

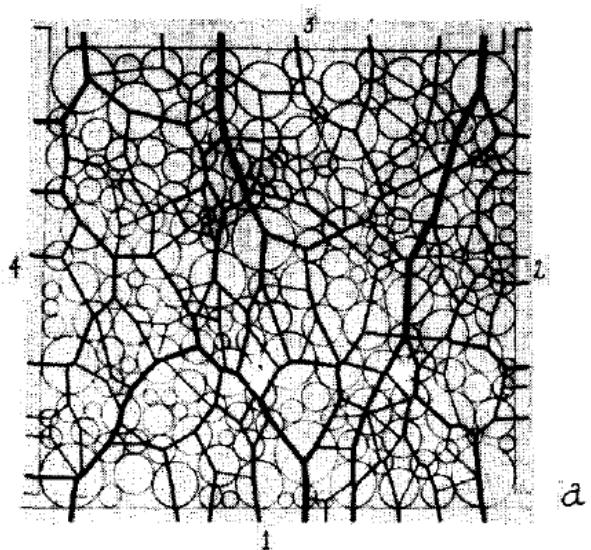
Wave propagation and fluid transport: linking measurements and modelling

Prof. Catherine O'Sullivan
Dept. Civil and Environmental Engineering
Imperial College London

cath.osullivan@imperial.ac.uk

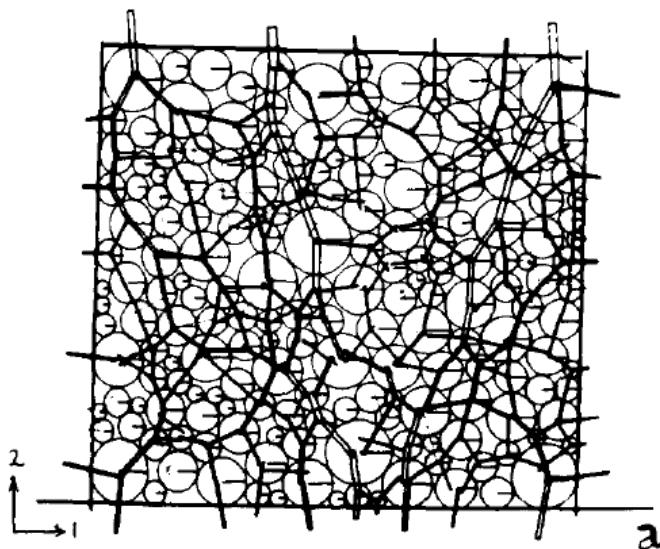
<https://www.imperial.ac.uk/people/cath.osullivan>

Cundall and Strack (1979)



Force vector plots obtained by De Josselin de Jong and Verruijt (1969) in photoelastic experiments

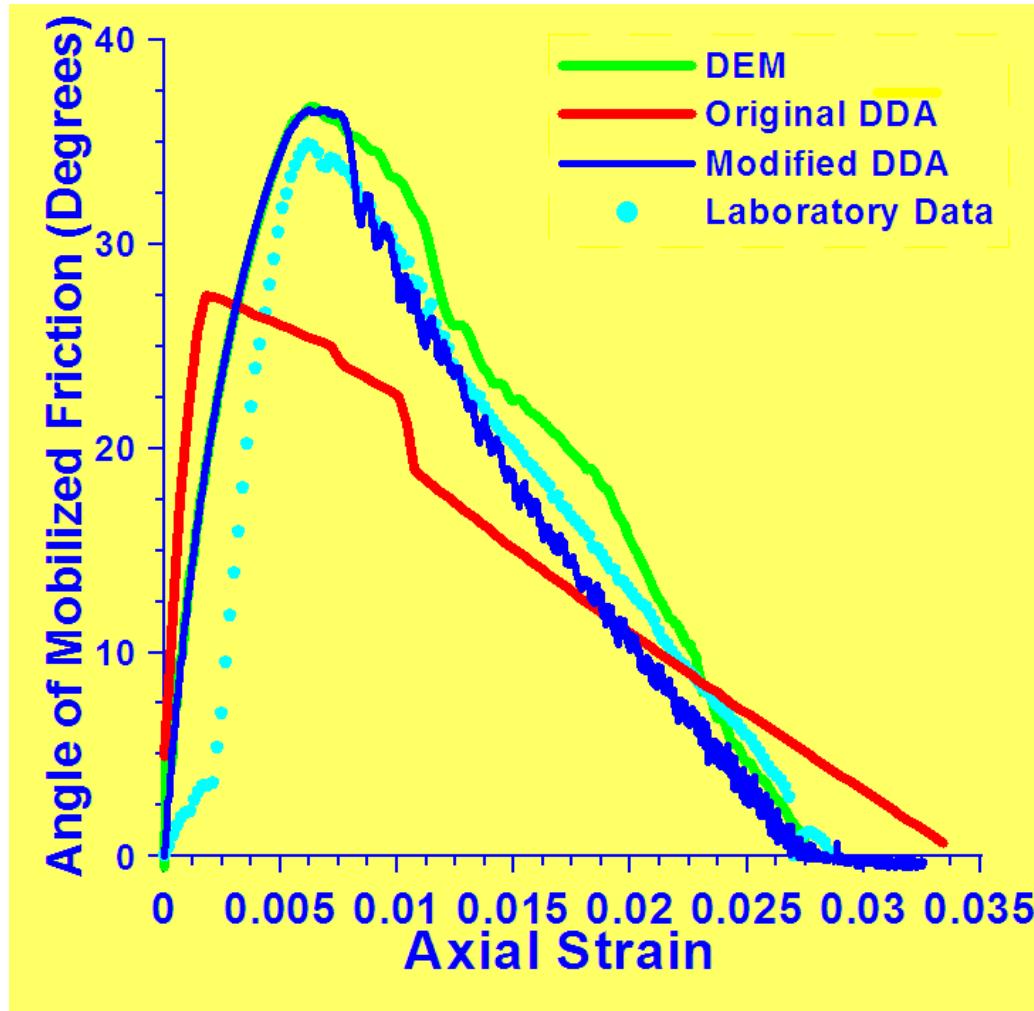
$$\text{Ratio } F_H/F_V = 0.39$$



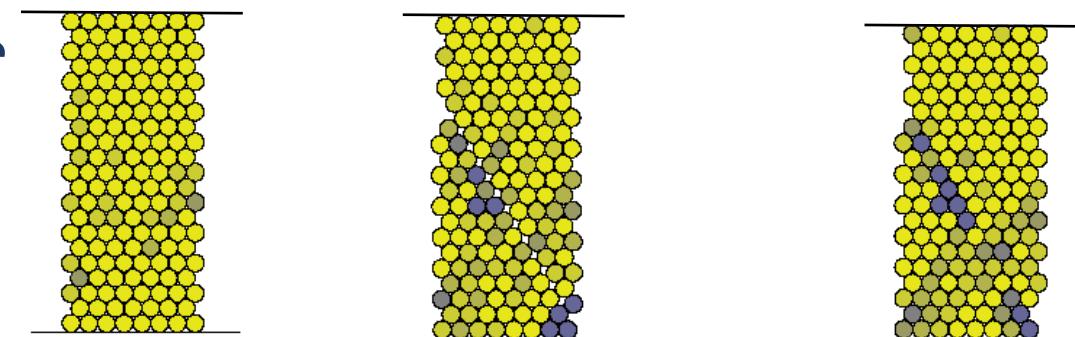
Force vector plots obtained in Cundall and Strack's DEM simulation

$$\text{Ratio } F_H/F_V = 0.43$$

Validation tests and simulations: steel rods



DEM Analysis Laboratory Test



Outline:

I want to present some examples that show that:

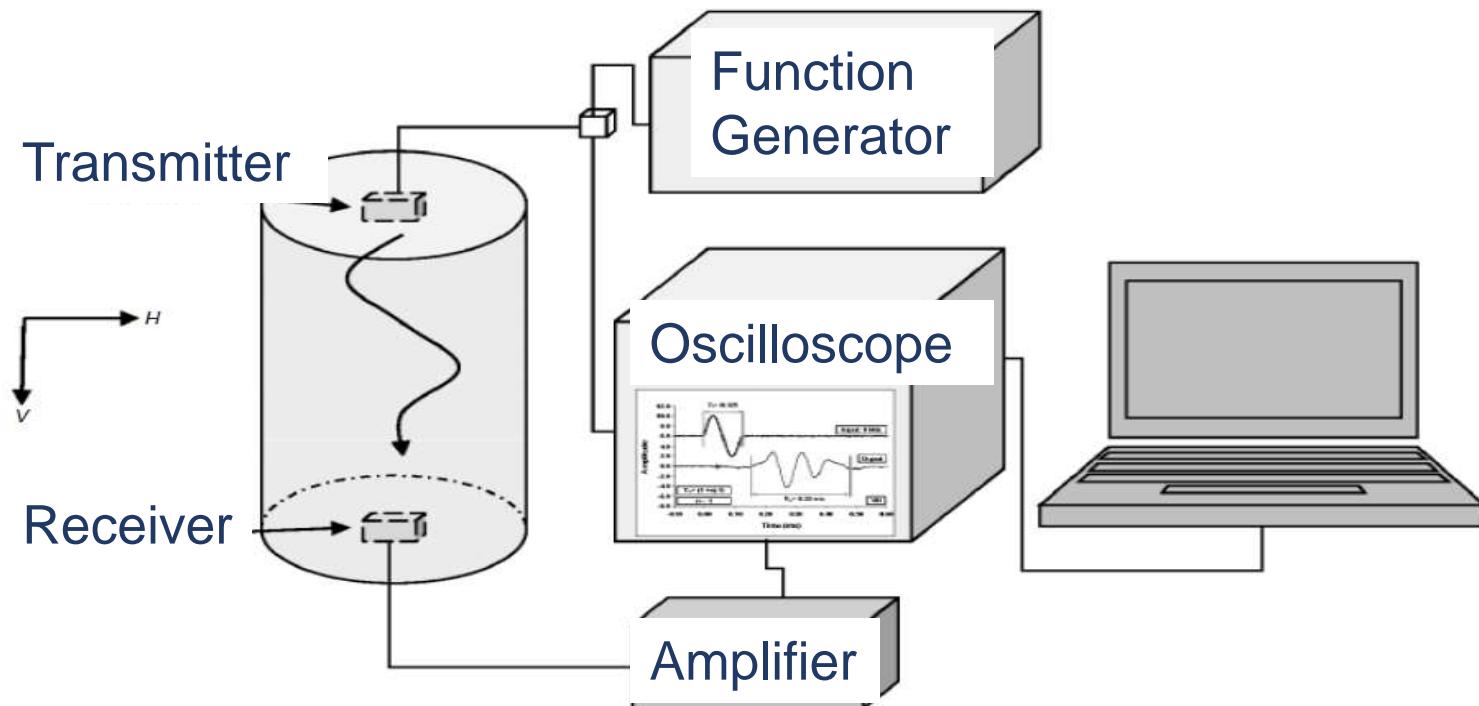
1. DEM simulations can help us design new testing approaches.
2. DEM simulations can inform how we can interpret element test data to infer fabric.
3. PIV opens the possibility for us to better understand how to use CFD to study flow in the pores of soil.

Outline:

I want to present some examples that show that:

- 1. DEM simulations can help us develop new testing approaches.**
2. DEM simulations can inform how we can interpret element test data to infer fabric.
3. PIV opens the possibility for us to better understand how to use CFD to study flow in the pores of soil.

Laboratory Geophysics



$$G = \rho V_S^2$$

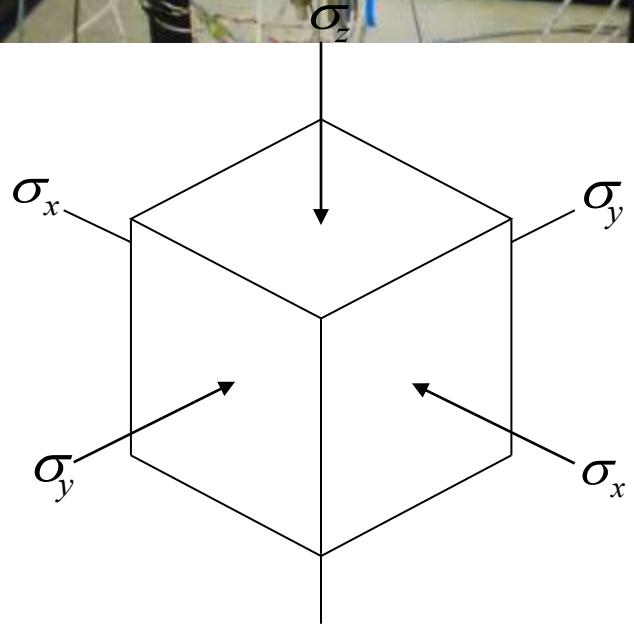
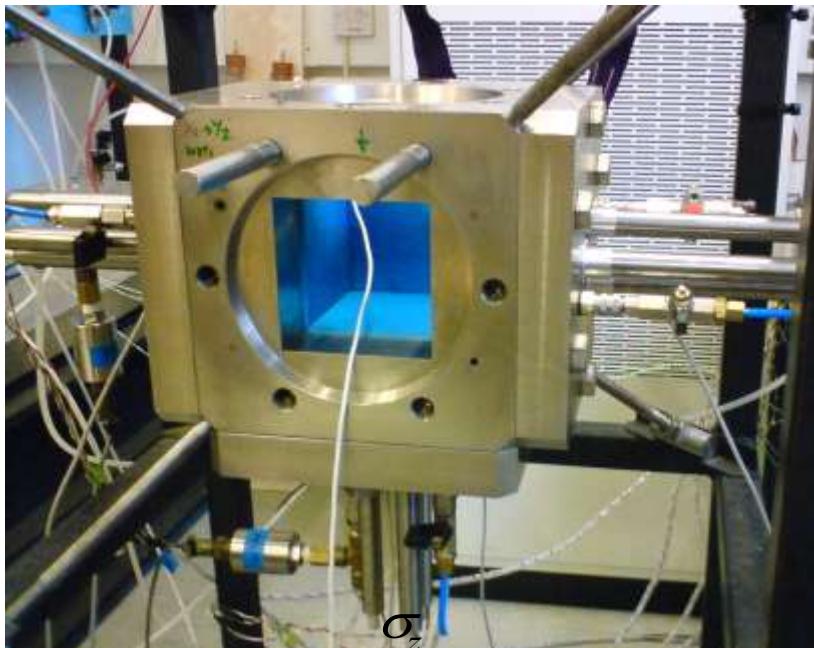
G = shear stiffness
 ρ = material density
 V_S = shear wave velocity

Cubical cell apparatus.

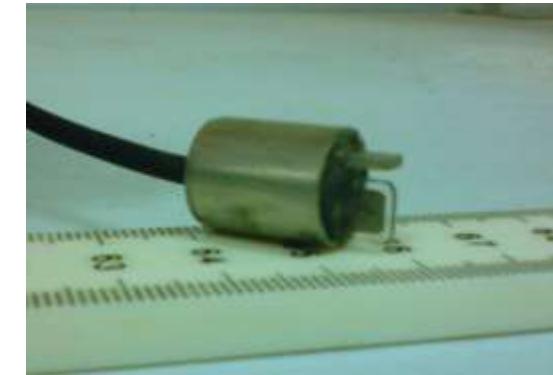
Cubical Cell Apparatus
University of Bristol

Allows independent control of three principal stresses

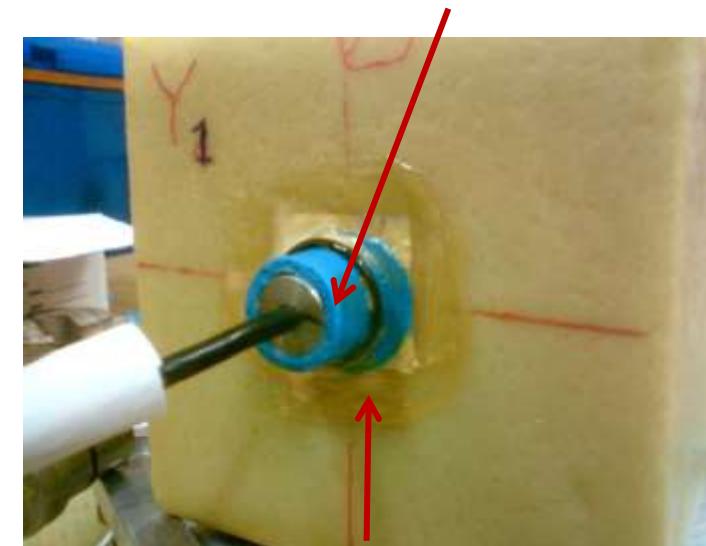
(Sadek, 2006)



T-shaped bender/extender elements

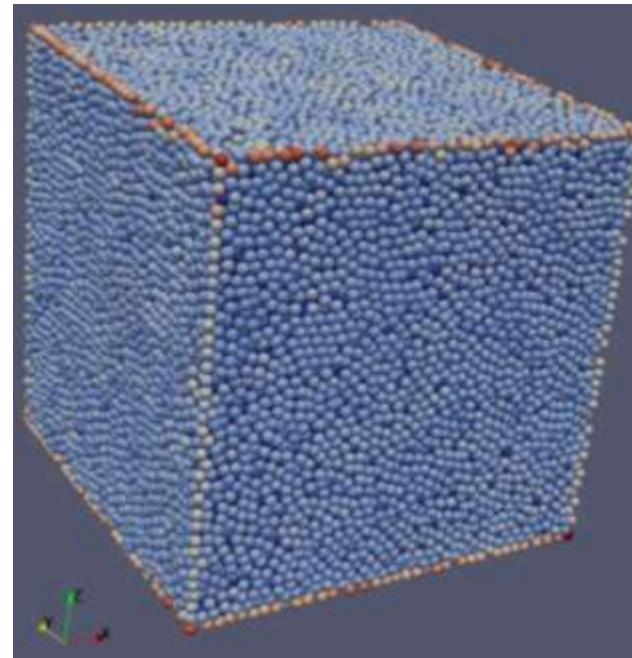
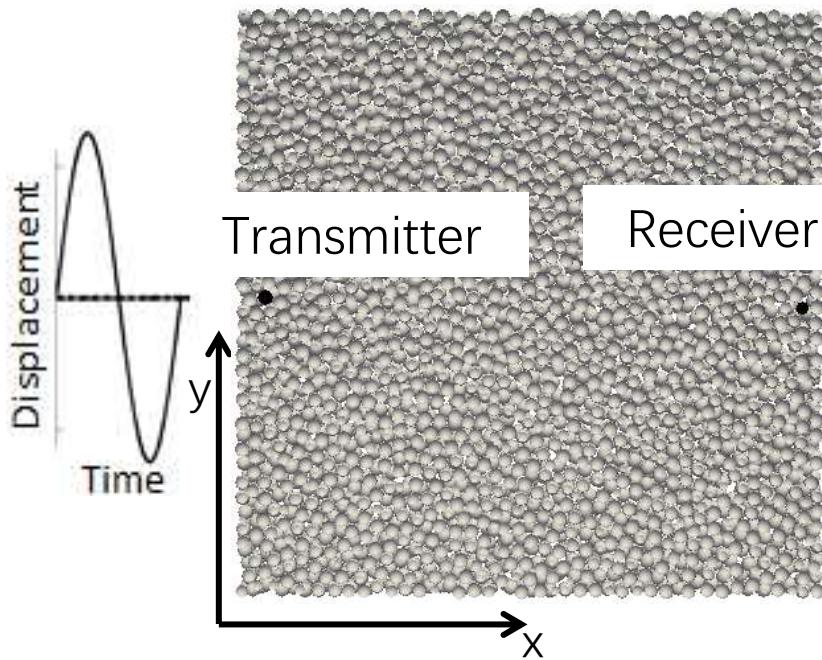


Sealing grommet to prevent loss of vacuum



Layers of latex adhesive solution

DEM simulations of wave propagation



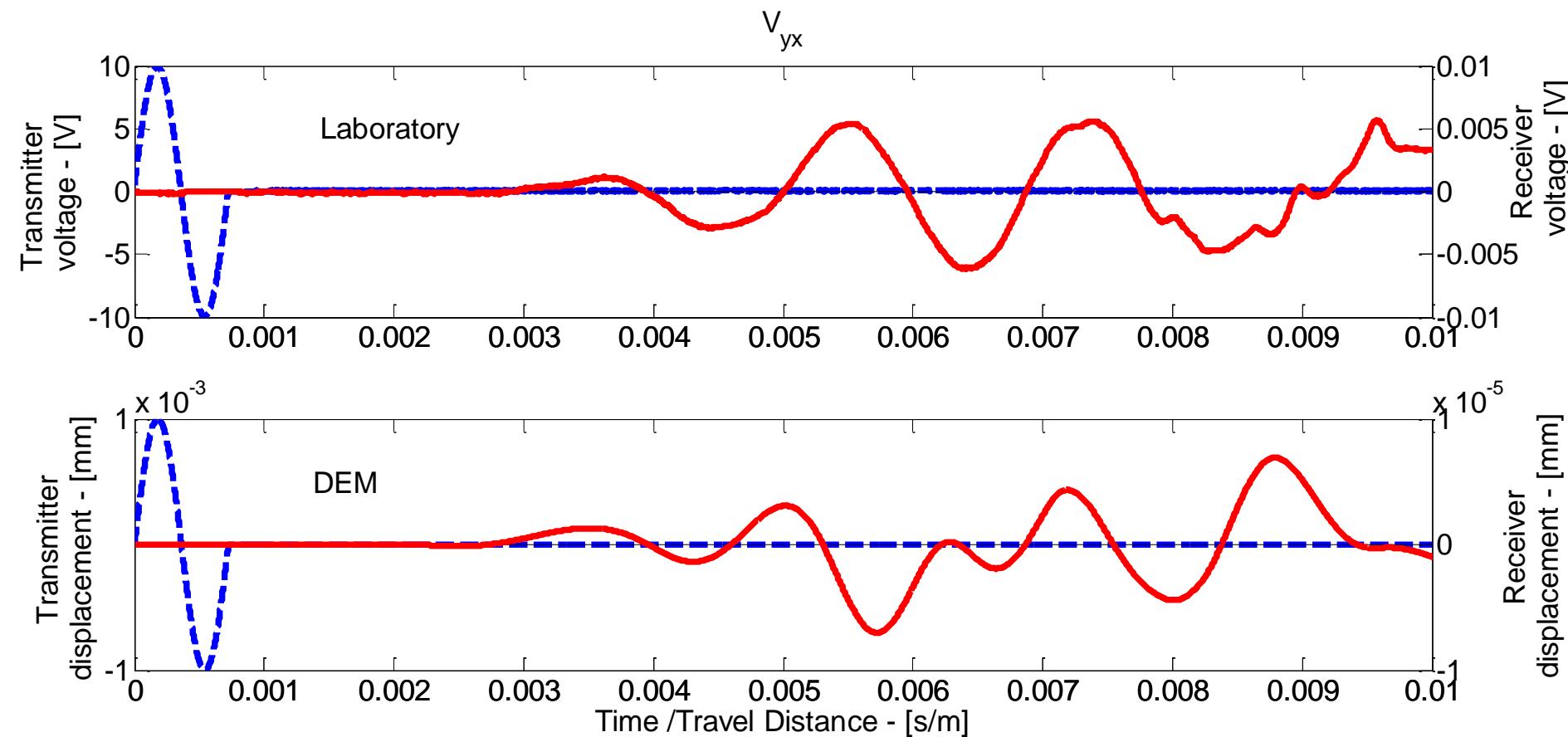
- Simulated using PFC 3D
- Flexible membrane boundaries
- Simplified Hertz-Mindlin contact model – input G and ν for particle
- Bender/extender elements modelled as point sources

Signal comparison: Time domain

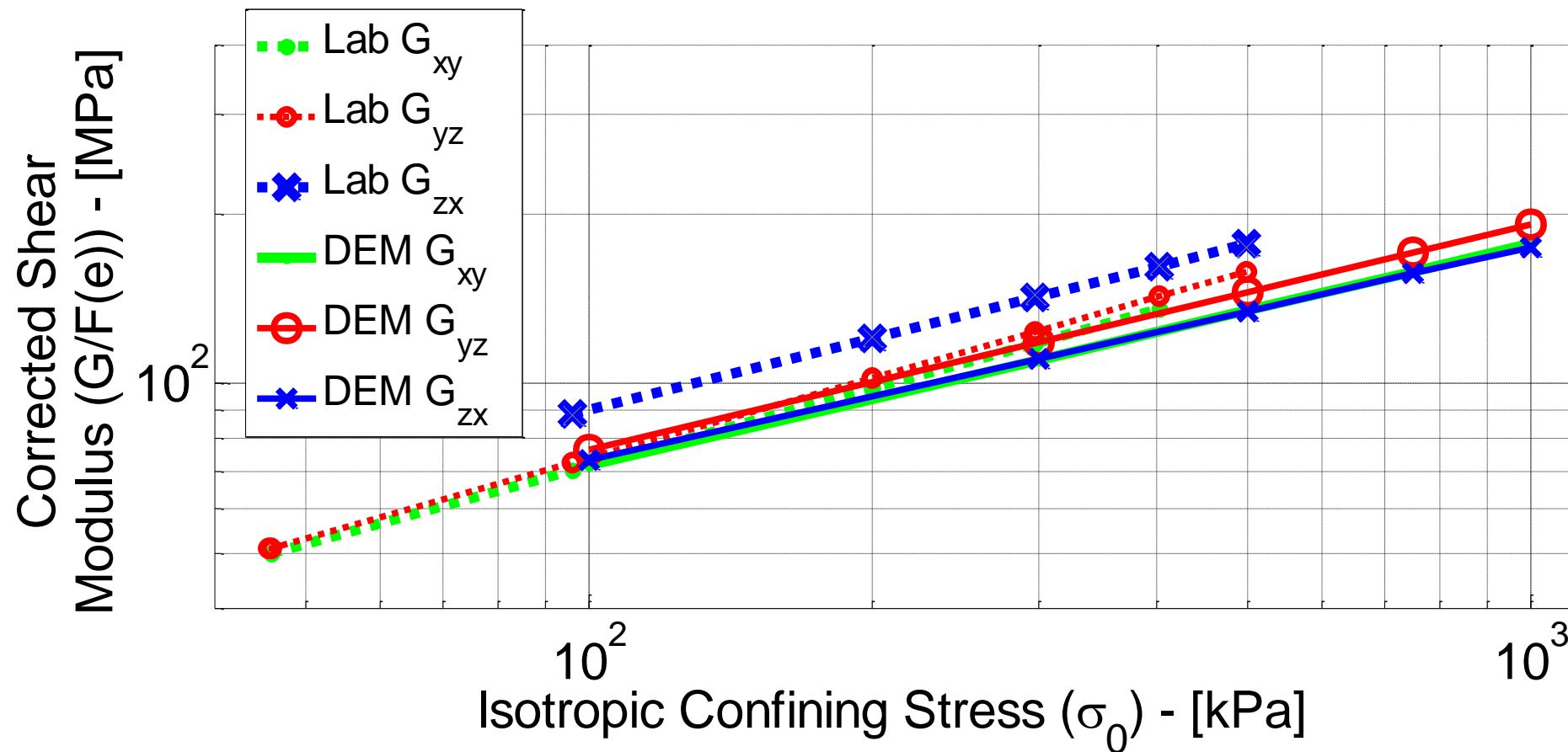
Isotropic stress of 100 kPa

Sinewave pulse with frequency of 15 kHz

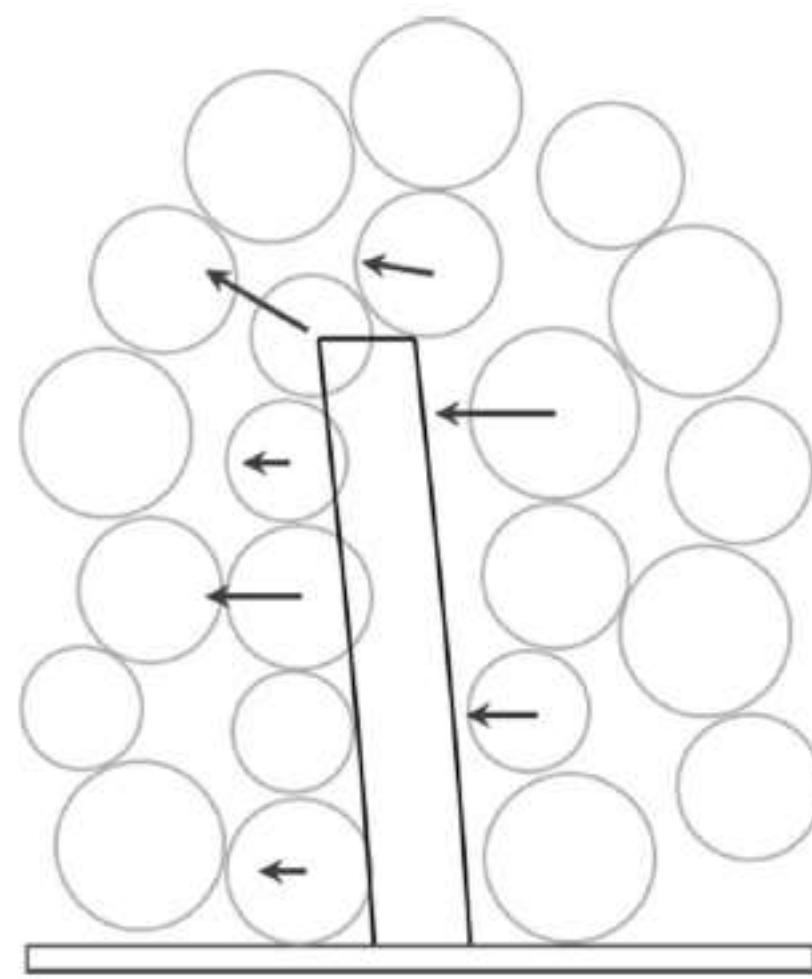
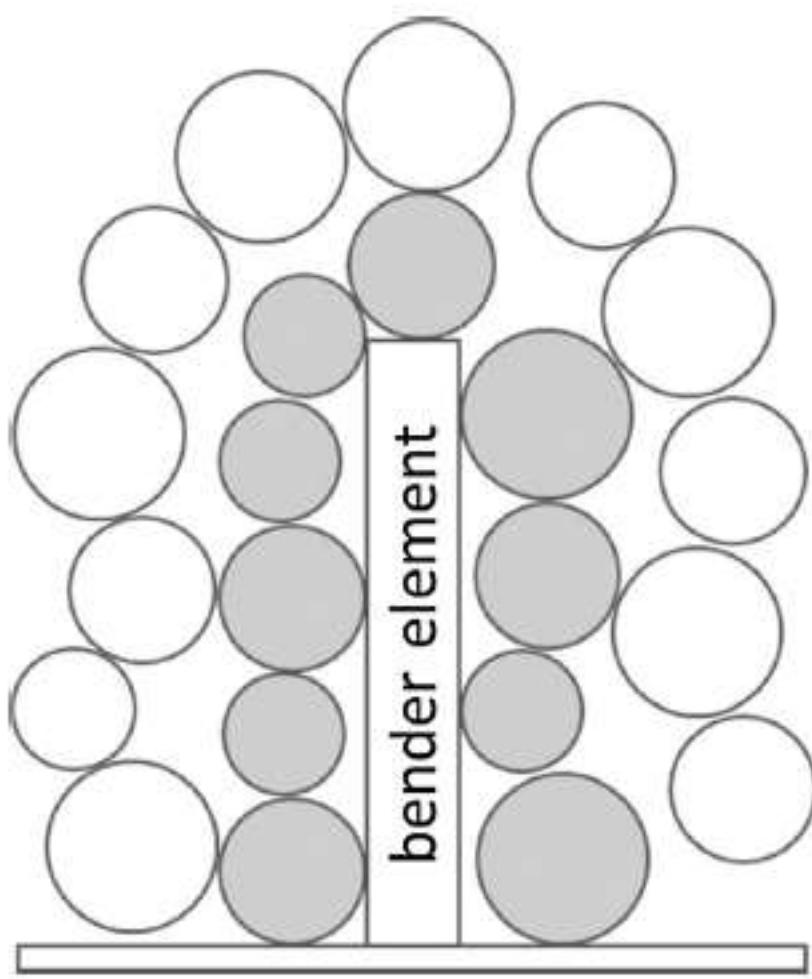
Transmitted signal
Received signal



