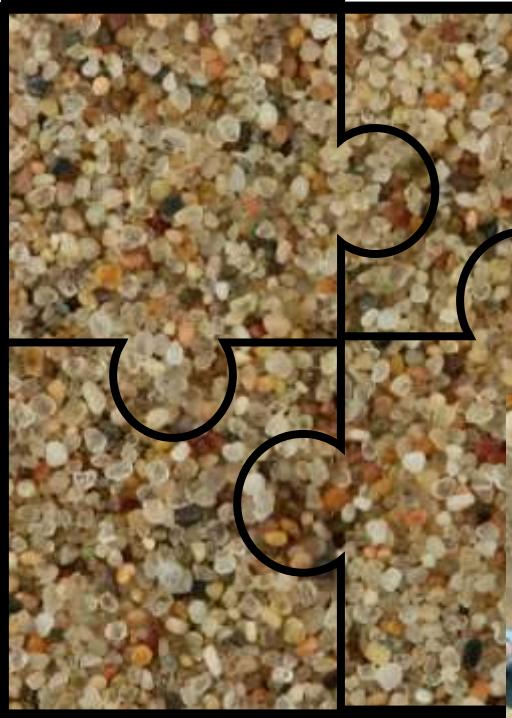
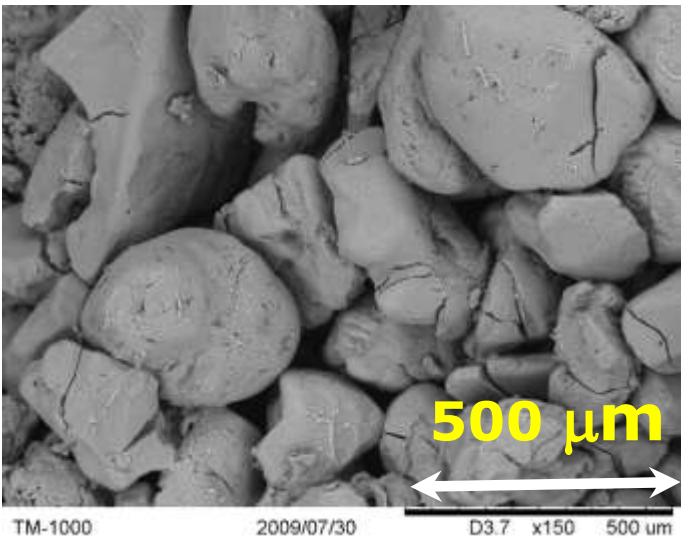
# 3D nature of soil strength



Spring and rigid link model of  
single force chain



# Reigate sand



PhD Research of Dr. Joana Fonseca

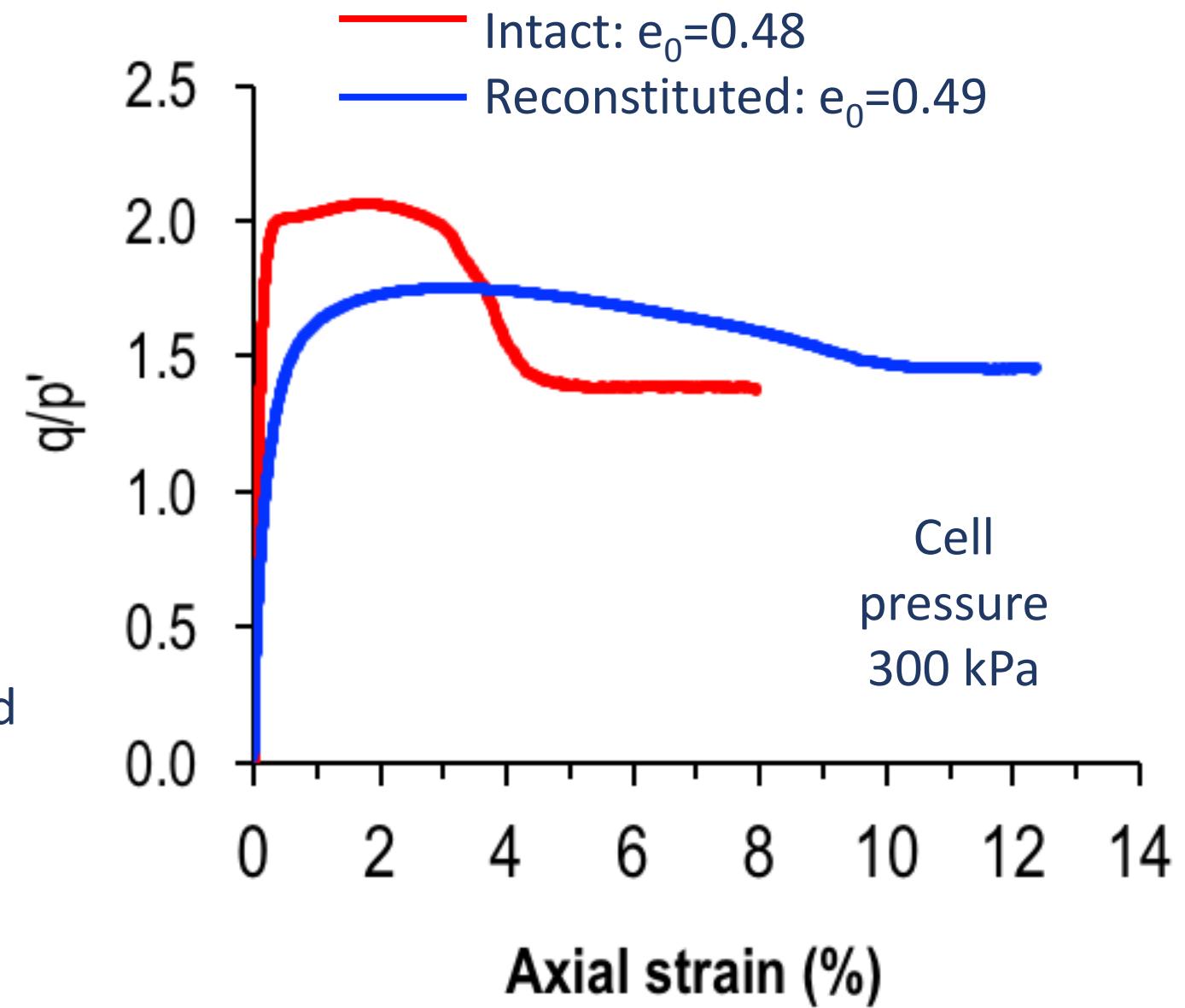
# Reigate sand – response in triaxial compression



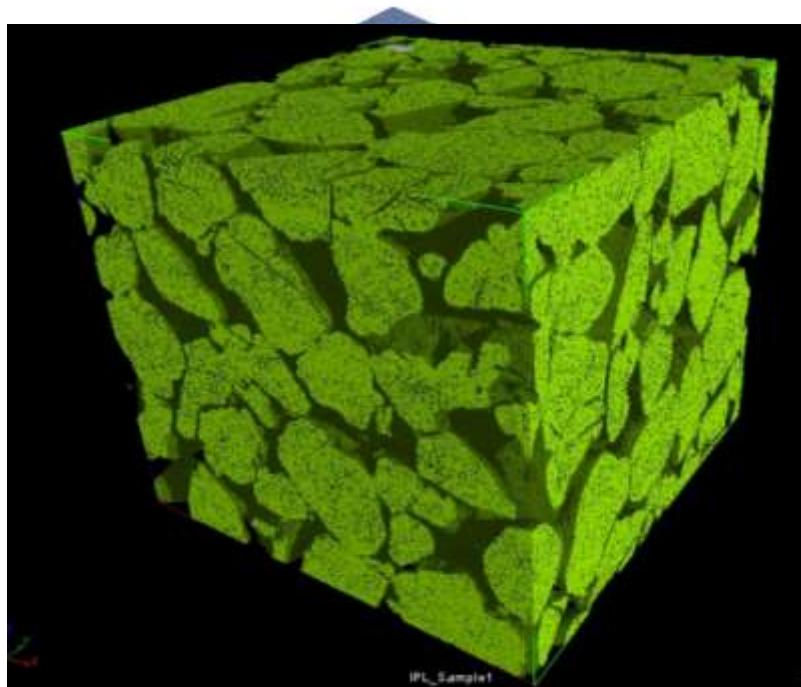
Intact  
material



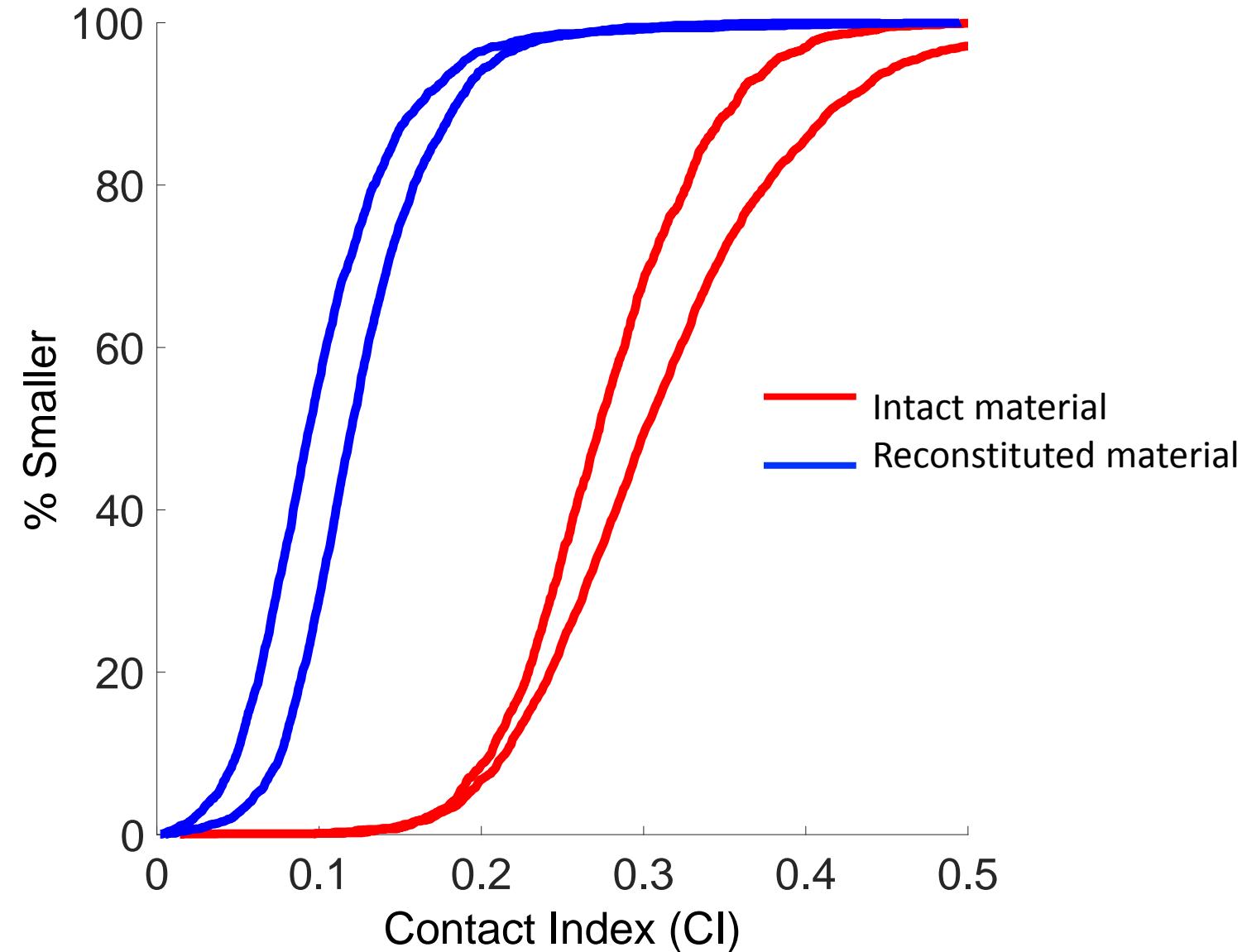
Reconstituted  
material



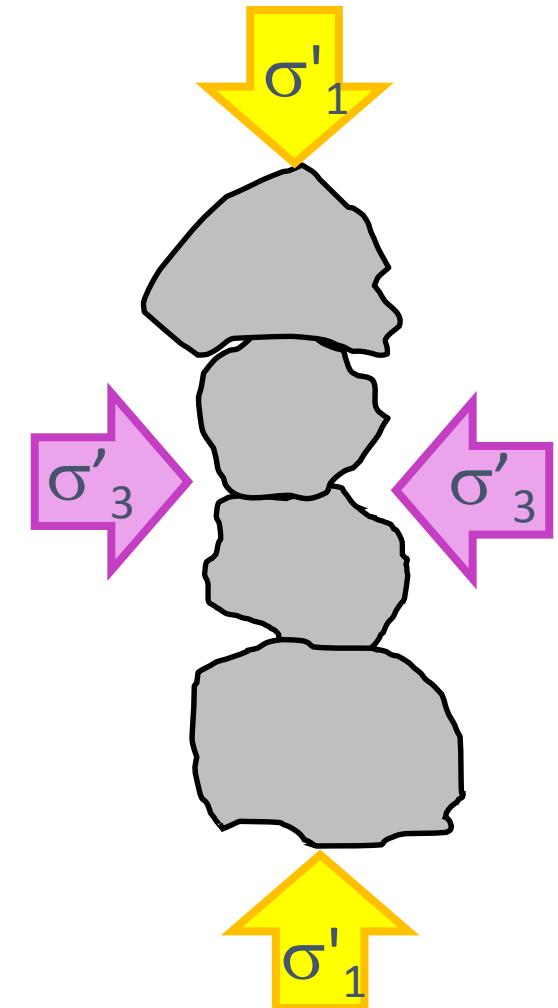
# Reigate sand – particle-scale analysis



$$\text{Contact Index} = \frac{\text{Contact area}}{\text{Particle surface area}}$$



# Contact network and strength



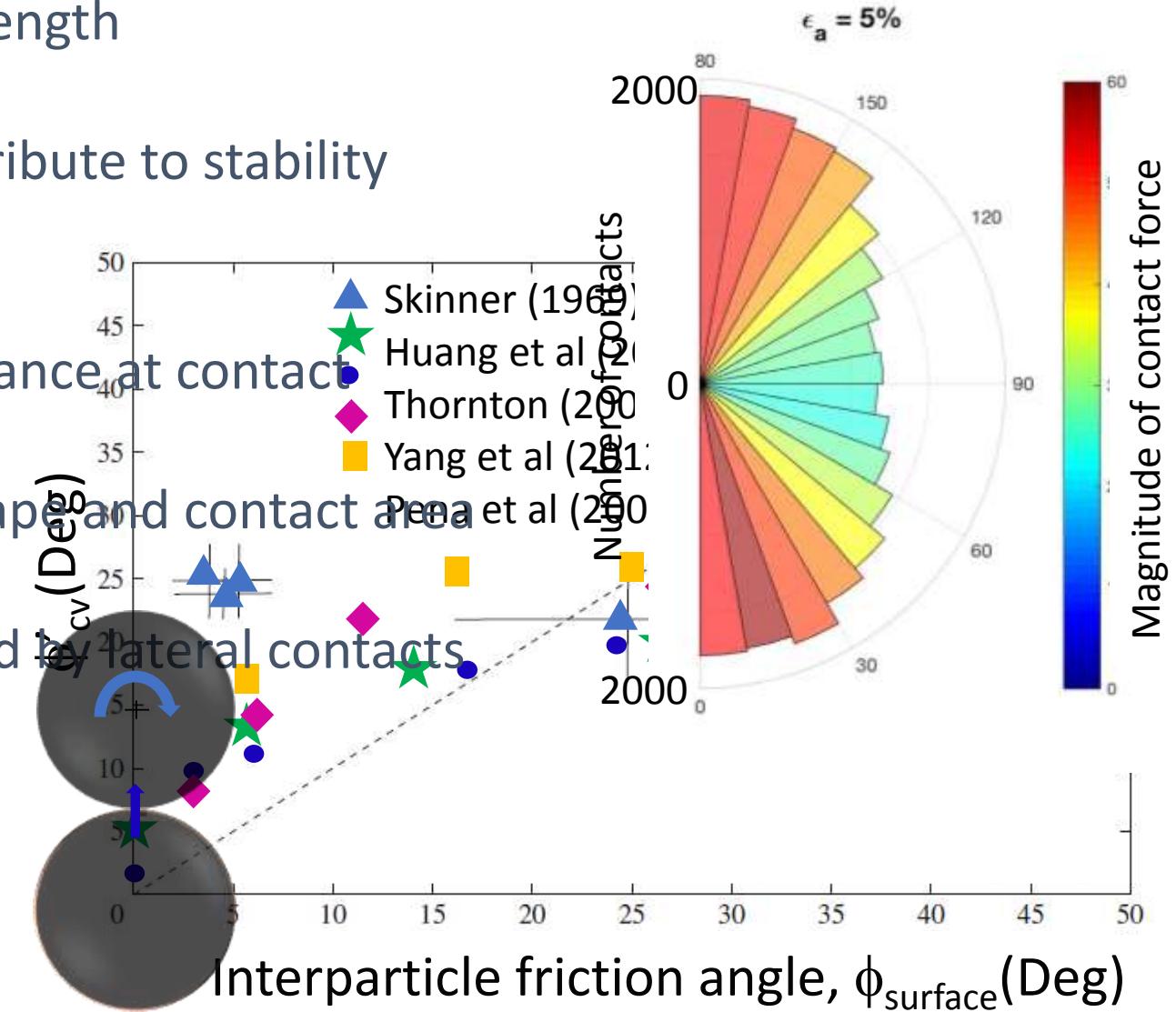
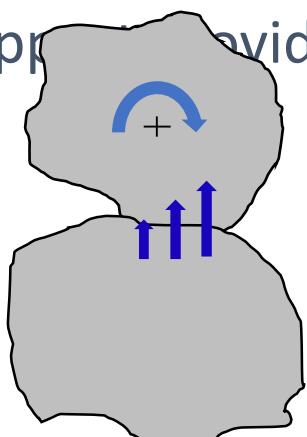
Force chain stability significantly influences sand strength

Factors which contribute to stability

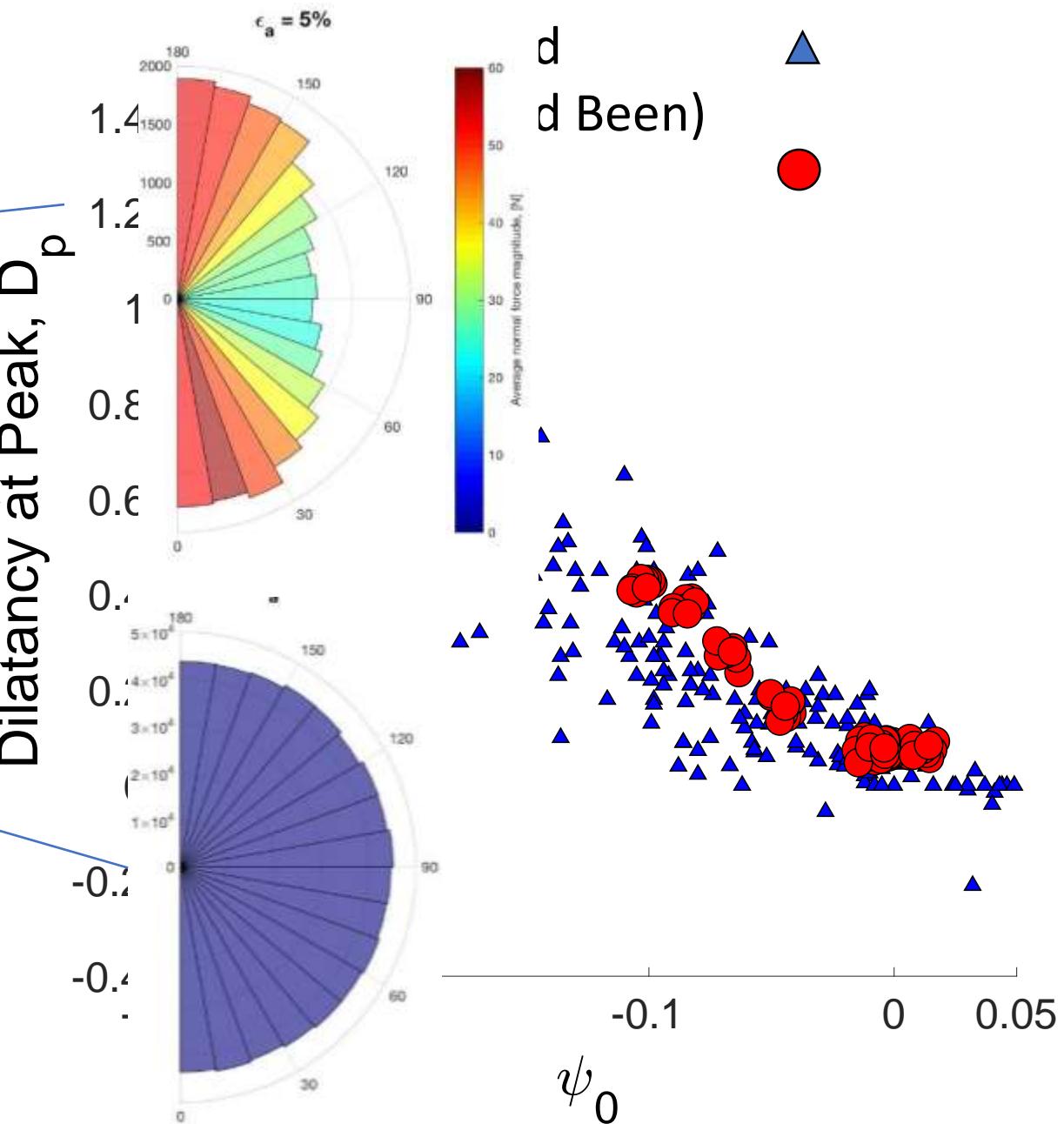
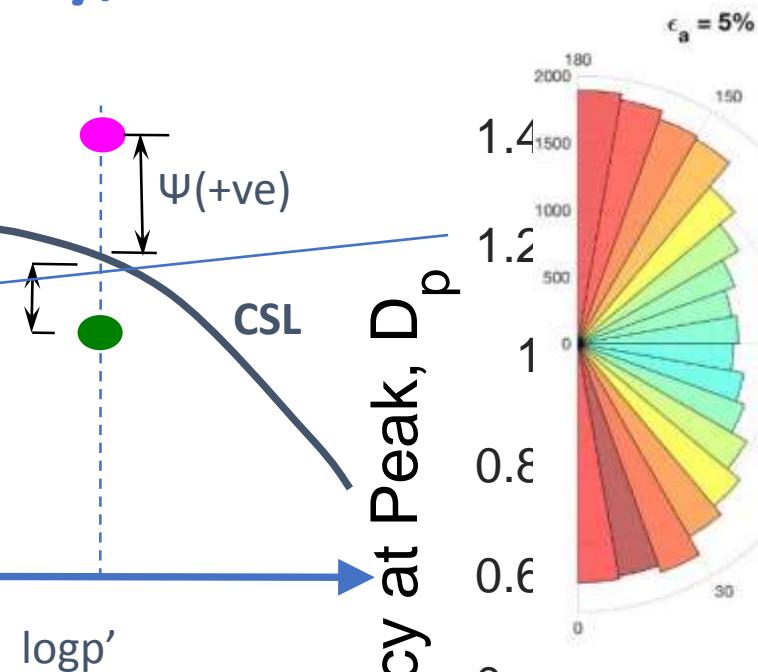
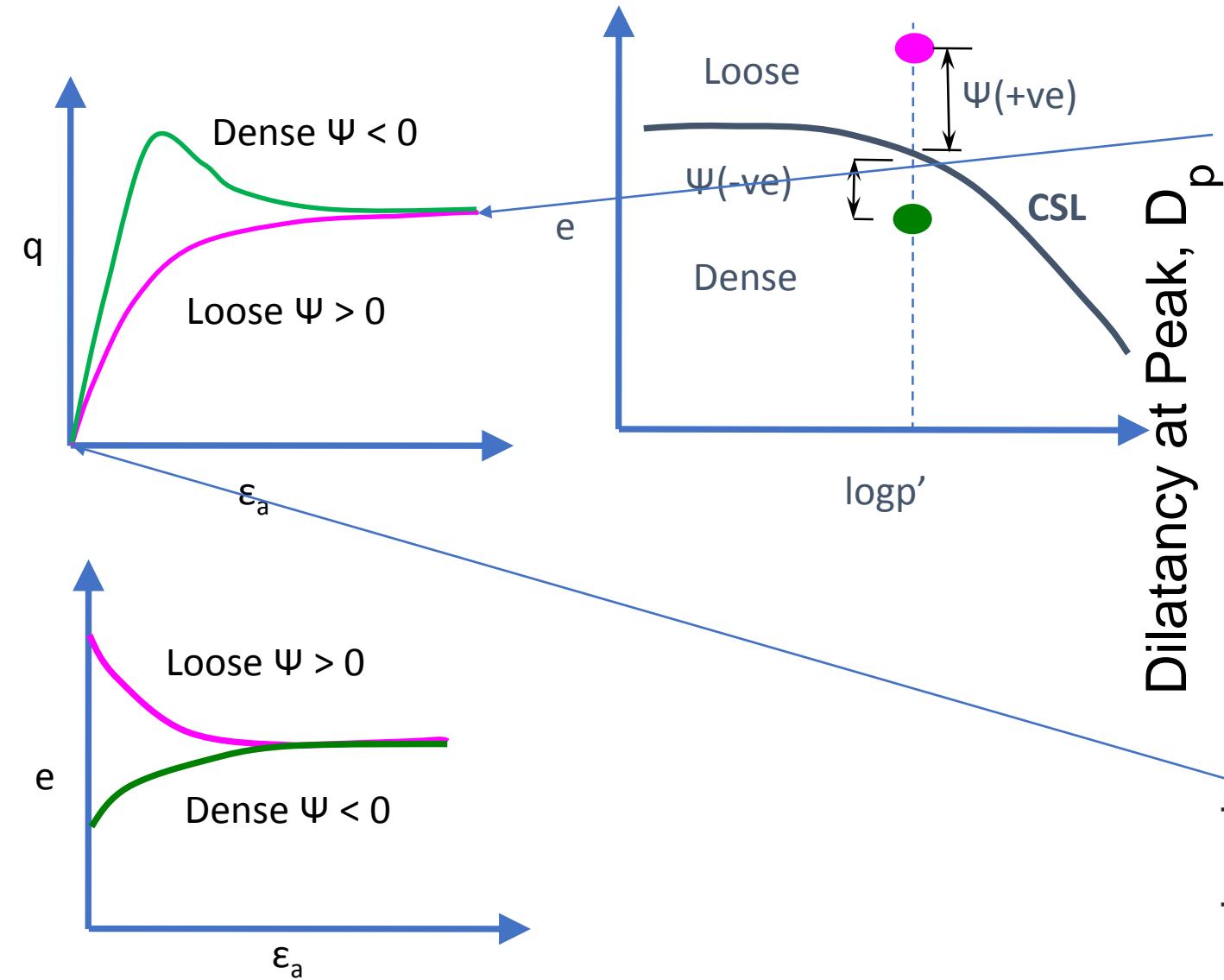
- Friction
- Rotational resistance at contact points

Depends on shape and contact area

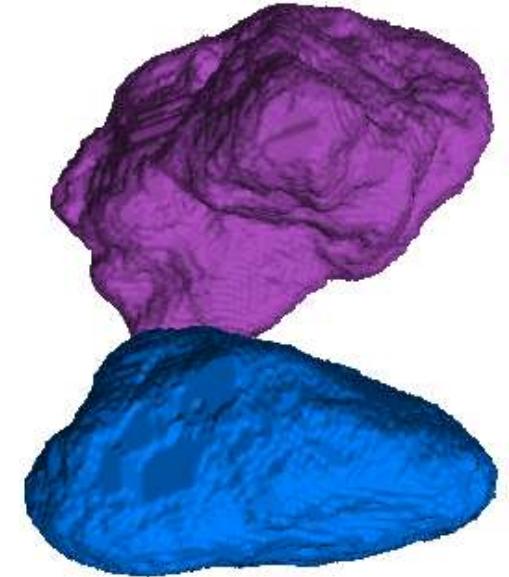
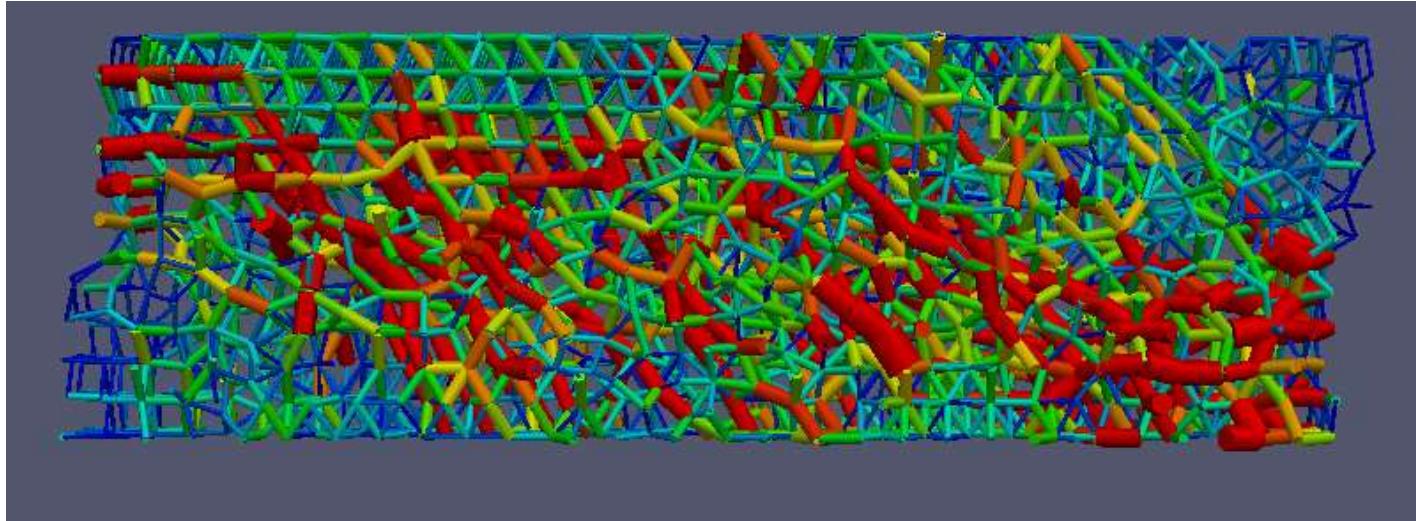
- Support provided by lateral contacts



# Strength, dilatancy, fabric



# Strength: collective behaviour

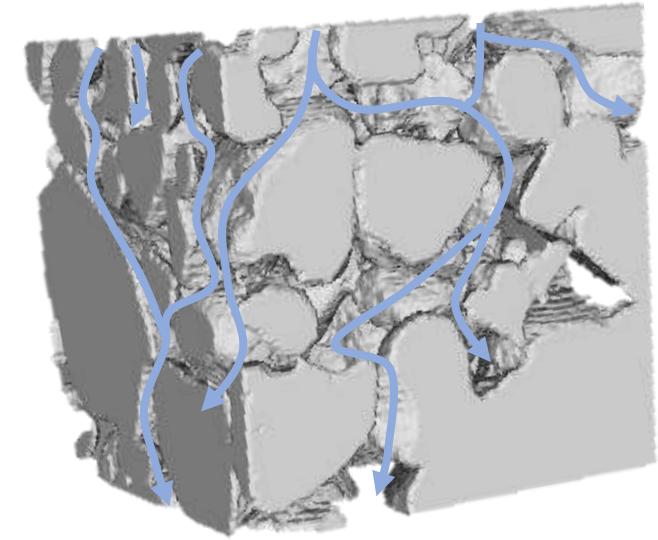


Granular materials are complex networks of contacting particles

A reductionist approach that considers a single interaction will not explain the overall material behaviour

