Imperial College London

DEM, dams and dikes

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DEM8 recognises dikes

The boy with his finger in the dike

Kinderdijk

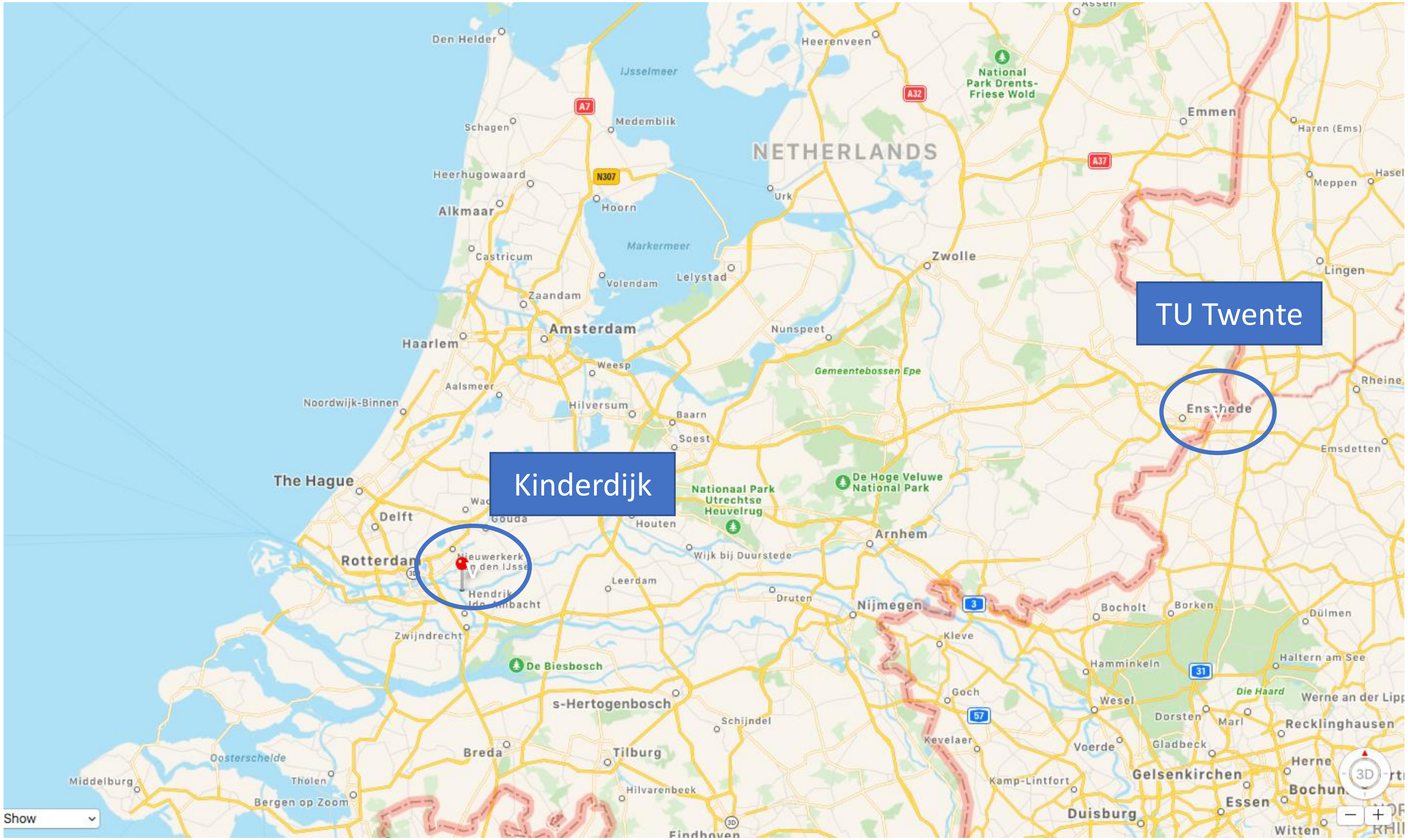
742 years old

To drain the polder, a system of 19 windmills was built around 1740

UNESCO world heritage site

https://www.kinderdijk.com/

Kinderdijk



Kinderdijk
TU Twente
NETHERLANDS
Den Helder
IJsselmeer
Heerenveen
National Park Drents-Friese Wold
Emmen
Haren (Ems)
Schagen
Medemblik
Heerhugowaard
Alkmaar
Hoorn
Urk
Meppen
Markermeer
Castricum
Volendam
Lelystad
Zwolle
Lingen
Zaandam
Amsterdam
Haarlem
Nunspeet
Weesp
Gemeentebossen Epe
Aalsmeer
Rheine
Noordwijk-Binnen
Hilversum
Baarn
Enschede
Soest
Emsdetten
The Hague
Nationaal Park Utrechtse Heuvelrug
De Hoge Veluwe National Park
Delft
Gouda
Houten
Arnhem
Rotterdam
Wijk bij Duurstede
Leerdam
Druten
Nijmegen
Bocholt
Borken
Dülmen
Zwijndrecht
Kleve
Hamminkeln
Haltern am See
De Biesbosch
Die Haard
Wesel
Goch
Dorsten
Marl
s-Hertogenbosch
Schijndel
Recklinghausen
Voerde
Gladbeck
Kevelaer
Breda
Tilburg
Oosterschelde
Herne
Gelsenkirchen
Middelburg
Tholen
Kamp-Lintfort
Bergen op Zoom
Hilvarenbeek
Essen
Duisburg
Witten
Show
3D

Dutch Dikes

Total land area Netherlands: 41,528 km²

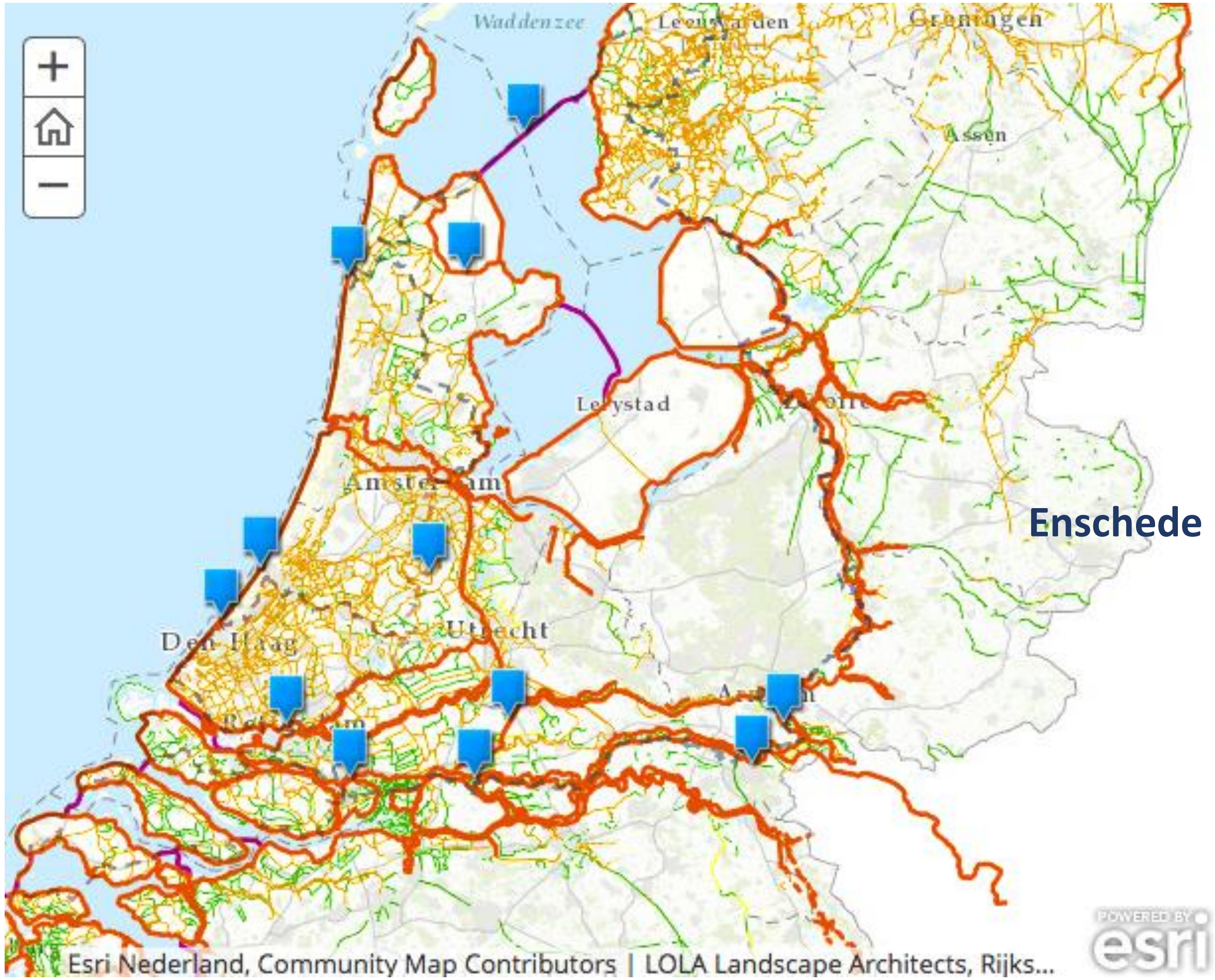
26% below mean sea level (NAP)

66% of the area is flood prone

9 million people live in these low areas

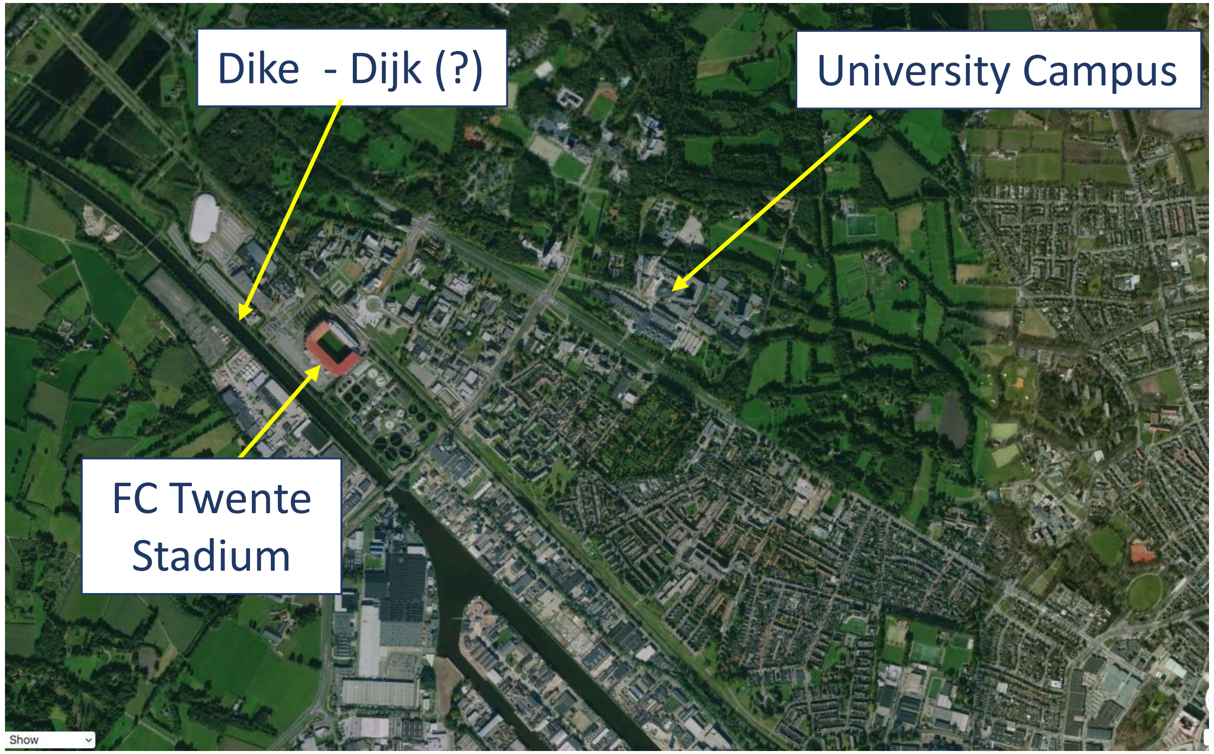
70% of GNP is earned in flood-vulnerable area

The Dutch dike network extends for over 22,000 kilometres



http://dutchdikes.net/dike-map/

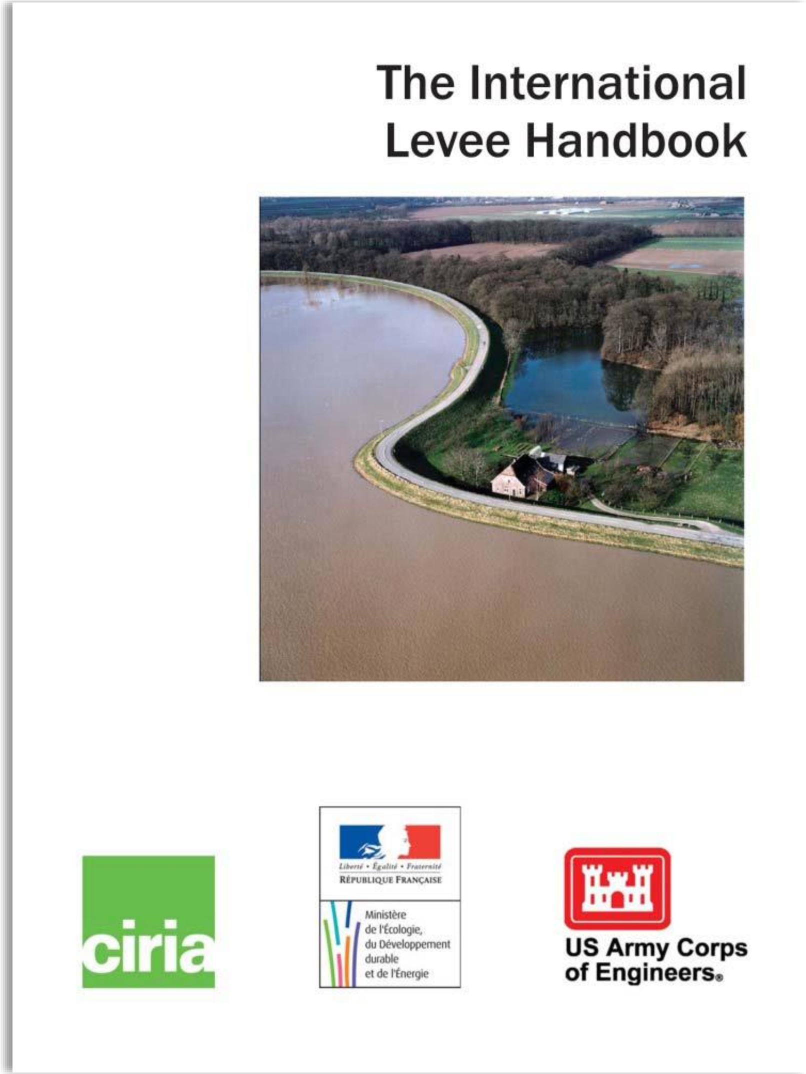
Dikes near here



Strengthening of Twente Canal (Twentekanaal)

https://www.destentor.nl/zutphen/ingenieuze-techniek-moet-dijkverzakking-twentekanaa
bij-zutphen-voorkomen-br-br~ab84c24e/?referrer=https://www.google.com/

The International Levee Handbook - 2013



- Joint research project of CIRIA (UK), French Ministry for Ecology and US Army Corps of Engineers
- Funding from France, UK, USA, Ireland and the Netherlands

International perspective: US

30,000 documented miles of levee in the US

Breach in 17th Street Canal levee in New Orleans, Louisiana, on August 31, 2005

American River Levees California

http://www.watereducation.org/tour/bay-delta-tour-2018-0

International perspective: United Kingdom

UK Environment Agency responsible for 9,000 km of flood embankment

The RAF dropped 270 tonnes of ballast to fill a breach in the river bank


The RAF dropped 340 tonnes of ballast

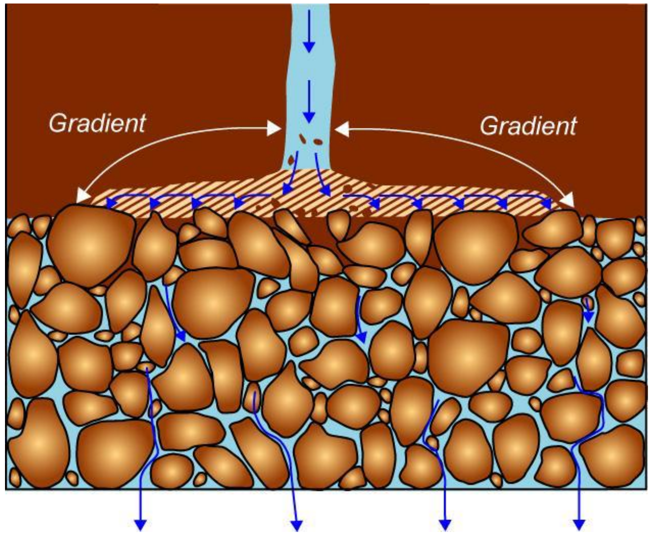
Engineers are now working on a more permanent solution to the breach in the River Steeping

580 homes in the Wainfleet area were evacuated after the River Steeping burst its banks this June

https://www.bbc.co.uk/news/uk-england-lincolnshire-48646801
https://www.bbc.co.uk/news/uk-england-lincolnshire-48707396

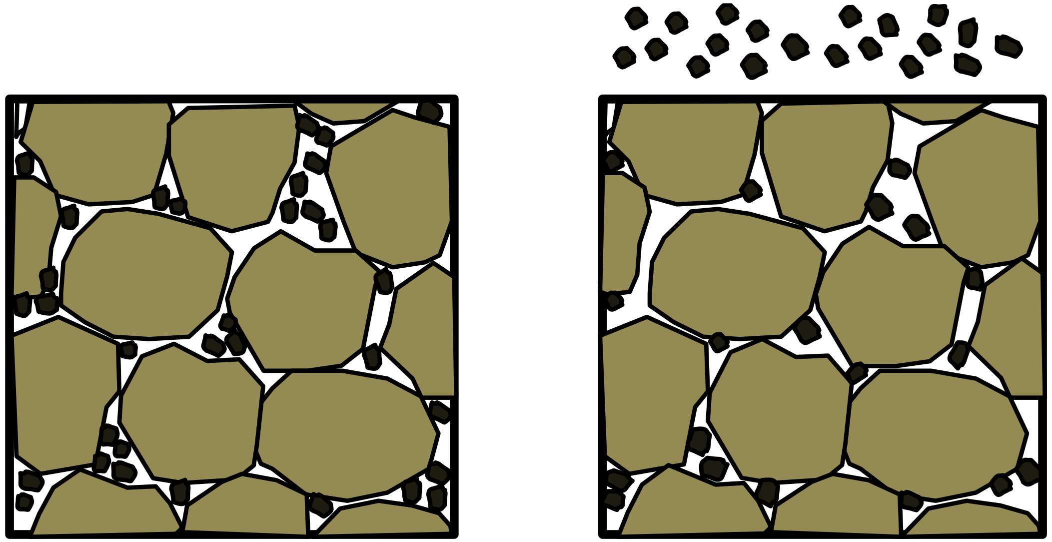
Design issues requiring a particulate perspective

1. Base – filter compatibility



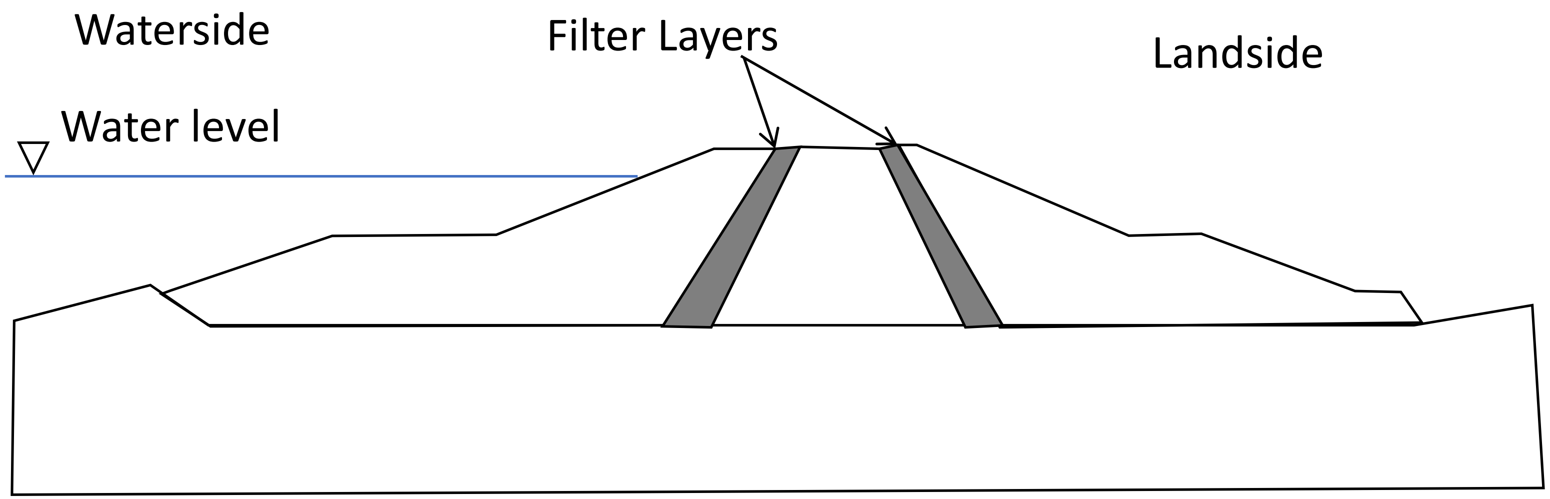
(FEMA, 2011)

2. Internal instability / suffusion

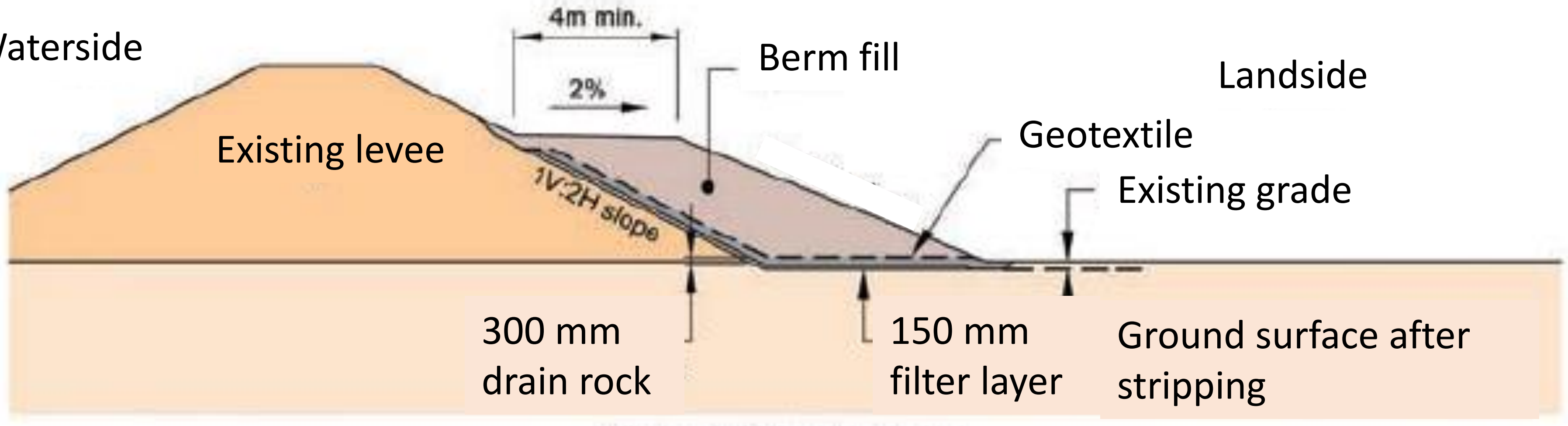


After Slangen and Fannin

Filters: Dikes



Engineered levee

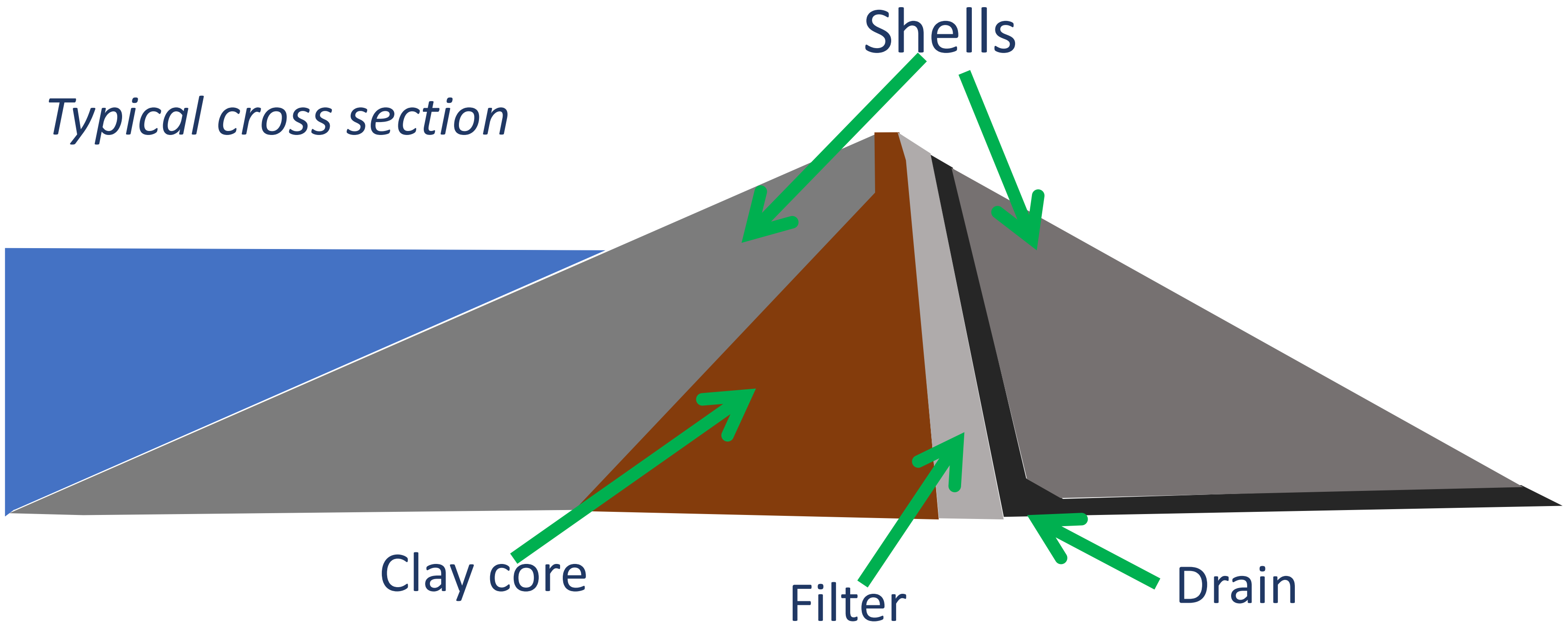


Drained Stability Berm

Retrofit of existing levee

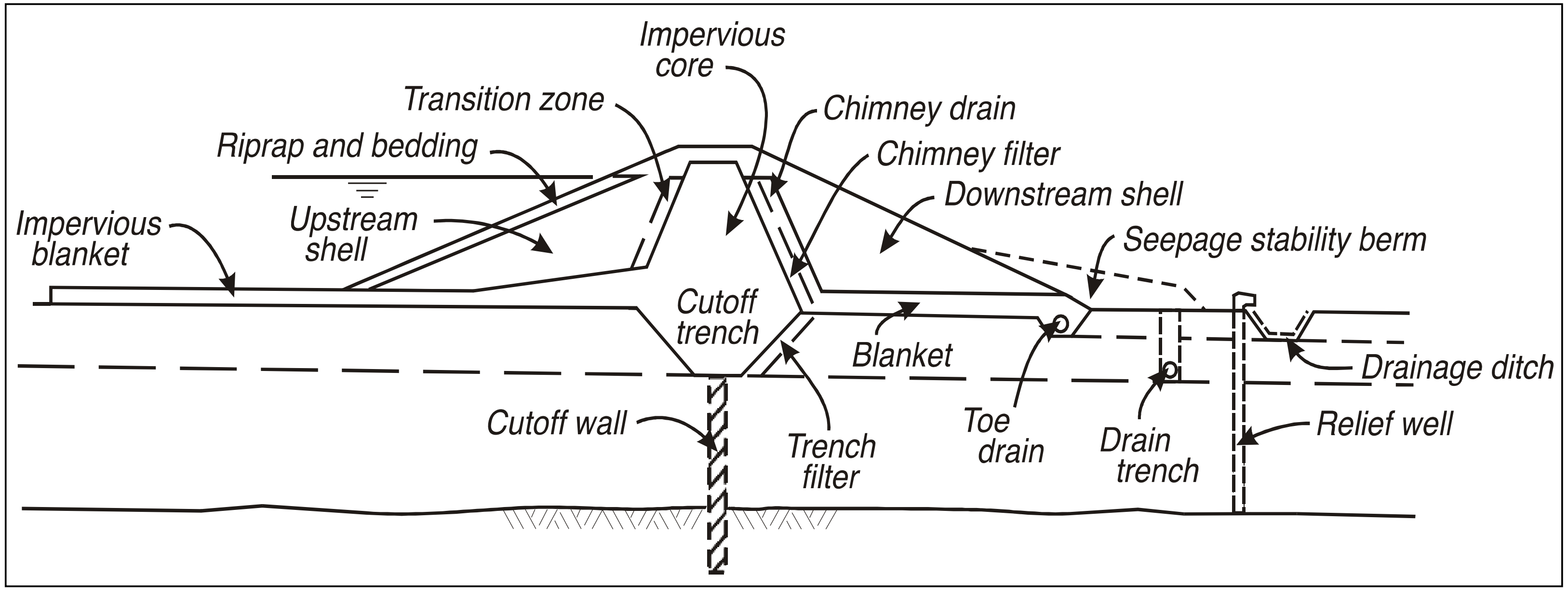
(International Levee Handbook, 2013)

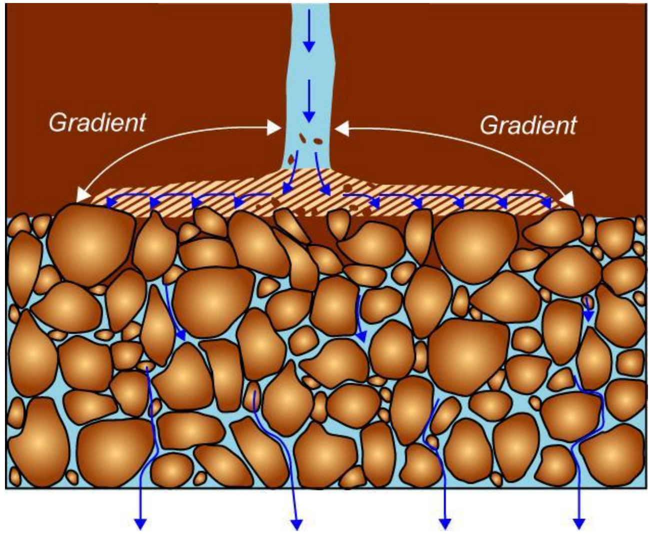
Filters: Embankment dams



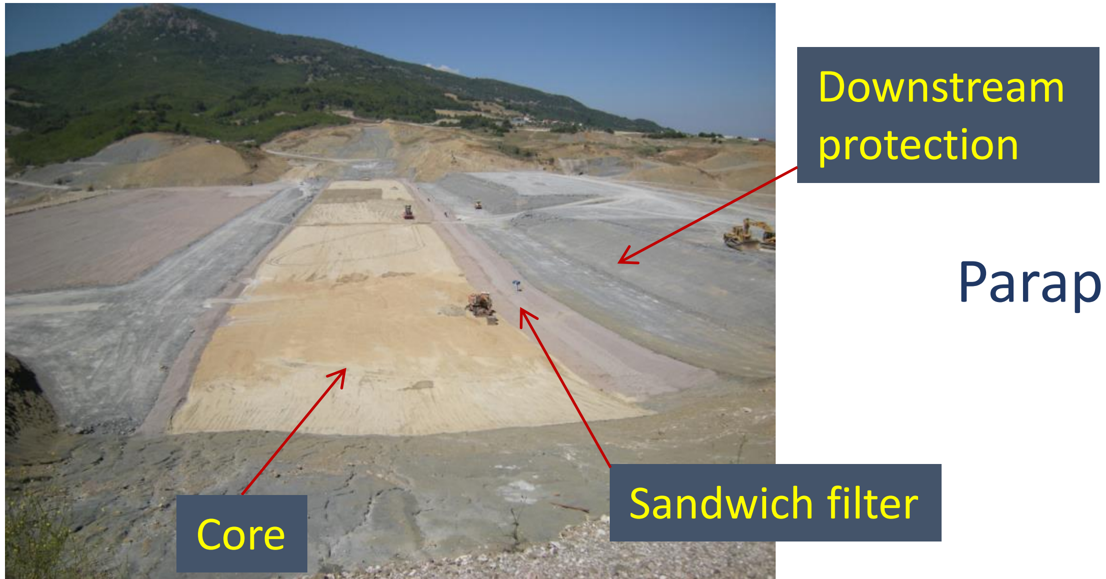
- Dams can be over 100 m high
- Water seeps through dam continuously
- Seeping water can preferentially erode fines
- In the UK about 2,500 dams retain reservoirs exceeding 25,000 m^3
- In the US there are about 90,580 dams

Filters: Embankment dams





(FEMA, 2011)



Paraperios dam - May 26 2010

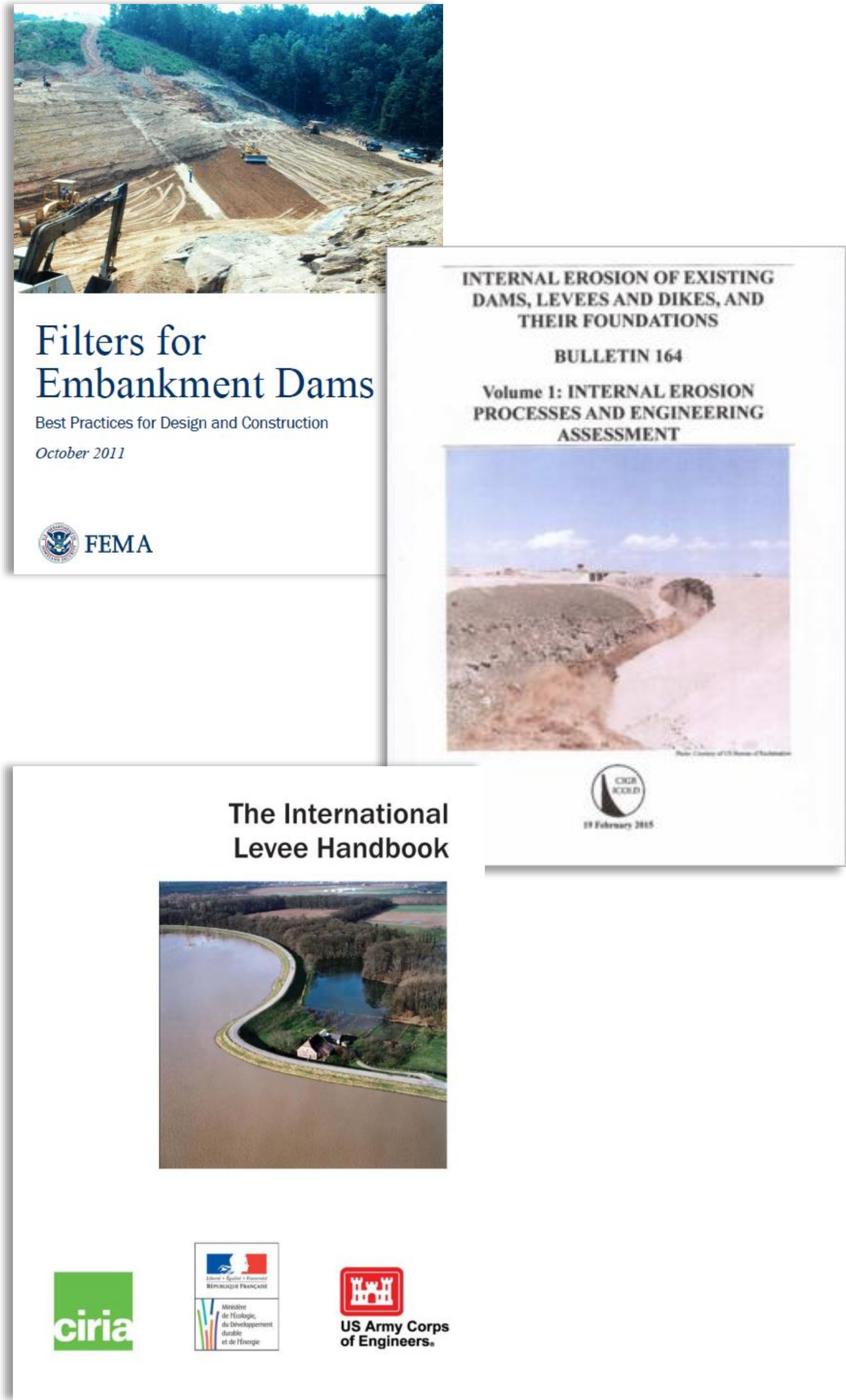
Role of filters

Filters are designed and constructed to achieve specific goals such as preventing internal soil movement and controlling drainage (FEMA, 2011)

Five filter functions govern the capability of providing control for internal erosion.

1. Retention.
2. Self Filtration or stability.
3. No cohesion
4. Drainage.
5. Strength. ICOLD (2015)

Filter layers help to promote filtration, by preventing soil from migrating especially from the impervious core. (International Levee Handbook, 2013)



Role of filters

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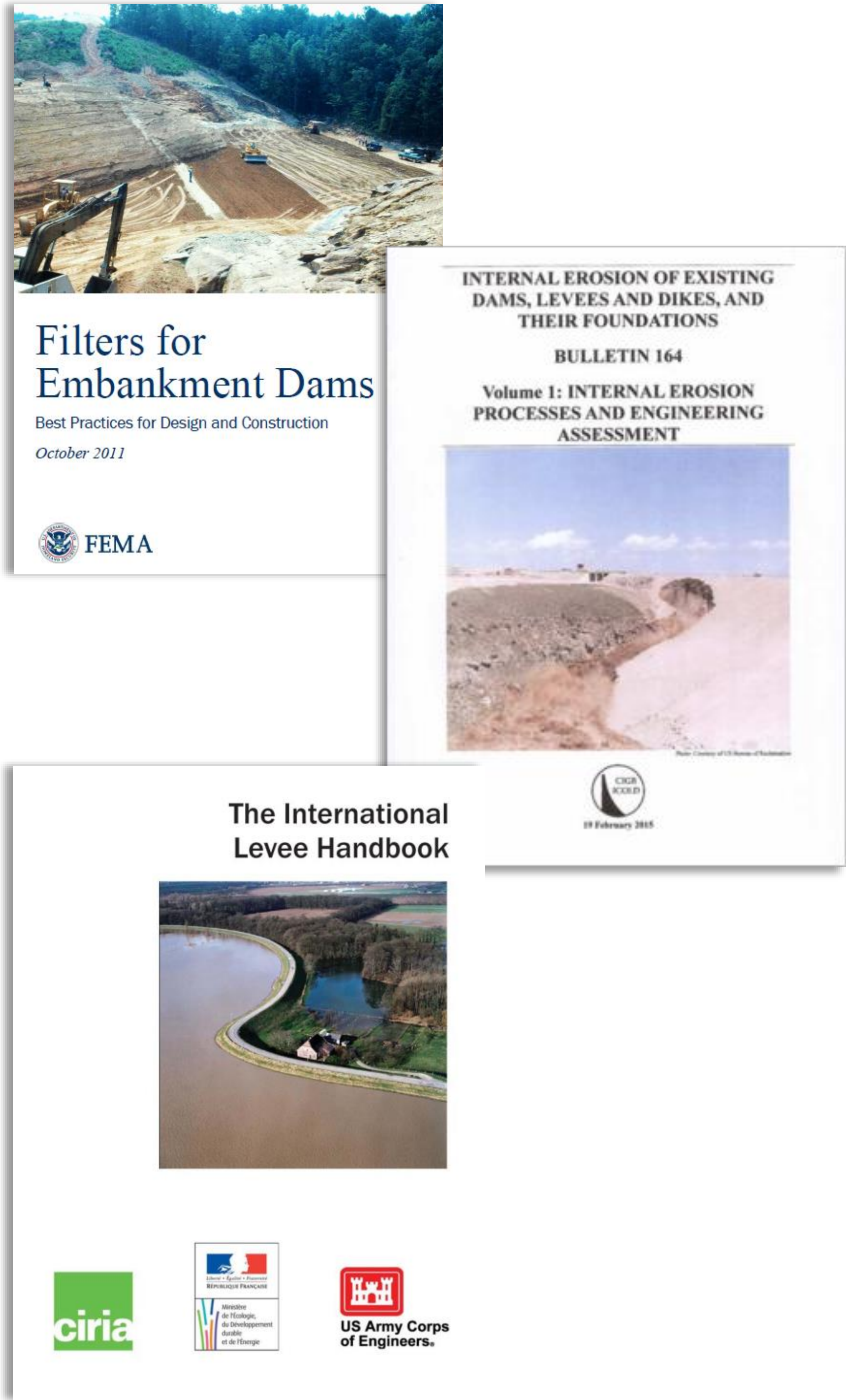
Five filter functions govern the capability of providing control for internal erosion.

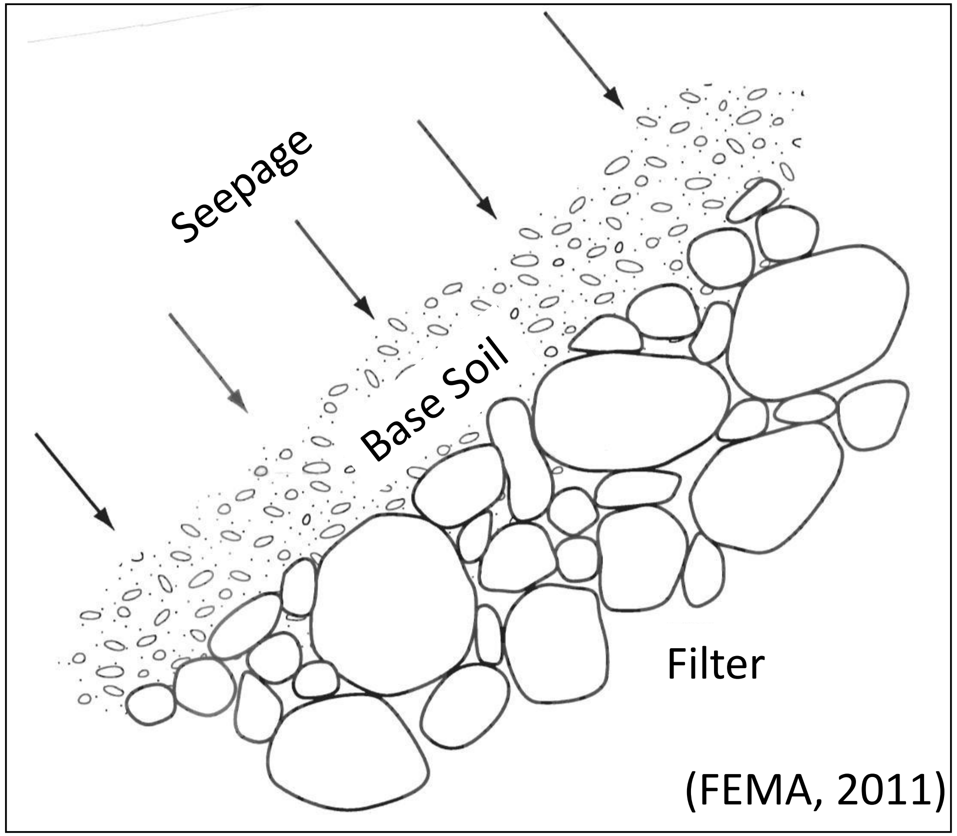
1. Retention.
2. Self Filtration or stability.
3. No cohesion
4. Drainage *(permeability).*
5. Strength.   ICOLD (2015)

Filter layers help to promote filtration, by preventing soil from migrating especially from the impervious core. (International Levee Handbook, 2013)



Retention

The voids in the filter should be sufficiently small to prevent erosion of the base soil (ICOLD,2015)

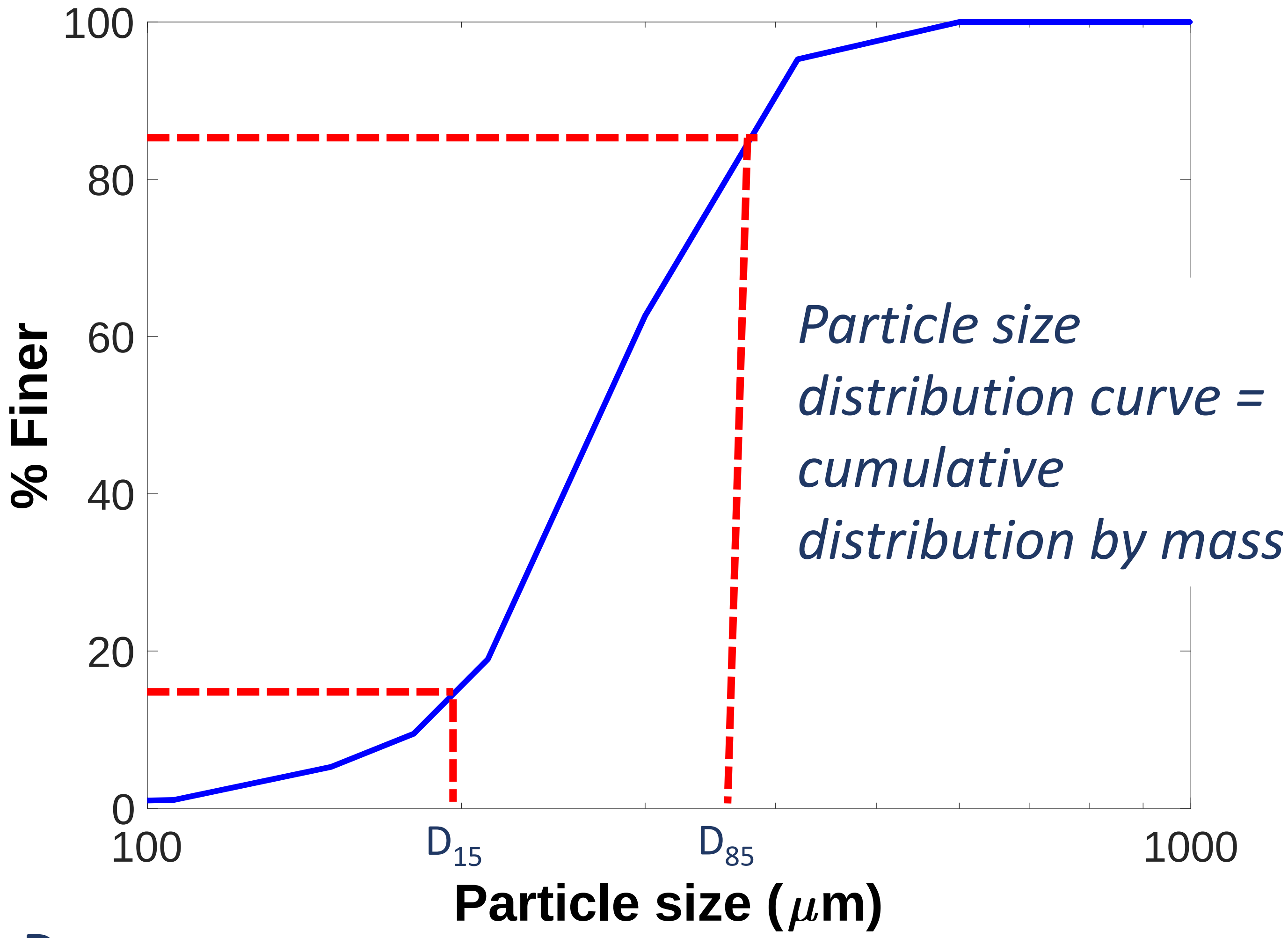


Empirical rules used in design:

- Consider particle size distribution
- Terzaghi's filter rule / Sherard & Dunnigan (1989)
  - D_{15F} of filter
  - D_{85B} of base
  - For retention $D_{15F} < 4\ D_{85B}$
- Controlling constriction size – largest particle that can pass through filter

(ICOLD,2015)

Filter particle size distribution



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

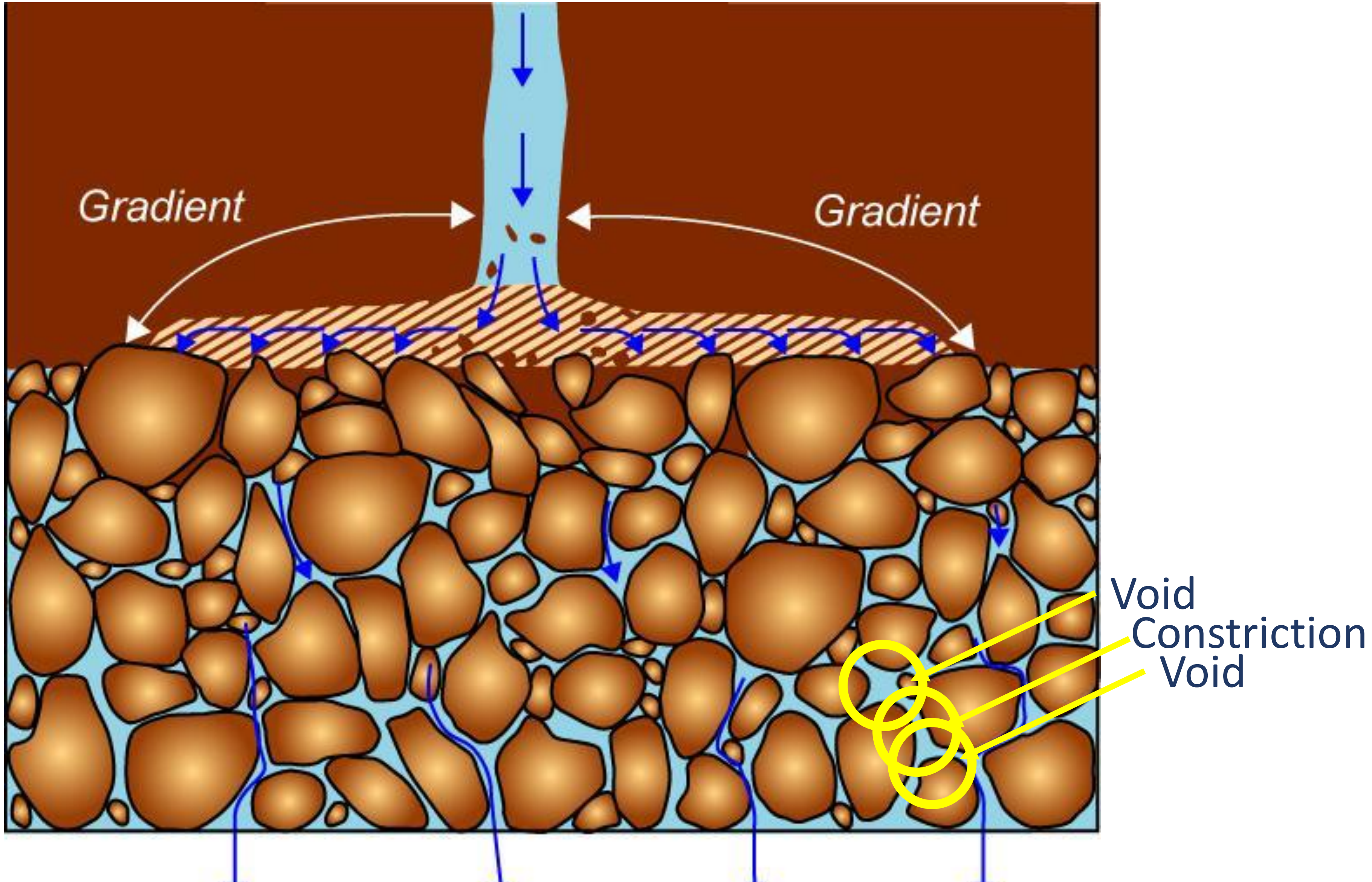
85% of particles by mass are smaller than D_{85}

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

Research questions: Filter retention

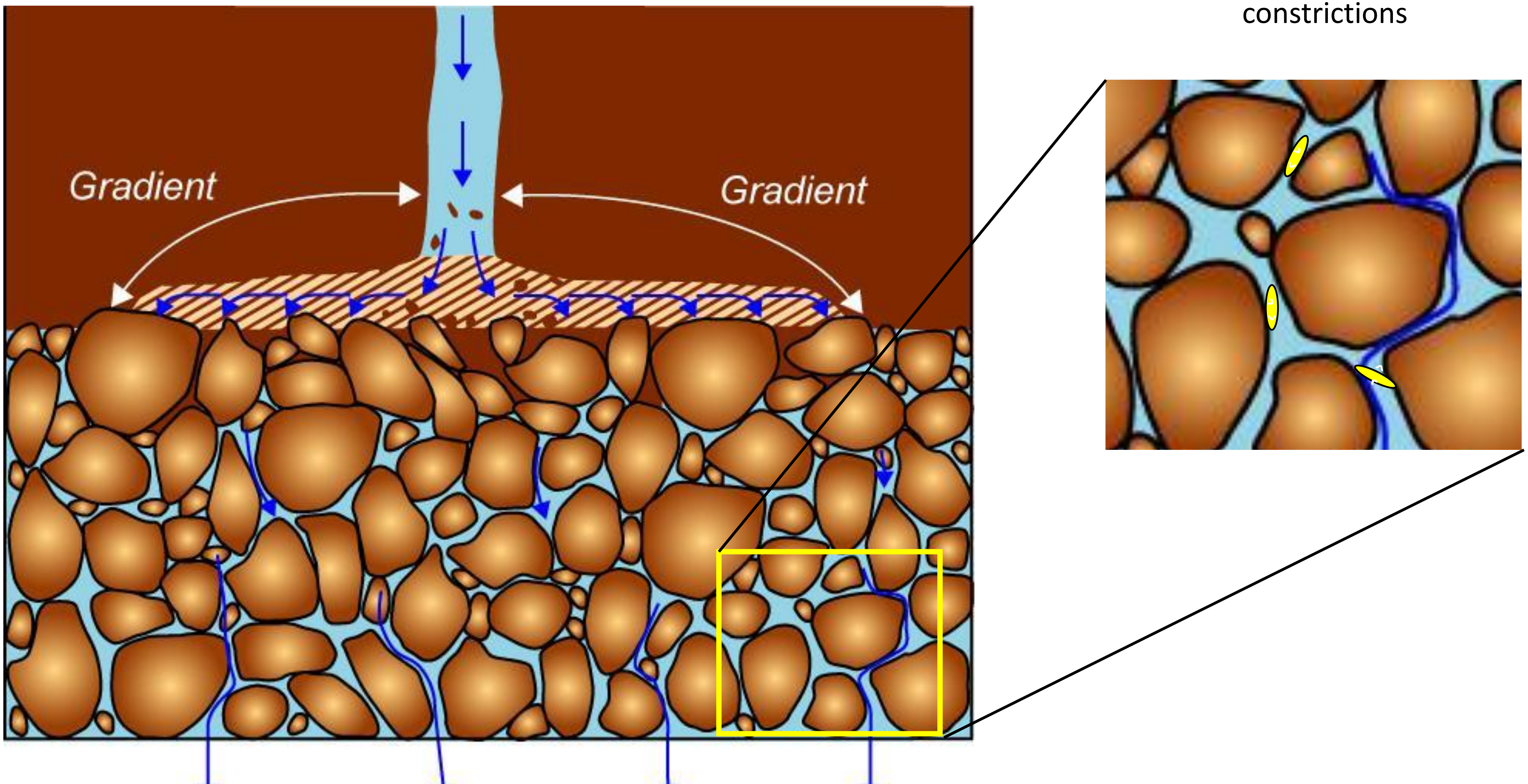
- What is the relationship between the size of constrictions and D_{15F}?
- Does particle scale analysis support use of the ratio D_{15F} / D_{85B} in design?