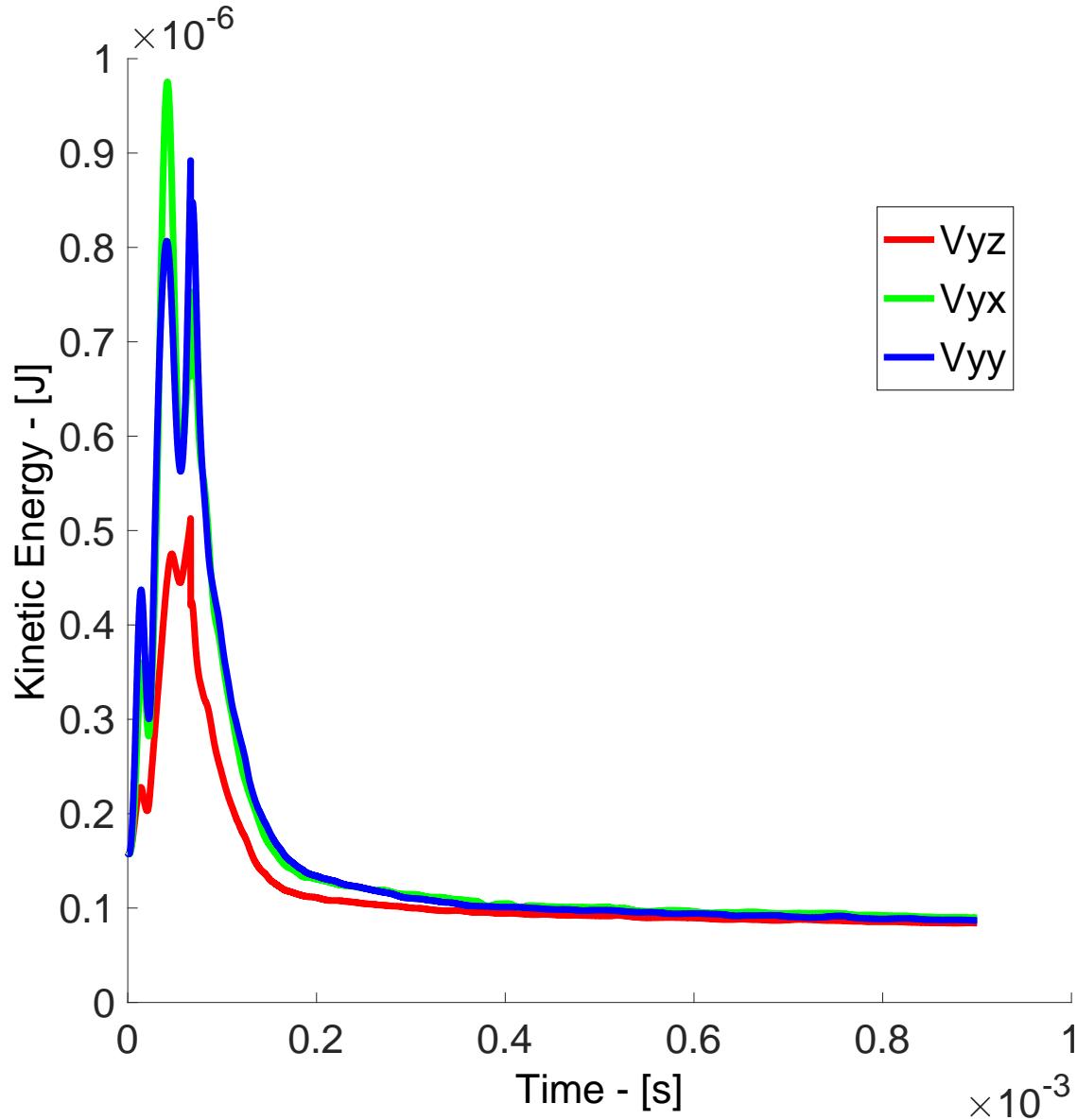
Shear stiffness vs confining pressure



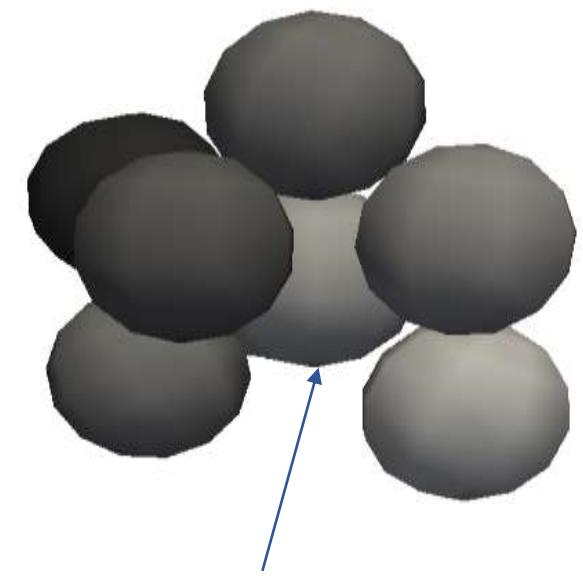
Bender element testing



Influence of transmitter connectivity



Local fabric tensor:

$$\Phi_{yz} = 0.207$$
$$\Phi_{yx} = 0.407$$
$$\Phi_{yy} = 0.386$$


Transmitter grain

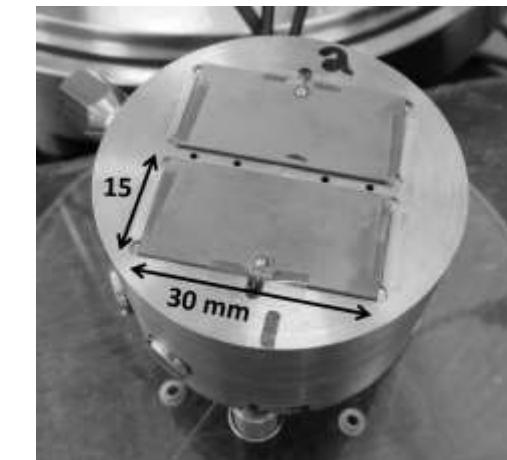
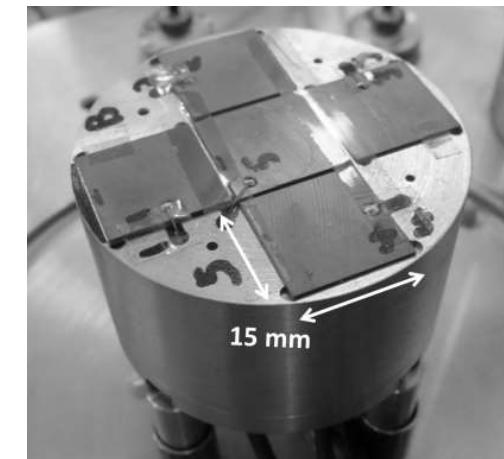
Shear plate technology



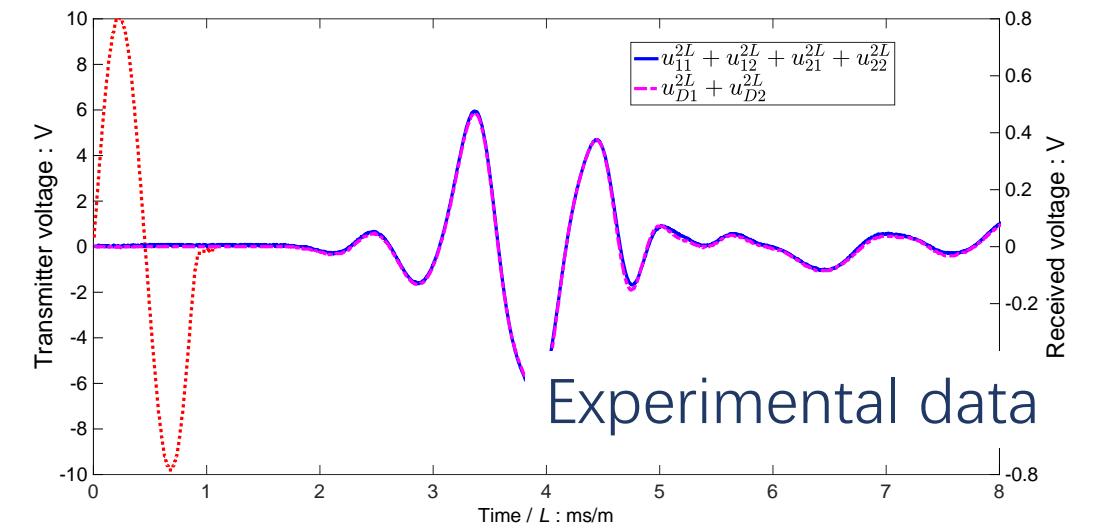
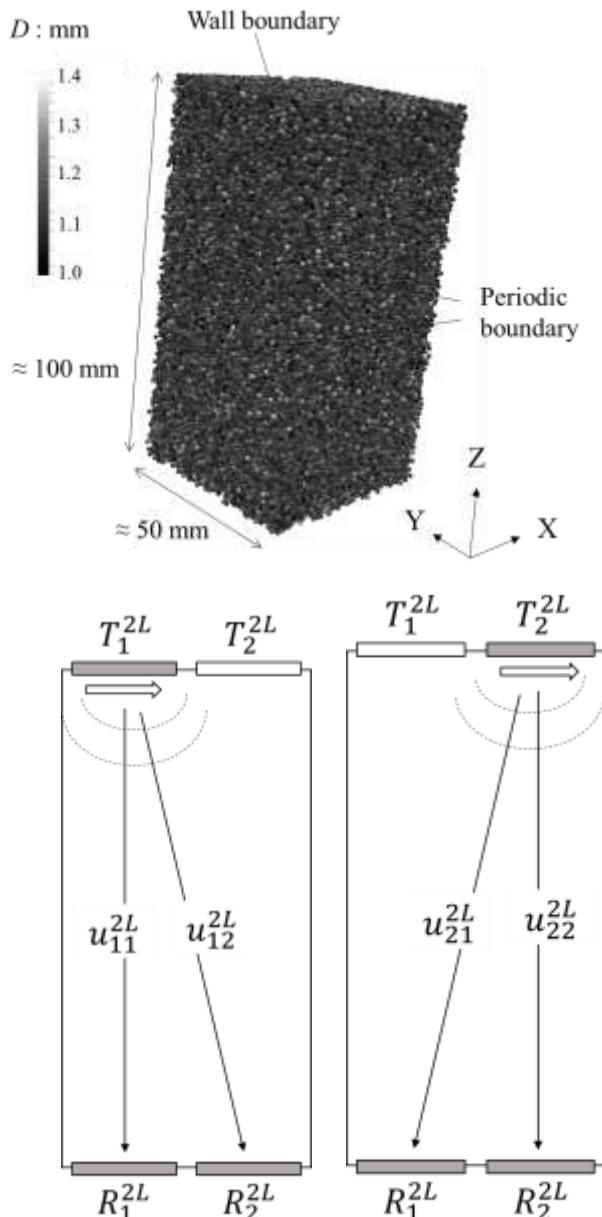
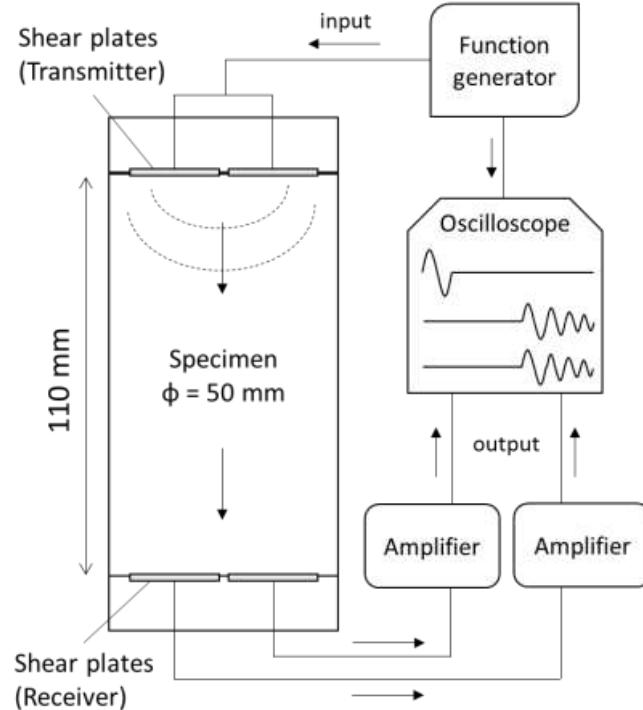
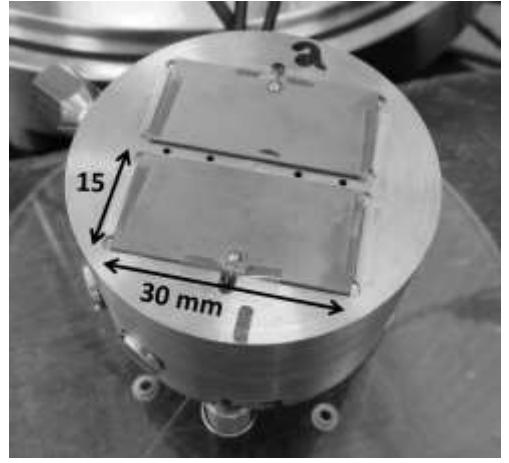
Bender elements



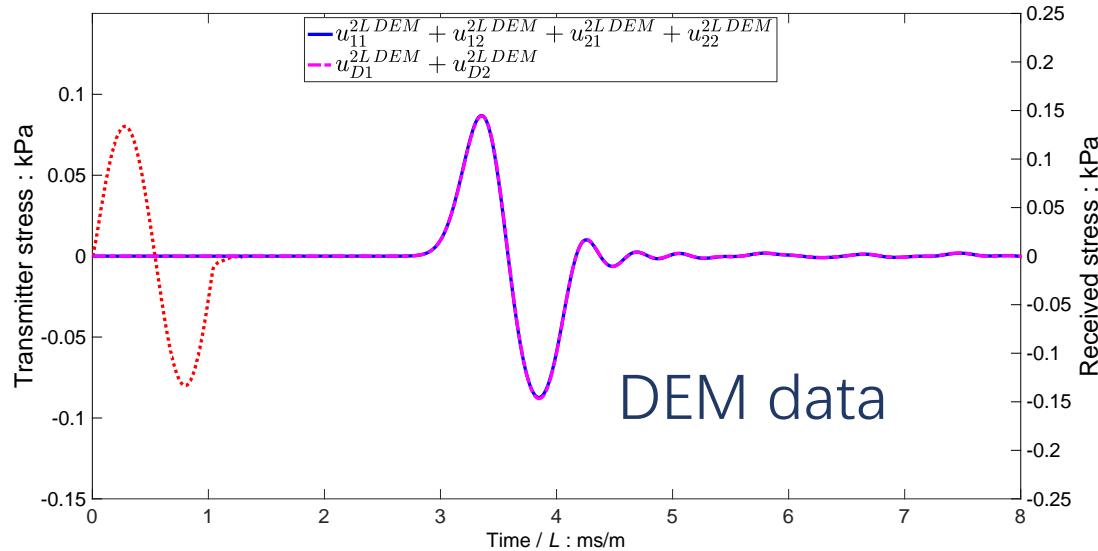
Shear plates



Shear plate technology

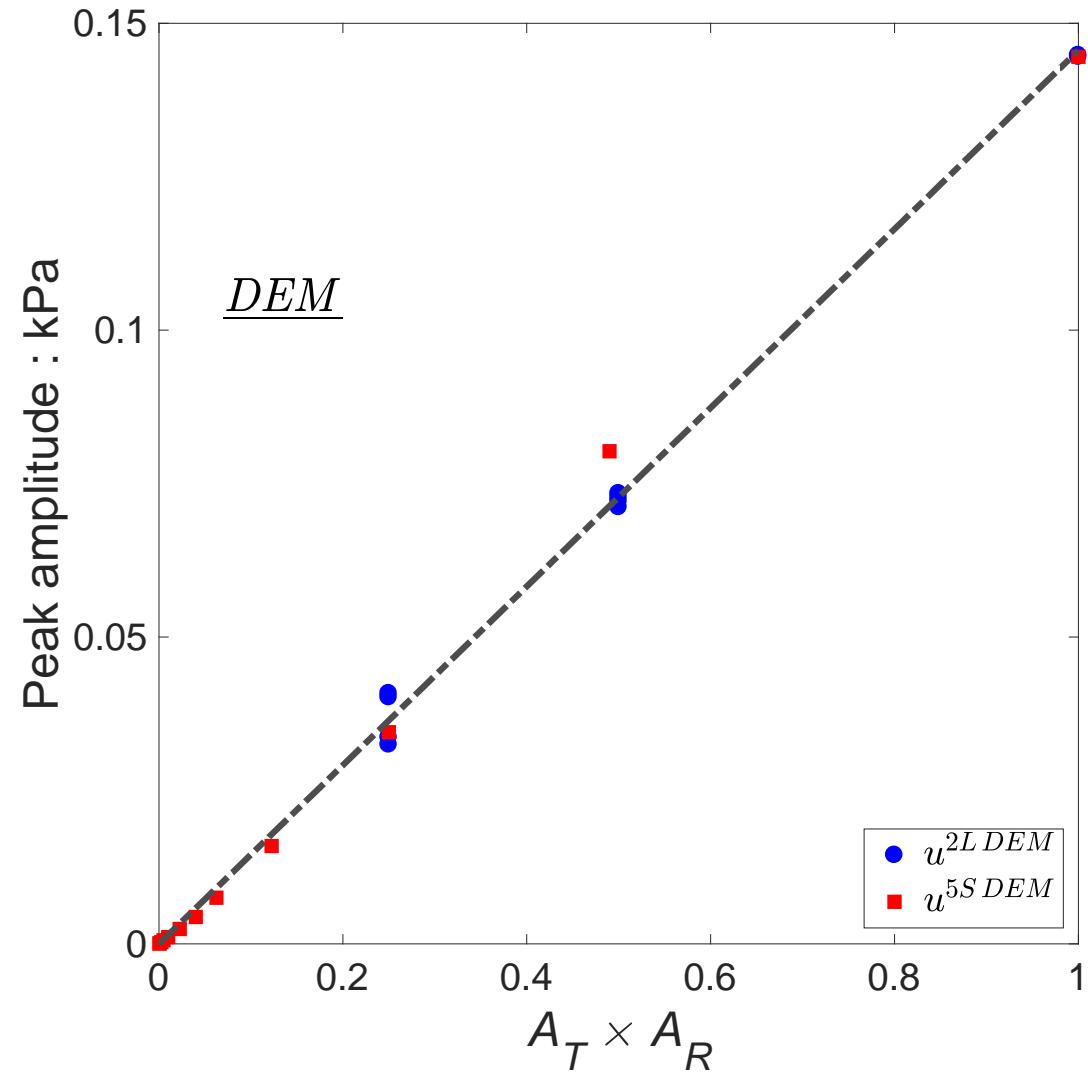
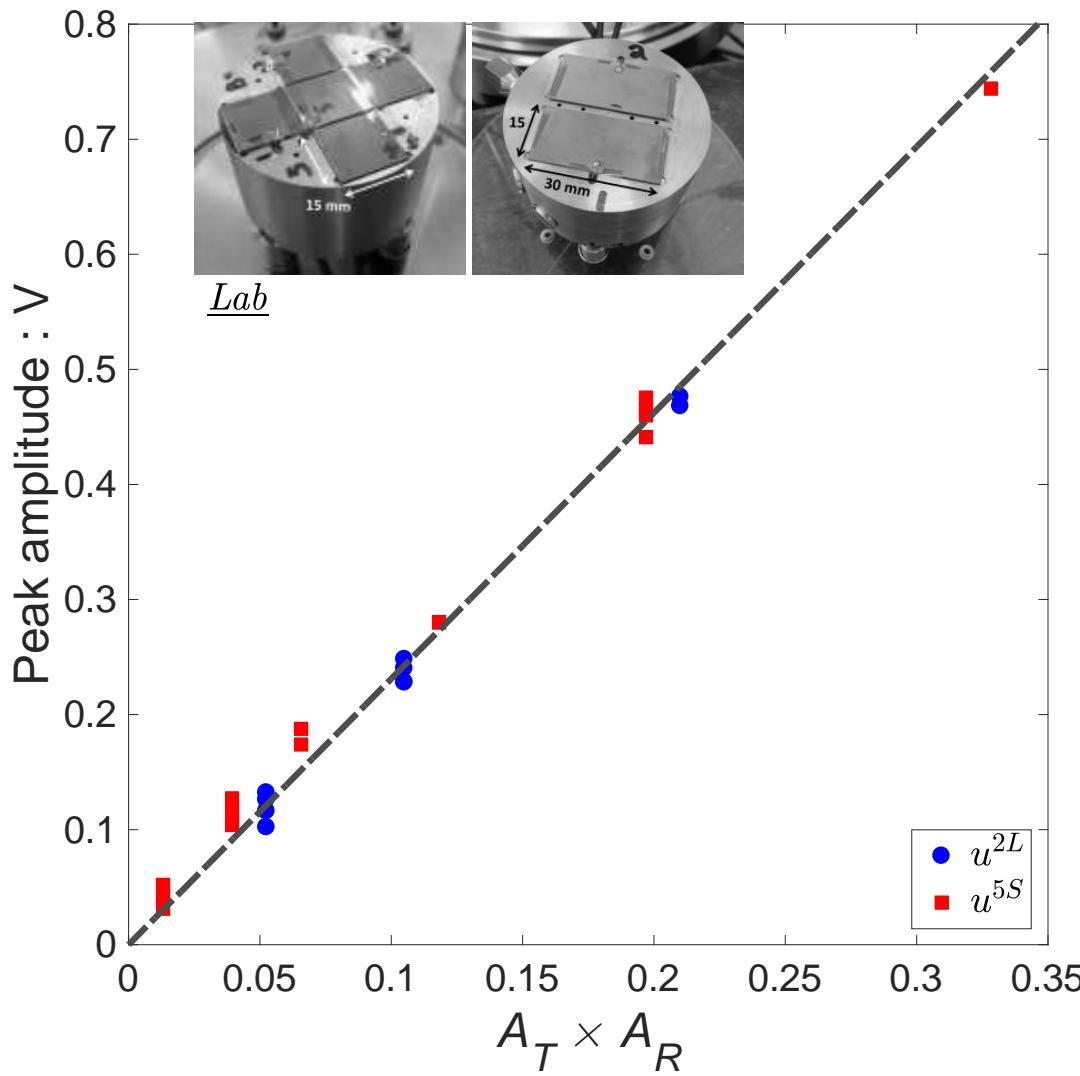