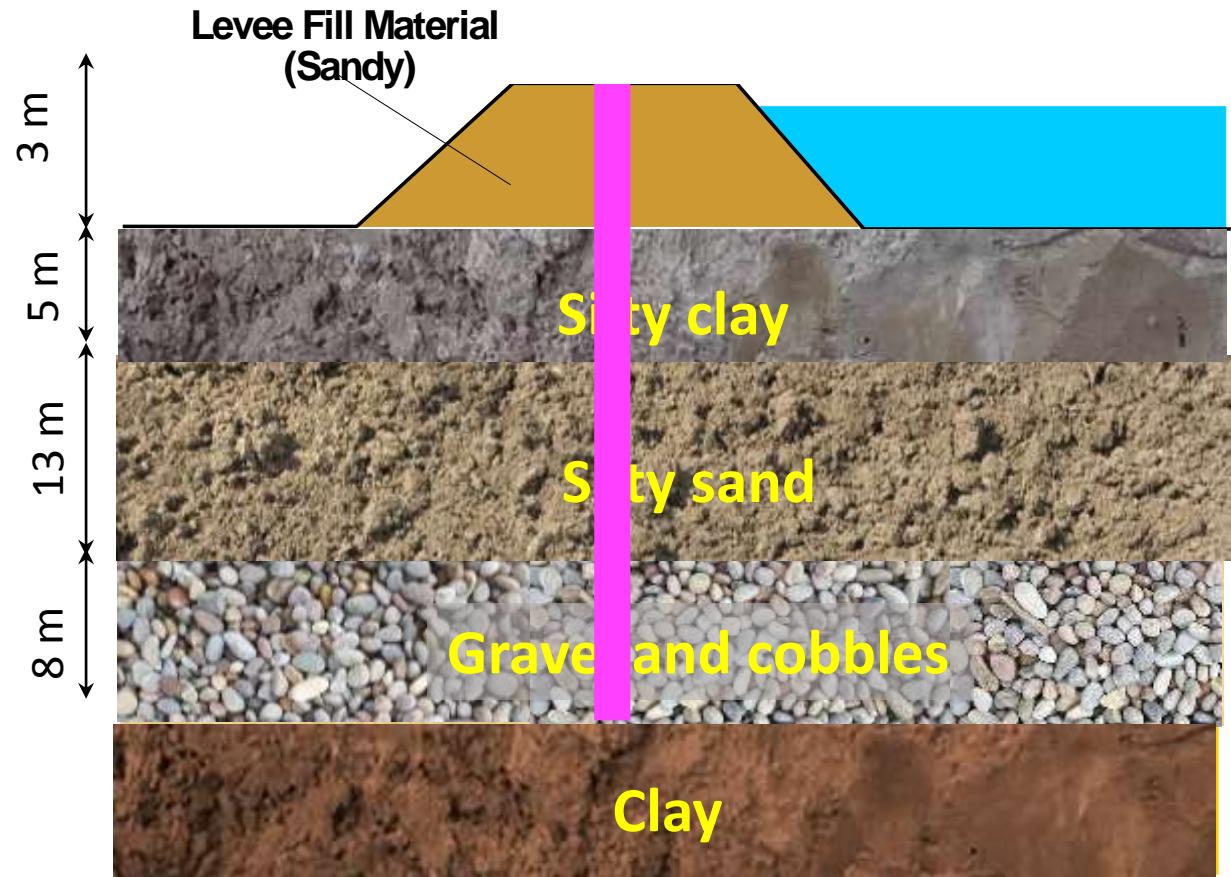
The collective behaviour of the system needs to be considered

# Sand behaviour



Seepage

# Flood embankments

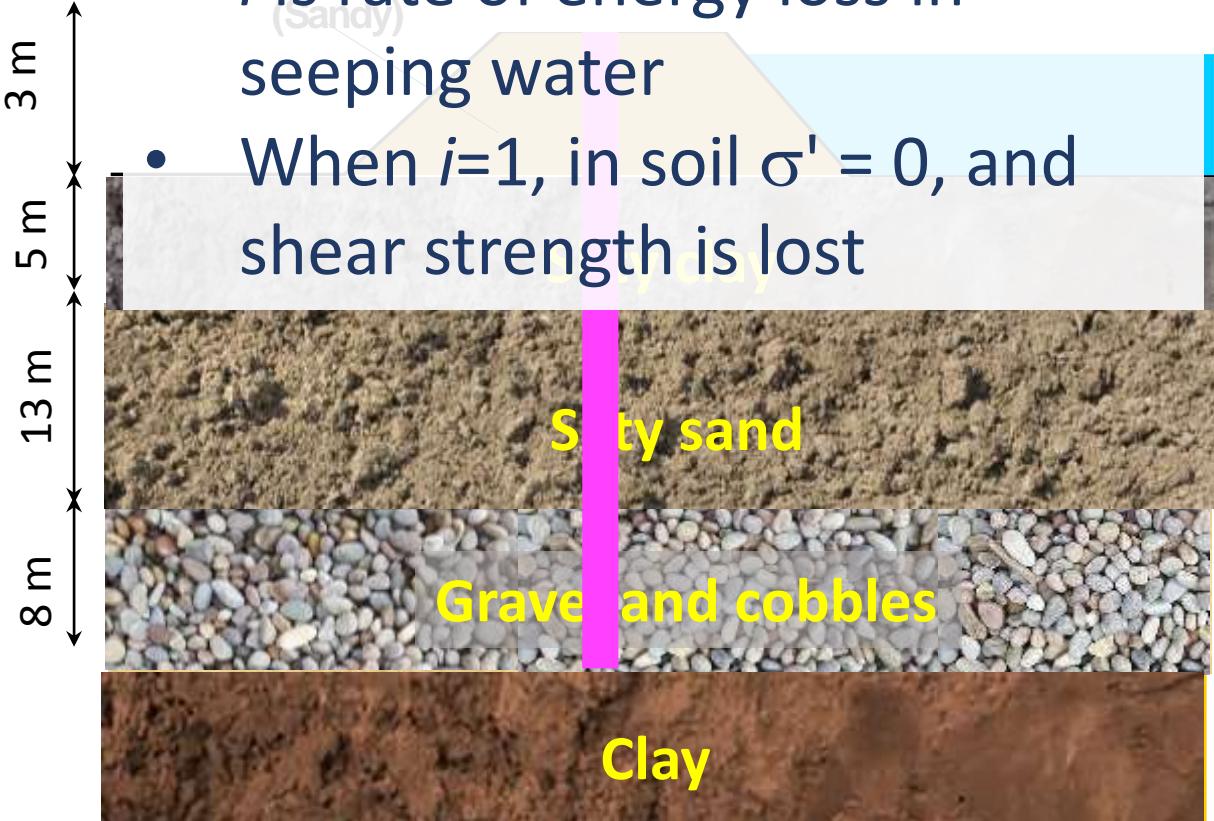


# Flood embankments



Design aim :

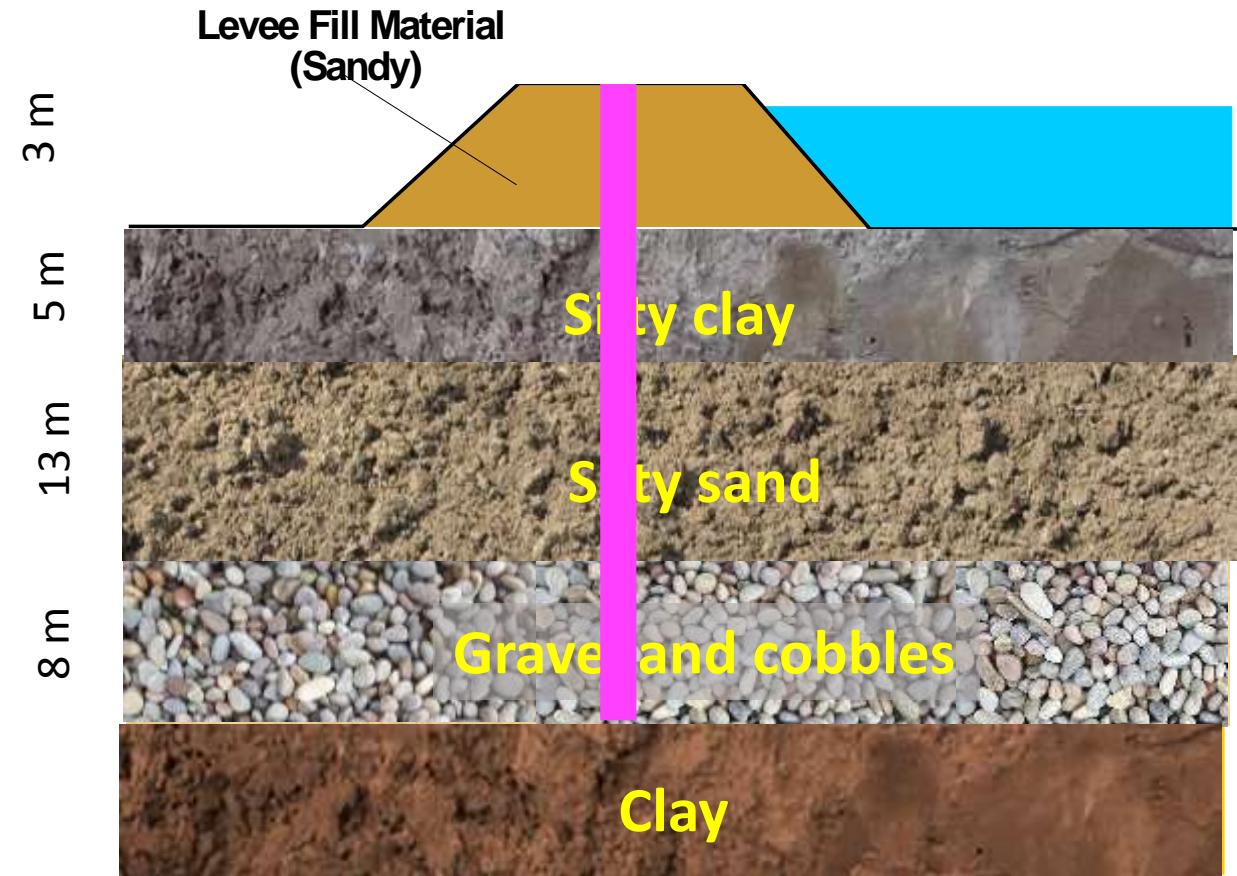
- Reduce downstream hydraulic gradient,  $i$
- $i$  is rate of energy loss in seeping water
- When  $i=1$ , in soil  $\sigma' = 0$ , and shear strength is lost



# Flood embankments



Construction completed in 2015



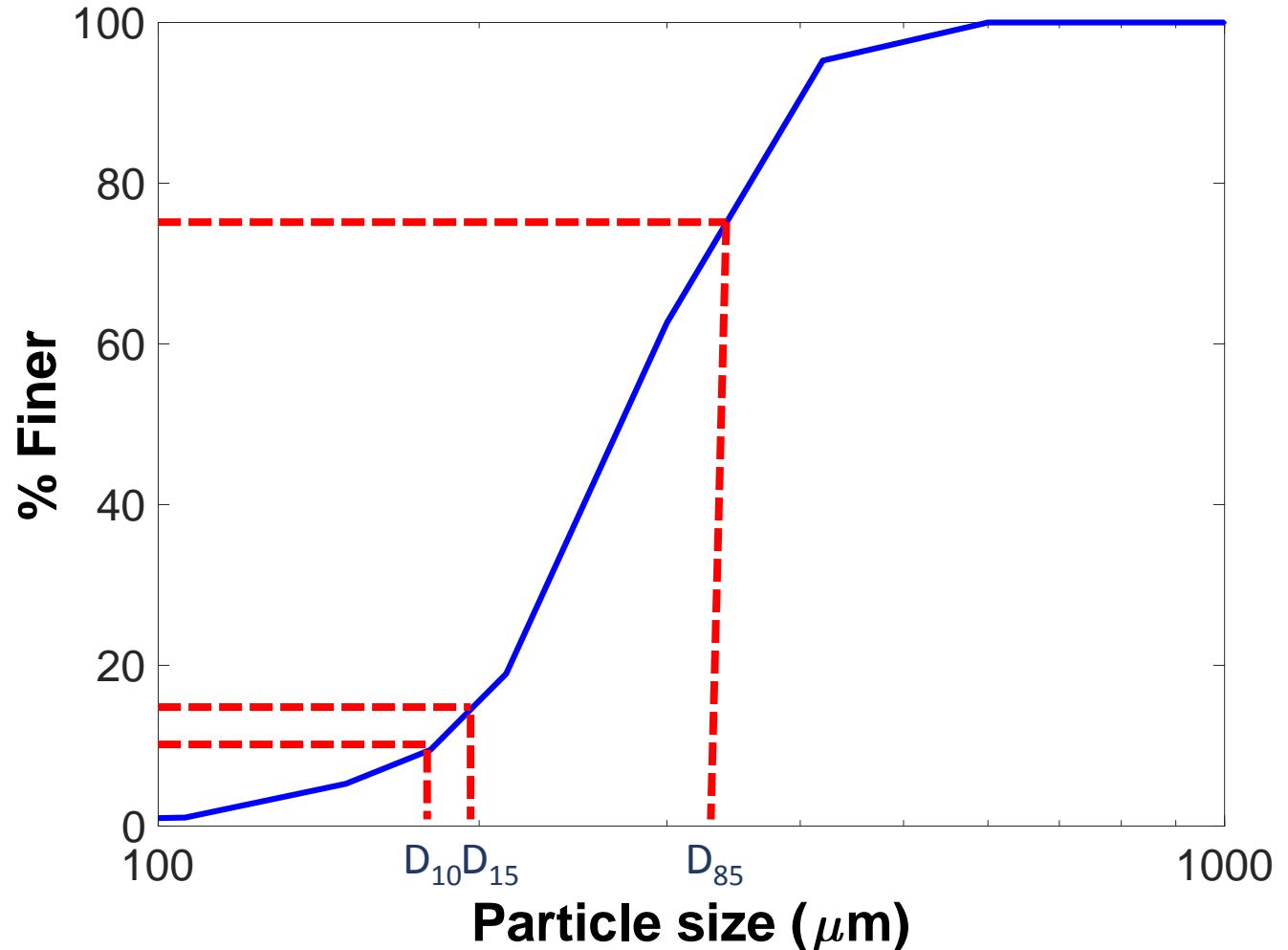
# Filter particle size distribution



10% of particles by mass are smaller than  $D_{10}$

15% of particles by mass are smaller than  $D_{15}$

85% of particles by mass are smaller than  $D_{85}$



Filter retention  $D_{15F} < 4 D_{85B}$

# Permeability

Permeability is a measure of resistance to flow – quantifies how much energy the water needs to exert to pass through the soil

Soil Type	Degree of permeability	Permeability (m/s)
Clean gravels	High	$> 1 \times 10^{-3}$
Sand and gravel mixtures	Medium	$1 \times 10^{-3} - 1 \times 10^{-5}$
Very fine sands, silty sands	Low	$1 \times 10^{-4} - 1 \times 10^{-7}$

$$\text{Hazen (1892): } k = CD_{10}^2$$

$k$  = permeability

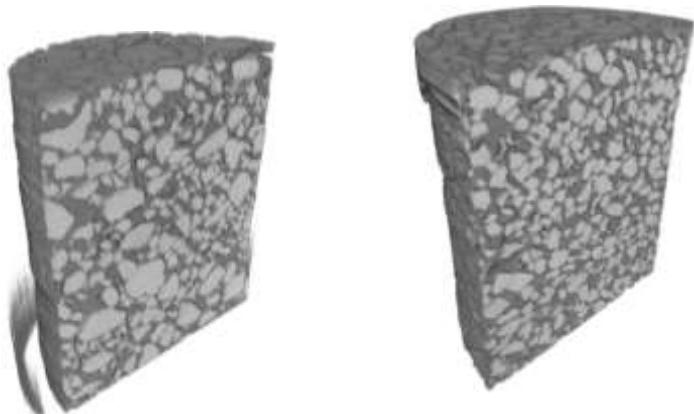
Empirical approach

Doesn't consider void ratio

Uncertainty over choice of C

# Seepage – samples considered

Micro CT



Leighton  
Buzzard Sand  
 $C_u=3$

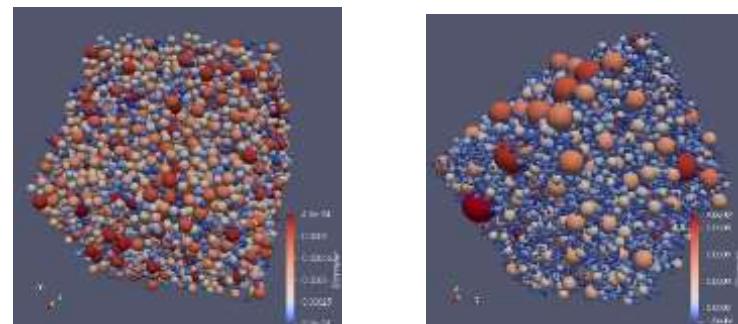
Leighton  
Buzzard Sand  
 $C_u=1.5$



Glass Beads  
 $C_u=3$

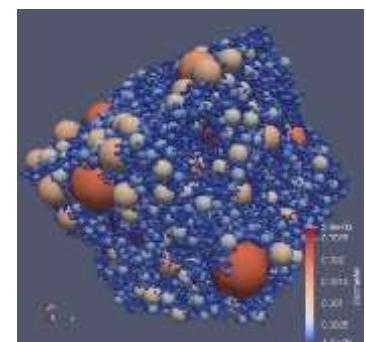
(Taylor, 2017)

DEM Simulations



Spheres  
 $C_u=1.2$

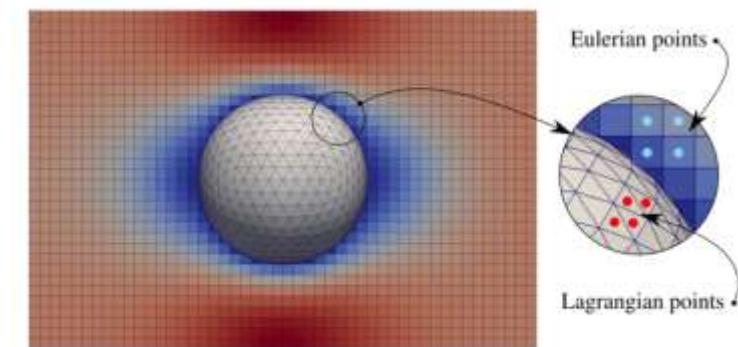
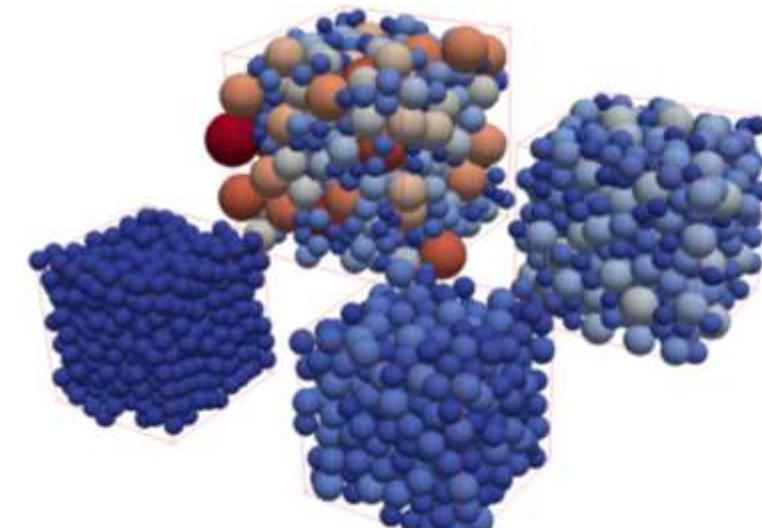
Spheres  
 $C_u=3.0$



Spheres  
 $C_u=6.0$

(Shire, 2014)

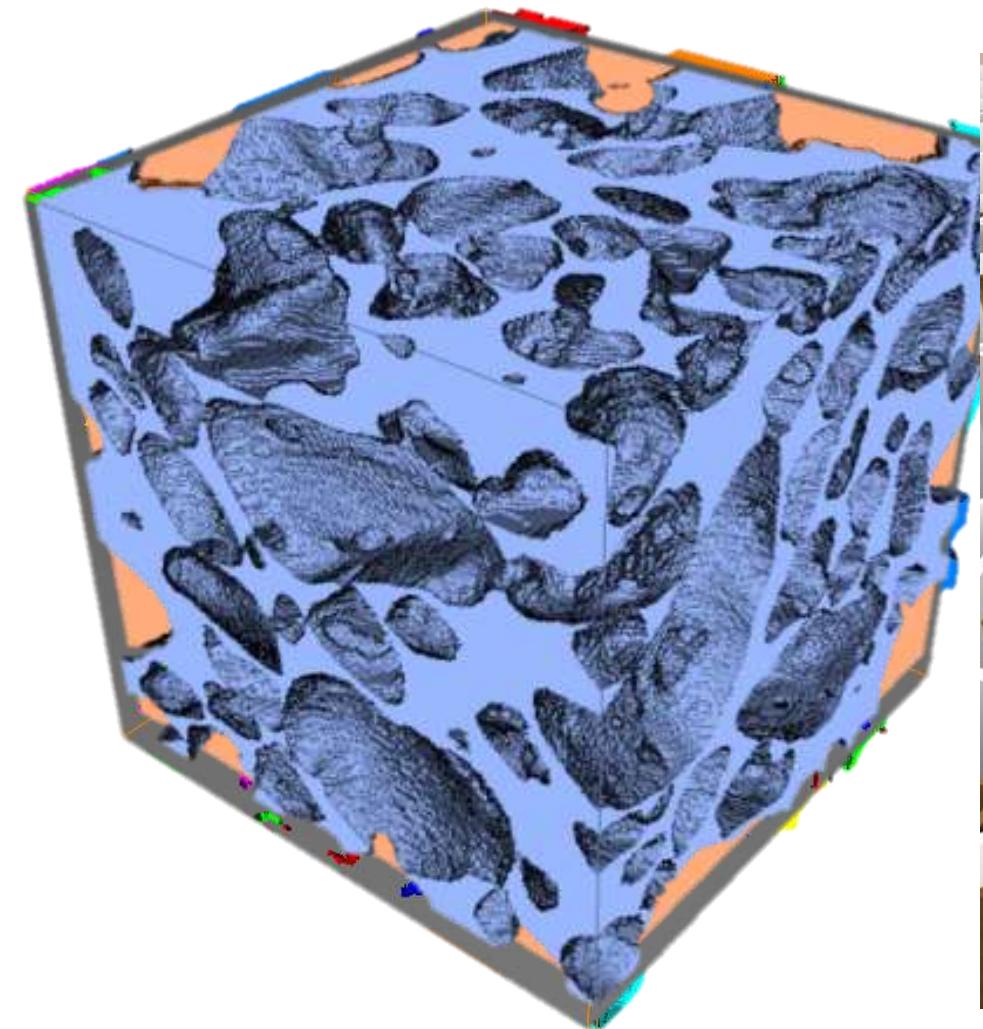
CFD-DEM



Multi-flow (van Wachem et al.)

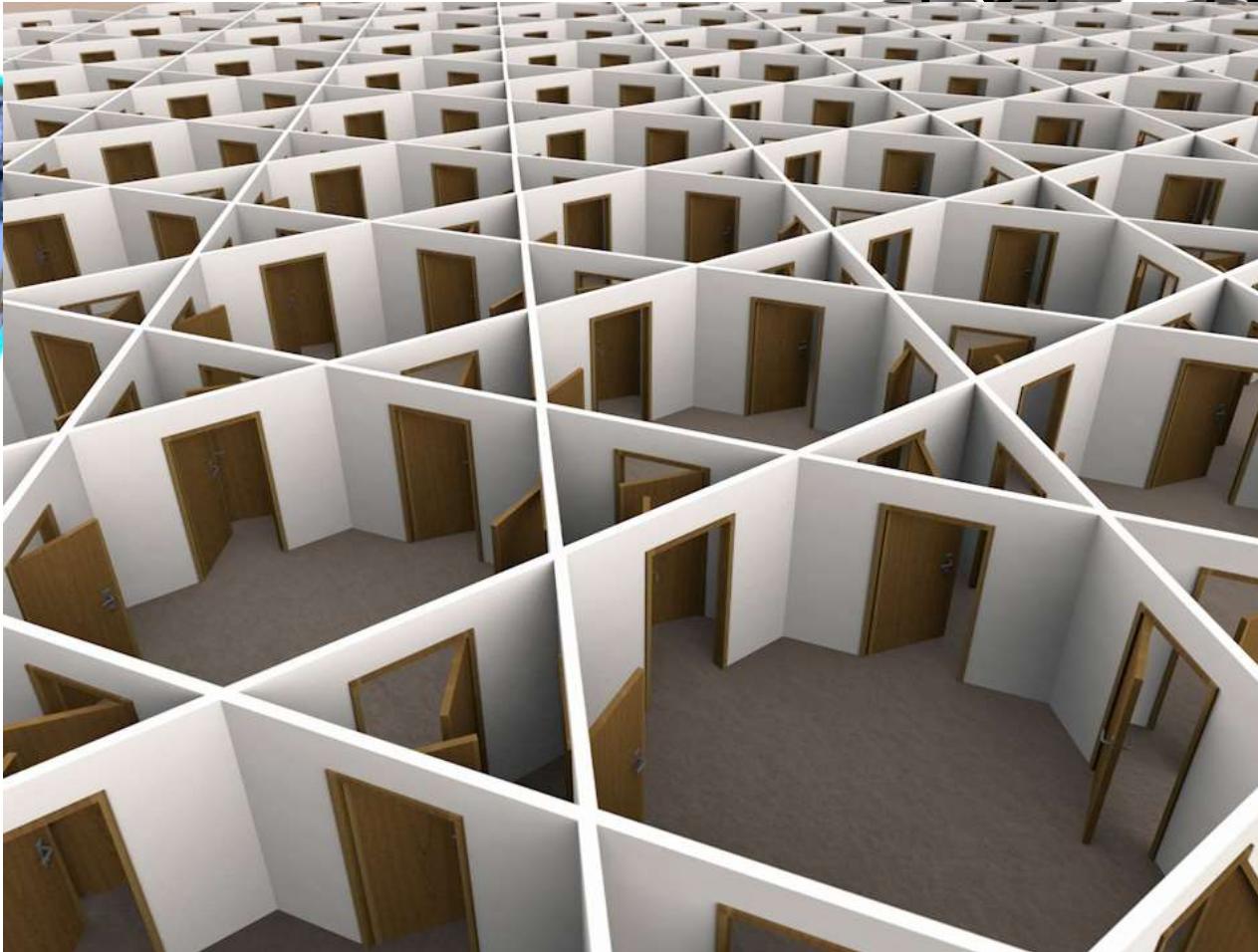
(Knight, 2018)

# Void space topology



Micro CT

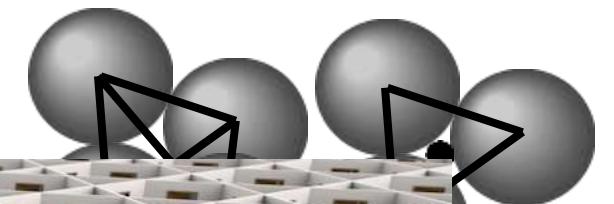
Taylor et al. (2017)



<http://www.christiani.biz/project/office-rooms-maze-illustration/>

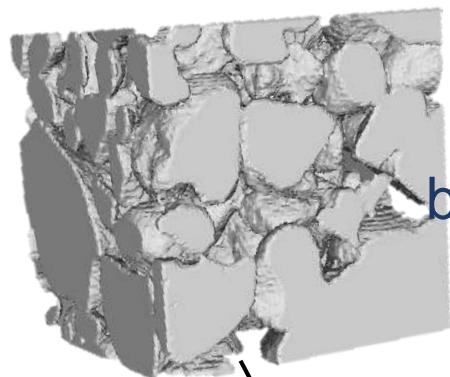
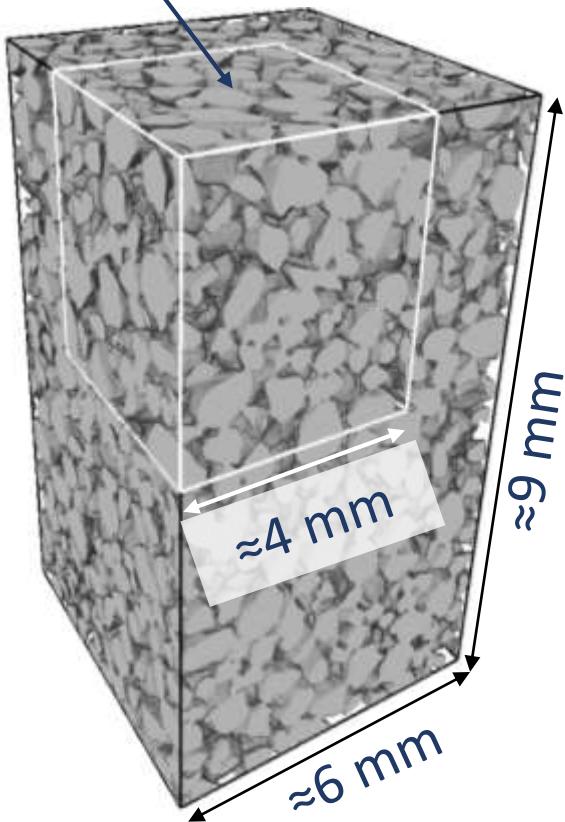
DEM

Shire (2014)

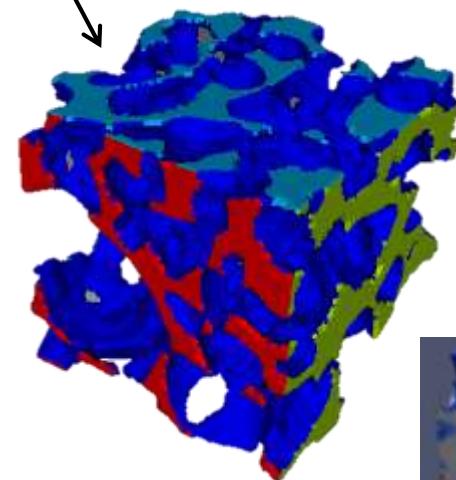


# Fluid flow simulations

Sub-volume for  
CFD analyses

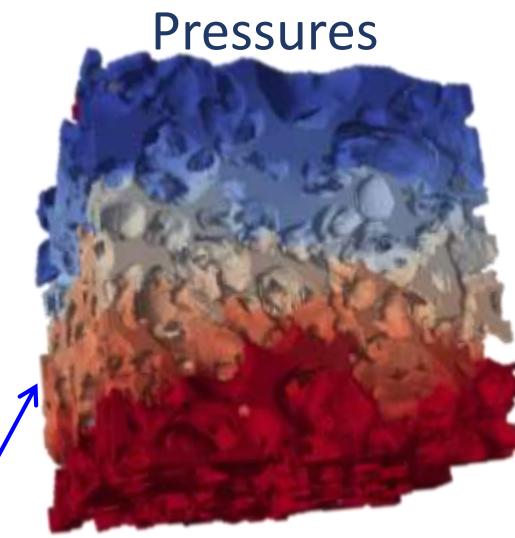
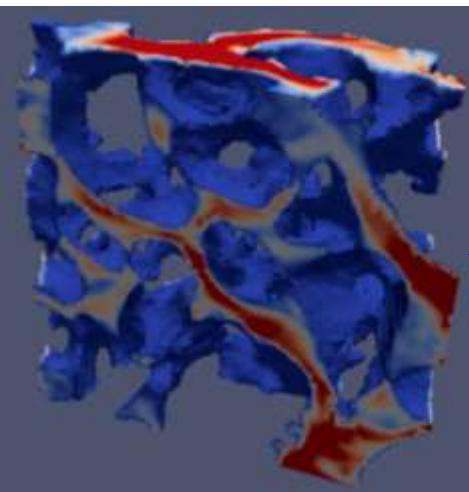