Retention

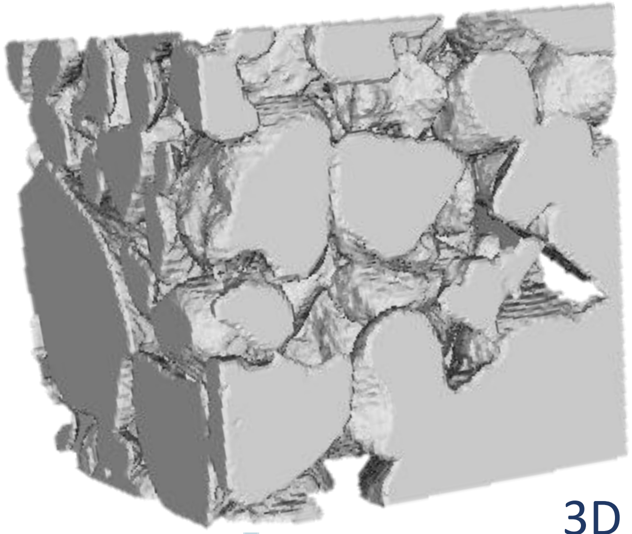


Retention

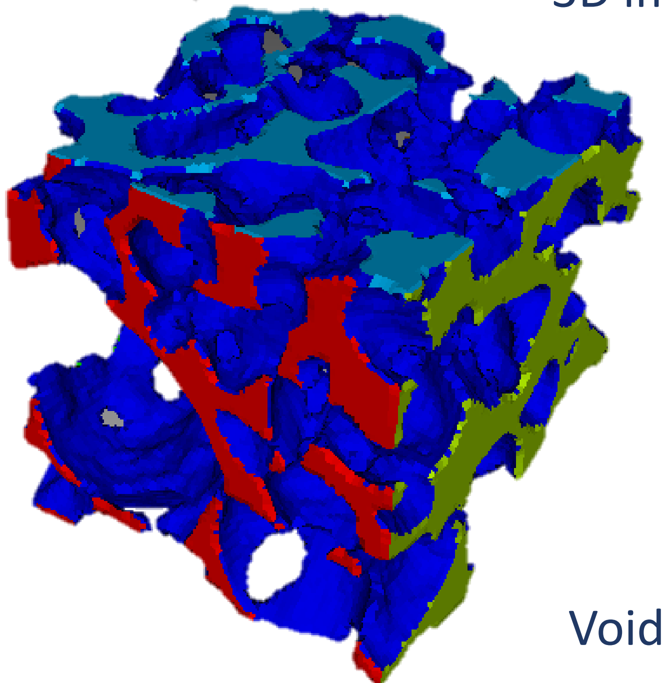
Fine core particles get trapped in constrictions



Quantifying constriction size & frequency



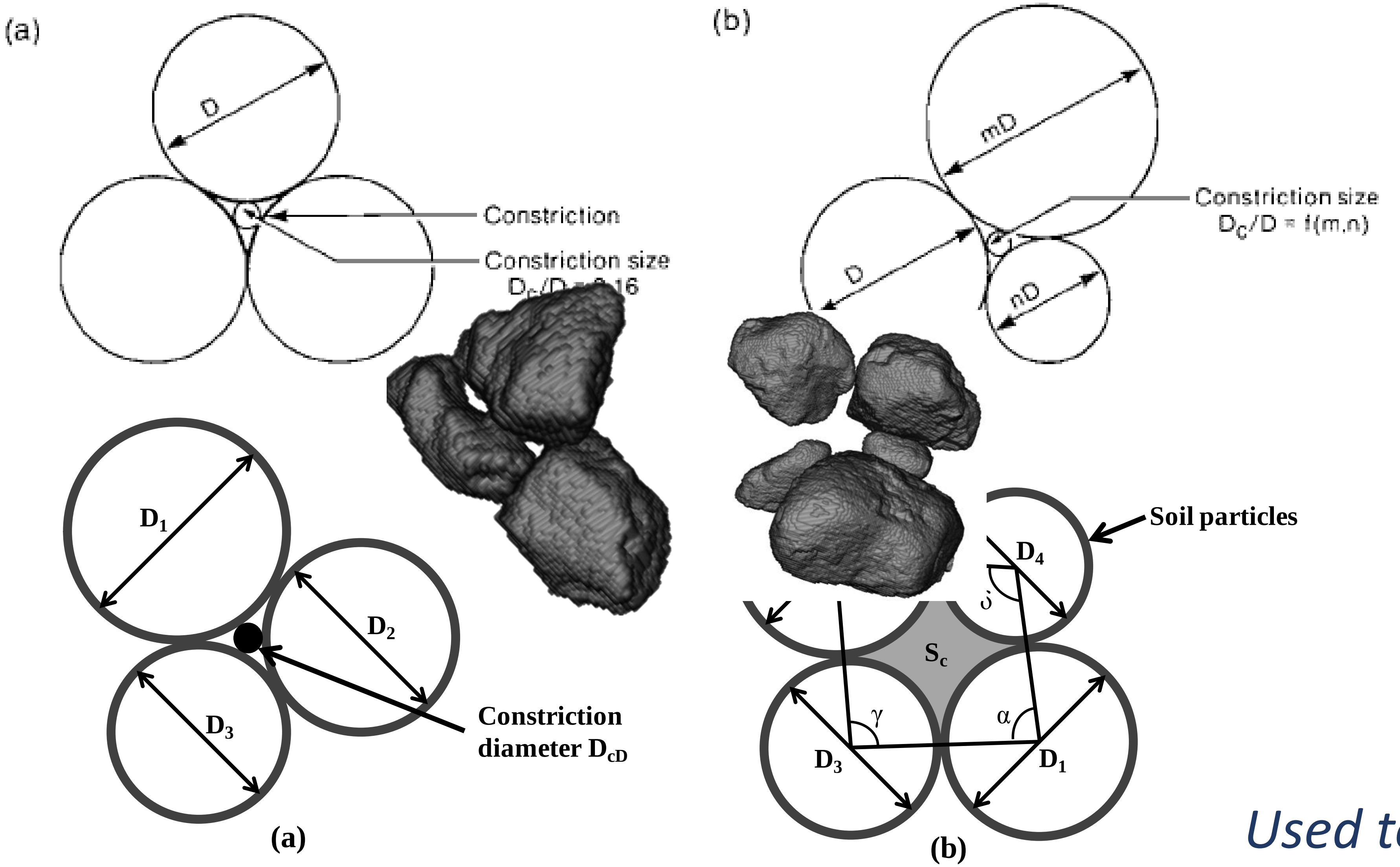
3D image of sand from micro CT



Void space from microCT

- Ability to image pore space is a recent advancement
- Pore space topology is complex
- Pore space is continuous
- Division between individual voids / pores is subjective

Analytical approach to quantify constriction sizes



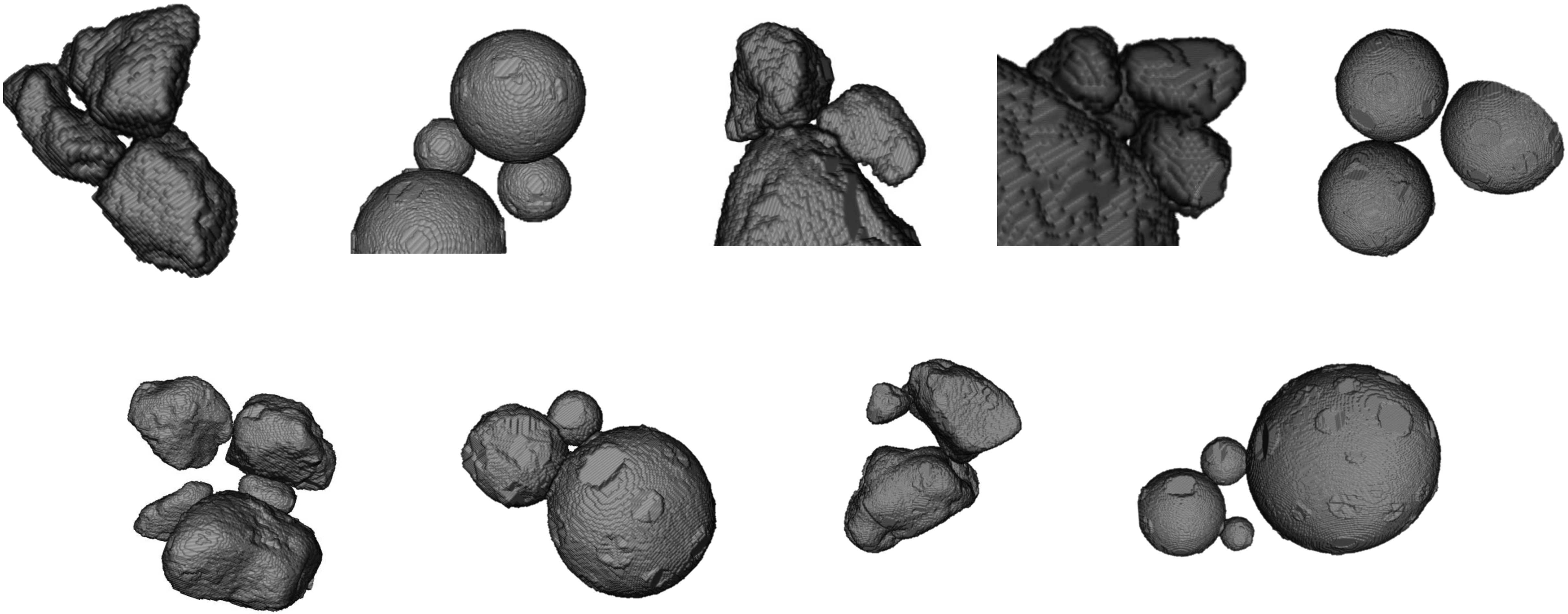
Coplanar spheres

Kenney et al. (1985)

Silvera et al. (1985)

Used to justify design criteria

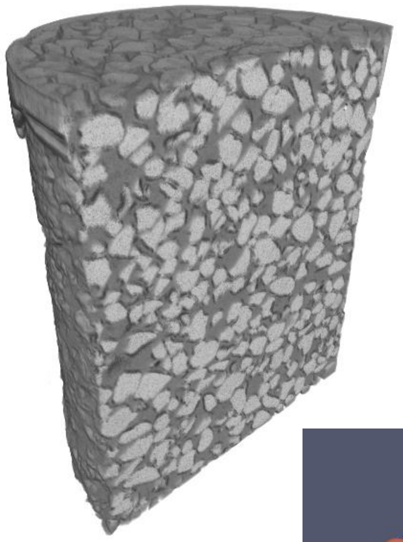
Real constrictions from microCT data

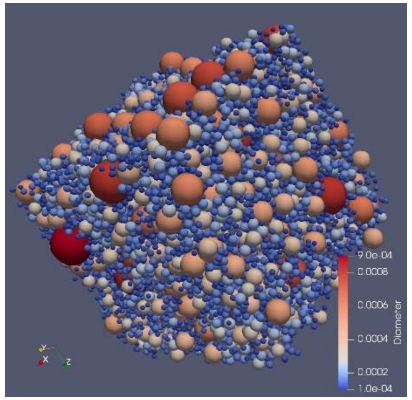


Taylor et al. Géotechnique (2019)

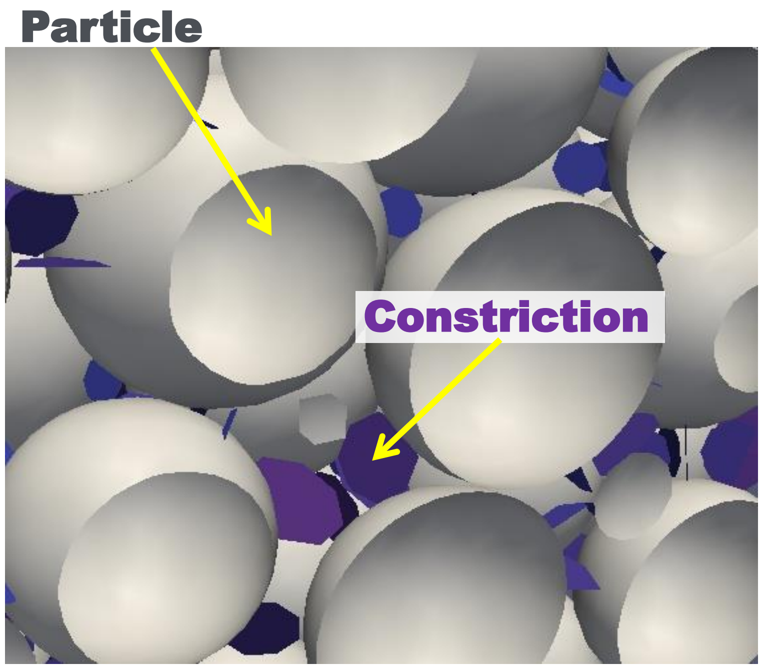
Determining constriction size distribution

Generate particle scale data

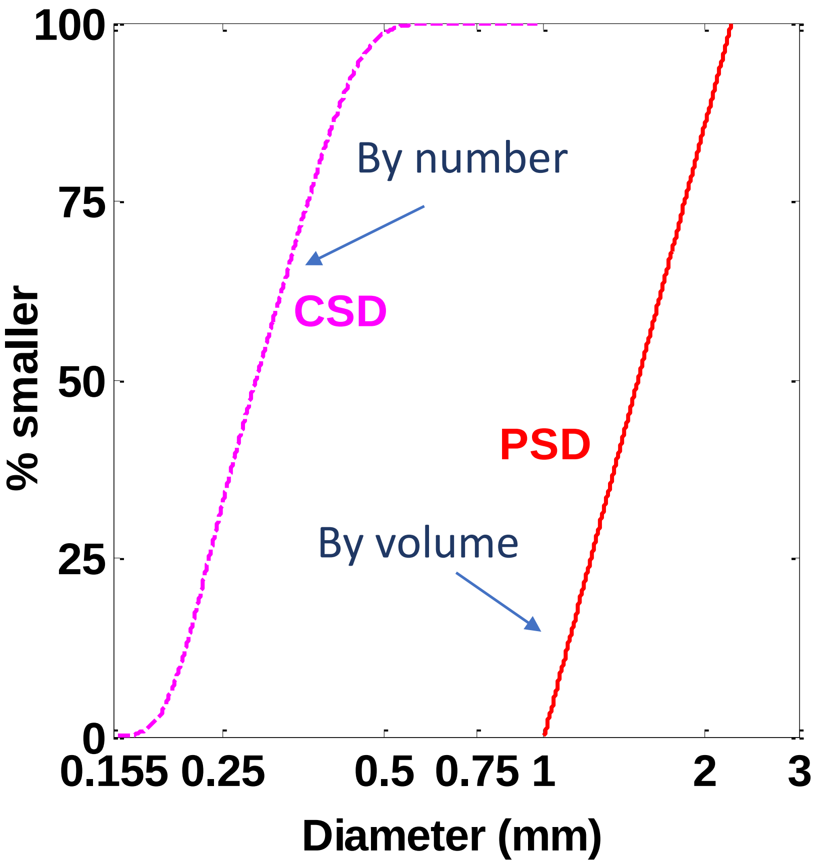




Apply void partitioning algorithm

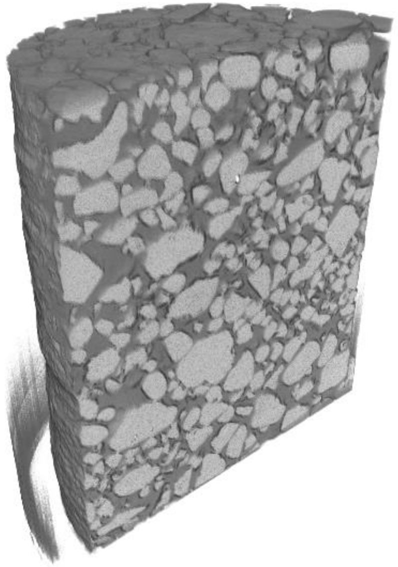


Calculate Constriction Size Distribution

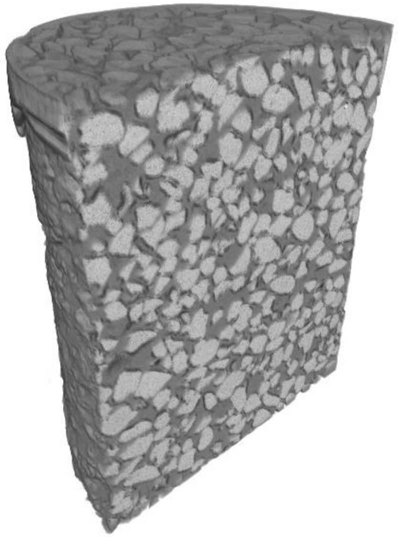


Samples considered to study retention

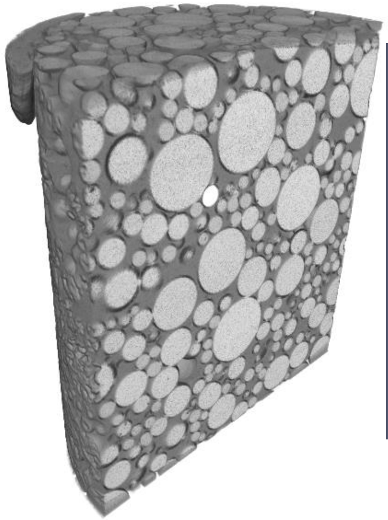
Micro Computed Tomography



Leighton Buzzard Sand C_u=3



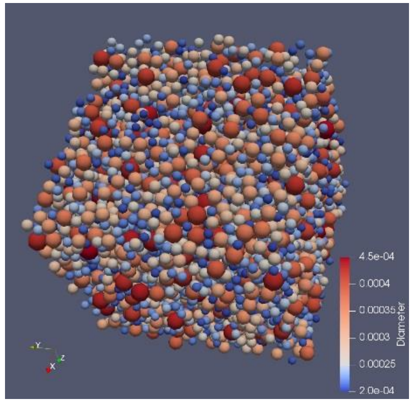
Leighton Buzzard Sand C_u=1.5



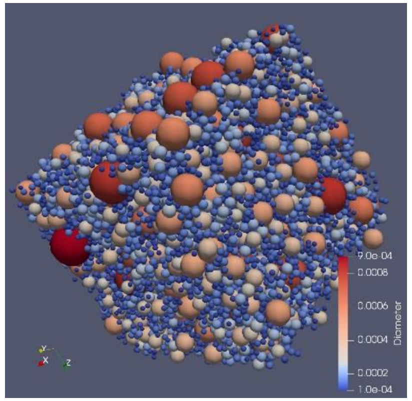
Glass Beads C_u=3

(Taylor, 2017)

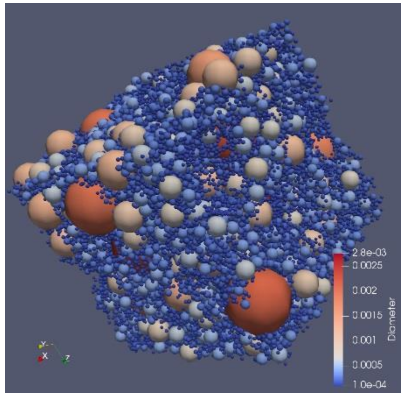
DEM Simulations



Spheres C_u=1.2



Spheres C_u=3.0

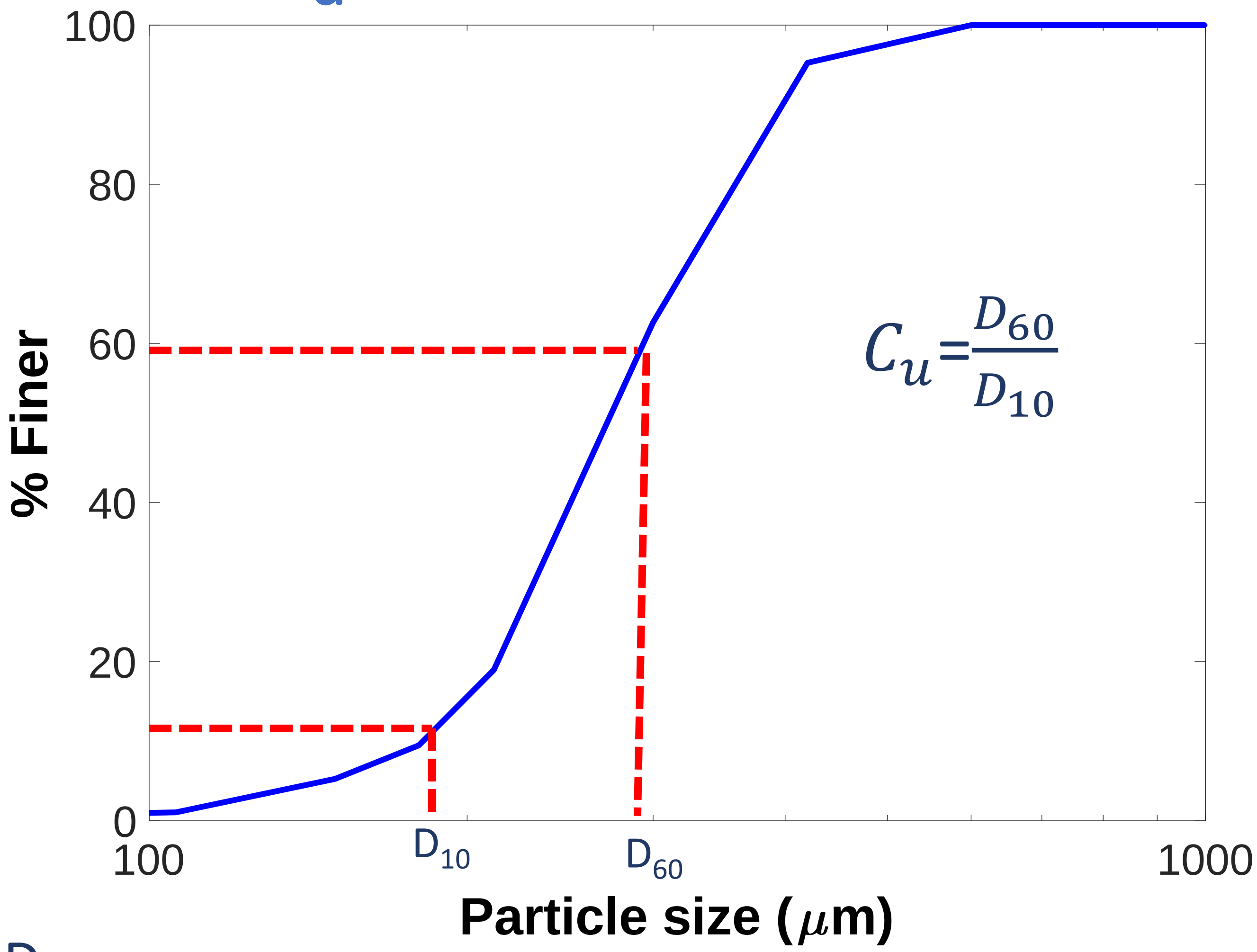


Spheres C_u=6.0

(Shire, 2018)

Do not consider possibility of filters containing fines

Coefficient of uniformity, C_u



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

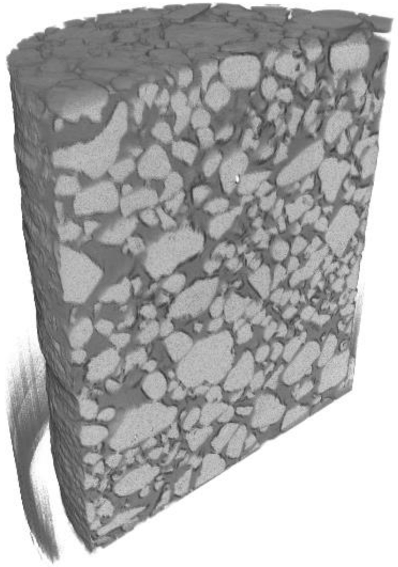
60% of particles by mass are smaller than D_{60}

Cumulative distribution by volume / mass

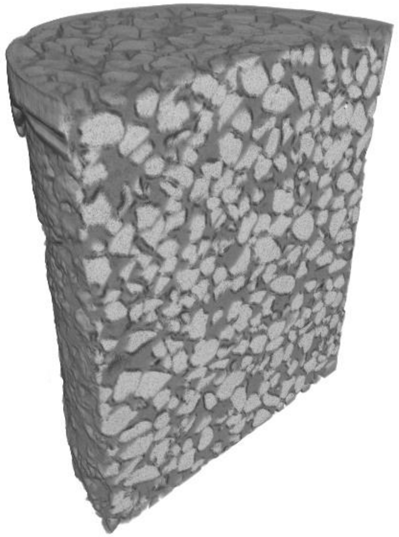
Samples considered to study retention

Micro Computed Tomography

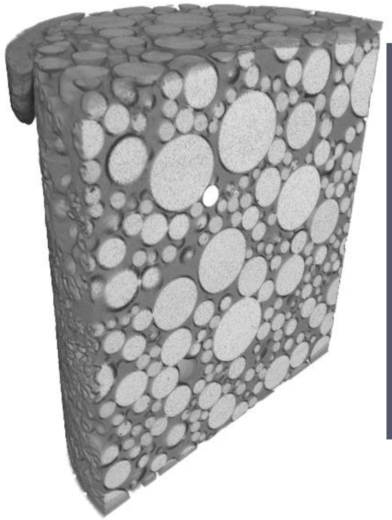
DEM Simulations



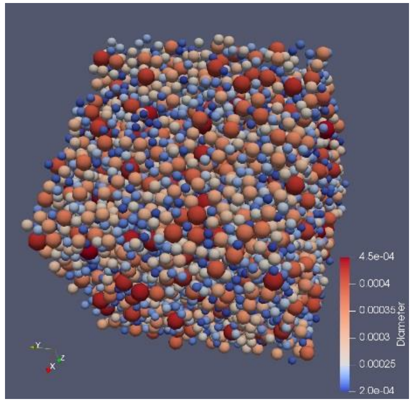
Leighton Buzzard Sand
C_u=3



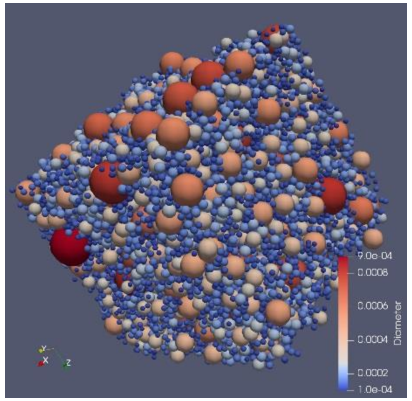
Leighton Buzzard Sand
C_u=1.5



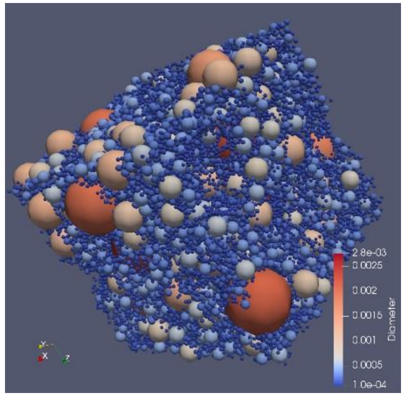
Glass Beads
C_u=3



Spheres
C_u=1.2



Spheres
C_u=3.0



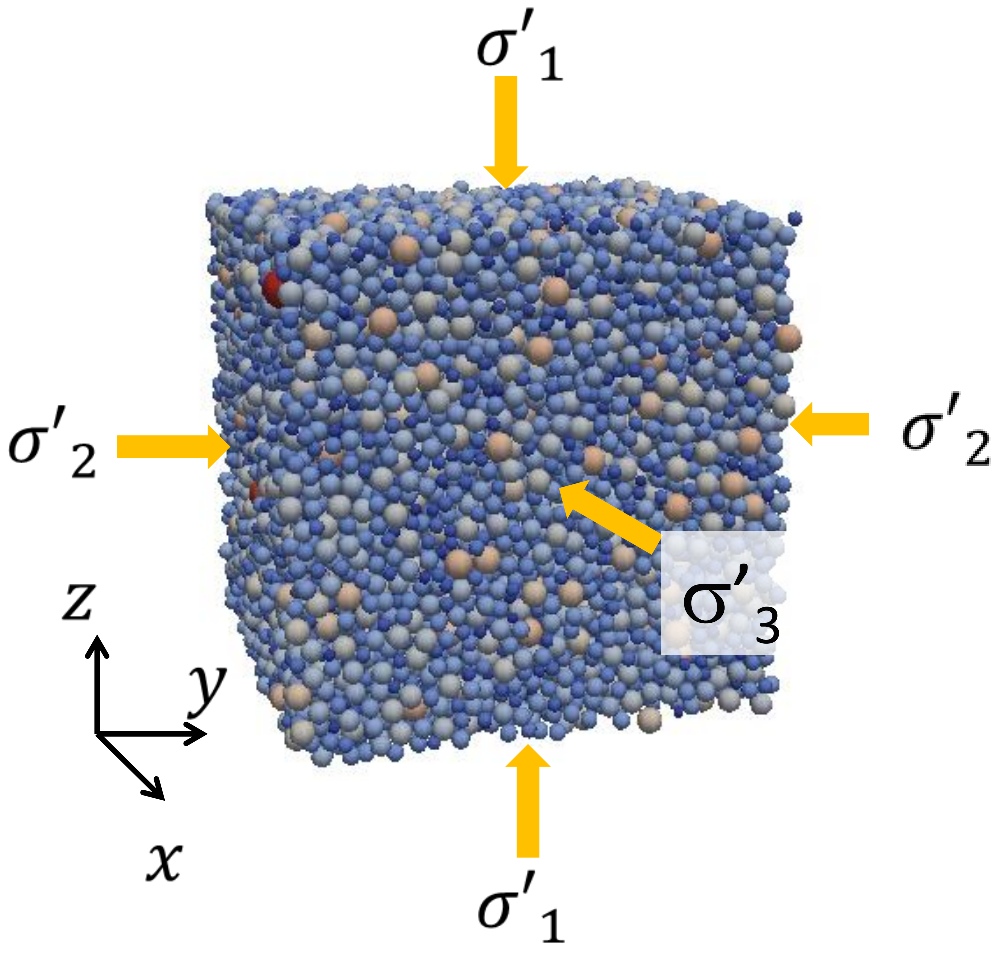
Spheres
C_u=6.0

(Taylor, 2017)

(Shire, 2018)

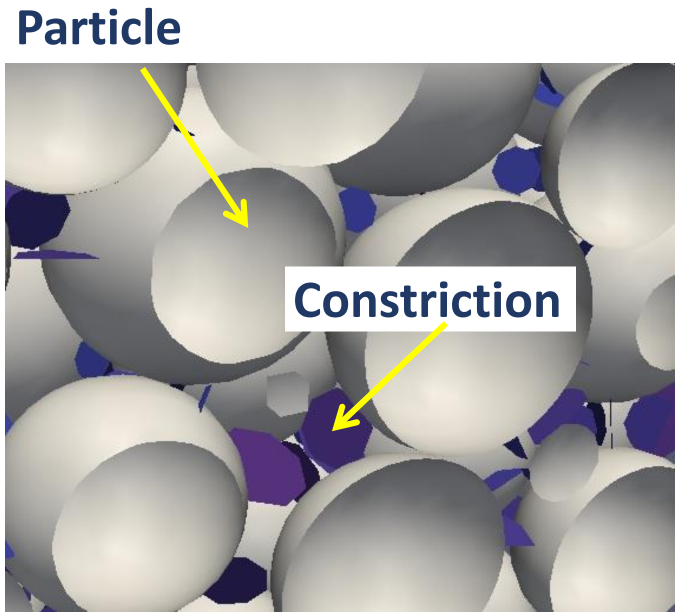
Do not consider possibility of filters containing fines

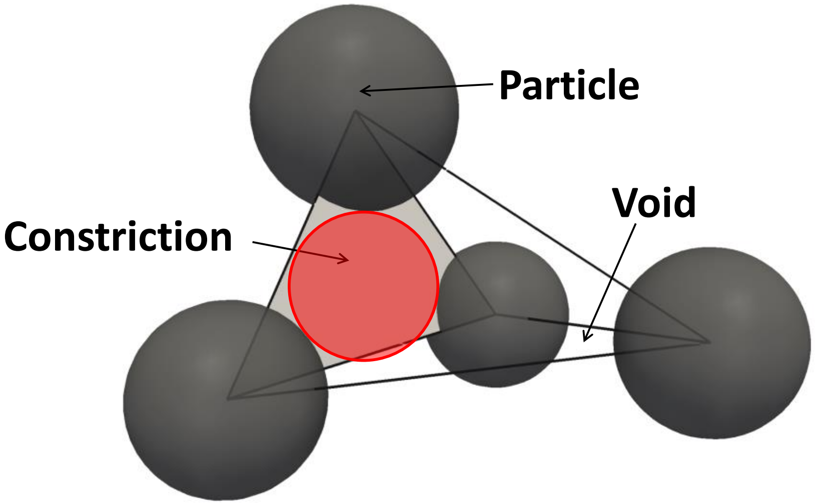
DEM simulations



- LAMMPS (Plimpton, 1995; Sandia National Laboratories)
- Development and testing by Dr. Kevin Hanley (formerly Imperial College, now Edinburgh)
- Validation using lattice packings / Benchmarking against PFC
- Periodic boundaries, Hertz-Mindlin contact model
- Used Imperial College HPC clusters
- Isotropic compression of to 60,000 spherical particles

DEM constrictions: Triangulation method





Triangulation of particle centres weighted by particle radii

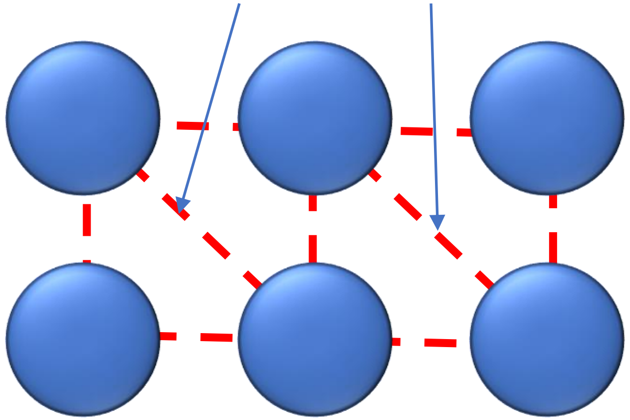
Tetrahedra faces define void boundaries

Constrictions located on tetrahedra faces

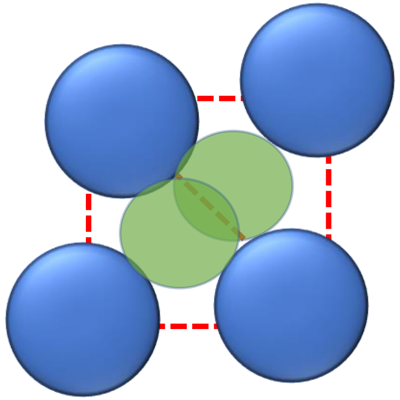
Al Raoush et al. (2033); Reboul et al. (2010)