Experimental data

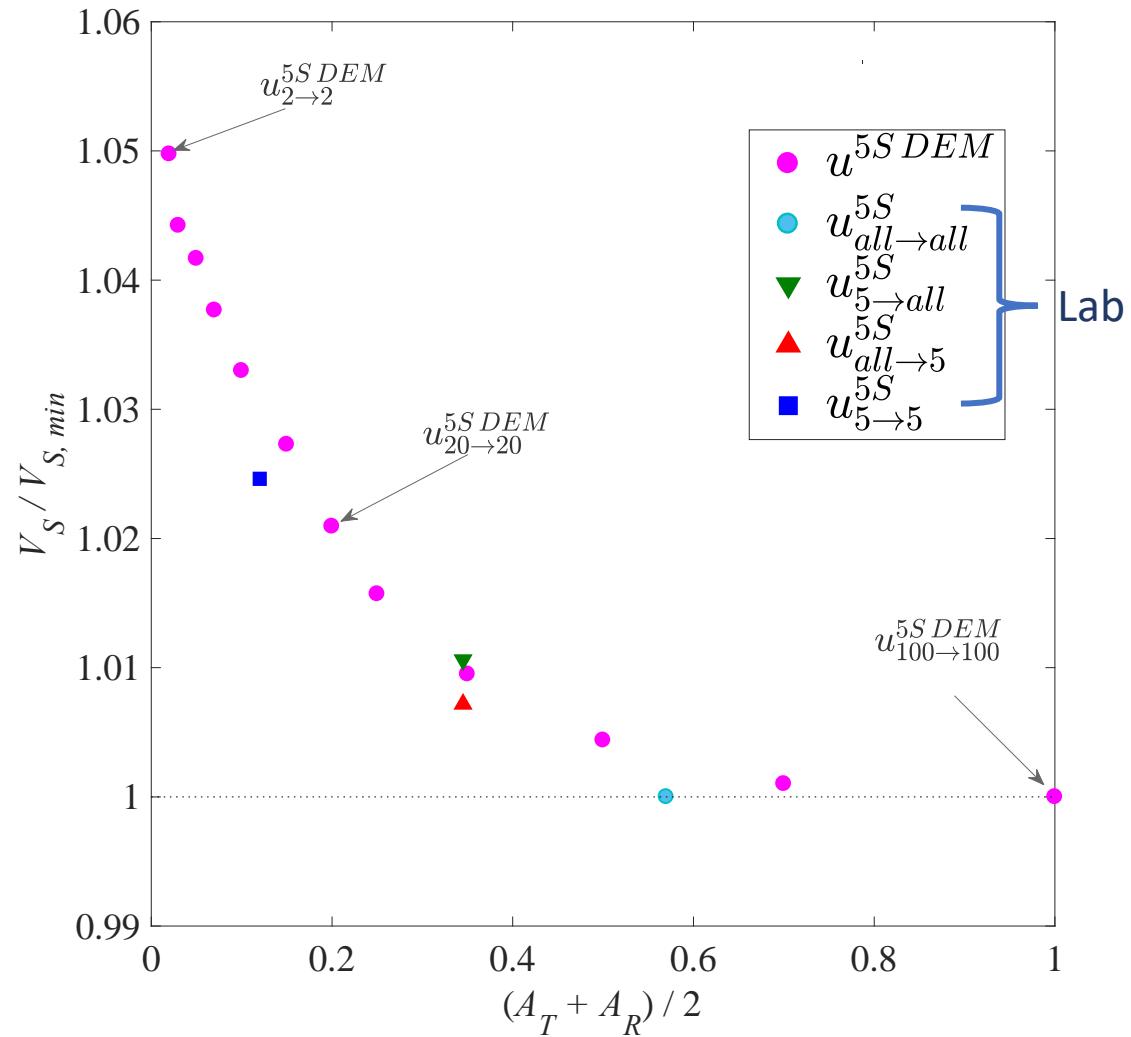
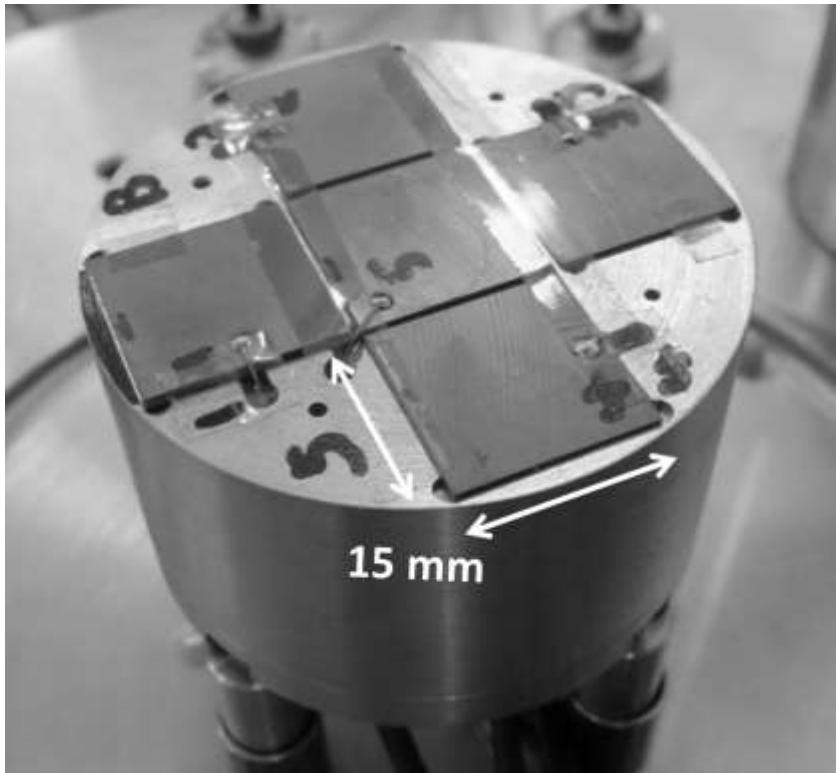


DEM data

Shear plate technology



Shear plate technology

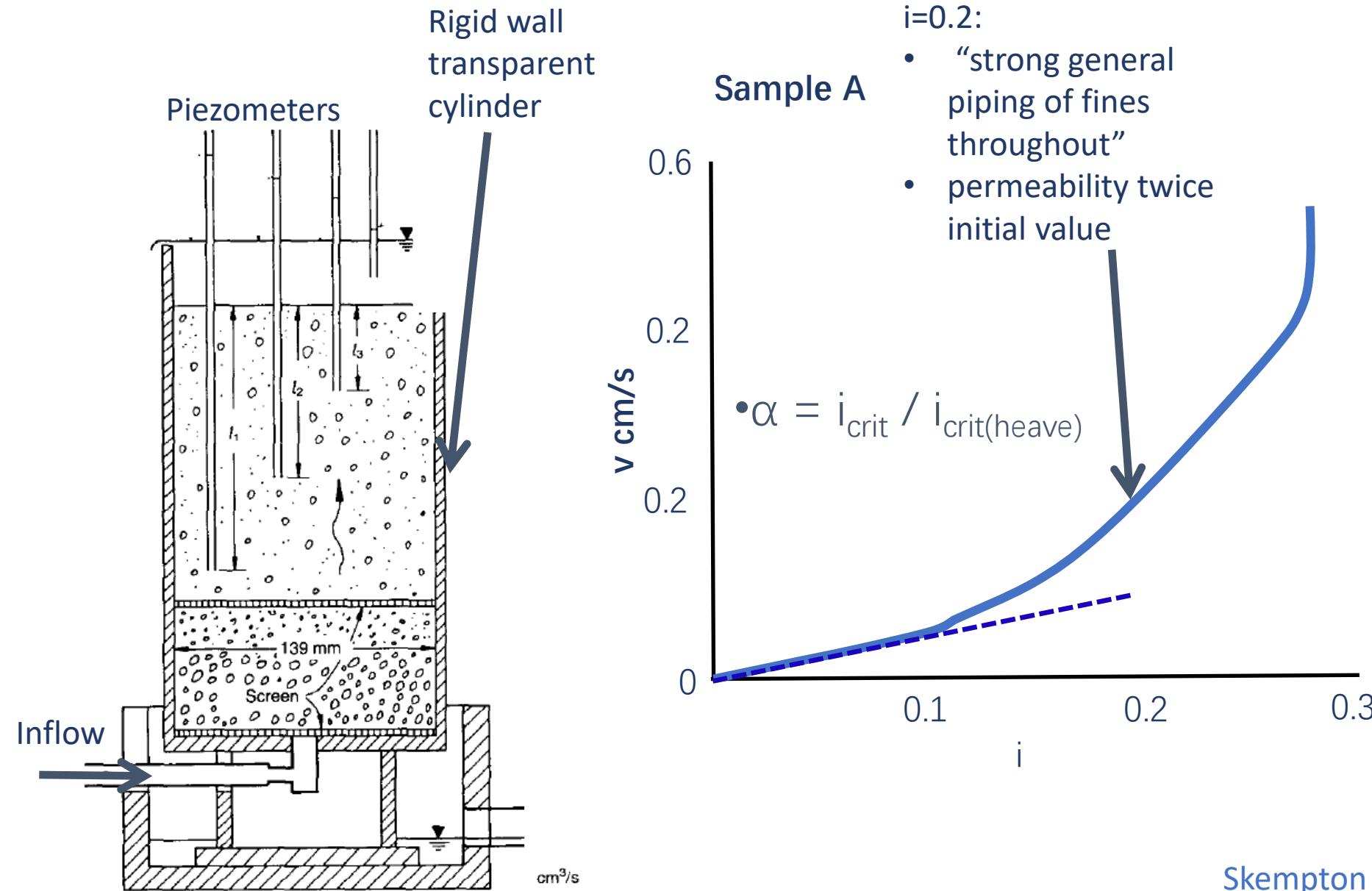


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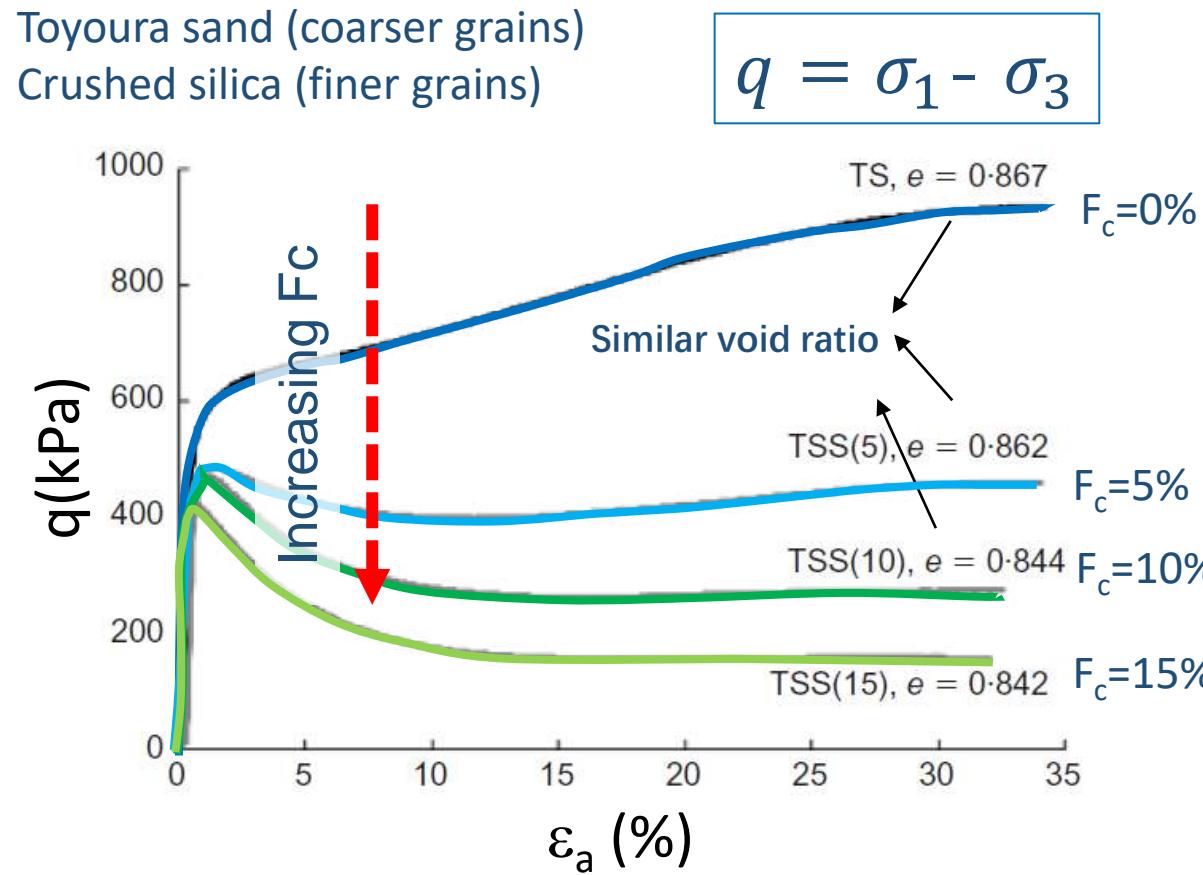
Internal instability in gap-graded soils



Robert Negri MSc

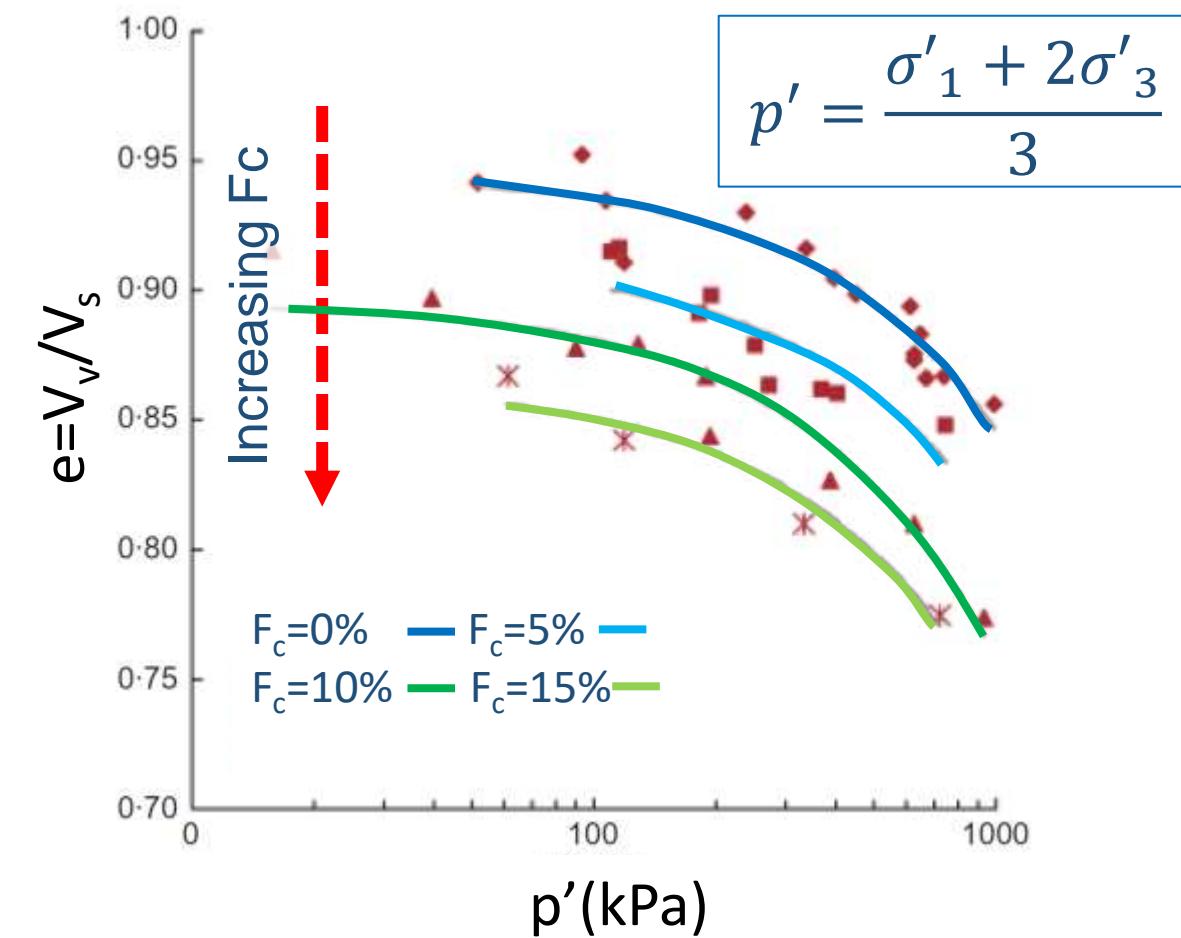
Effect of F_c on Shearing response

Undrained stress-strain behaviour
(Modified from Yang and Wei, 2012)



Increase in F_c leads to an increase in undrained strain-softening

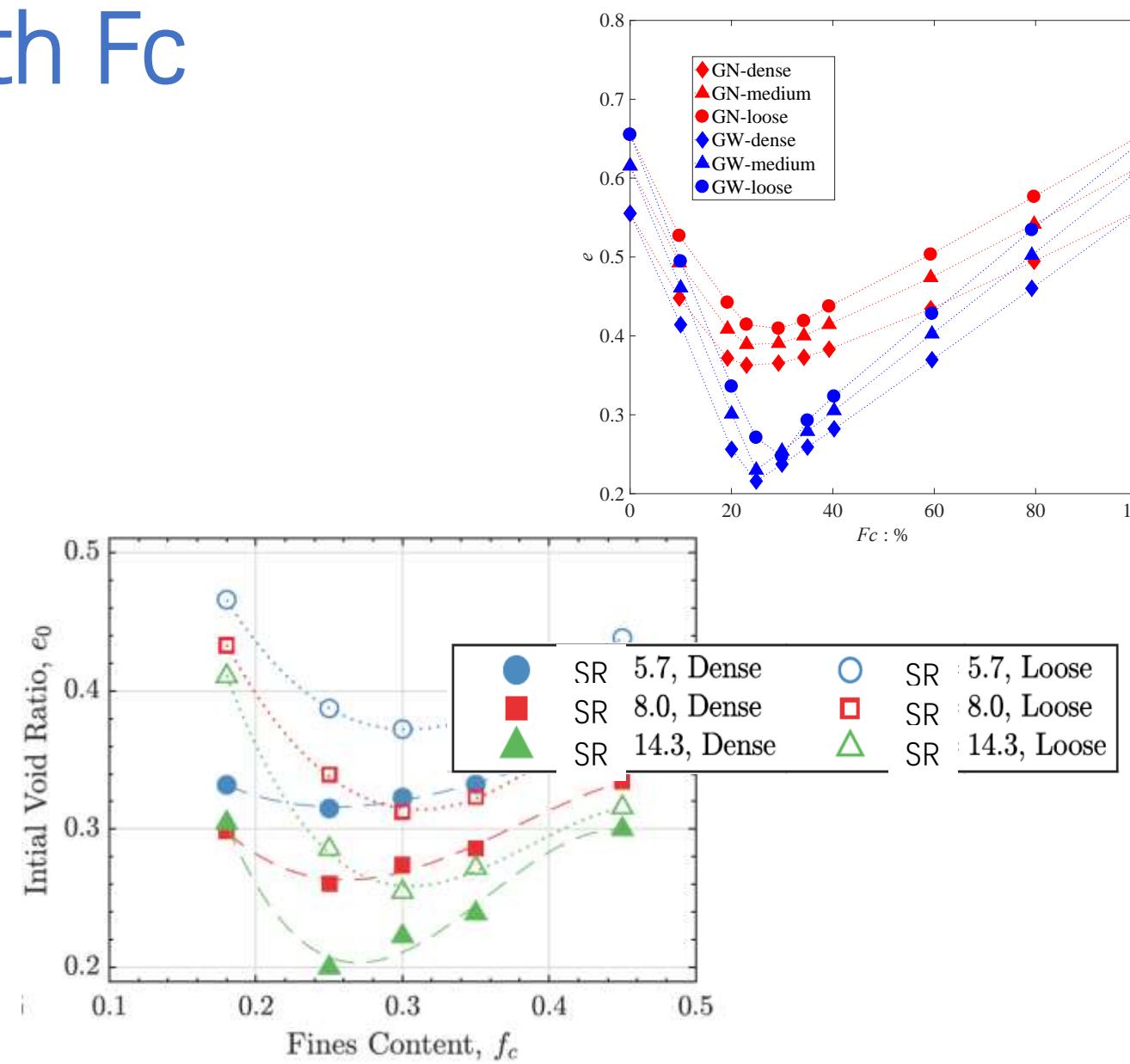
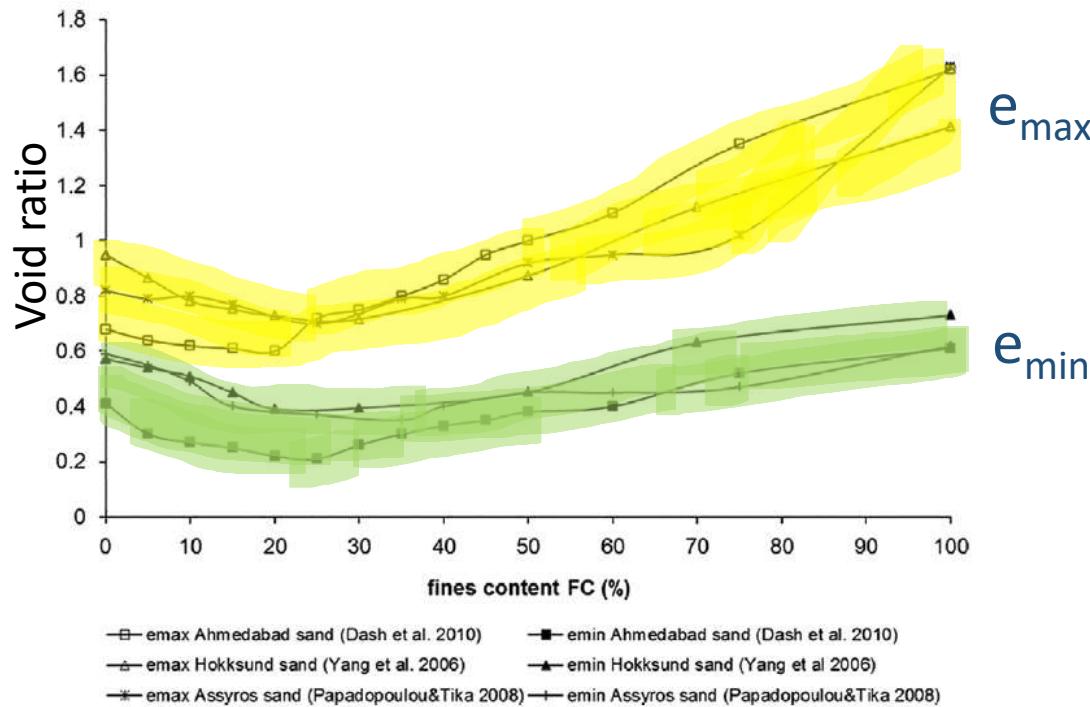
Critical state locus
(Modified from Yang and Wei, 2012)



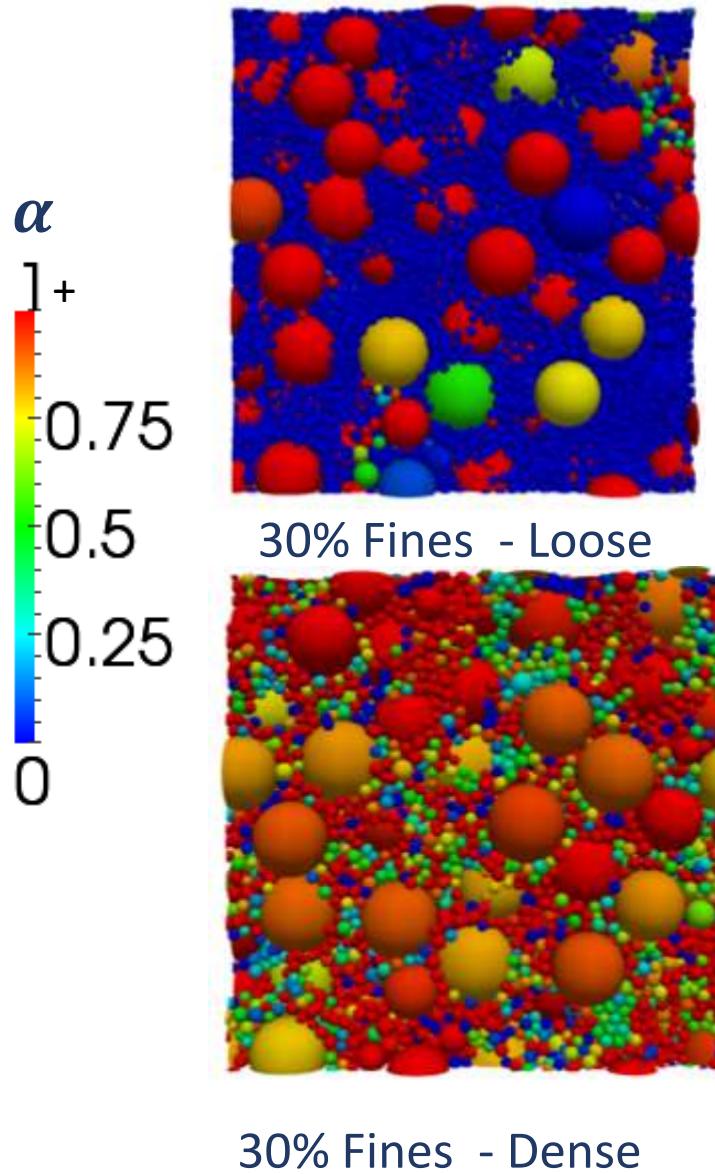
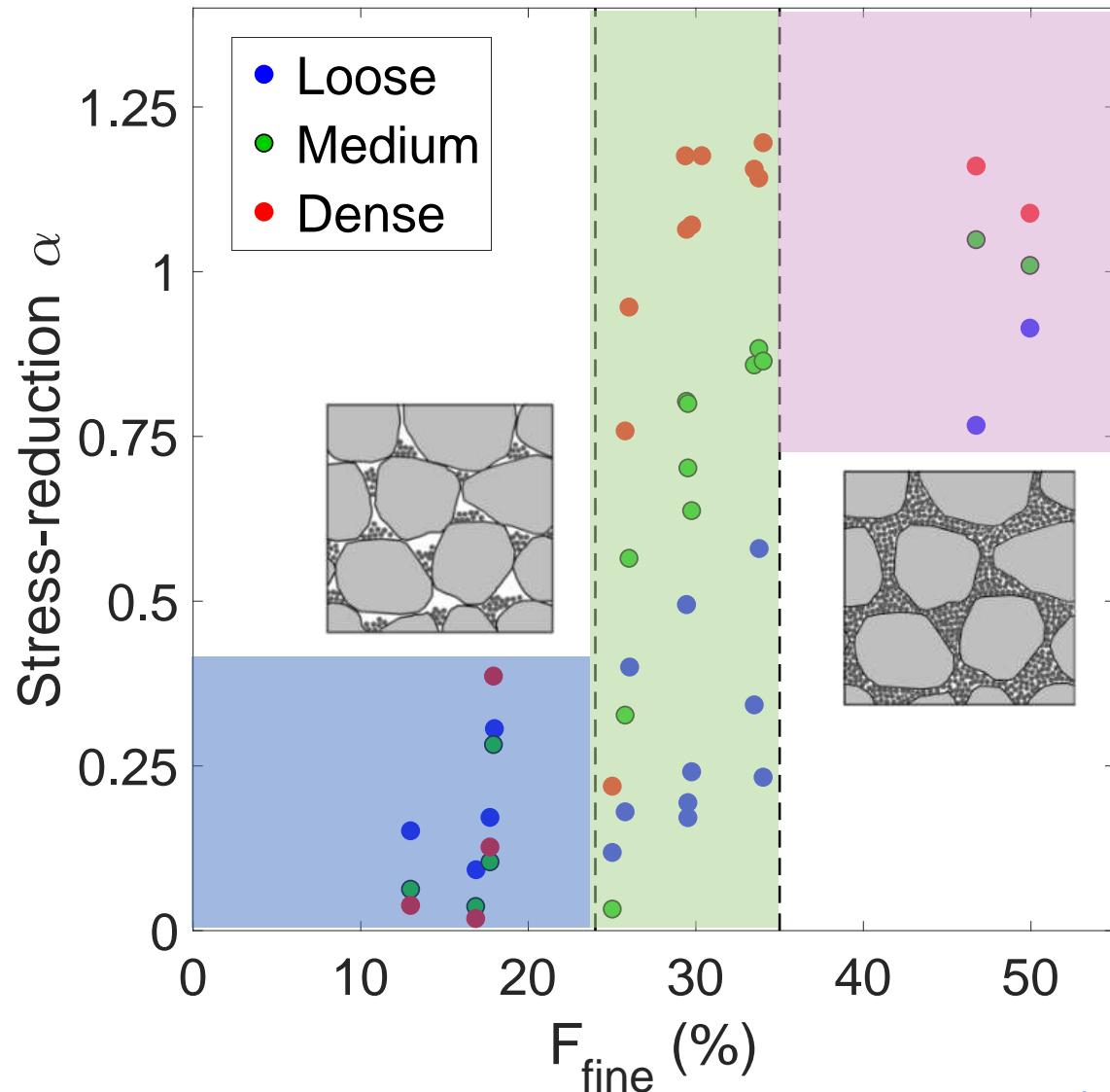
Increase in F_c leads to a downward shift to the critical state line (CSL) (in e -log p' plane)

Variation in void ratio with Fc

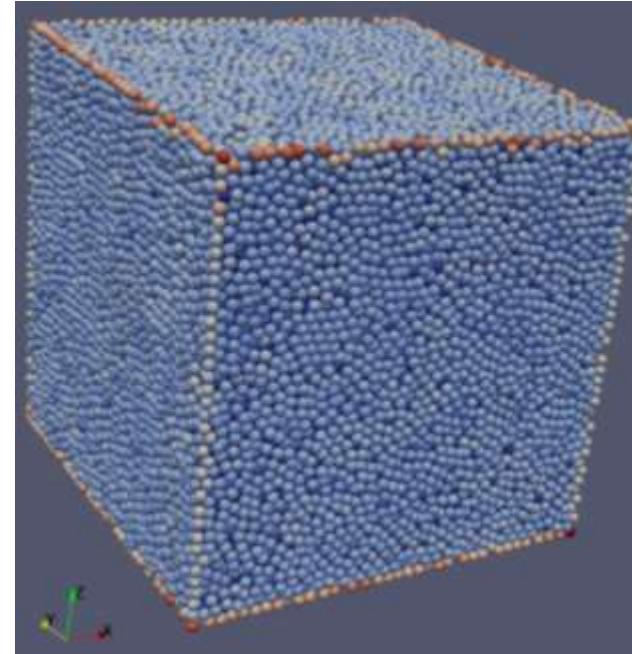
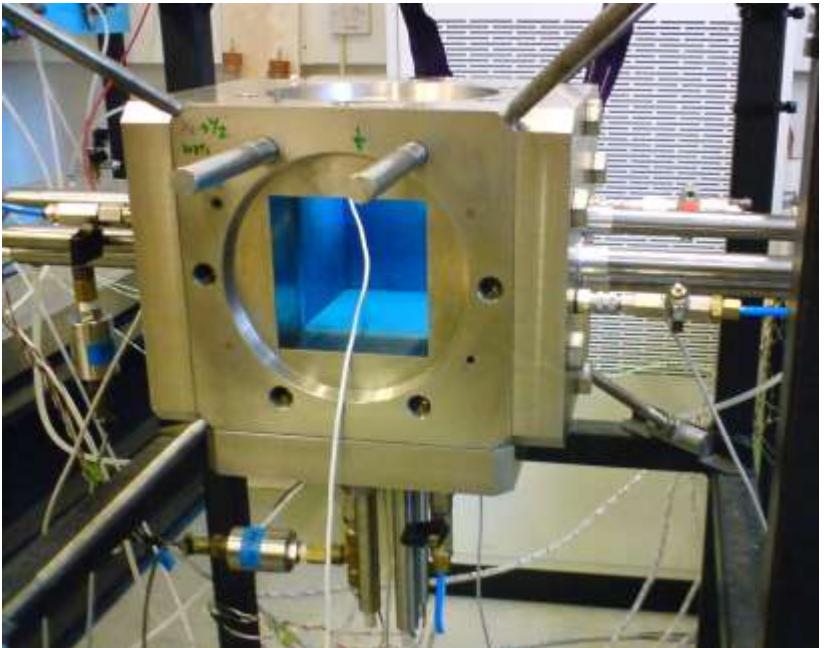
Collation of published experimental studies



Stress transmission in gap-graded soils



Cubical cell apparatus.