Micro-CT  
binary image

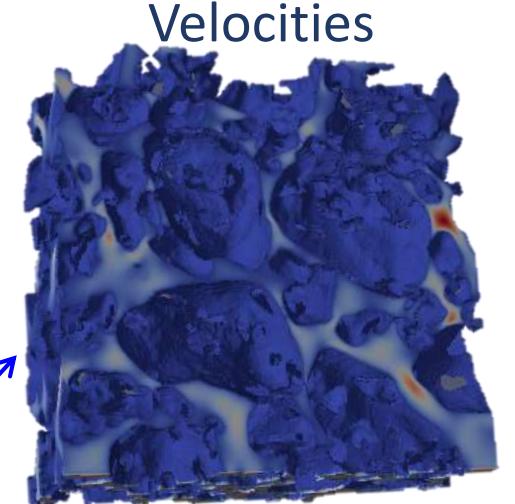


Finite volume  
mesh

OpenFOAM  
simulation

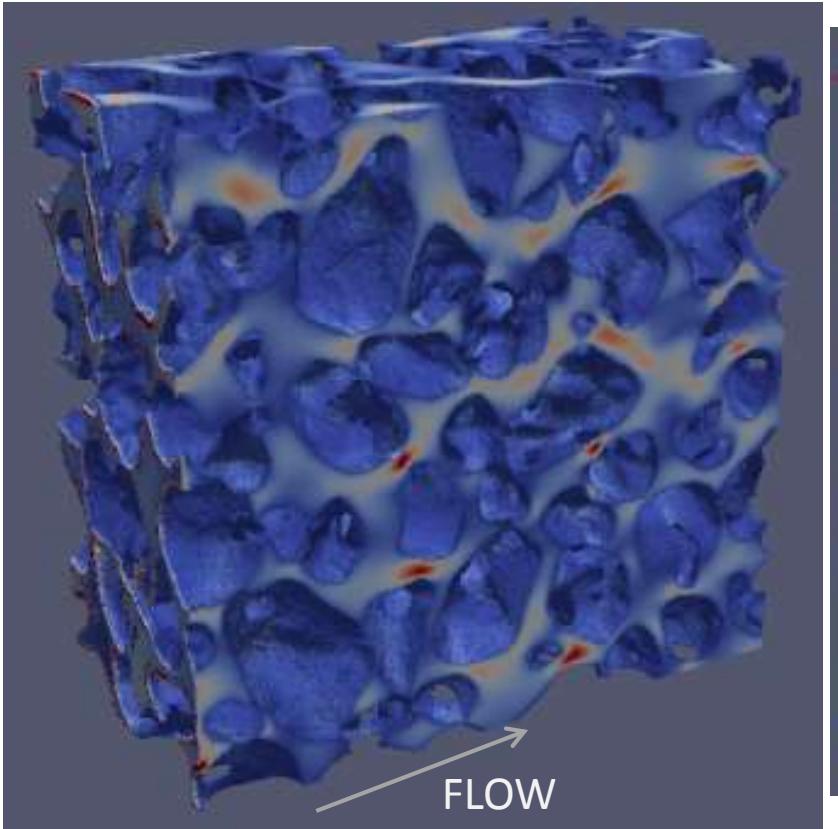


Pressures



Velocities

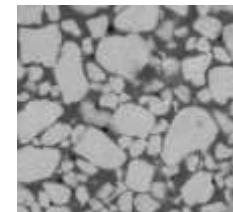
# Fluid flow velocity



High velocity

Low velocity

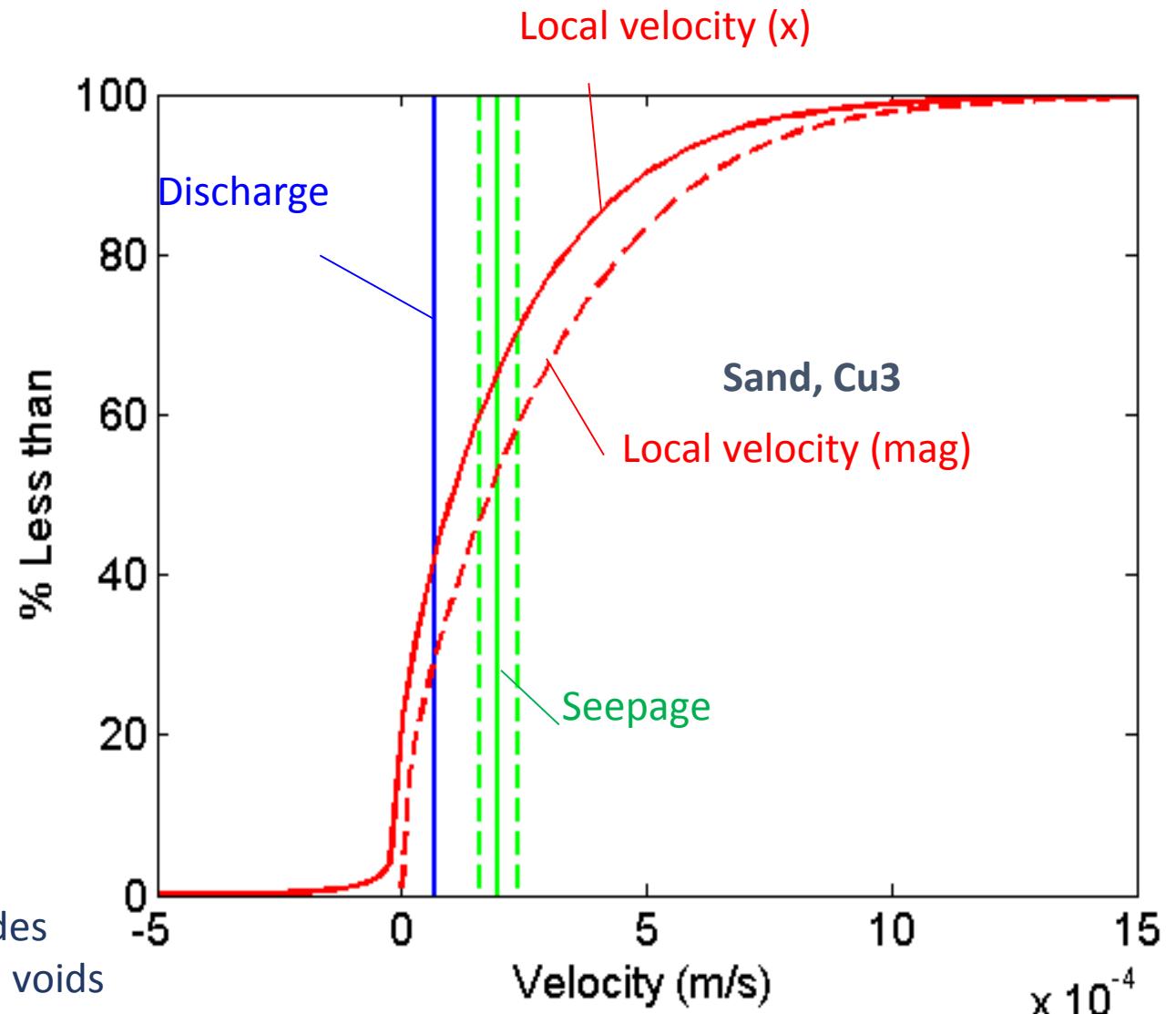
$$\text{Velocity} = V_{\text{discharge}} = \frac{Q}{A}$$



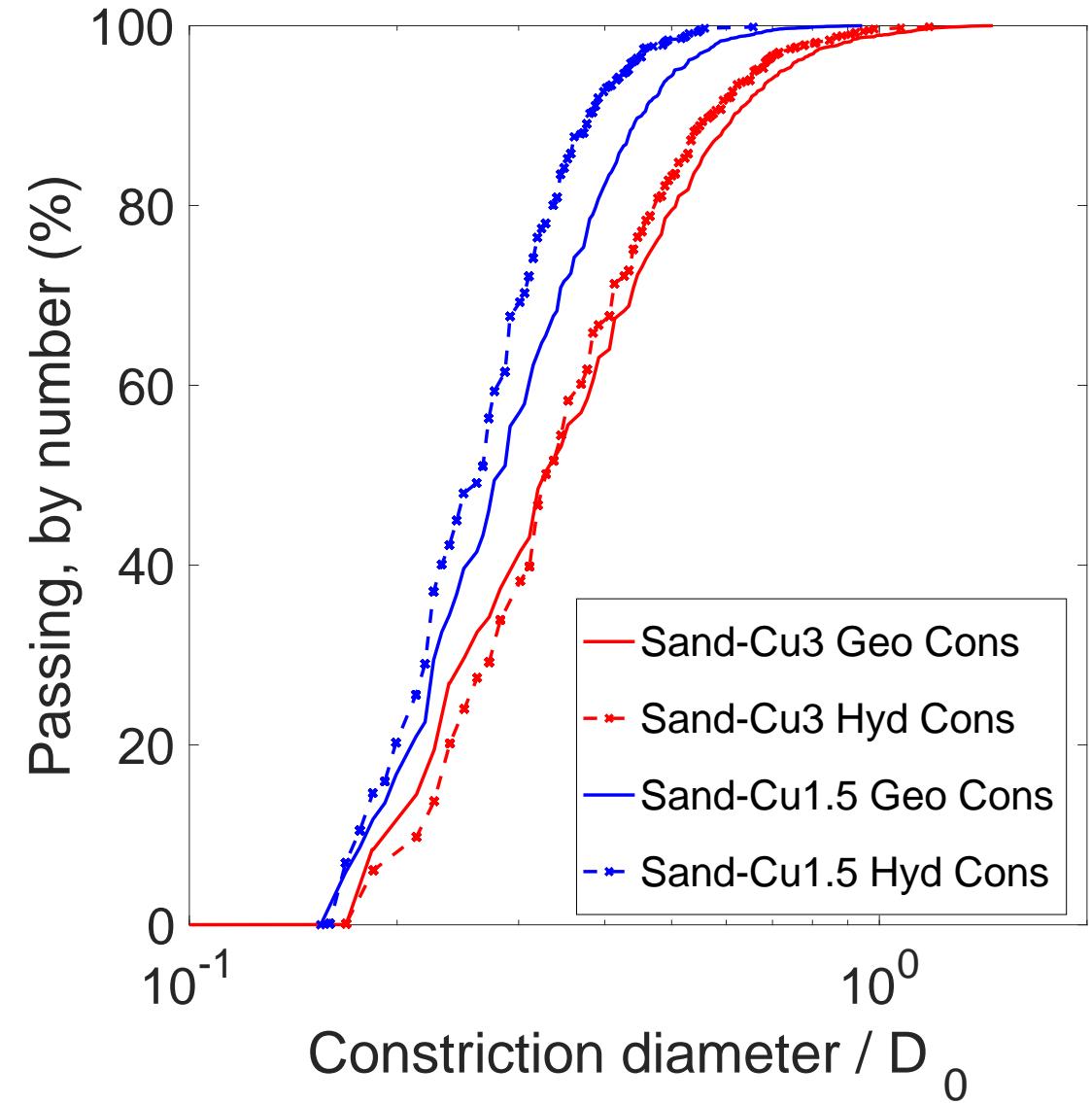
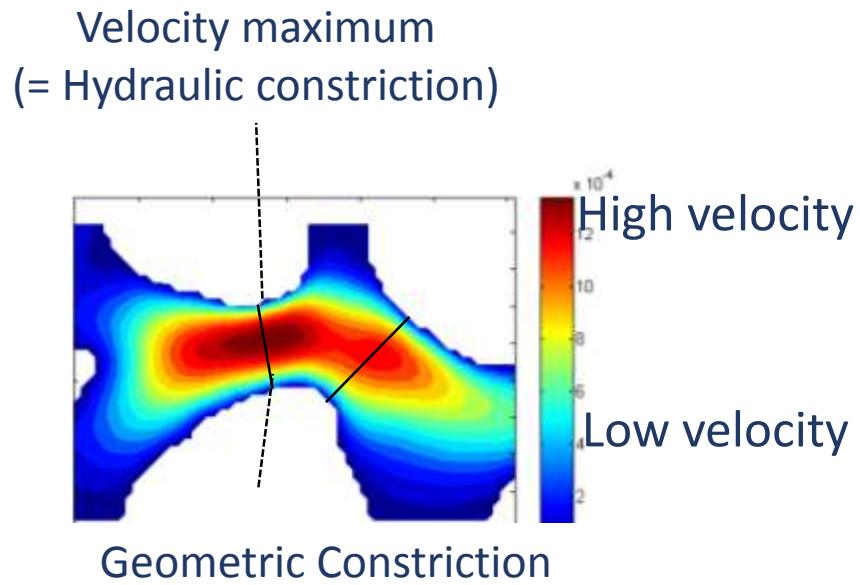
Area A includes  
particles and voids

$$V_{\text{seepage}} = \frac{V_{\text{discharge}}}{n}$$

$$n = \text{porosity} = \text{Volume of voids} / \text{Total volume}$$

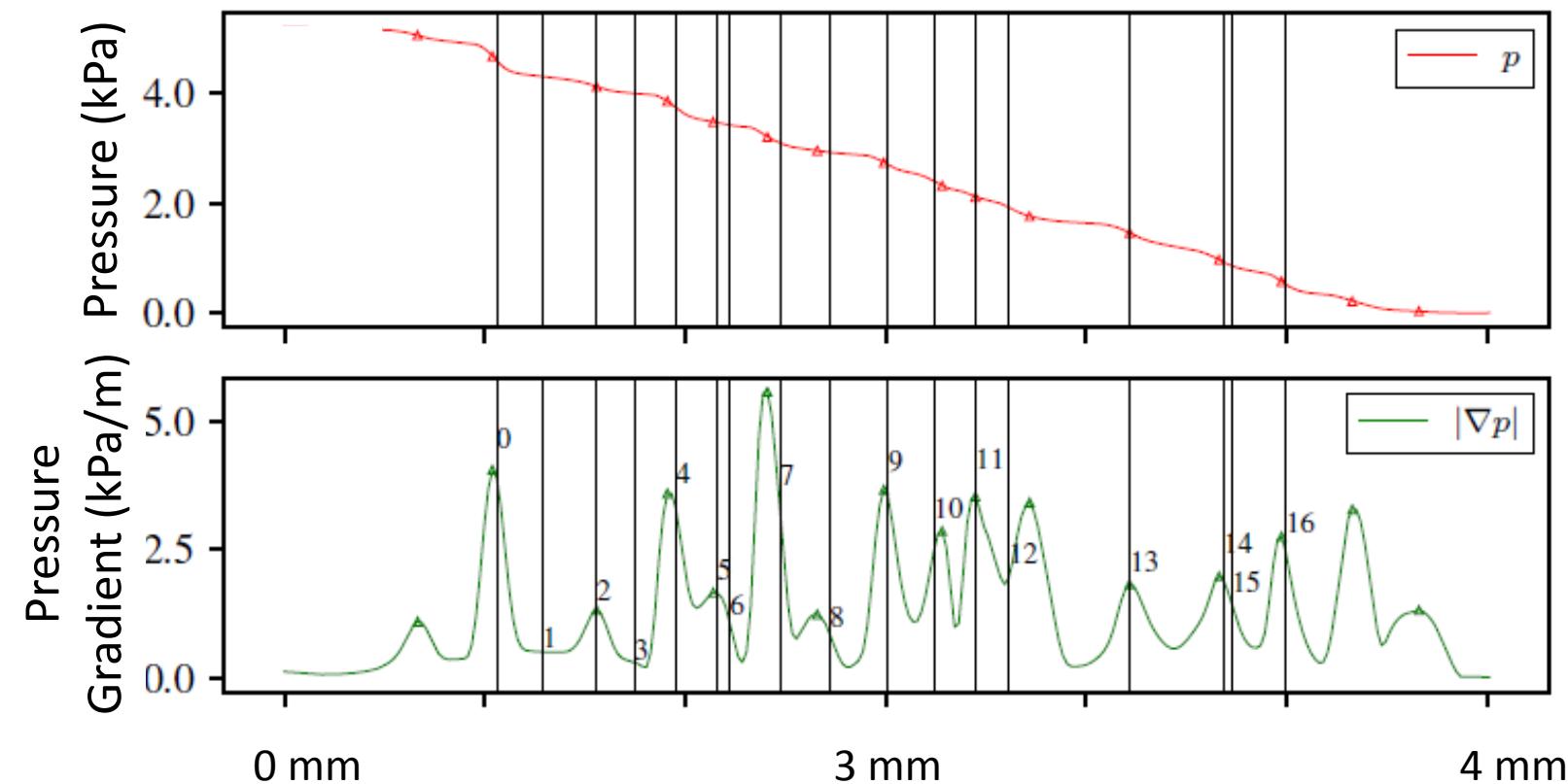
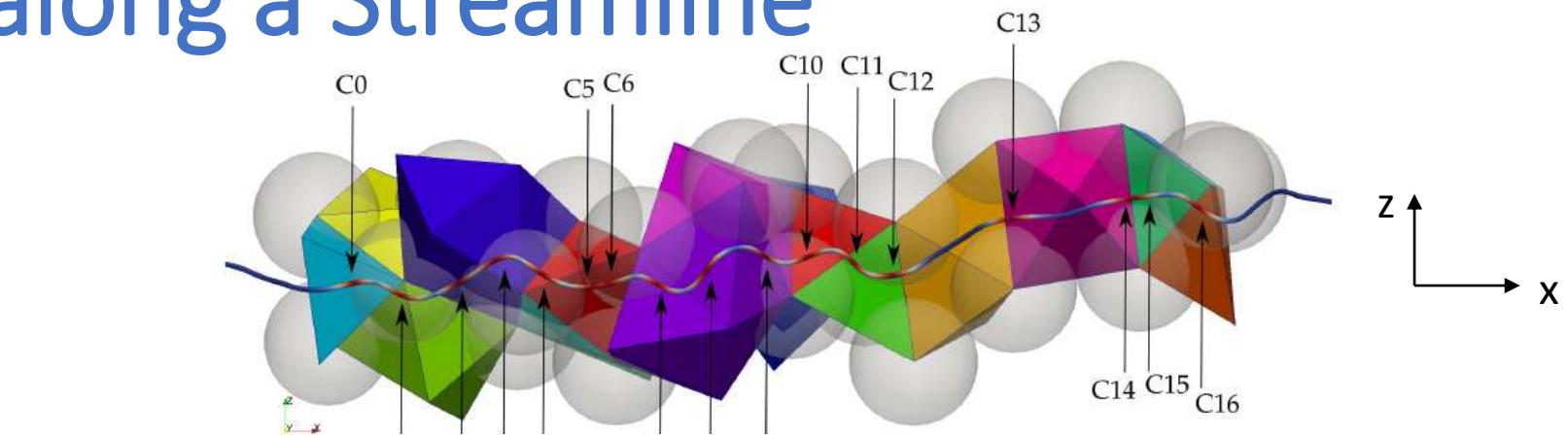
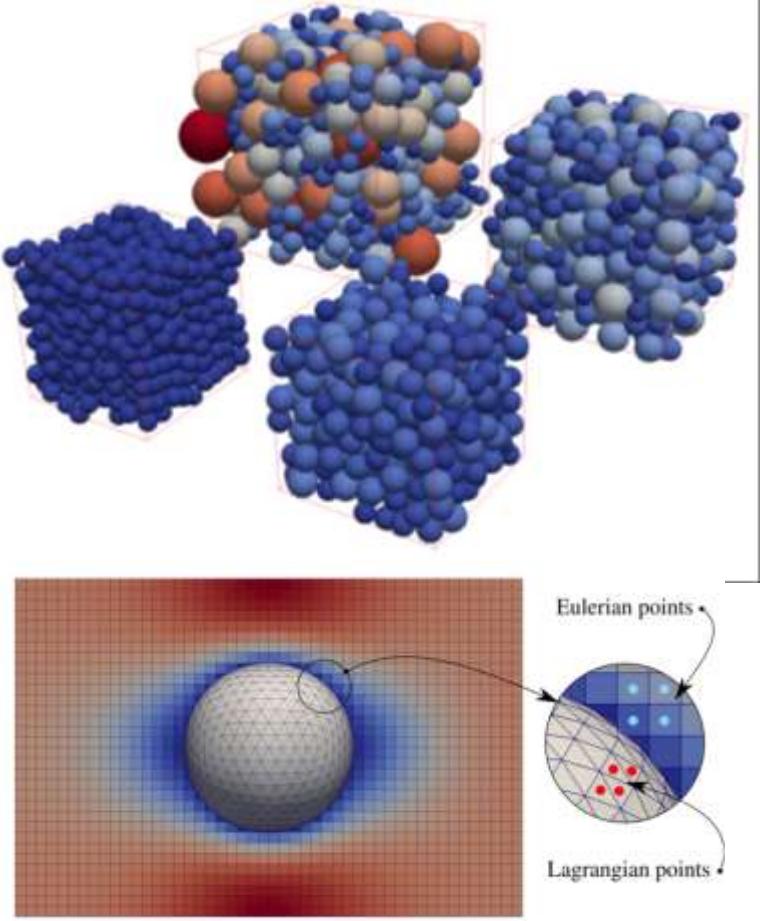


# Constrictions and seepage



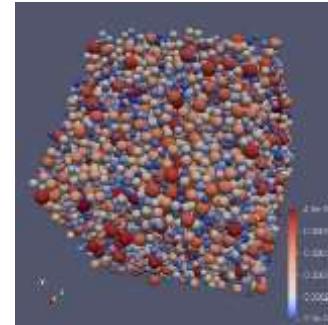
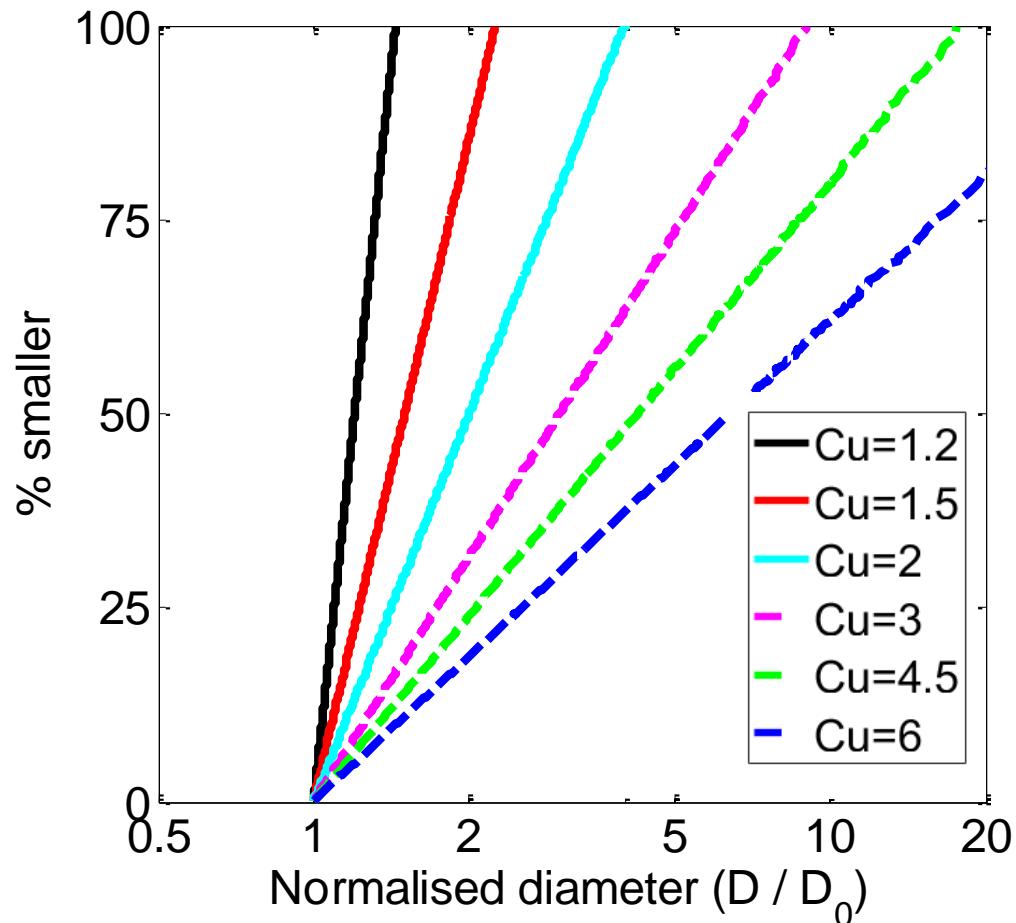
# Tracing Flow along a Streamline

CFD-DEM

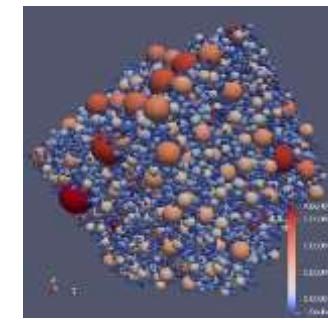


# Constriction size distributions (DEM)

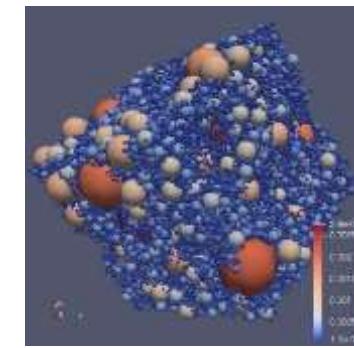
Particle size distribution



Spheres  
 $C_u = 1.2$



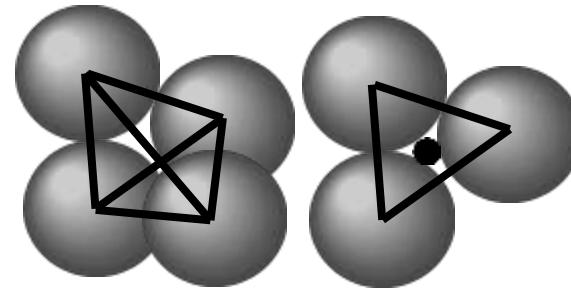
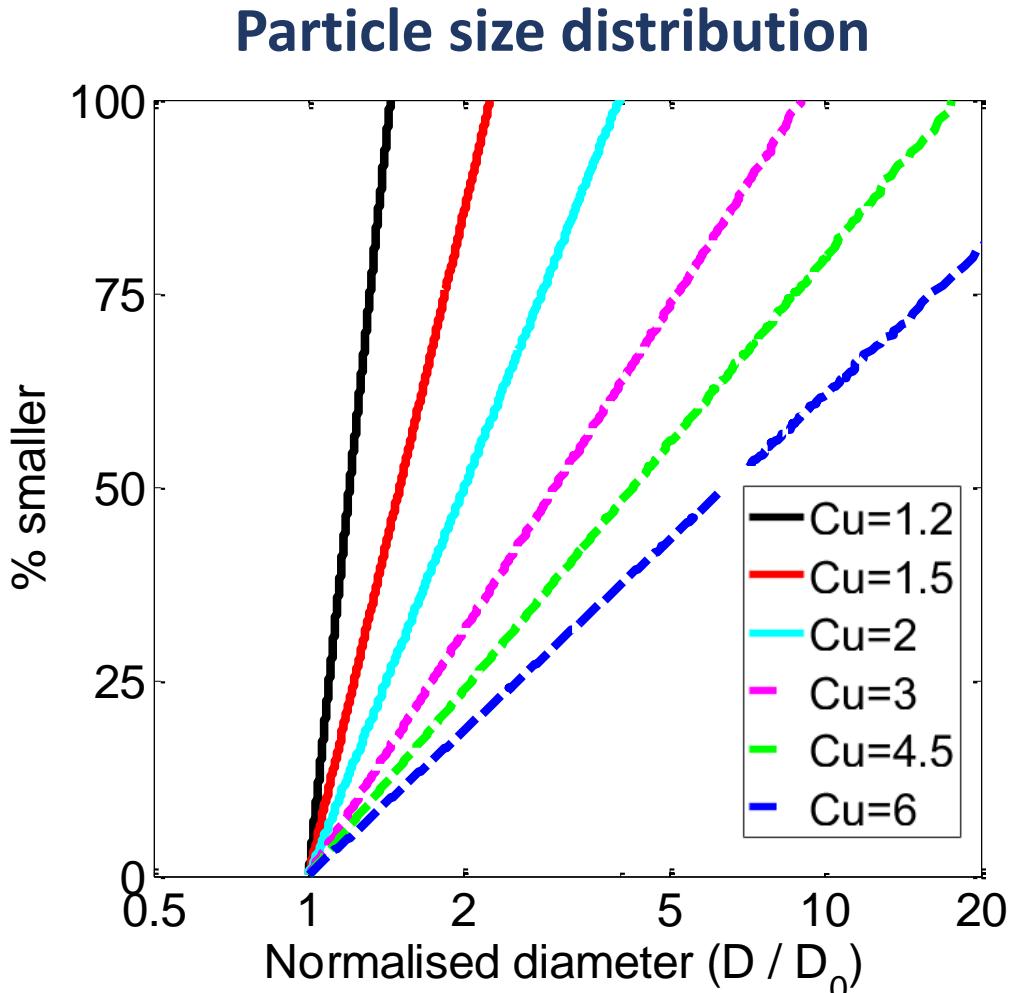
Spheres  
 $C_u = 3.0$



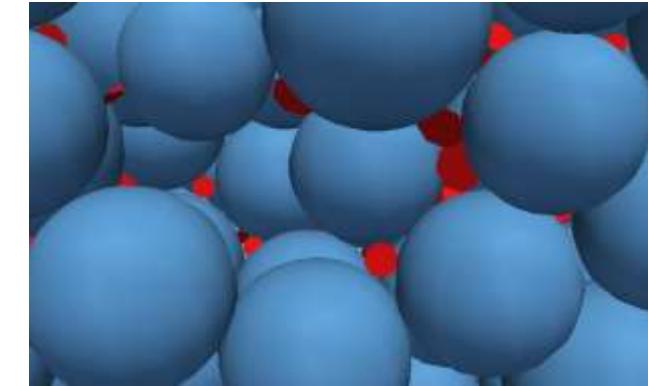
Spheres  
 $C_u = 6.0$

(Shire, 2014)

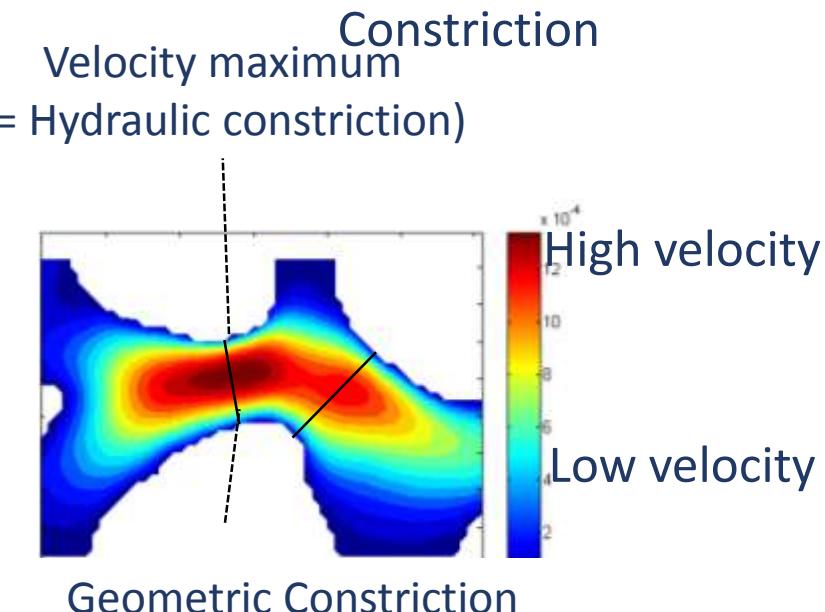
# Constriction size distributions (DEM)