DEM constrictions: Triangulation method

False identification of constrictions due to over-segmentation

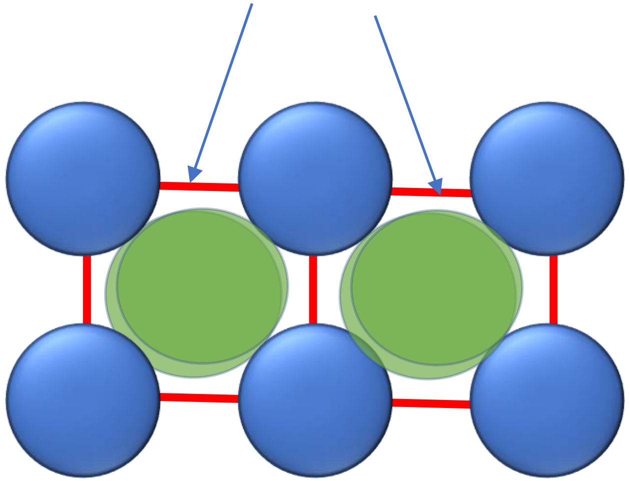


Delaunay triangulation based on particle centroids



Identify spheres tangent to particles forming Delaunay cell

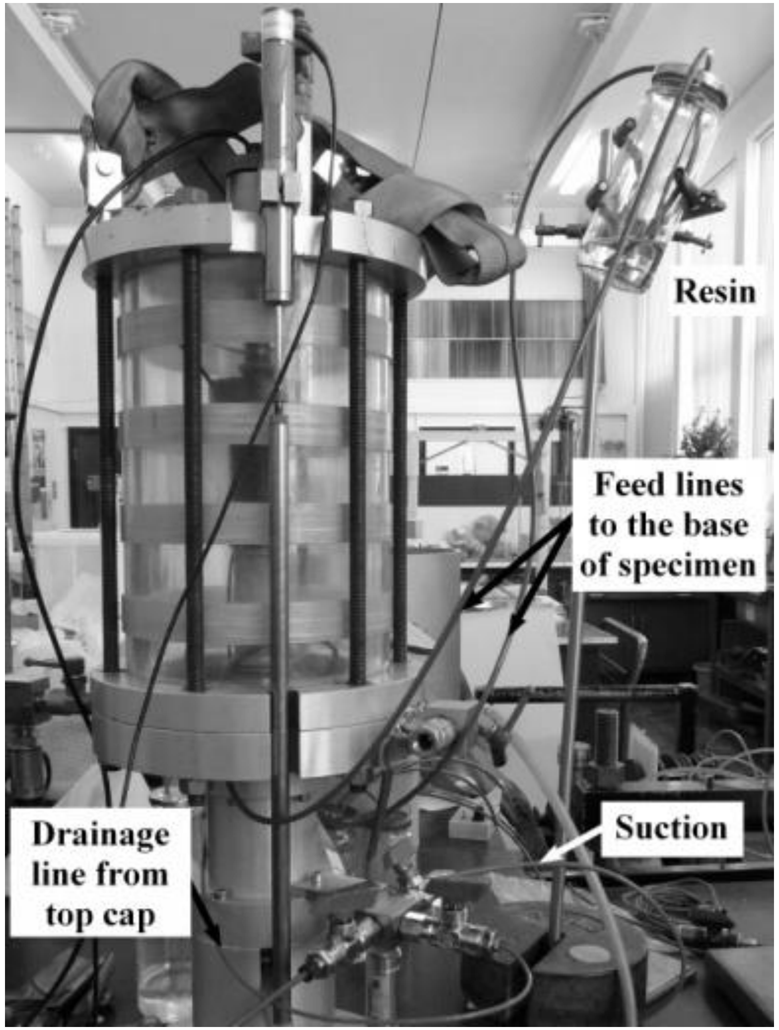
Valid constrictions

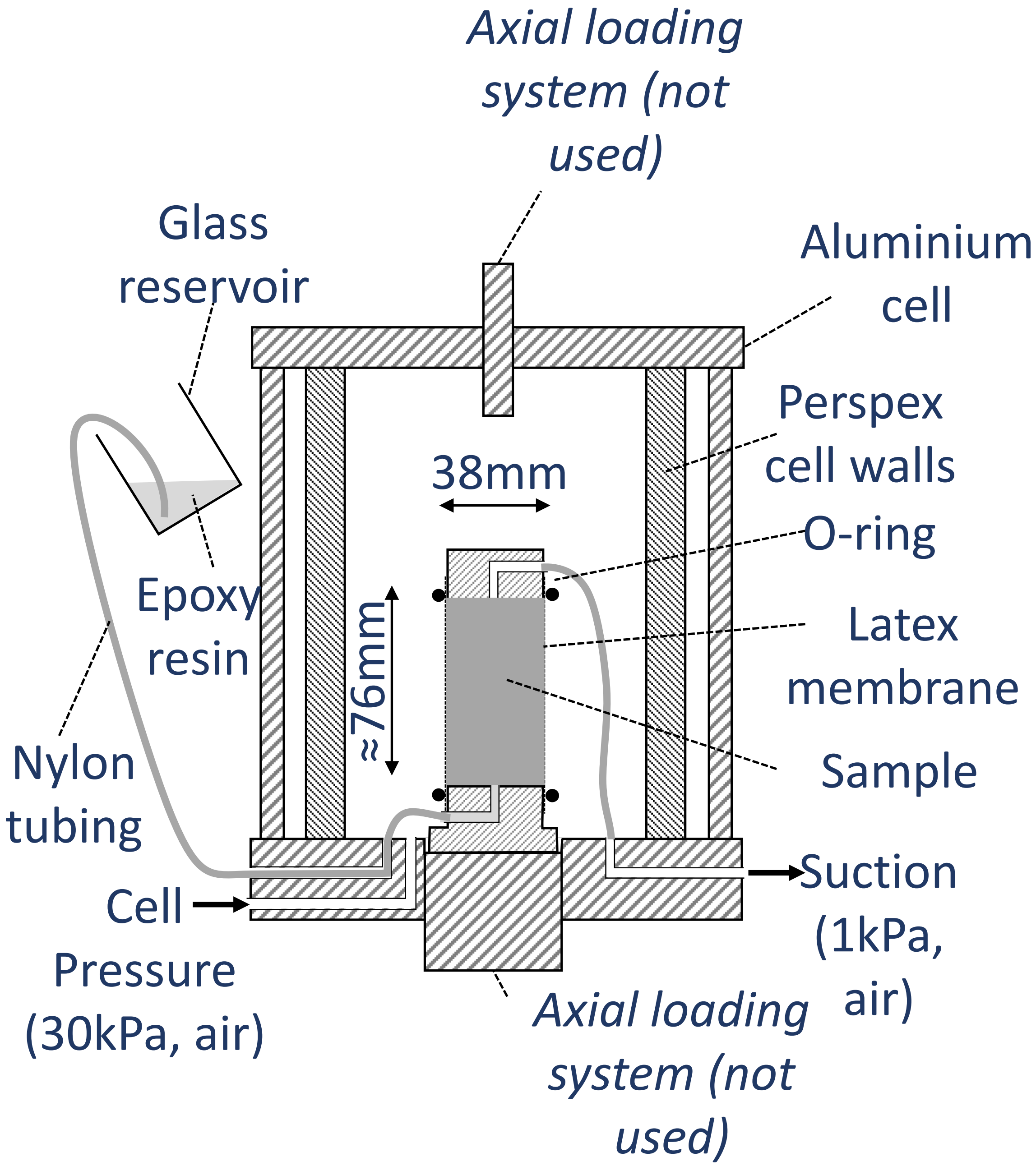


Where tangent spheres overlap Delaunay cells are merged

User decides magnitude of overlap

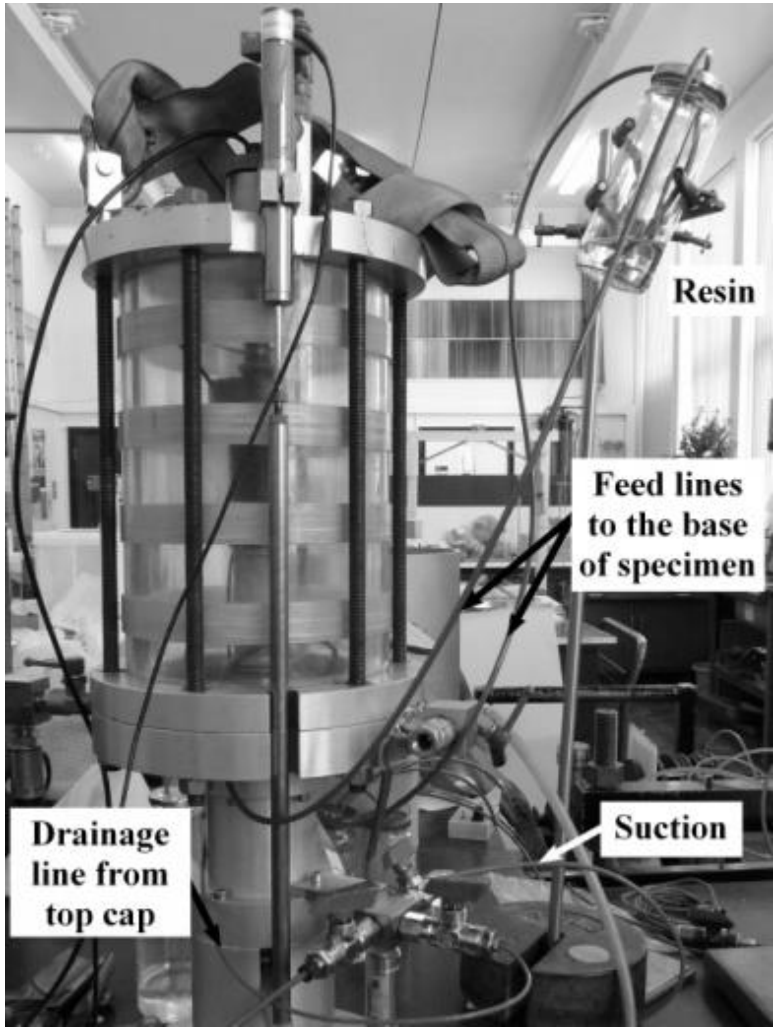
Experimental approach

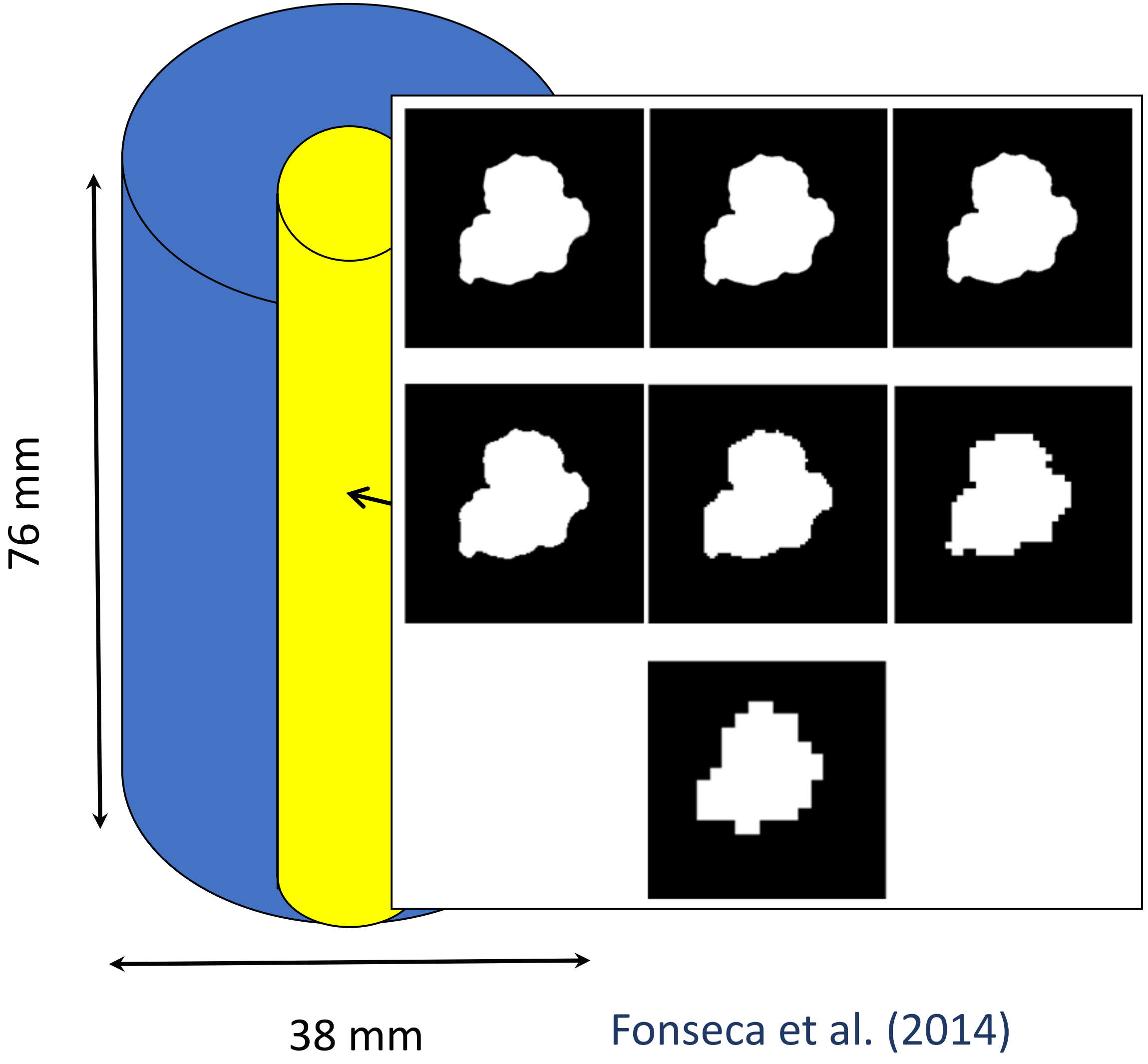




PhD Research of Dr. Howard Taylor

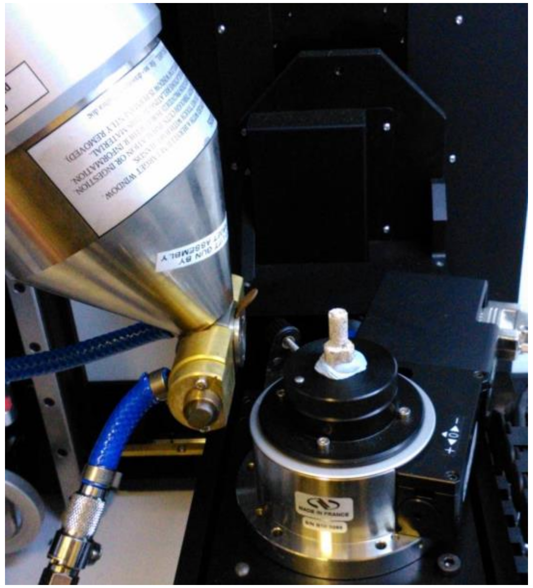
Experimental approach



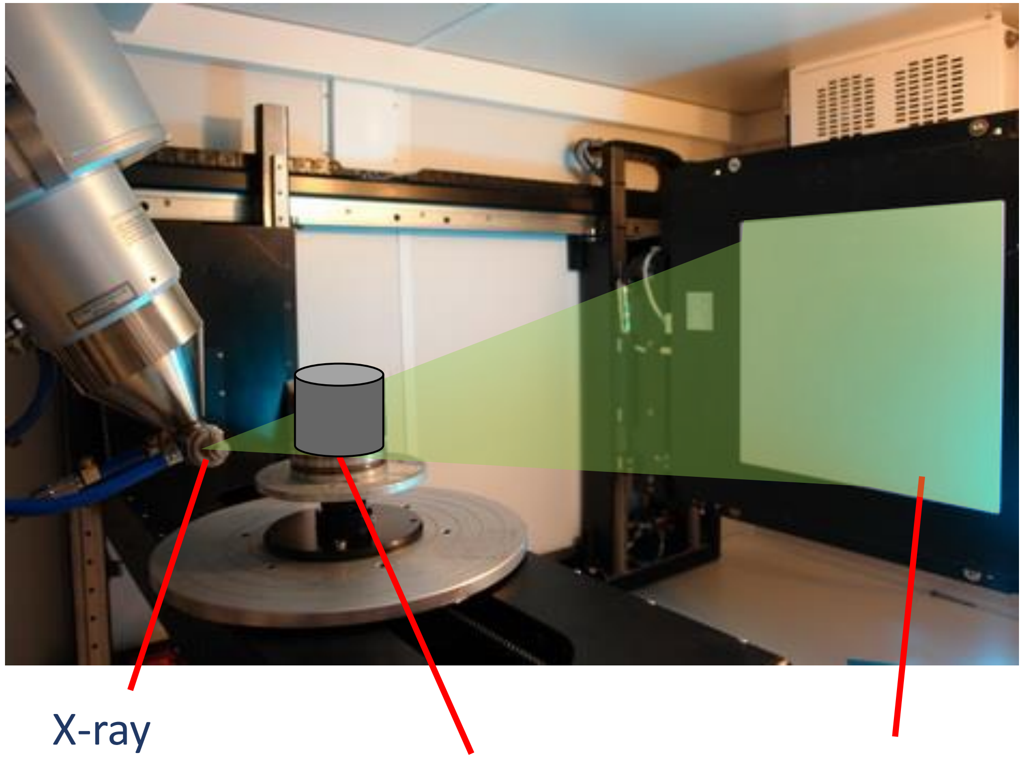


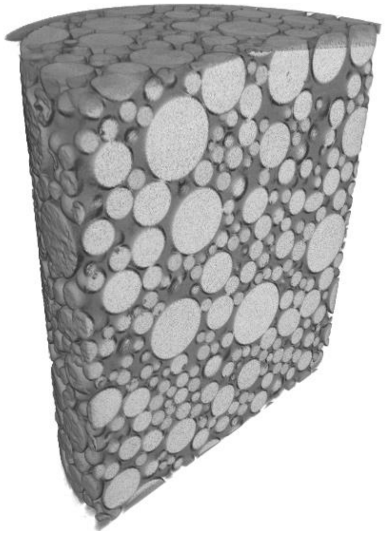
Fonseca et al. (2014)
Géotechnique

Micro Computed Tomography (microCT)

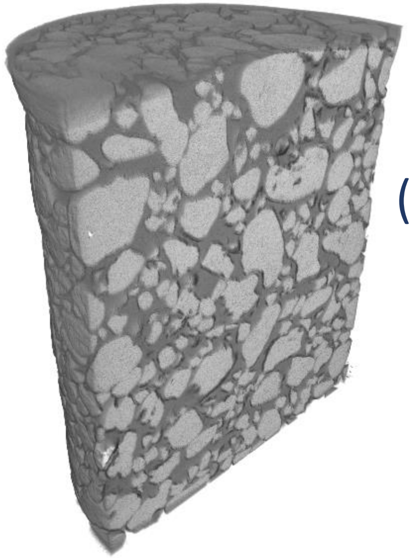


Nikon XT-H-224 scanner
Voxel size ≈ 10x10x10 μm^3



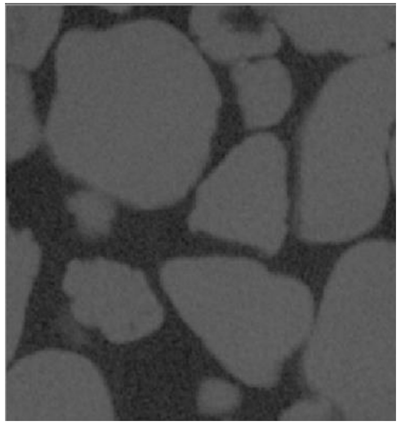


Cu3 - Glass Beads
e = 0.46
(medium→dense



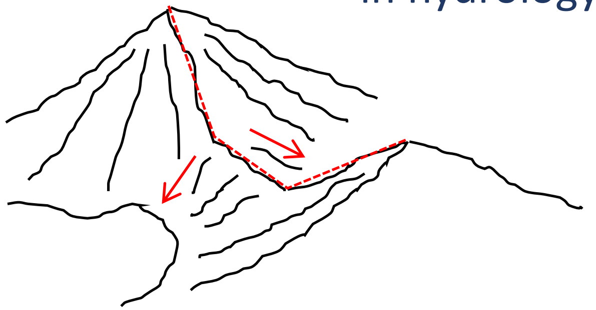
Cu3 – Sand
e = 0.51
(medium density)

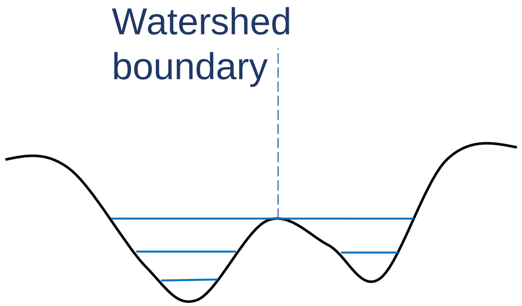
Segmentation of void space

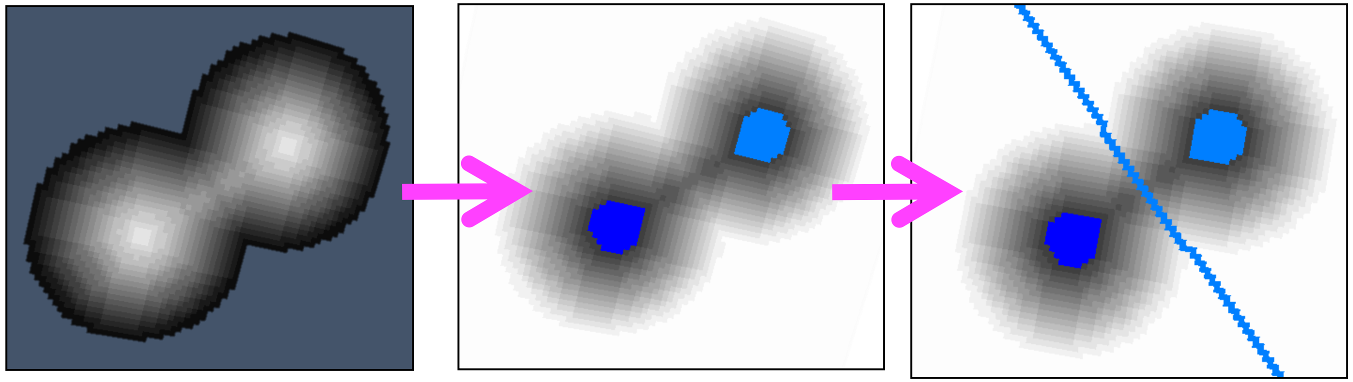


Threshold to identify gray level differentiating void space and particles

Watershed concept in hydrology







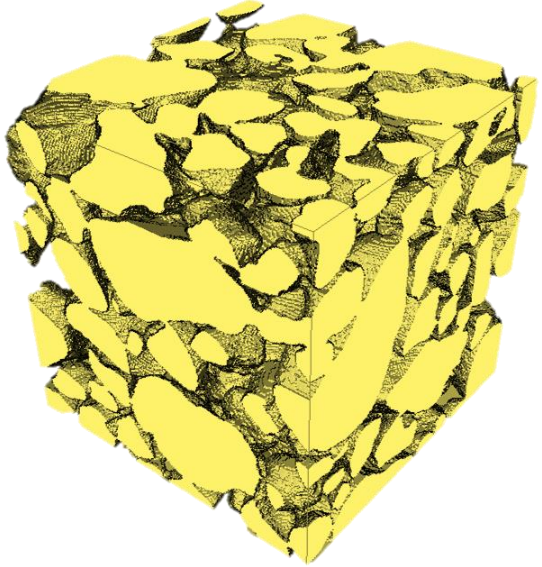
Distance map

Centre locations

Watershed boundary

Performed using "Avizo Fire" software

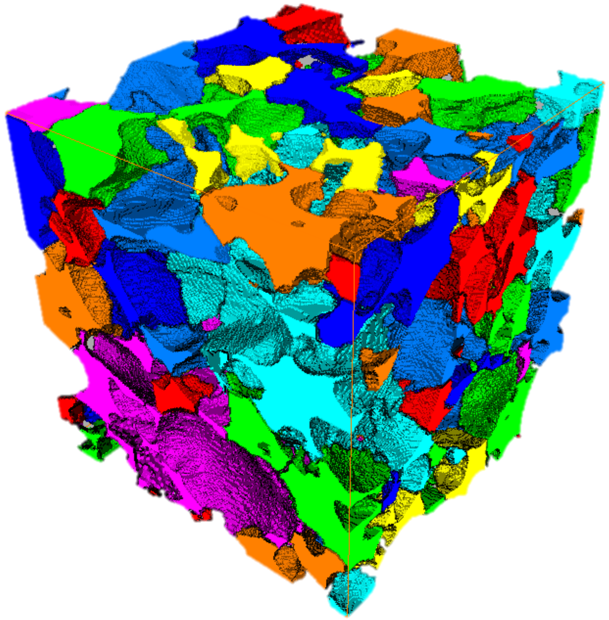
Identifying constrictions in μCT



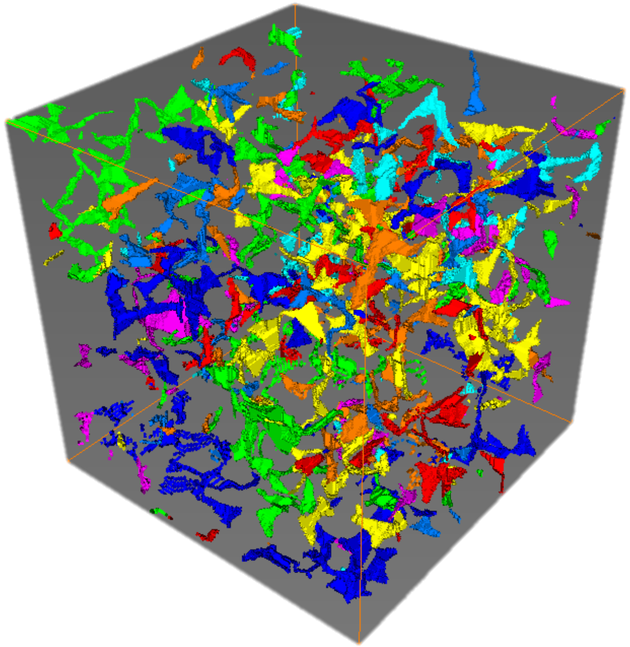
μCT image

Watershed

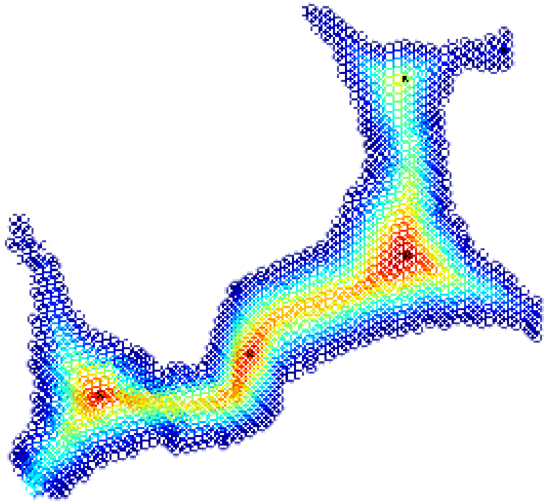
Segmentation



Voids



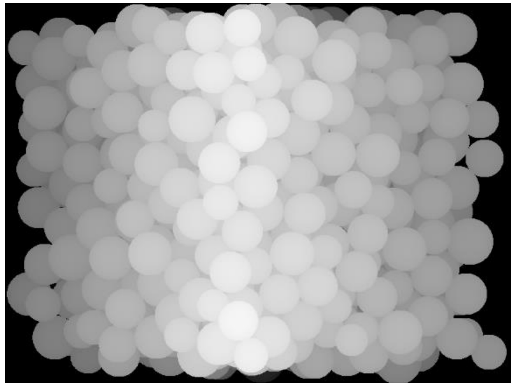
Void Boundaries



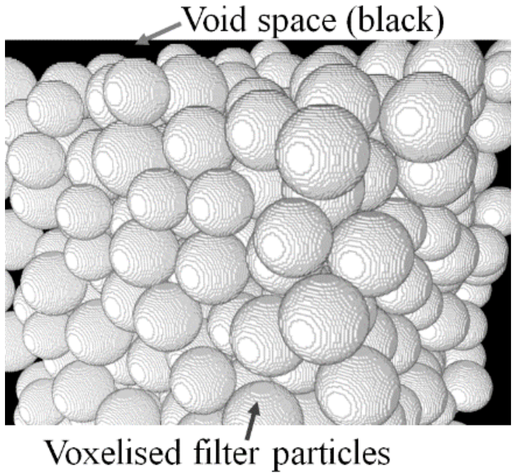
Constrictions local maxima of distances to particles

Taylor et al. (2017)

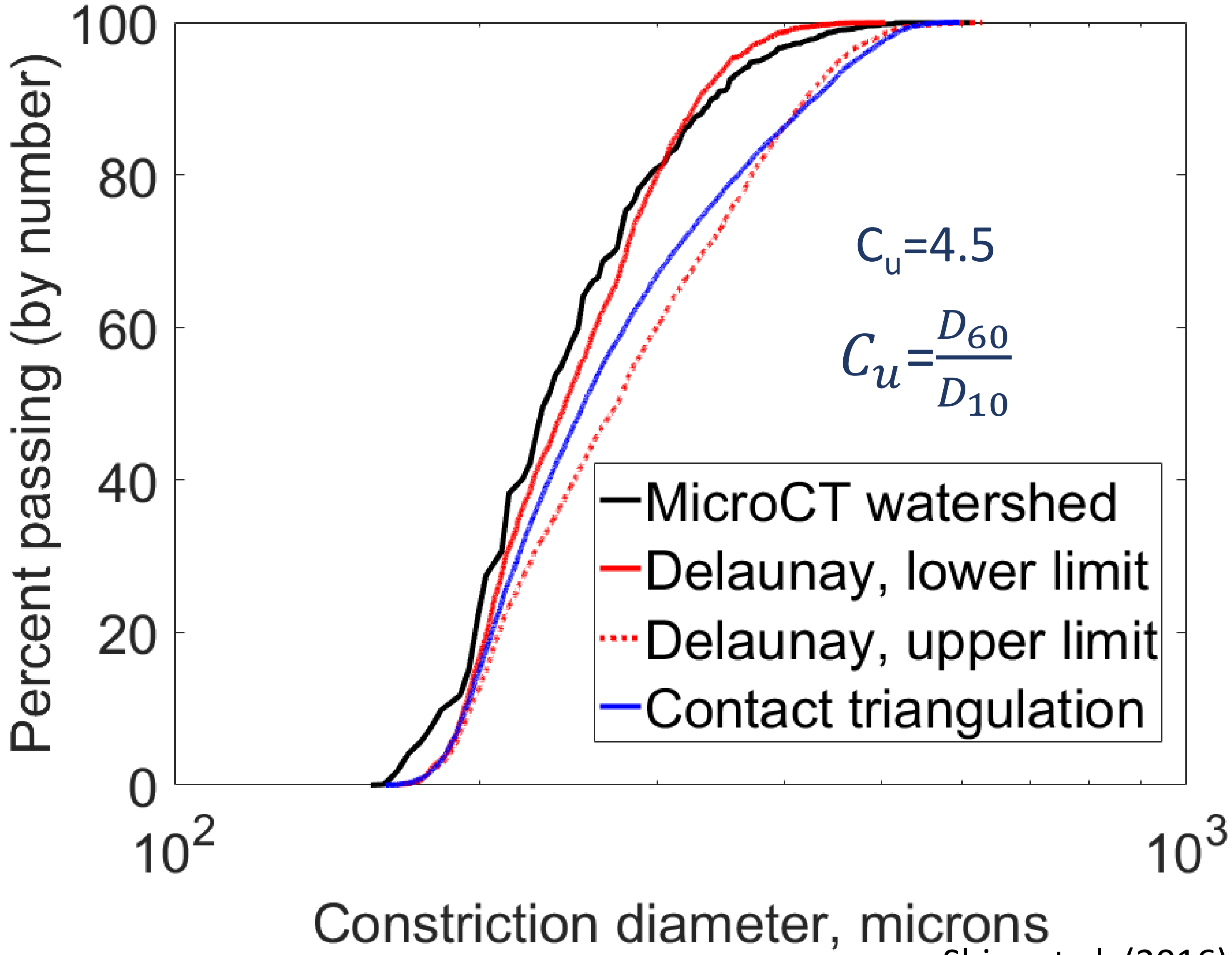
Comparison of constriction size distributions



DEM Sample

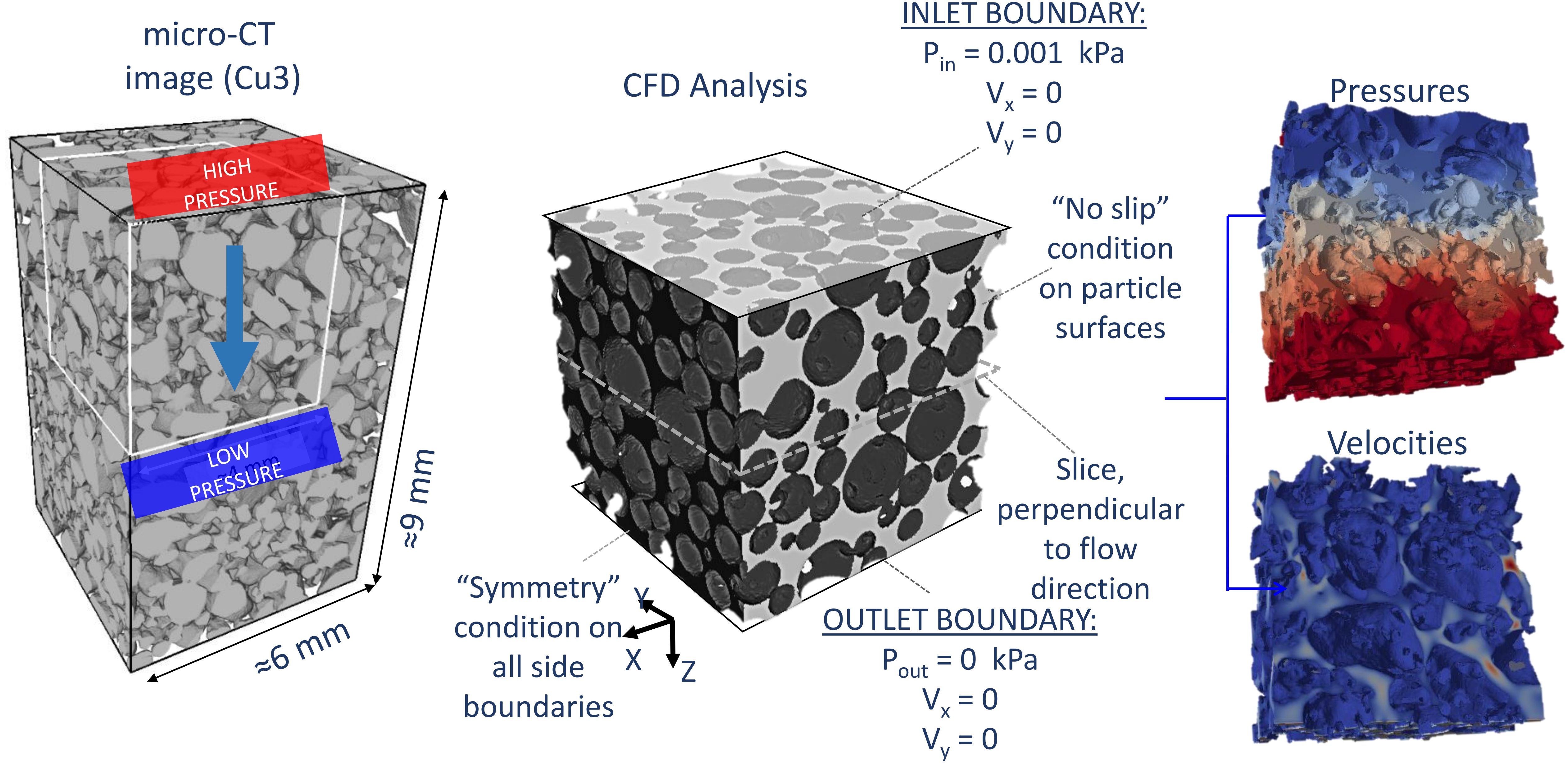


Voxelized DEM Sample:

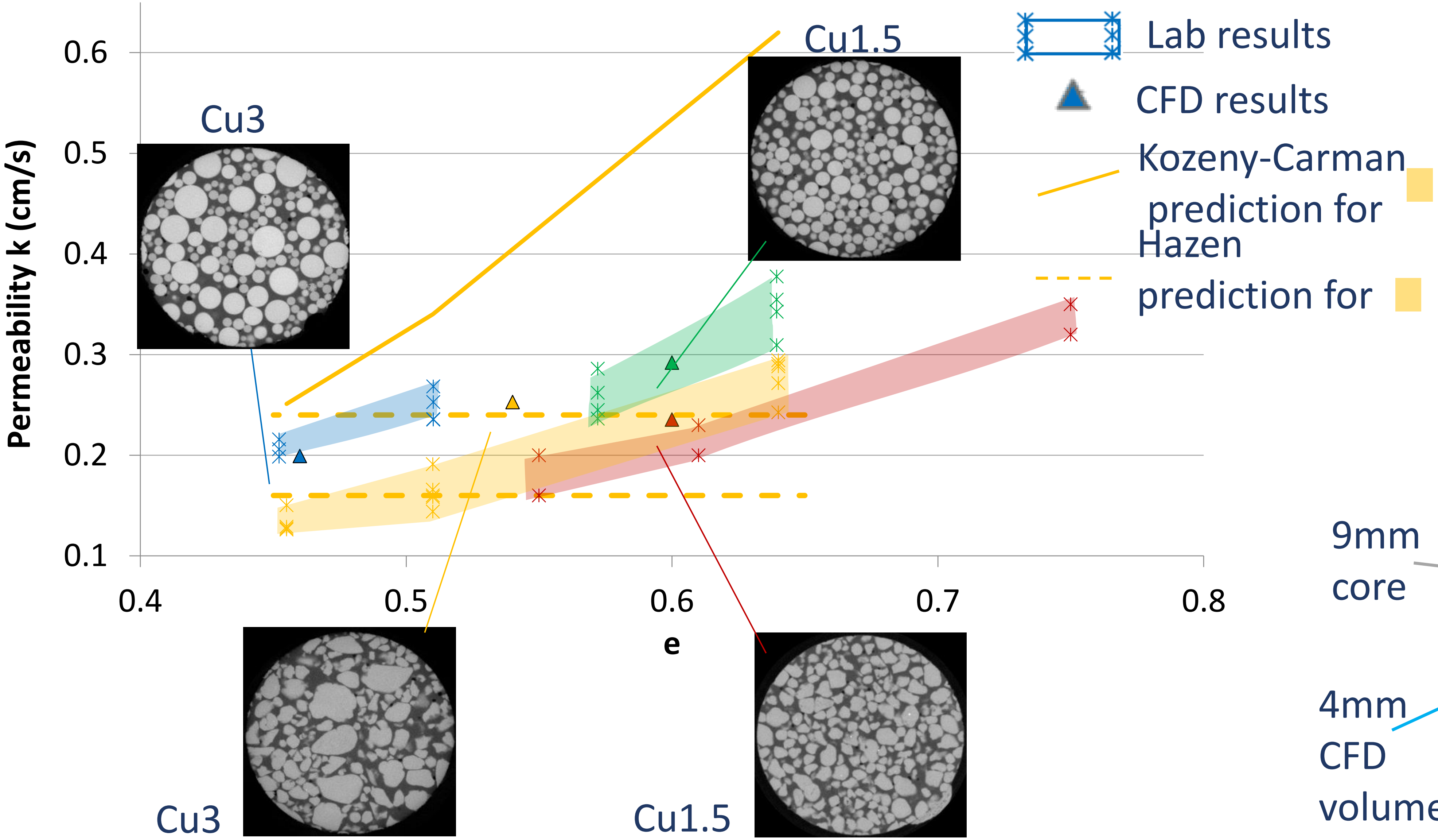


Shire et al. (2016)

Fluid flow simulations



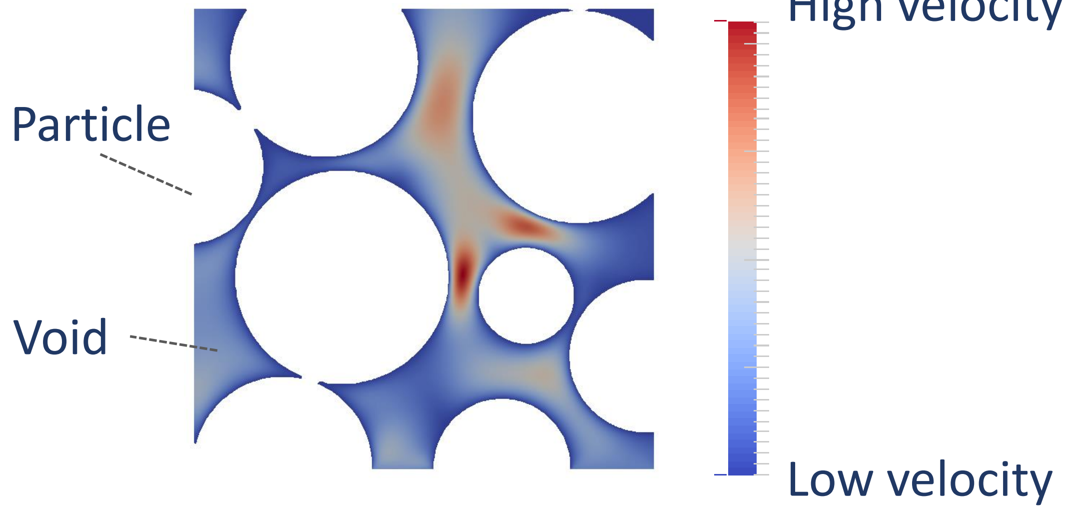
Comparison of CFD and permeameter data

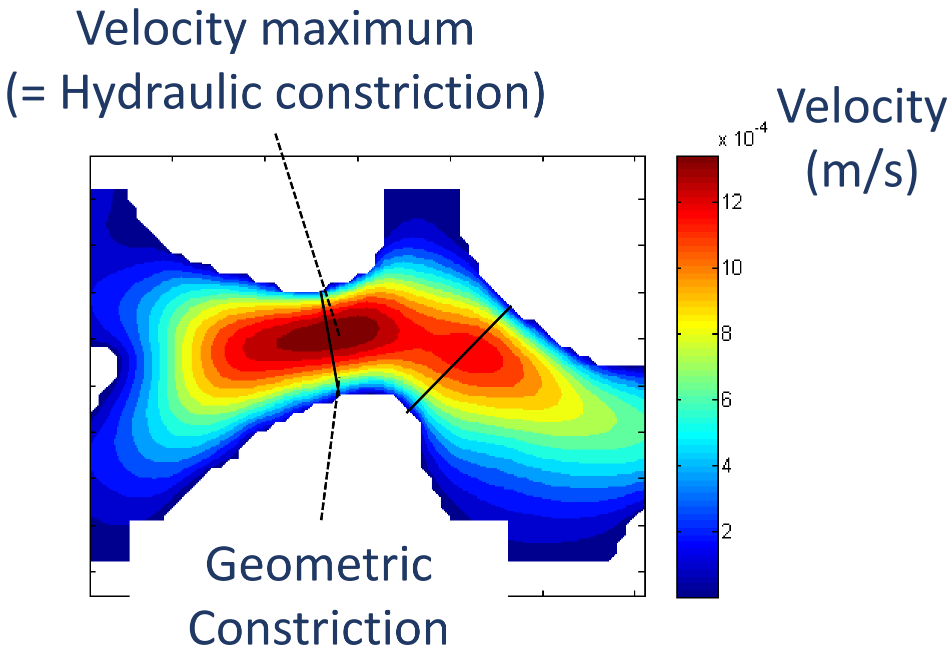


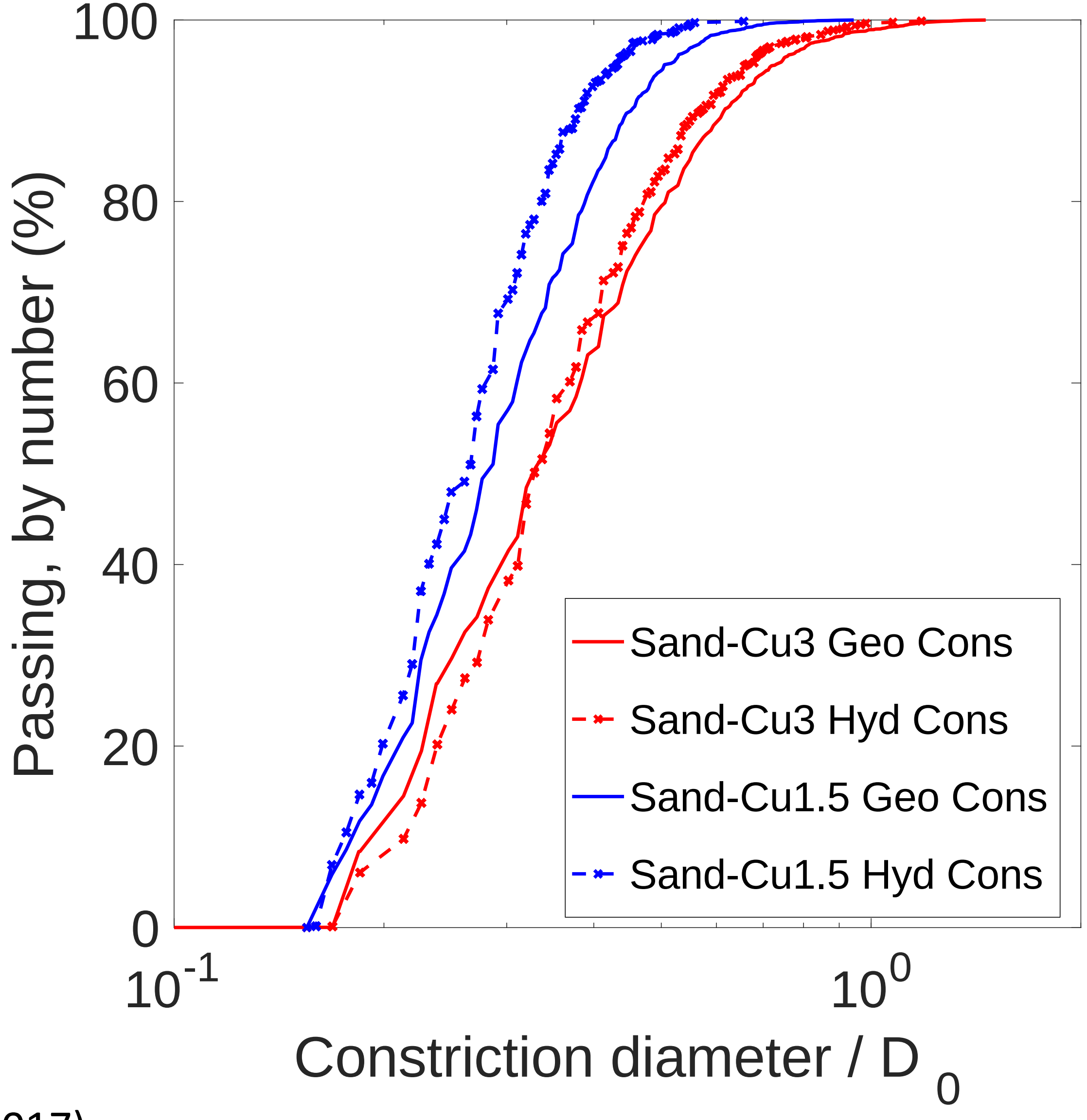
75mm permeameter

38mm triaxial

Comparison of geometric and hydraulic constrictions



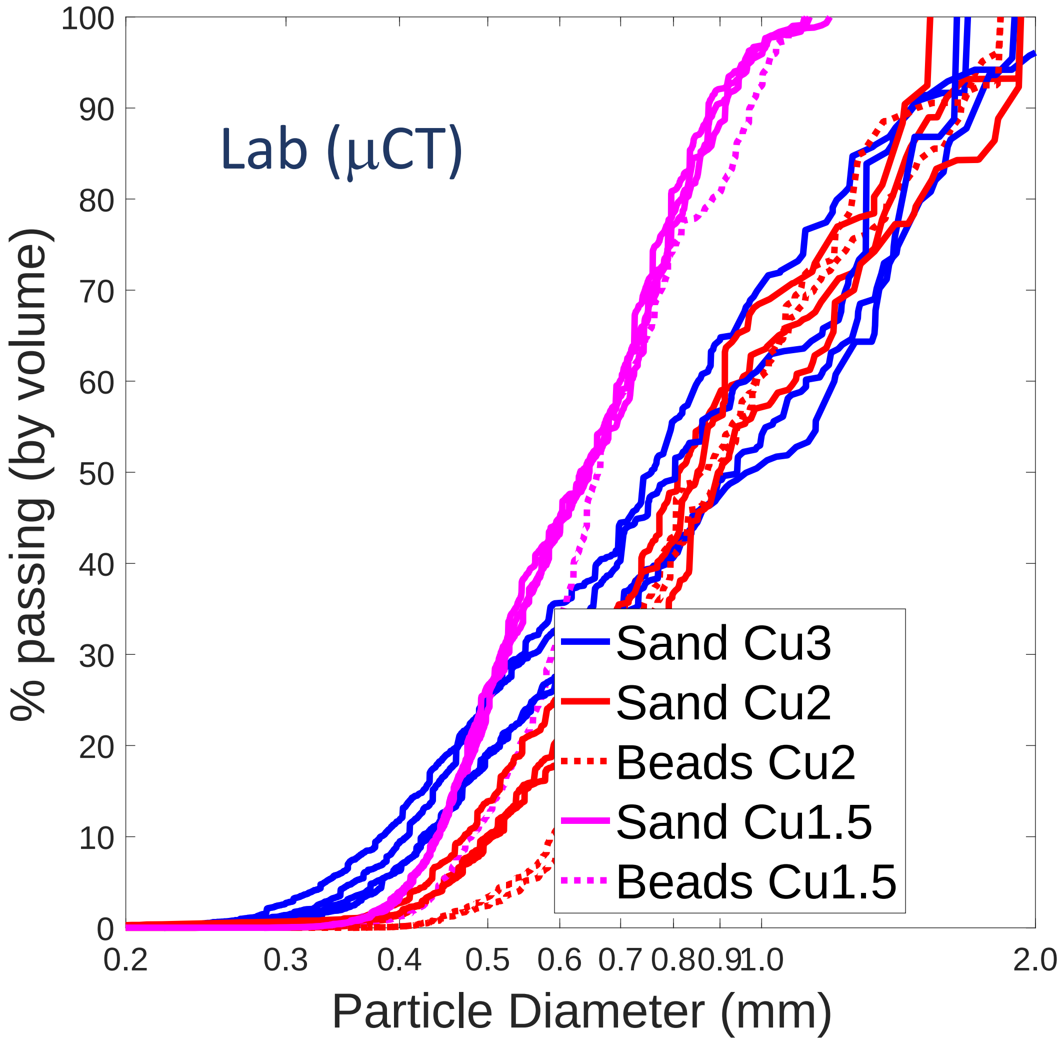


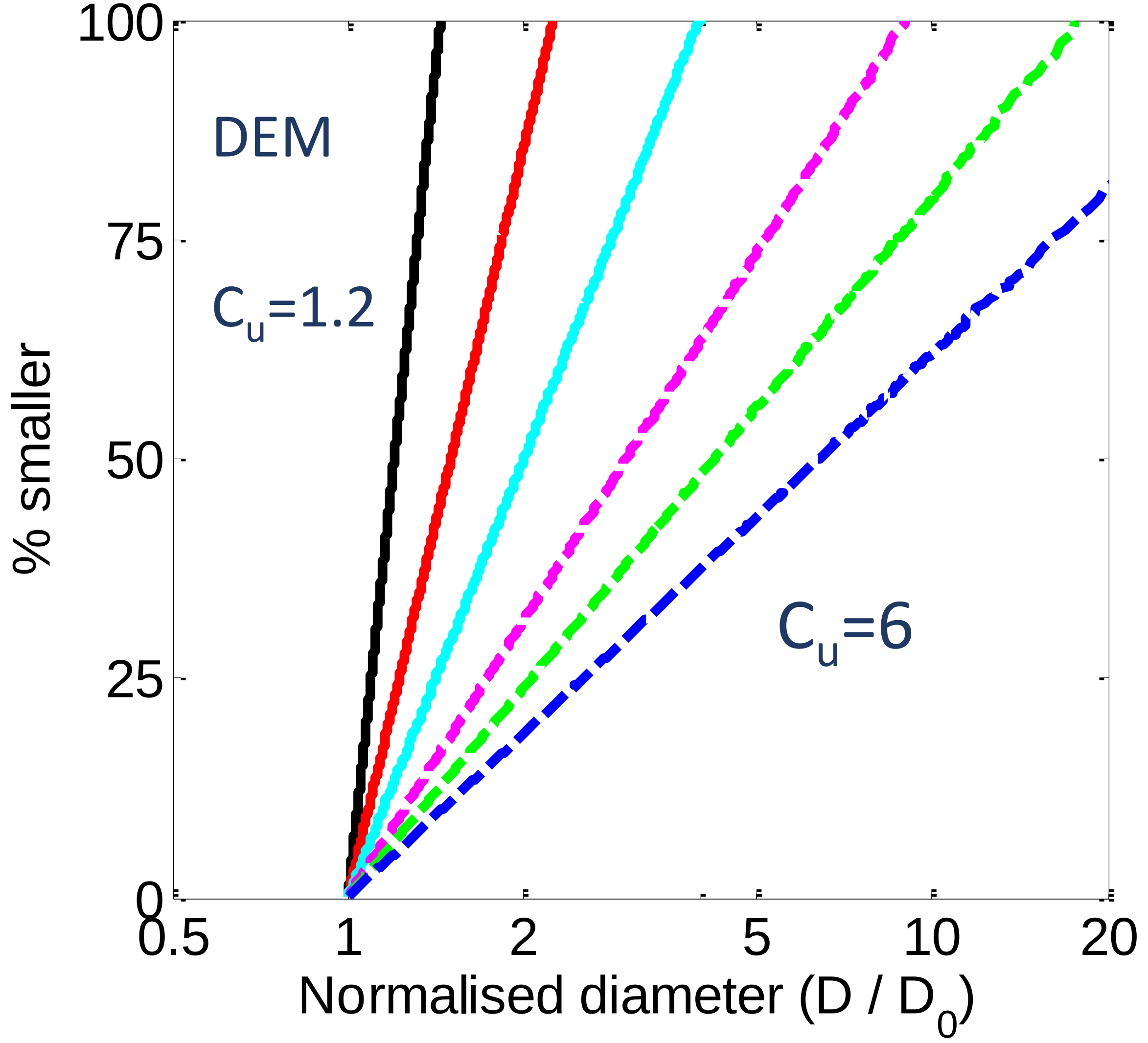


Taylor et al. (2017)

Particle Size Distributions

$$C_u = \frac{D_{60}}{D_{10}}$$

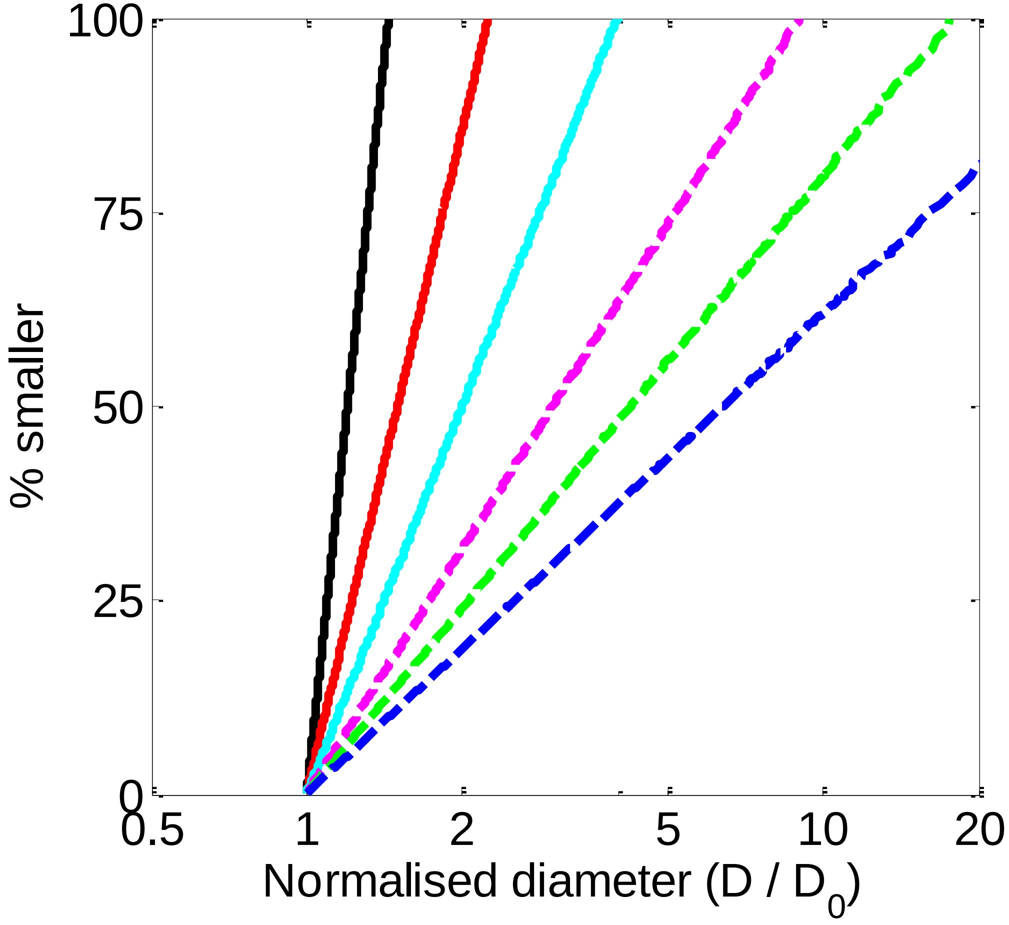




Taylor et al. (2018)