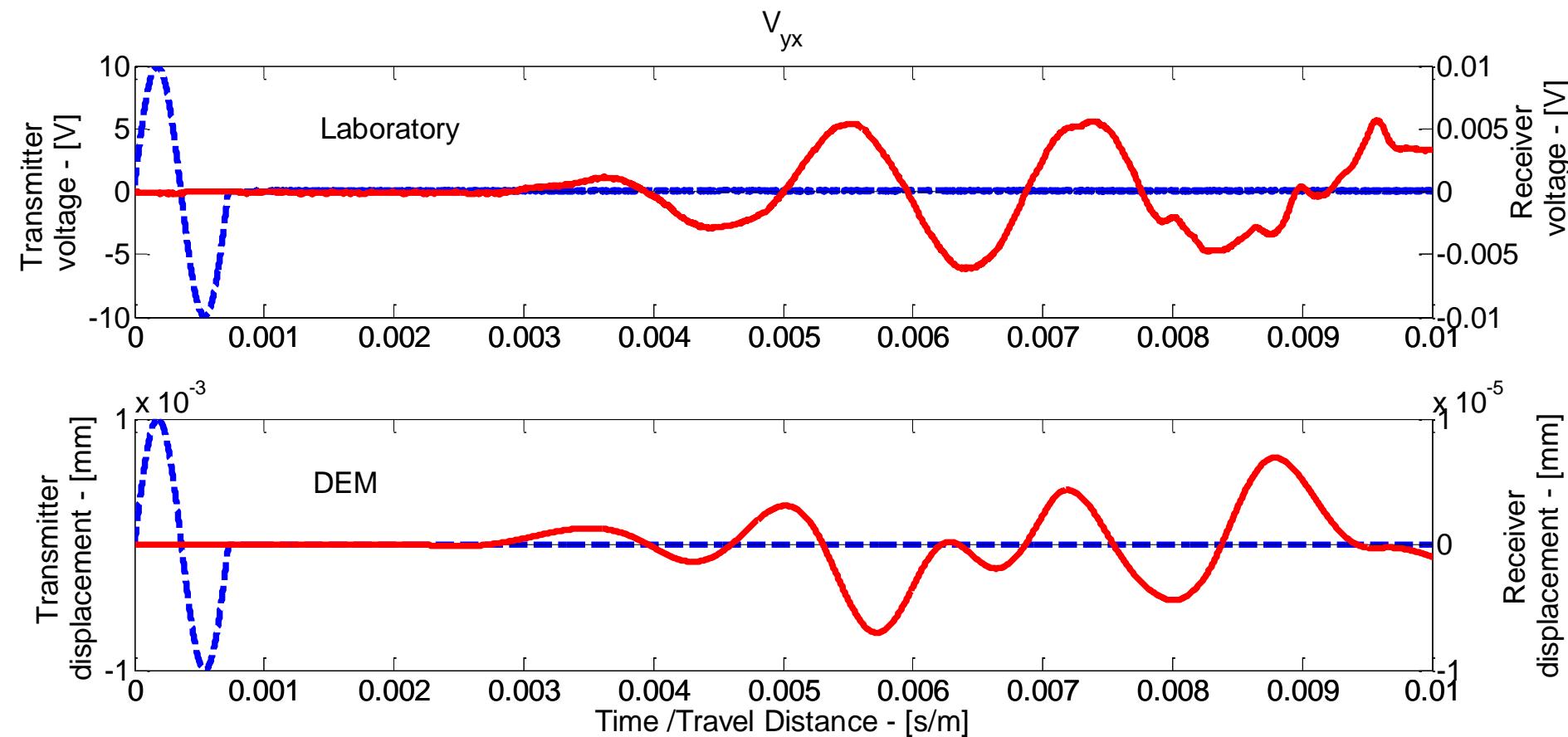


Signal comparison: Time domain

Isotropic stress of 100 kPa

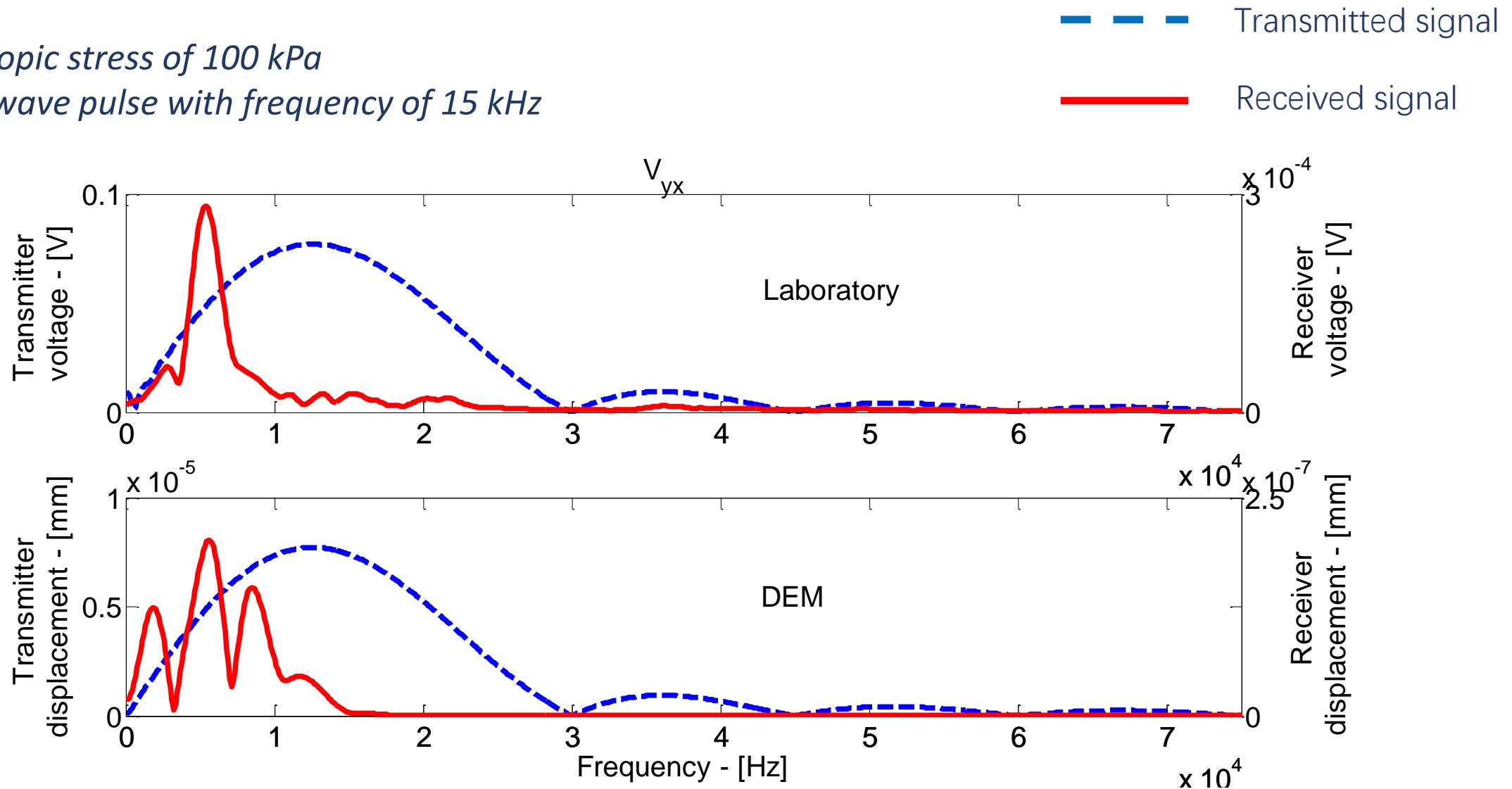
Sinewave pulse with frequency of 15 kHz

Transmitted signal
Received signal

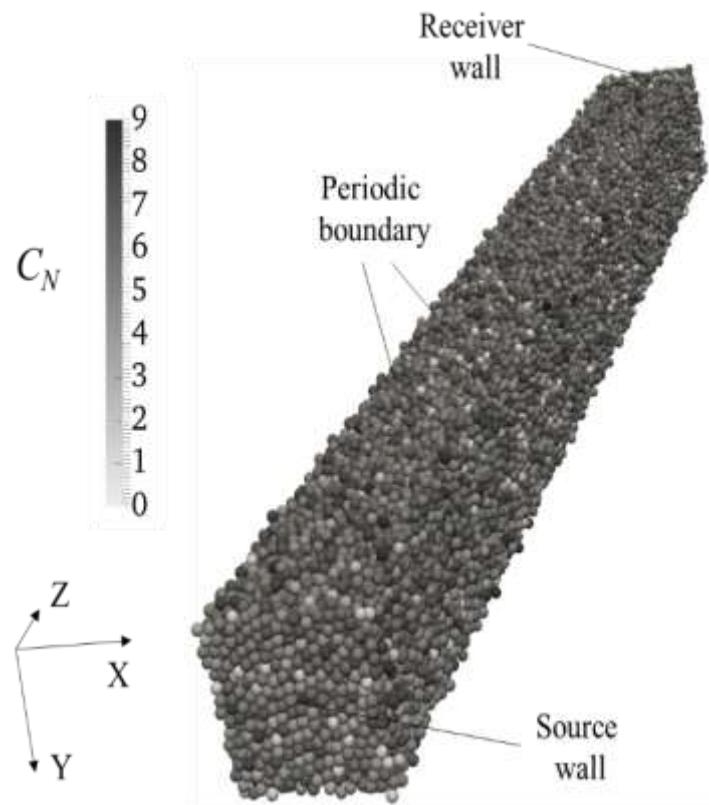


Signal Comparison: Frequency domain

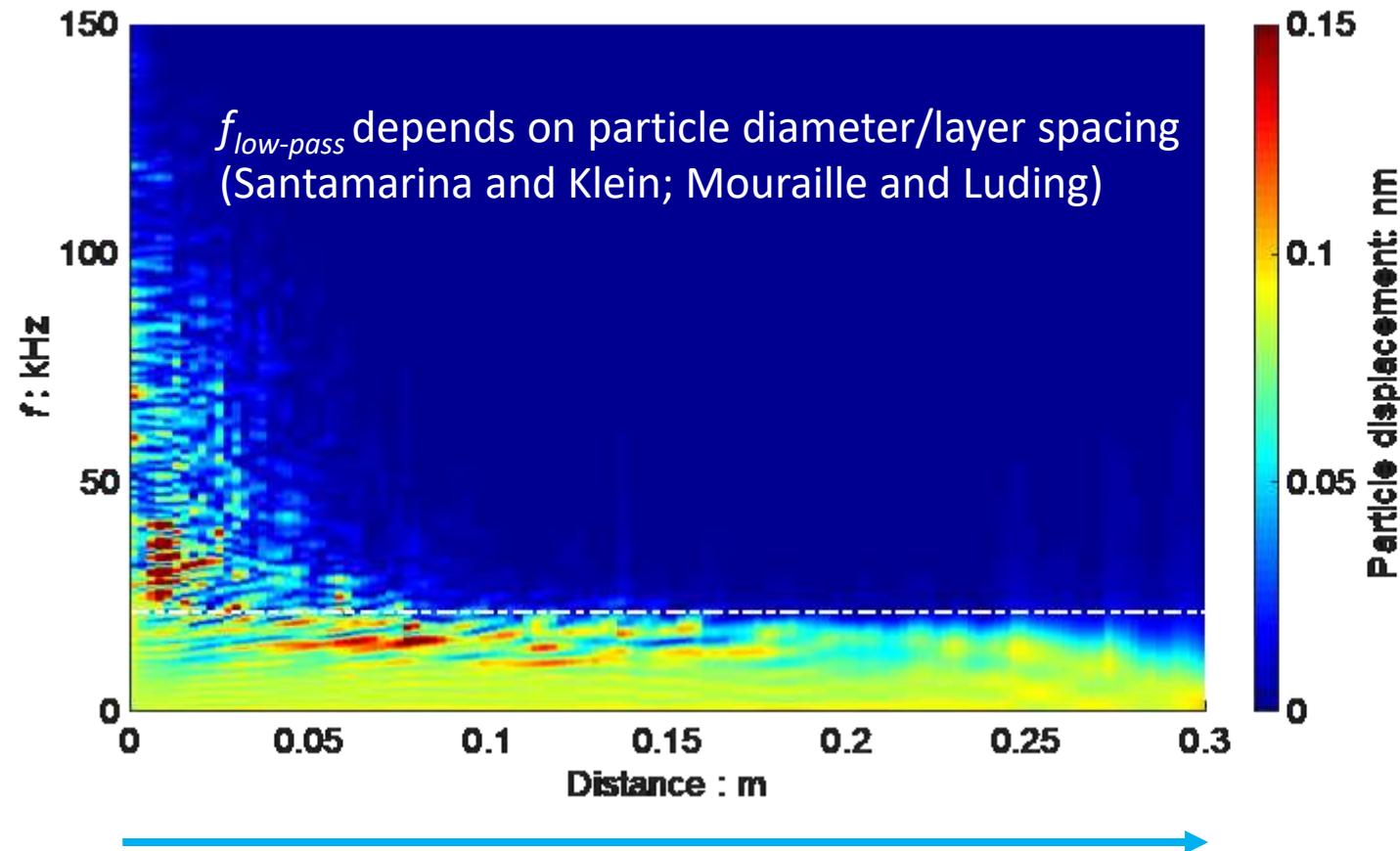
Isotropic stress of 100 kPa
Sinewave pulse with frequency of 15 kHz



Influence of e and stress on $f_{low-pass}$

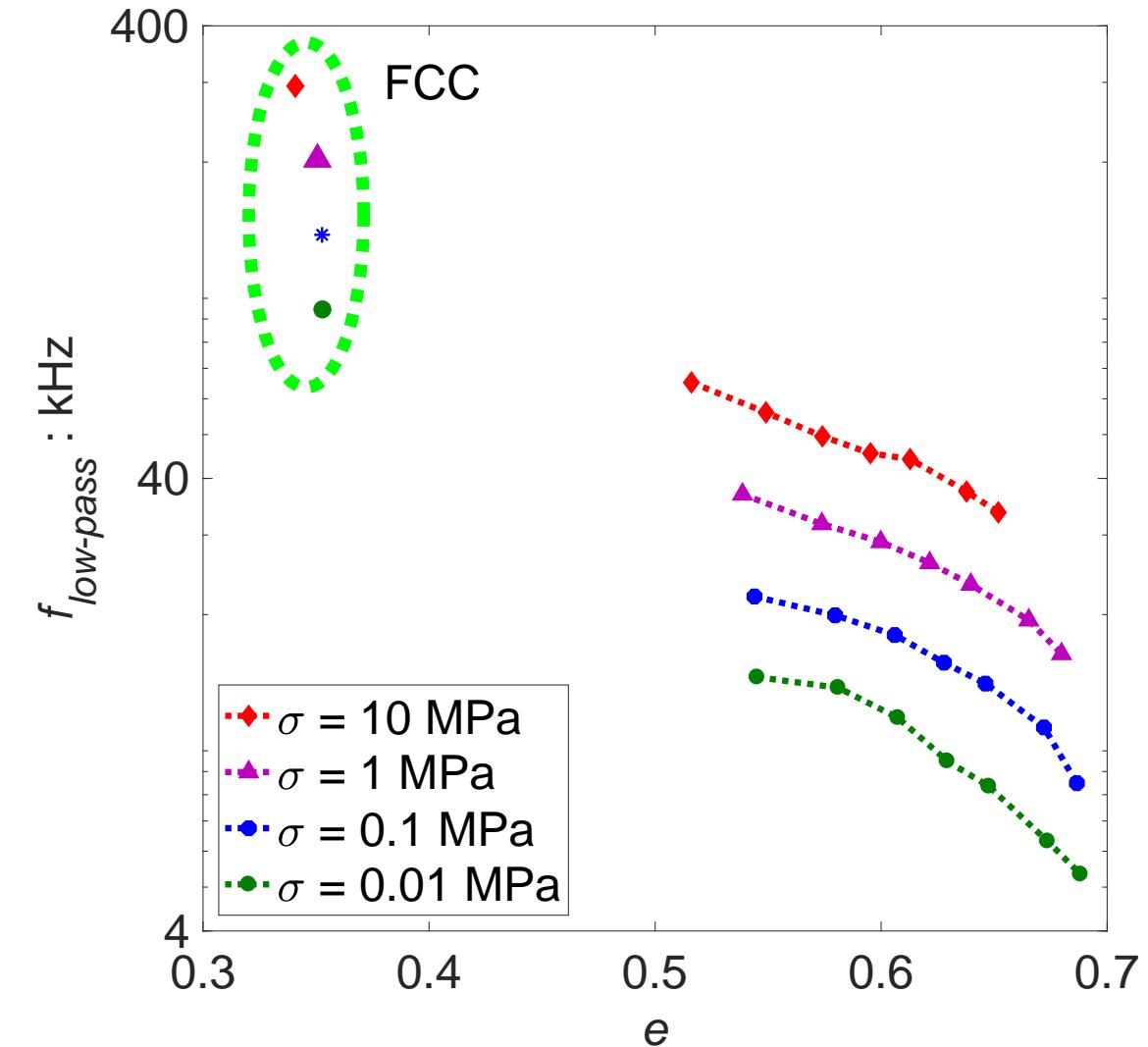
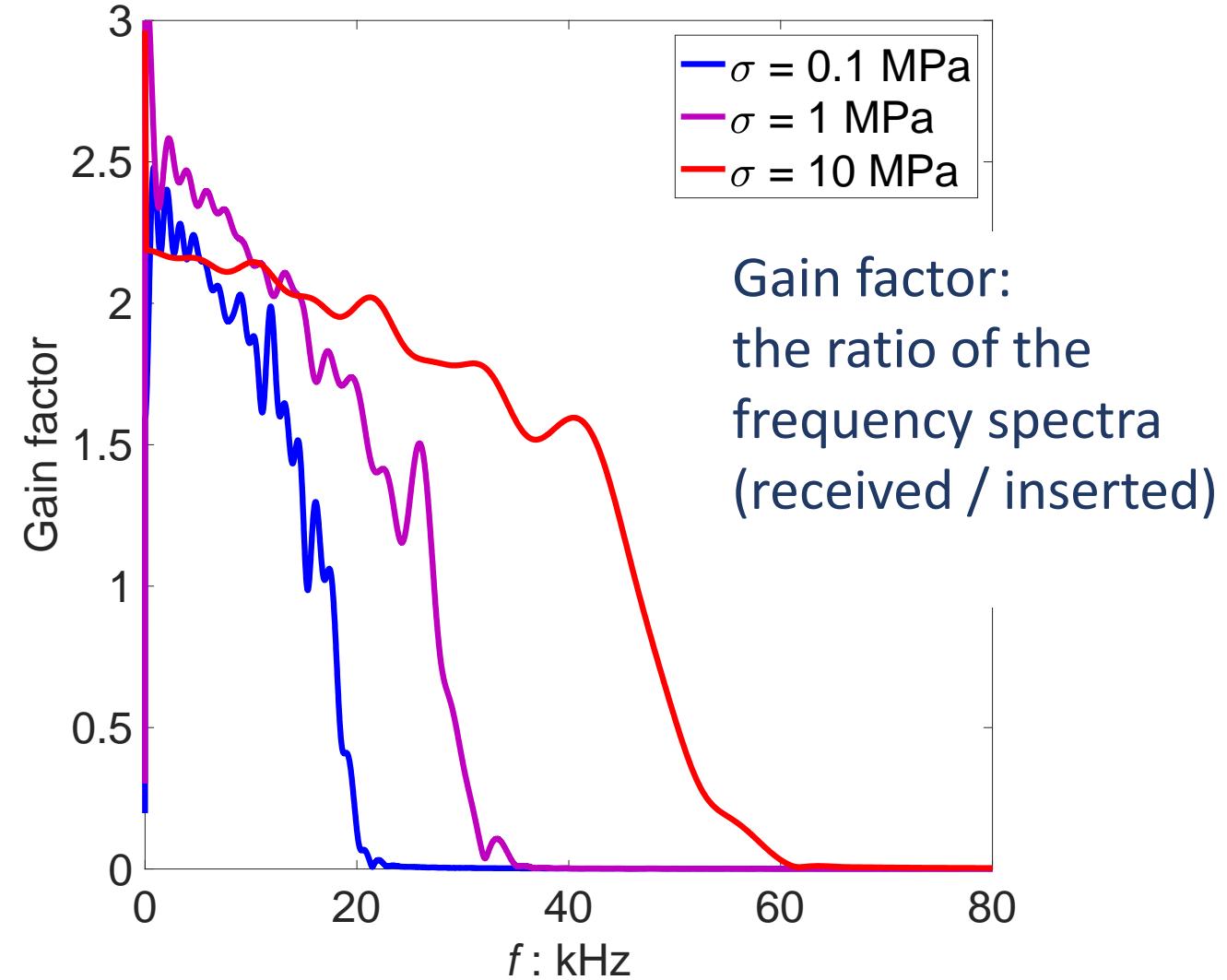


Random monodisperse sample:
35,201 particles

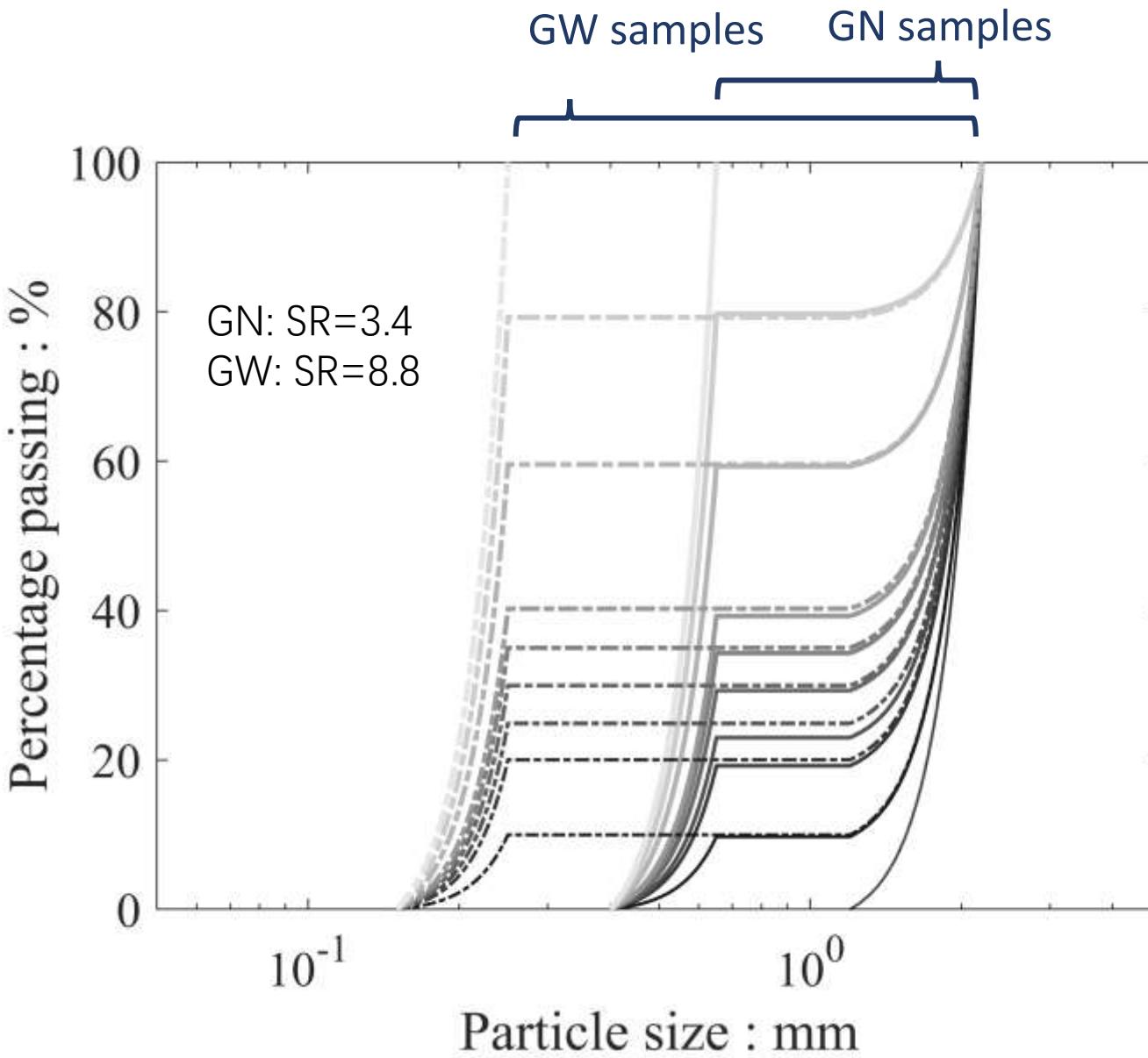


Moving along sample from source to receiver

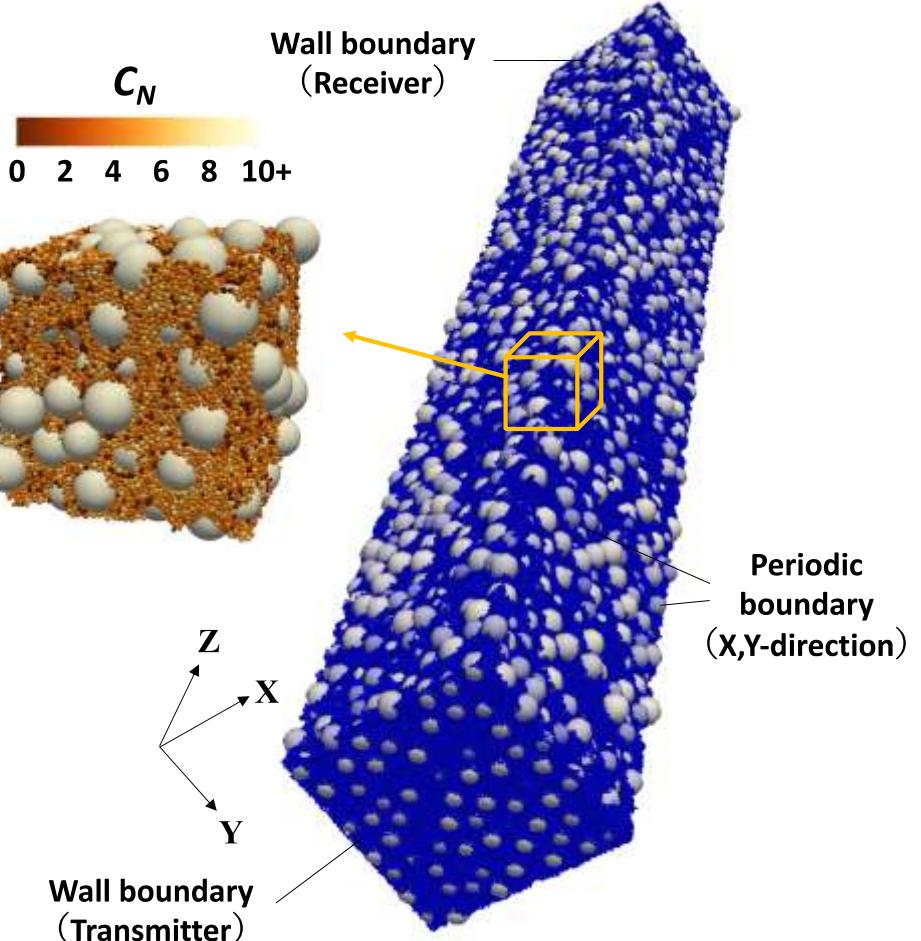
Influence of e and stress on $f_{low-pass}$