Delaunay triangulation of particles



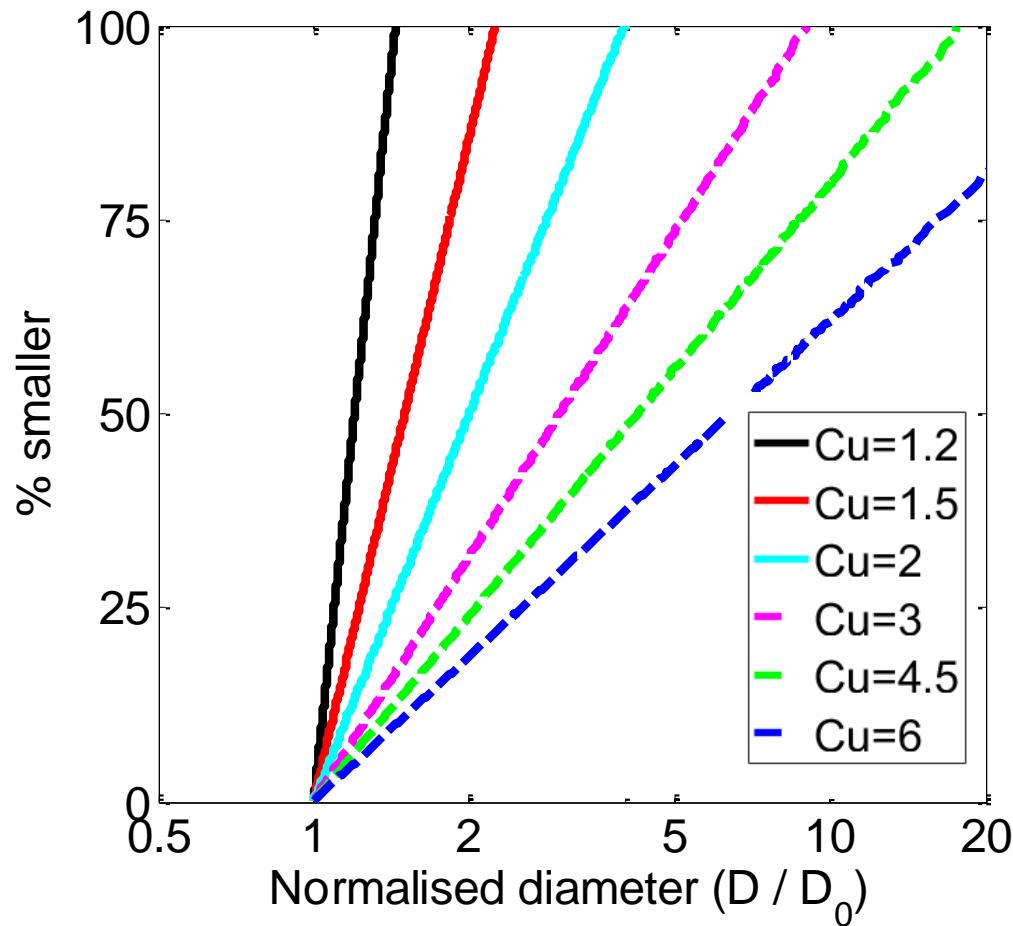
Validity of geometric partitioning demonstrated in CFD analyses



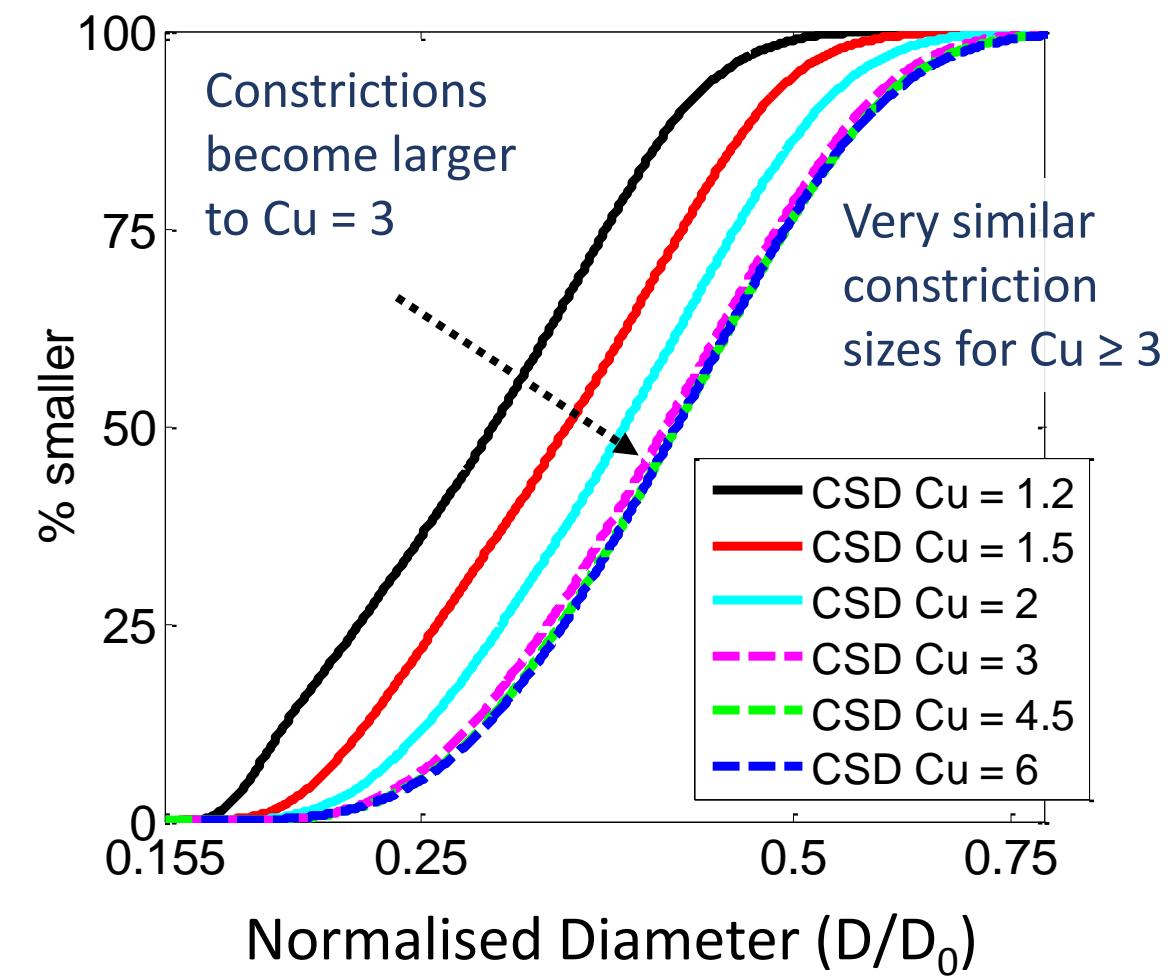
(Shire, 2014)

# Constriction size distributions (DEM)

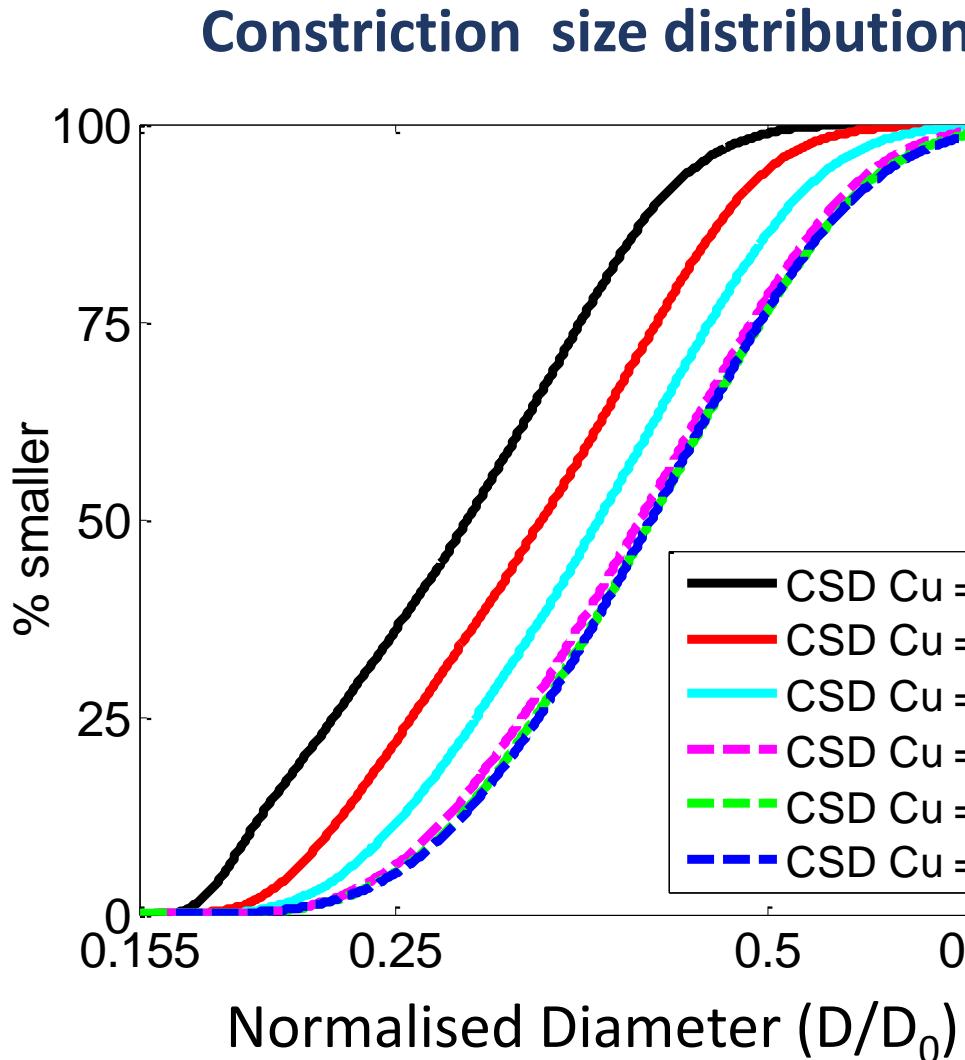
Particle size distribution



Constriction size distribution



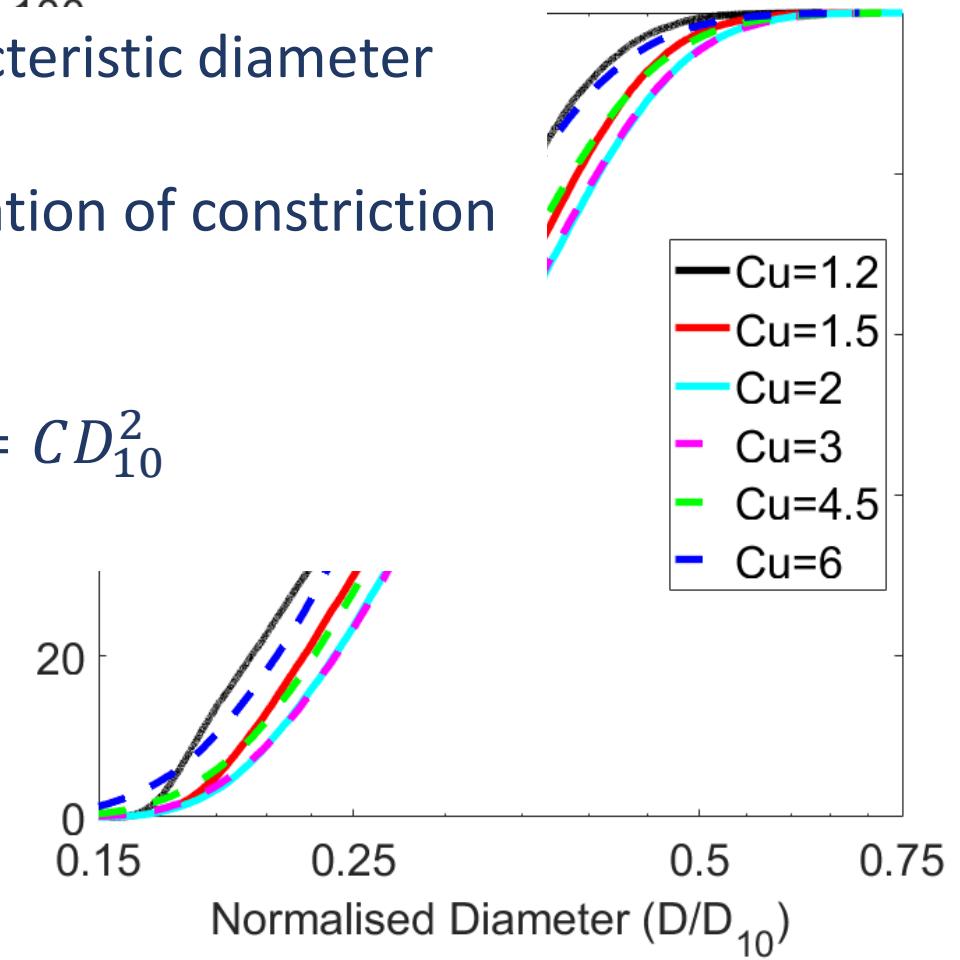
# Constriction size distributions (DEM)



Constriction size distribution  
normalised by  $D_{10}$

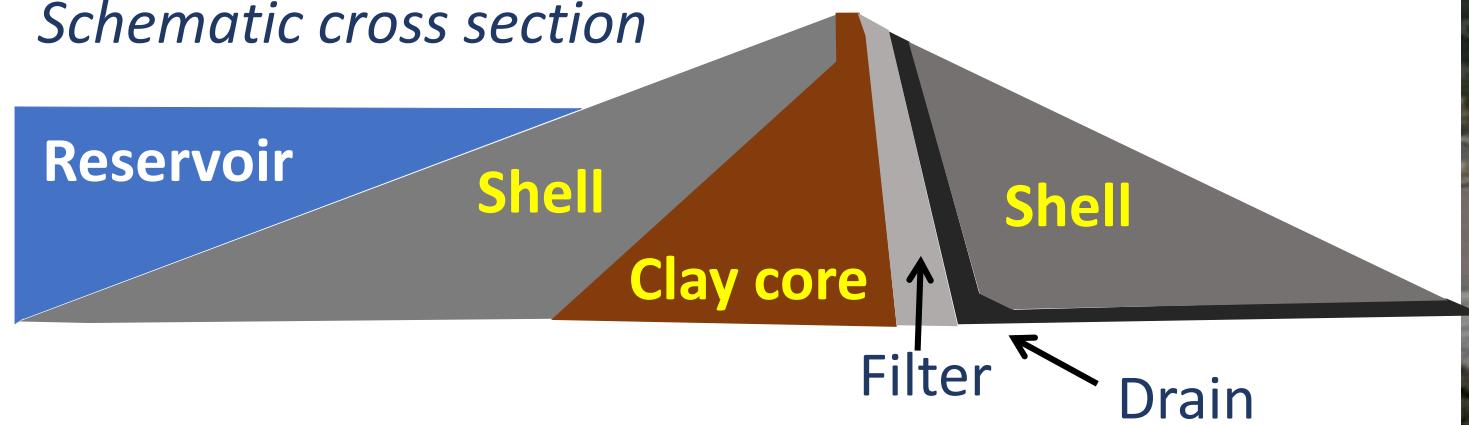
$D_{10}$  = characteristic diameter  
Gives indication of constriction sizes in soil

$$\text{Hazen: } k = CD_{10}^2$$



# Embankment dams

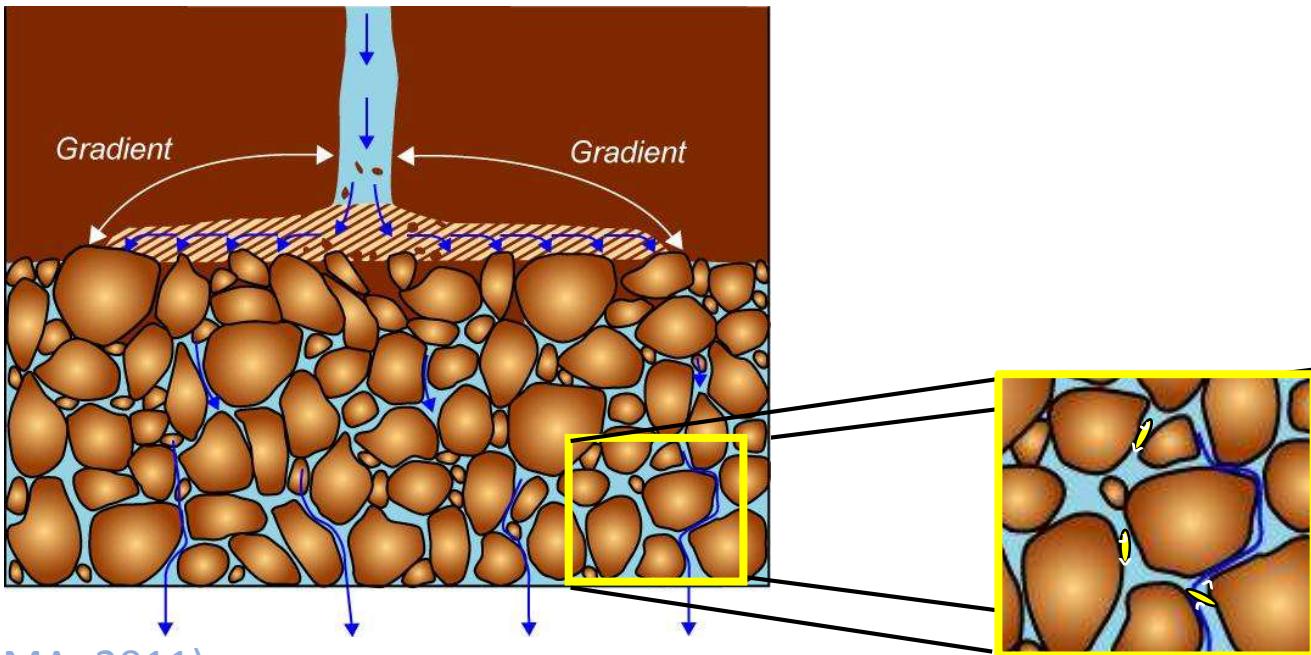
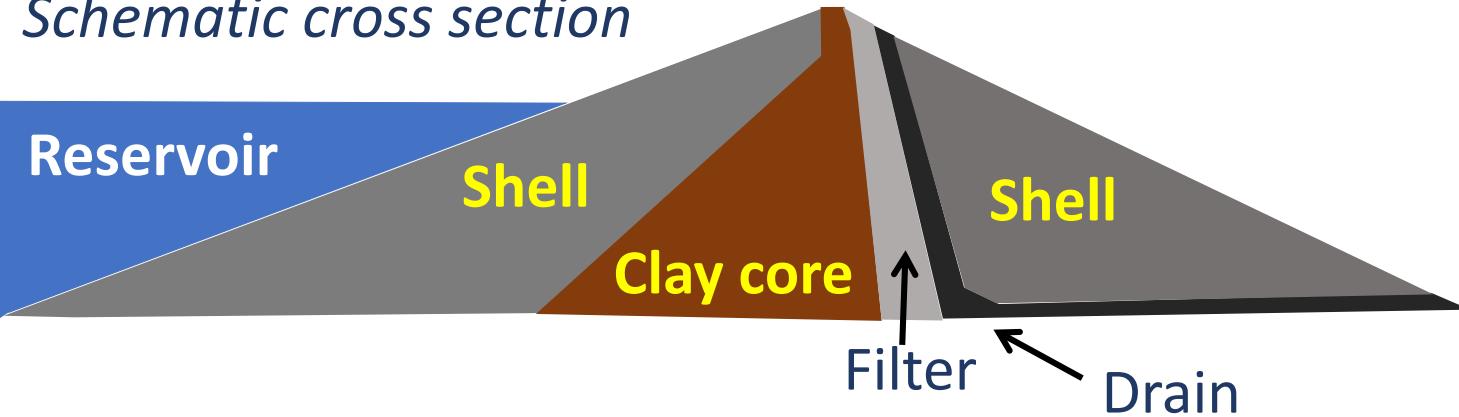
*Schematic cross section*



Paraperios dam - May 26 2010

# Filters

Schematic cross section



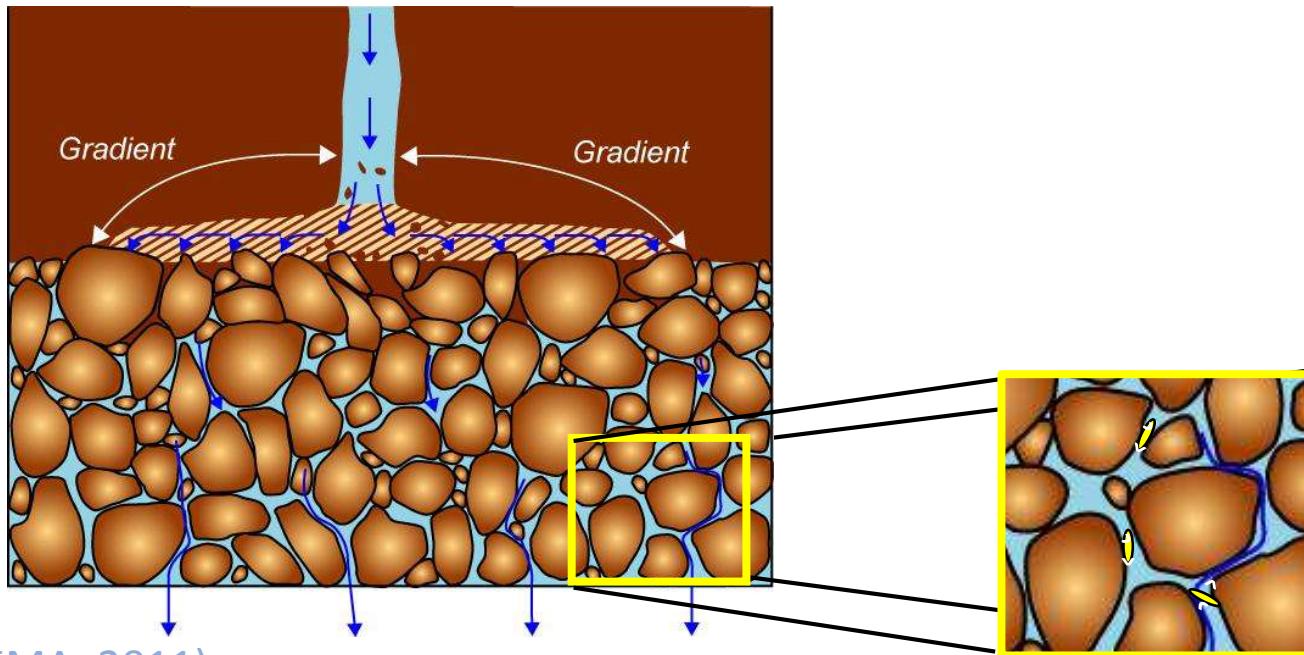
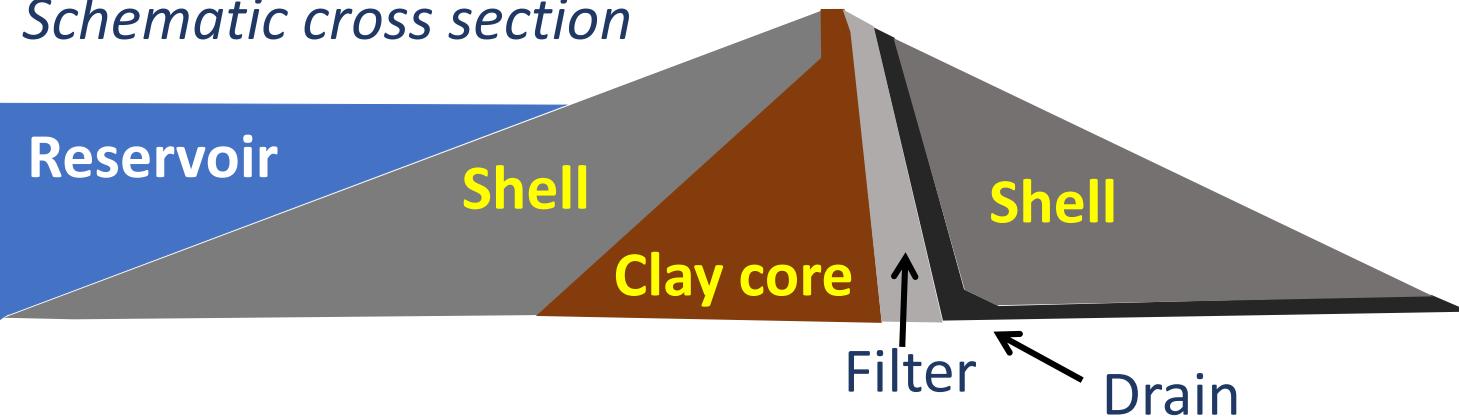
(FEMA, 2011)

Seeping water can move particles in the embankment

# Filters

# Filters

Schematic cross section



(FEMA, 2011)

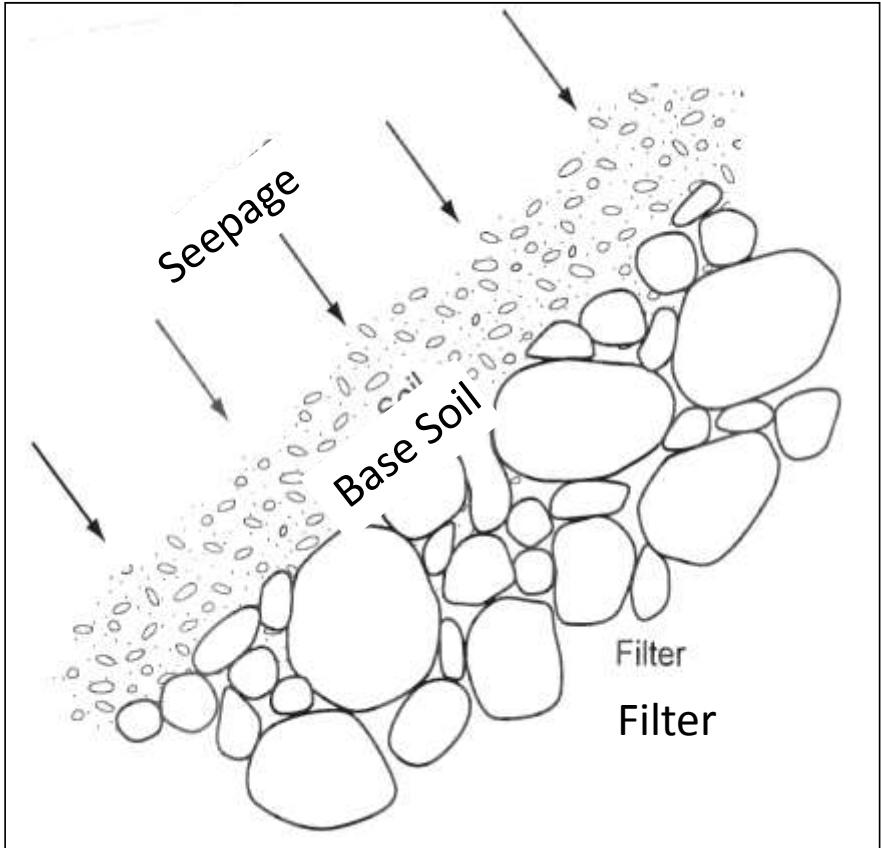
Seeping water can move particles in the embankment

When a filter works:

Fine core particles get trapped in constrictions in void space

Water flows so there is no build up of pressure

# Filters

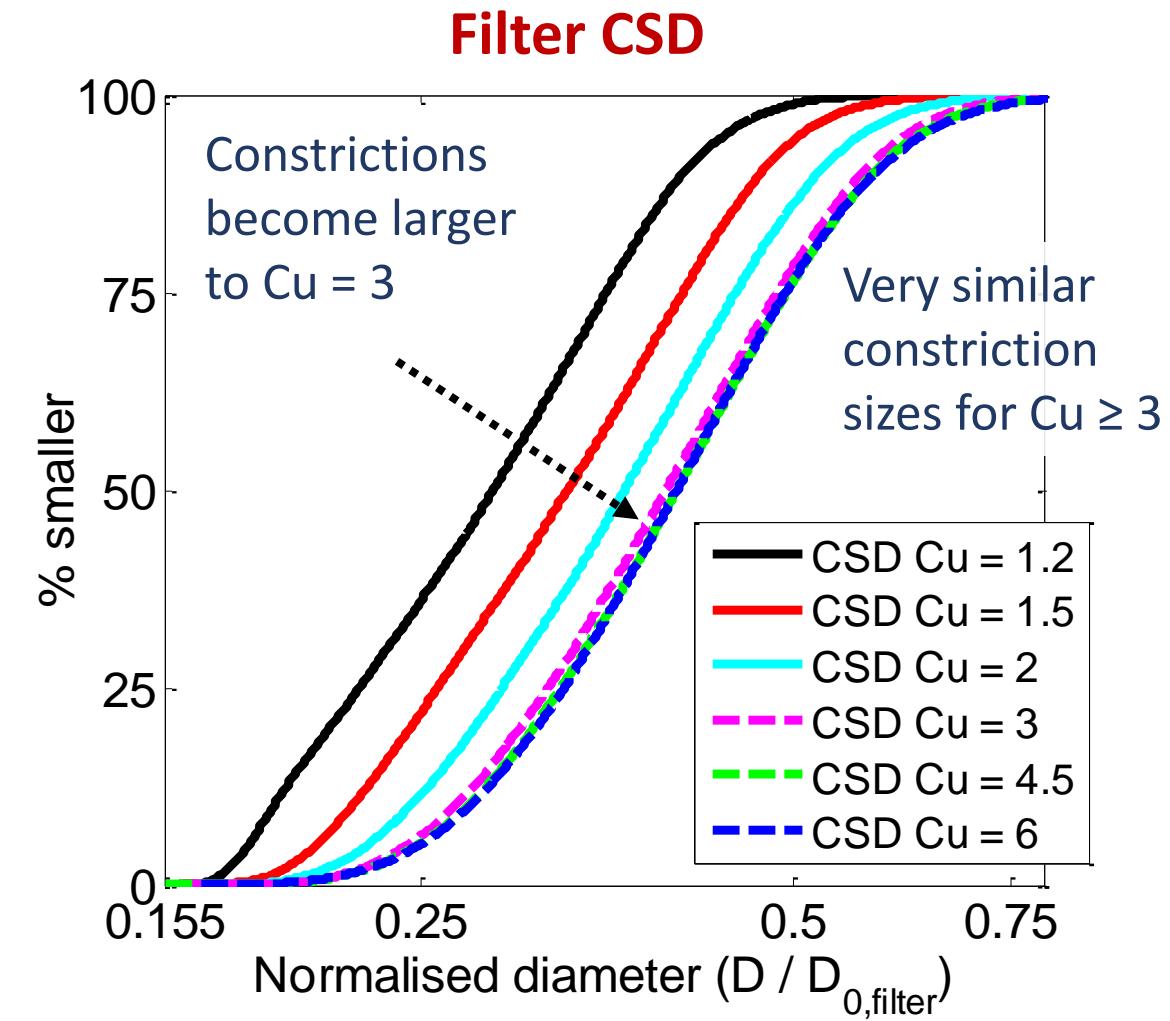
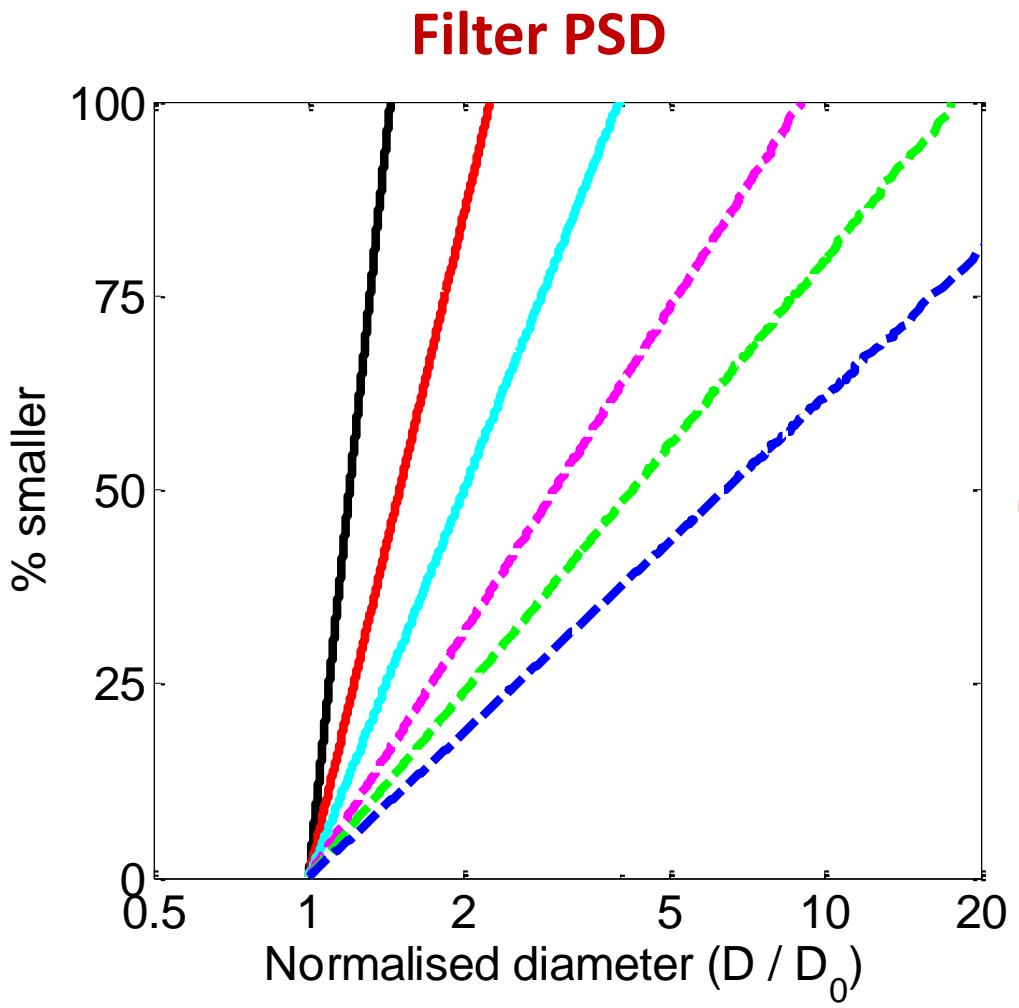