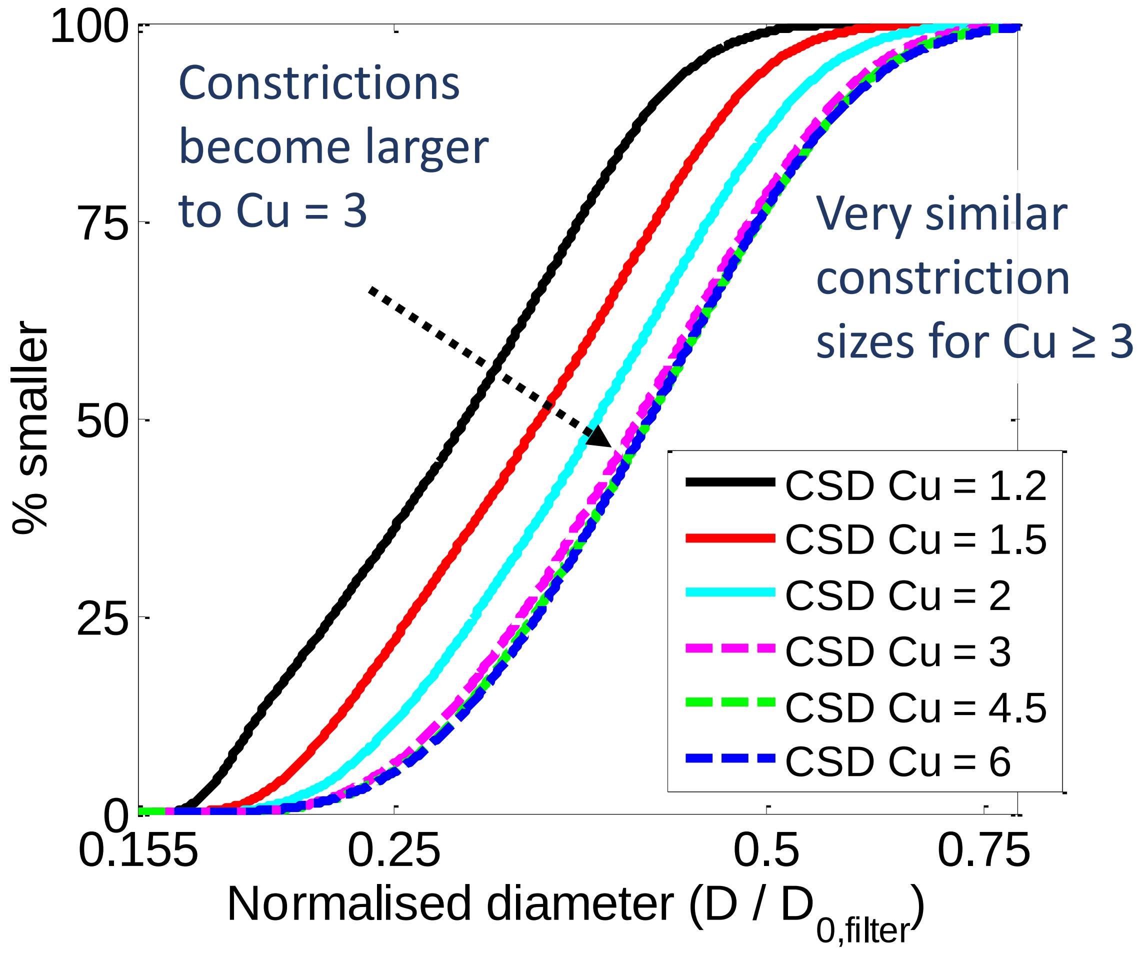
Constriction Size Distributions (DEM)

Filter PSD



Cumulative distribution by volume

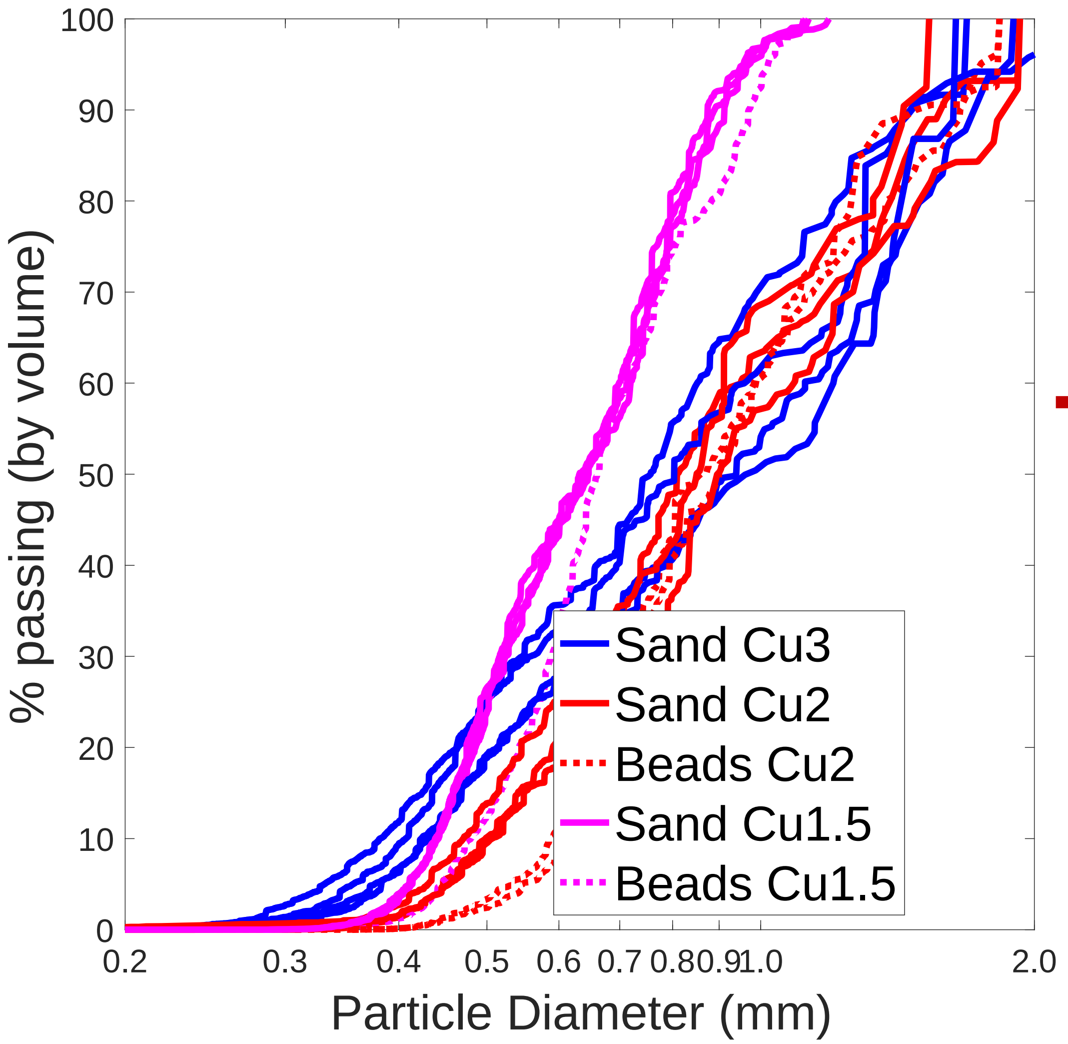
Filter CSD



Cumulative distribution by number

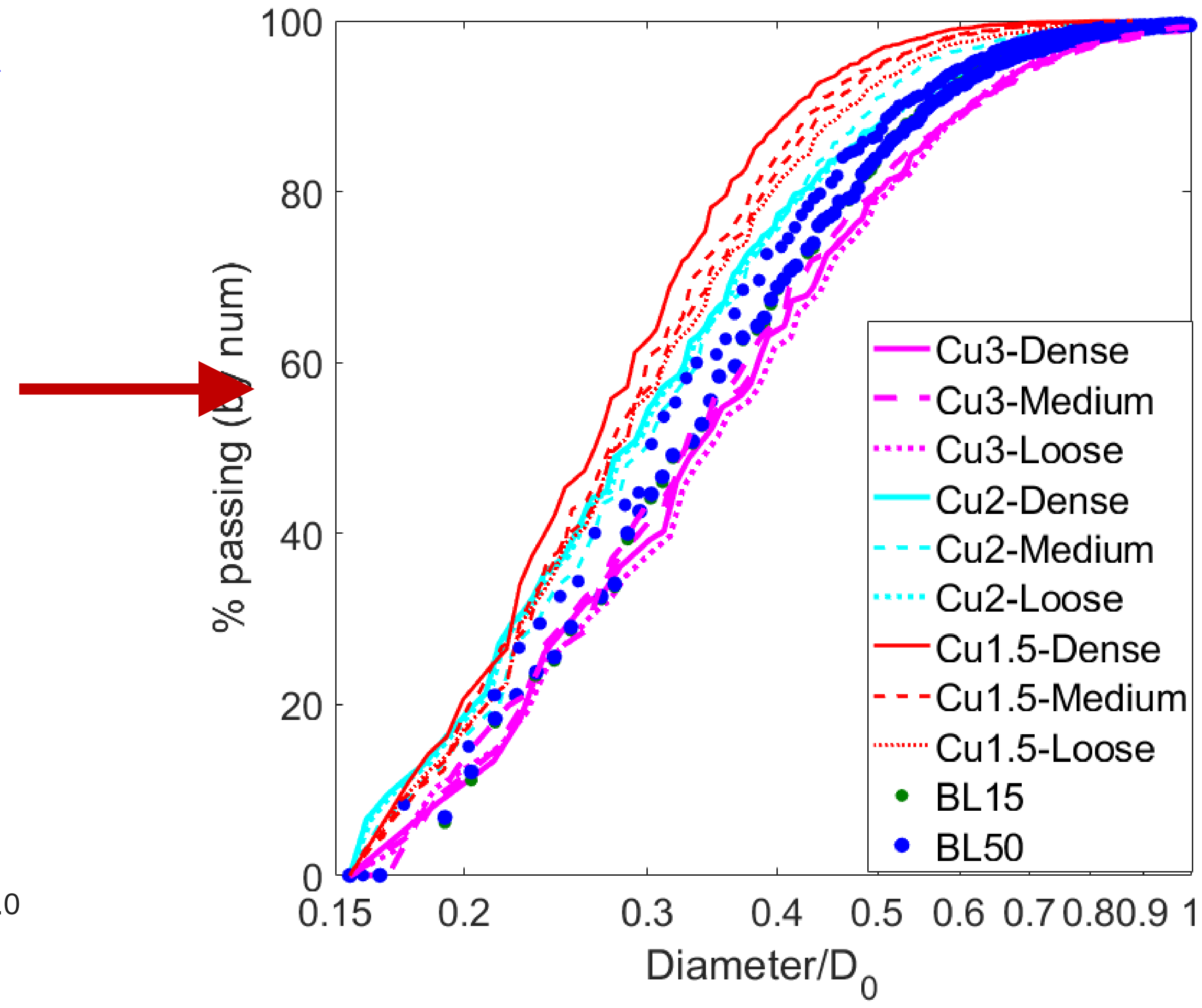
Constriction size distributions (CSDs) μCT

Filter PSD



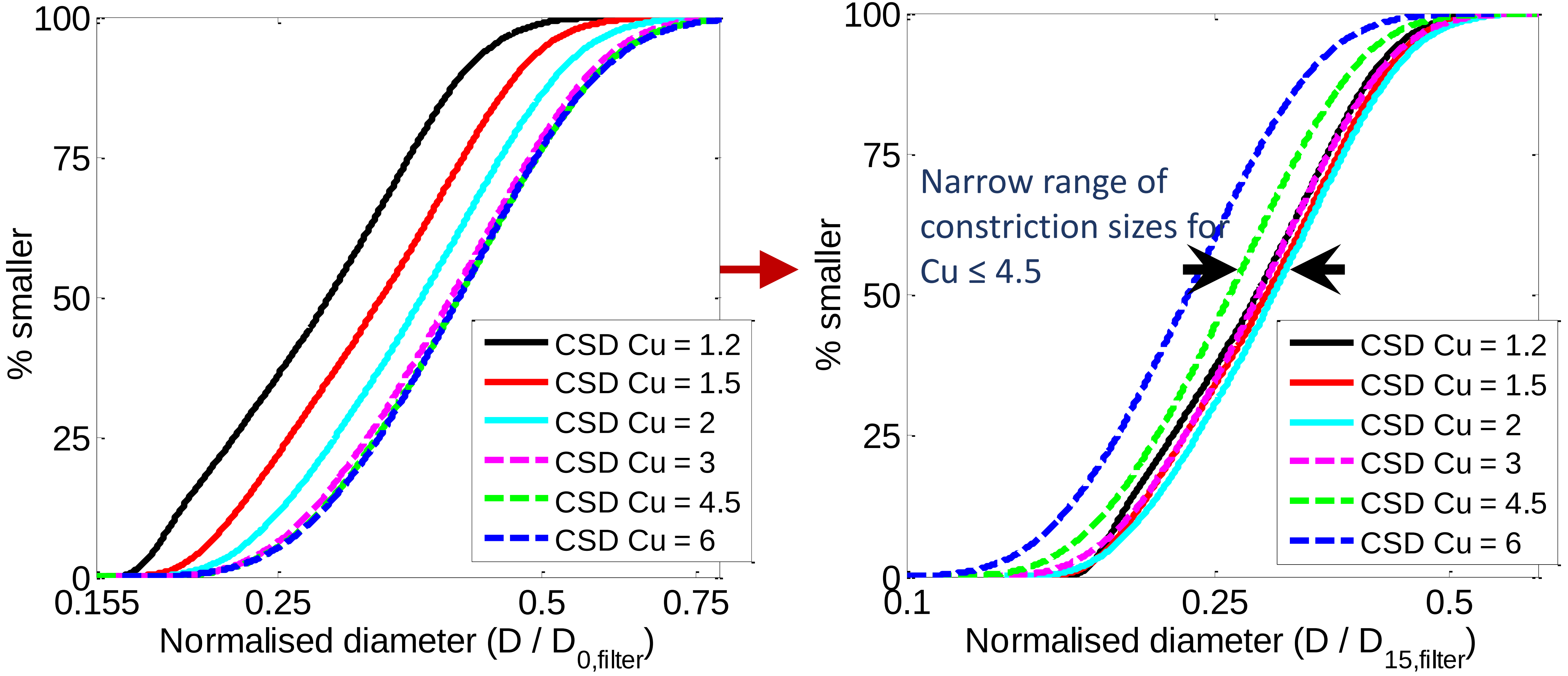
Cumulative distribution by volume

Filter CSD

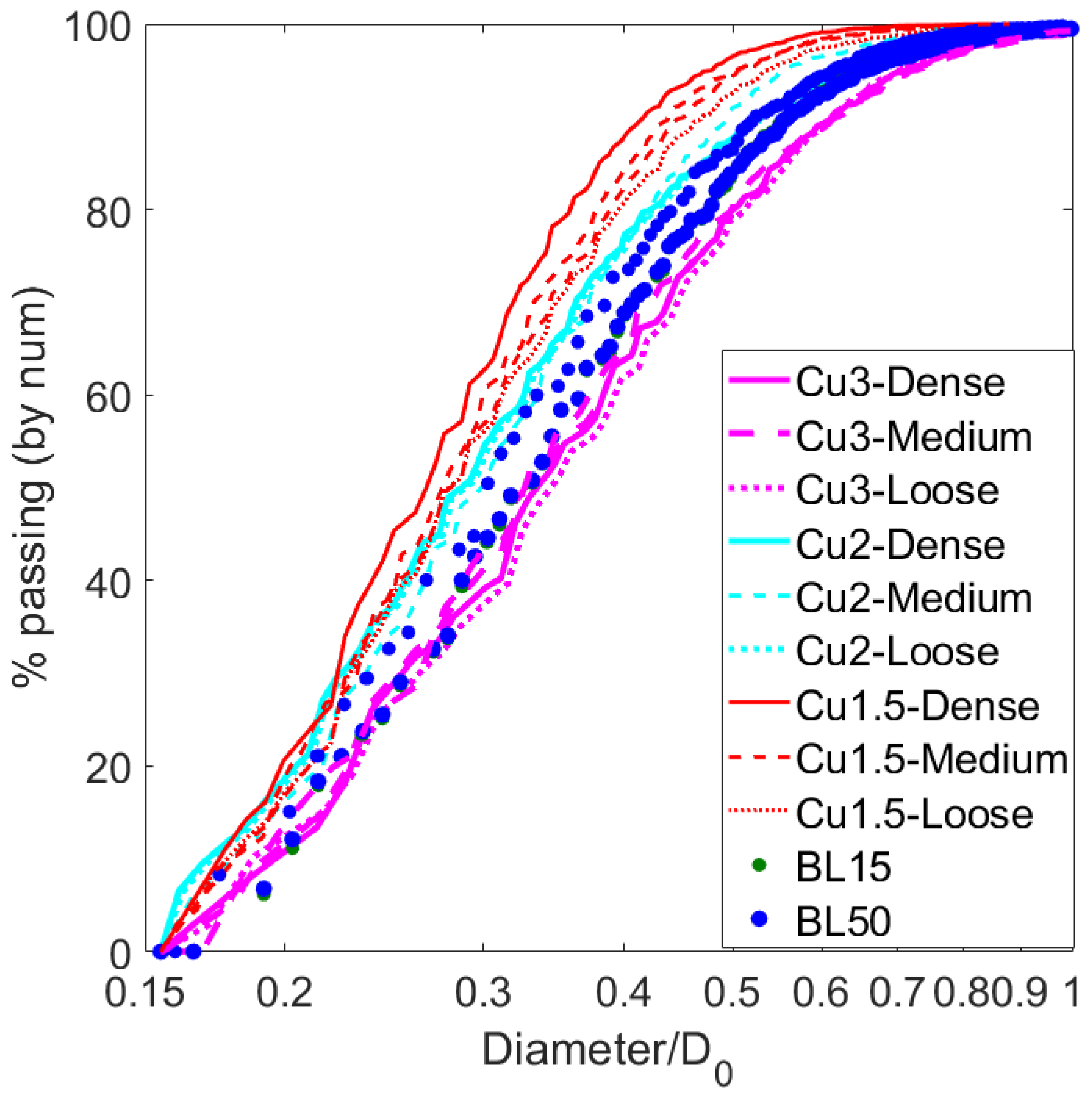


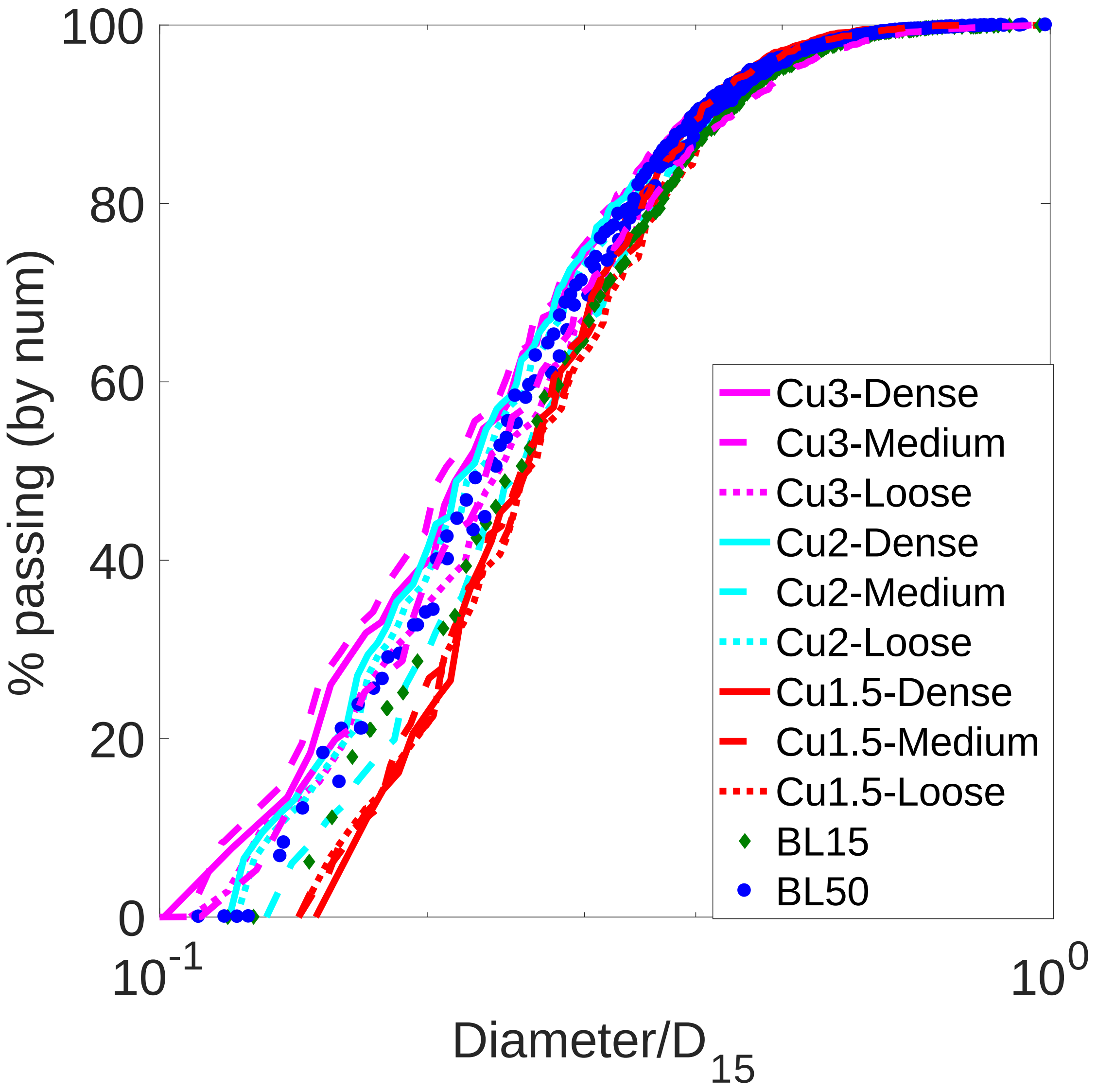
Cumulative distribution by number

Constriction Size Distributions (DEM)

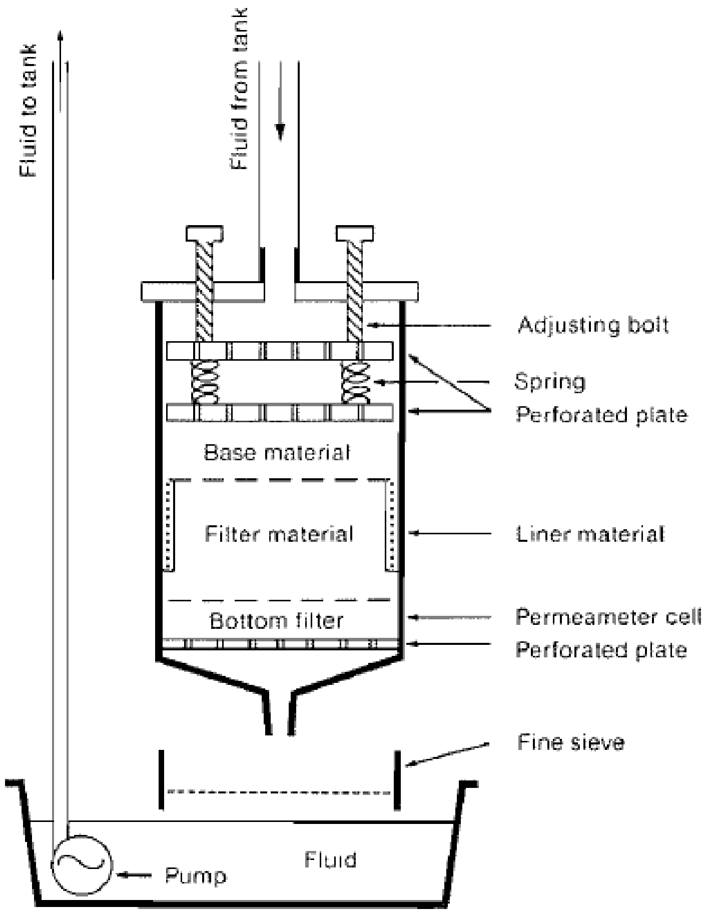


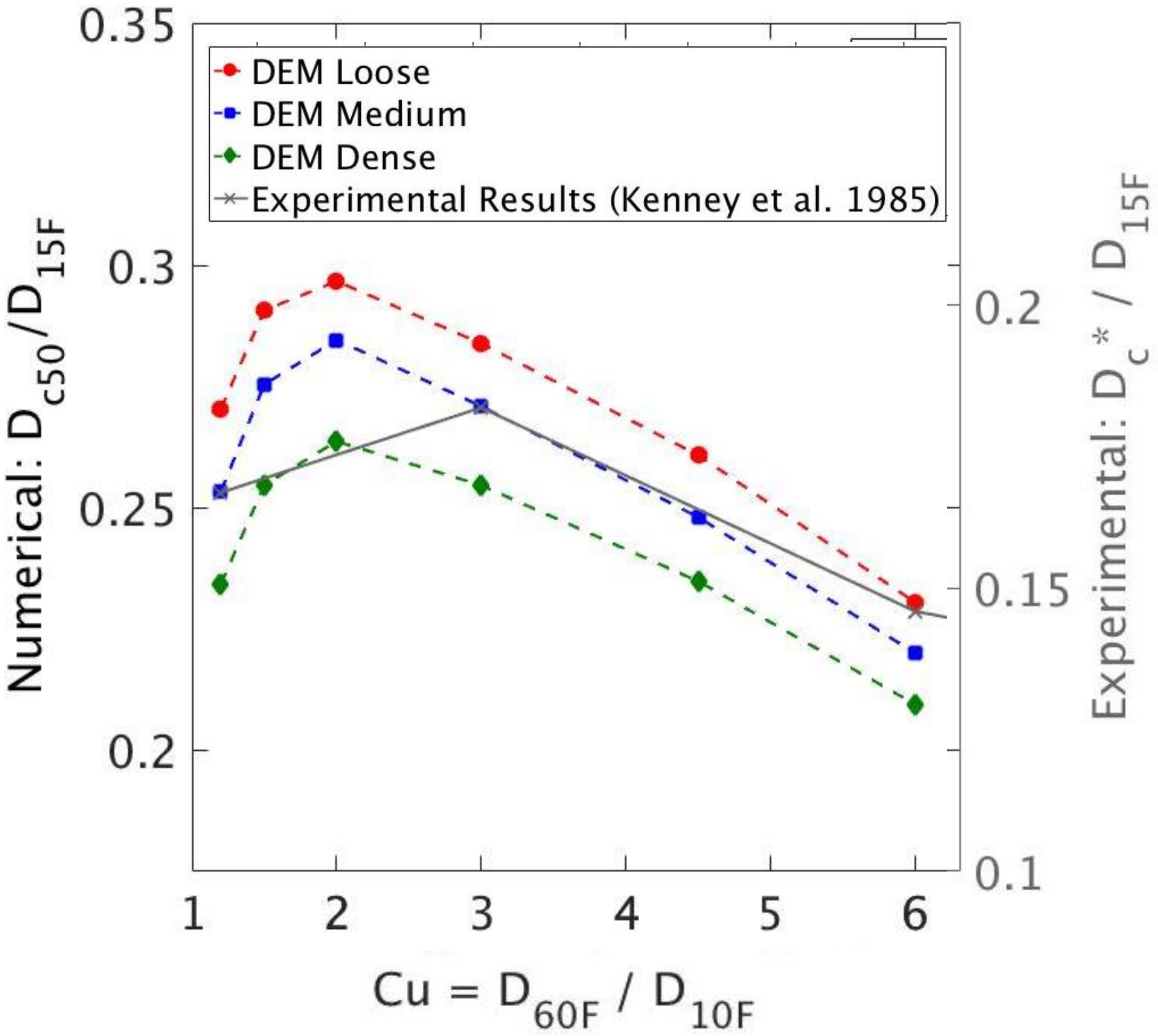
Constriction Sizes µCT





Controlling constriction size

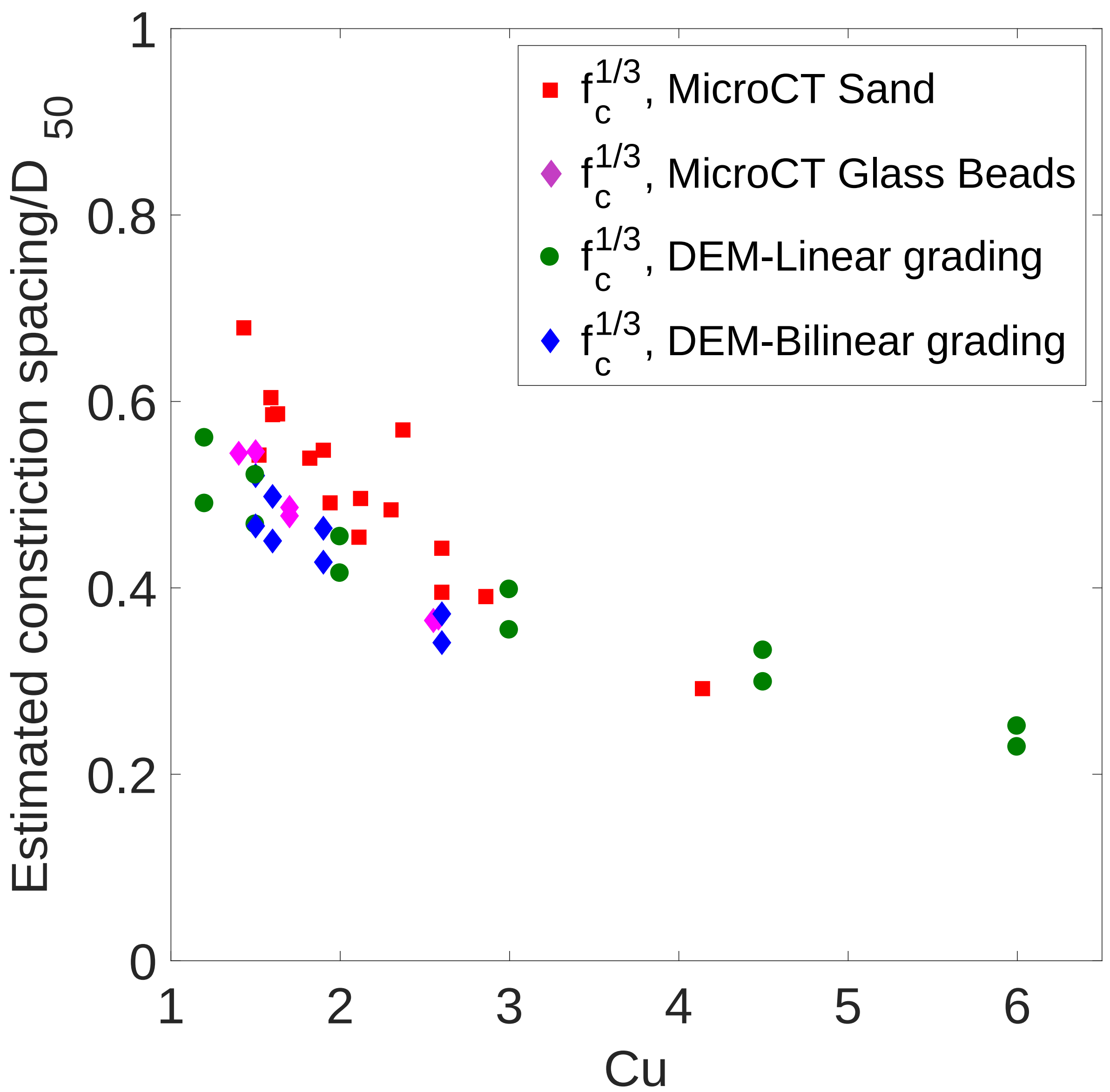


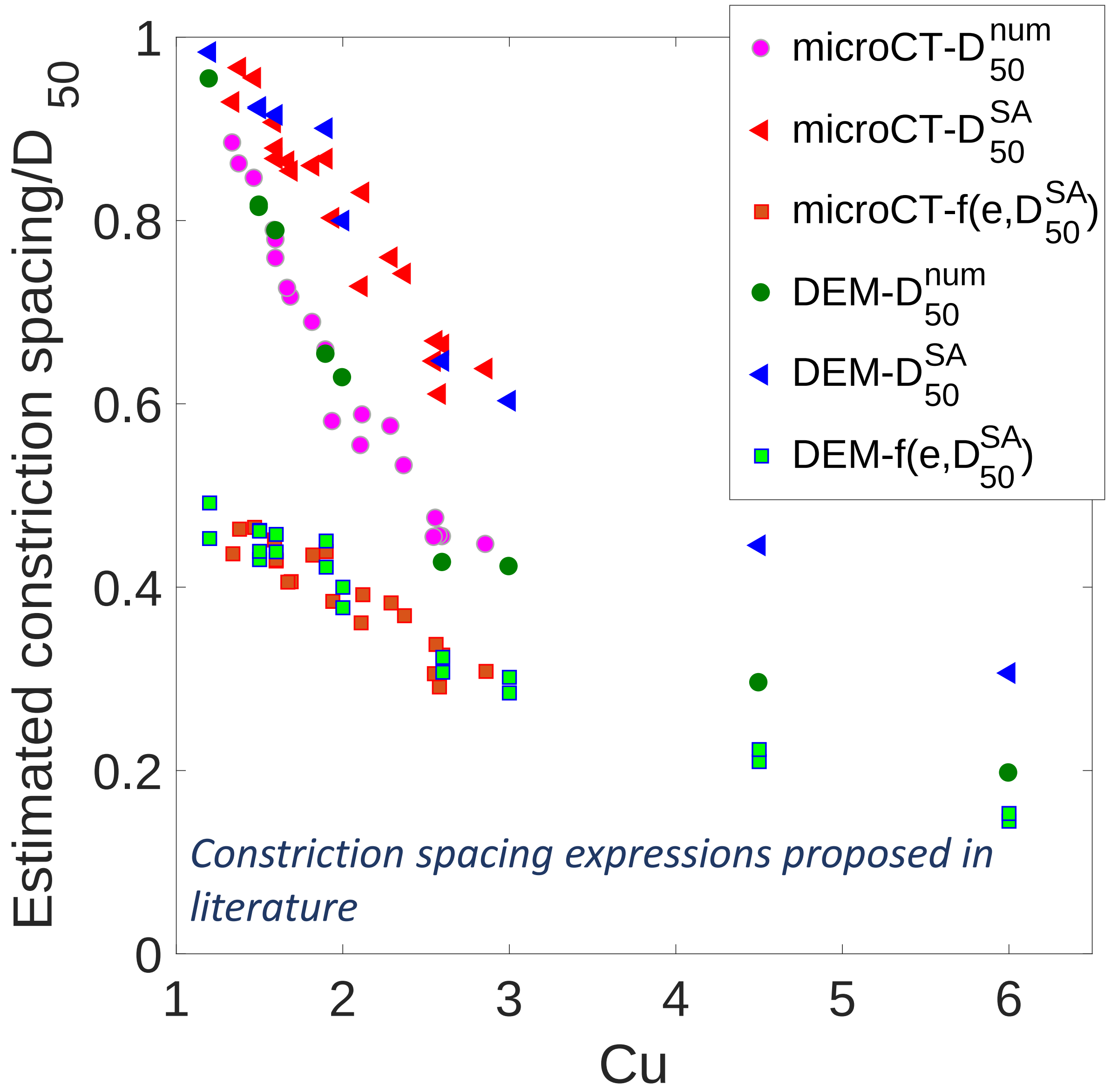


Kenney et al (1985): Base- Filter tests: Base-filer tests

Dc* = controlling constriction diameter = largest particle that can pass through filter

Filtration – Constriction Density / Spacing



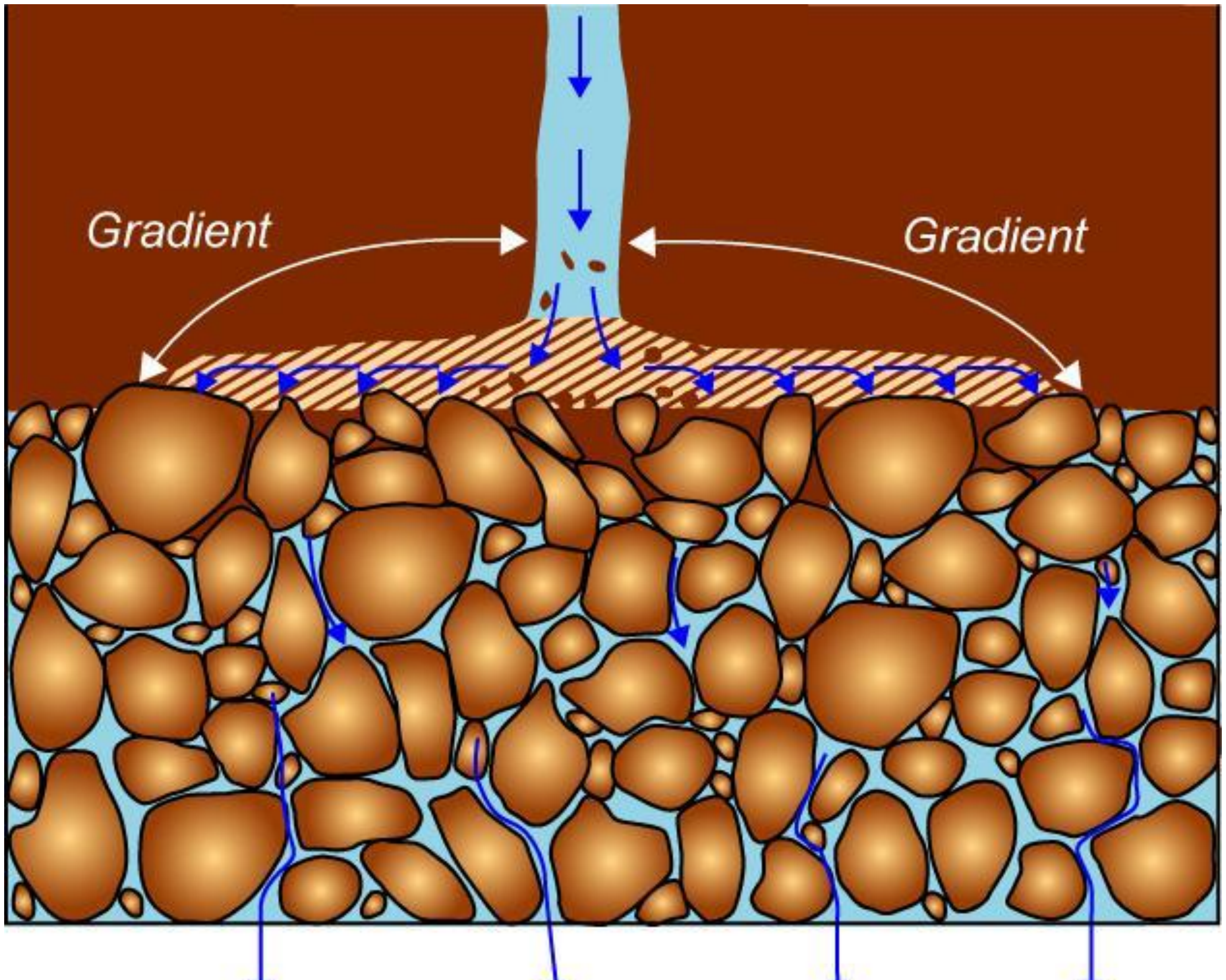


Research questions: Filter retention

- What is the relationship between the size of constrictions and D_{15F}?

- **Does particle scale analysis support use of the ratio D_{15F} / D_{85B} in design?**

Retention of Base



Base material: clay or silt with small particle size

Filter – large particle size to achieve drainage

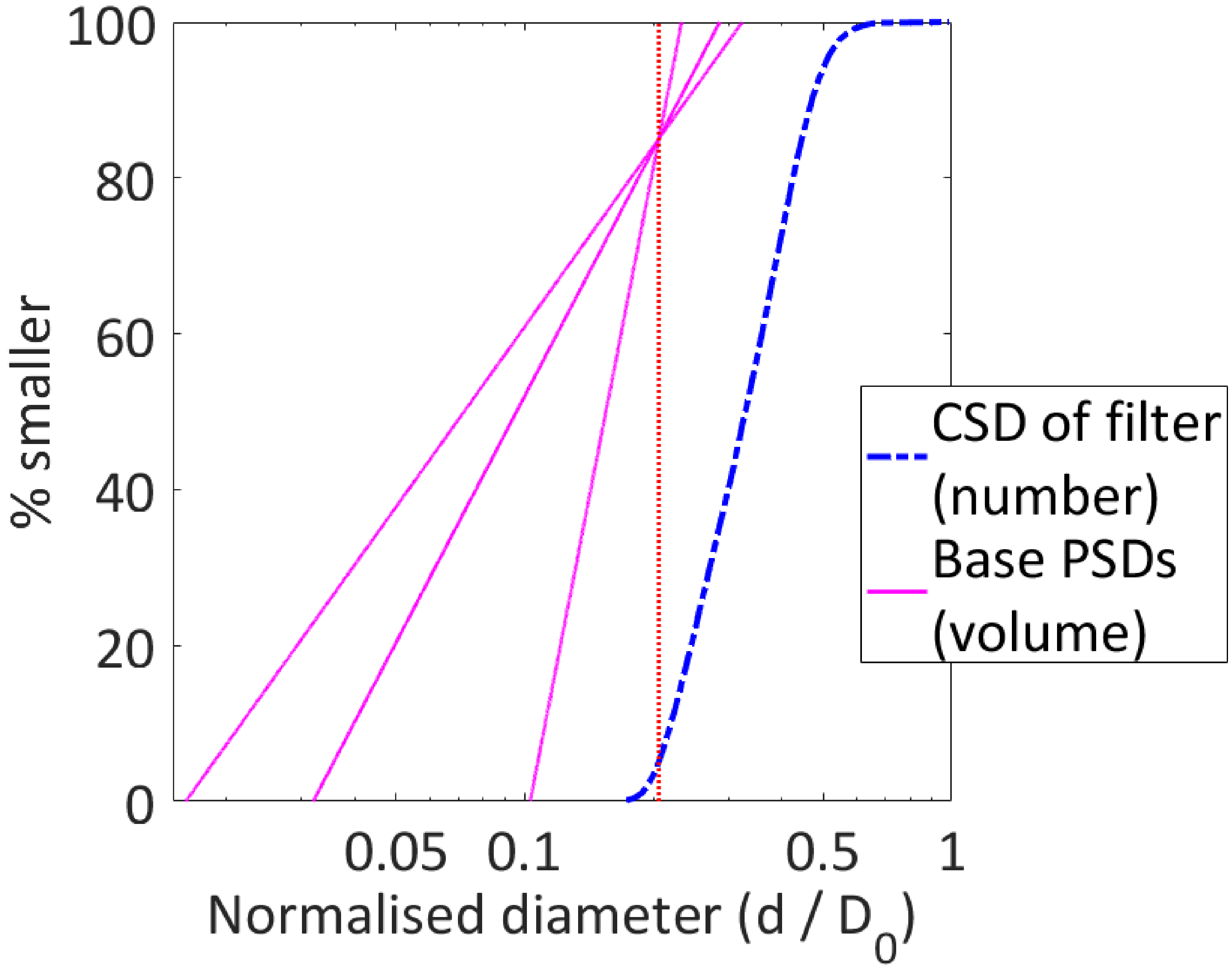
(FEMA, 2011)

Retention – Network model

Can't judge a filter's effectiveness simply by visual comparison of the CSD of the filter and the PSD of the base material to be retained

CSD – cumulative distribution by number

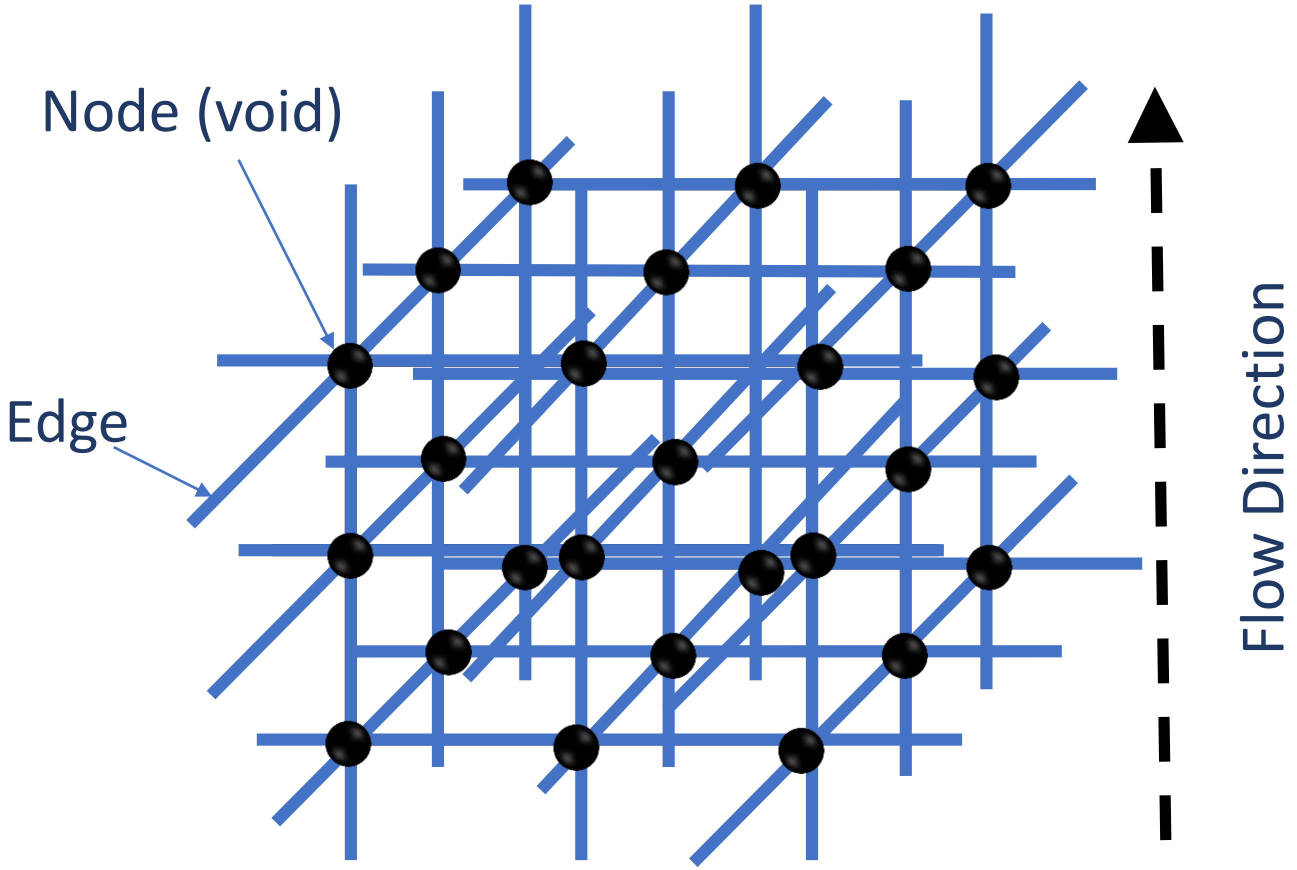
PSD – cumulative distribution by volume



PhD Research of Dr. Thomas Shire

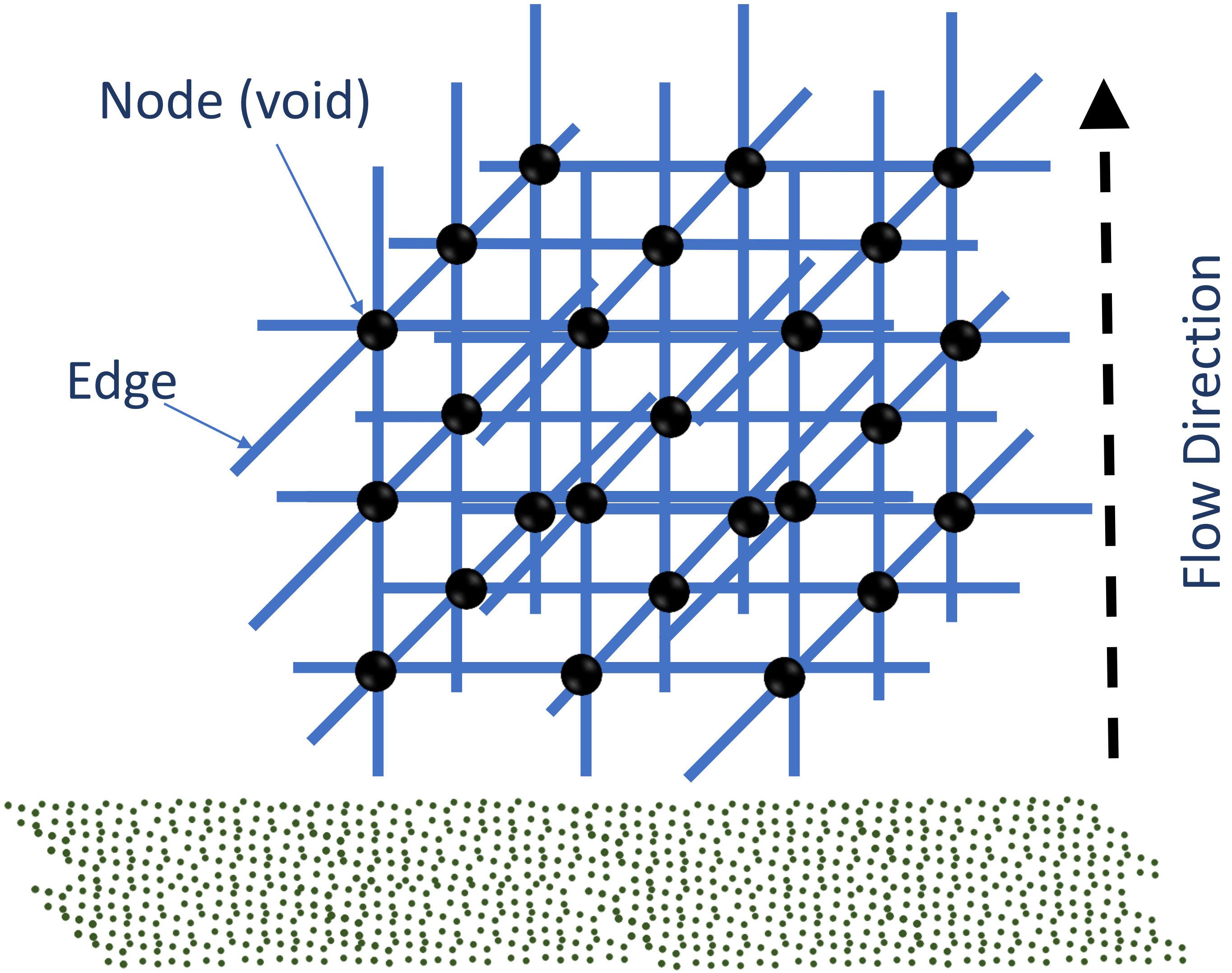
Filtration – Network model

- Network model – lattice topology
- Nodes = individual voids
- Edges = inter void connections
- Edge diameters = constriction diameters



Filtration – Network model

- Simulates migration of finer base particles through network
- Fluid flow not explicitly considered
- Simple algorithm means up to 400 million base particles could be considered on a desktop pc