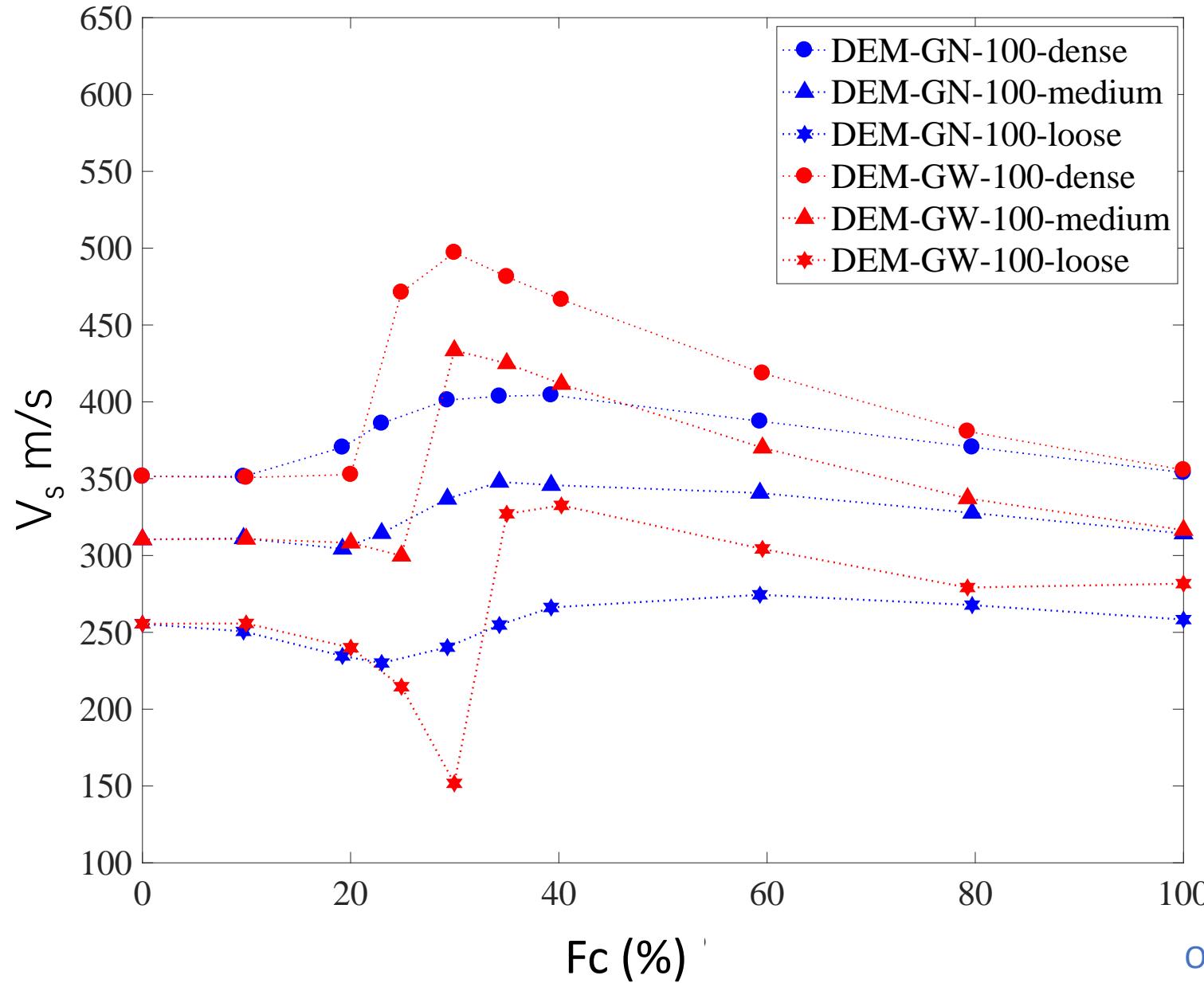
Gap-graded samples considered



Up to 2.29 million particles in samples



Influence of FC on V_s

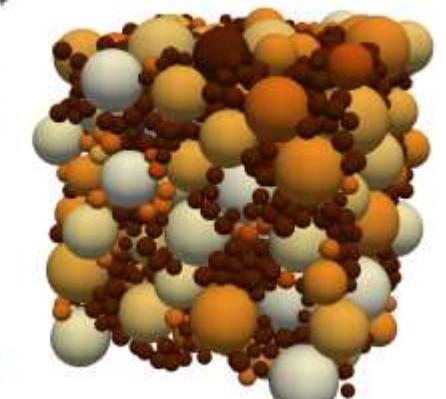


GN: SR=3.4

Fc=20%

Coordination number

C_N

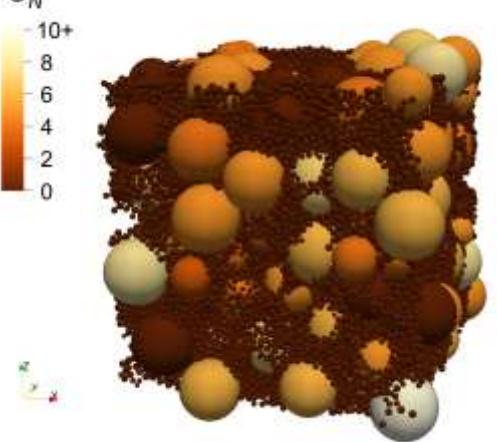


GW: SR=8.8

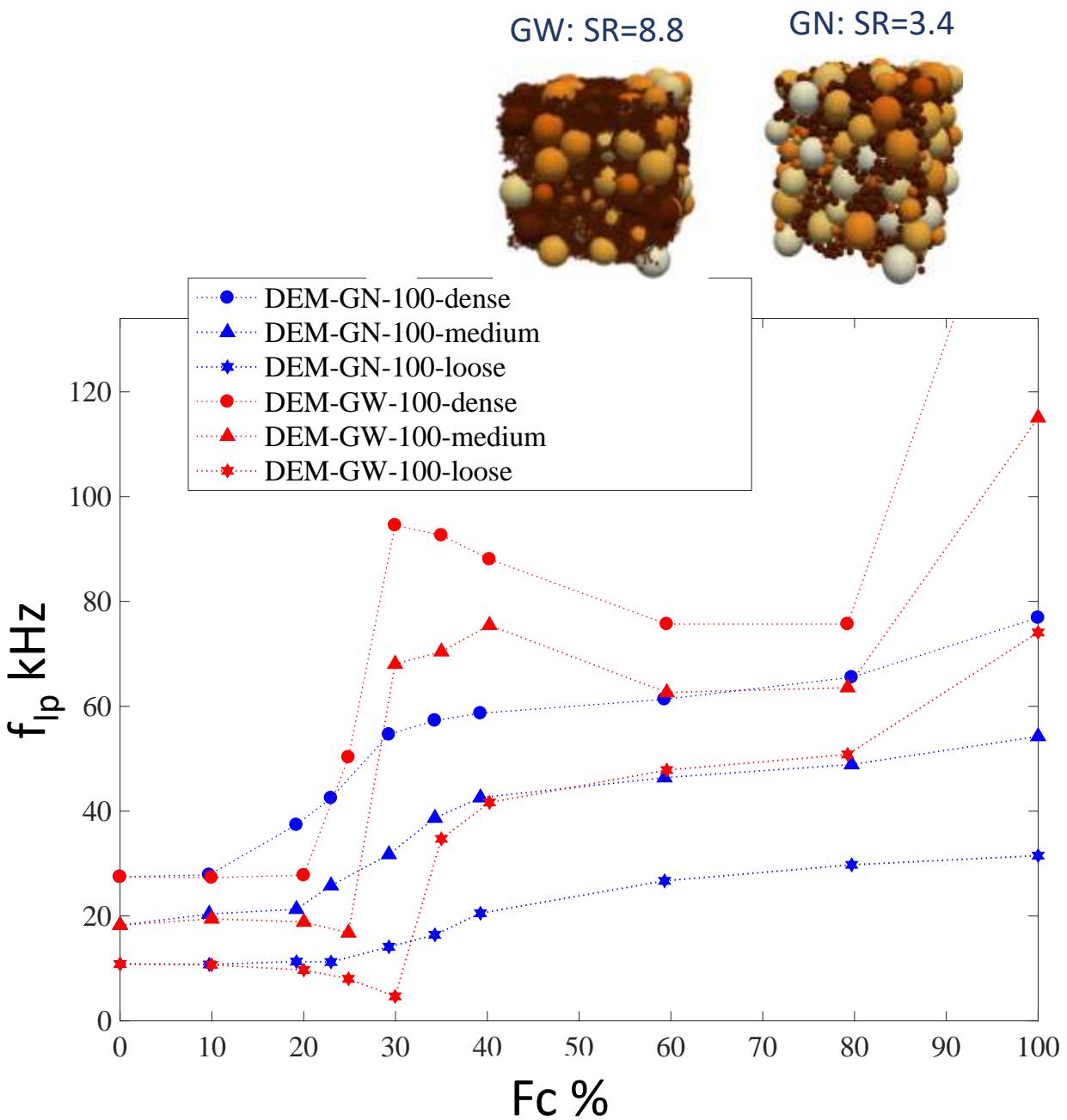
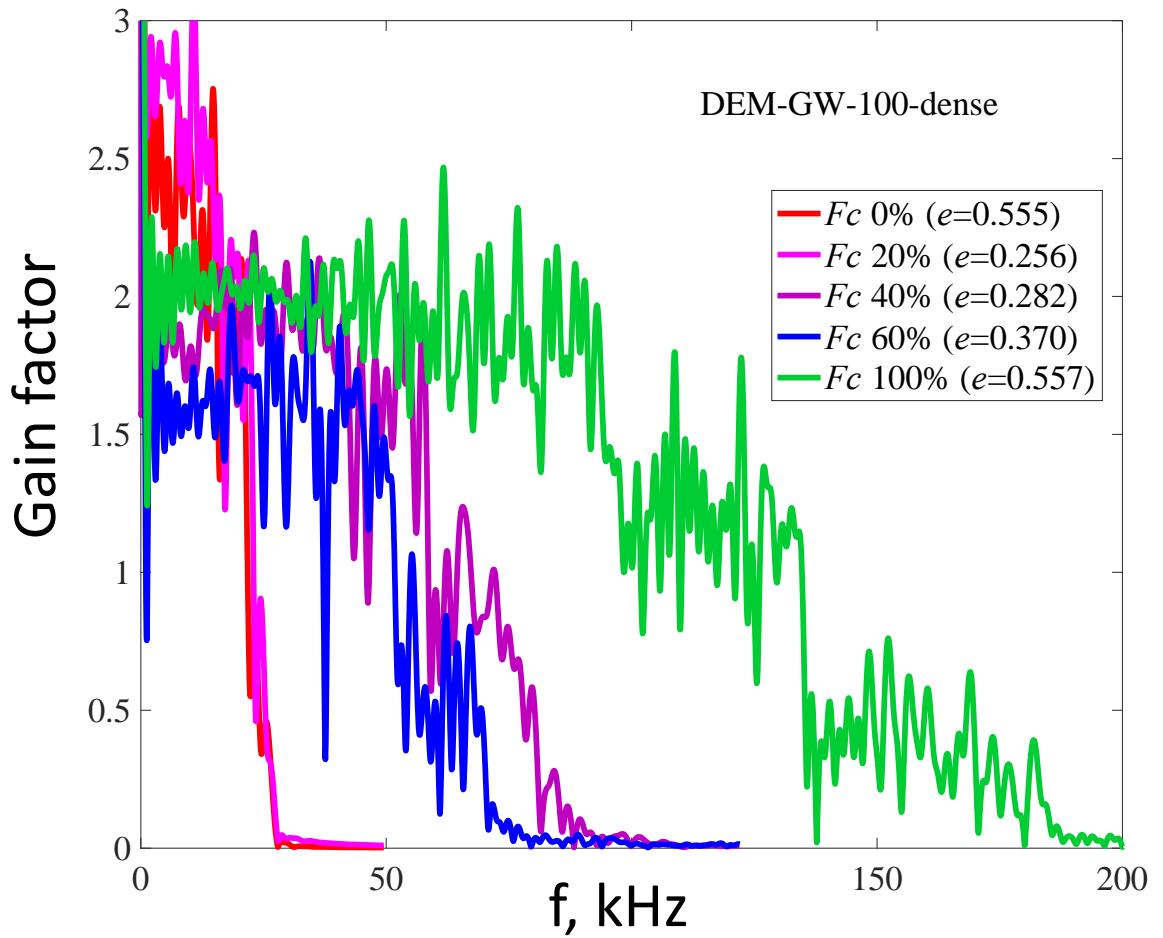
Fc=20%

Coordination number

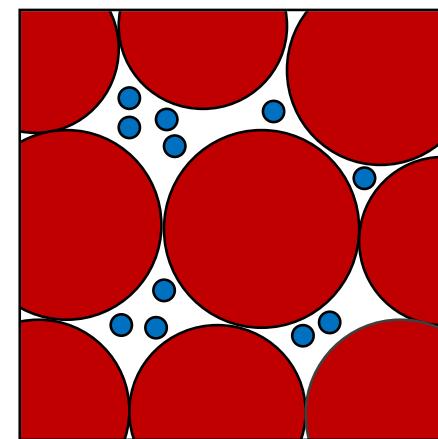
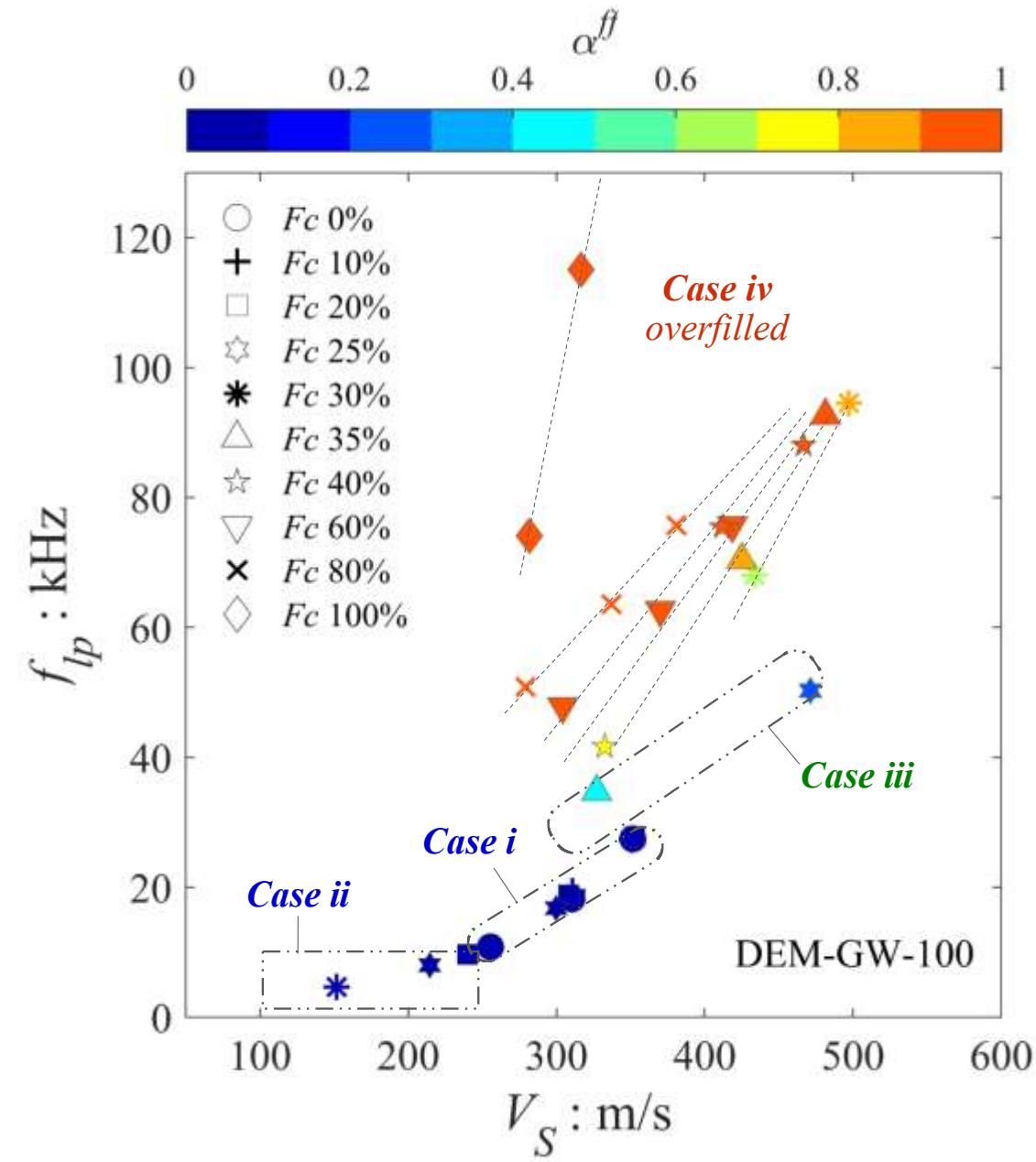
C_N



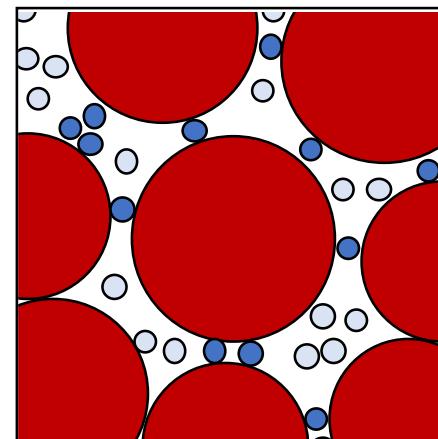
Influence of Fc on f_{lp}



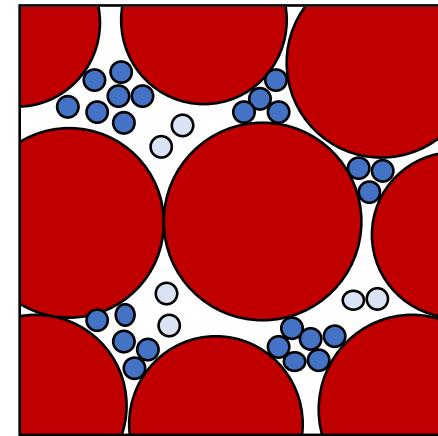
Relating F_c to f_{lp} and V_s



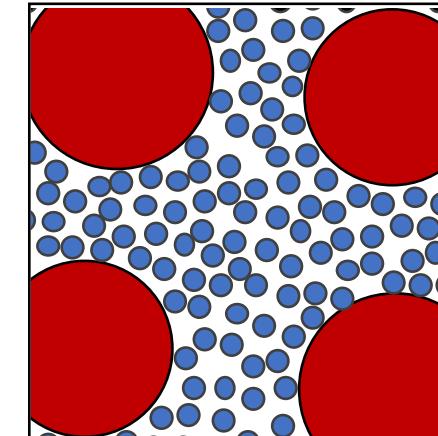
Case i



Case ii



Case iii



Case iv

Bulk density

$$\text{Bulk density: } \rho = \frac{M_s}{V}$$

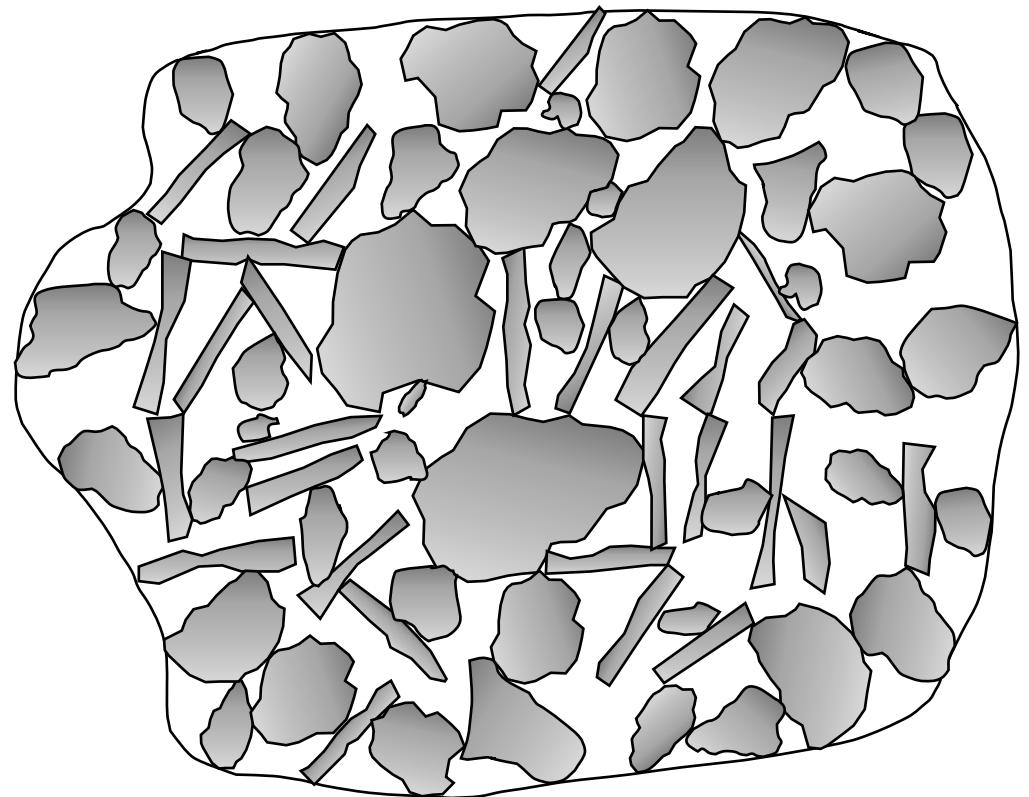
$$V \text{ total volume} = V_v + V_{sol}$$

M_s mass of soil grains

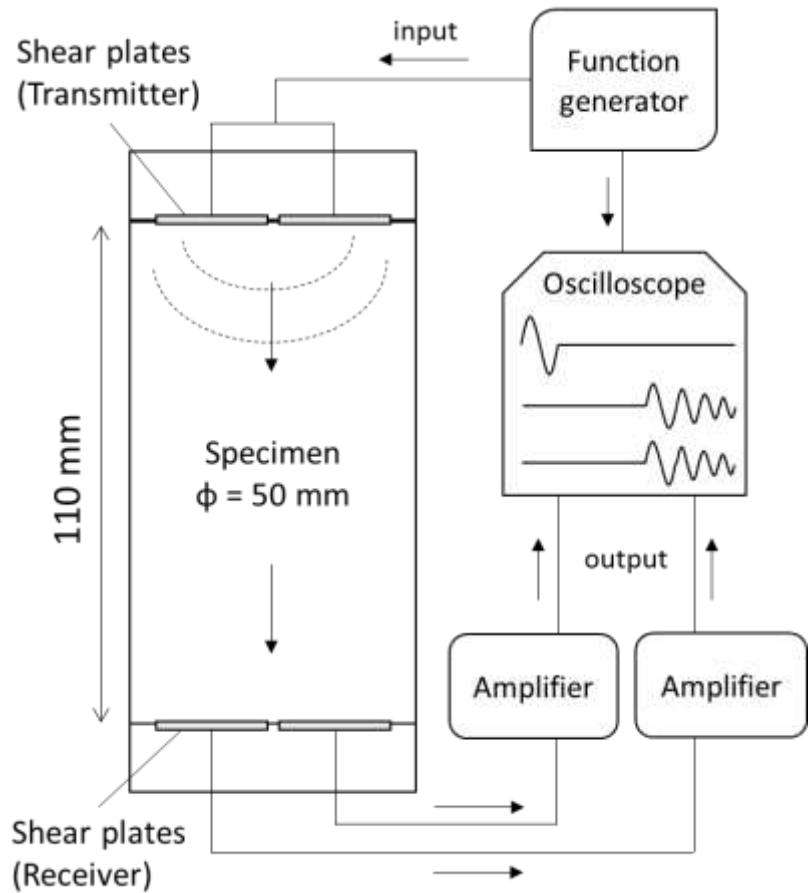
Mechanical bulk density:

$$\rho_m = \frac{M_s - M_s^0 \text{ or } 1}{V}$$

$M_s^0 \text{ or } 1$ mass of grains with 0 or 1 contact



Macro-scale, continuum stiffness



$$G = \rho V_s^2$$

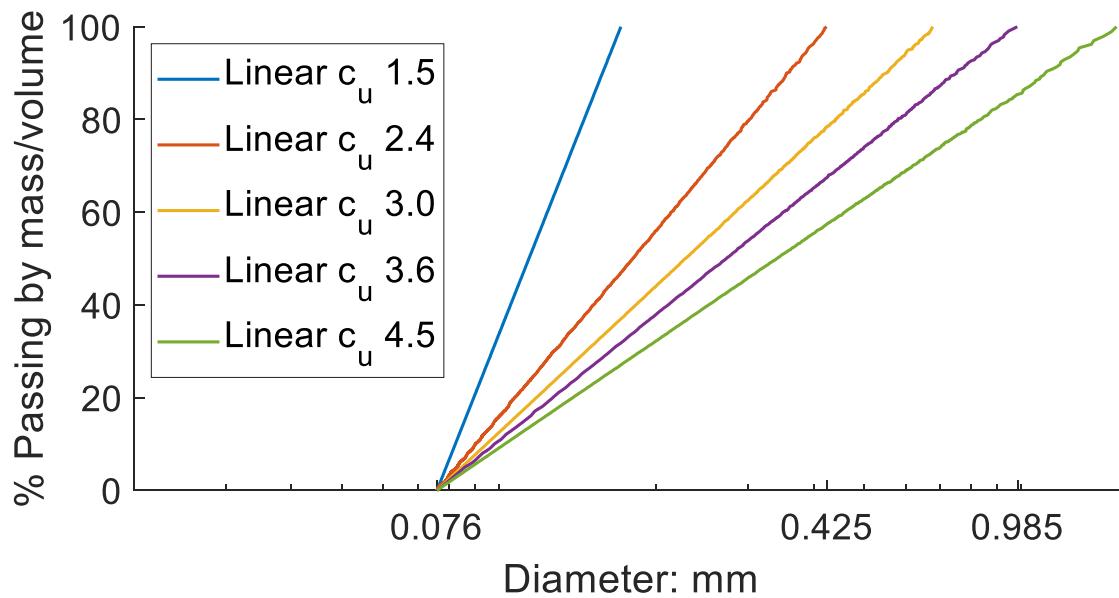
G = Shear stiffness

V_s = Shear wave velocity

$$G = \rho V_s^2 \quad \text{or} \quad G = \rho_m V_s^2 ?$$

Measuring shear wave velocity using
laboratory geophysics

Gradings considered in DEM study



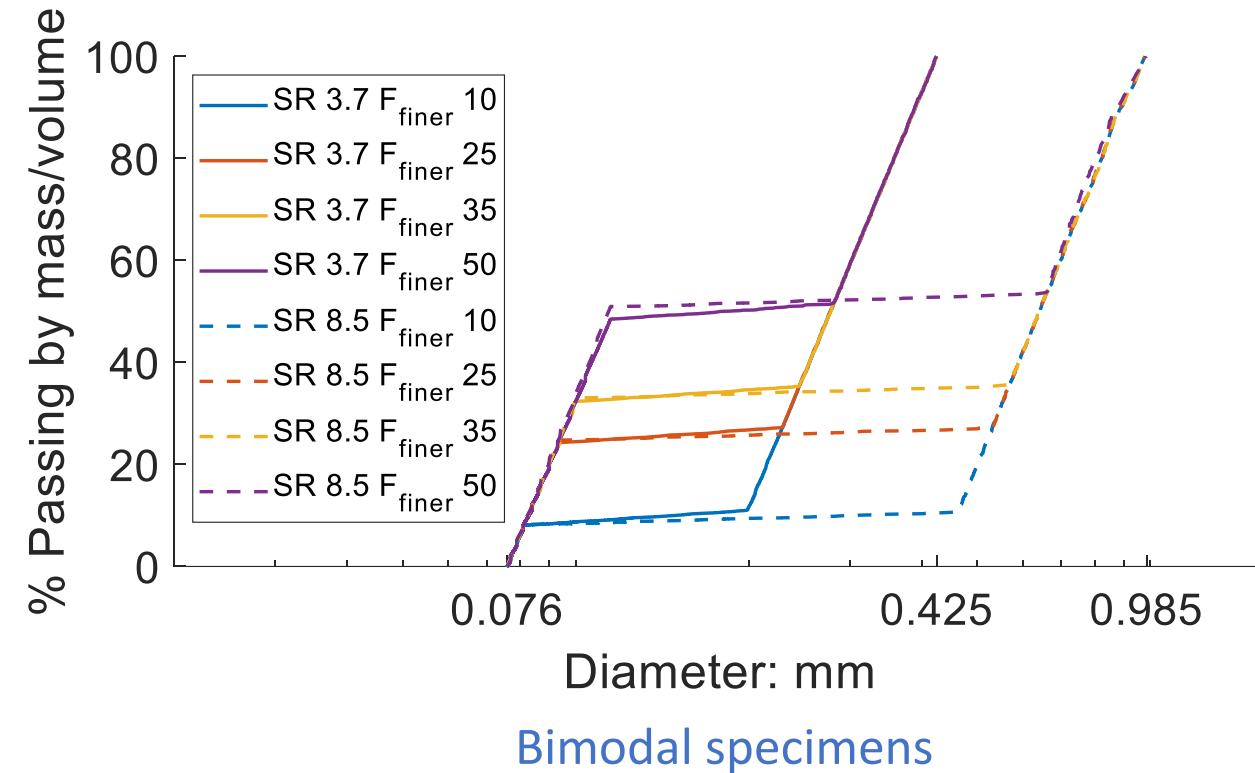
Linear specimens

$$C_u = d_{60}/d_{10}$$

Measure of polydispersity

60% of particles by volume are smaller than d_{60}

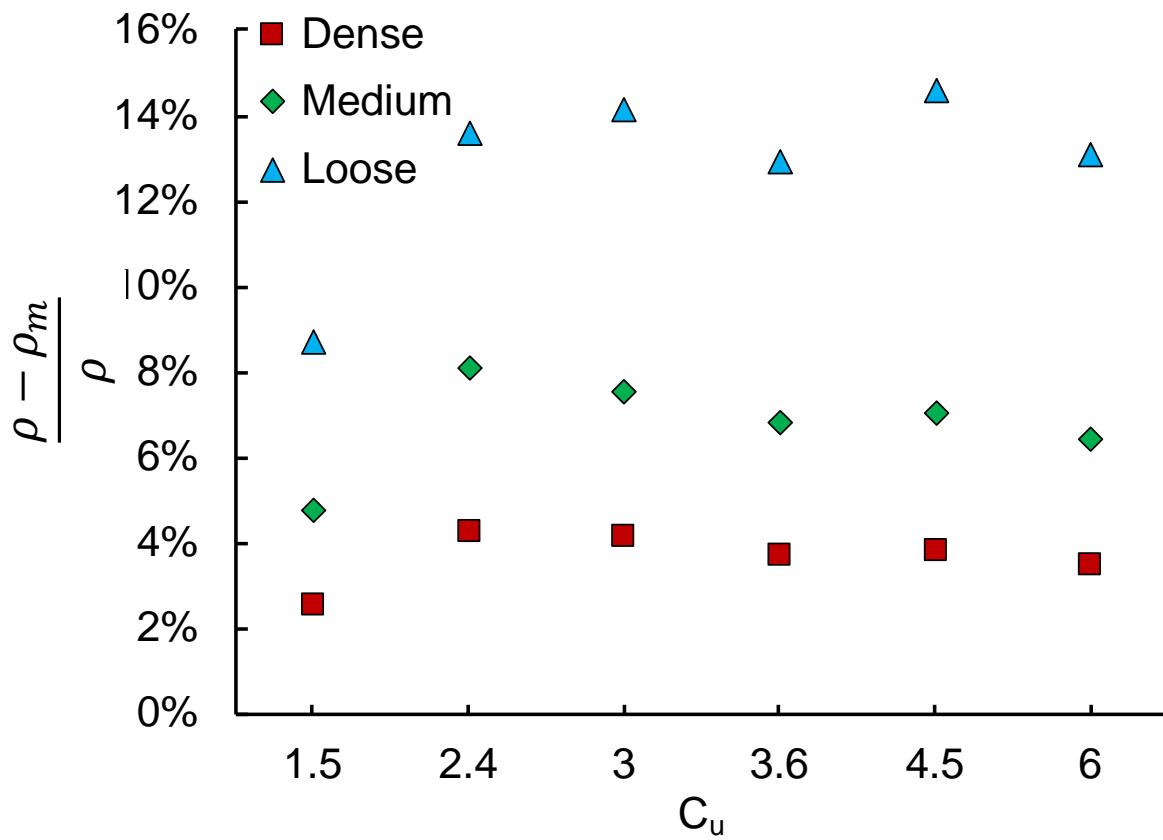
10% of particles by volume are smaller than d_{10}