(FEMA, 2011)

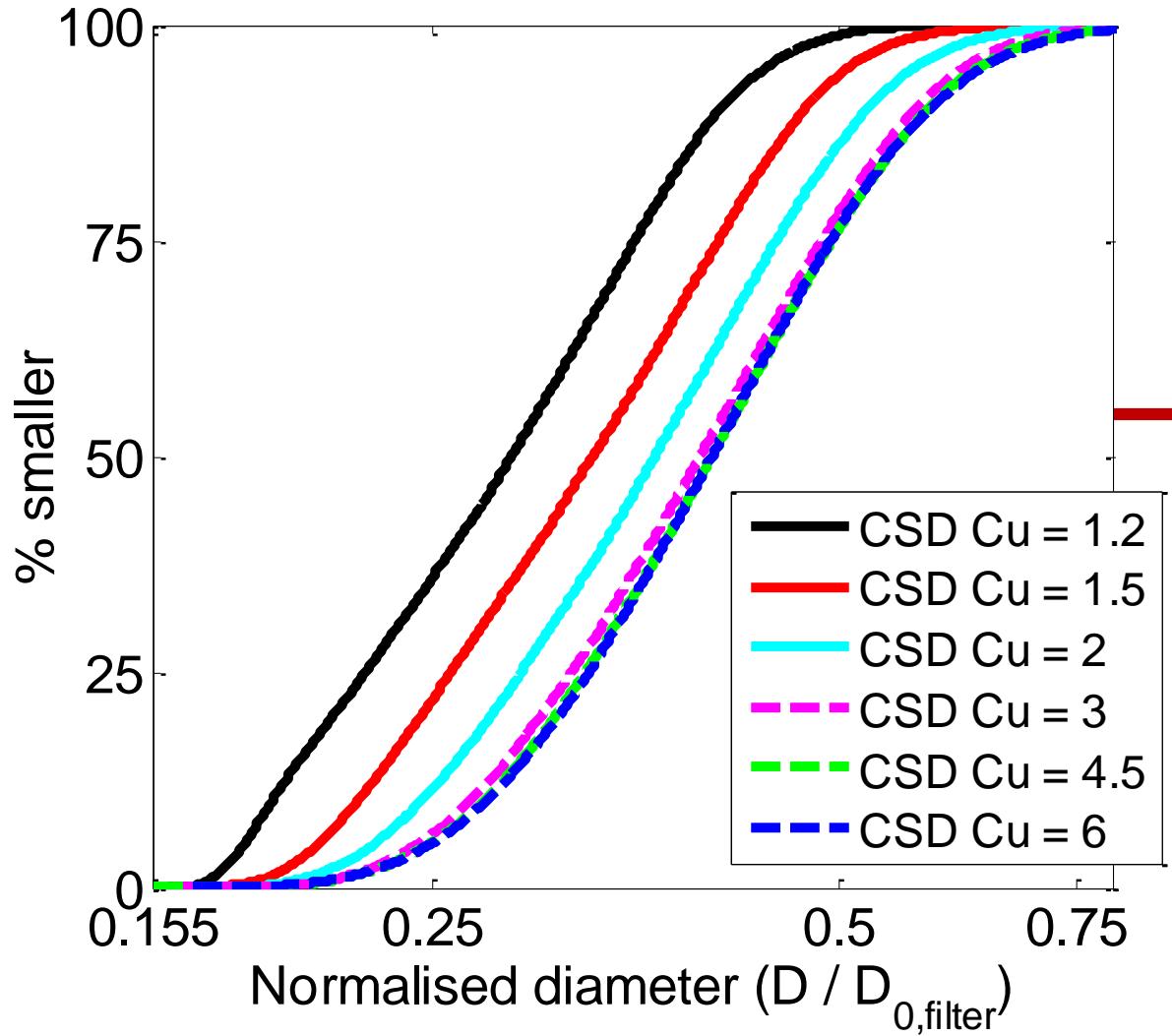
Terzaghi's filter rule / Sherard & Dunnigan (1989):

- $D_{15F}$  of filter
- $D_{85B}$  of base
- For retention  $D_{15F} < 4 D_{85B}$   
(ICOLD, 2015)

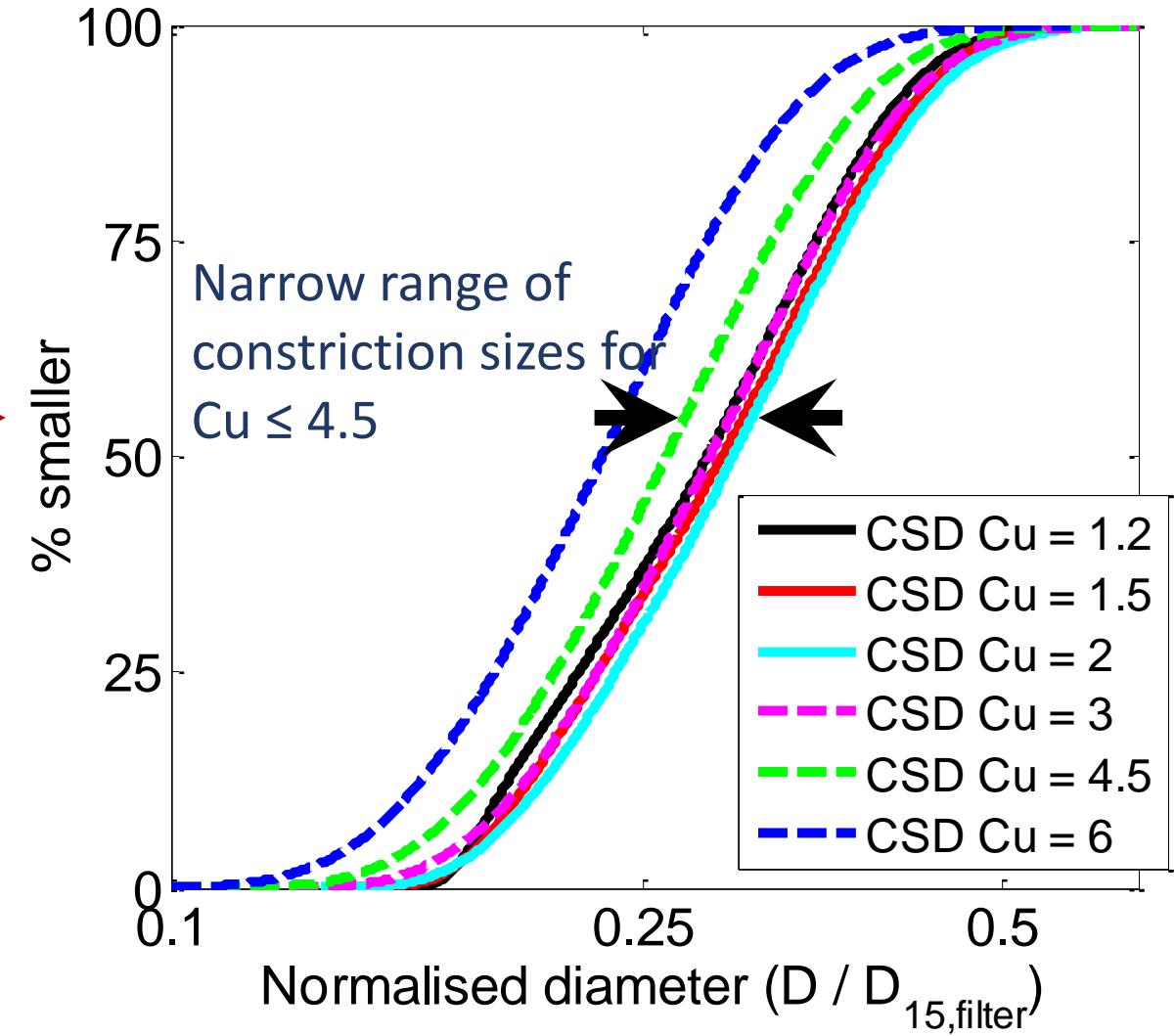
# Constriction size distributions (DEM)



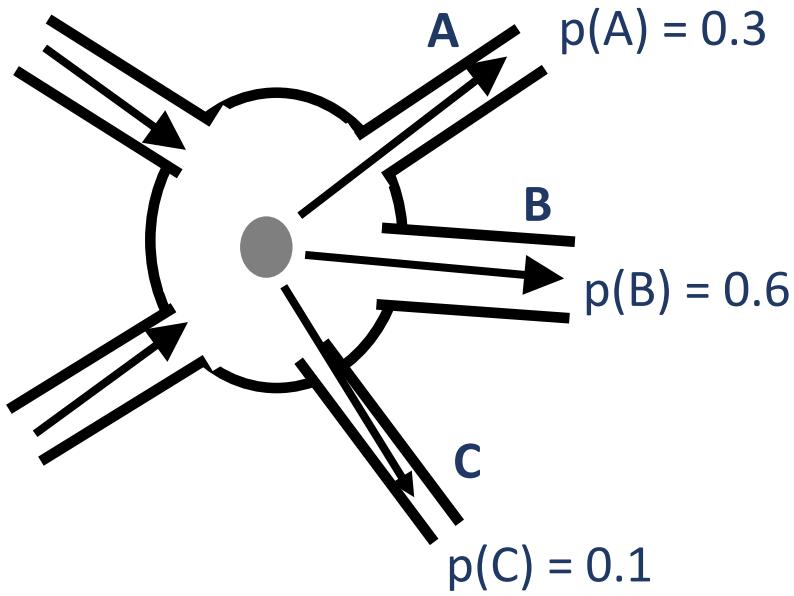
# Constriction size distributions (DEM)



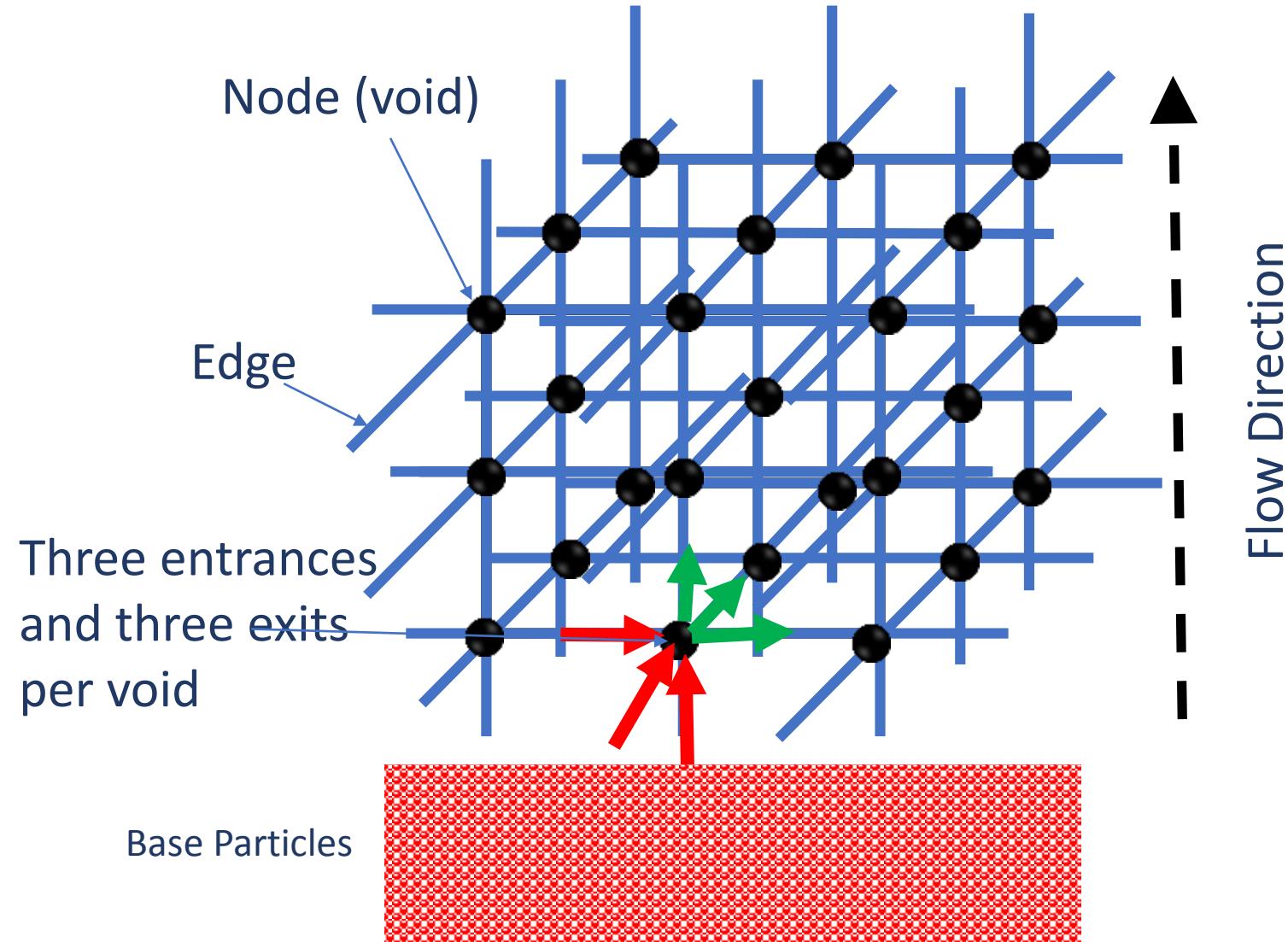
Shire and O'Sullivan (2016)



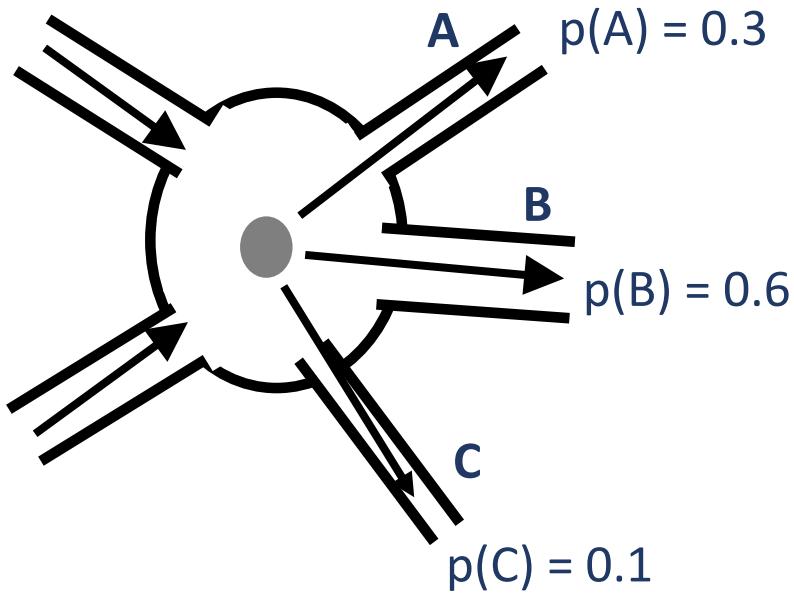
# Filtration – Network model



- Likelihood of moving forward depends on constriction area
- No consideration of flow
- Up to 400 million base (clay core) particles

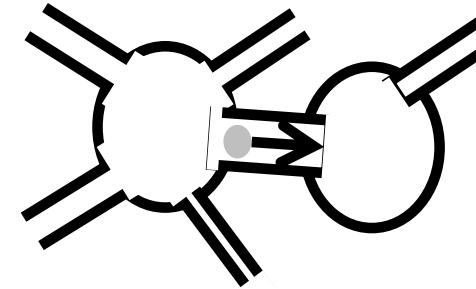


# Filtration – Network model

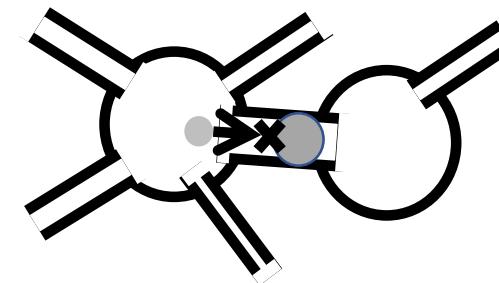


- Likelihood of moving forward depends on constriction area
- No consideration of flow
- Up to 400 million base (clay core) particles

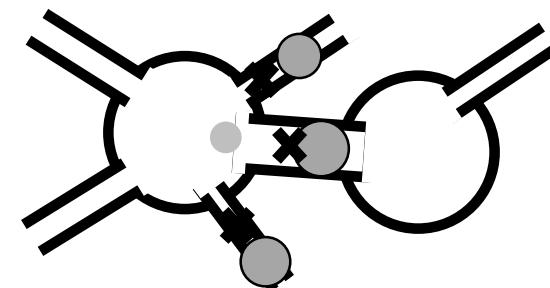
Base particle moves through constriction



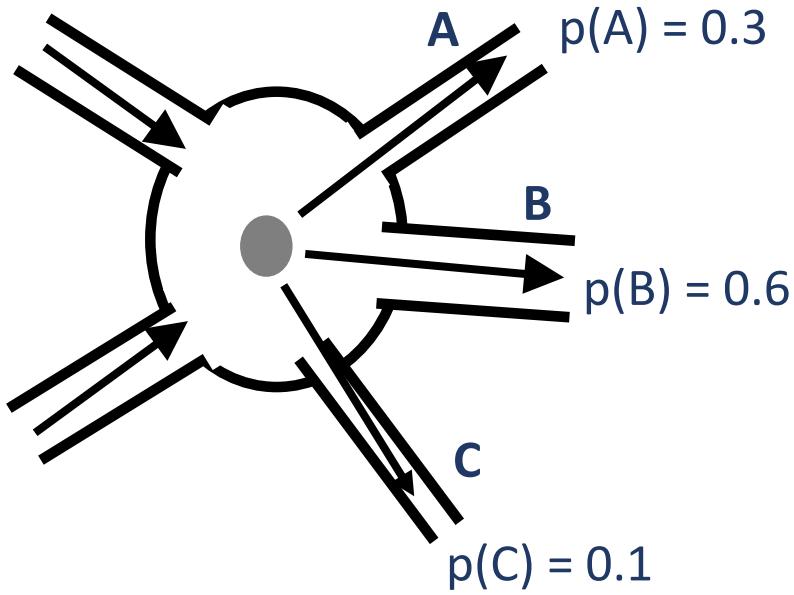
Base particle retained + constriction blocked



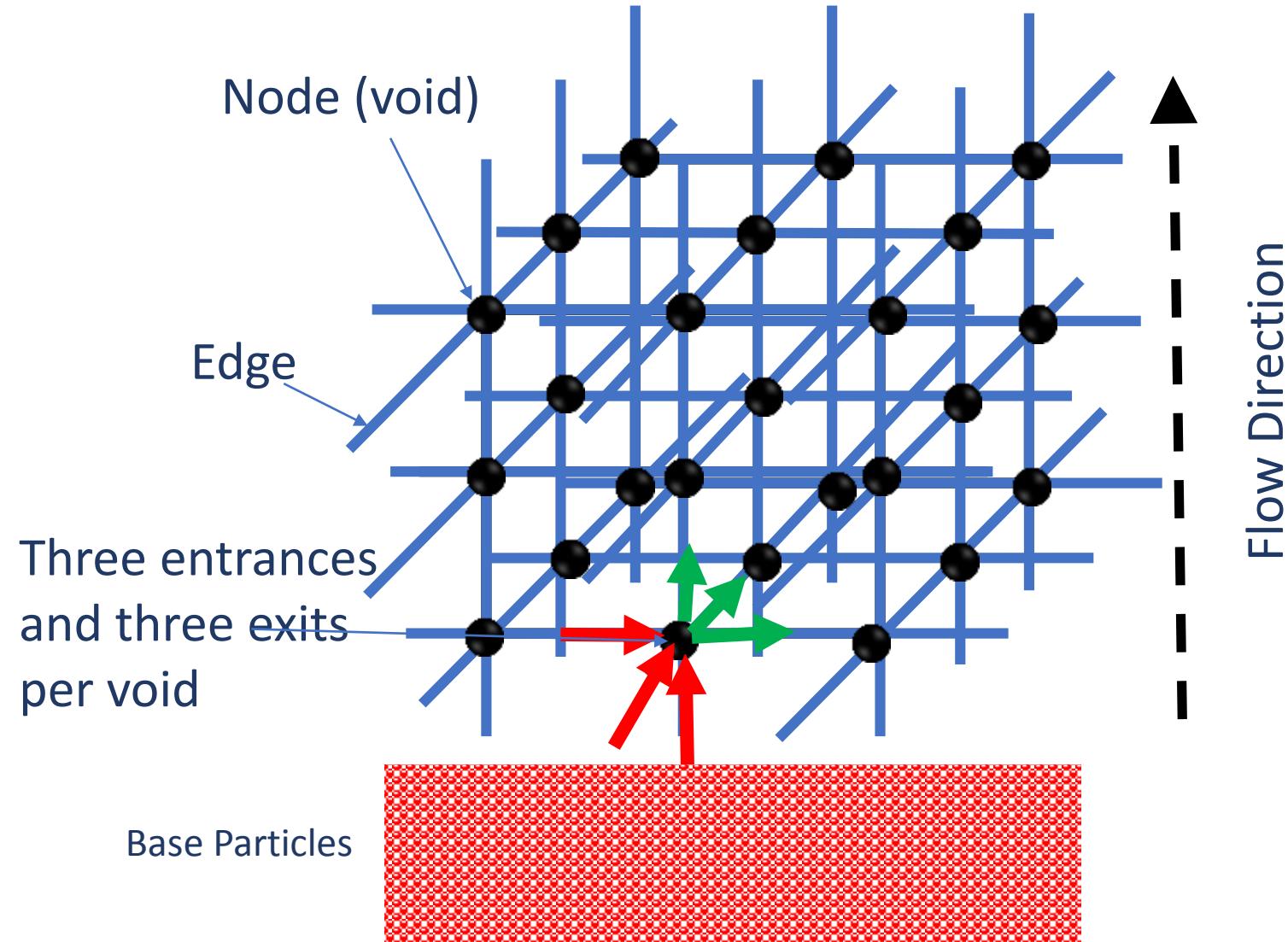
Base particle retained in void



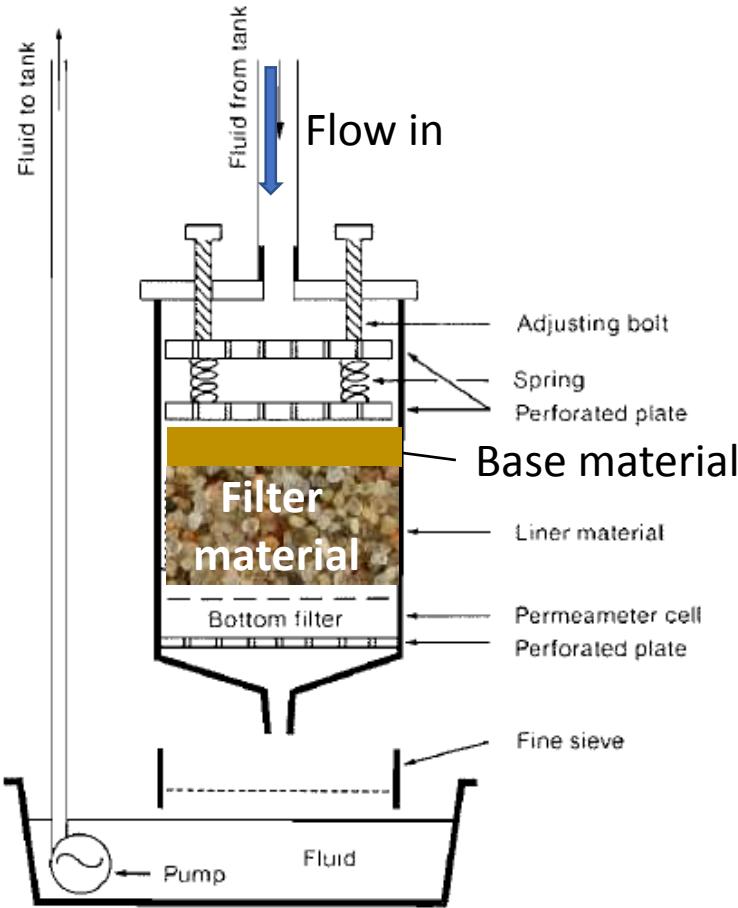
# Filtration – Network model



- Likelihood of moving forward depends on constriction area
- No consideration of flow
- Up to 400 million base (clay core) particles



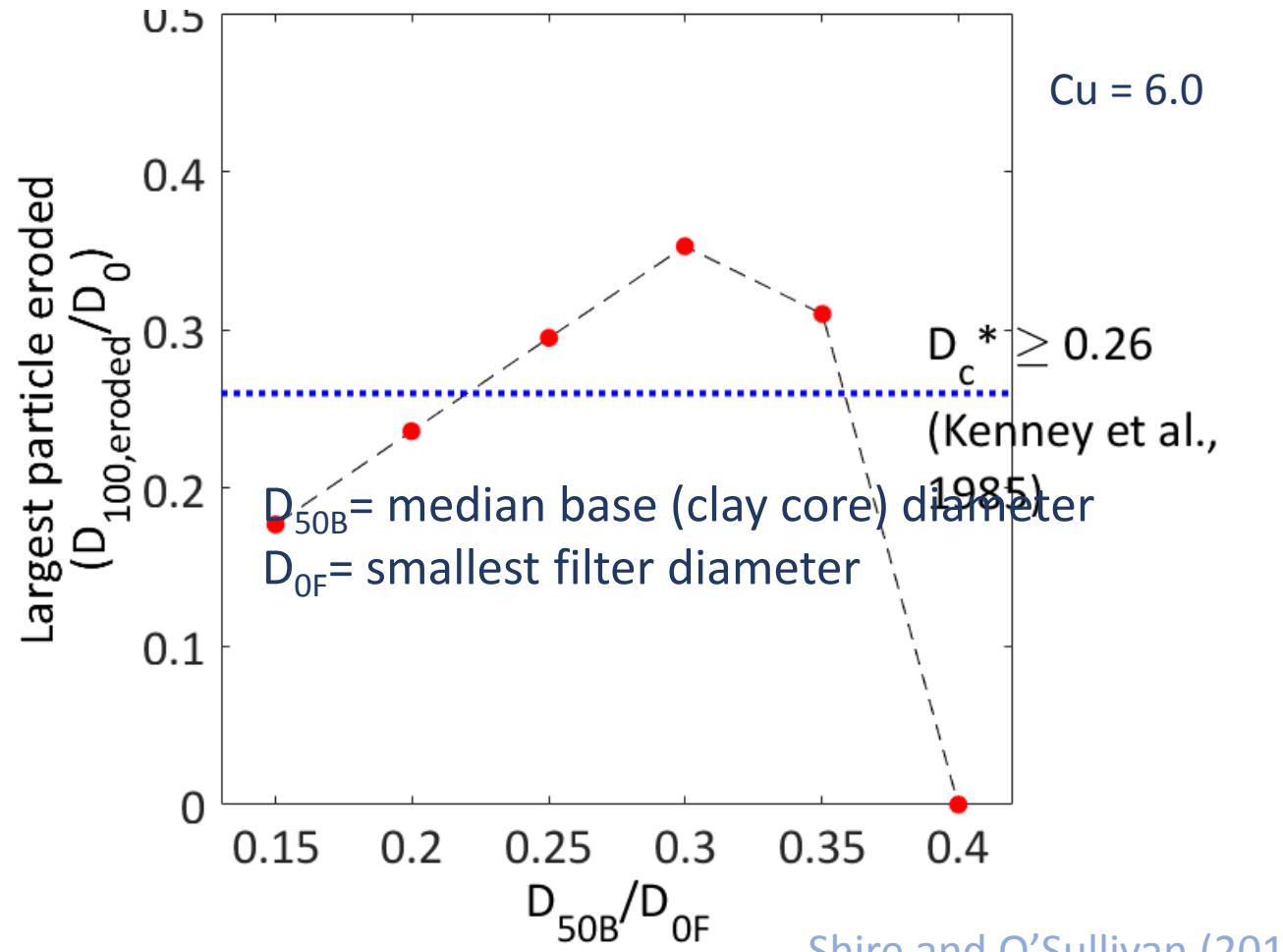
# Controlling constriction size



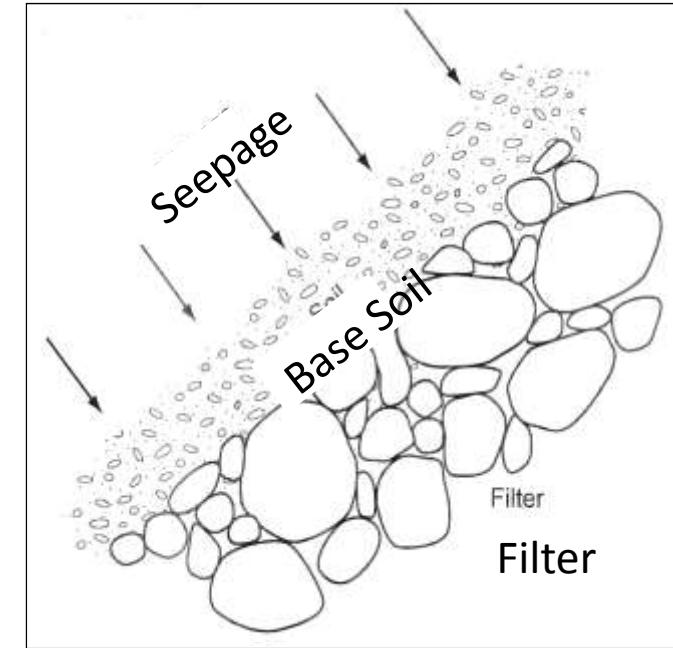
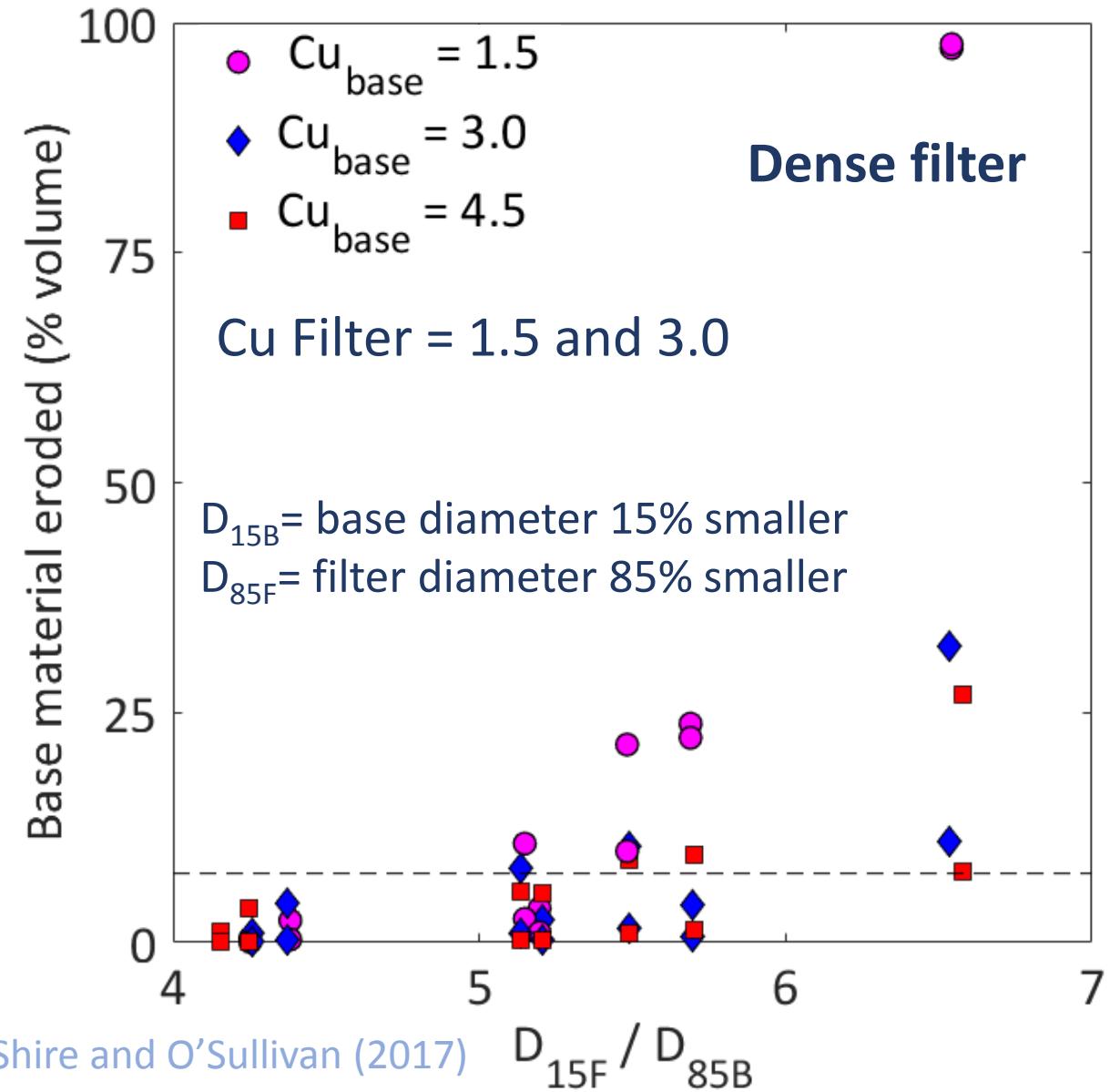
Kenney et al (1985): Base- Filter tests: Base-filer tests