Filtration – Network model

- Network model – lattice topology
- Nodes = individual voids
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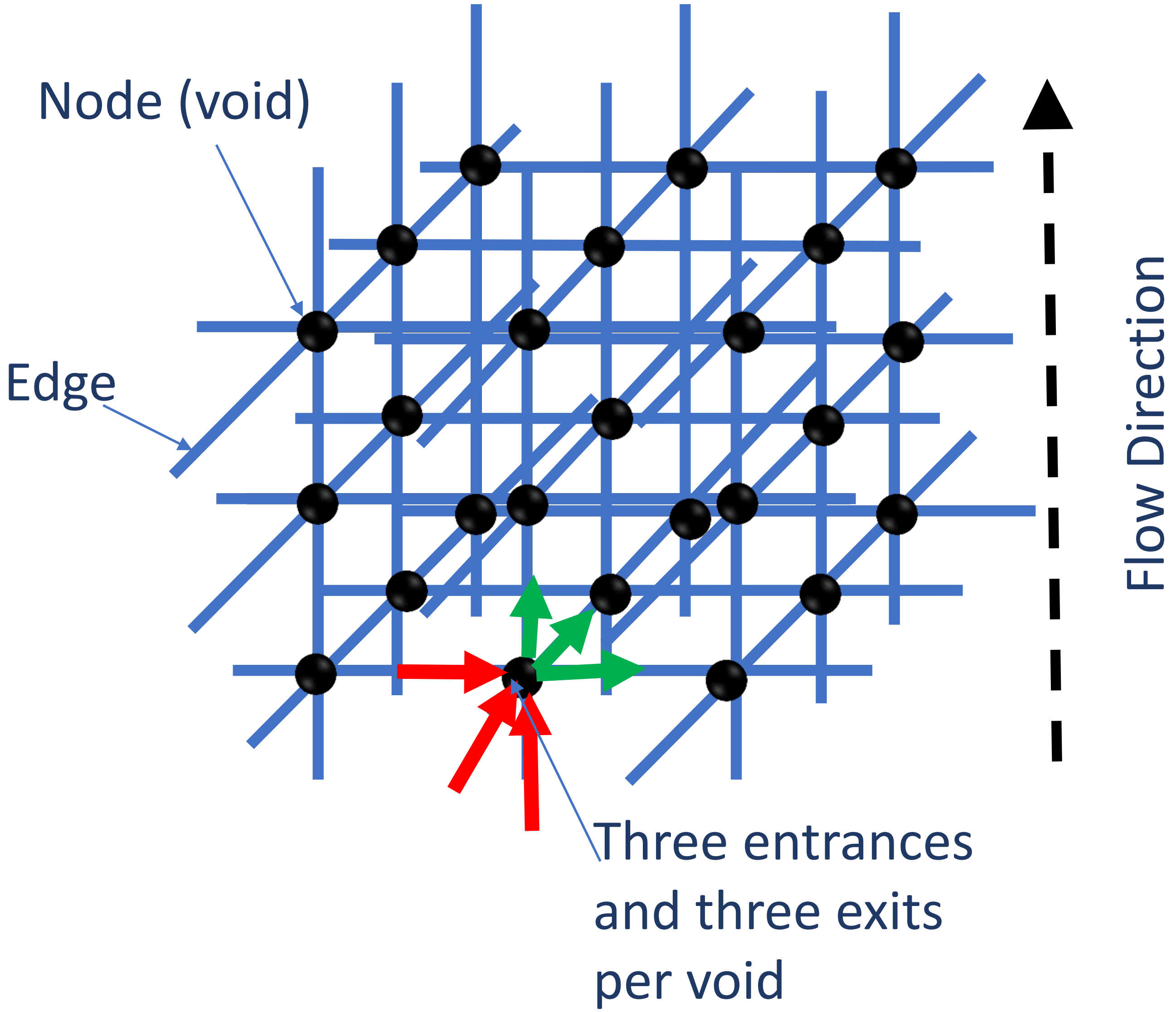
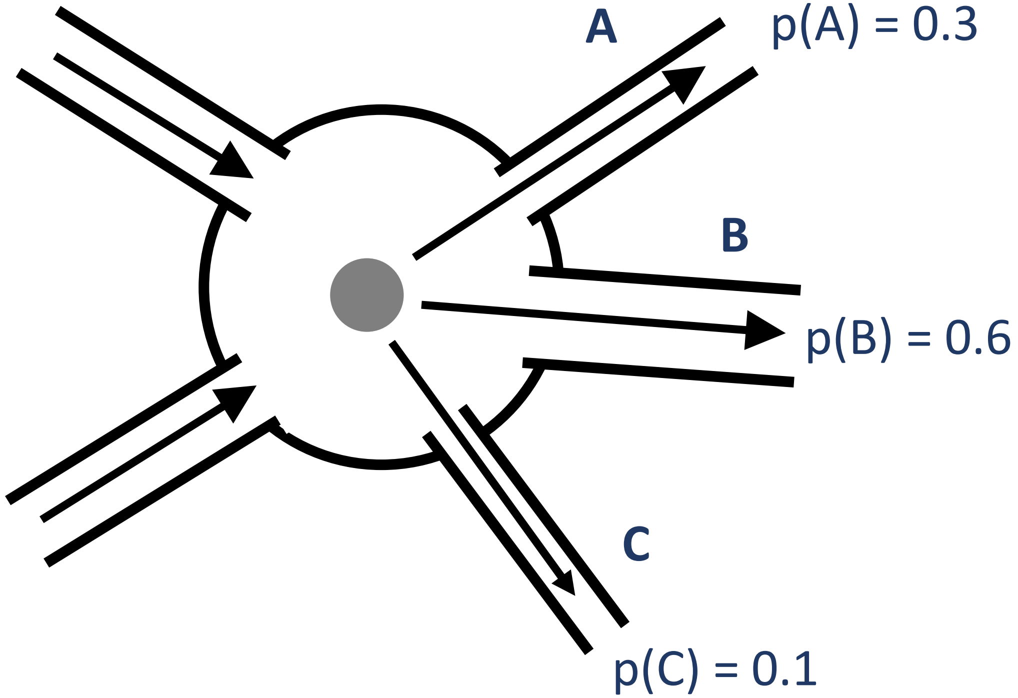
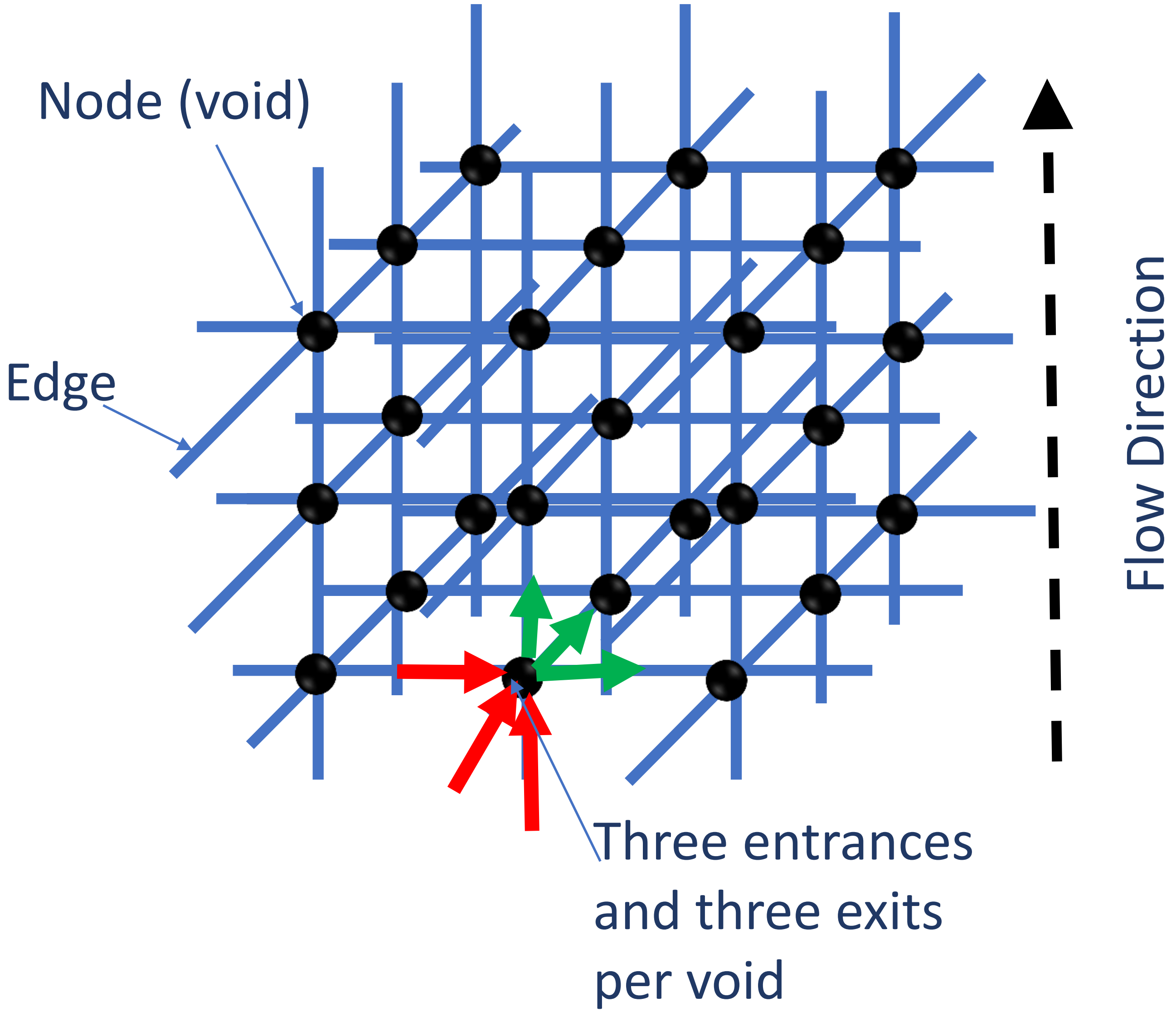


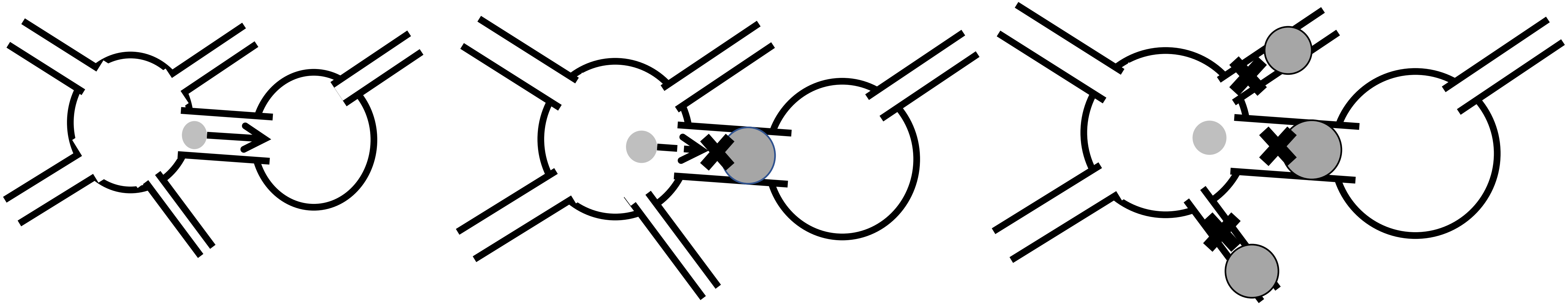
Area based random walk



Likelihood of selecting a target edge to move through depends on constriction area



“Random walk” of base particles through network

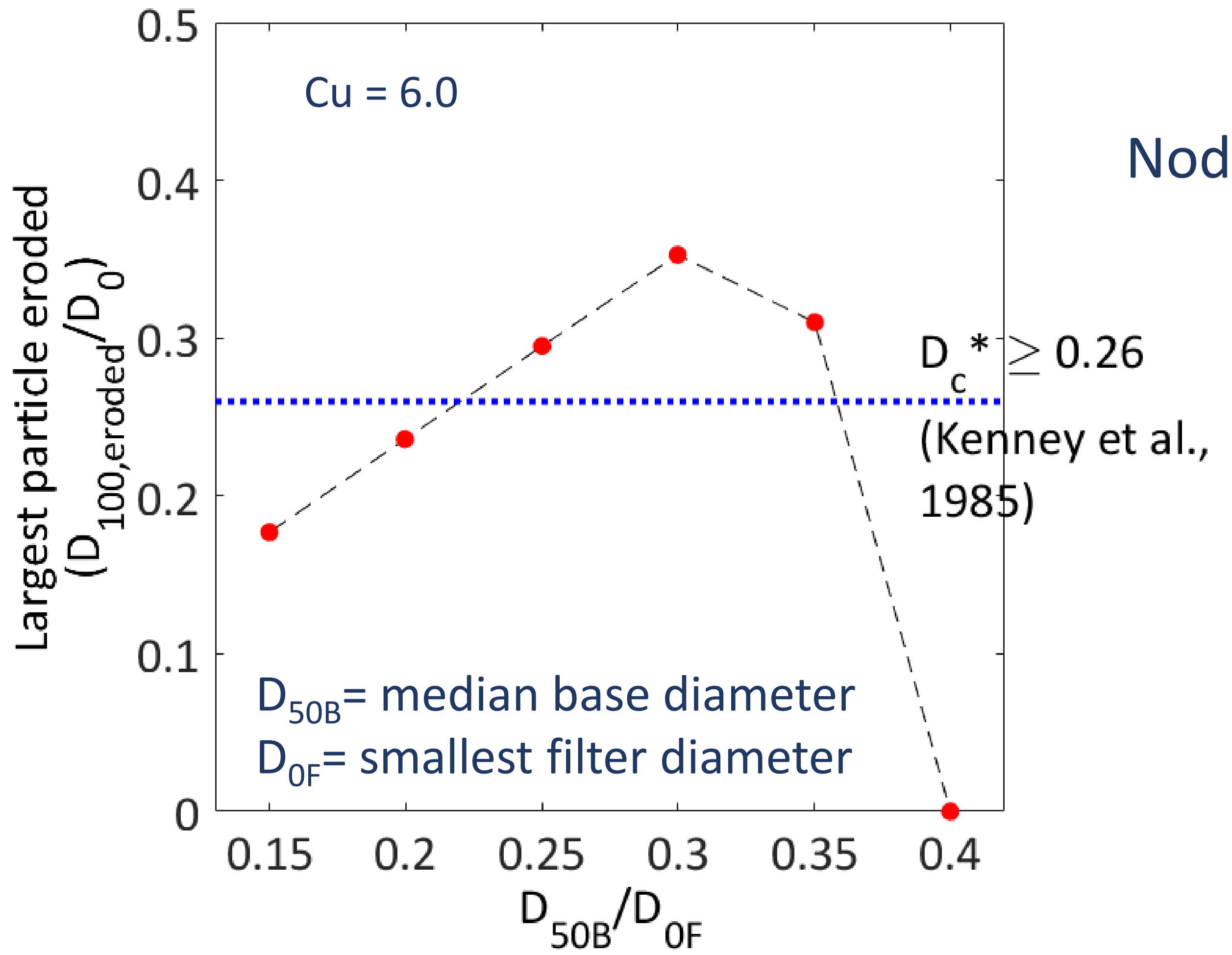


Base particle moves through constriction

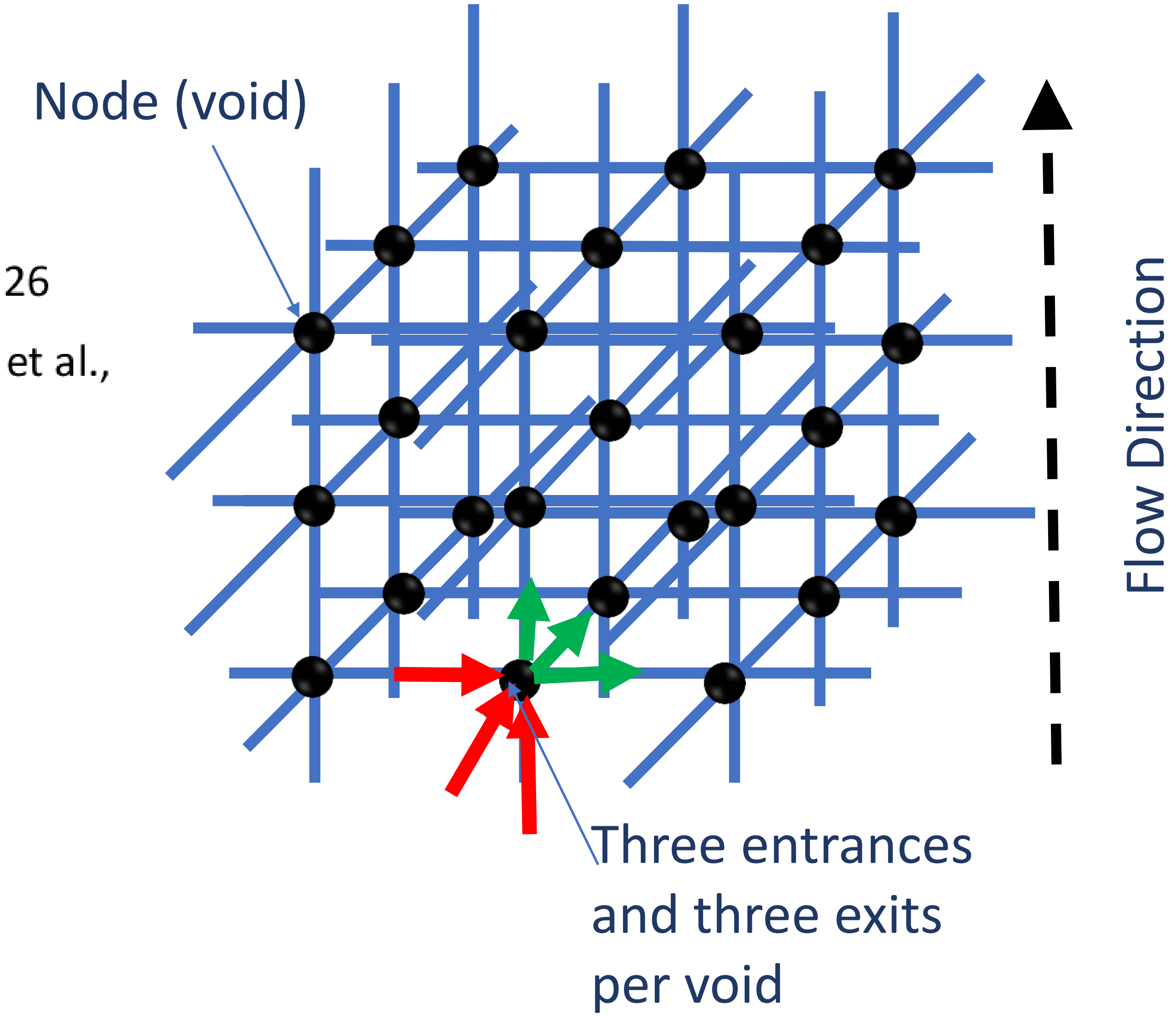
Base particle retained + constriction blocked

Base particle retained in void

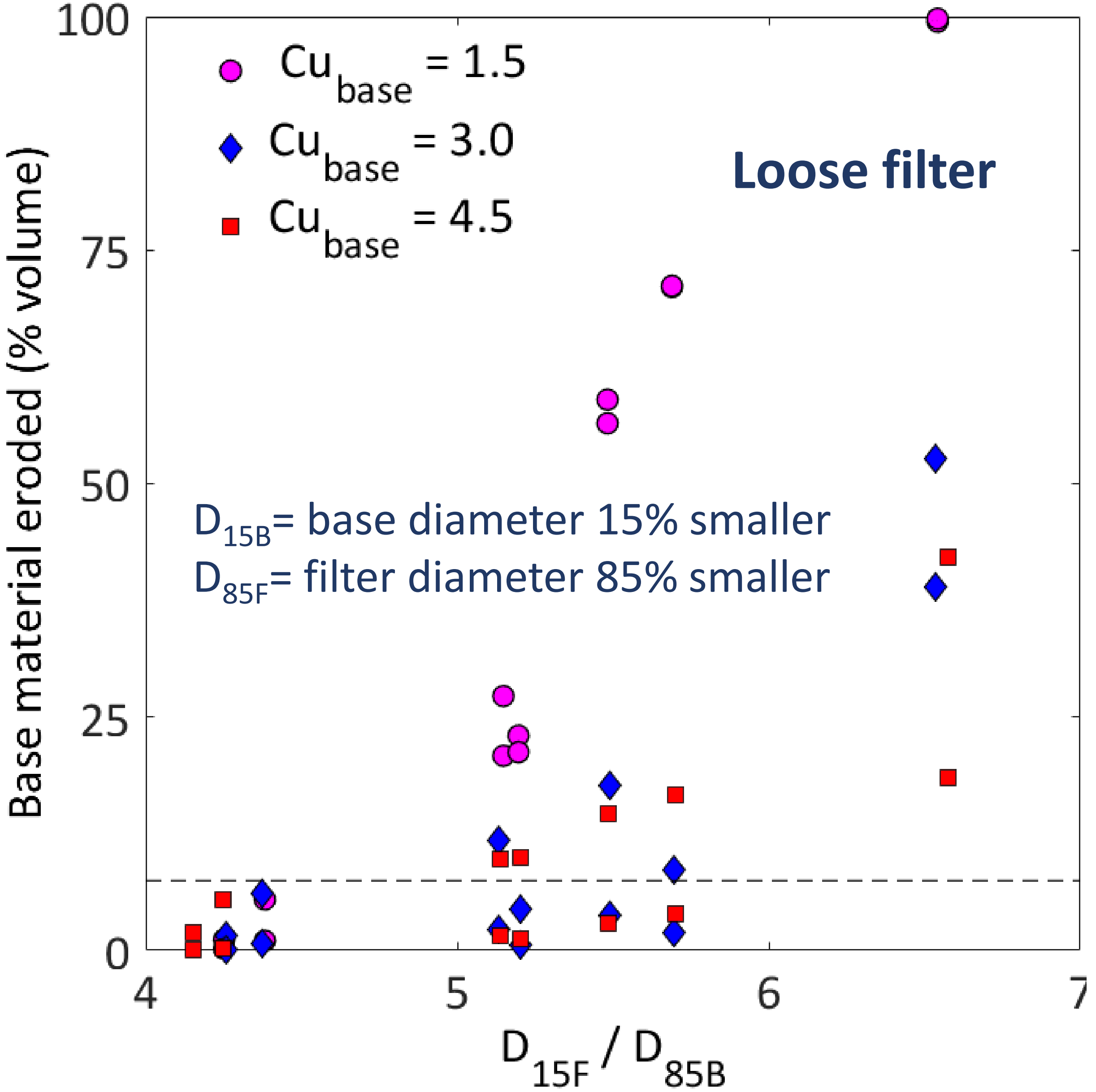
Filtration – Network model



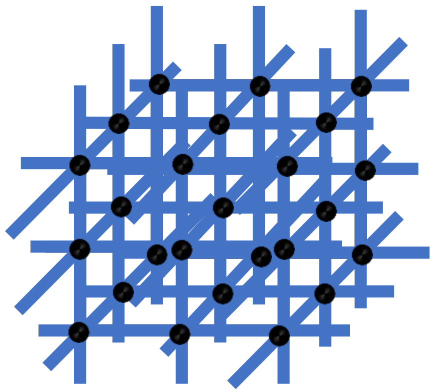
Filter Cu =1.2, 3, 6, largest base particle eroded agrees with experimental data



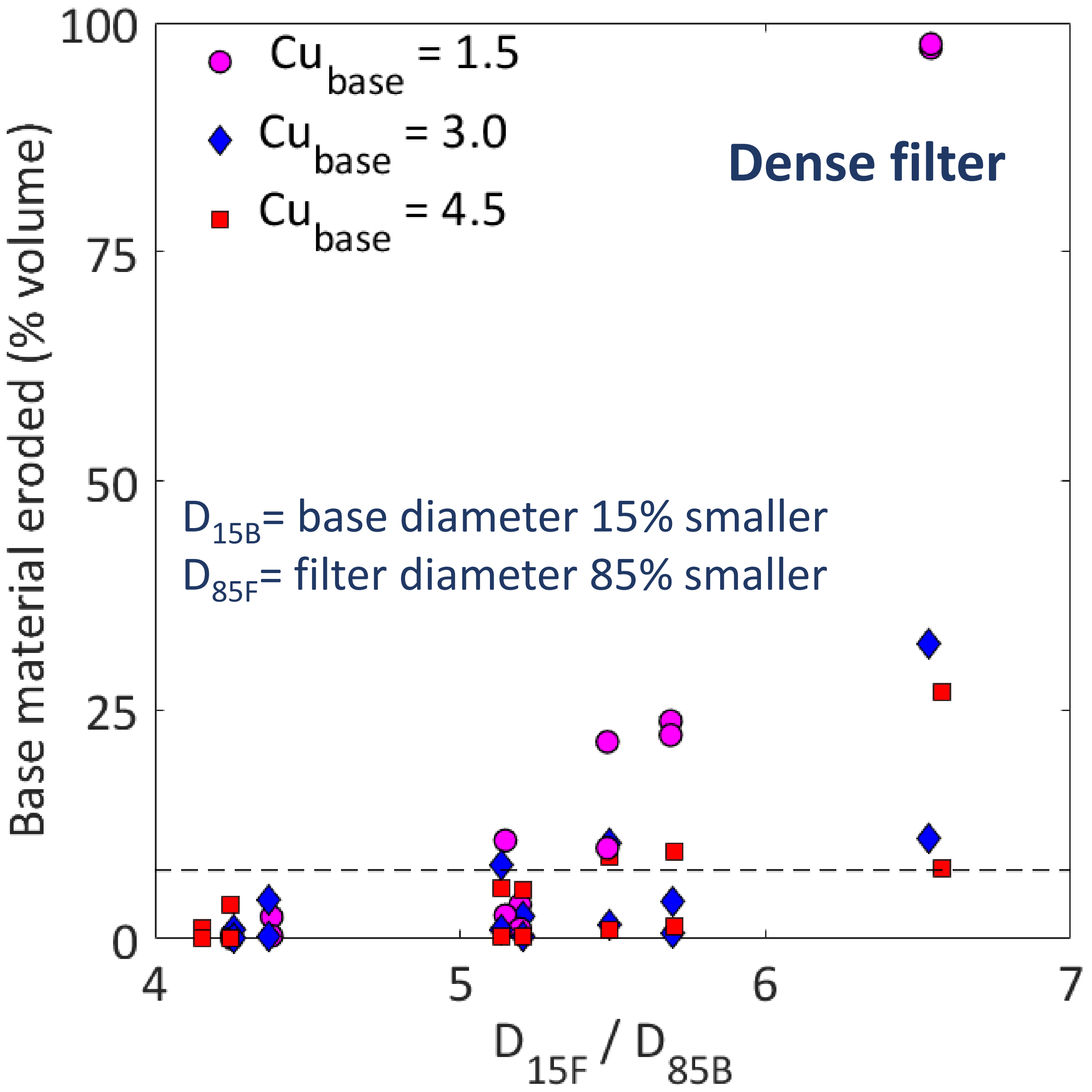
Filtration – Network model



- Cu Filter = 1.5 and 3.0
- Network model that considers only constriction sizes and not full void space topology confirms experimental observation that filter characteristic diameter (D_{15F}) controls filtration



Filtration – Network model



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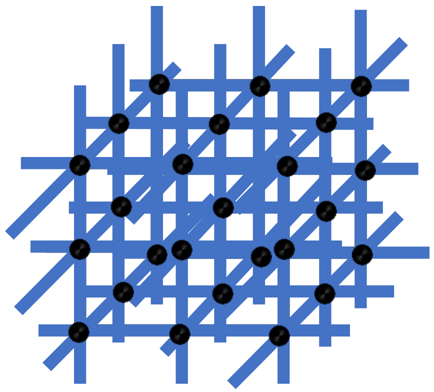


Research questions: Filter retention

- Normalization of constriction size distributions by D_{15F} gives a narrow set of curves, supporting idea that D_{15F} is indicative or representative of the constrictions sizes in a filter.

- Network analyses support use of D_{15F}/ D_{85B} to judge retention capacity. Analyses also support idea that effective retention requires $D_{15F} < 4\ D_{85B}$ in line with recent ICOLD documents.

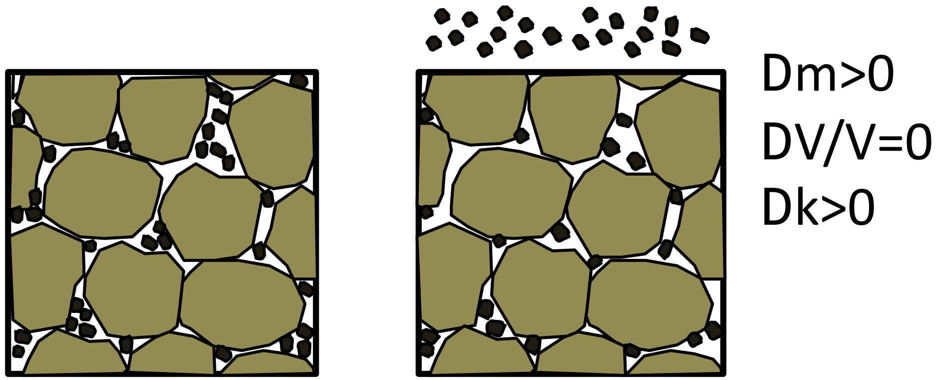
Suffusion

- **suffusion** is the selective erosion of the fine particles from the matrix of coarse particles under the action of a hydraulic gradient

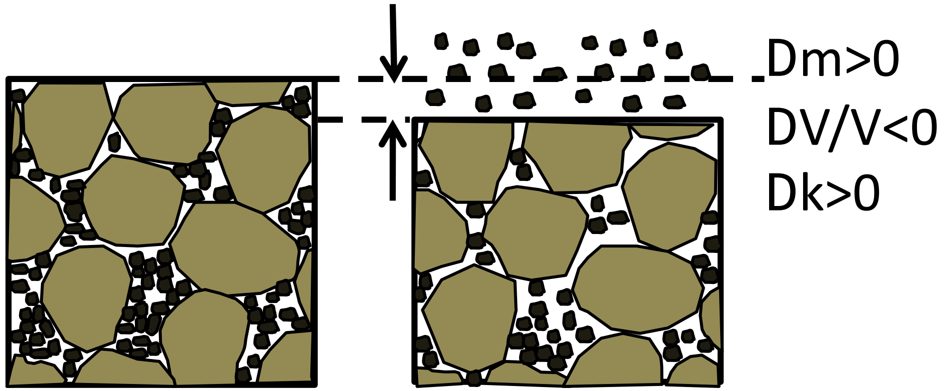
- **suffusion** is sometimes associated with lack of volume change, **suffosion** associated with volume change

- **internally unstable soils** are susceptible to suffusion / suffusion – **internal instability** general term

m - mass
V - volume
k - hydraulic conductivity



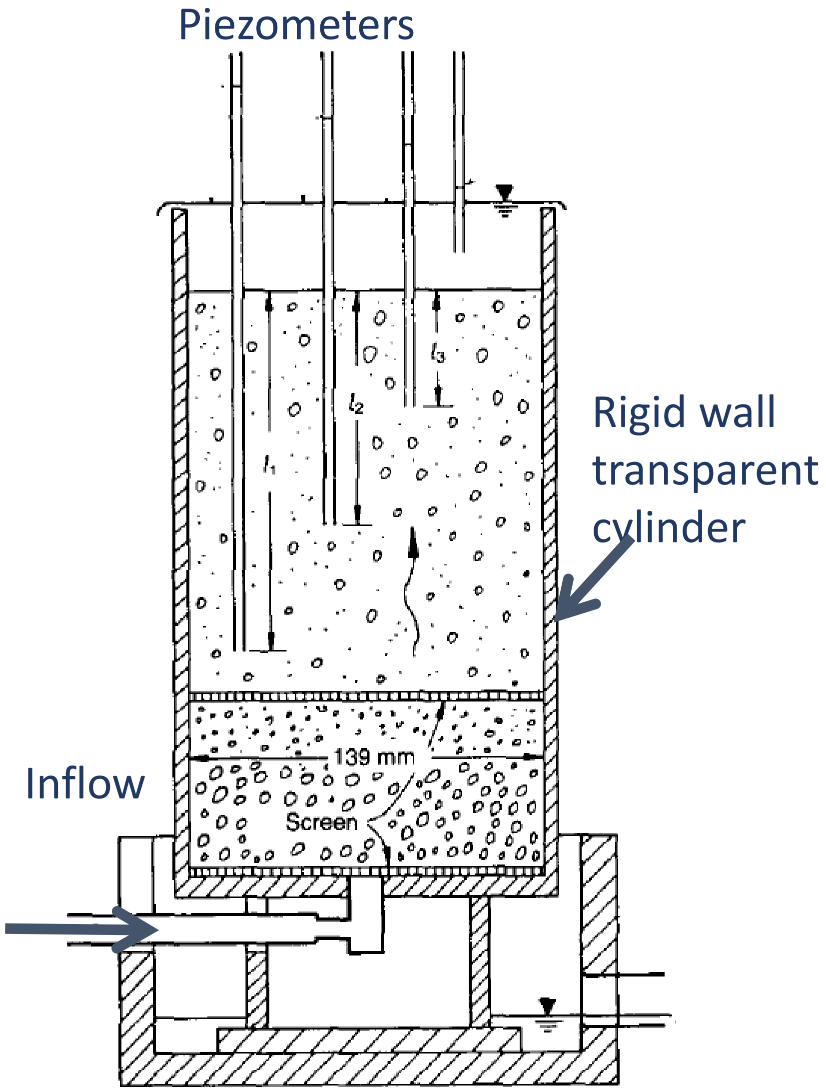
Instability without volume change

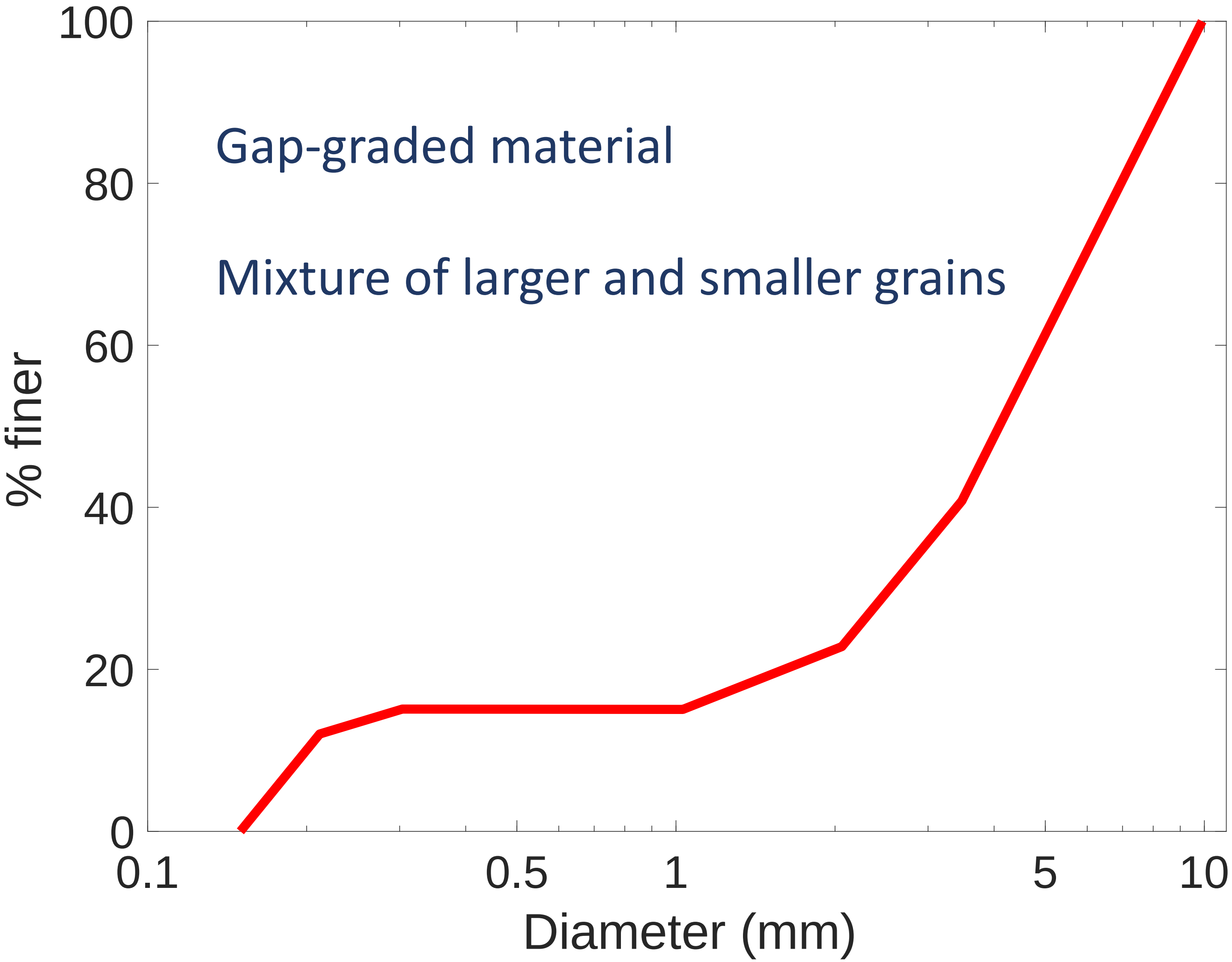


Instability with volume change

After Slangen and Fannin

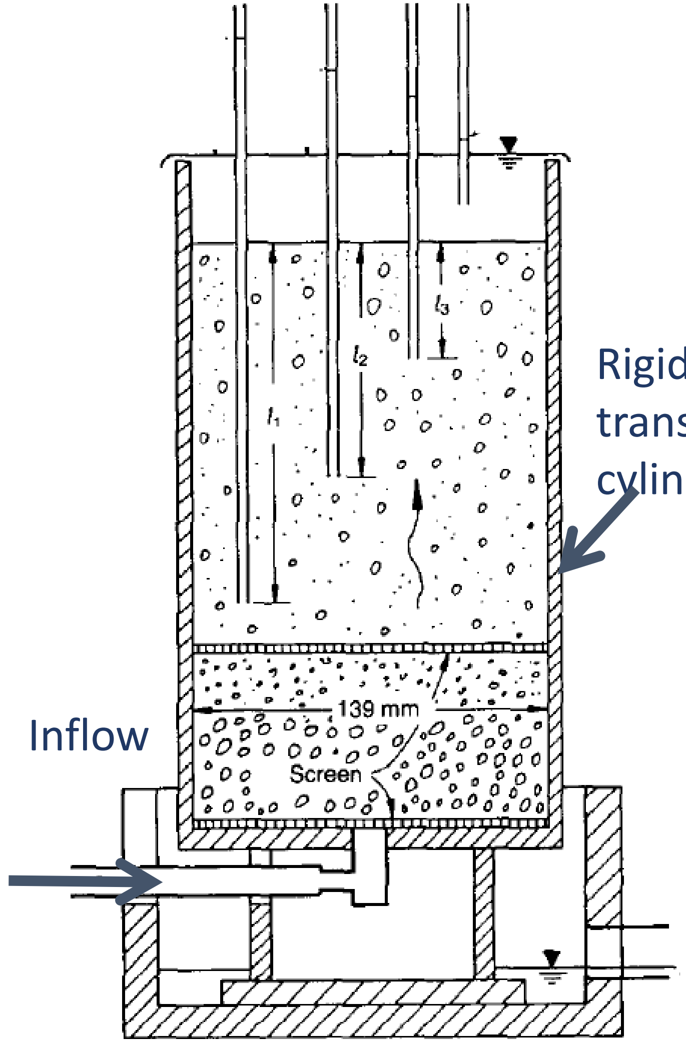
Skempton and Brogan Permeameter Experiments





Skempton and Brogan Permeameter Experiments

Piezometers

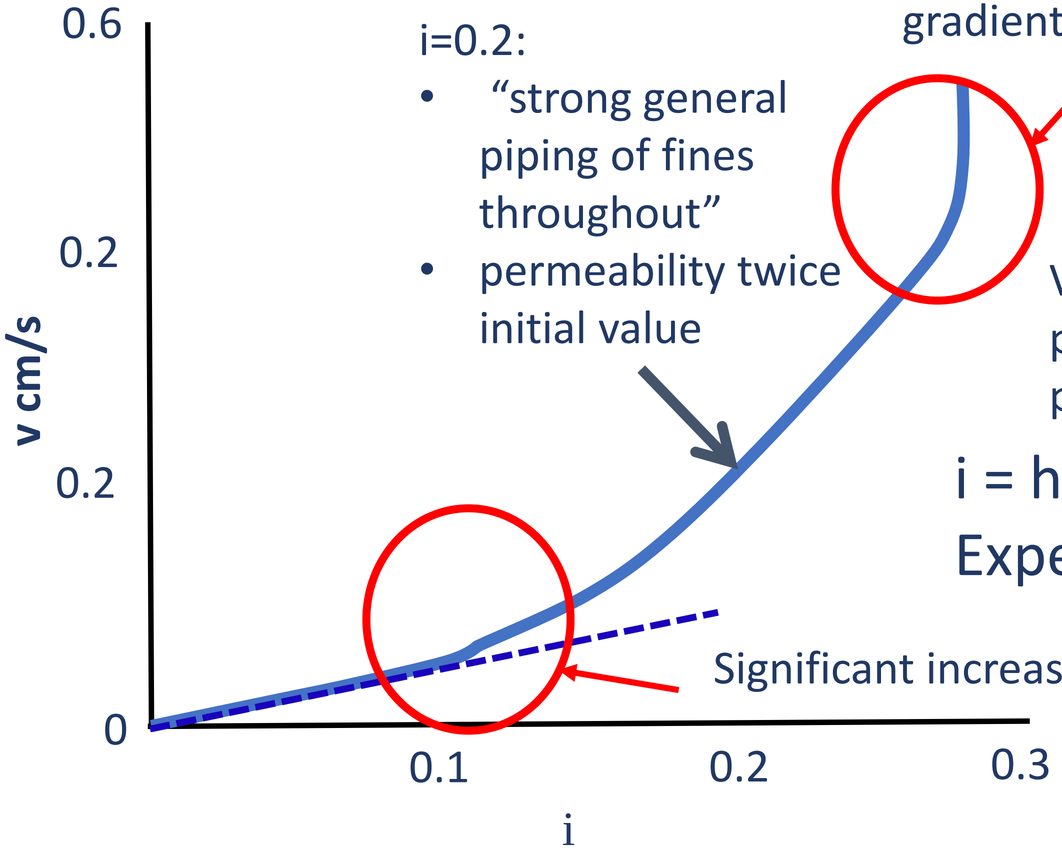


Rigid wall transparent cylinder

Inflow

Skempton and Brogan (1994)
Géotechnique

Sample A



i=0.2:

- "strong general piping of fines throughout"
- permeability twice initial value

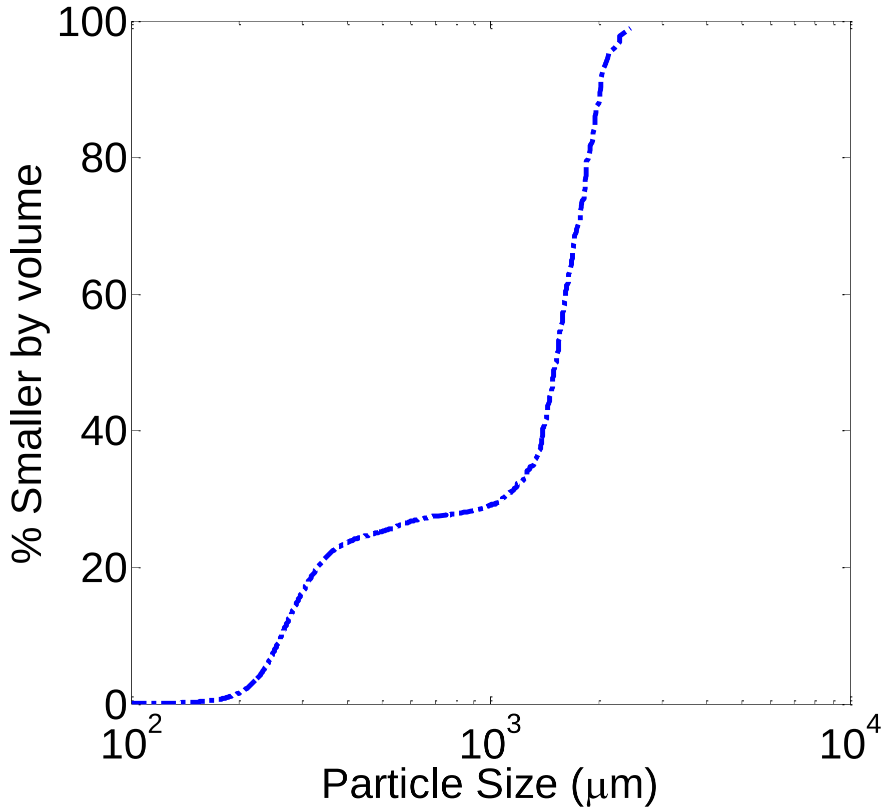
Clear that complete failure is happening at a low hydraulic gradient

Variations in permeability will cause preferential flow

i = hydraulic gradient
Expect v = ki

Significant increase in permeability

Internal Instability



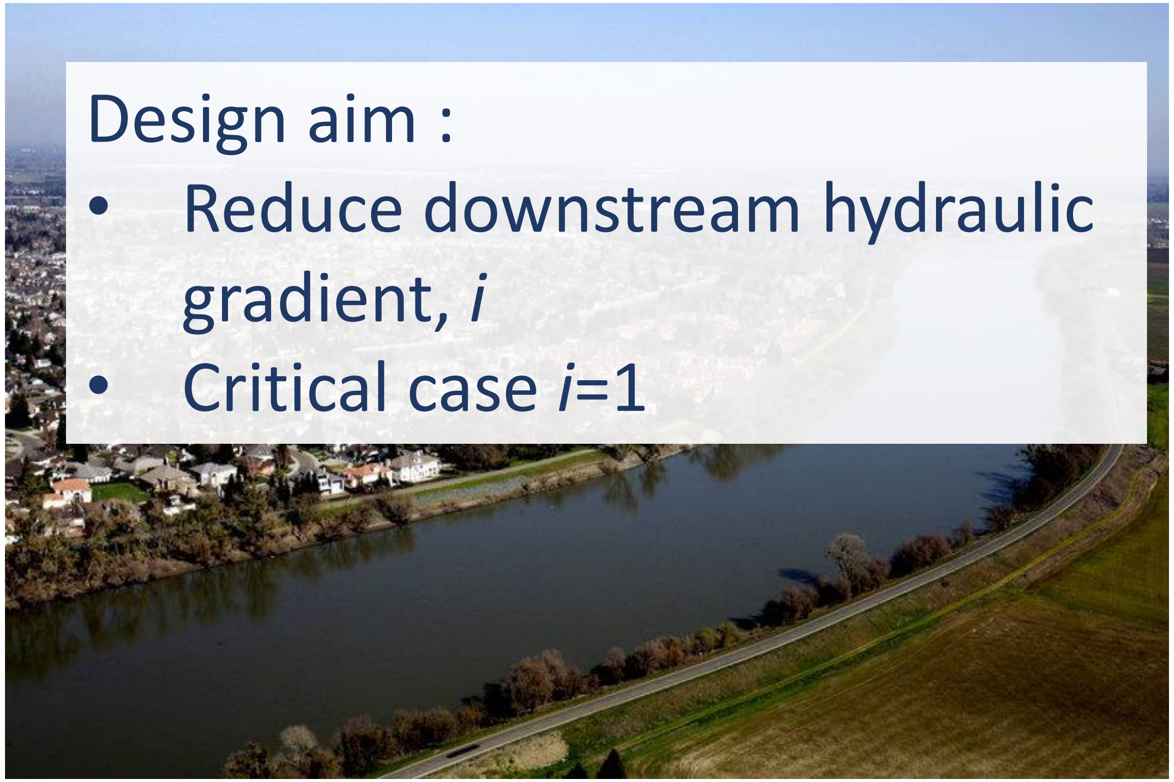
Robert Negri MSc

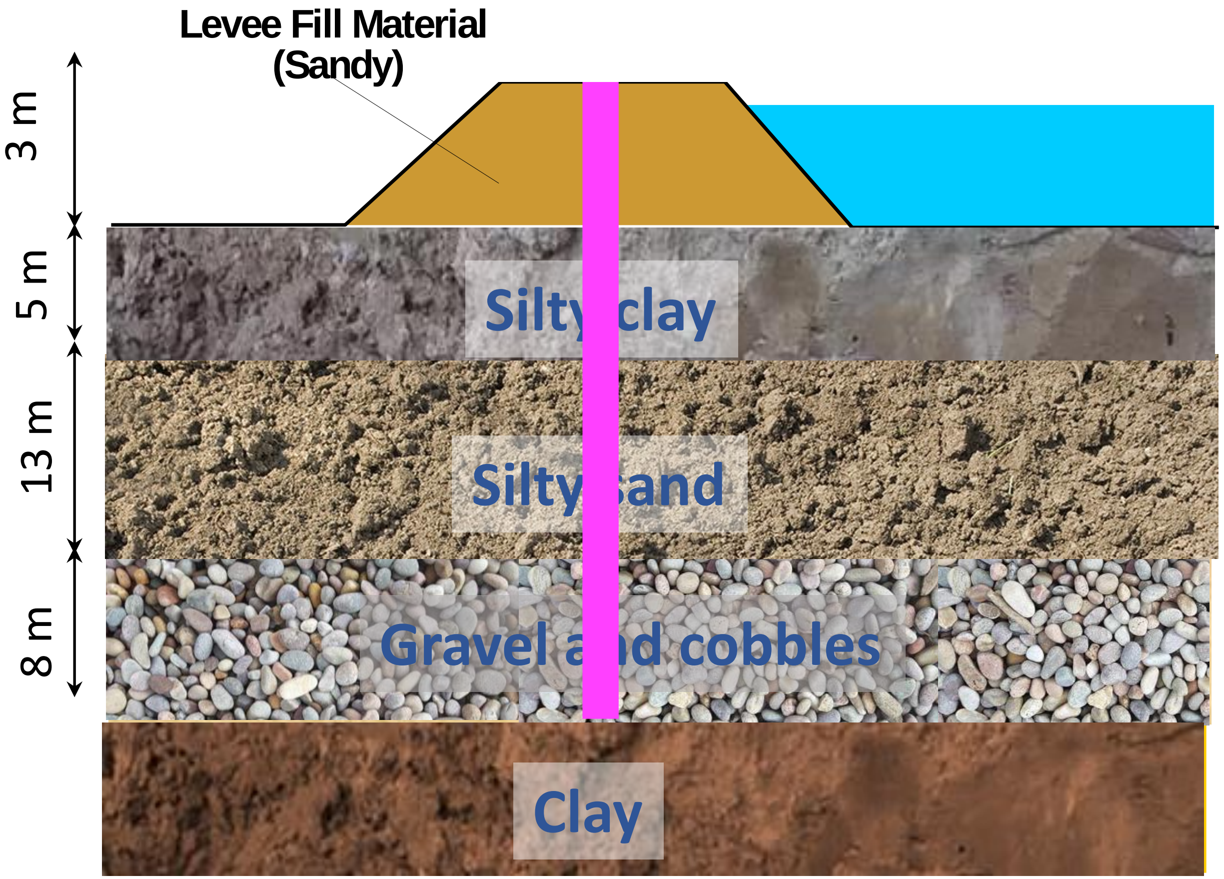
MSc student photo of internal instability