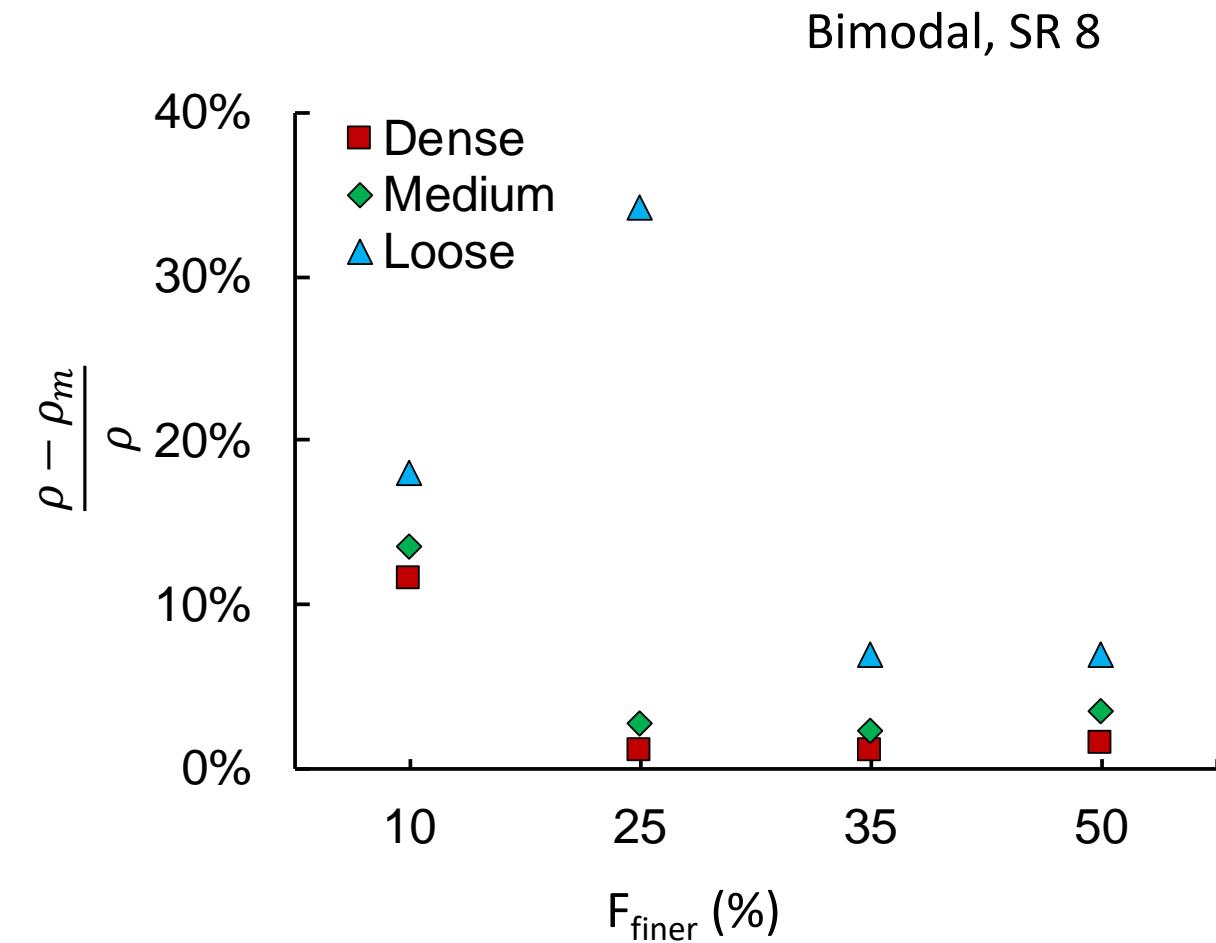
Bimodal specimens

Density and mechanical density

ρ_m considers only stress-transmitting particles



$$C_u = d_{60}/d_{10}$$

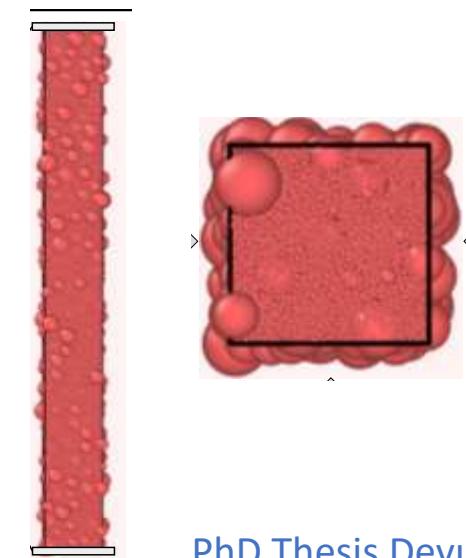
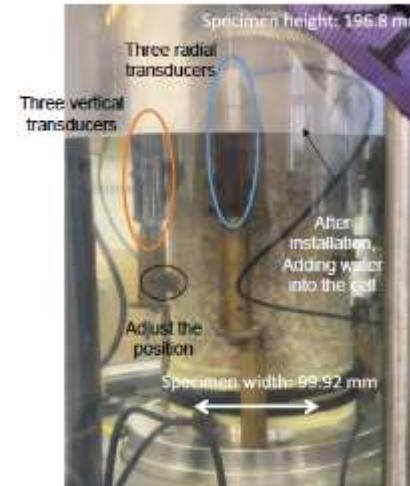
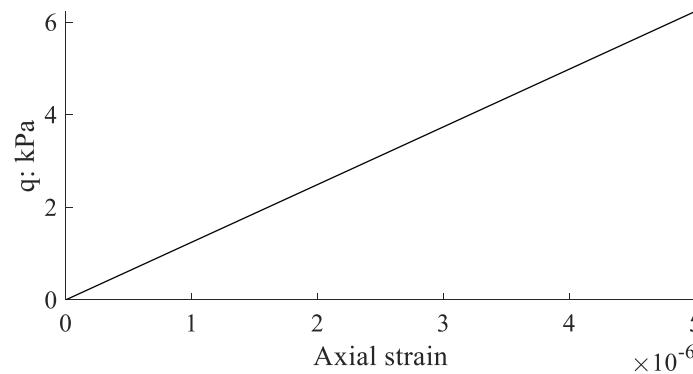
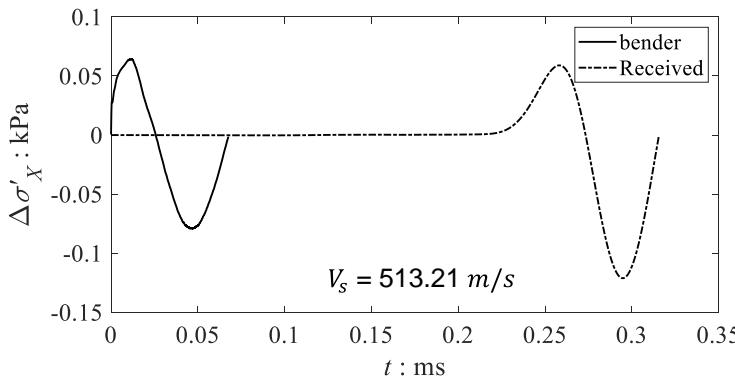
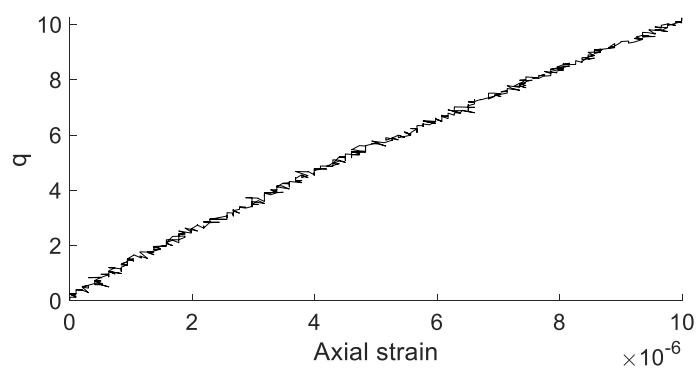
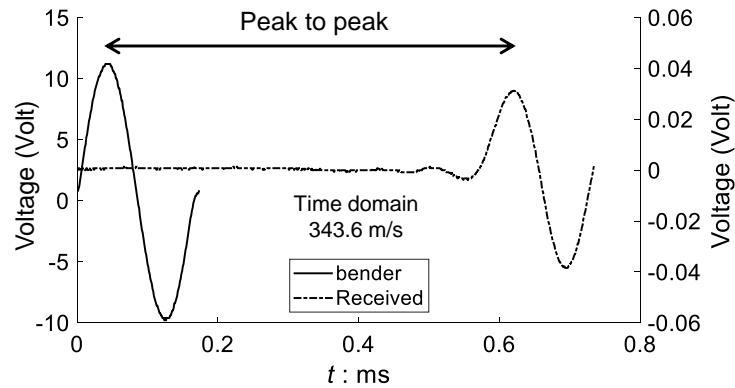


Bimodal, SR 8

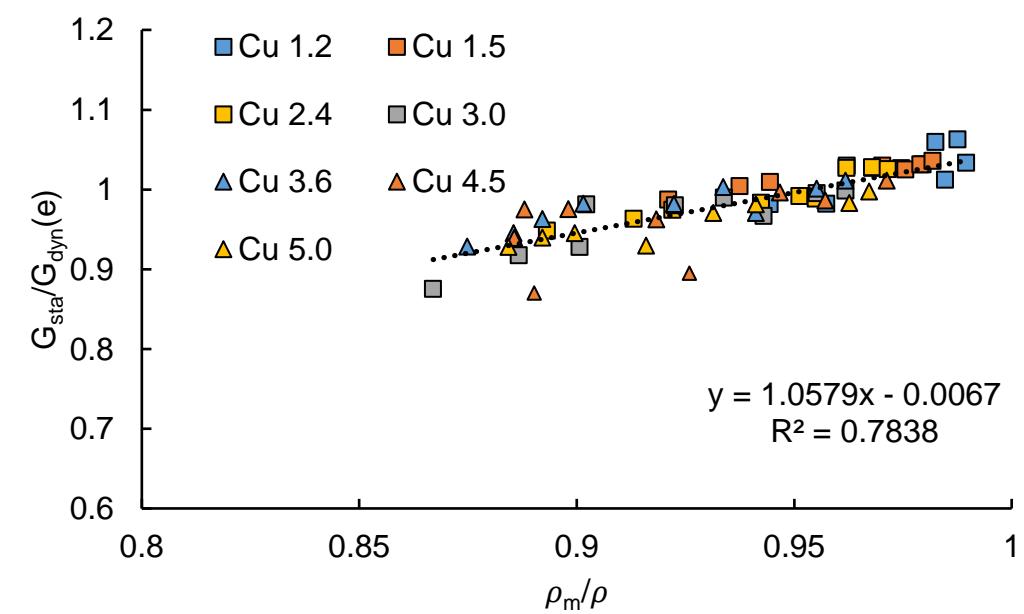
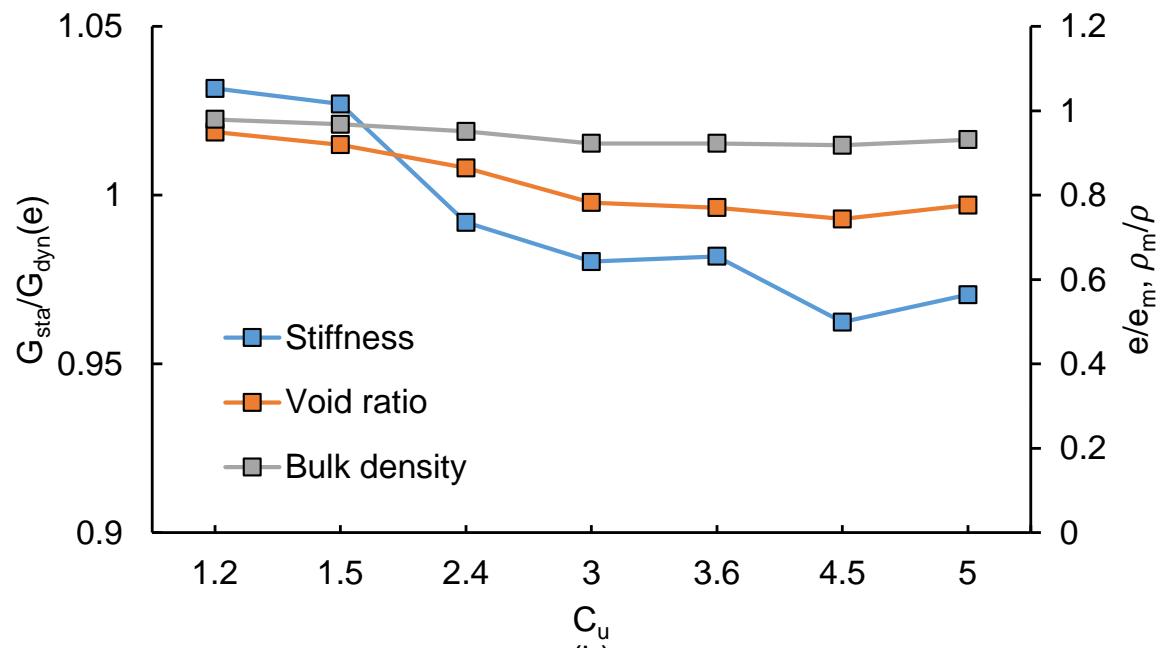
Approaches to measure stiffness

$$G_{sta} = \frac{\delta q}{3\delta\varepsilon_q^e}$$

$$\delta\varepsilon_q^e = 2(\delta\varepsilon_1 - \delta\varepsilon_3)/3$$

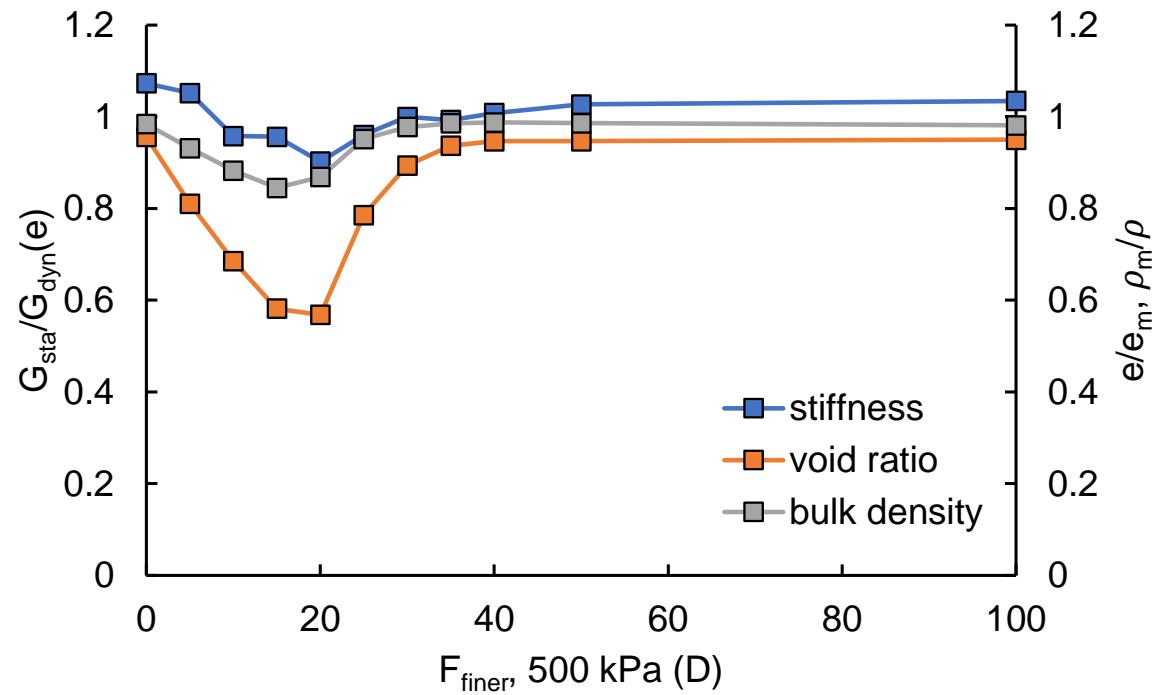


Density, mechanical density and G

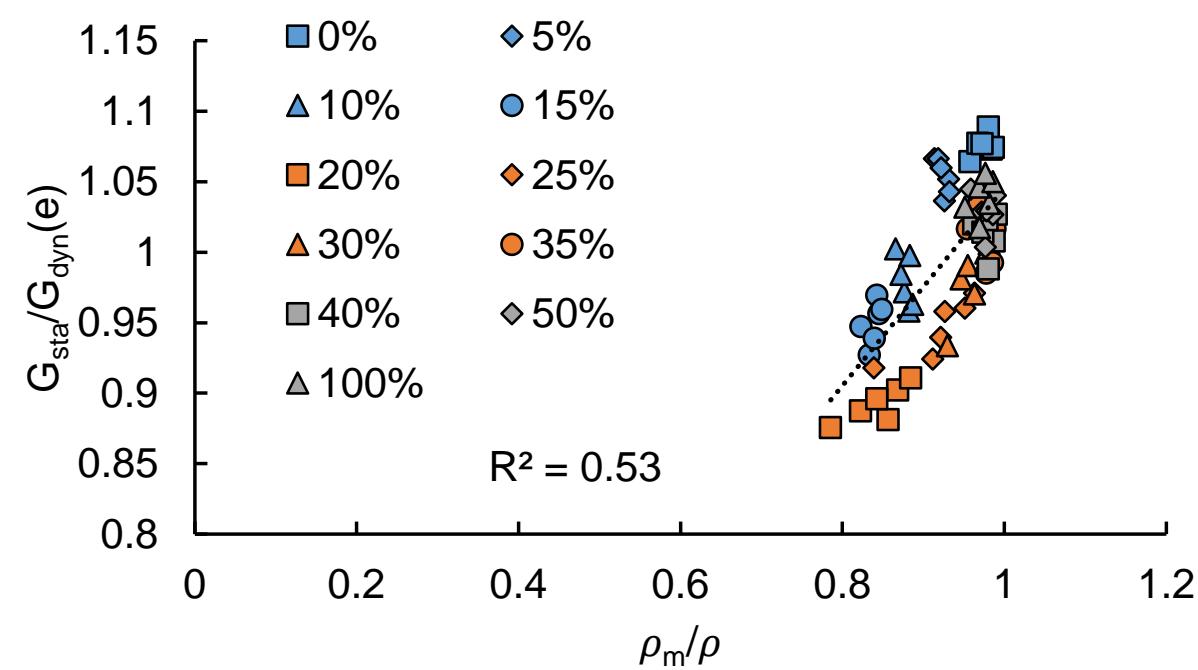


Medium-dense DEM specimens

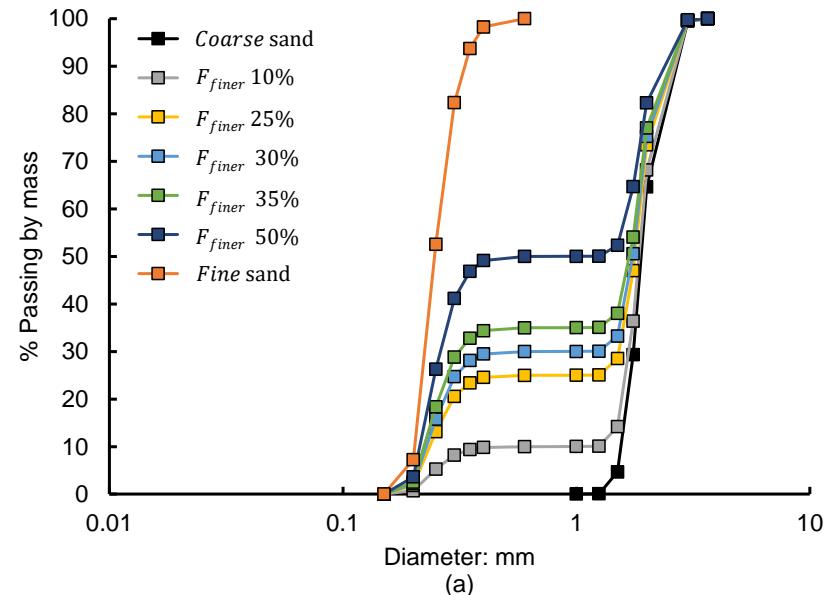
Density, mechanical density and G



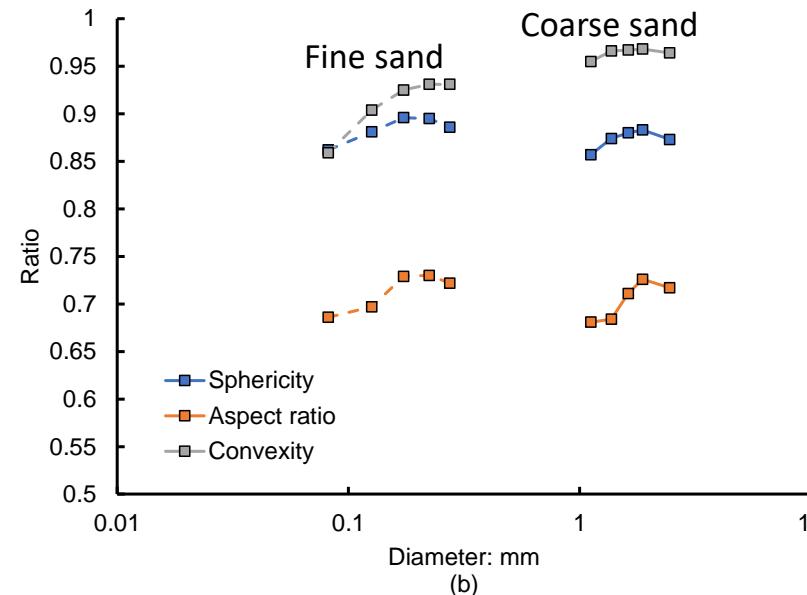
DEM sample: Dense SR=8, $p=500$ kPa



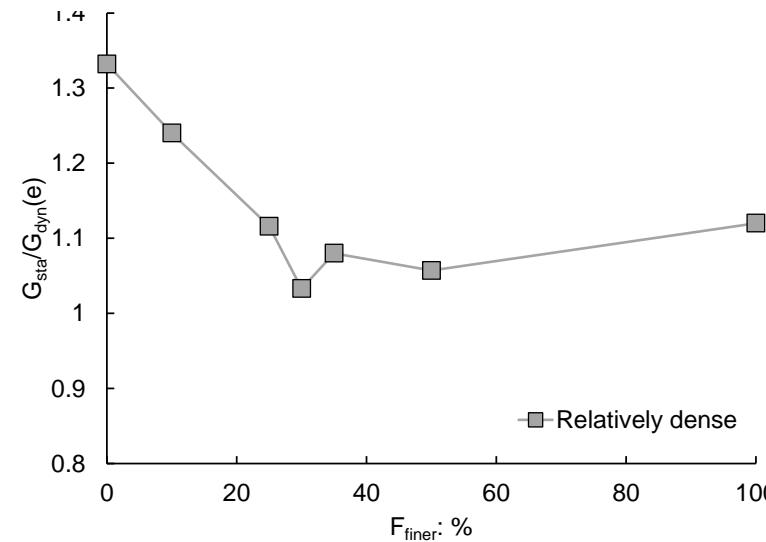
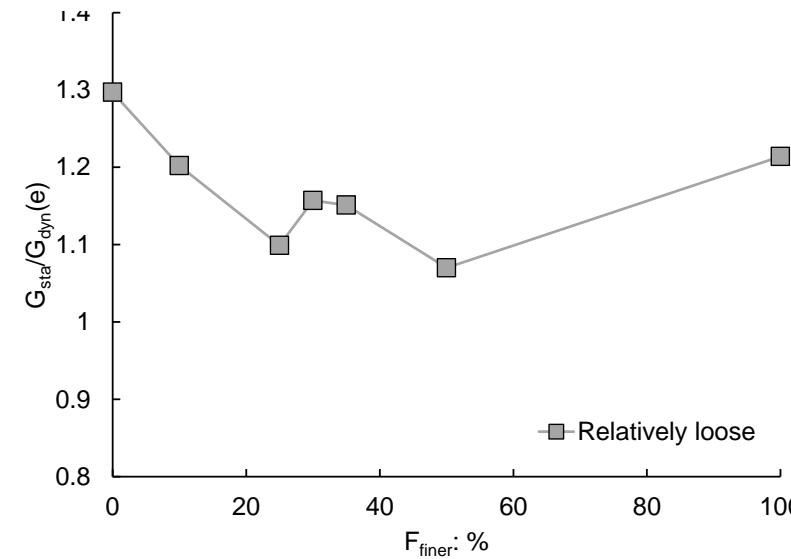
Density, mechanical density and G



(a)