$D_c^*$  = controlling constriction diameter = largest particle that can pass through filter

Largest base particle eroded agrees with experimental data for range of base material sizes ( $D_{50B}$ ) and filter Cu = 1.2, 3, 6



# Filtration – Network model

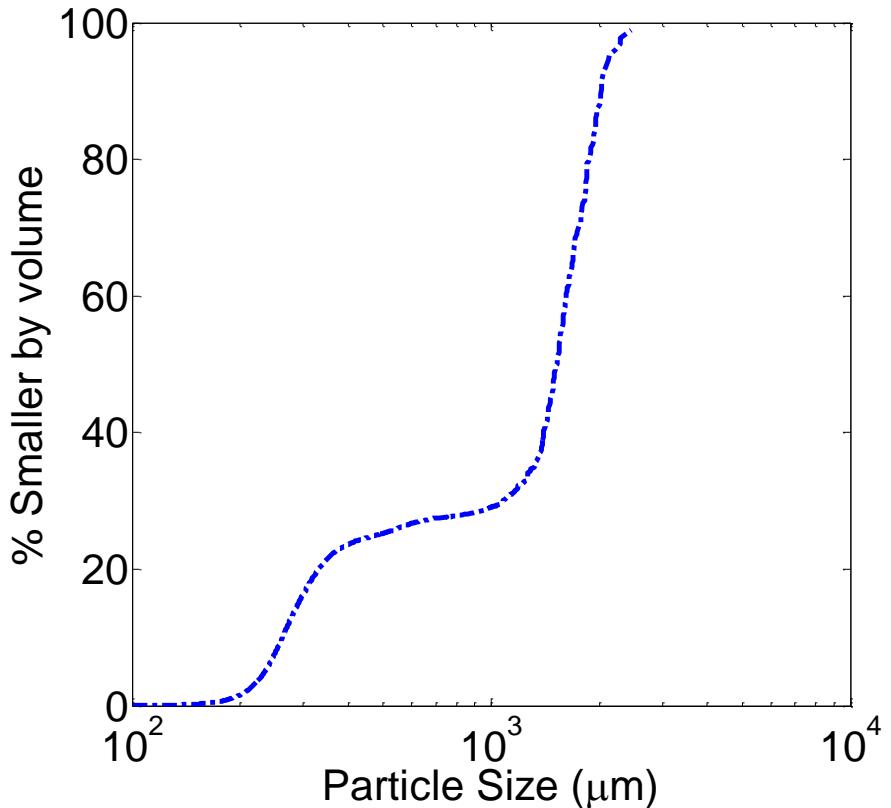


(FEMA, 2011)

Terzaghi's filter rule / Sherard & Dunnigan (1989):

- $D_{15F}$  of filter
  - $D_{85B}$  of base
  - For retention  $D_{15F} < 4 D_{85B}$
- (ICOLD, 2015)

# Internal Instability



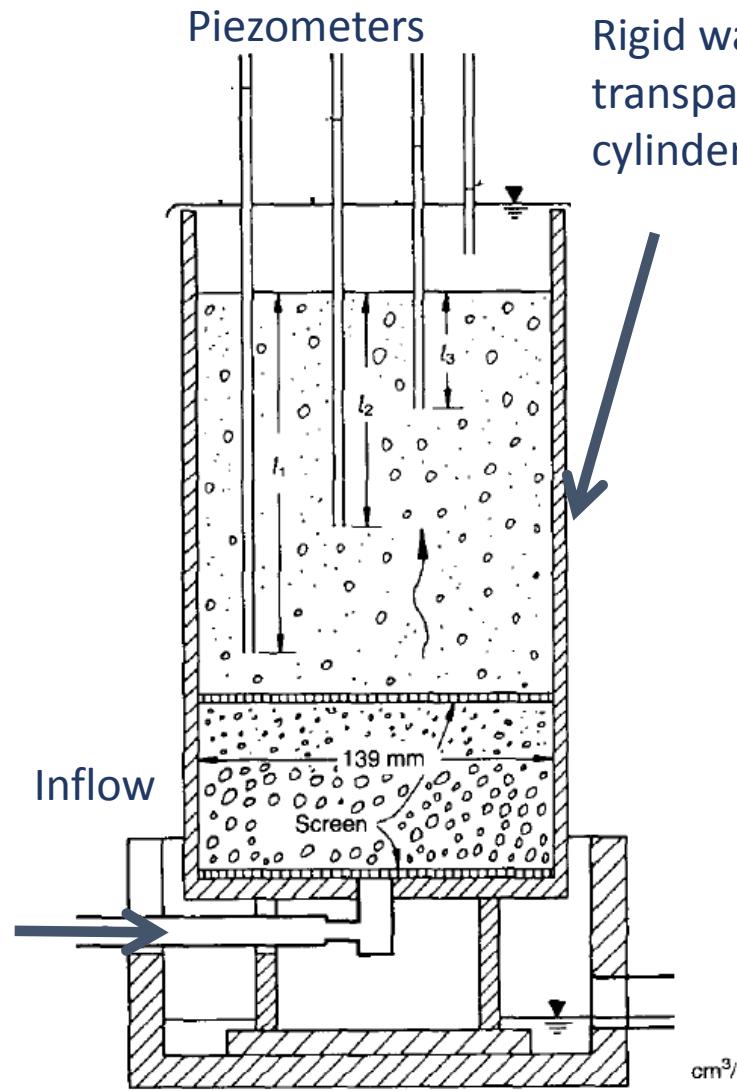
Robert Negri MSc

- In gap graded materials erosion can happen at low hydraulic gradients

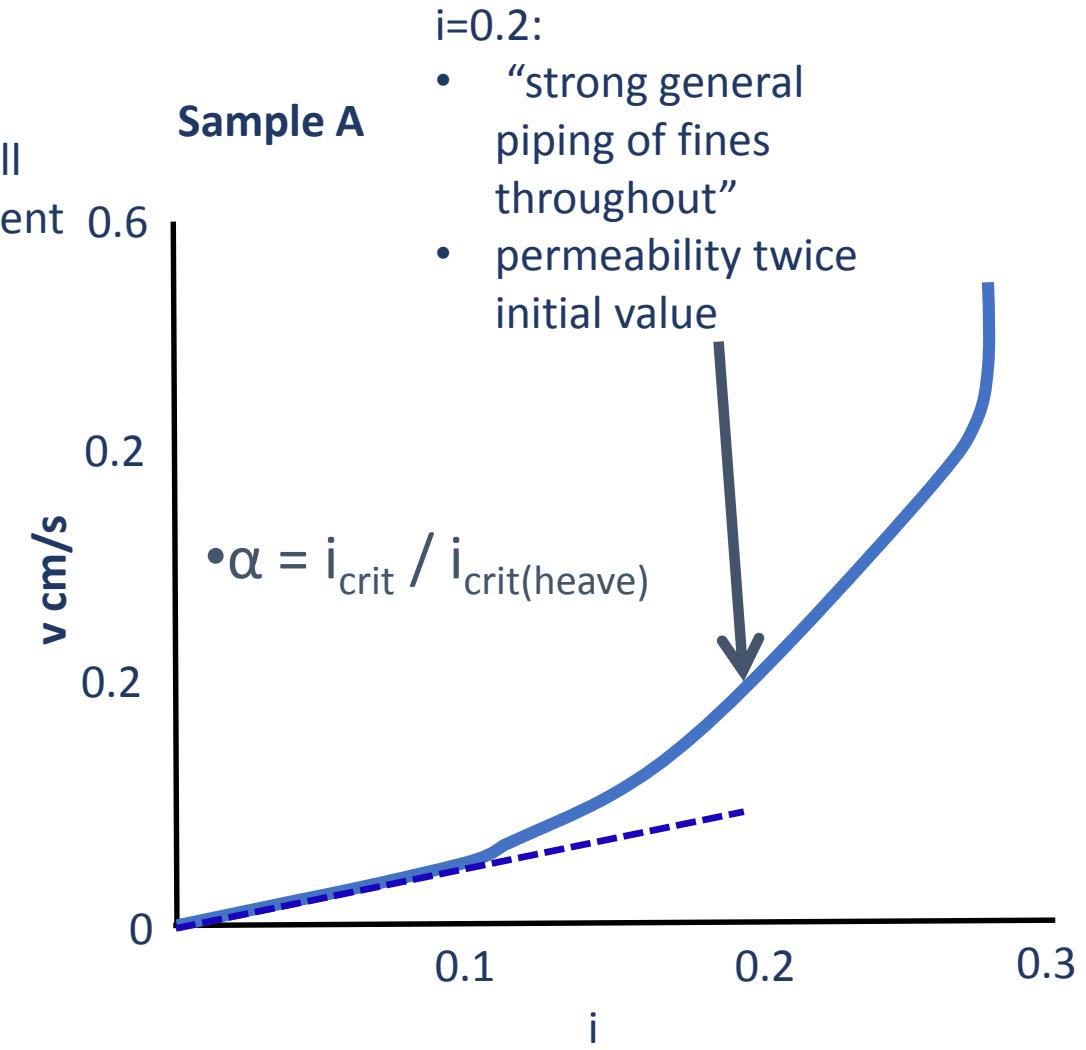
# Skempton and Brogan permeameter experiments



Prof. Skempton



Sample A



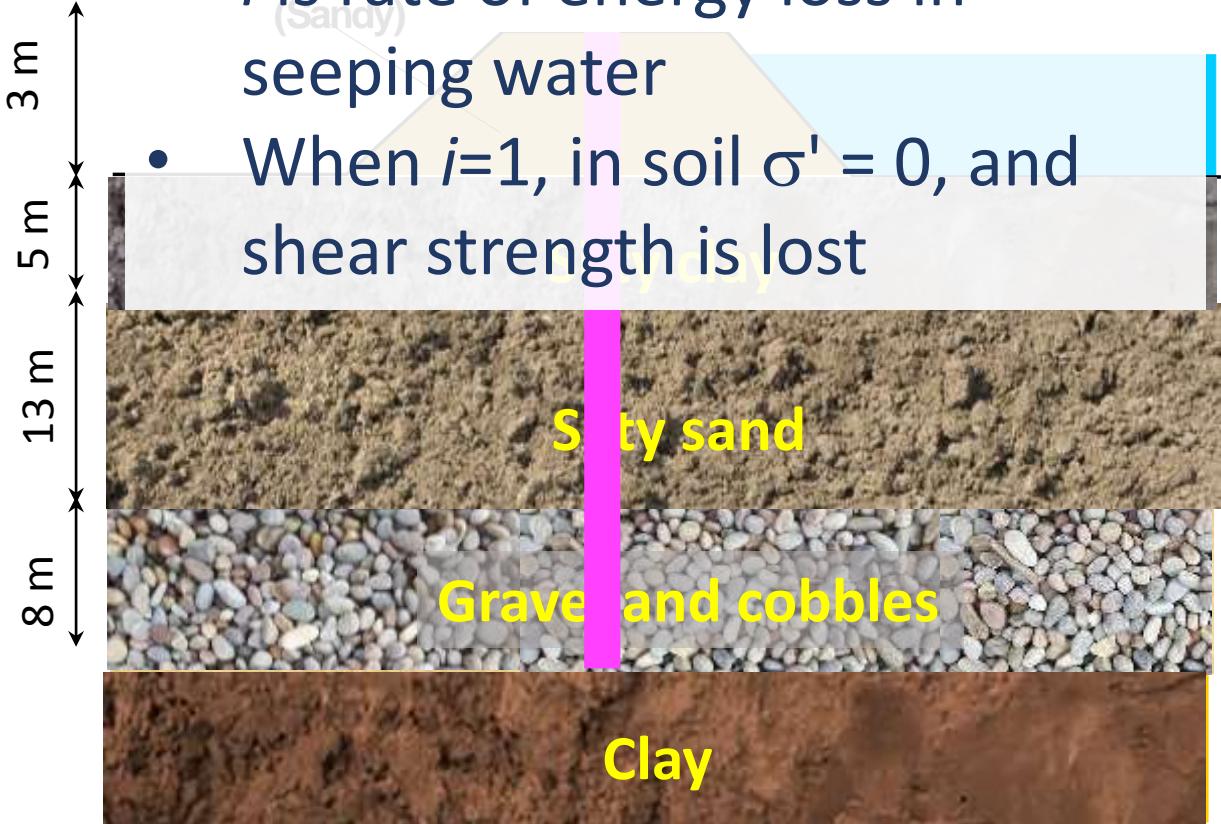
Skempton and Brogan (1994)  
Géotechnique

# Flood embankments



Design aim :

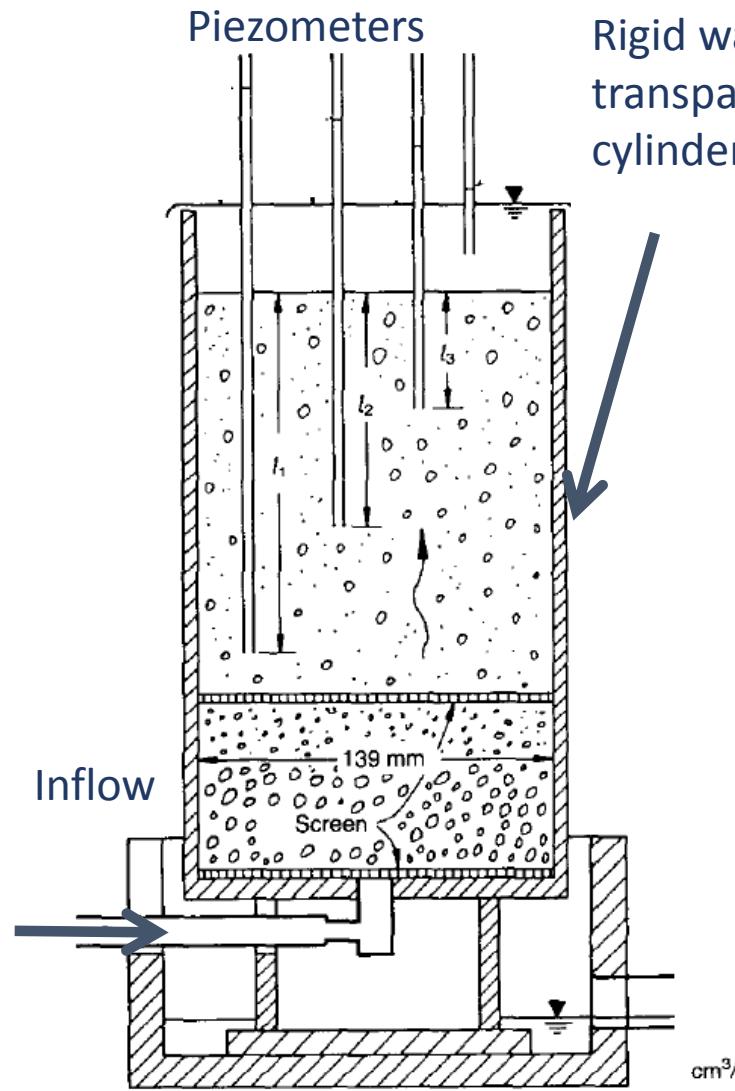
- Reduce downstream hydraulic gradient,  $i$
- $i$  is rate of energy loss in seeping water
- When  $i=1$ , in soil  $\sigma' = 0$ , and shear strength is lost



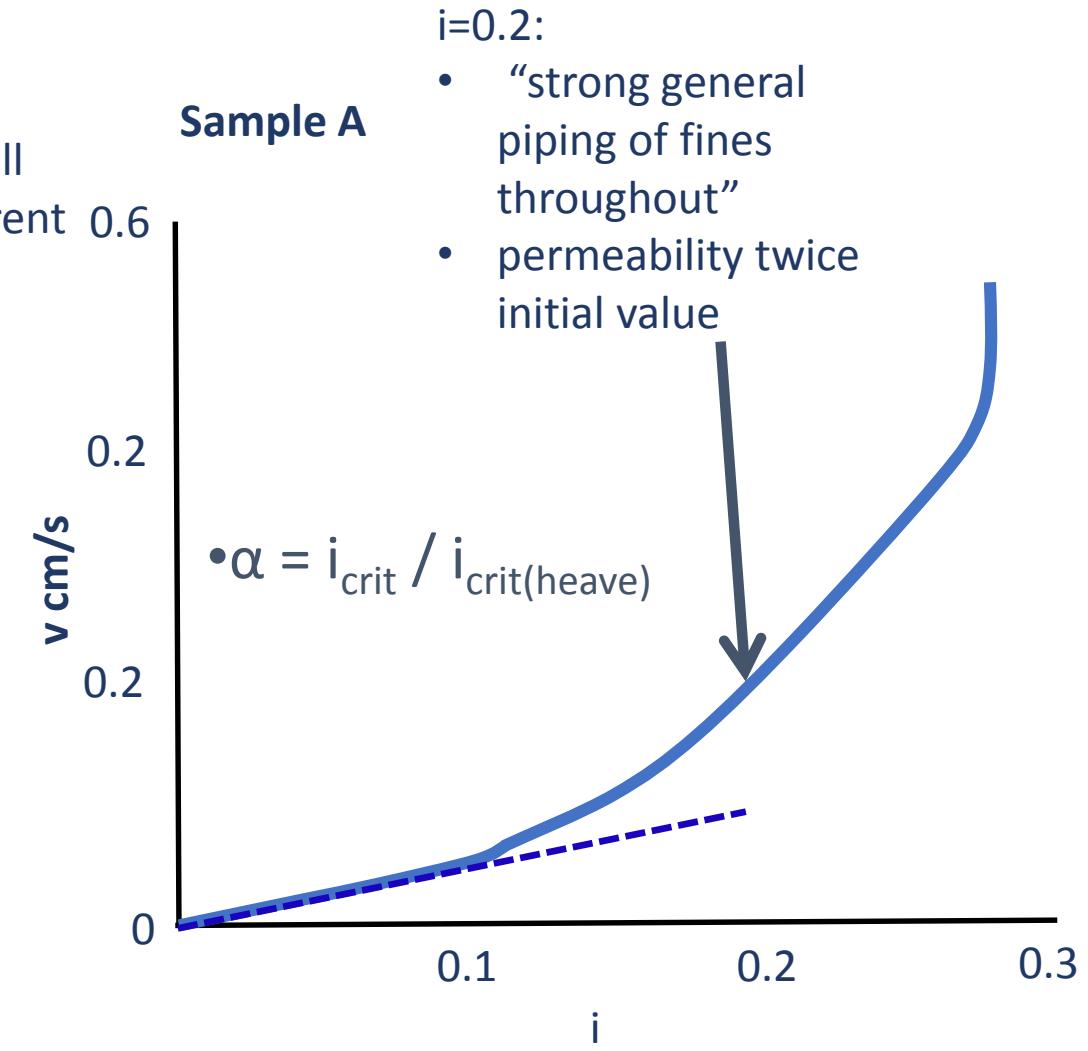
# Skempton and Brogan permeameter experiments



Prof. Skempton



Sample A



Skempton and Brogan (1994)  
Géotechnique

# $\alpha$ : proportion of stress carried by finer grains

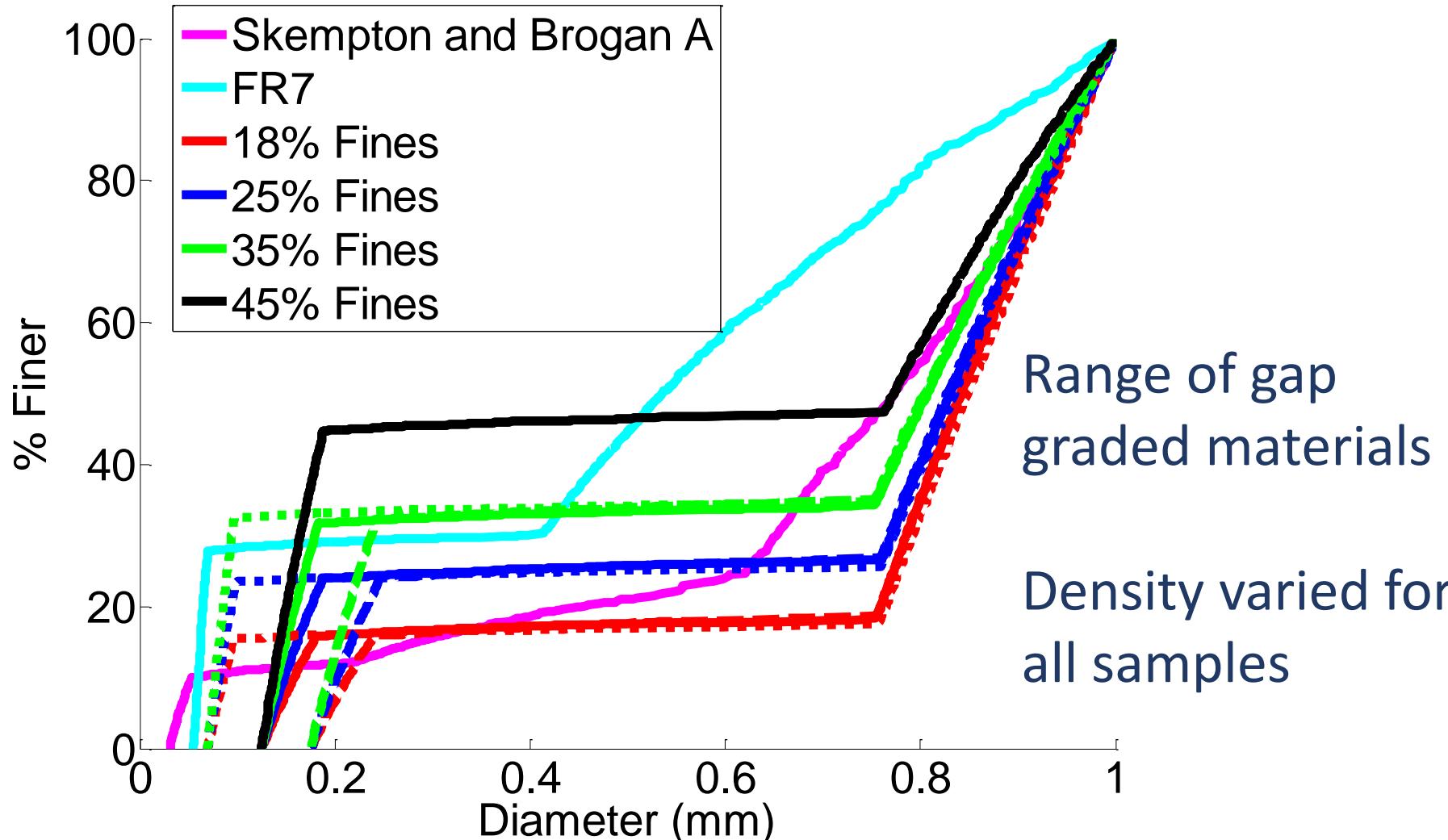
- Larger particles transfer most of stress
- Finer grains carry reduced effective stress
- $\alpha$  is proportion of stress carried by finer fraction

$$\sigma'_{\text{fines}} = \alpha \times \sigma'$$

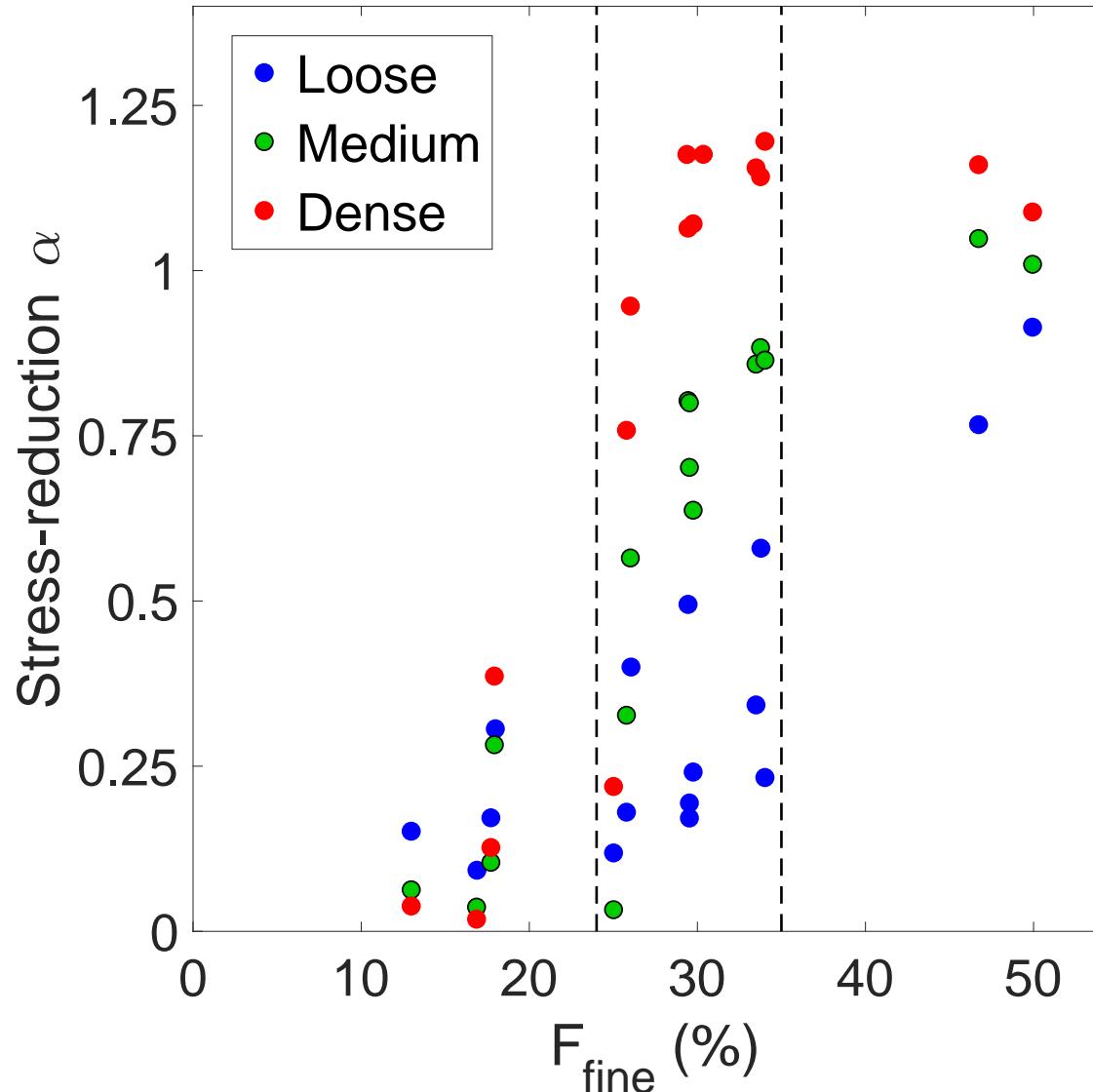
$$\alpha = i_{\text{crit}} / i_{\text{crit(heave)}}$$