Flood embankments

Design aim :

- Reduce downstream hydraulic gradient, *i*
- Critical case *i*=1



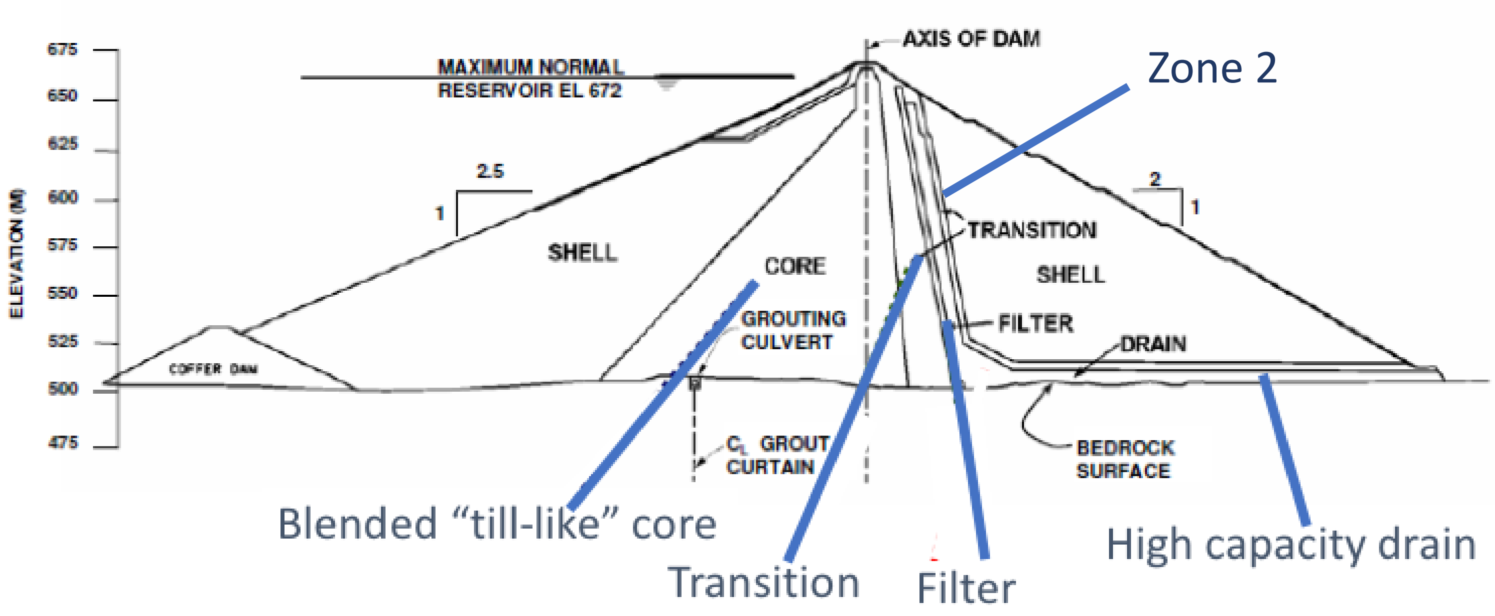


https://www.npr.org/2017/10/02/554994446/flood-prone-communities-struggle-to-meet-post-katrina-standards?t=1550590982035

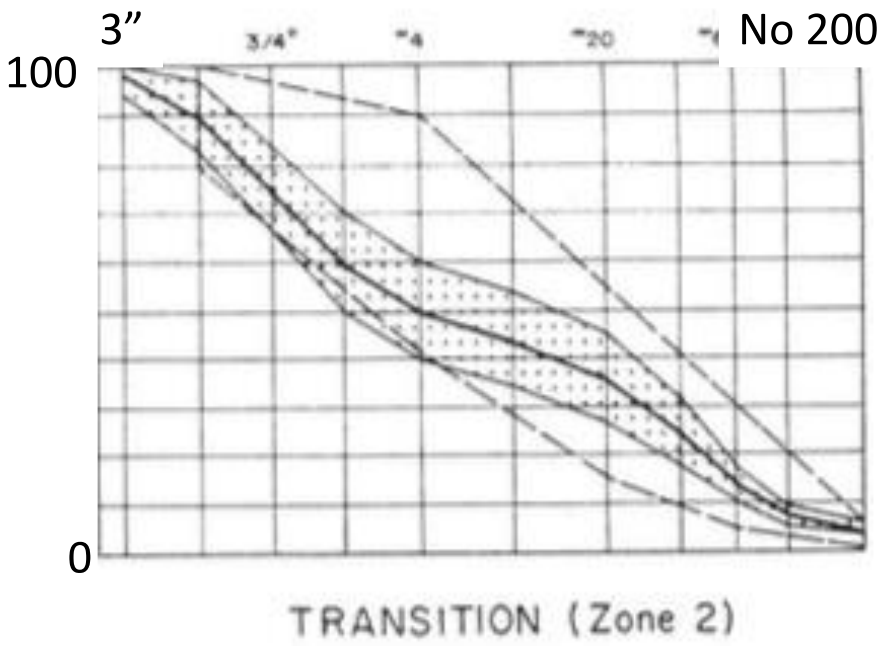
WAC Bennett Dam

- Located in British Columbia, Canada
- Owned by BC Hydro
- High as a 60-storey building and two kilometres wide
- Holds back 360 kilometres of Williston Lake, the largest reservoir in North America

Bennett dam transition



BC Hydro as cited by
Muir Wood (2007)



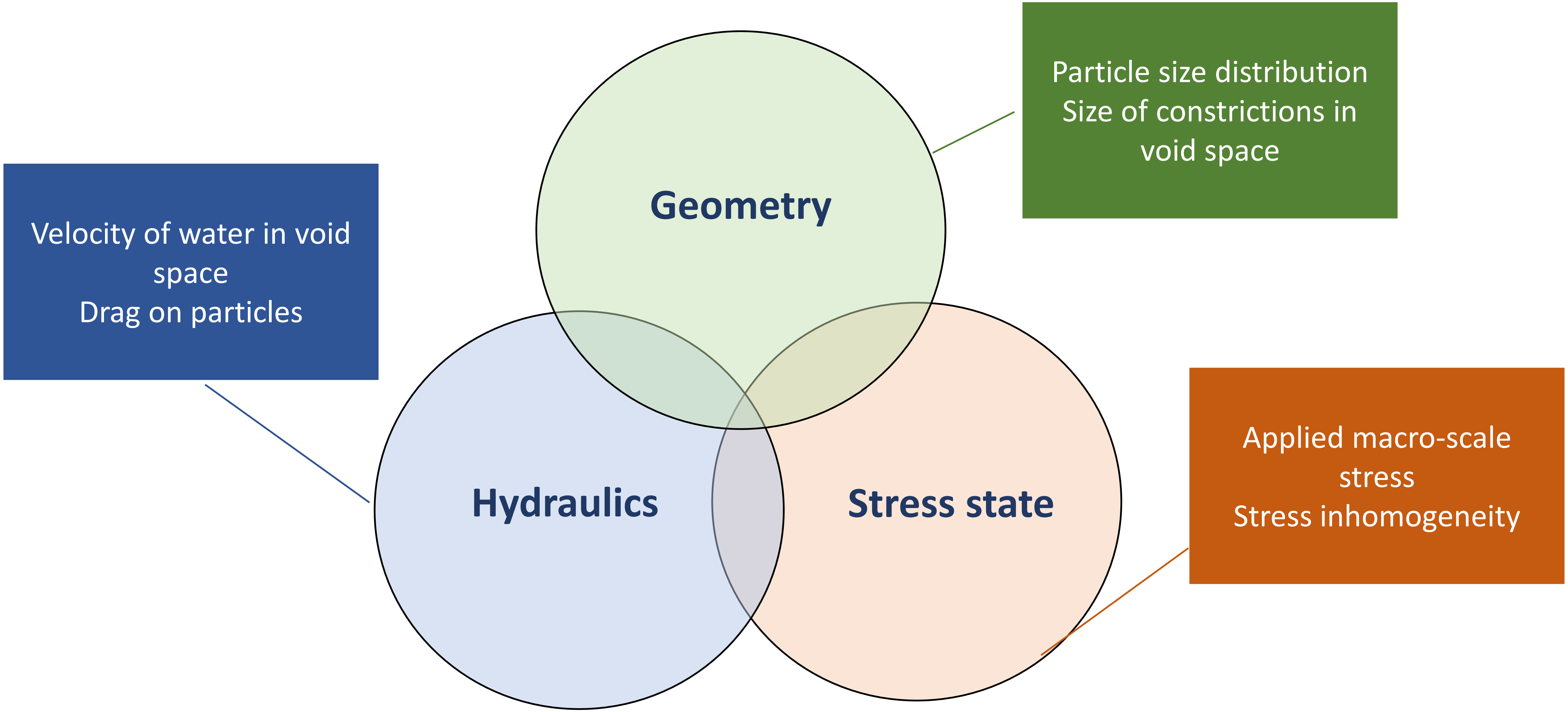
UBC Permeameter

https://www.imperial.ac.uk/media/imperial-college/faculty-of-engineering/civil/public/geotechnics/Fannin_1Sept17_London.pdf

WAC Bennett Dam

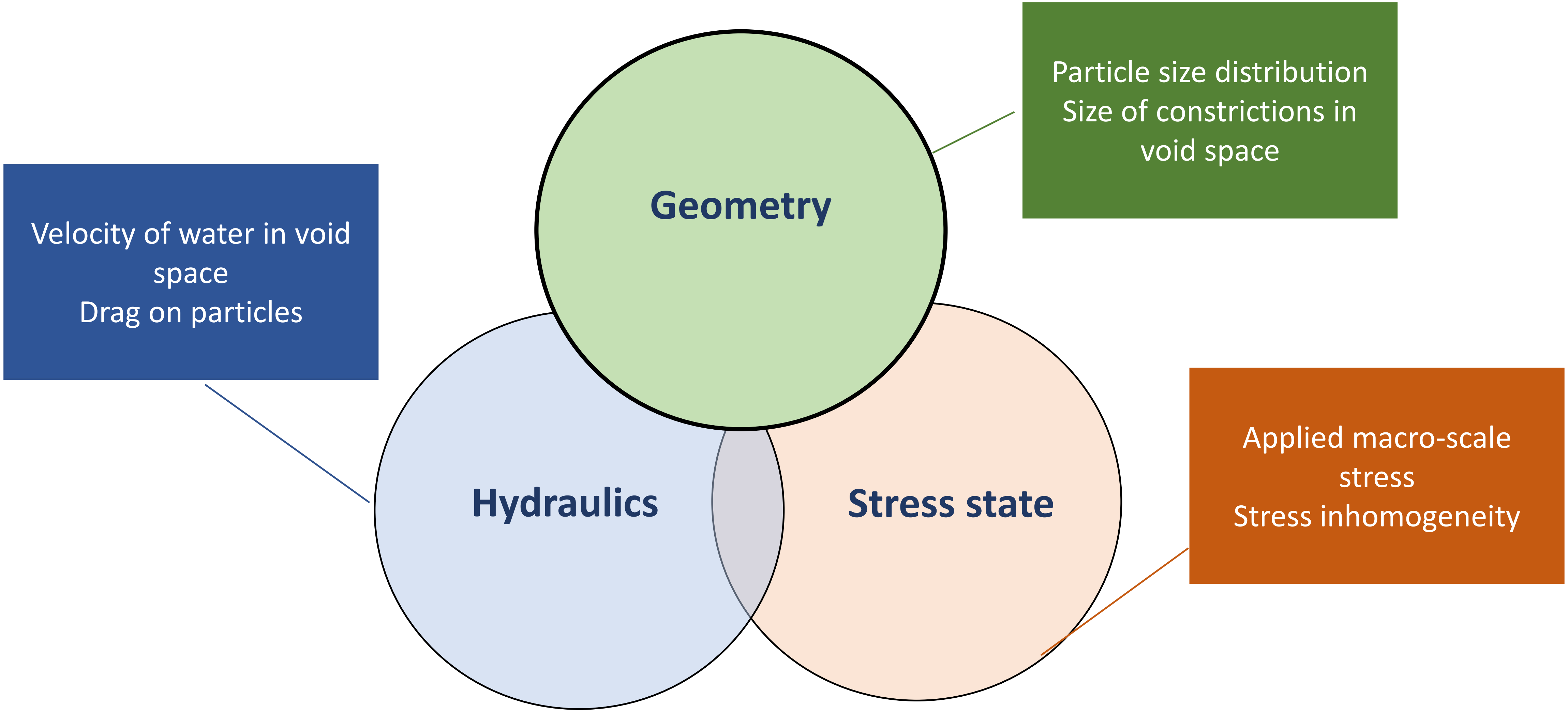
1996 Sinkhole at WAC Bennett Dam
(BC Hydro as cited by Muir Wood, 2007)

Factors influencing internal instability risk

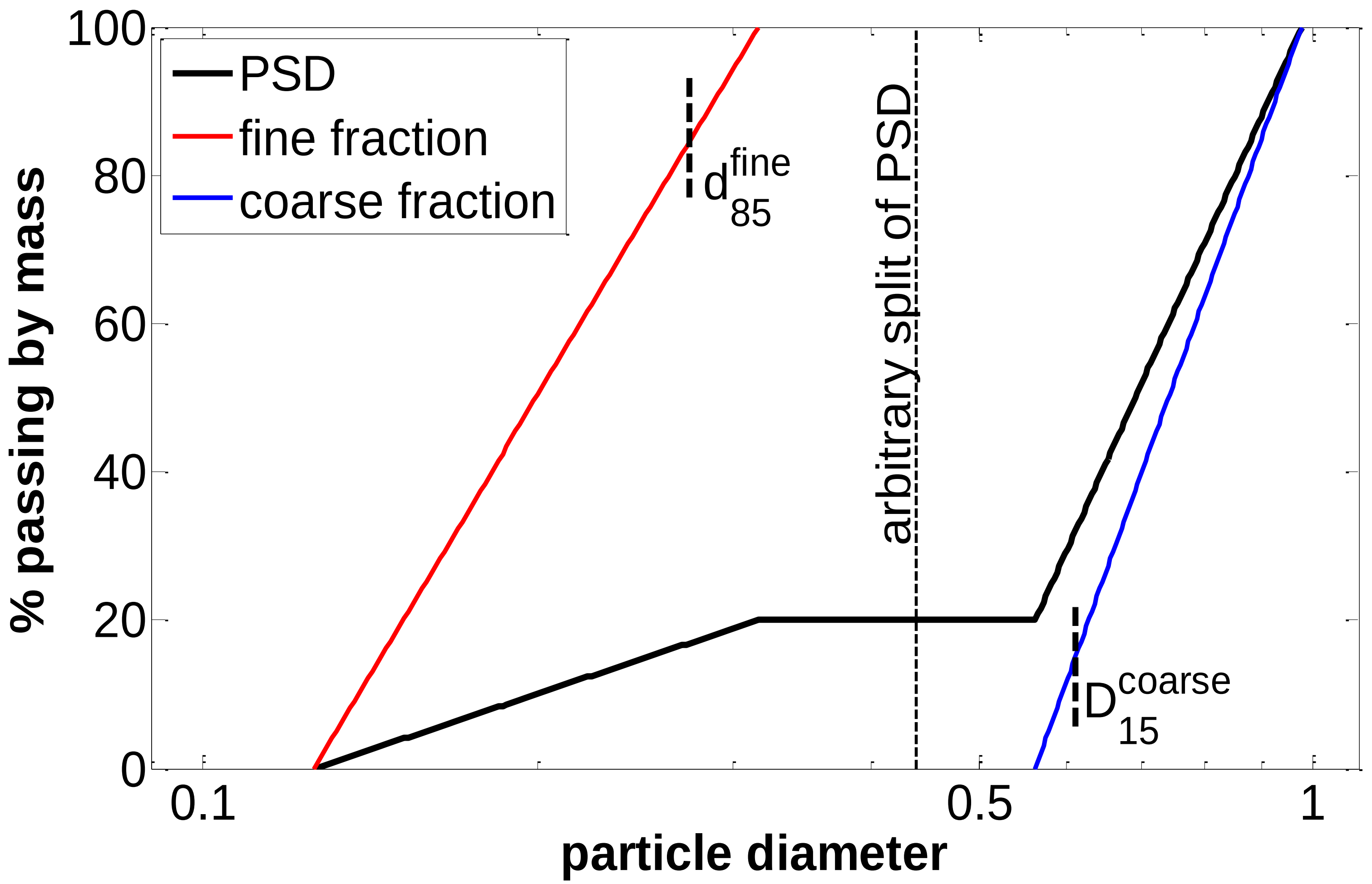


Venn diagram concept proposed by Fannin and Gardner

Factors influencing internal instability risk



Empirical Filter Criteria: Kézdi (1979)



Split PSD into coarse and fine "PSDs"

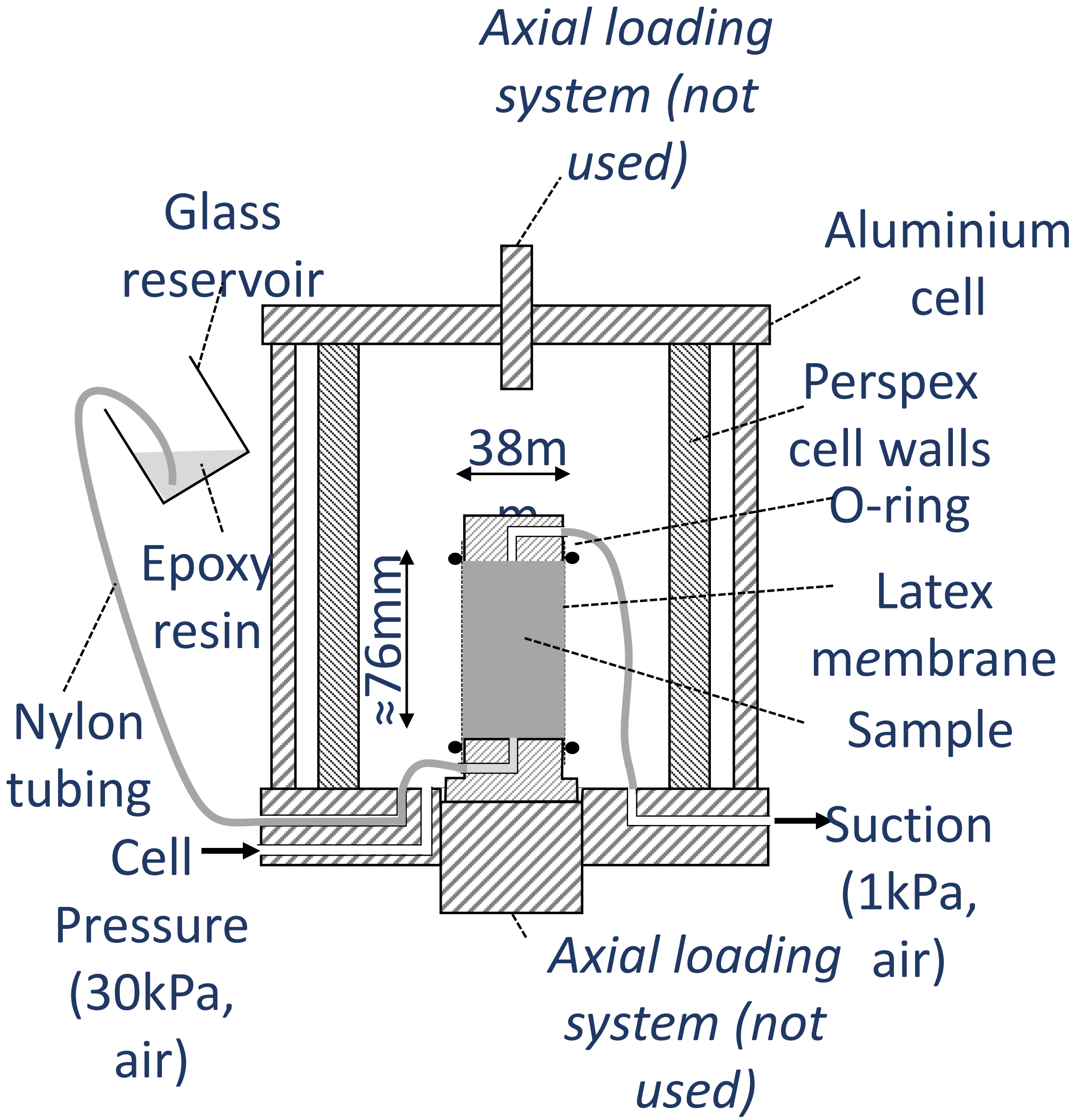
Stable if: d_{85}^{fine} > (D_{15}^{coarse}/ 4)

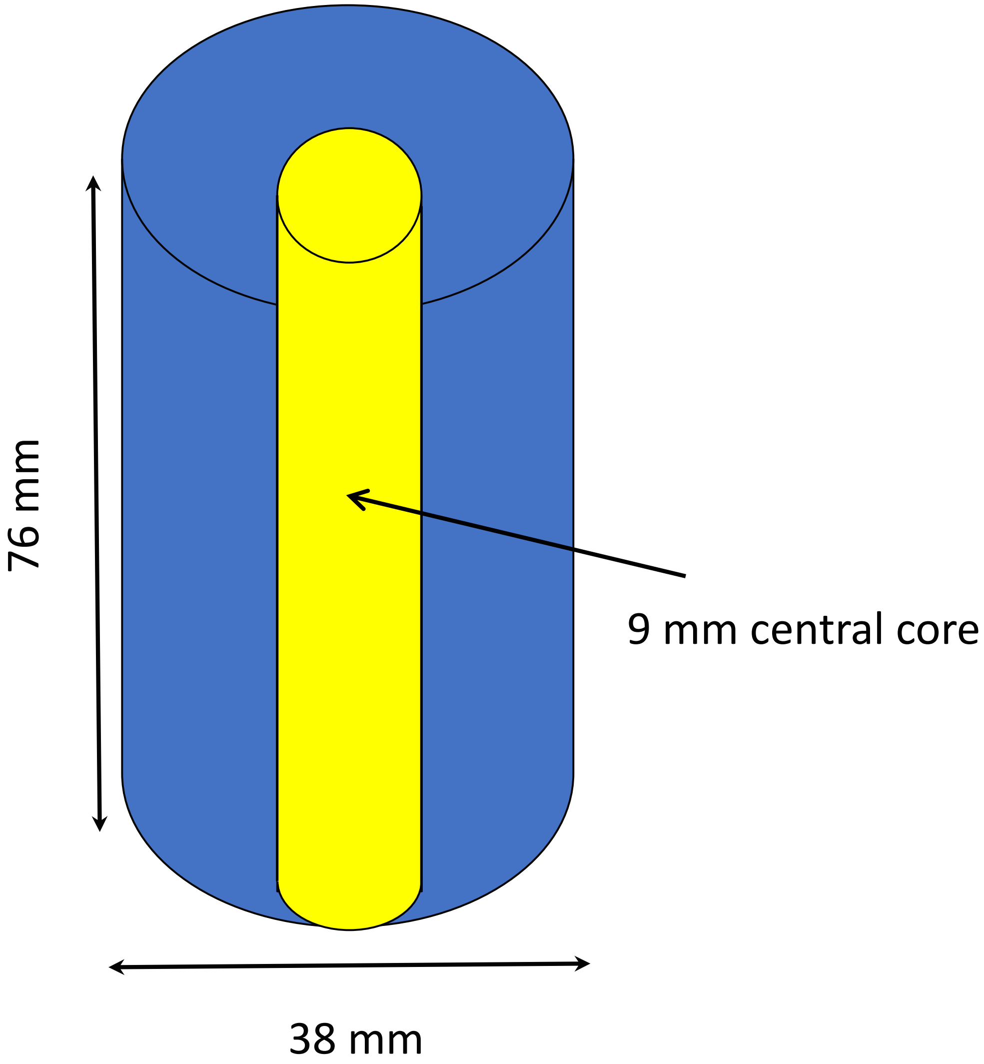
i.e. if

$D_{15}^{coarse}/d_{85}^{fine} < 4$

Relates to Terzaghi filter rule

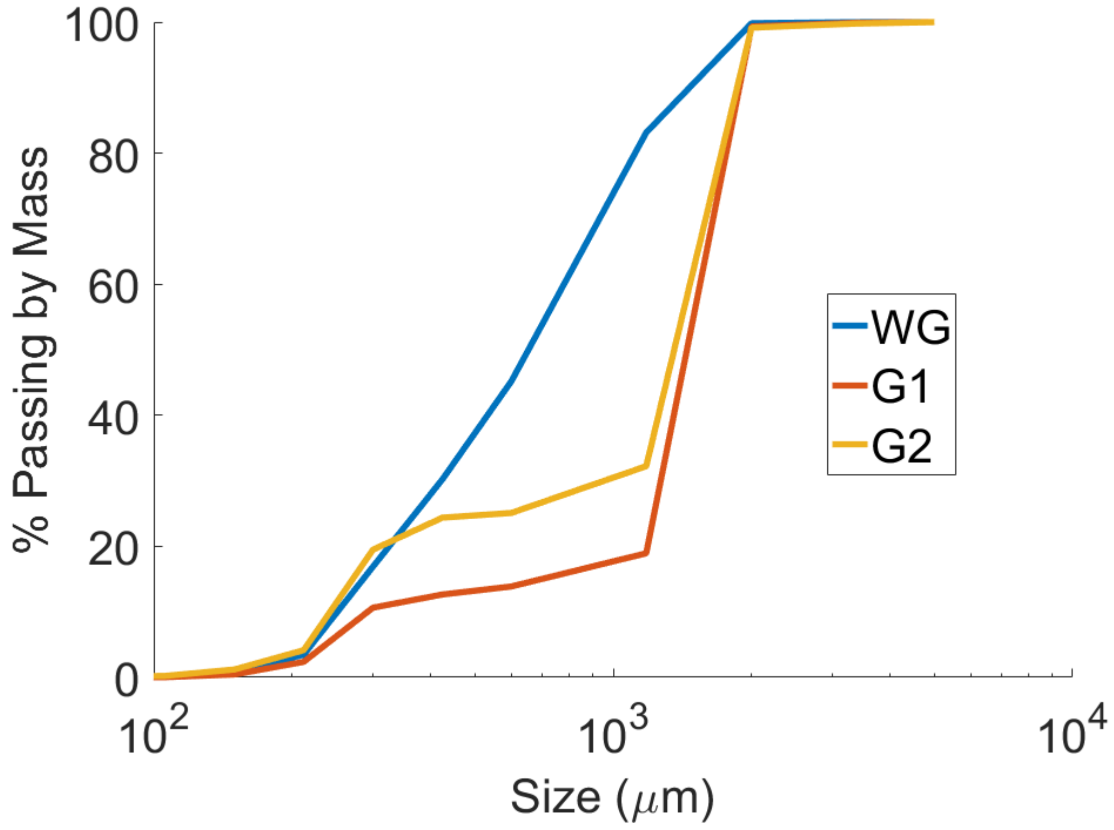
Microcomputed Tomography (μCT)





PhD Research of Dr. Howard Taylor

Internal Instability: µCT study materials

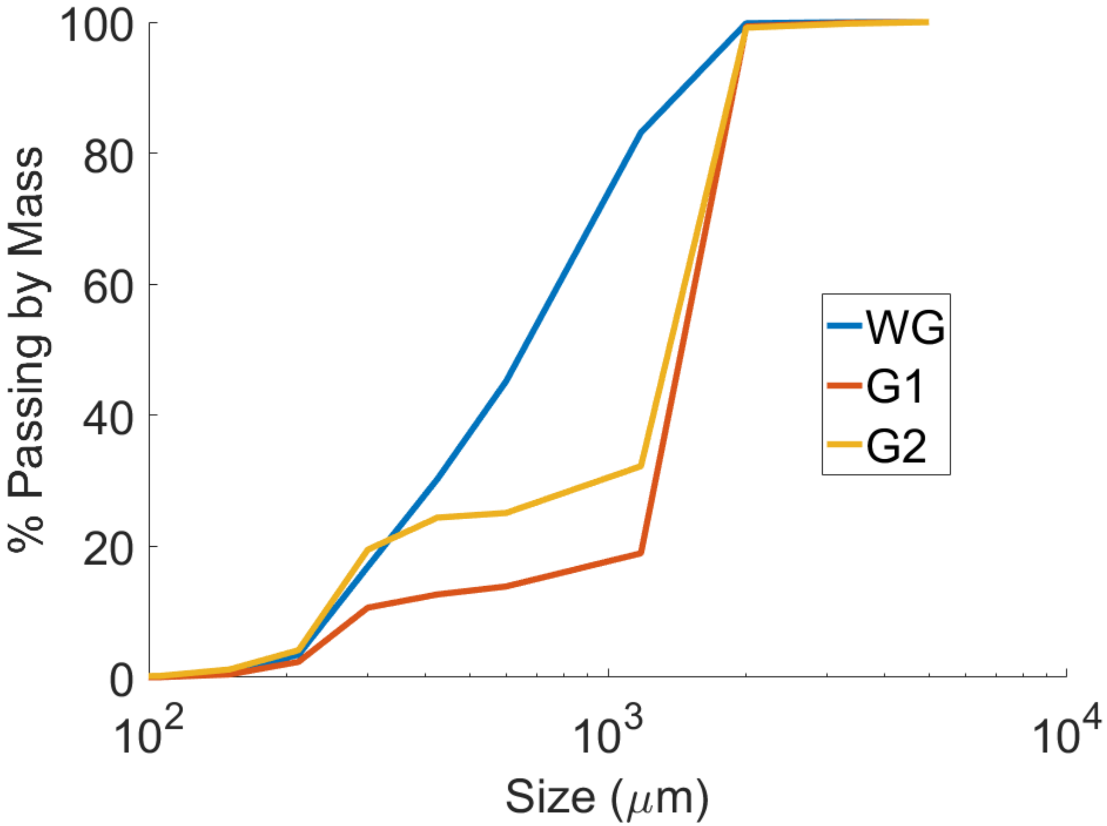


3 scan samples for each grading

- WG – Kézdi ratios 1.54-1.62
- G1 - Kézdi ratios 3.3 – 4.66
- G2 - Kézdi ratios 4.01 – 4.29

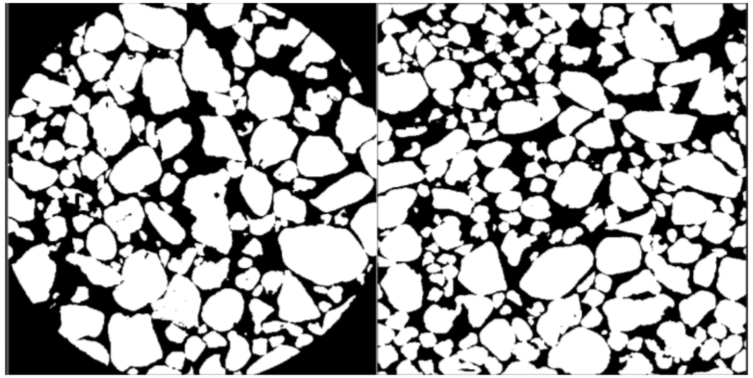
Post-doctoral Research of Dr. Joana Fonseca

Internal Instability: µCT study materials



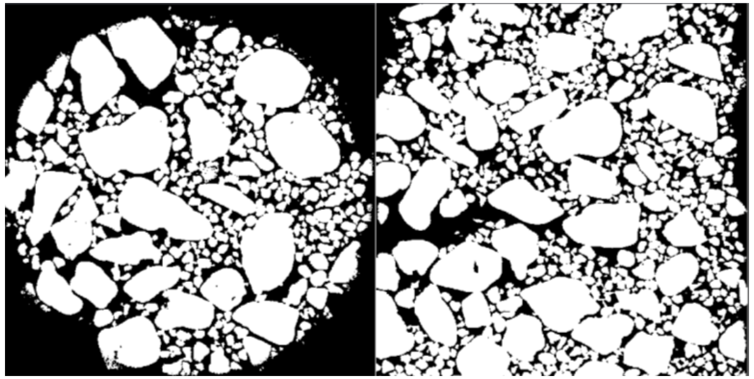
WG Middle

$D_{15}^{coarse}/d_{85}^{fine}=1.62$



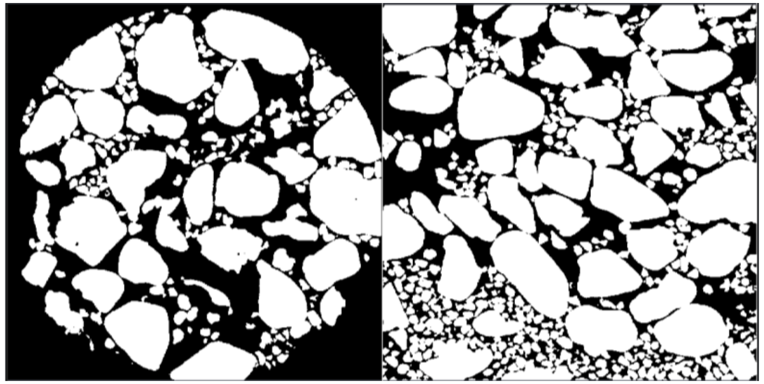
G1 Bottom

$D_{15}^{coarse}/d_{85}^{fine}=3.30$



G2 Middle

$D_{15}^{coarse}/d_{85}^{fine}=4.29$

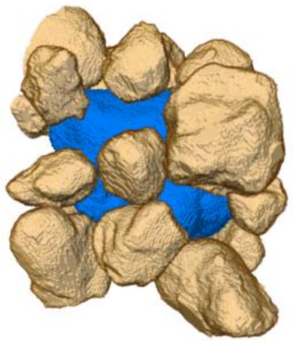


Post-doctoral Research of Dr. Joana Fonseca

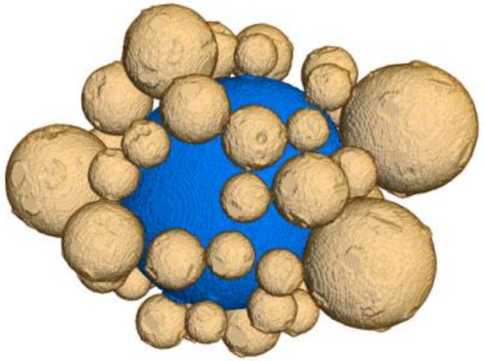
Coordination number

N_c = Coordination number

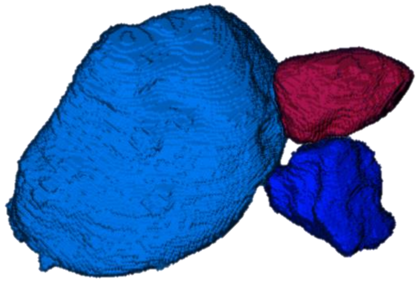
No of contacts per particle



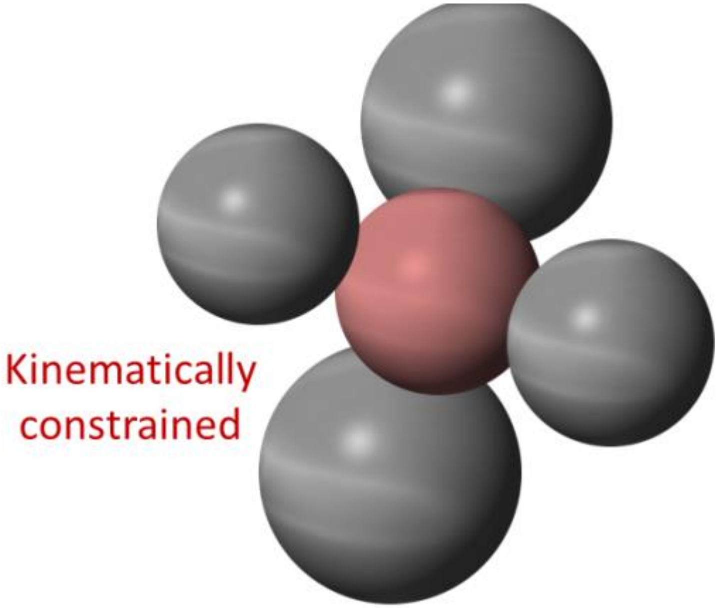
Leighton Buzzard
Sand
Blue particle
20 contacts

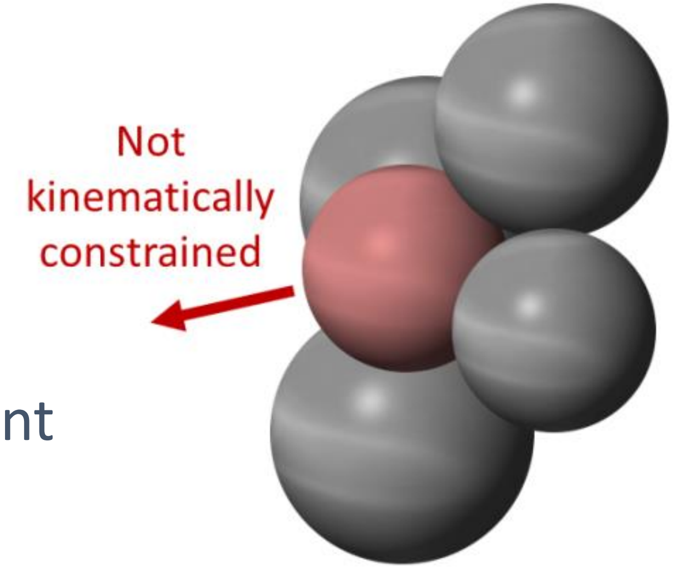


Glass beads
Blue particle
50 contacts



Leighton Buzzard
Sand
Blue particle
2 contacts





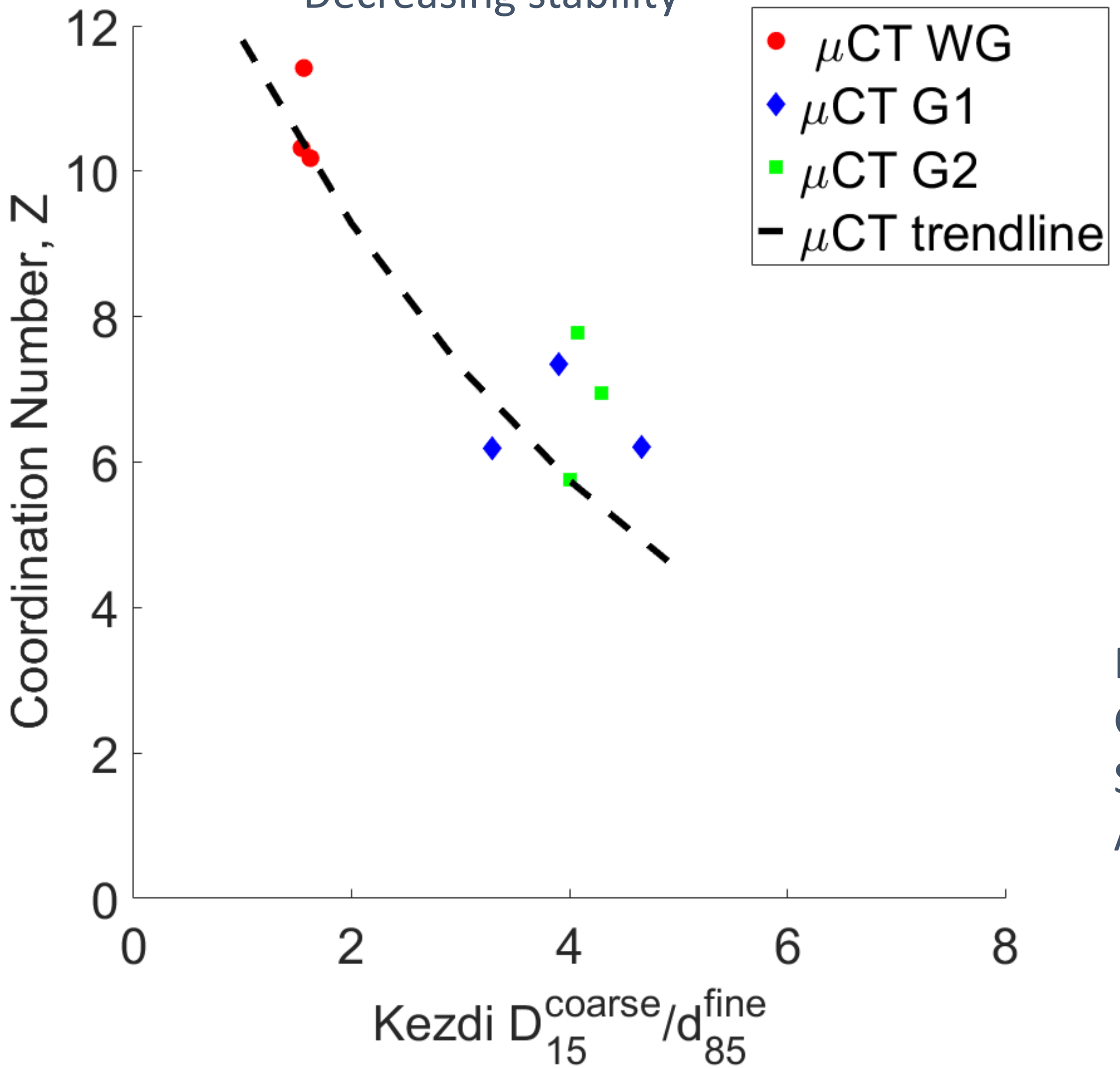
No of contacts gives indication of kinematic constraint

Images from H. Taylor

Variation in Coordination No. with Kézdi Ratio

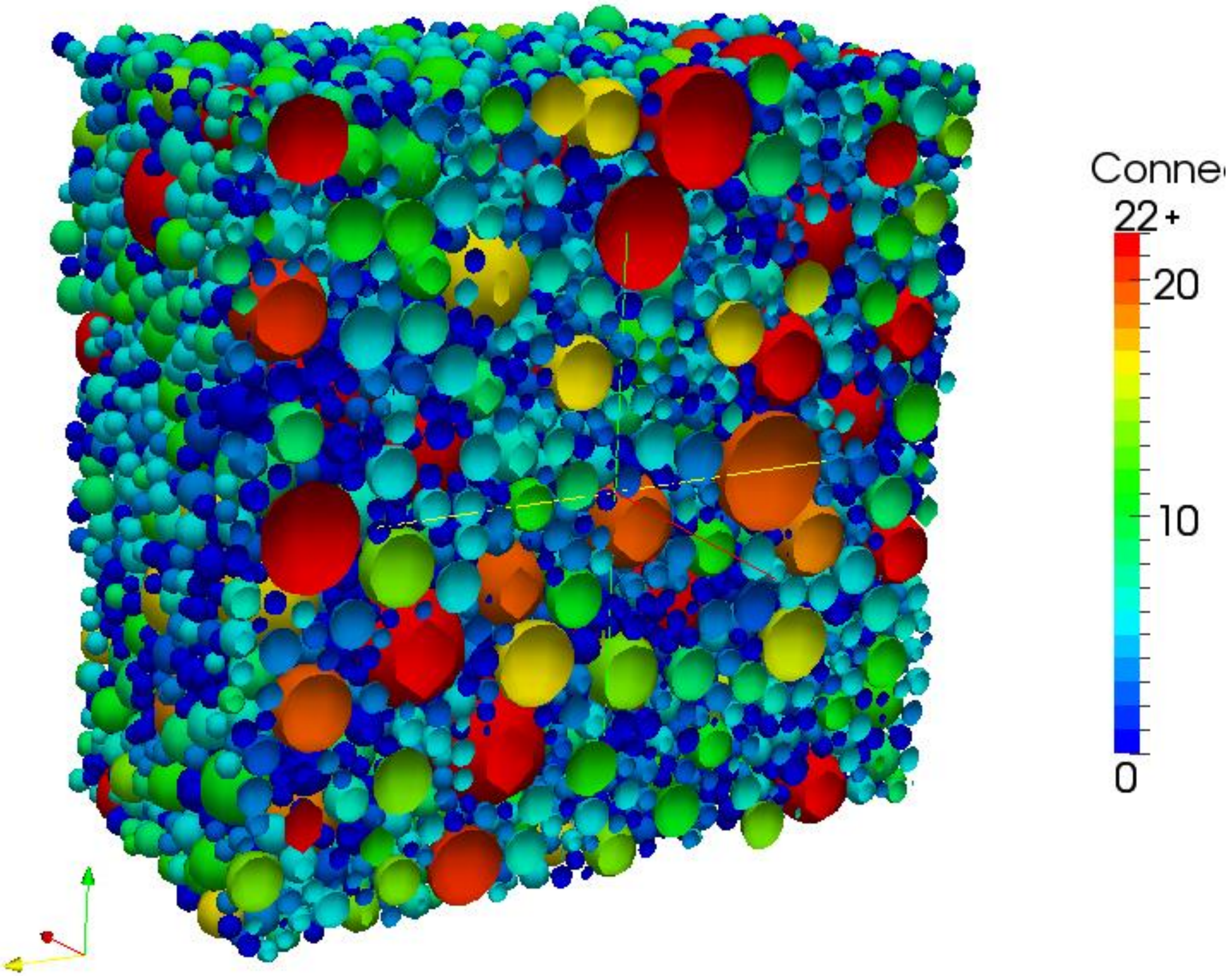
Increasing Kézdi no.