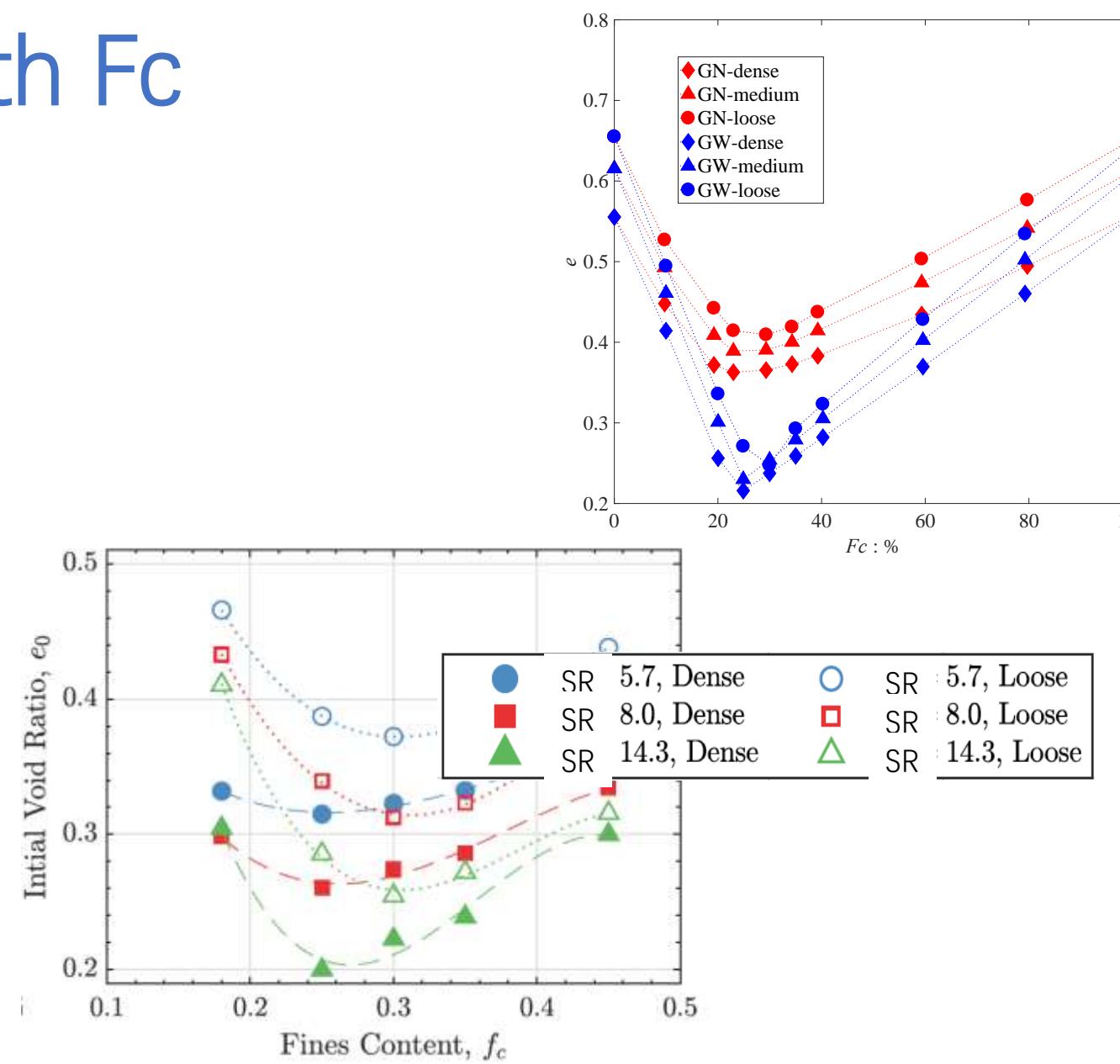
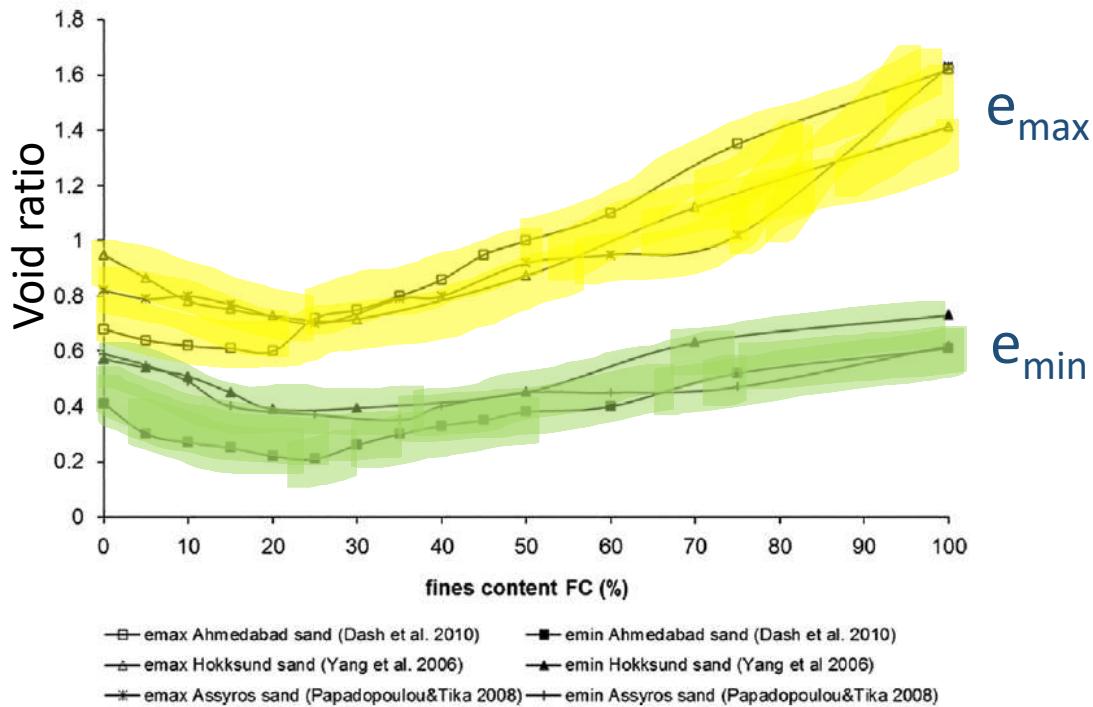
(b)



Experimental data on sand

Variation in void ratio with Fc

Collation of published experimental studies



Outline:

I want to present some examples that show that:

1. DEM simulations can help us design new testing approaches.
2. DEM simulations can inform how we can interpret element test data to infer fabric.
- 3. PIV opens the possibility for us to better understand how to use CFD to study flow in the pores of soil.**

Sheffield Permeameter Experiments

Solid and fluid with same refractive index

Fluorescent dye in fluid

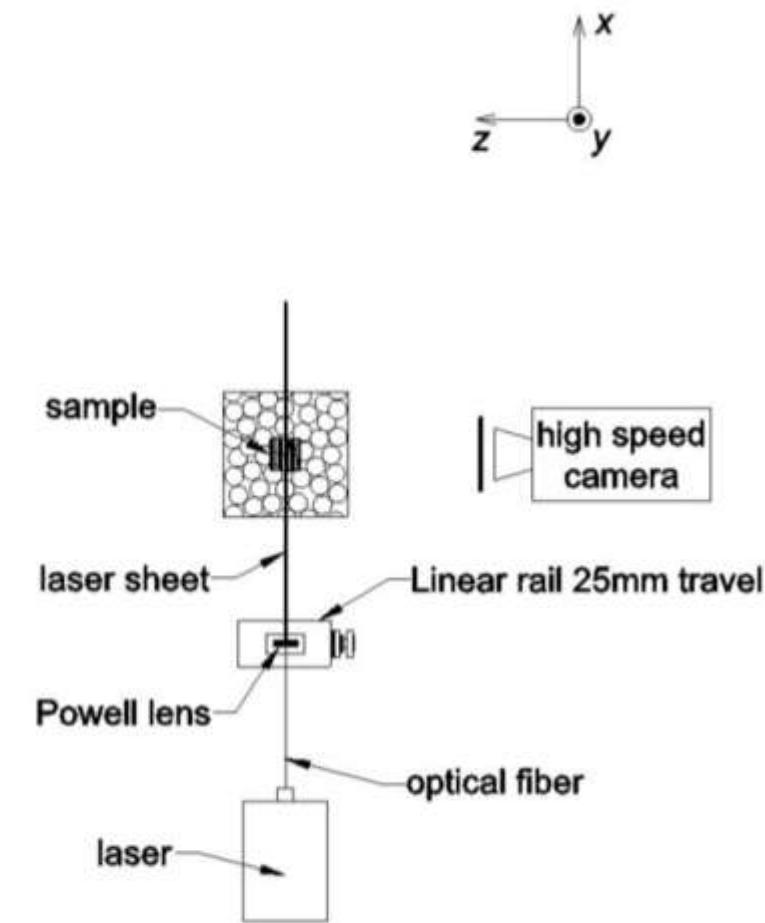
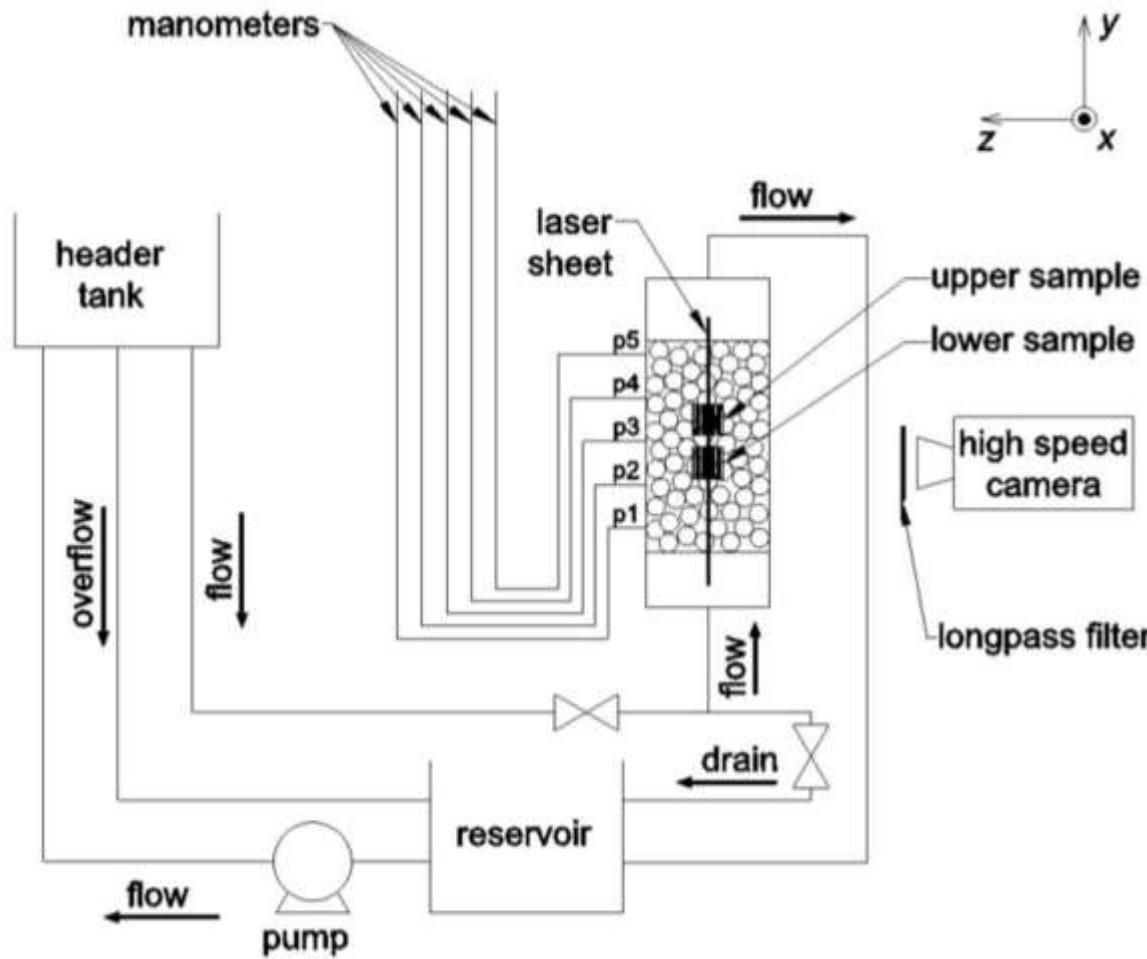
≈1 micron thick laser sheet illuminates plane

Particles dark against bright background



Model soil – crushed borosilicate

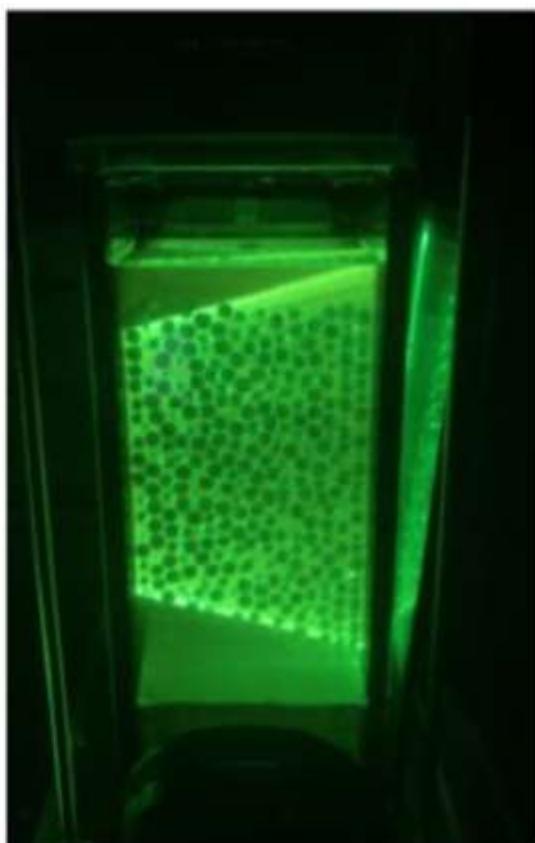
Sheffield Permeameter Experiments



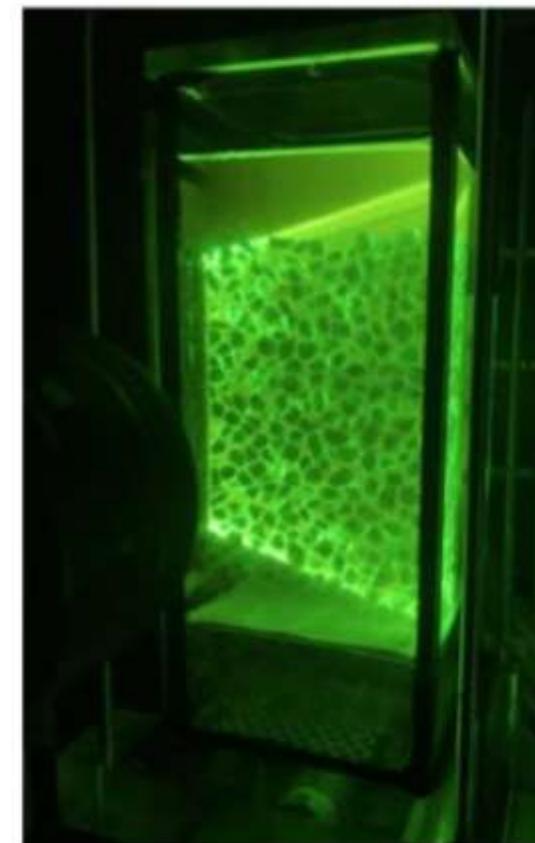
Sheffield Permeameter Experiments



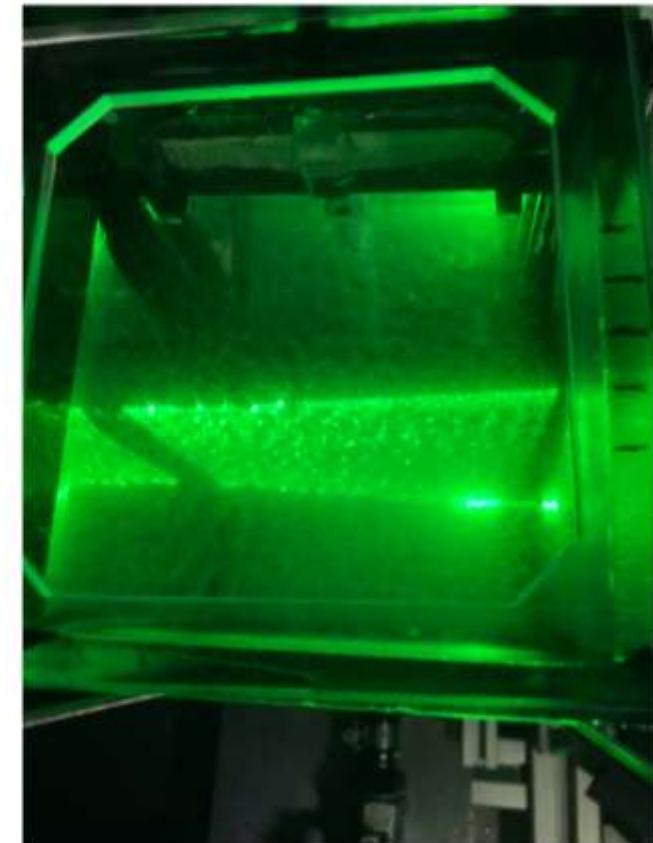
(a)



(b)



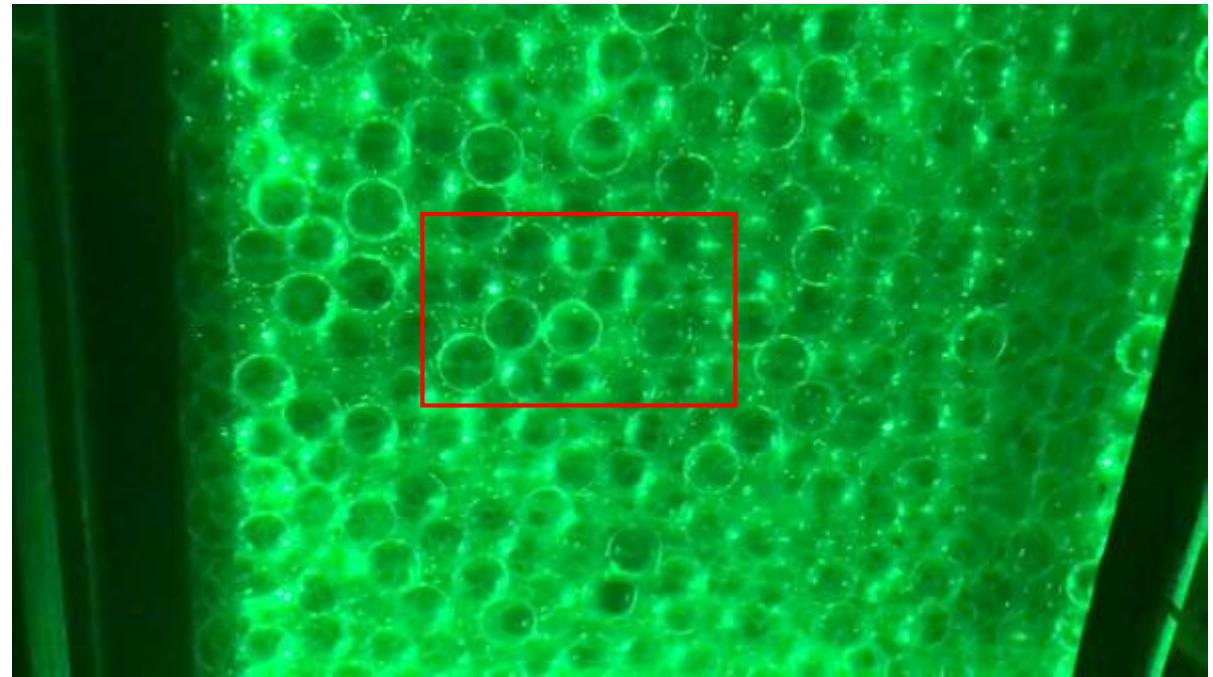
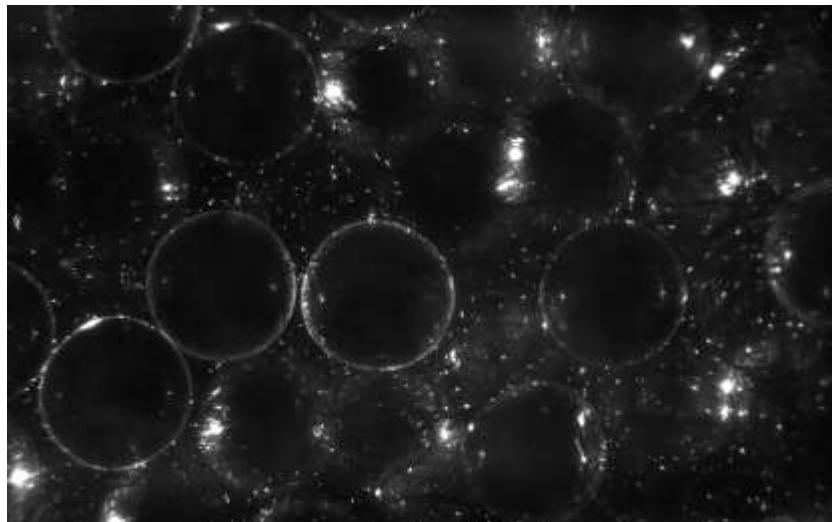
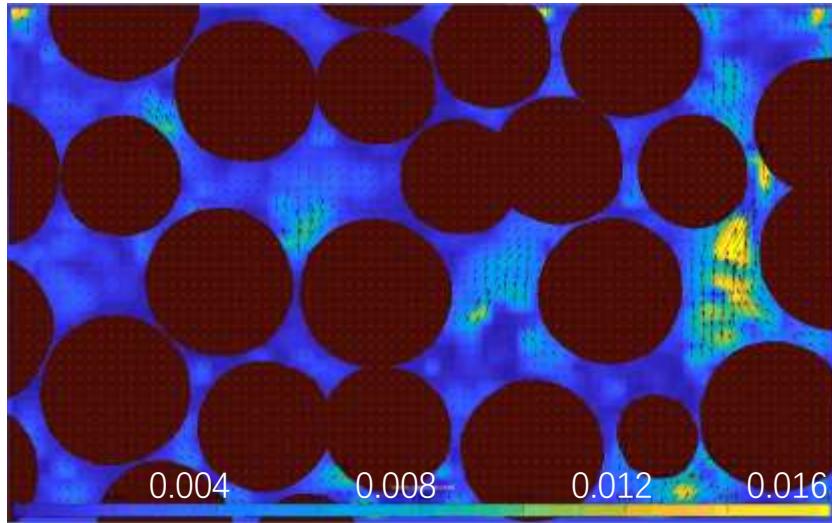
(c)



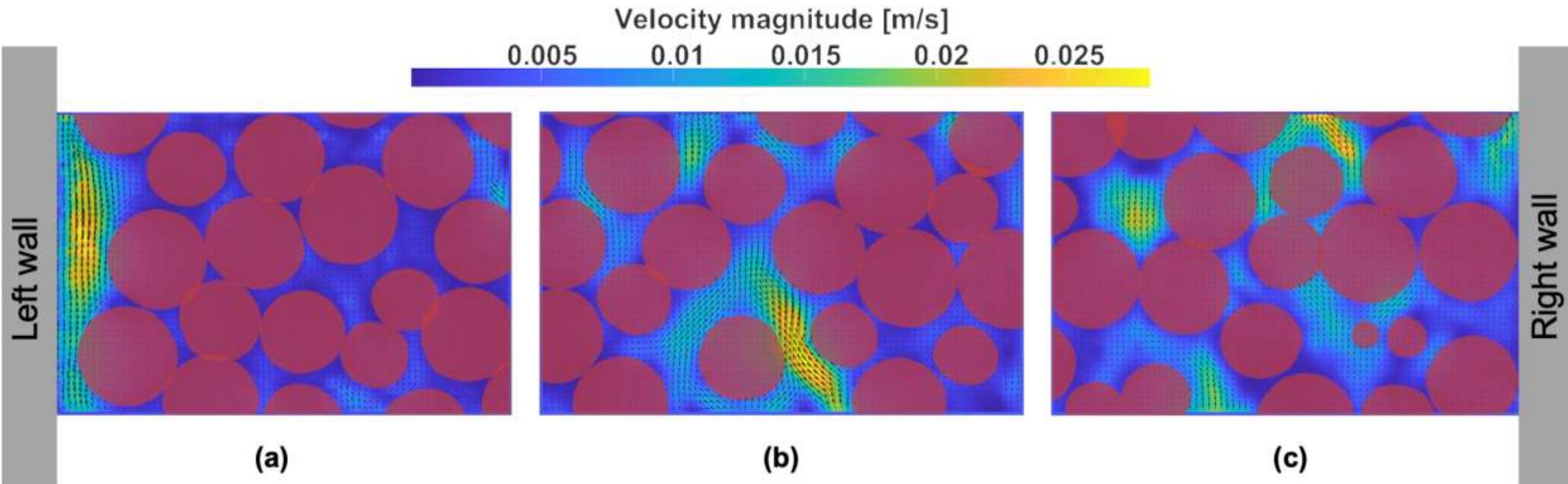
(d)

Sheffield Permeameter Experiments

Results: velocity magnitude (m/s), $d=7.5\text{mm}$, $i=0.028$

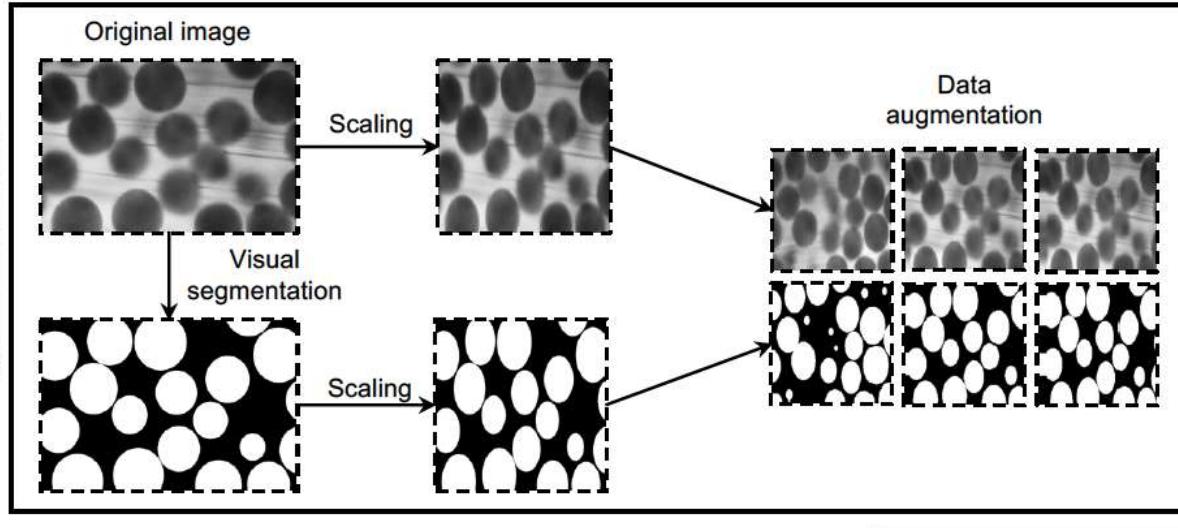


Sheffield Permeameter Experiments

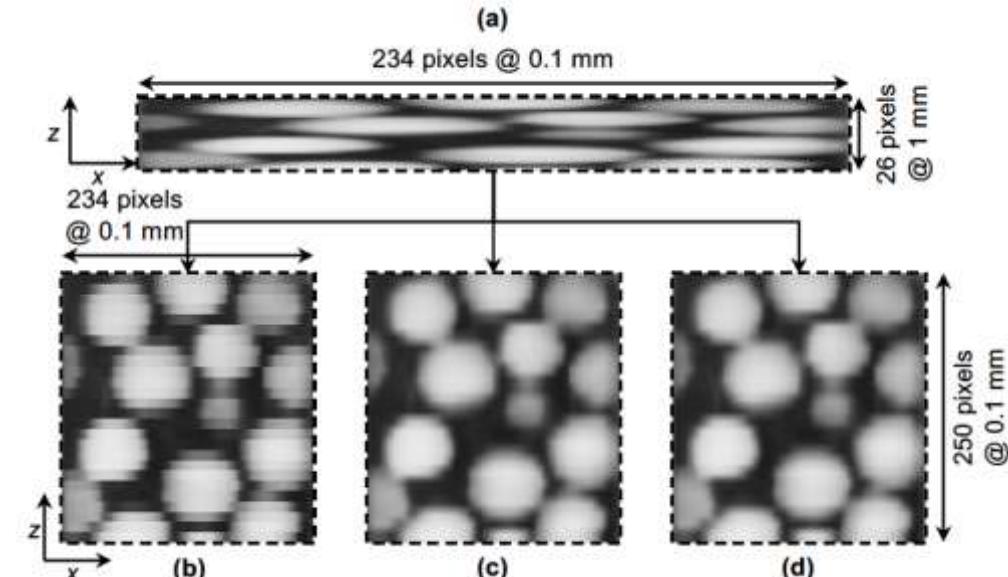


Sheffield Permeameter Experiments + CFD

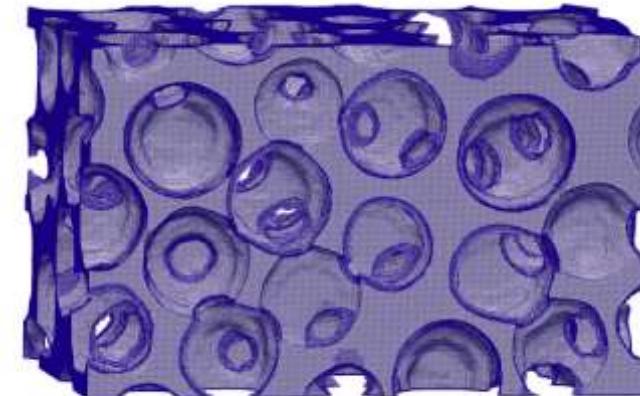
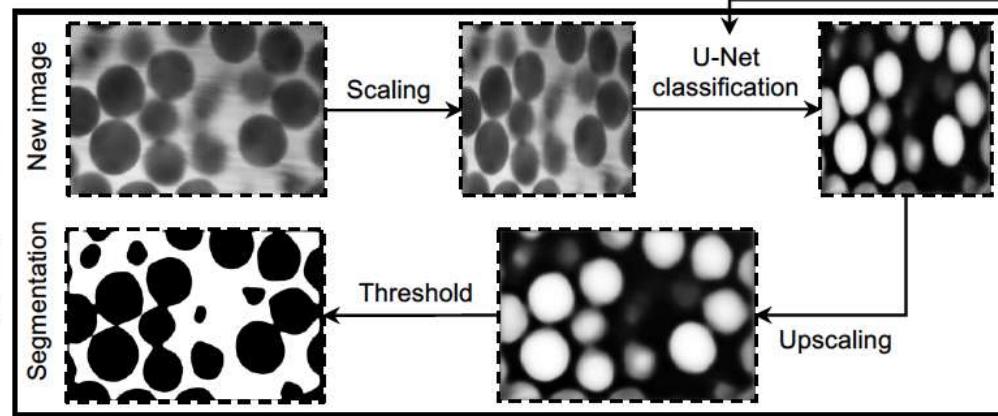
(a) Data preparation