# DEM simulations to investigate instability

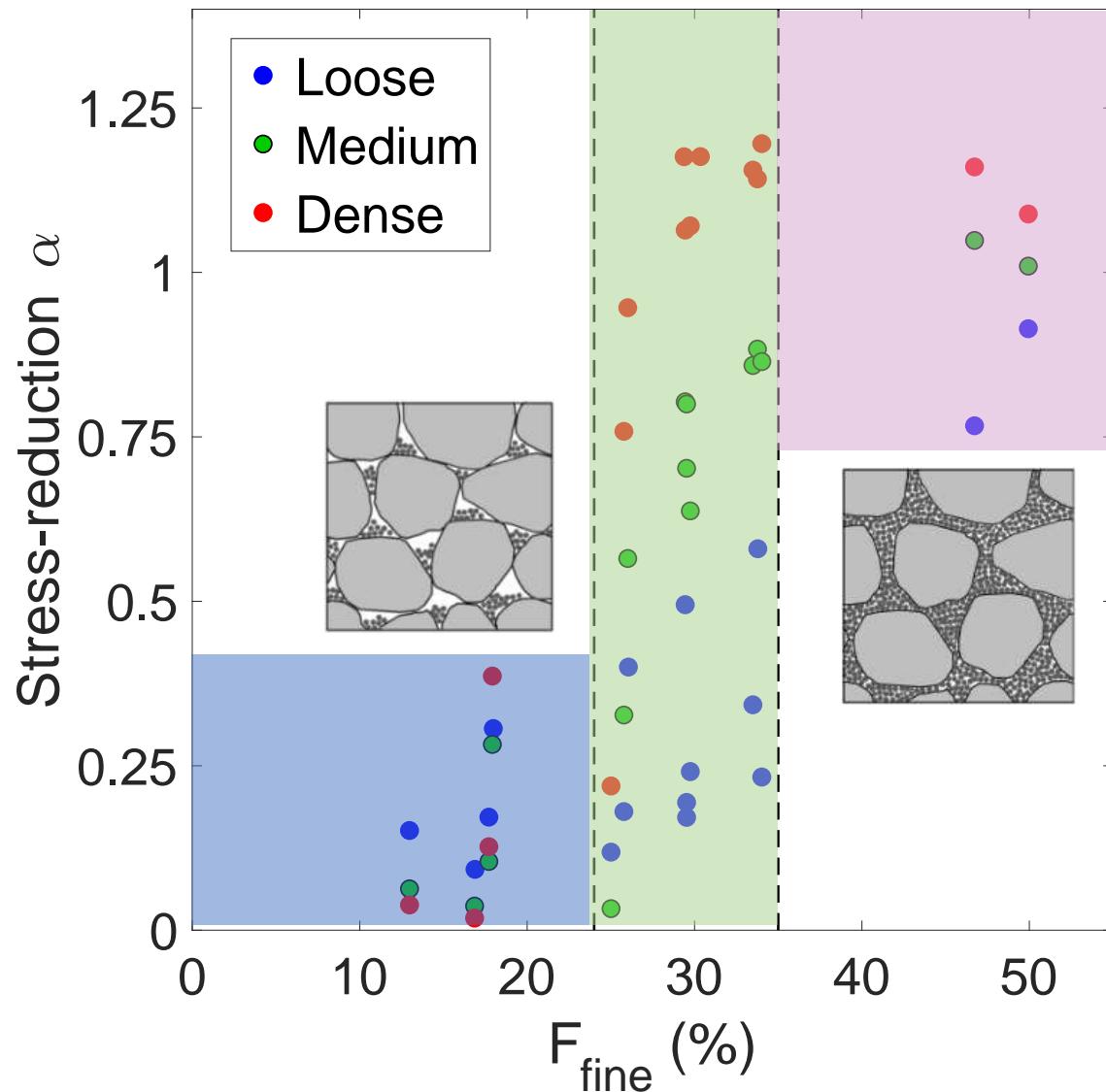


# Variation in $\alpha$ with fines content ( $F_{\text{fine}}$ )

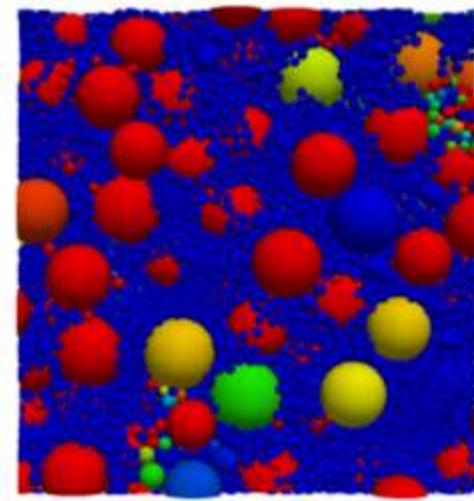


$\alpha$ : proportion of  
stress carried by  
finer fraction

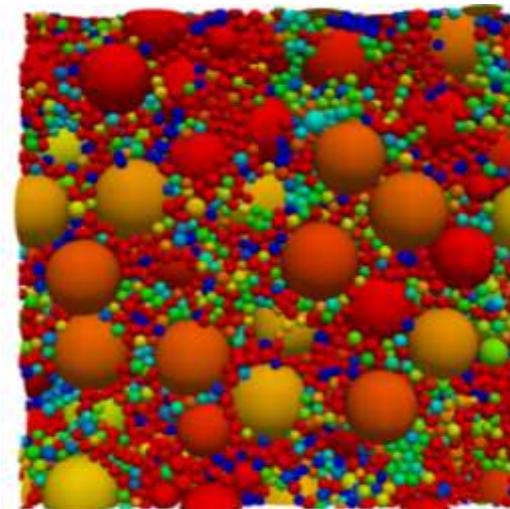
# Variation in $\alpha$ with fines content ( $F_{\text{fine}}$ )



$\alpha$   
1+  
0.75  
0.5  
0.25  
0



30% Fines - Loose



30% Fines - Dense

# Permeameter test simulations

- Simulate water flow through packed bed
- To establish link between  $\alpha$  and erosion likelihood

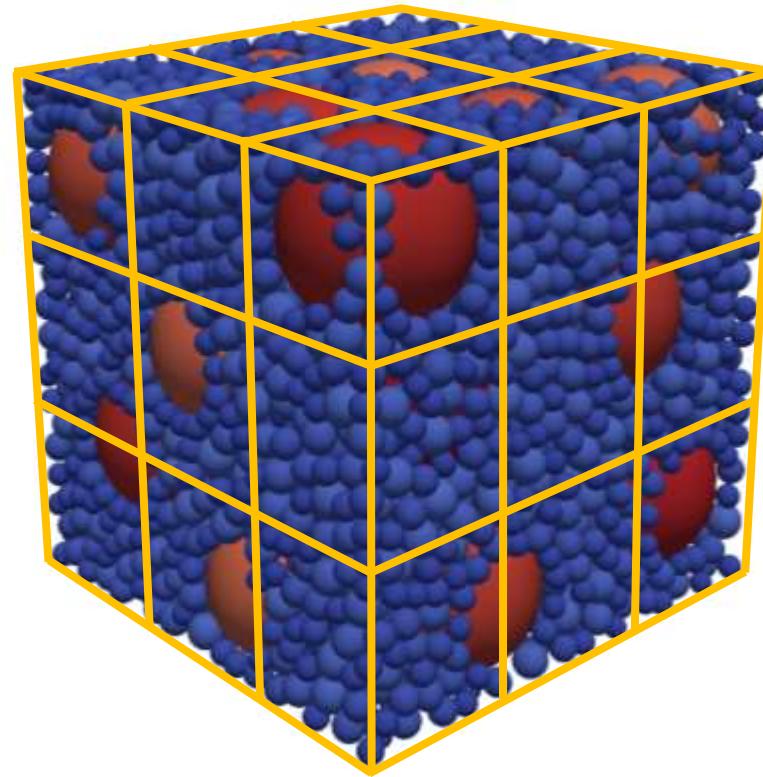
**DEM**  
For soil  
particles

-Porosity  
-Drag force



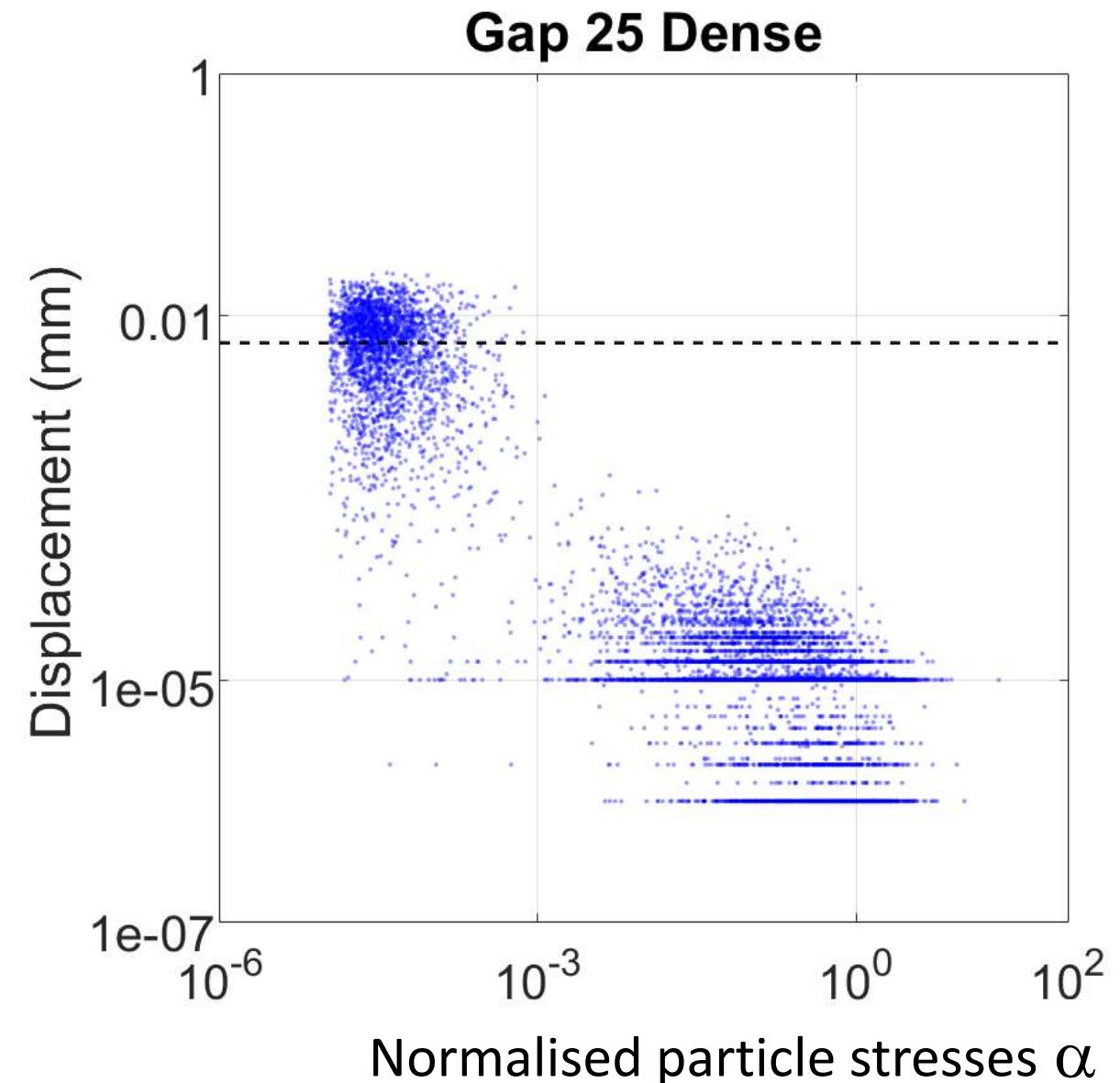
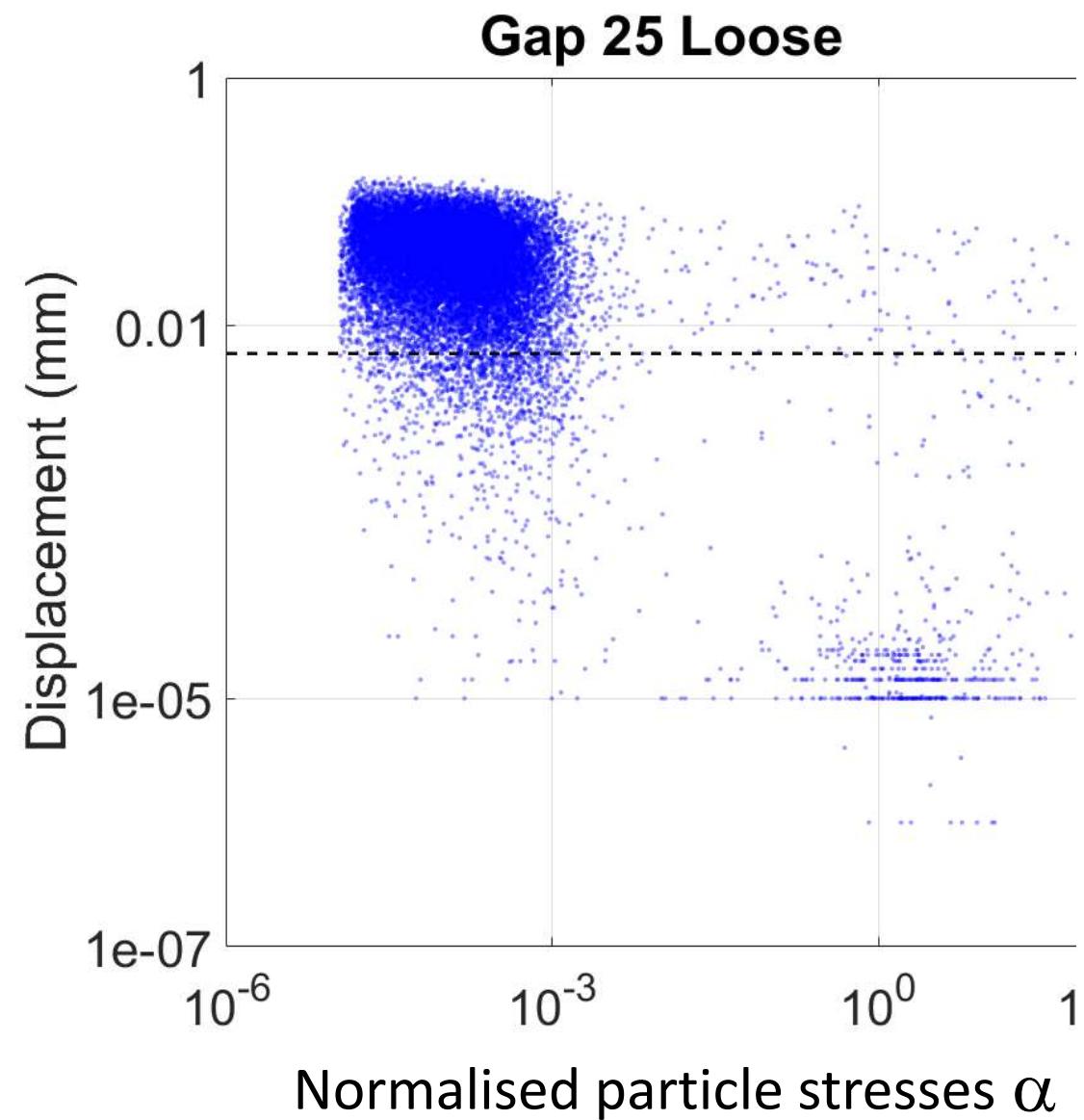
**CFD**  
For fluid

-Fluid velocity in each  
cell  
-Fluid pressure gradient  
at cell-scale

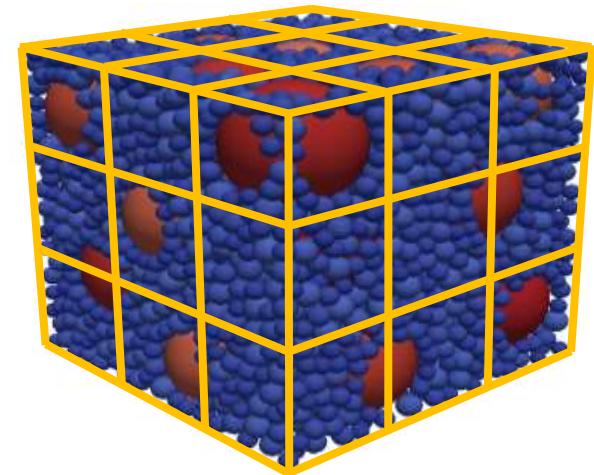


Coarse grid method proposed  
by Tsuji

# Particle stress and movement



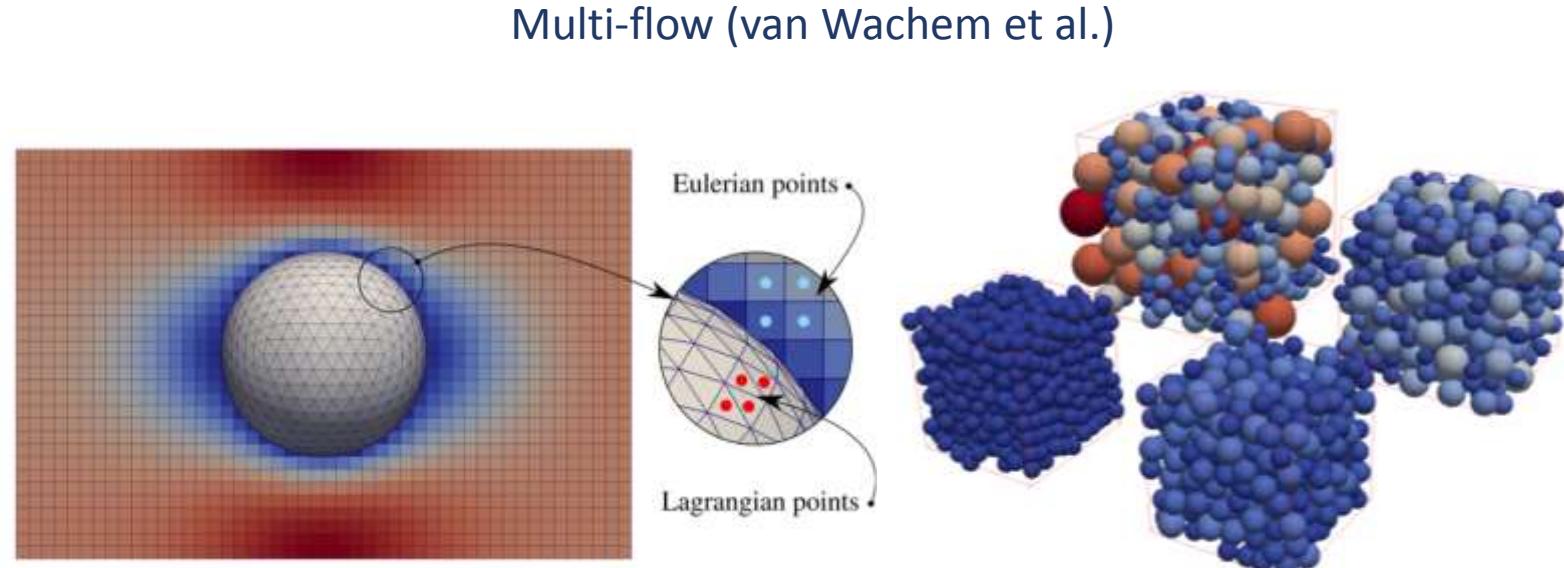
# Fluid particle interaction force - verification



Coarse Grid Approach:

Fluid properties averaged in cell

Fluid-particle interaction force calculated using empirical equation



Immersed Boundary Method:

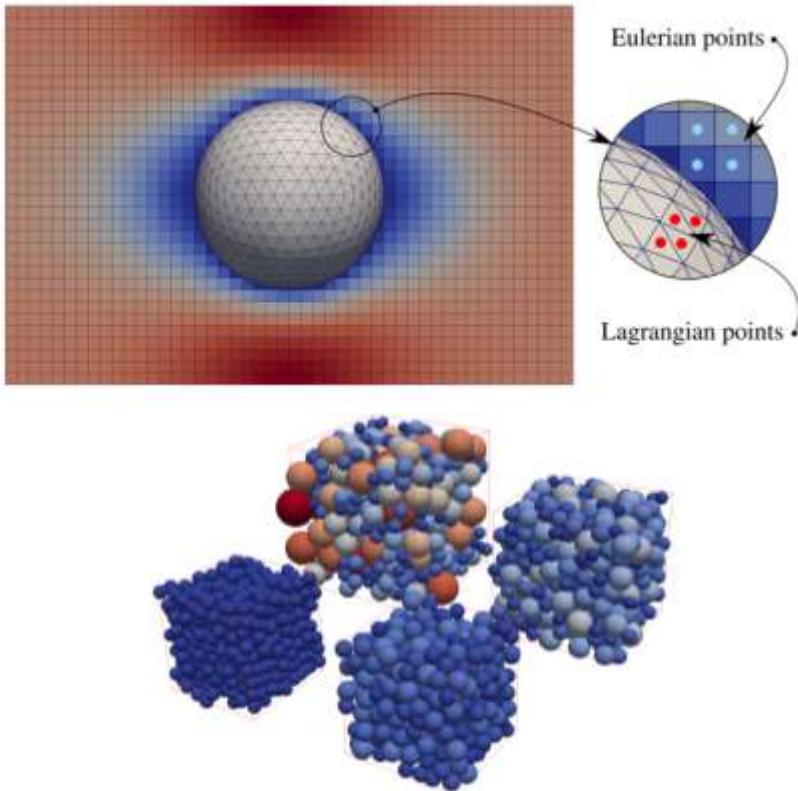
Fully resolved flow

Fluid-particle interaction force can be directly determined

Smaller samples – computational cost high  
(Knight, 2018)

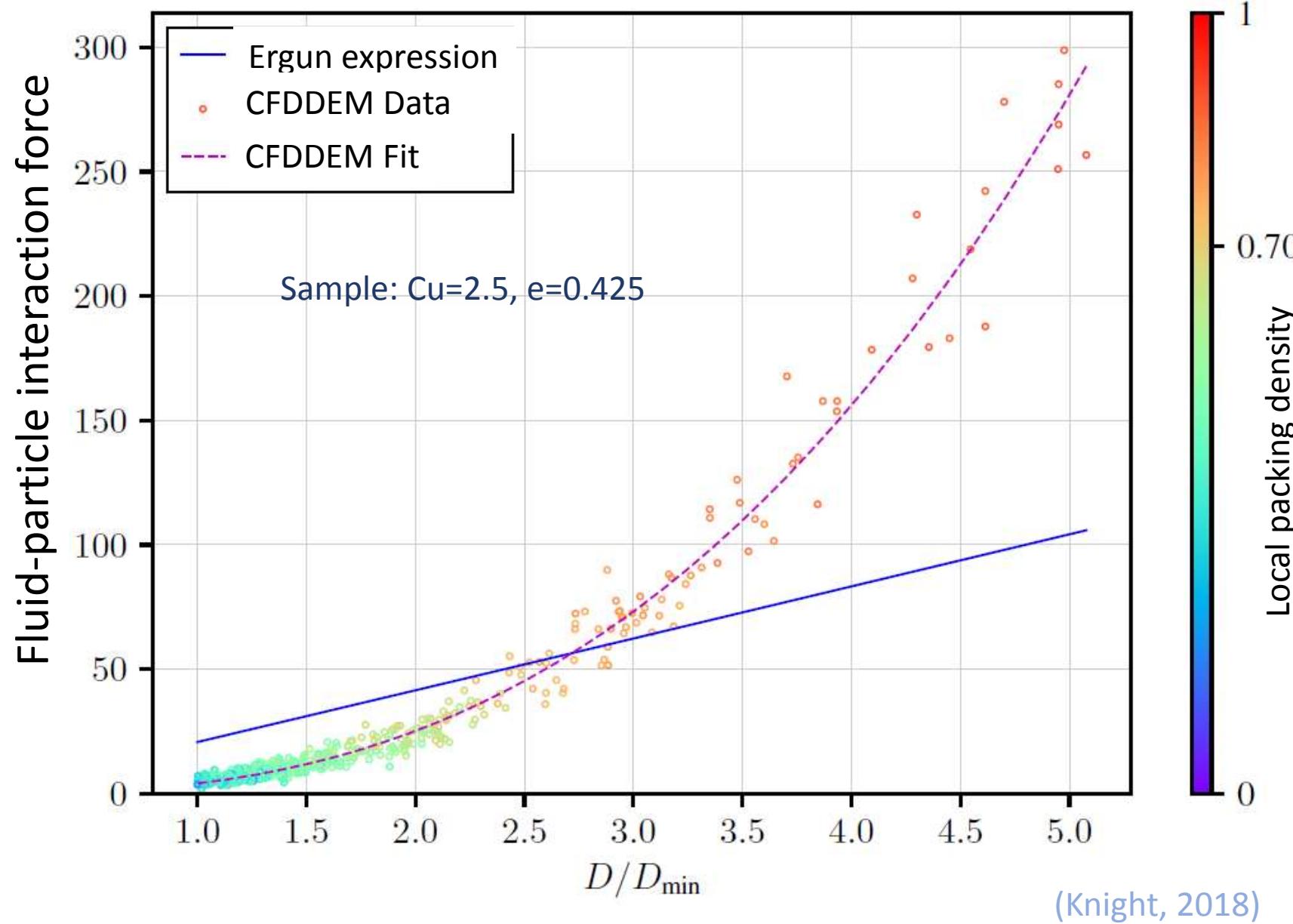
# Fluid particle interaction force - verification

Multi-flow (van Wachem et al.)

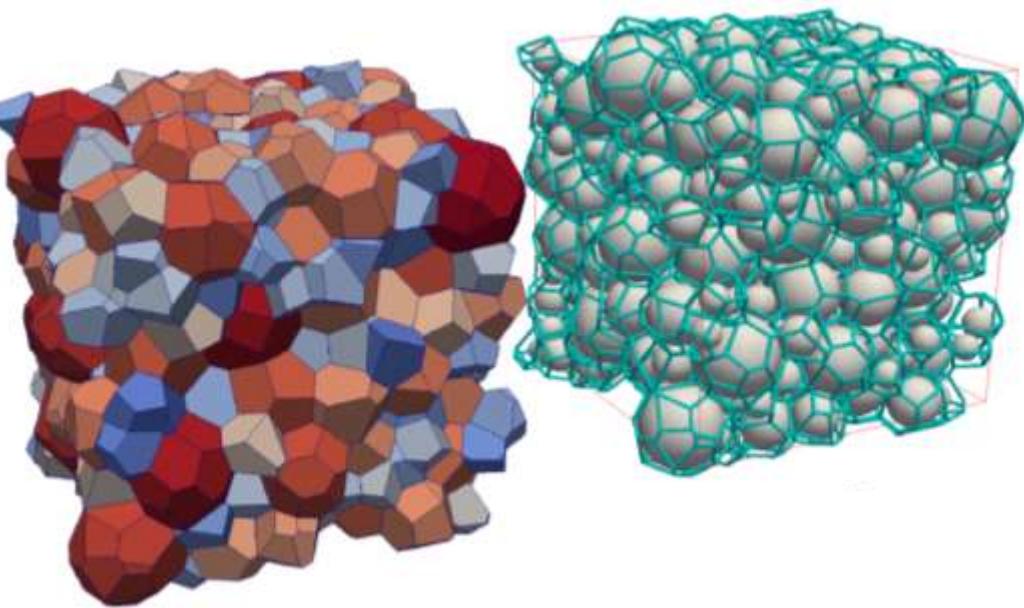


Fully resolved flow

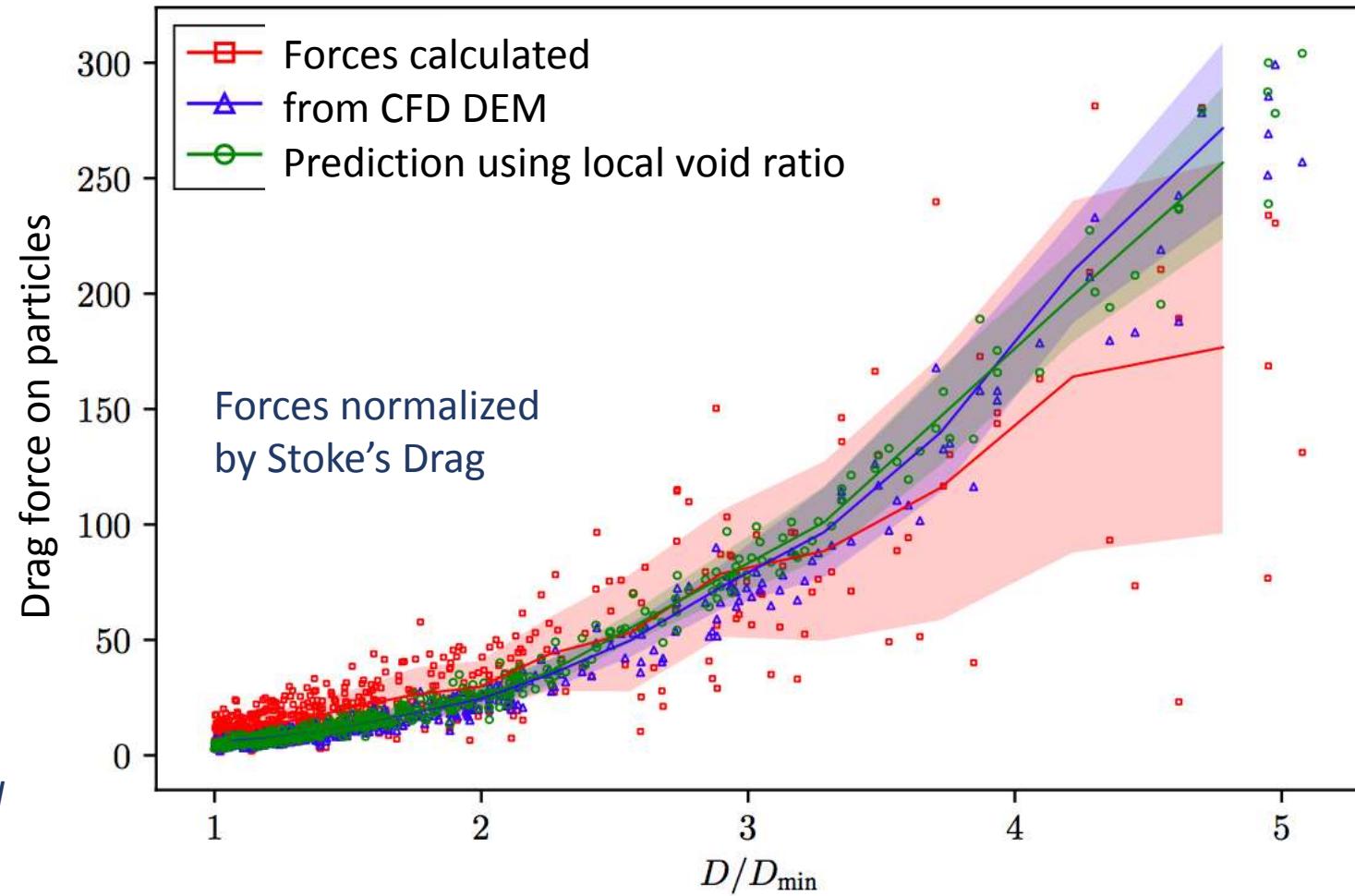
Fluid-particle interaction force  
can be determined