Decreasing stability



Fonseca et al. (2014)
Géotechnique
Shire and O'Sullivan (2013)
Acta Geotechnica

Discrete element method simulations



Spherical particles

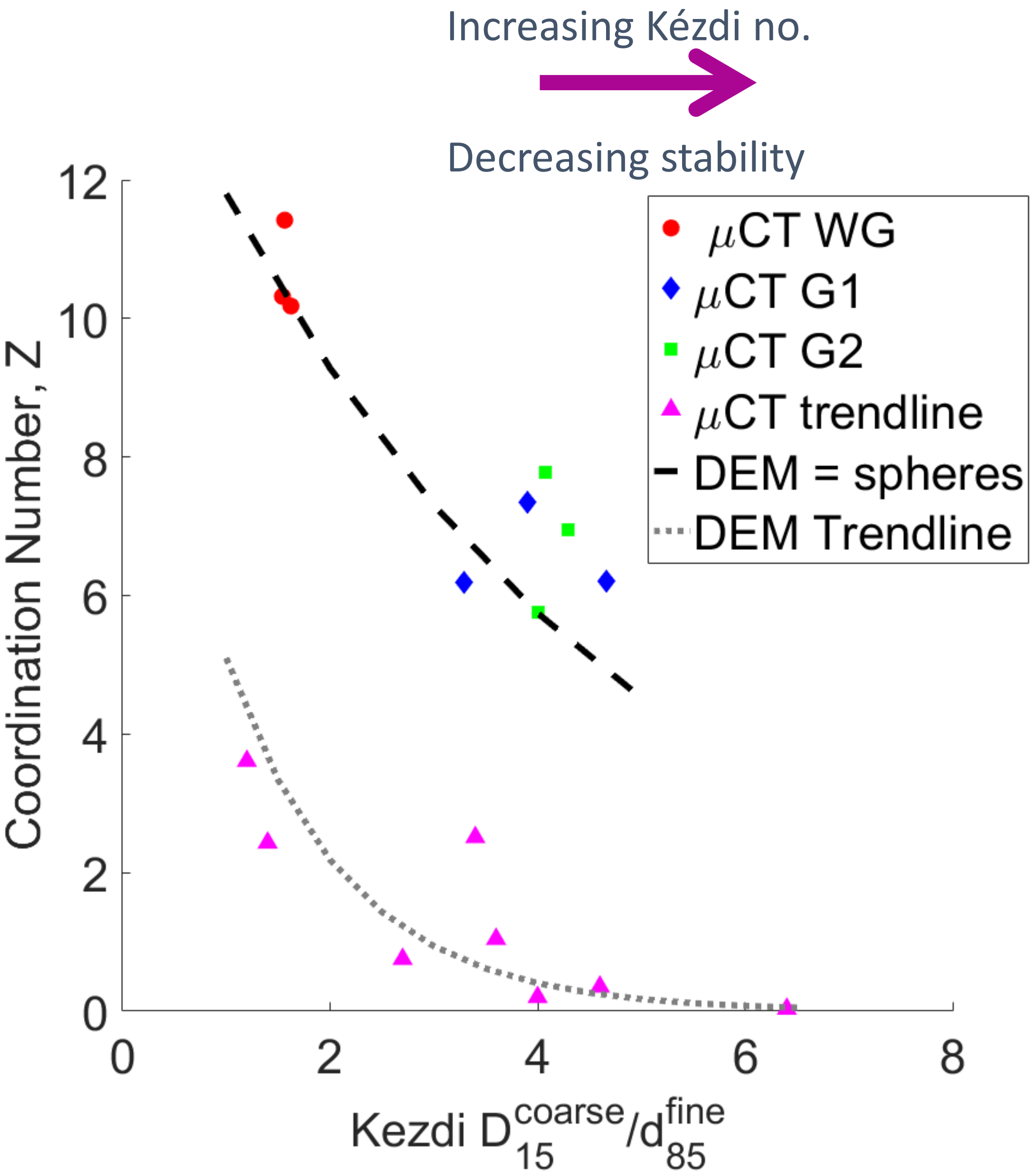
Simple contact models

Isotropic samples

Gravity neglected

Shire and O'Sullivan (2013)
Acta Geotechnica

Variation in Coordination No. with Kézdi Ratio



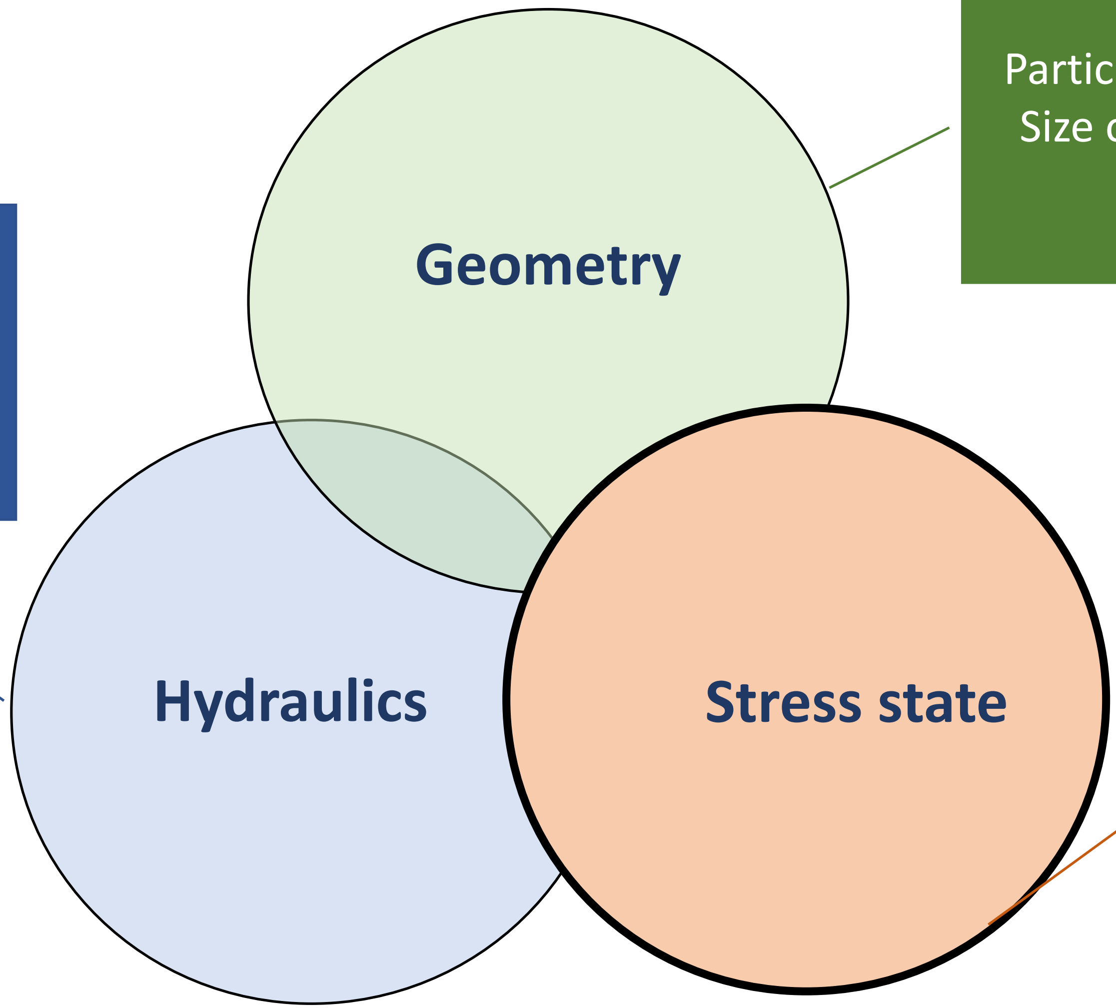
Fonseca et al. (2014) Géotechnique

Shire and O'Sullivan (2013) Acta Geotechnica

Factors influencing internal instability risk

Particle size distribution
Size of constrictions in void space

Velocity of water in void space
Drag on particles



Applied macro-scale stress
Stress inhomogeneity

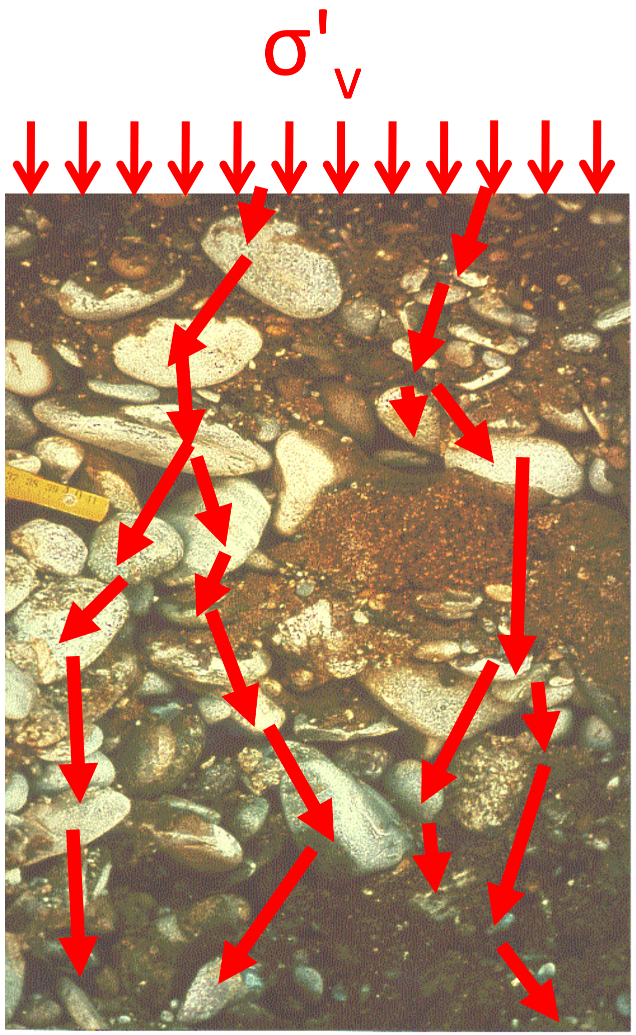
Stress Partition - α

- Hypothesis to explain erosion at low hydraulic gradients
- Based on observations of permeameter tests
- Coarse matrix transfers most of stress
- Finer grains carry reduced effective stress:

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

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

Skempton and Brogan (1994) Géotechnique



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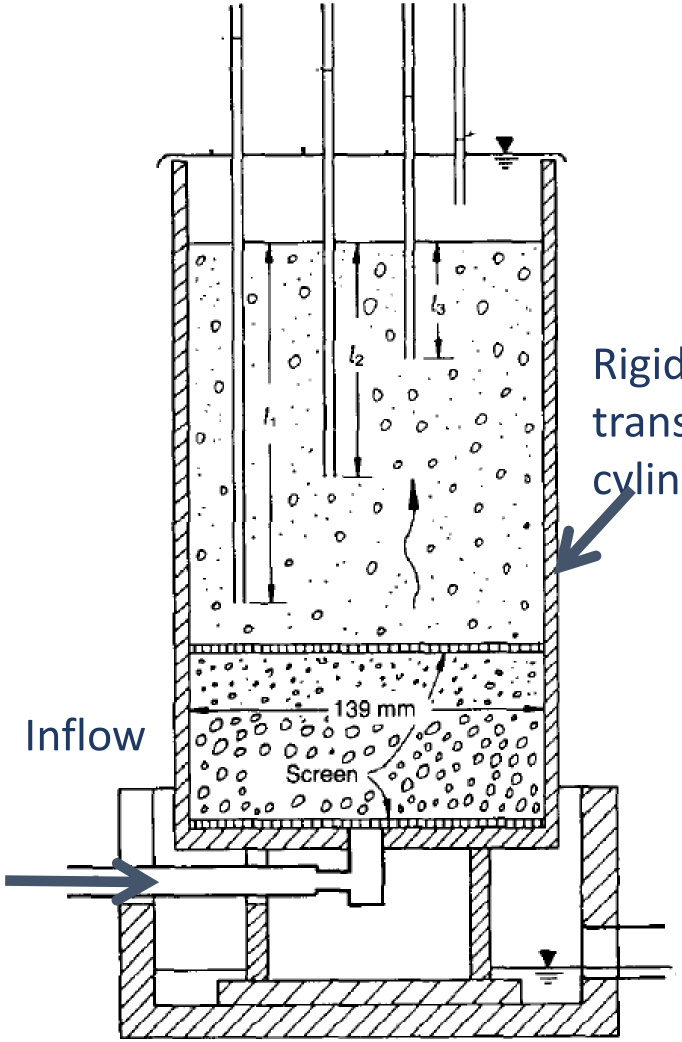
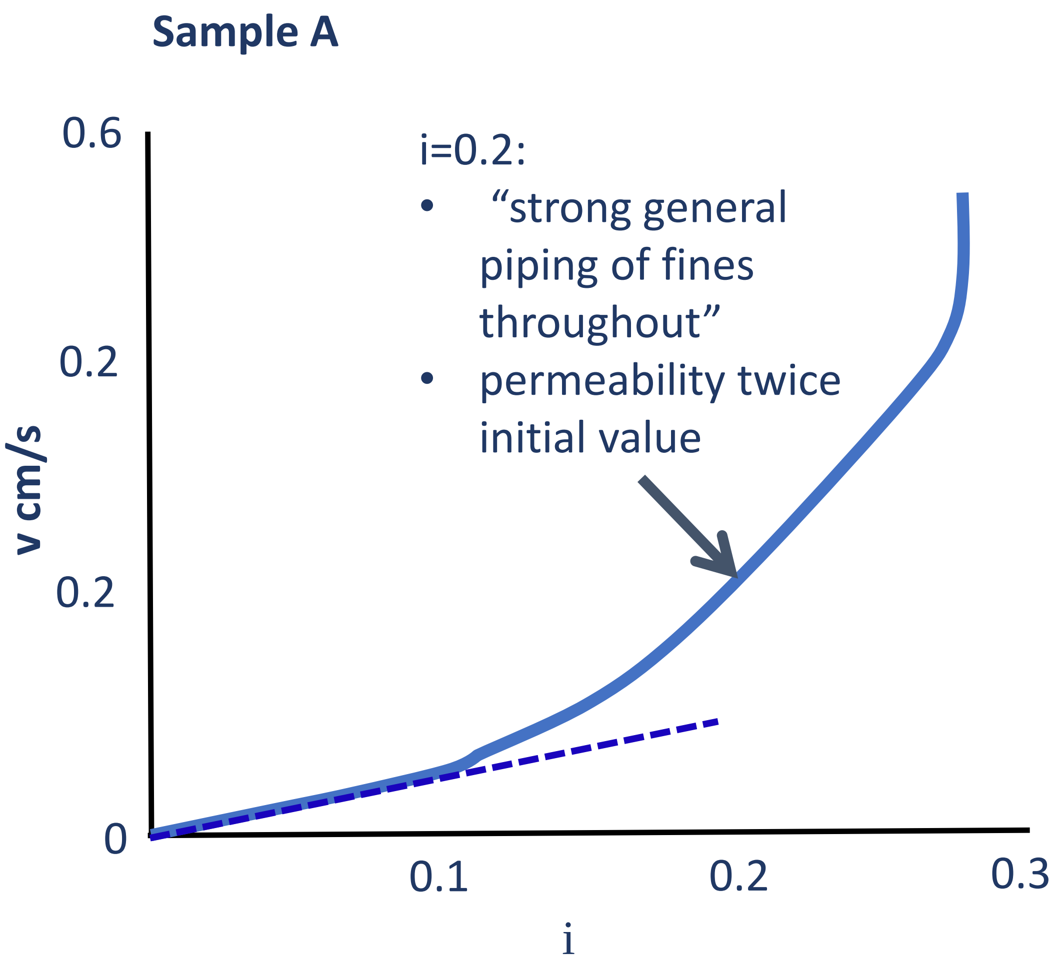
Skempton and Brogan (1994)
Géotechnique

PhD Research of Dr. Thomas Shire

Skempton and Brogan Permeameter Experiments

Skempton and Brogan (1994)
Géotechnique

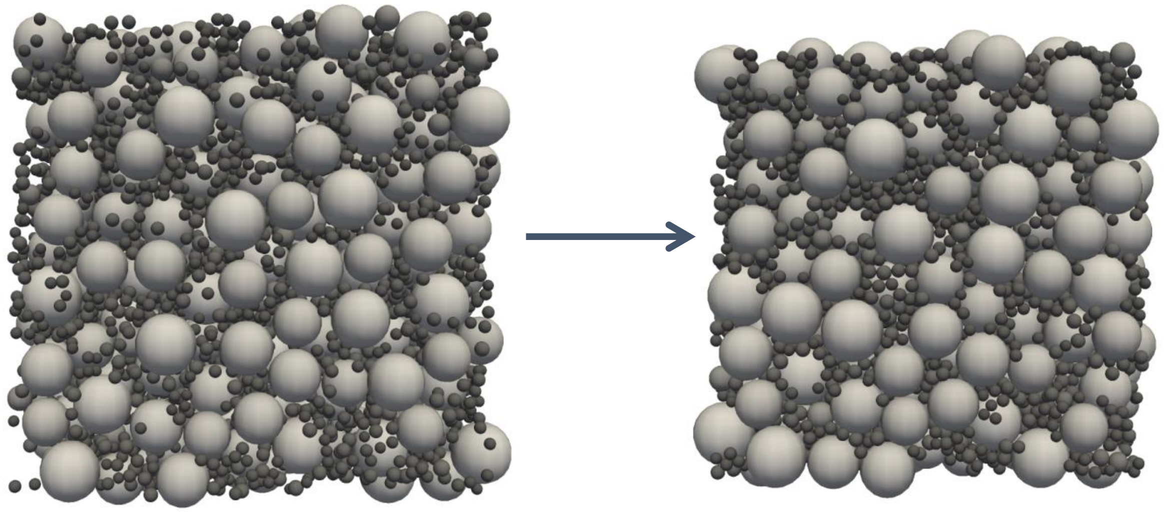




- $\alpha = i_{crit} / i_{crit(heave)}$

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

DEM Simulations to Investigate Instability



- DEM code granular LAMMPS with periodic boundaries
- Isotropic compression at to p' = 50kPa
- Sample density controlled using inter particle friction (μ):

  μ = 0.0 (Dense)

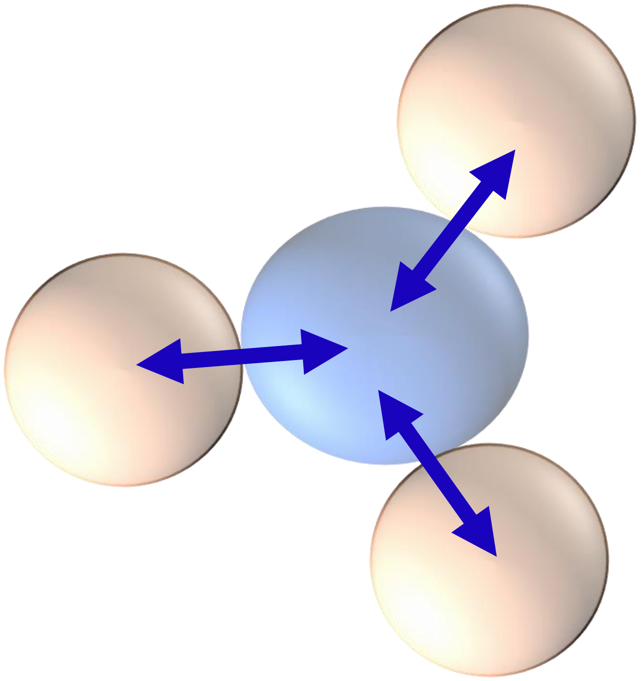
  μ = 0.1 (Medium dense)

  μ = 0.3 (Loose)

Shire et al. (2014) ASCE JGGE

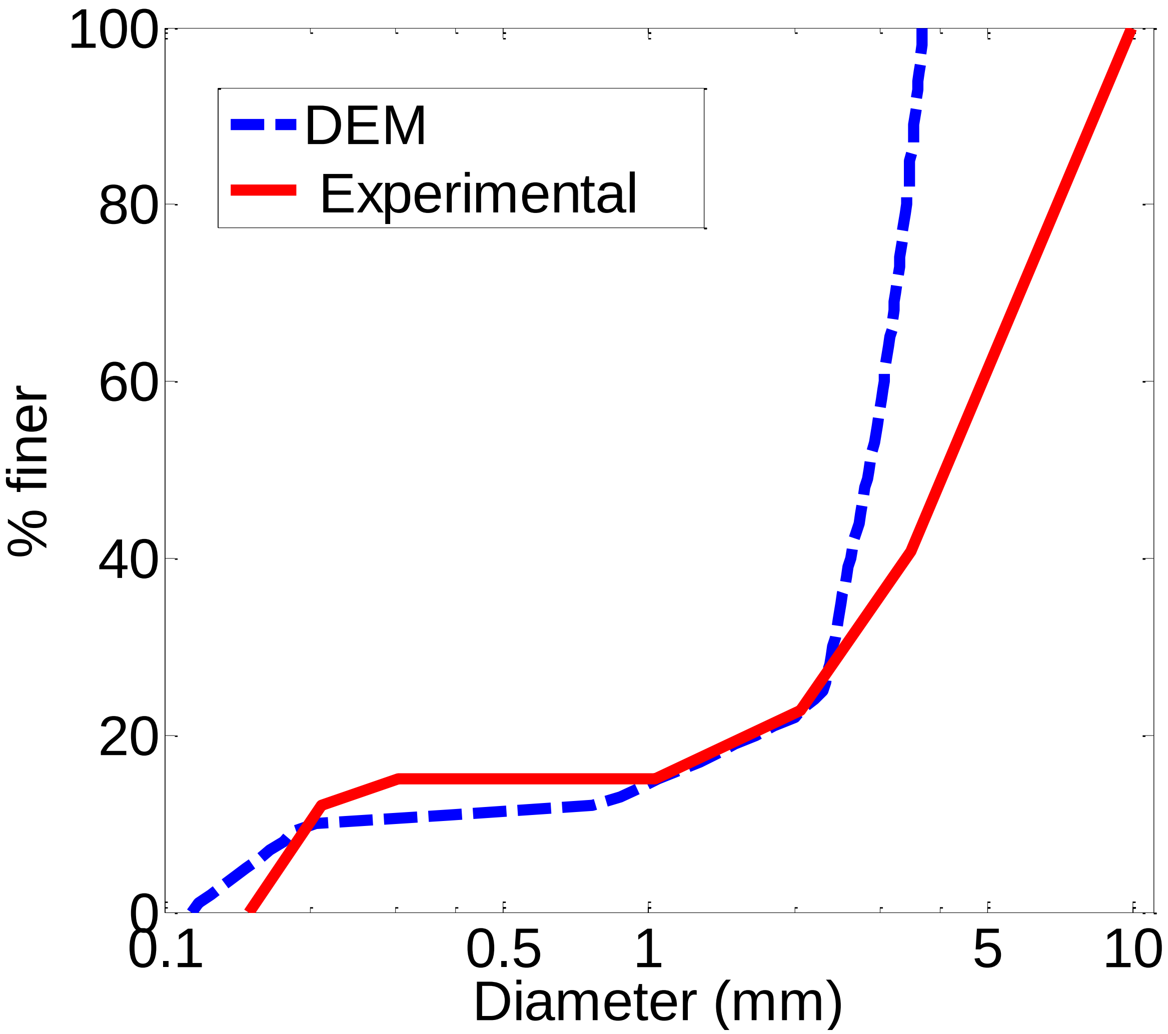
α – DEM Calculations

$$\alpha = \frac{p'_{fine}}{p'}$$



- p'=overall mean effective stress
- p'_{fine}=mean effective stress in finer fraction
- p' and p'_{fine} can be directly obtained from a summation of contact forces in DEM

Skempton and Brogan Sample A: comparison of α values



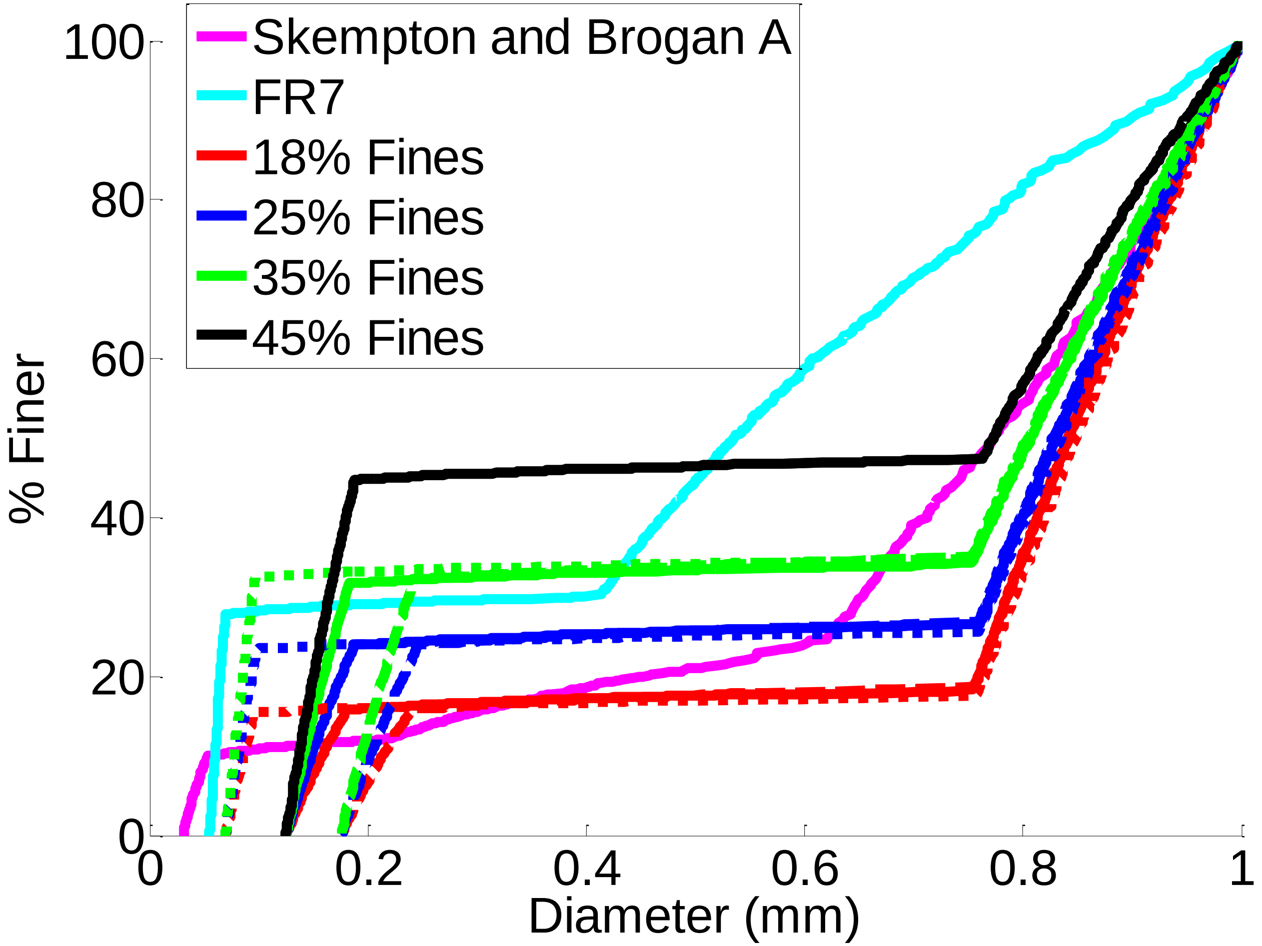
Density	α_{DEM}
Loose	0.15
Medium	0.06
Dense	0.04

$\alpha_{experiment}$=0.18

Experimental sample placed moist with no densification

Shire et al. (2014) ASCE JGGE

Link between α and particle size distribution

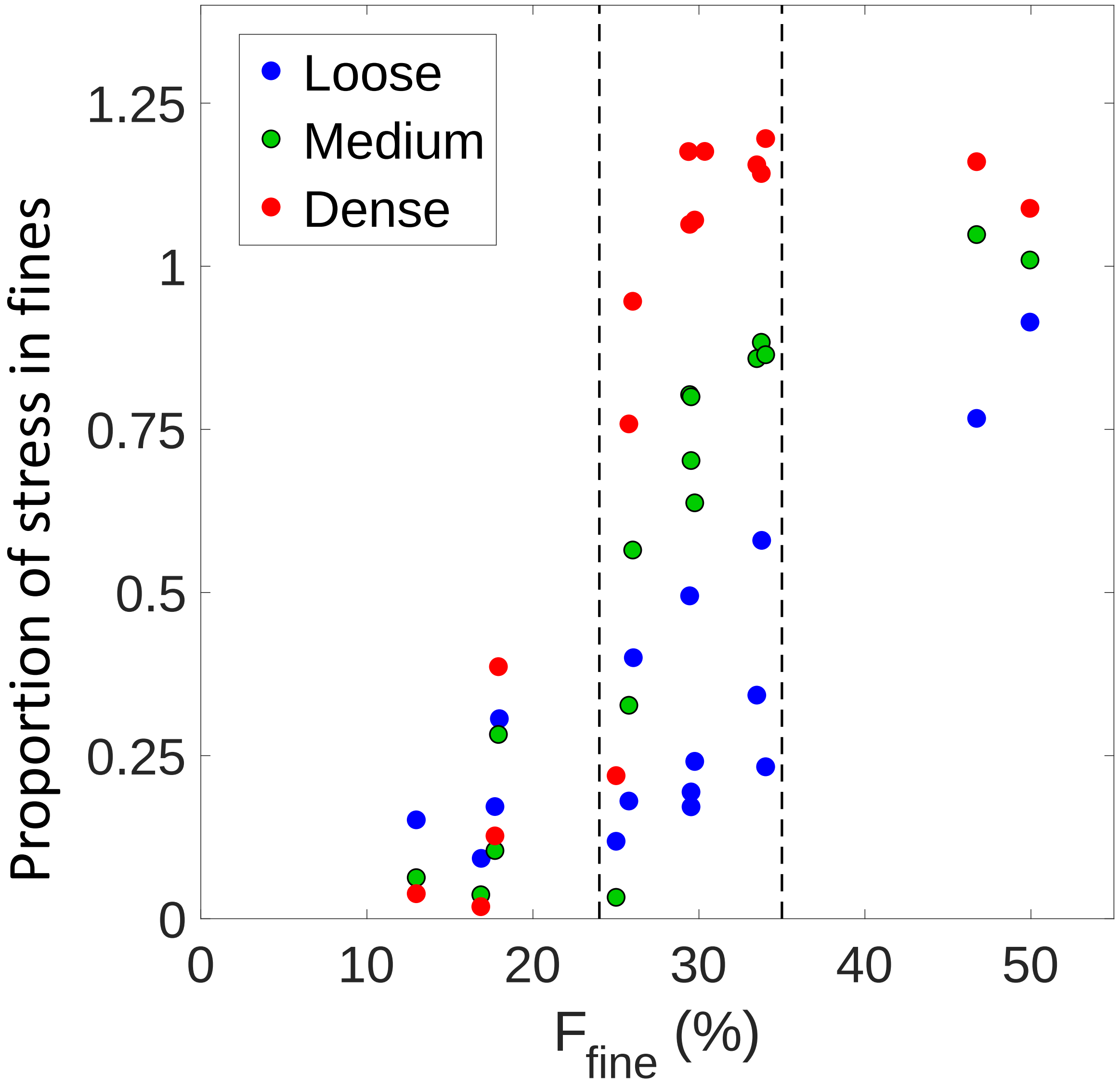


Looked at a range of gap graded materials

Density varied for all samples

Shire et al. (2014) ASCE JGGE

Variation in α with Fines Content (F_{fine})

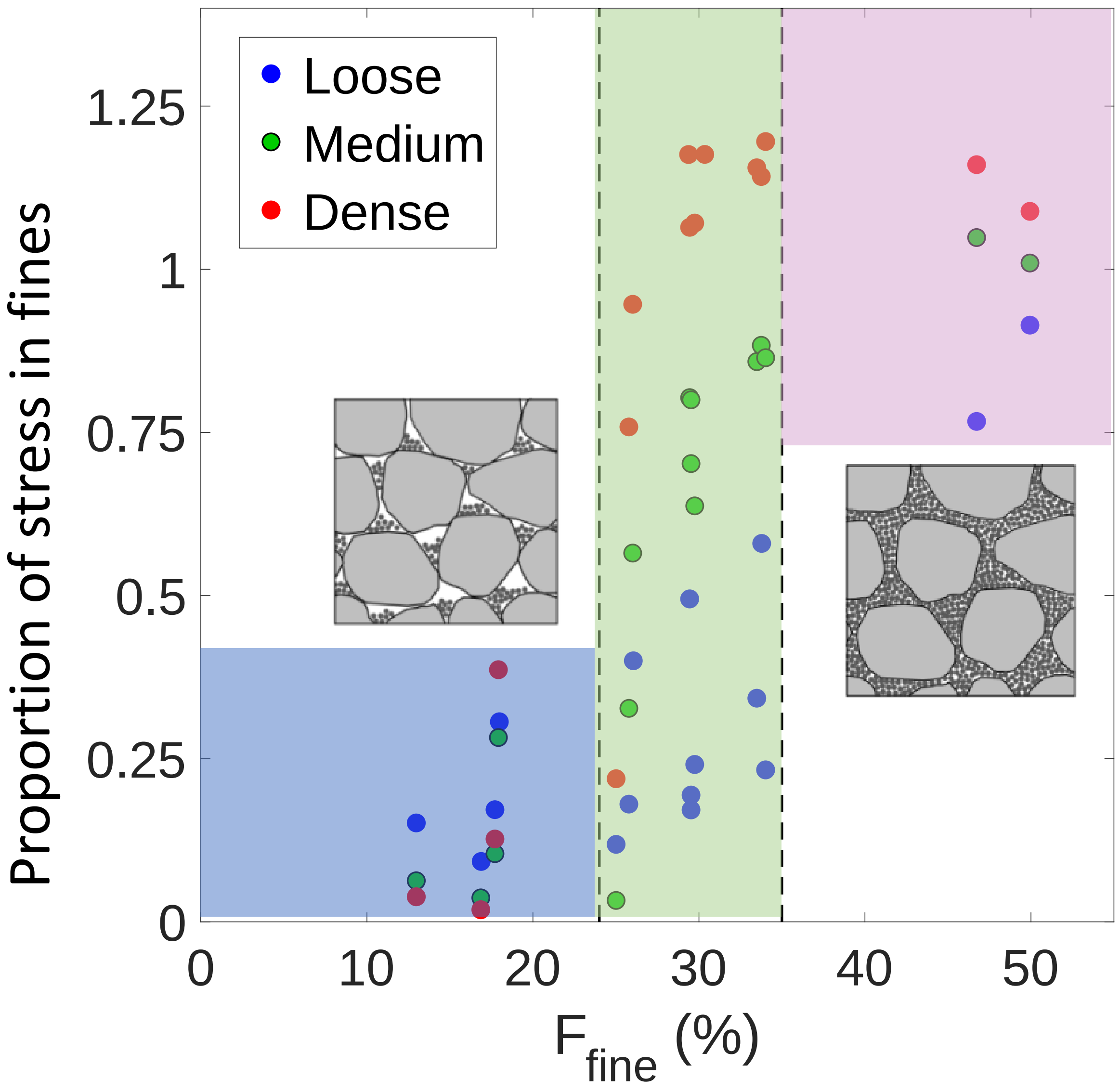


$$\sigma'_{fines} = \alpha \times \sigma'$$

α is proportion of stress carried by finer fraction

Shire et al. (2014) ASCE JGGE

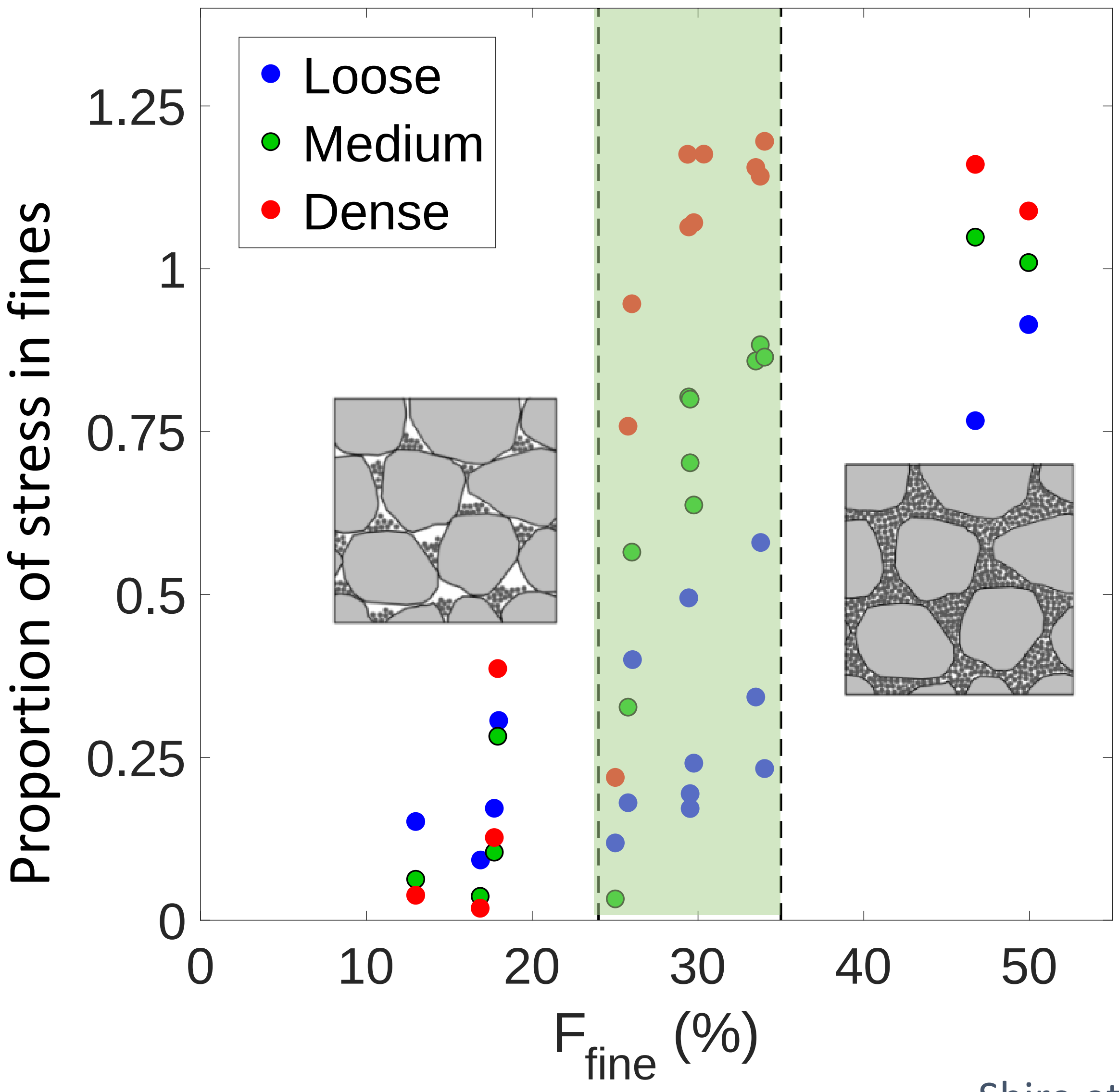
Variation in α with Fines Content (F_{fine})

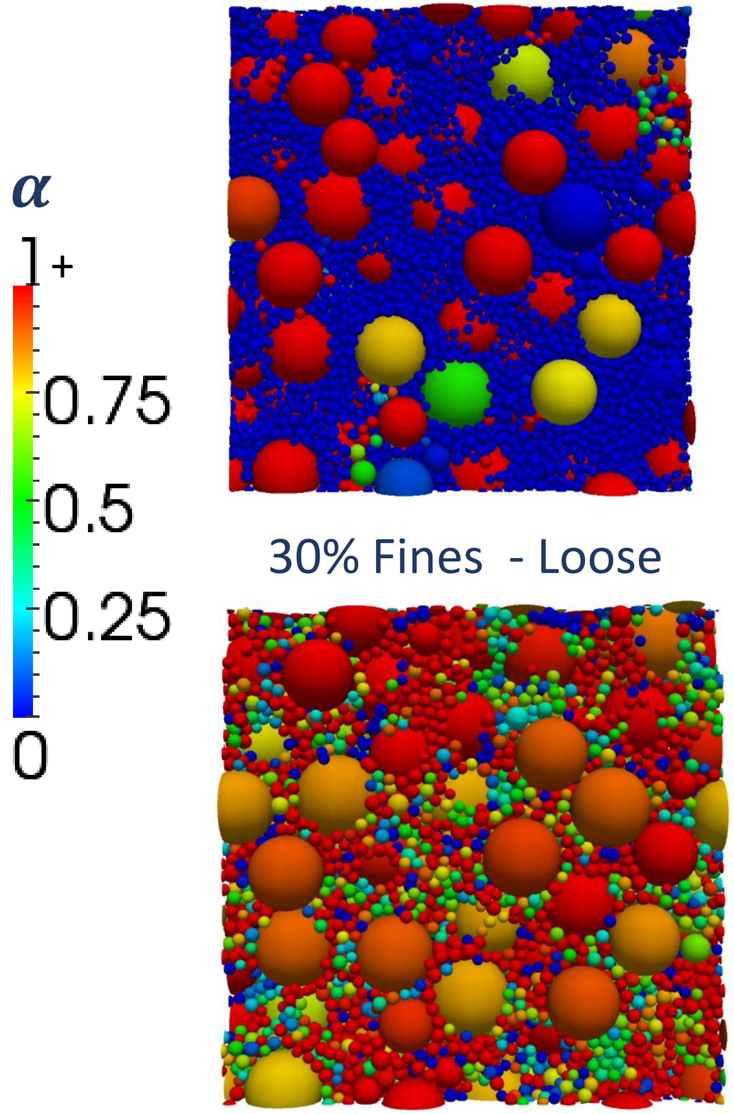


- Critical fines content where fines just fill voids: F_{fine}=24-29%
- Finer fraction separates coarse fraction particles: F_{fine}=35%
- Confirms hypotheses of Skempton and Brogan (1994)

Shire et al. (2014) ASCE JGGE

Variation in α with Fines Content (F_{fine})



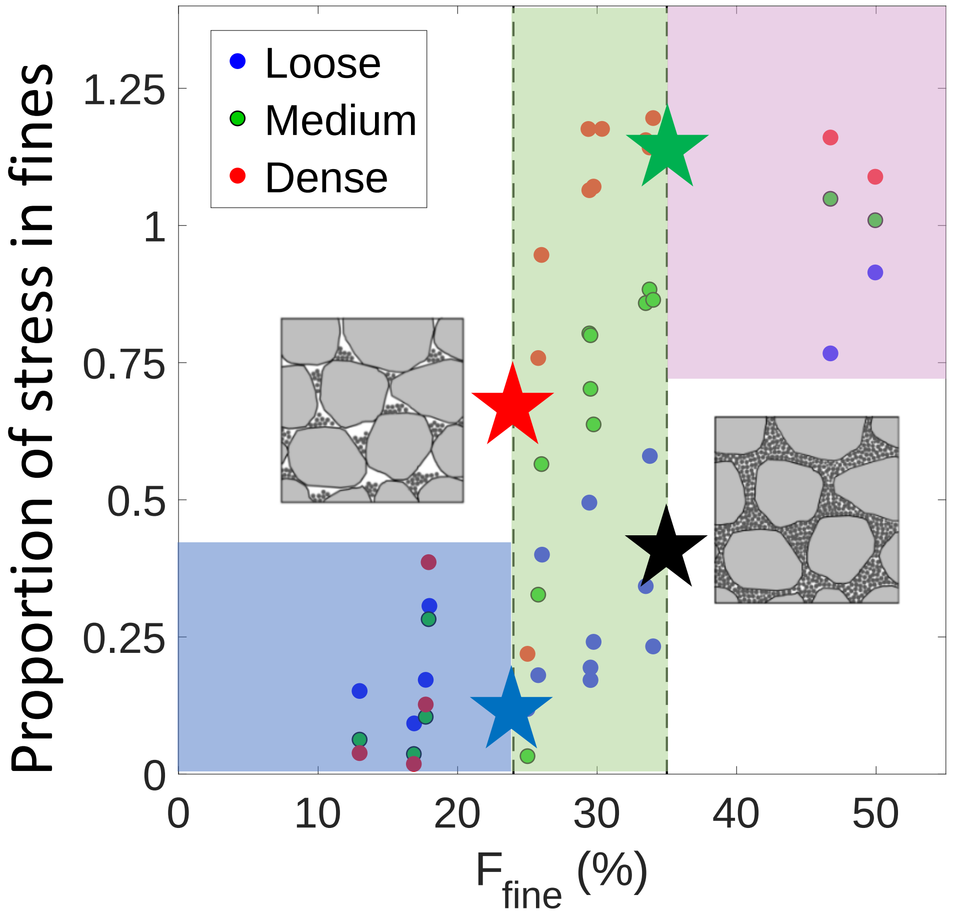


30% Fines - Loose

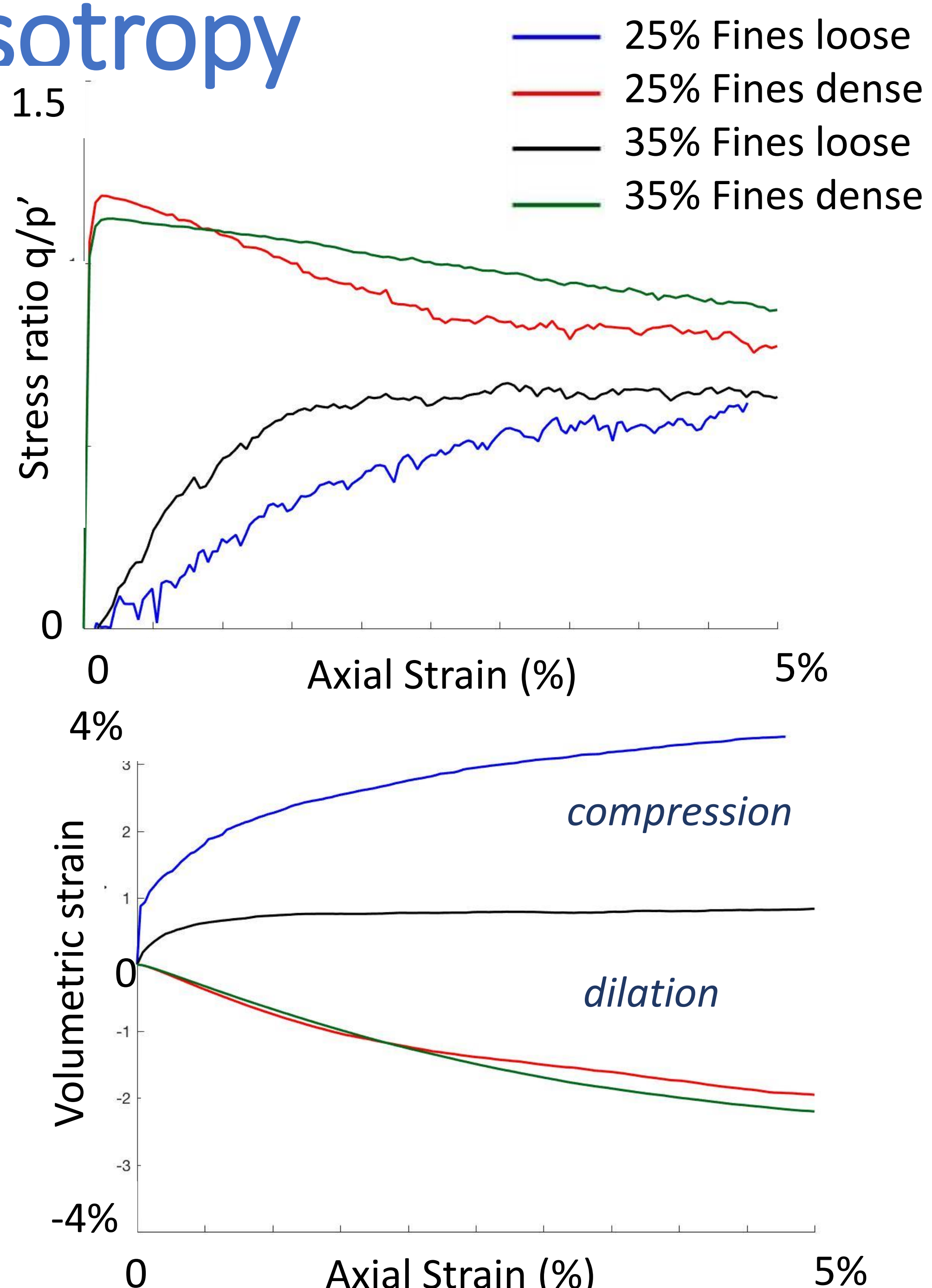
30% Fines - Dense

Shire et al. (2014) ASCE JGGE

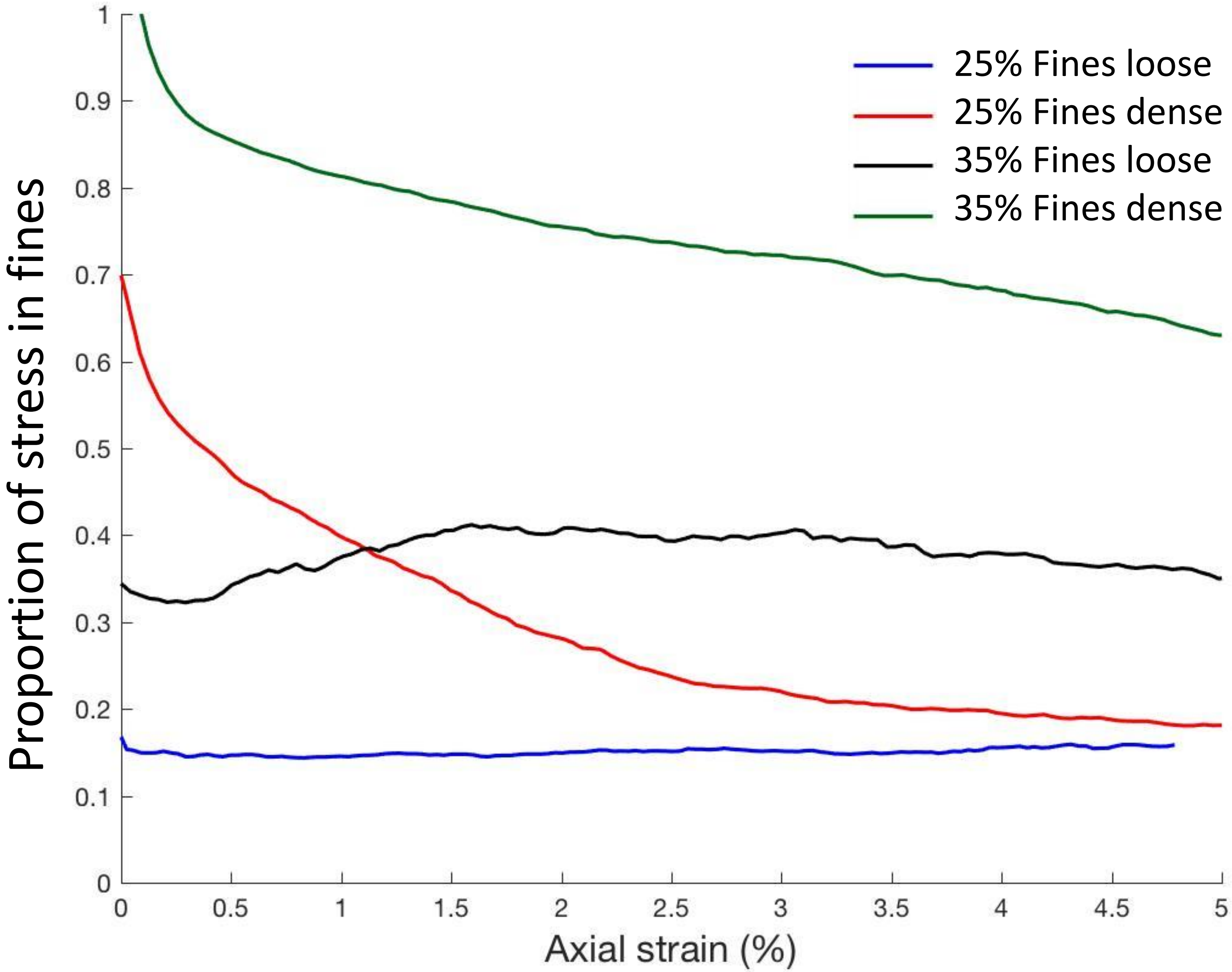
Variation in α with stress anisotropy



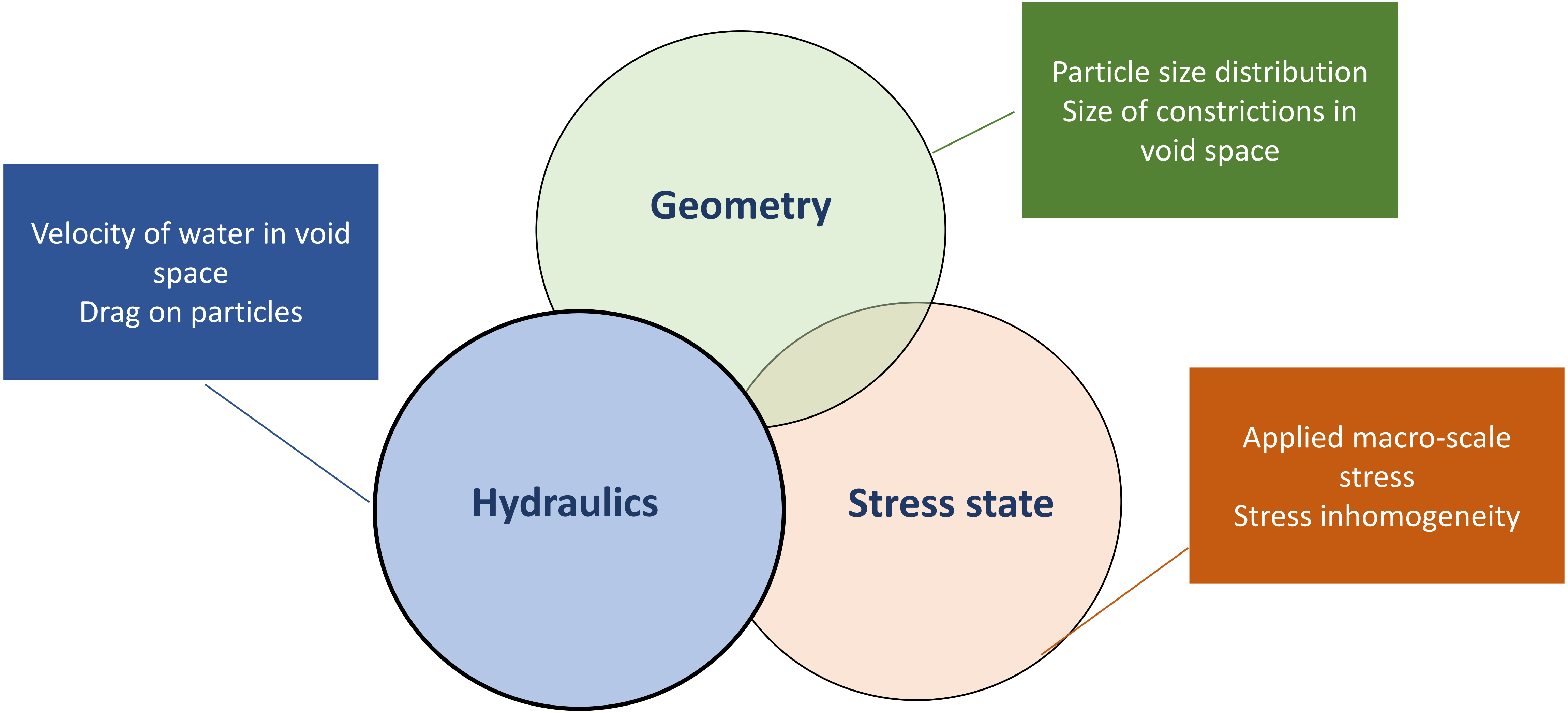
Triaxial compression – constant p’