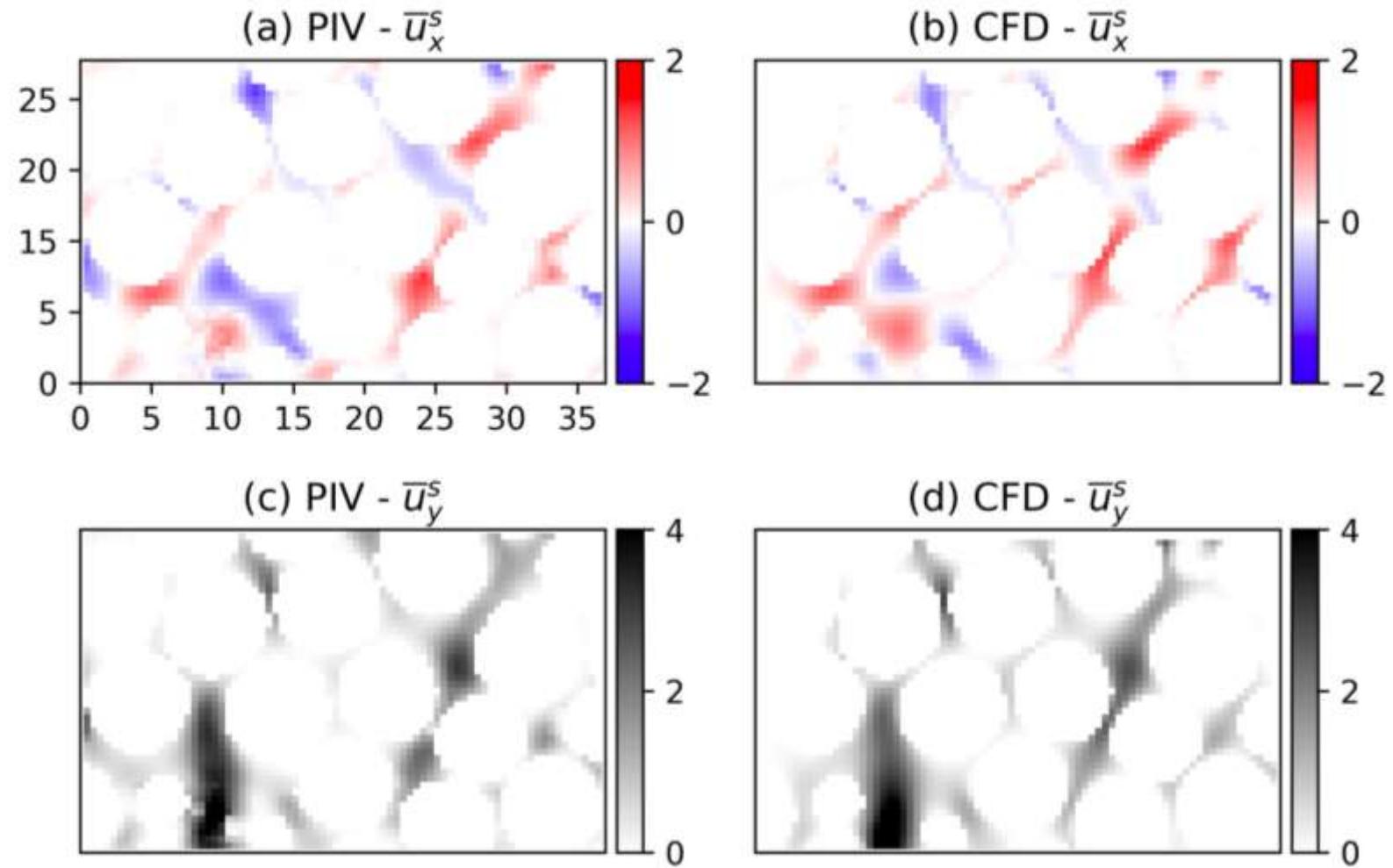
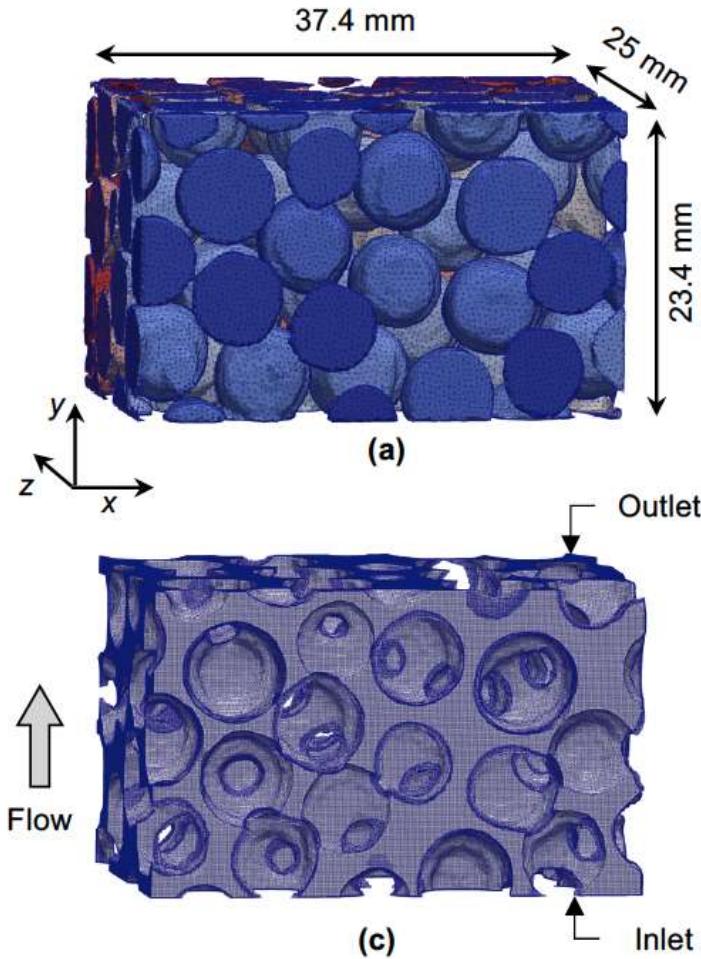
(b) U-Net training



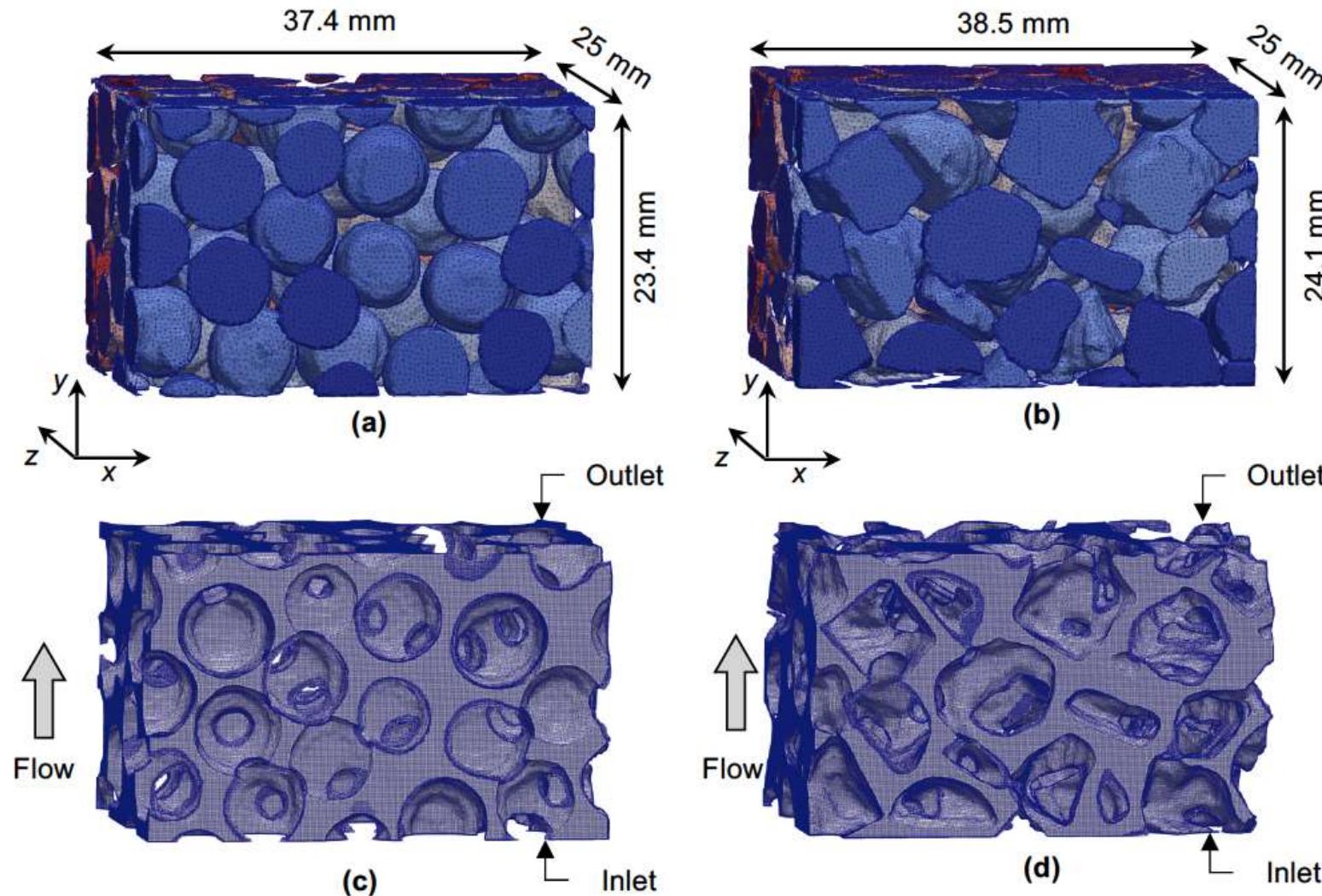
(c) Segmentation



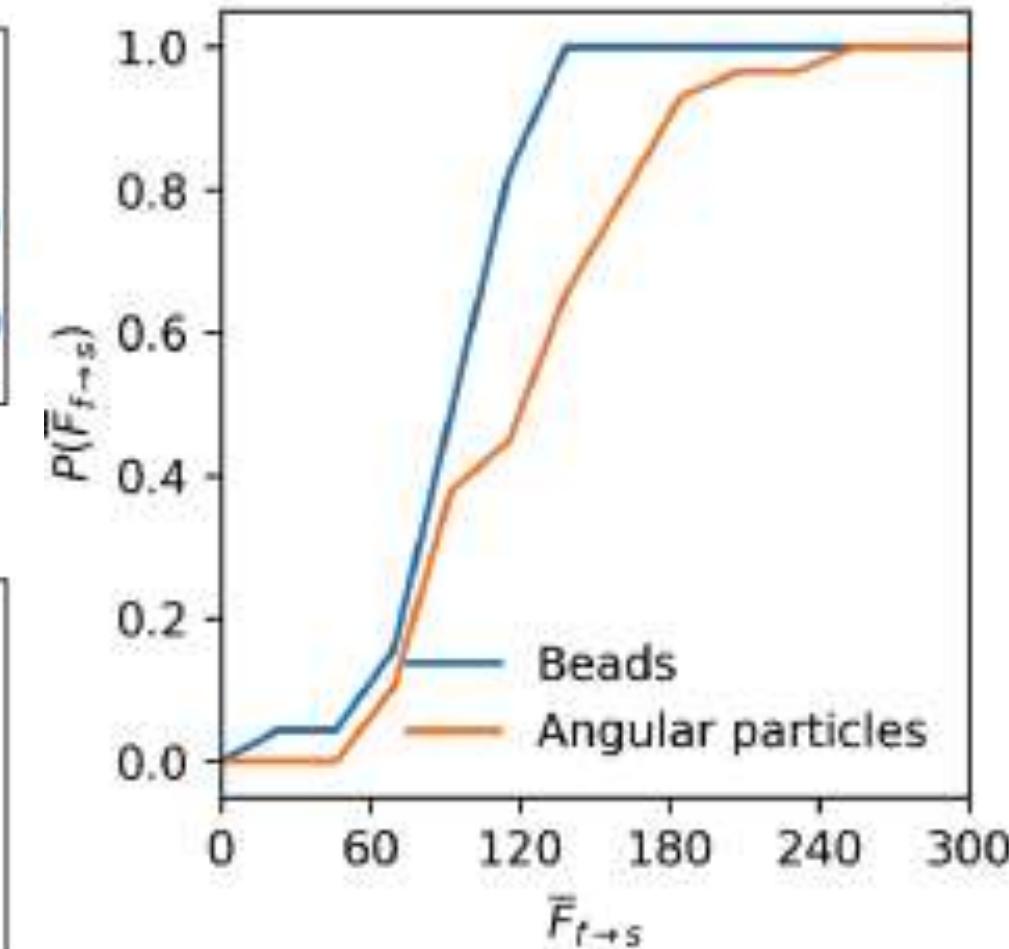
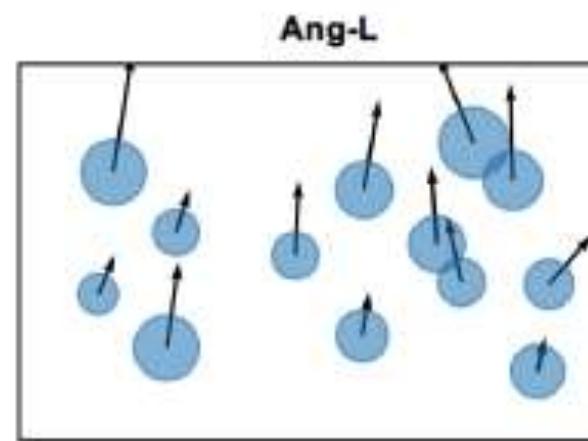
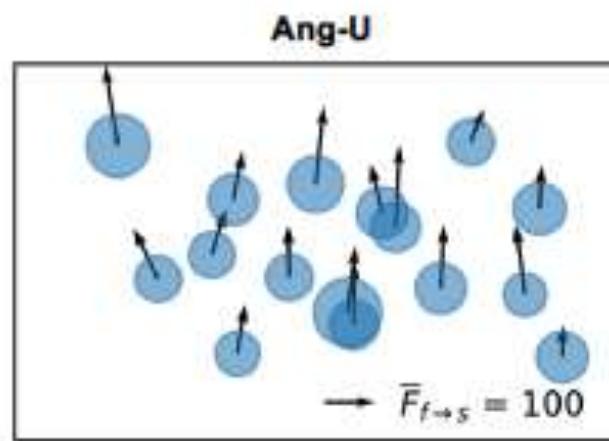
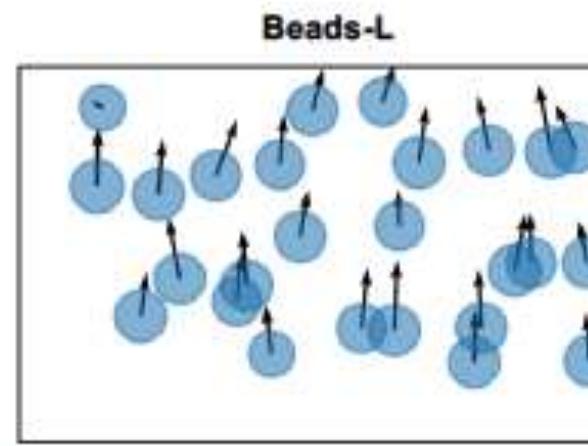
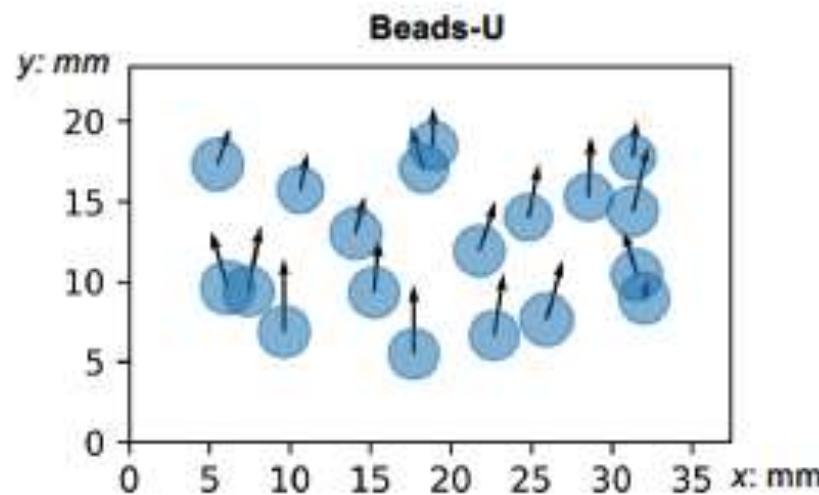
Sheffield Permeameter Experiments + CFD



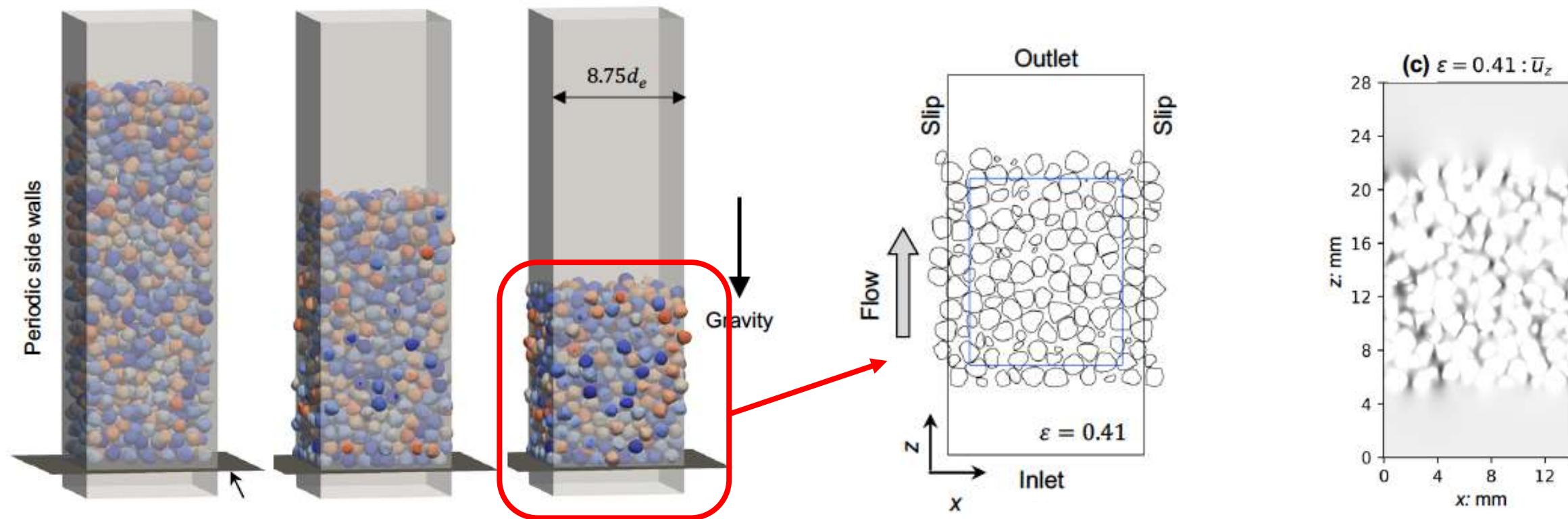
Sheffield Permeameter Experiments + CFD



Sheffield Permeameter Experiments + CFD

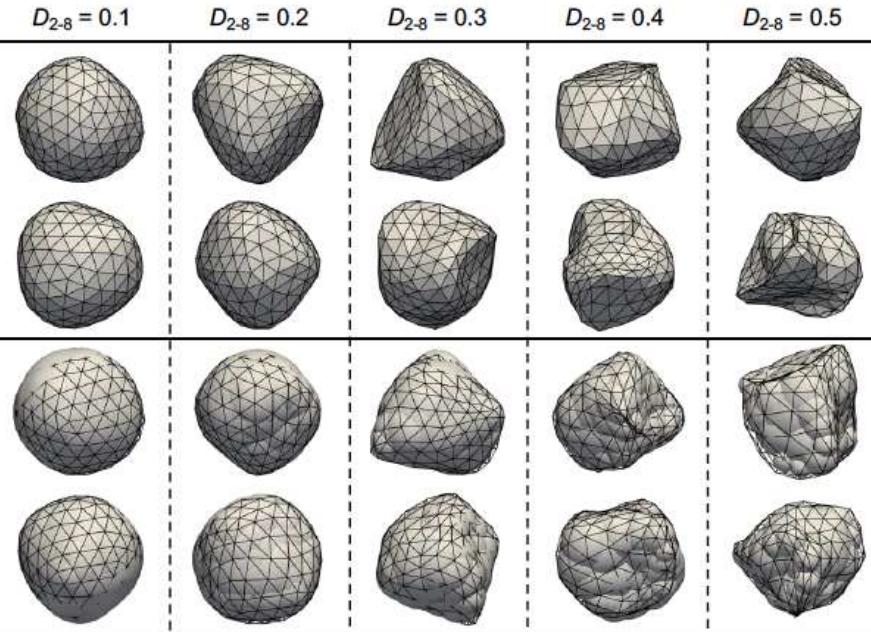


CFD to study fluid – particle interactions



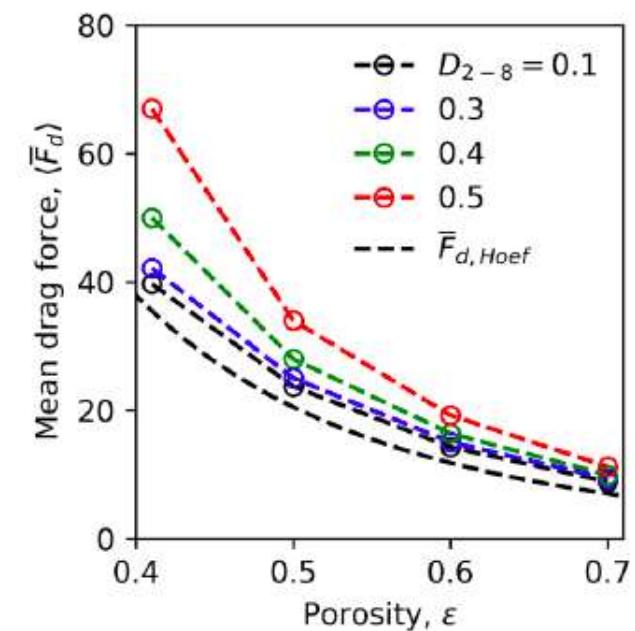
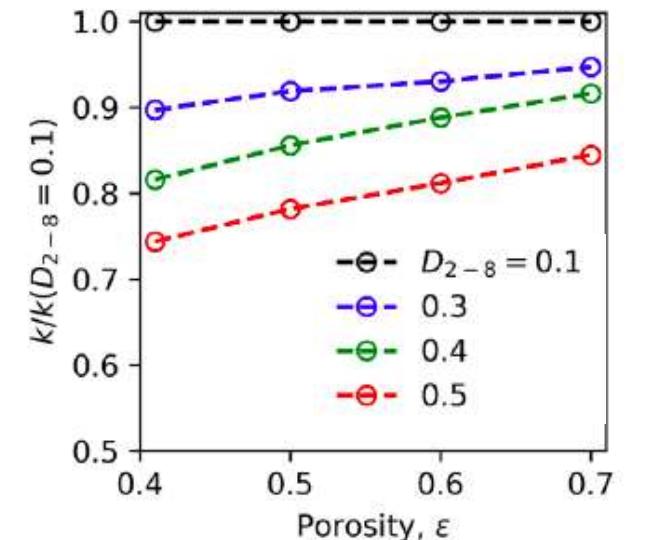
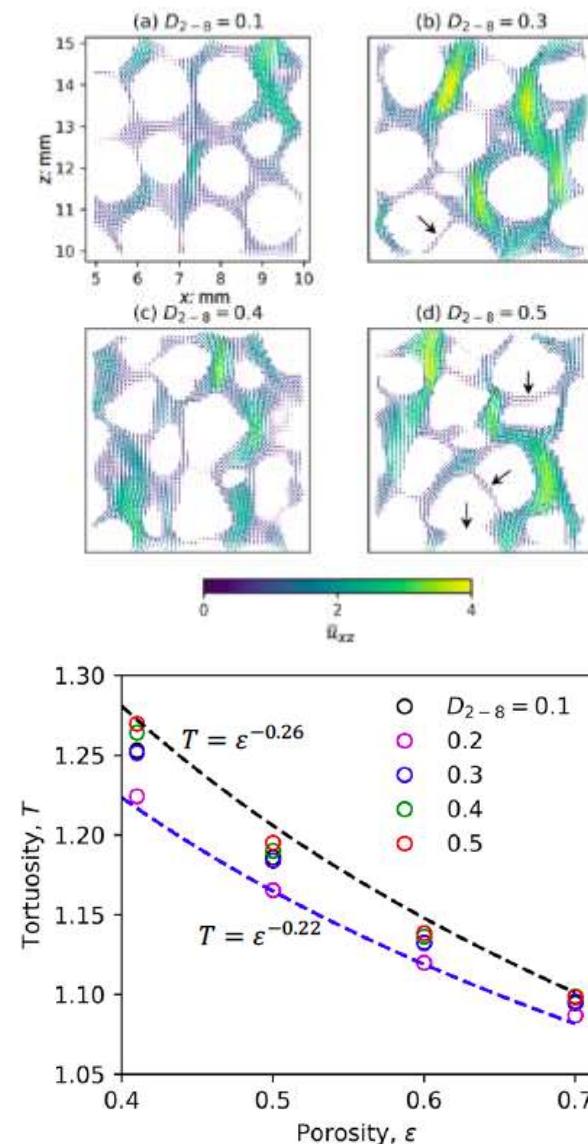
CFD to study fluid – particle interactions

Spherical harmonics to systematically control shape



Shape no significant effect on tortuosity or flow field

Shape does affect permeability and drag



Conclusions:

I hope I have shown that:

1. DEM simulations can help us design new testing approaches.
2. DEM simulations can inform how we can interpret element test data to infer fabric.
3. PIV opens the possibility for us to better understand how to use CFD to study flow in the pores of soil.

Acknowledgements



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