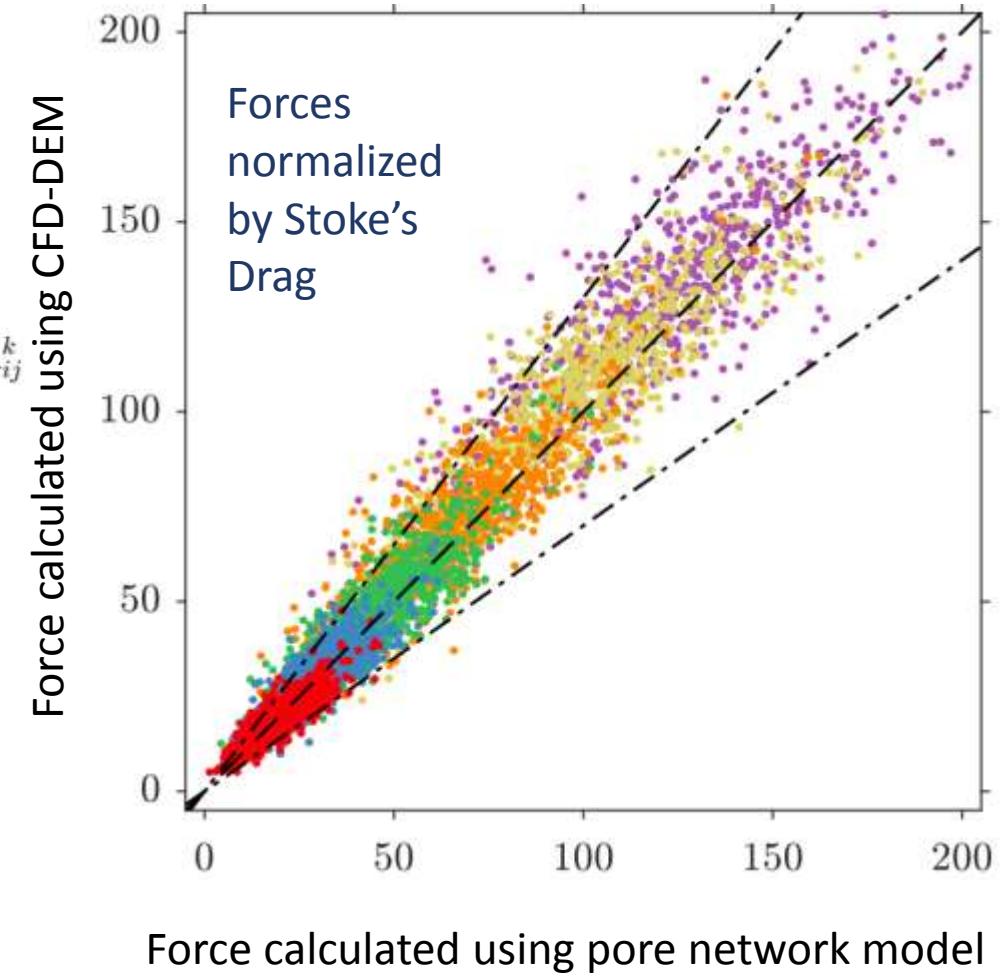
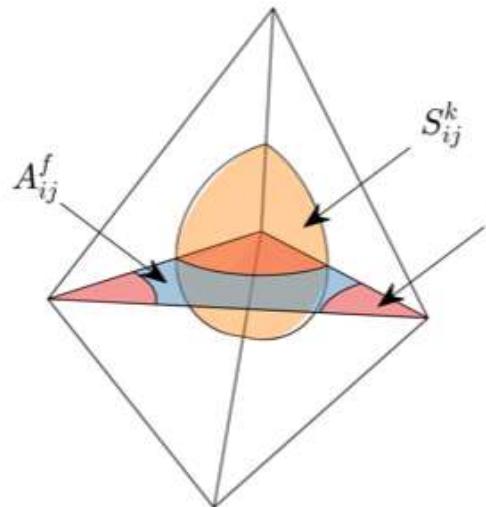
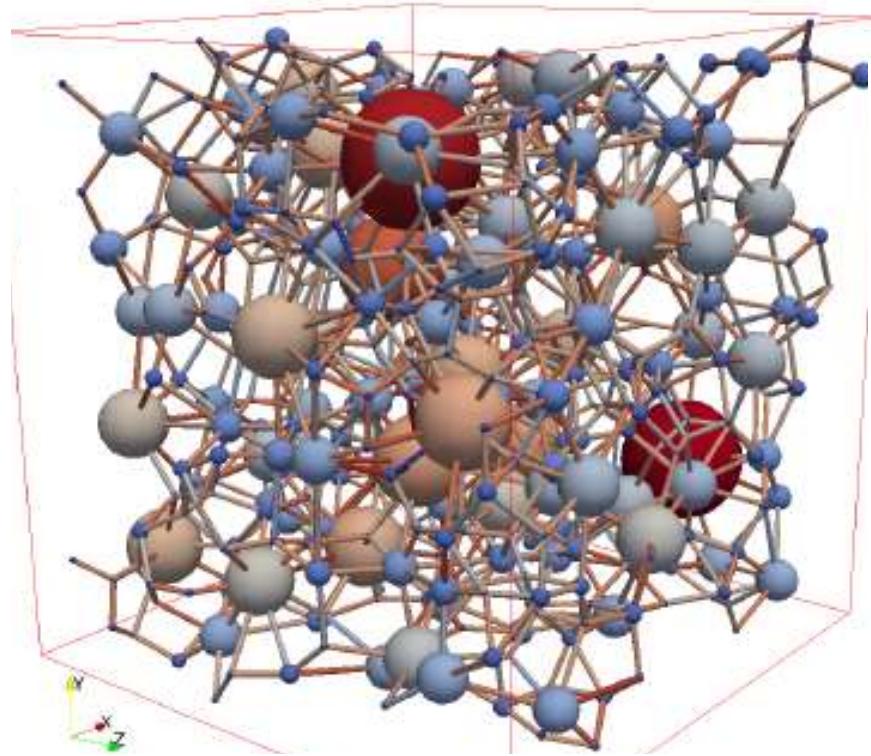
# Fluid particle interaction force using local void ratio



Tenneti et al. polydispersity correction also applied



# Network based approach to determine forces



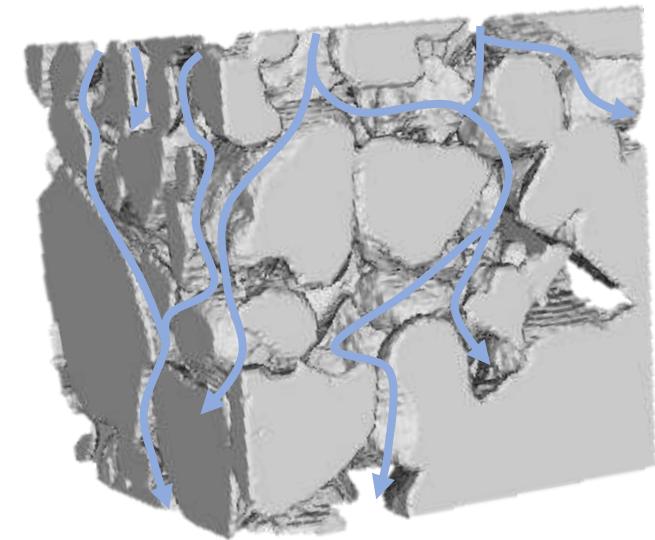
# Sand behaviour



Stiffness

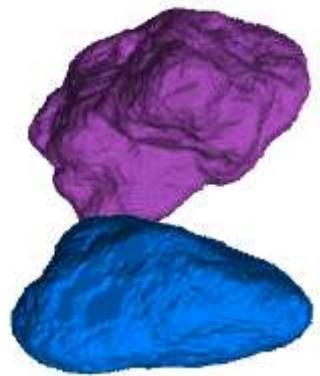
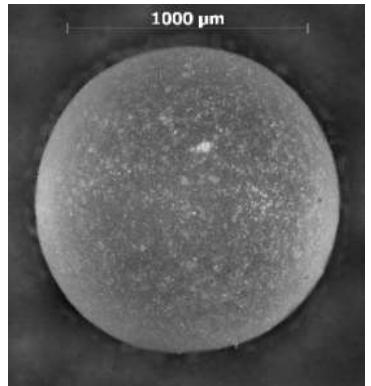


Strength

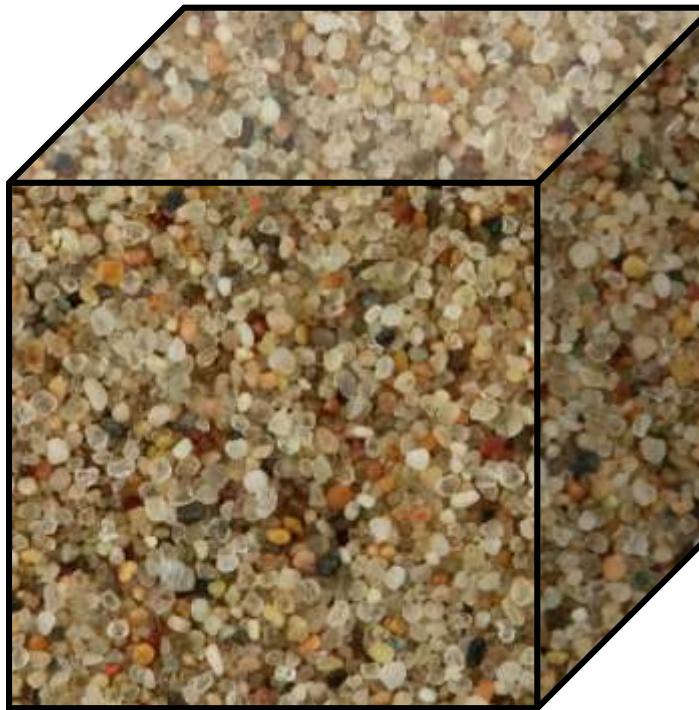


Seepage

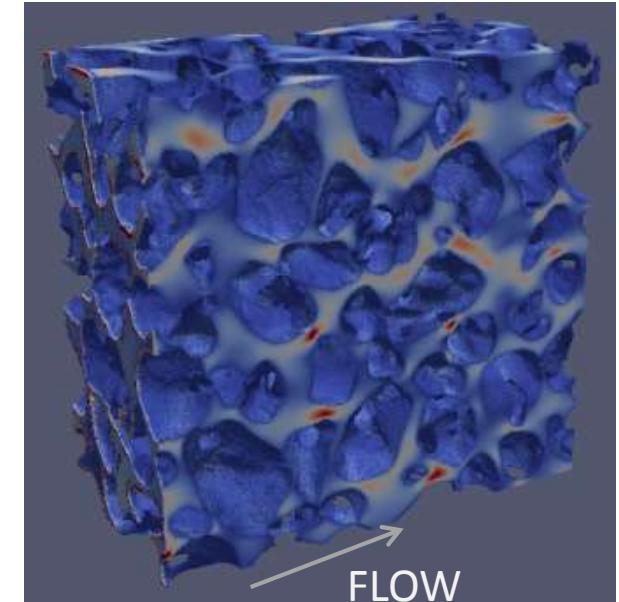
# Sand behaviour



Contact behaviour

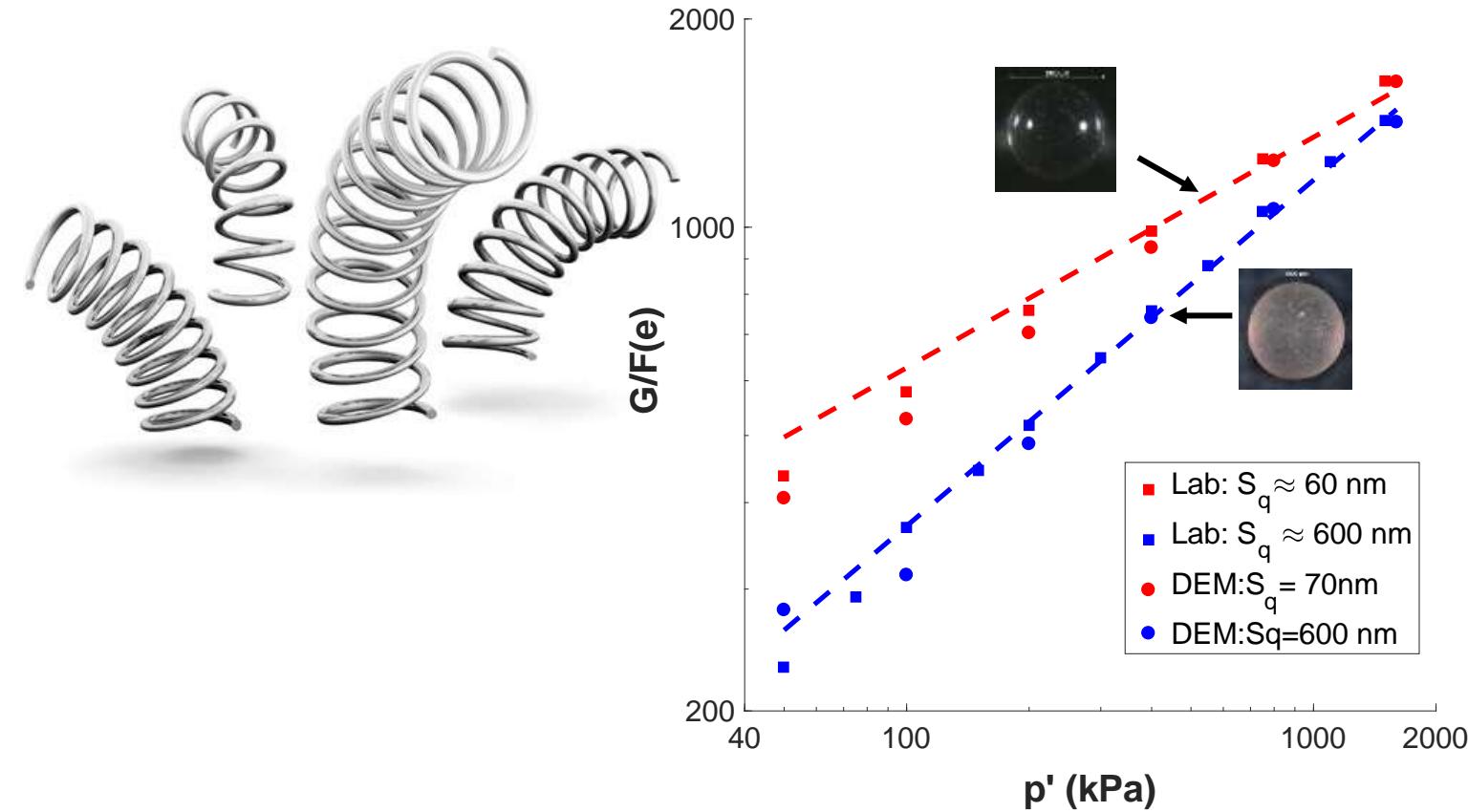


Collective behaviour



Coupled behaviour

# Conclusions: Stiffness

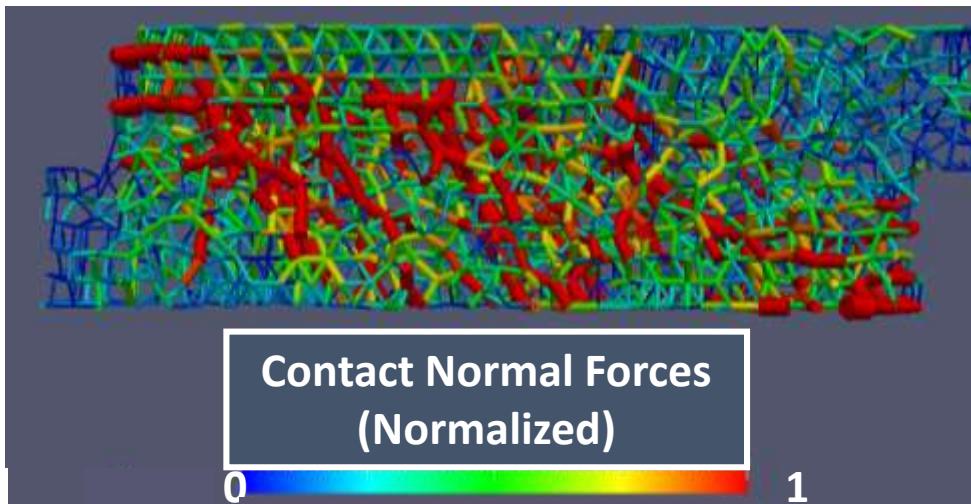


## Stiffness – Contact behaviour

Increasing particle surface roughness reduces stiffness and influences the stress:stiffness relationship

Models agree with physical experiments

# Conclusions: Strength



## Strength – Collective behaviour

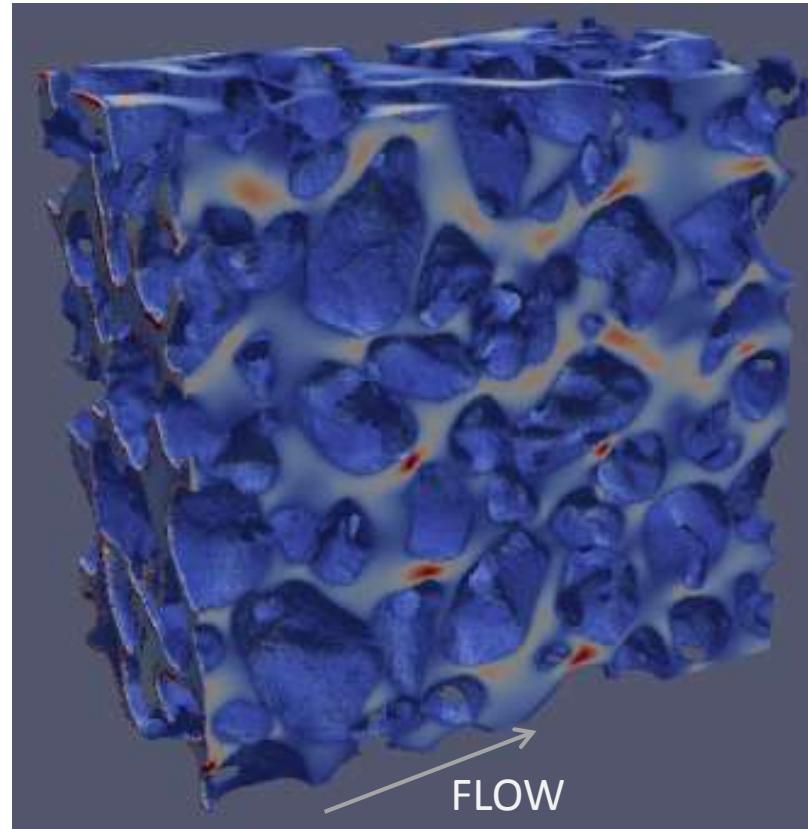
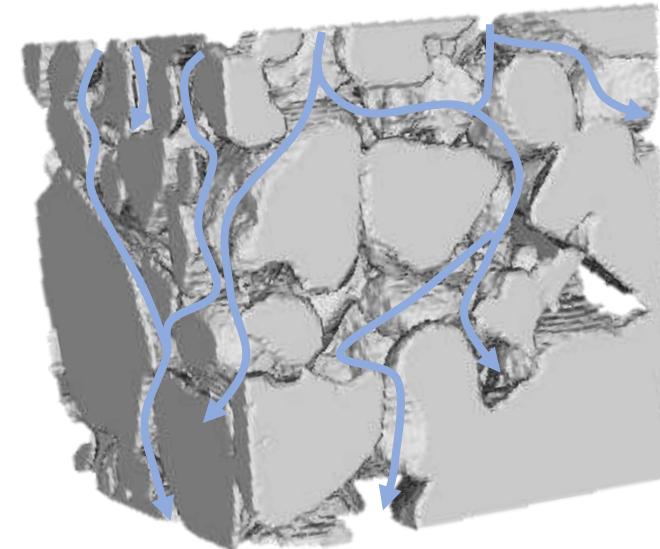
Chains of particles carrying relatively large stress transmit pressure through sand

Failure is associated with buckling of these chains

Friction, confining pressure and contact geometry contribute to force chain stability

# Conclusions: Seepage

## Seepage – Coupled behaviour



Most of the energy in seeping water is lost at the constrictions in the void space

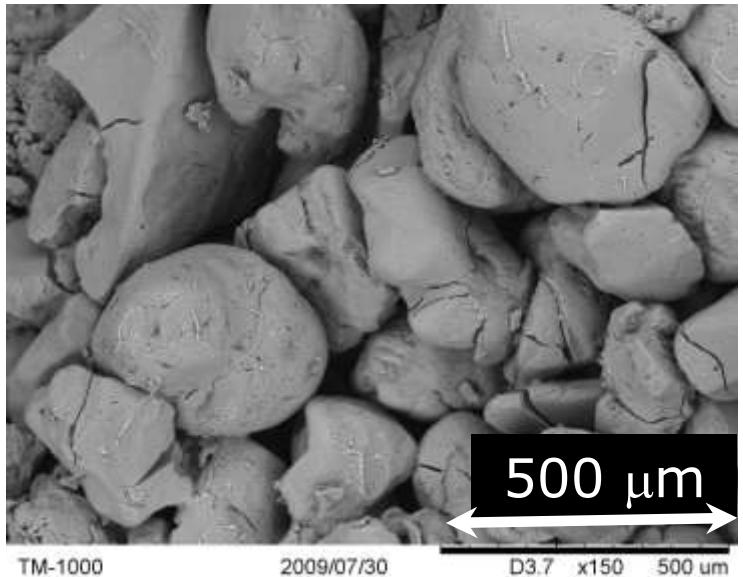
Constriction sizes determine filtration properties

Can link constriction sizes to characteristic diameters ( $D_{10}$ ,  $D_{15}$ )

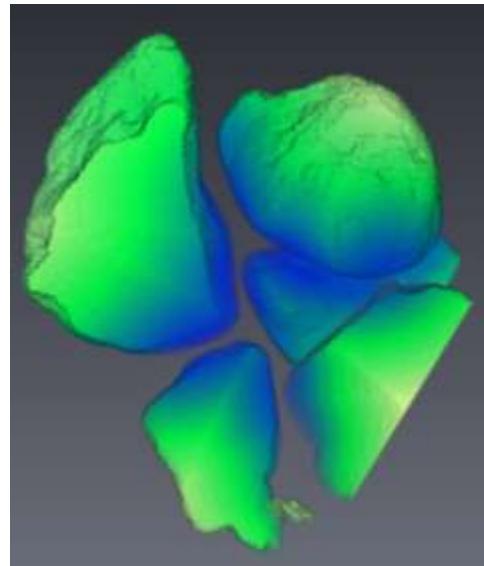
Accurate prediction of the forces imparted by seeping water is important to advance understanding of seepage induced instabilities

# Overall argument

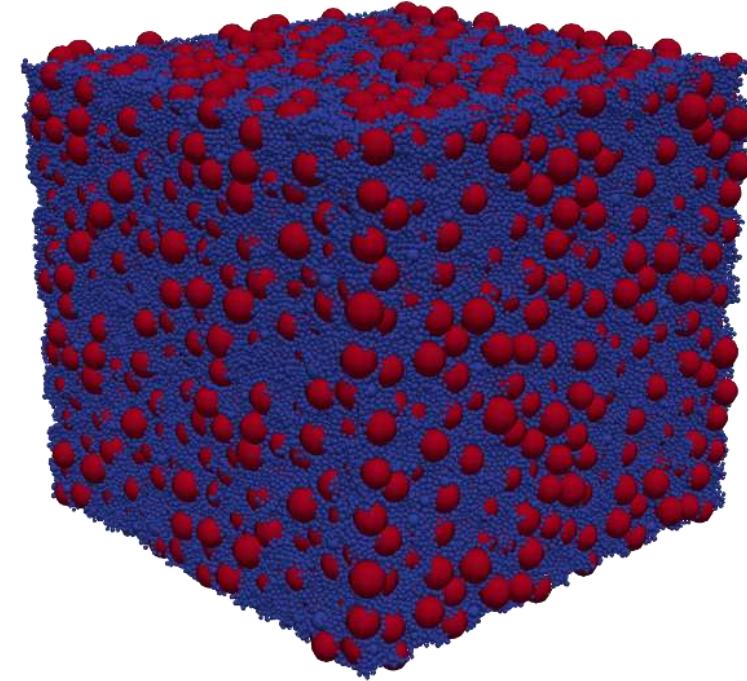
From an engineering perspective, it is worthwhile to look at the behaviour of sand from the perspective of an individual grain



Reigate Sand – PhD Research of  
Dr. Joana Fonseca

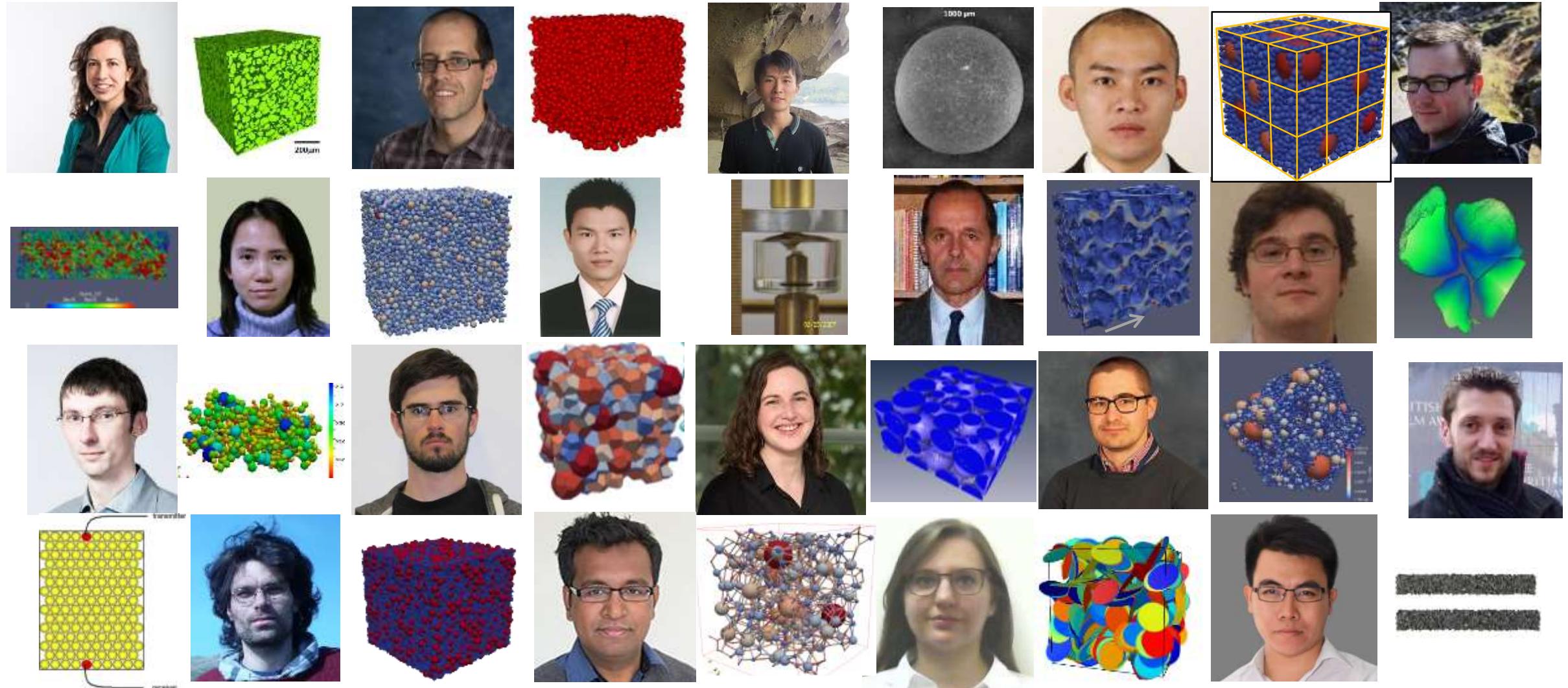


Leighton Buzzard Sand – PhD  
Research of Dr. Howard Taylor



DEM simulation of Gap Graded  
Sand  
Dr. A. Sufian & Ms. M. Artigaut

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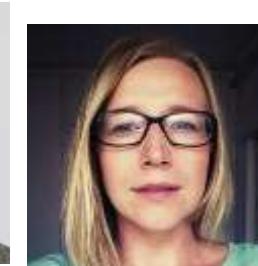
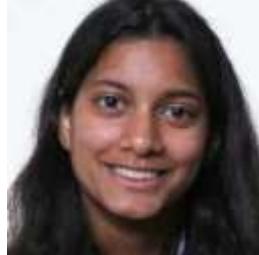
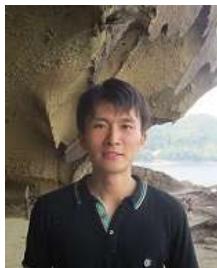
Tara Sassel

Chin Kang Shen

Thomas Shire

Te Cheng Su

Howard Taylor

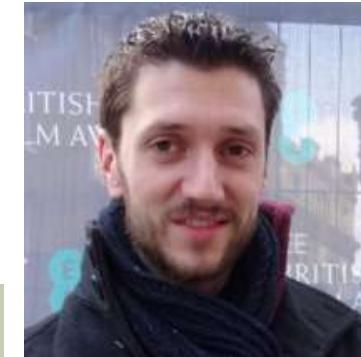


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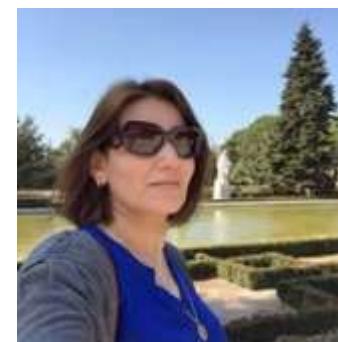
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George Marketos



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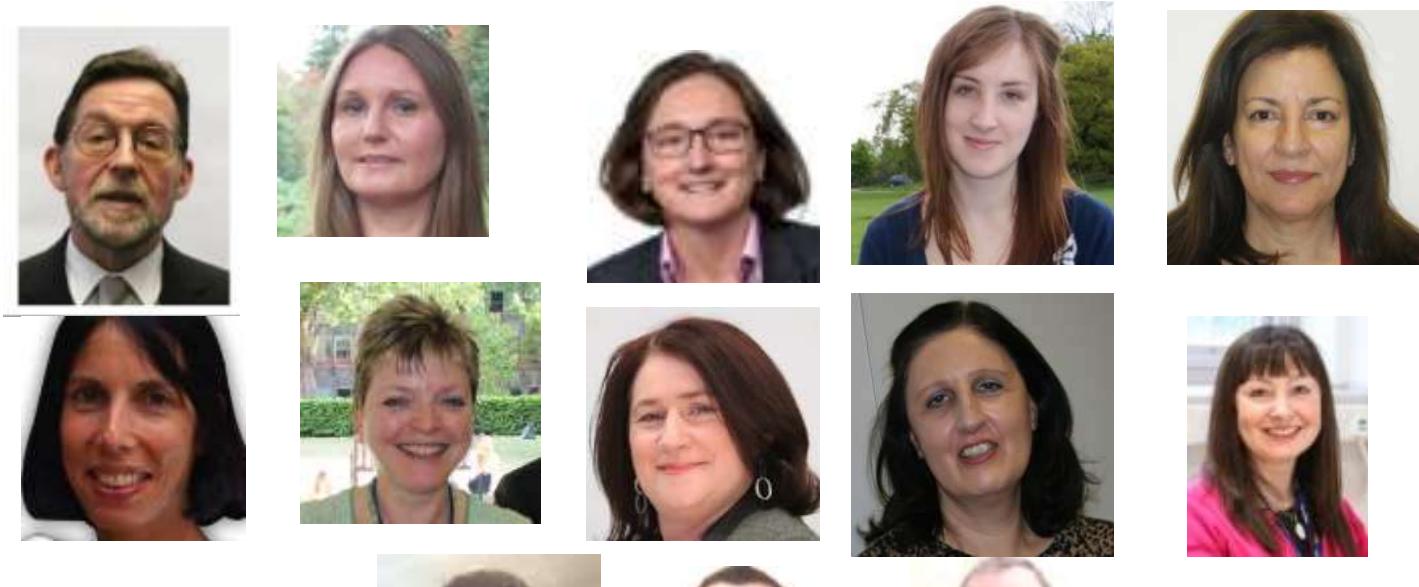
Ahmer Wadee

Lidija Zdravkovic

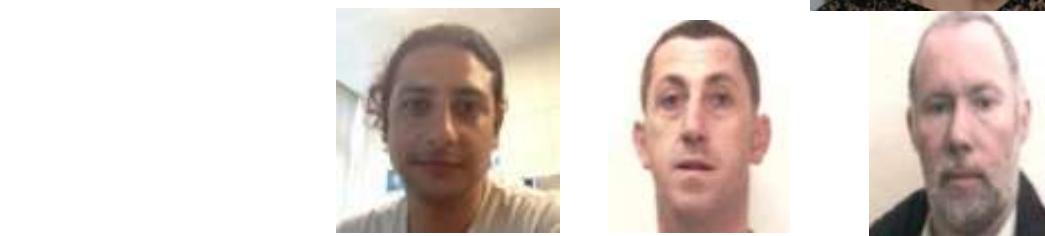


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