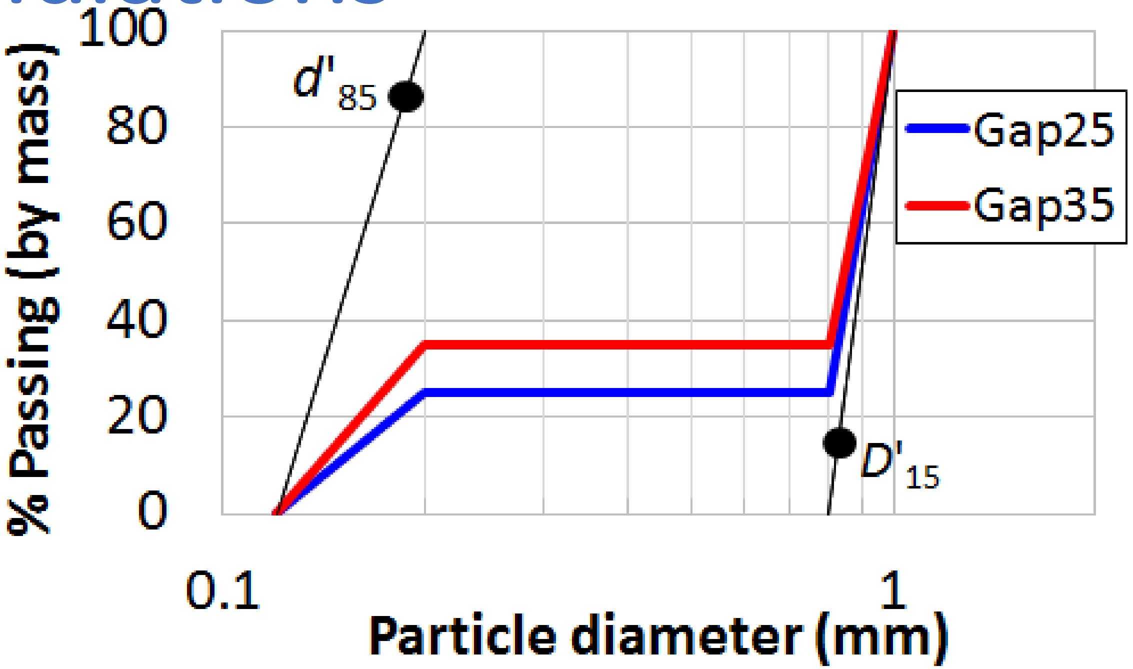
Variation in α with stress anisotropy



Factors influencing internal instability risk

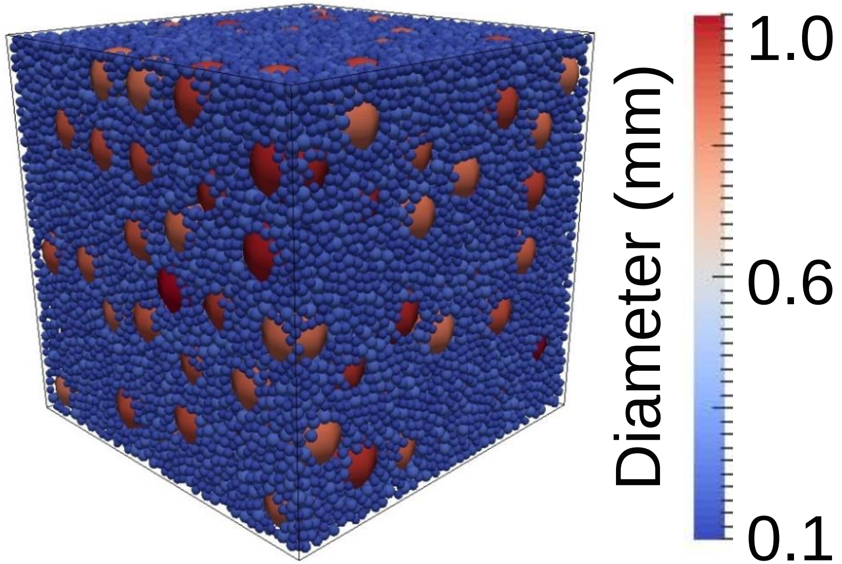


Permeameter test simulations



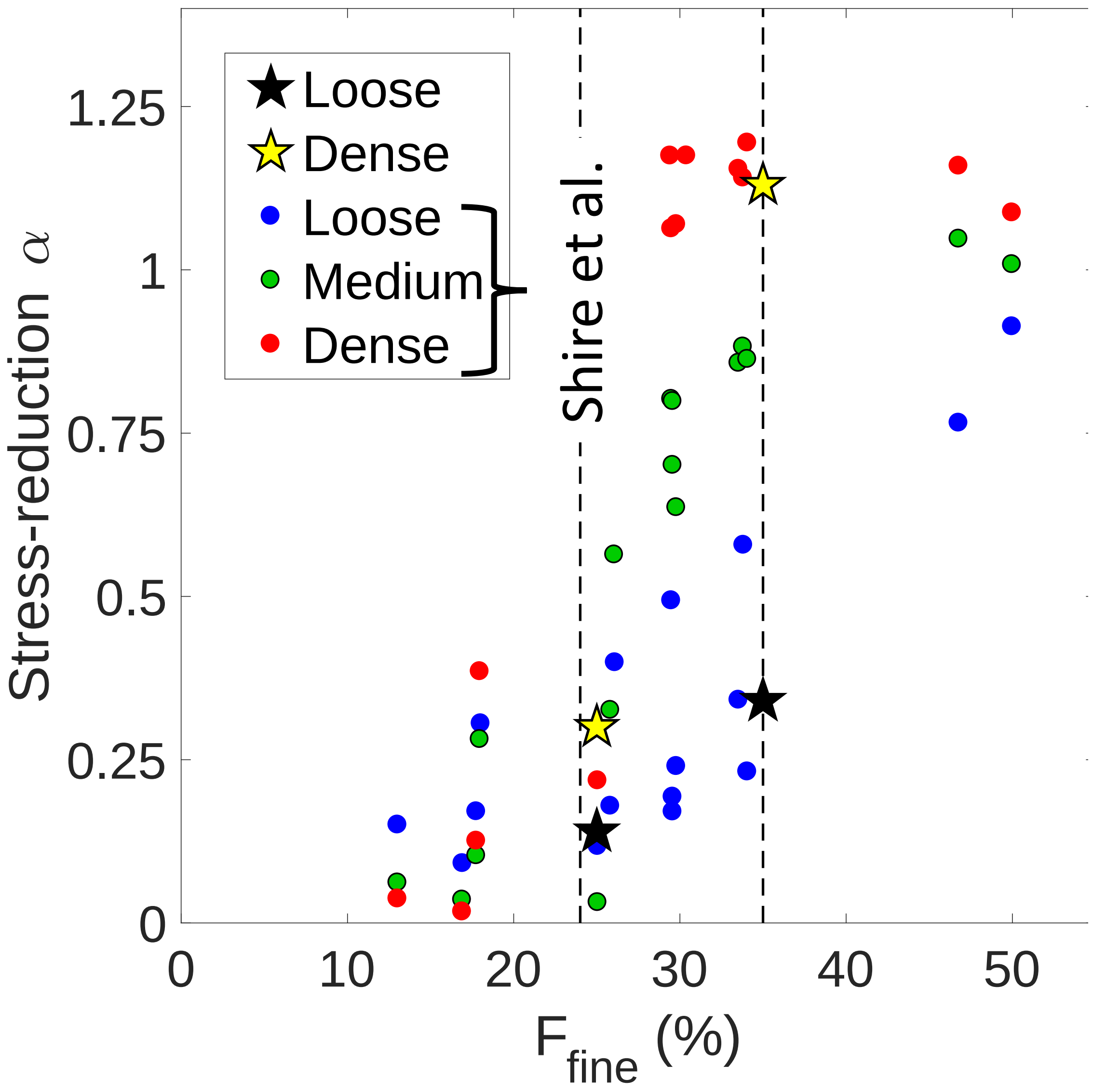
- PFC 3D Coupled with CCFD
- Circa 30,000 particles

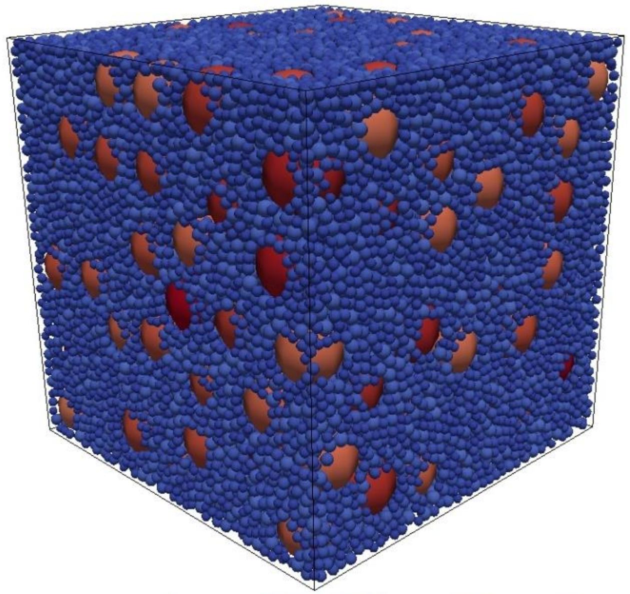
- Di Felice drag expression
- Particle assembly: 6.1 mm cube
- Fluid cell size: 1.2 mm



MPhil research of Kenichi Kawano

Virtual permeameter test samples

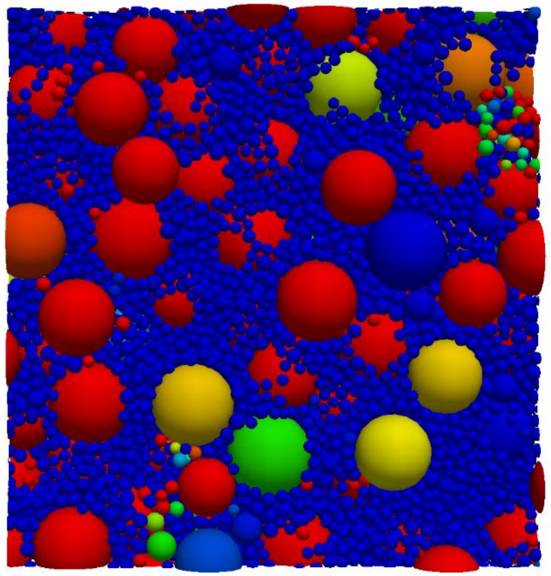




Current study:

PFC+CCFD

Rigid walls



Shire et al.

LAMMPS

Periodic boundaries

Permeameter test simulations

Combination of DEM (PFC3D) and CFD (CCFD)

- DEM for soil particles
- CFD for water seepage

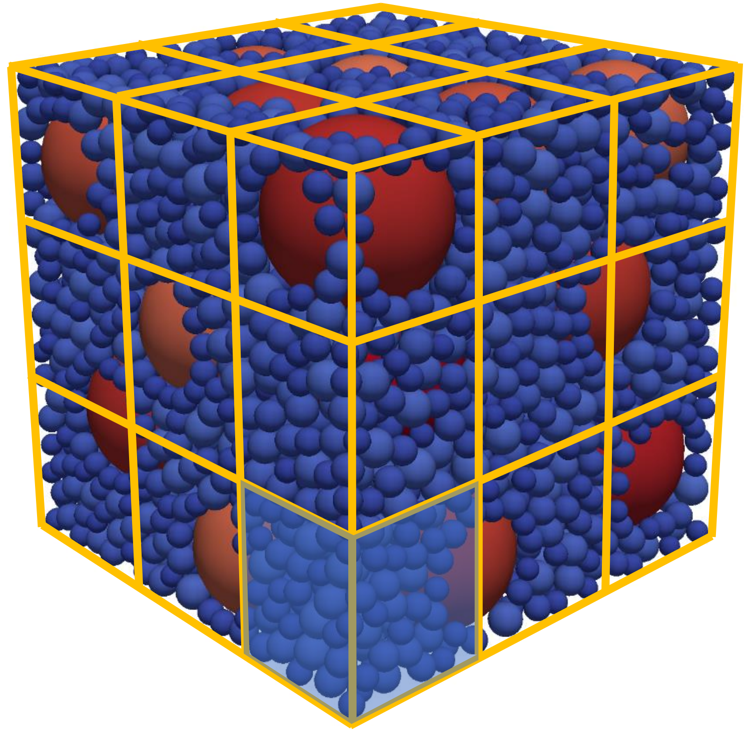
Data exchange

DEM ⟷ CFD

-Porosity
-Drag force

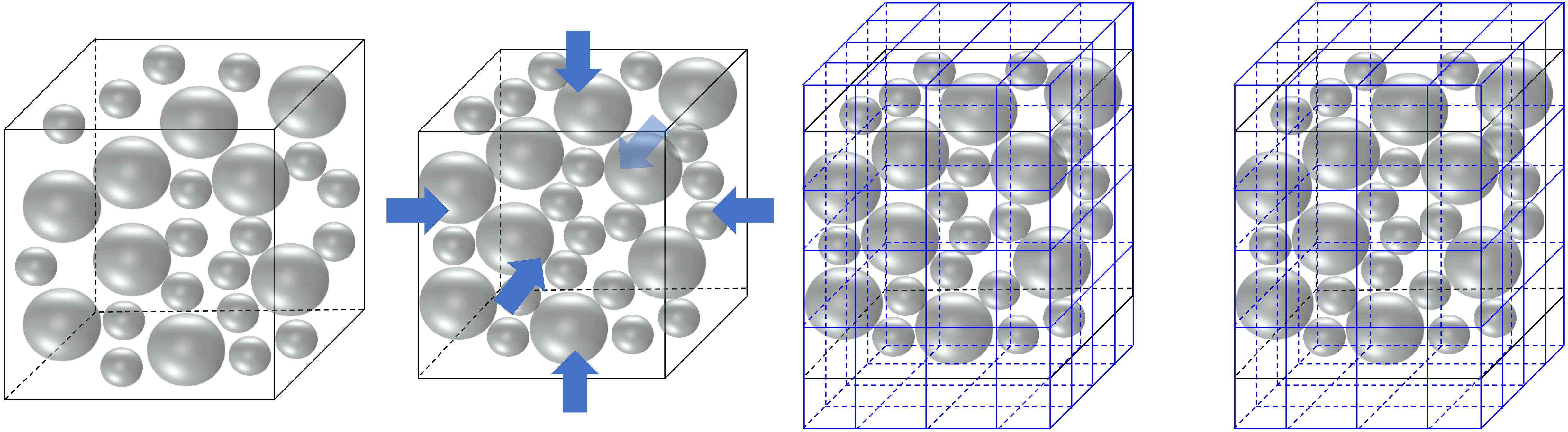
-Fluid velocity
-Fluid pressure gradient

Coarse grid method proposed by Tsuji



(Tsuji et al., 1993, Xu and Yu, 1997)

Permeameter test simulations



Create non-contacting cloud of spheres

Compress to 50kPa, Apply gravity

Create fluid mesh, Fix boundaries, Fix particle positions, Apply pressure gradient

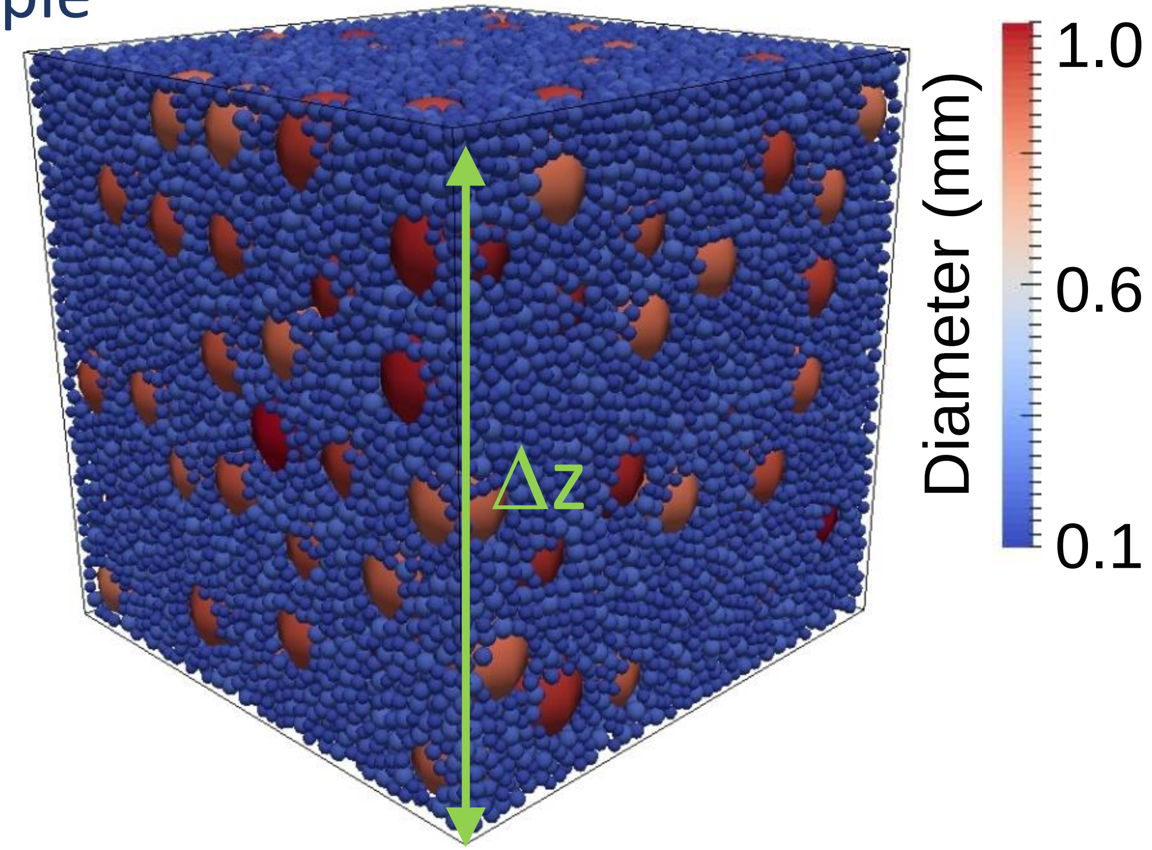
Steady state fluid, Release particles, Monitor response

Permeameter test simulations

- Applied pressure differential across sample (Δp)
- Increased hydraulic gradient (i) in steps
- As samples small

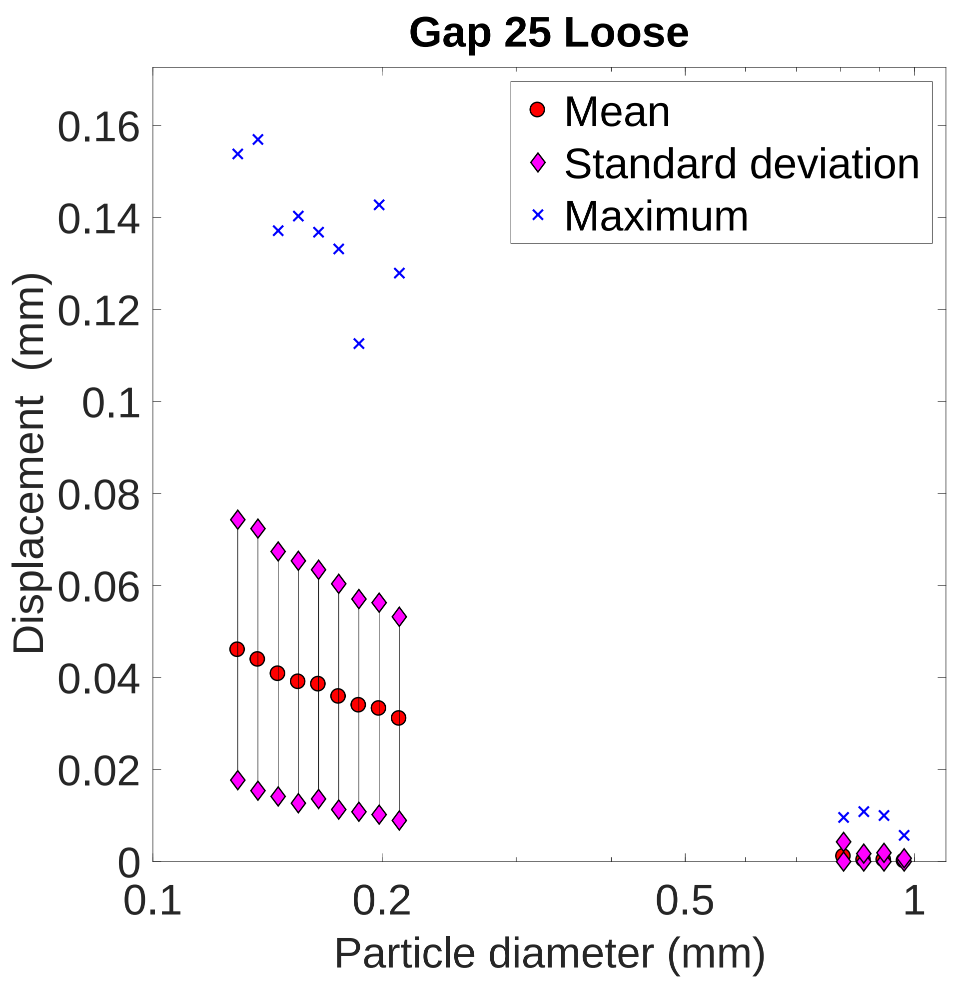
- $i = \frac{\Delta h}{\Delta z} \approx \frac{\Delta p}{\gamma_w \Delta z}$

- Δh=head drop across sample
- γ_w = unit weight of water
- Simulation gives permeability k ≈ 5x10^{-3} m/s



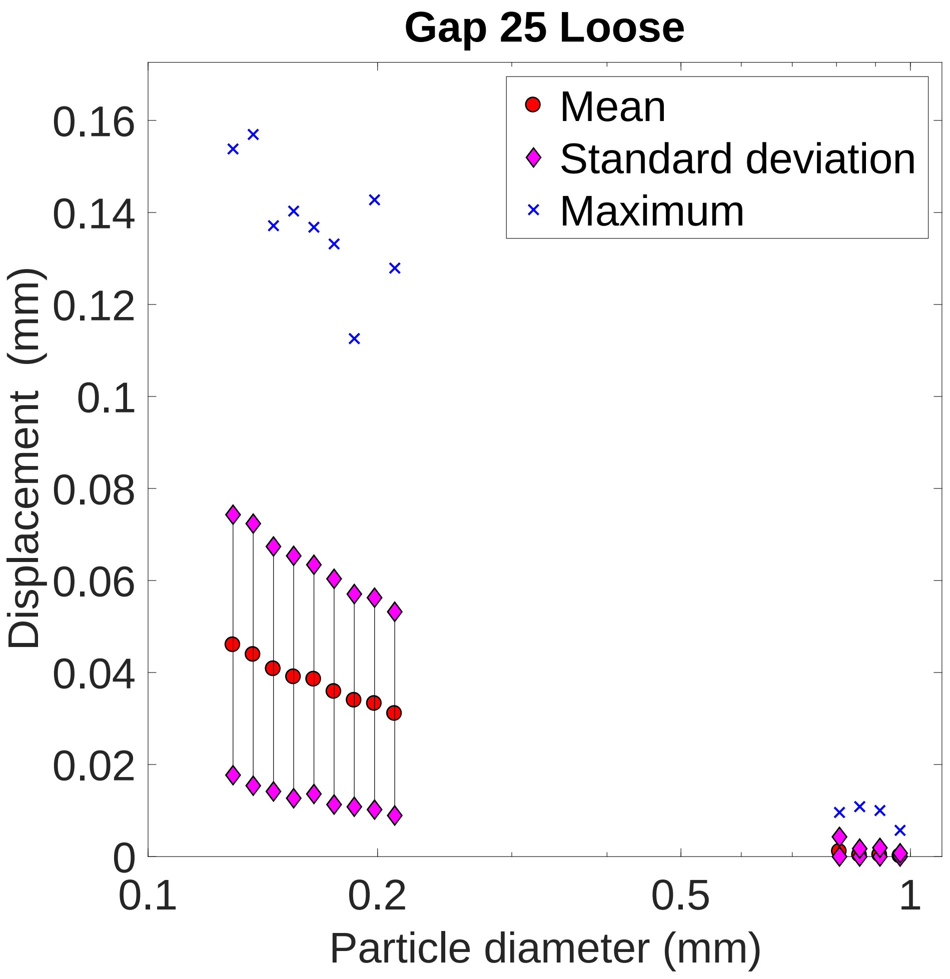
Kawano et al. (2017) Soils and Foundations

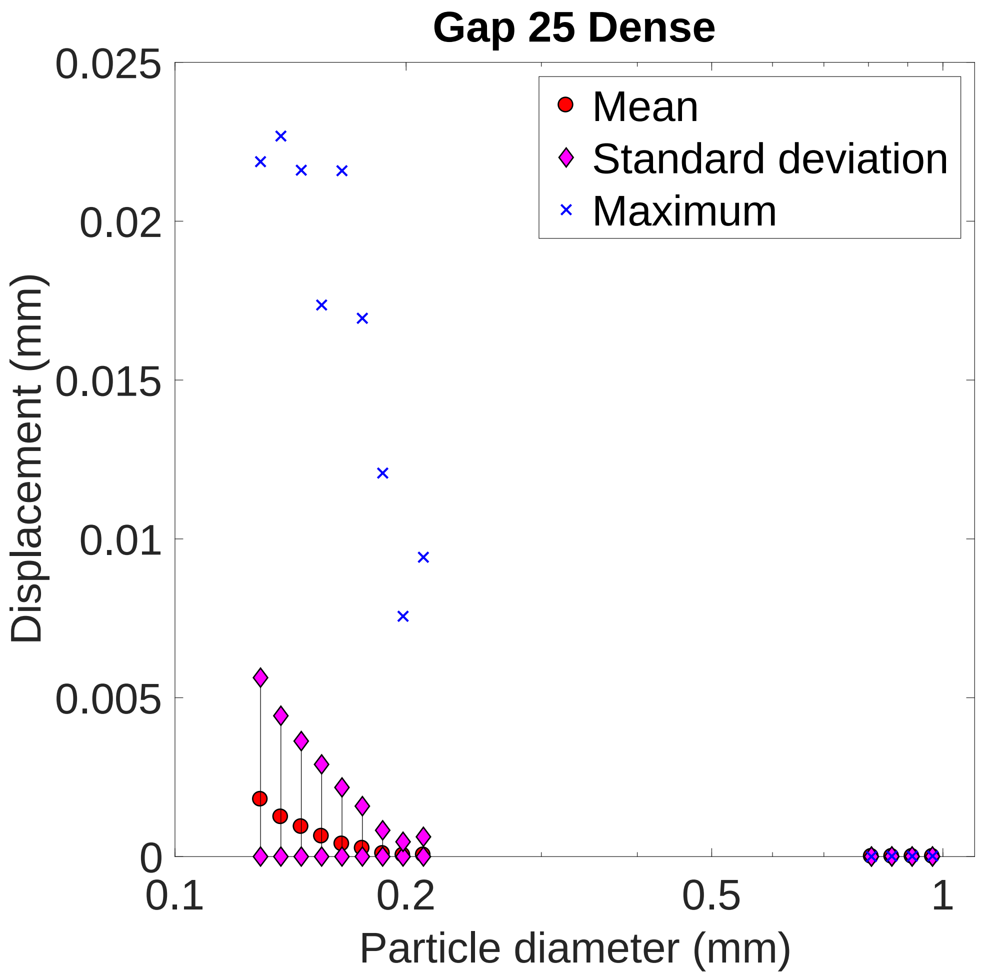
Particle displacements – for *i* = 1



Kawano et al. (2017) Soils and Foundations

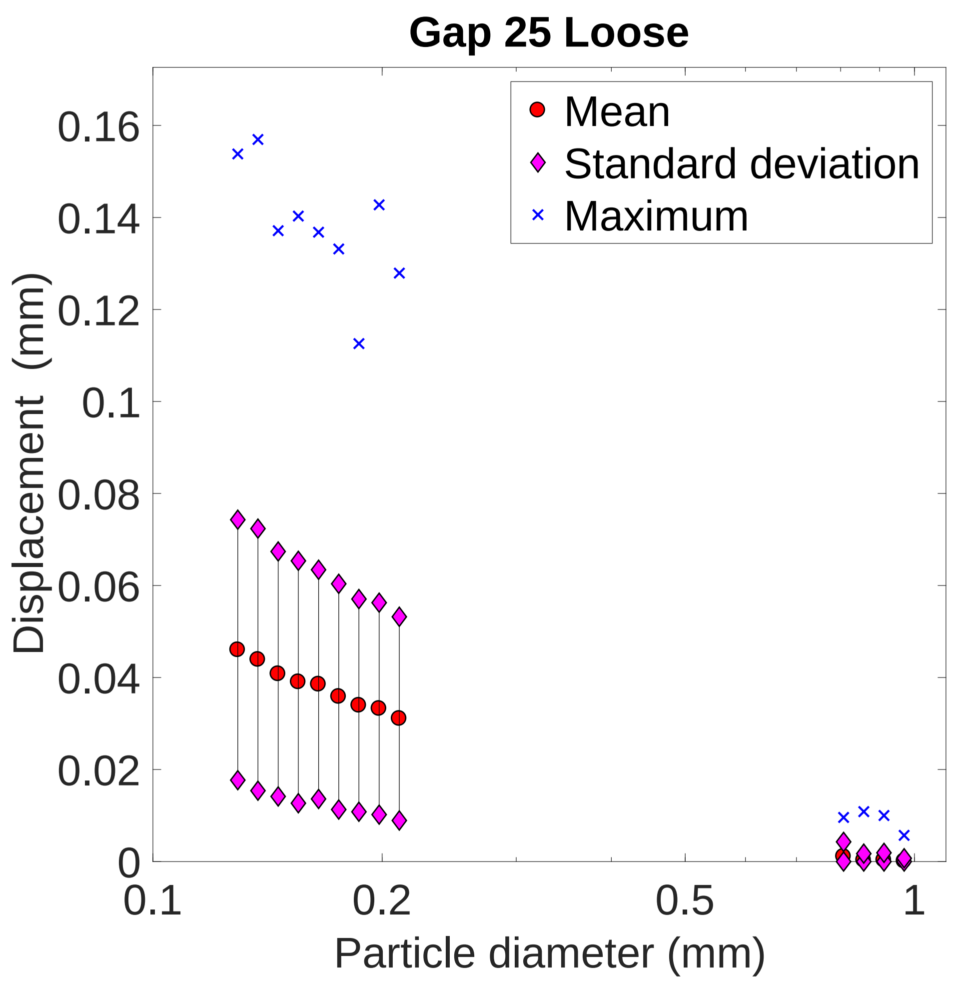
Particle displacements – for i = 1



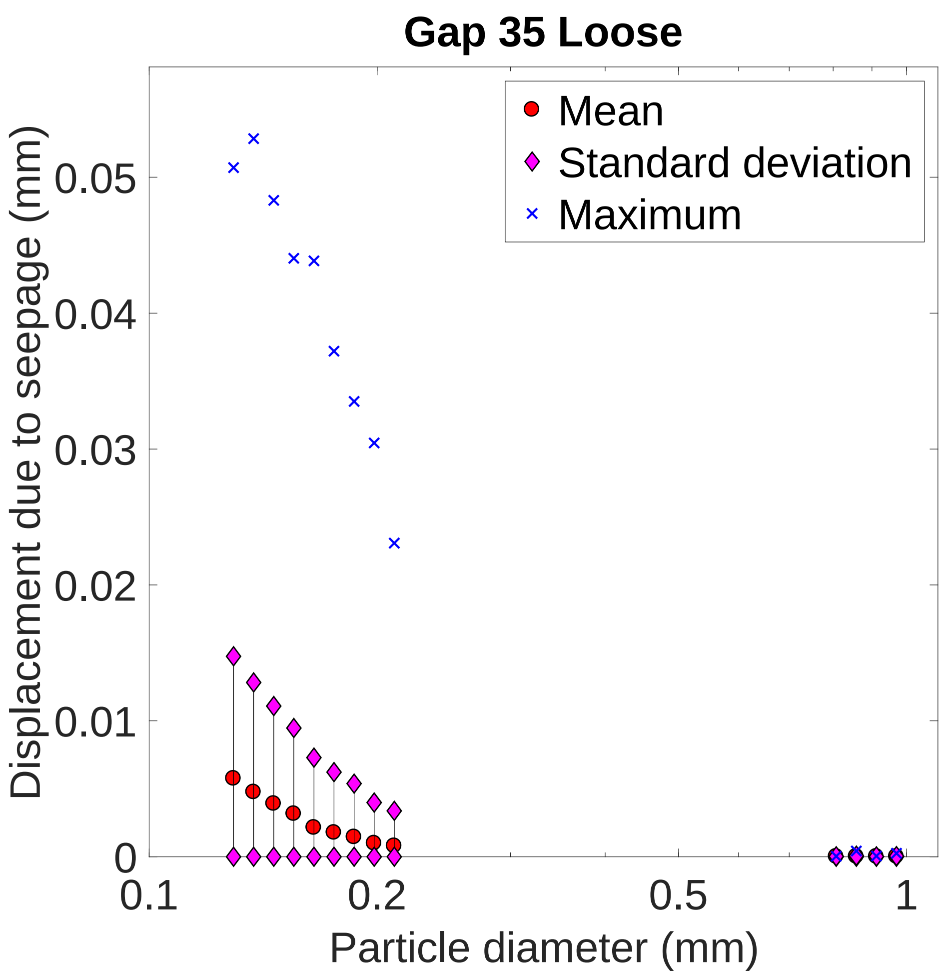


Increase in density

Particle displacements – for *i* = 1

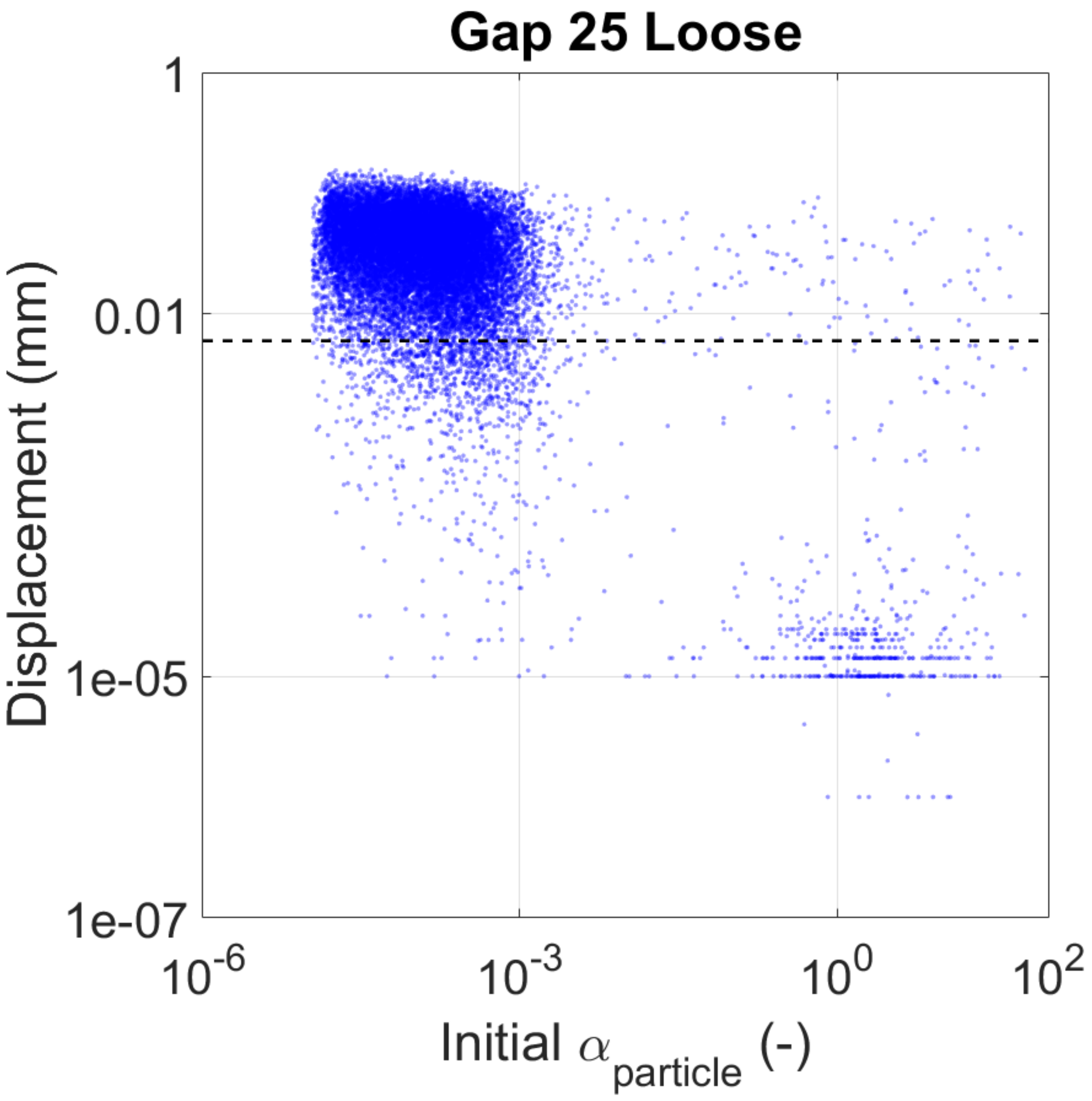


Just underfilled



Just overfilled

Particle displacements – for *i* = 1



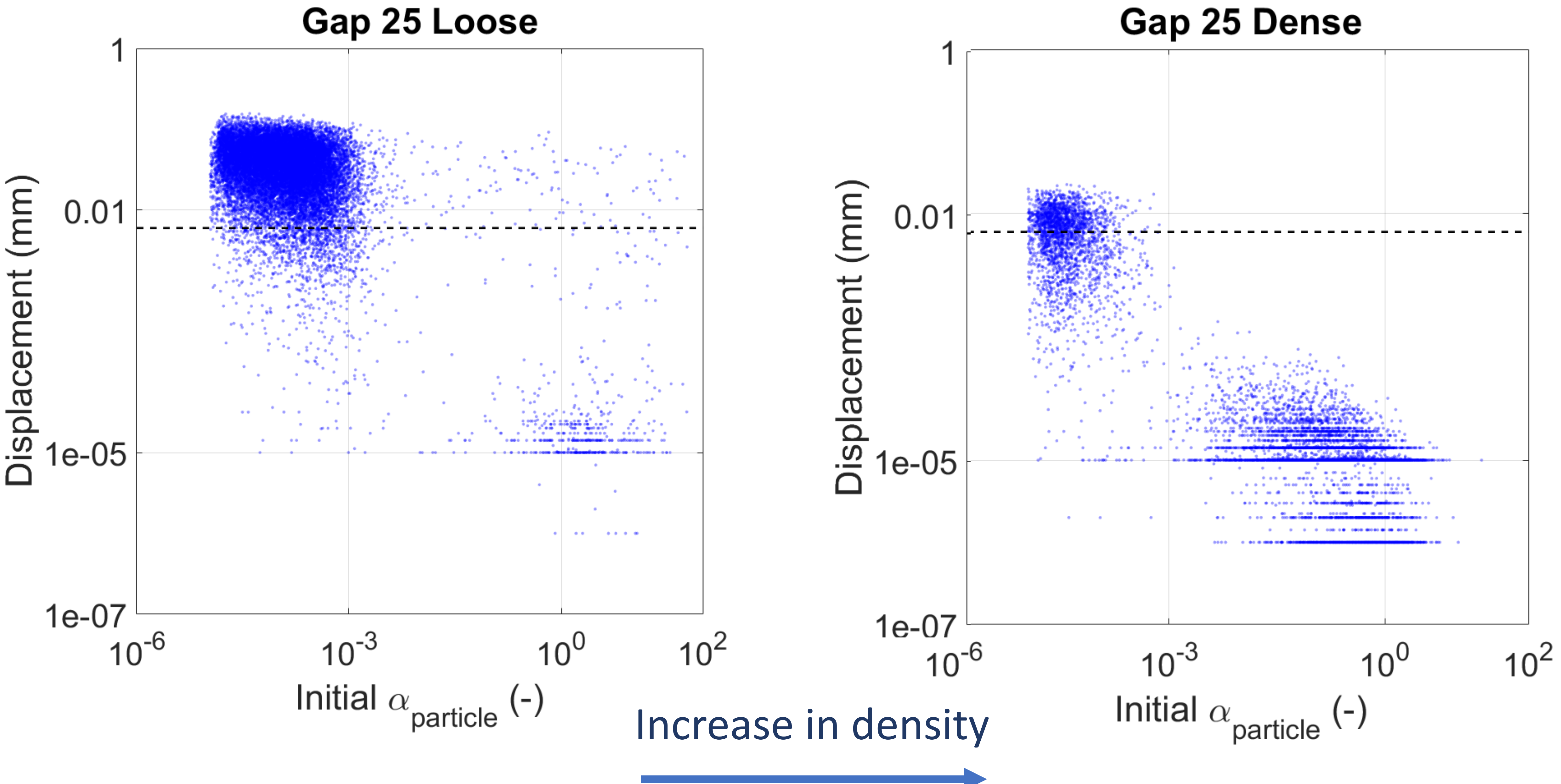
$$\alpha_{particle} = \frac{\sigma_{particle}}{\sigma_{overall}}$$

$\sigma_{particle}$ = average stress in a particle

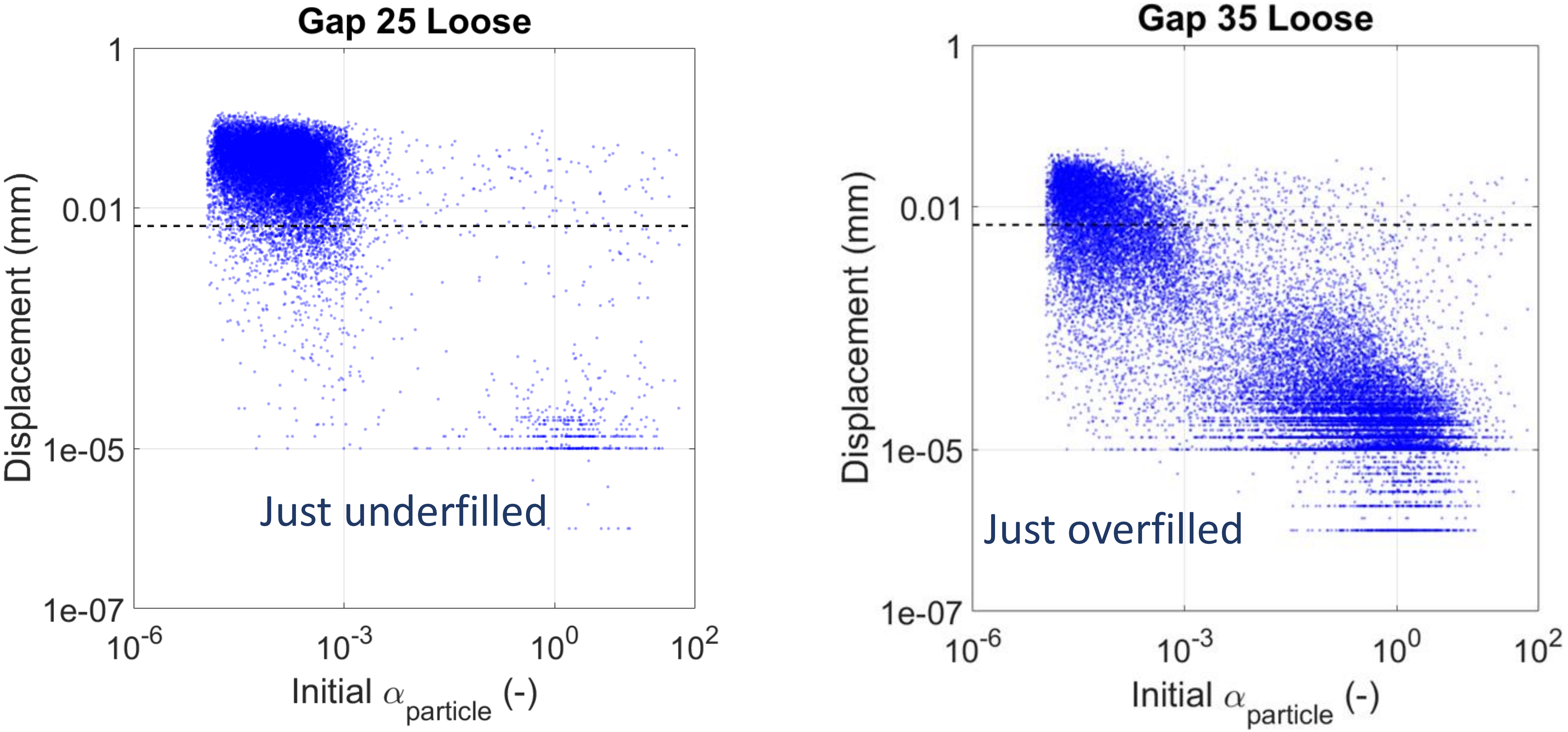
$\sigma_{overall}$ = overall sample stress

Kawano et al. (2017) Soils and Foundations

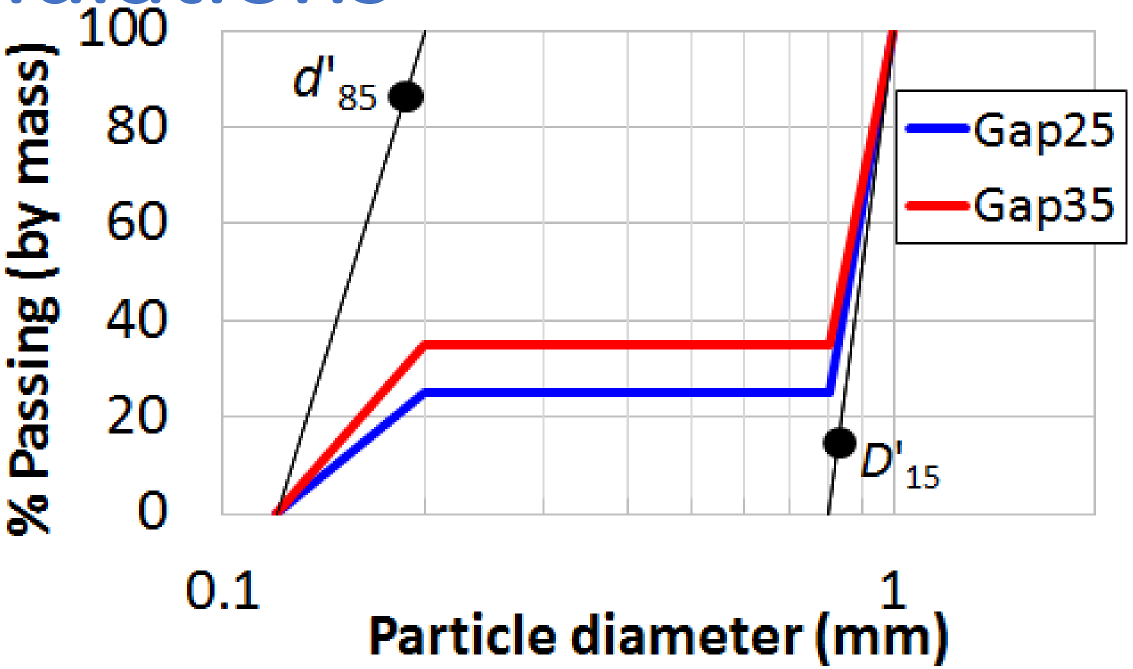
Particle displacements – for *i* = 1



Particle displacements – for i = 1



Permeameter test simulations



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- Di Felice drag expression
- Particle assembly: 6.1 mm cube
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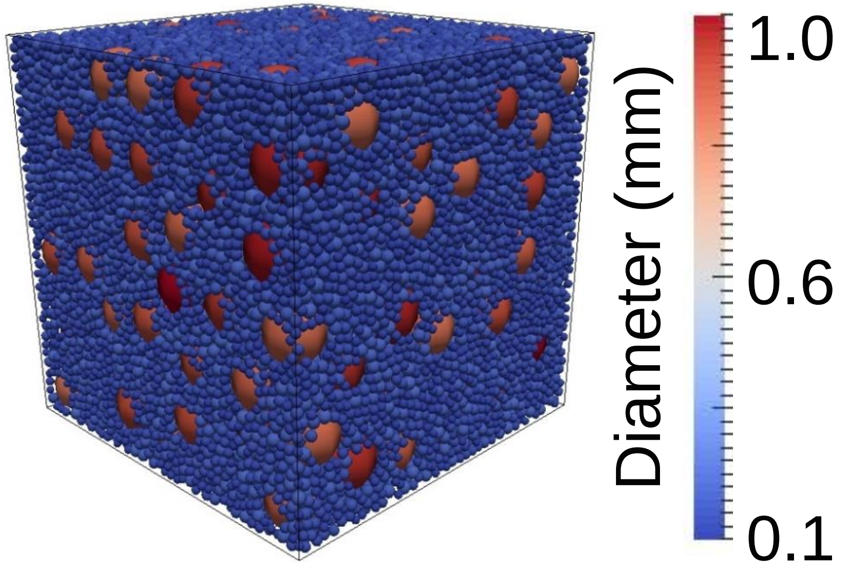


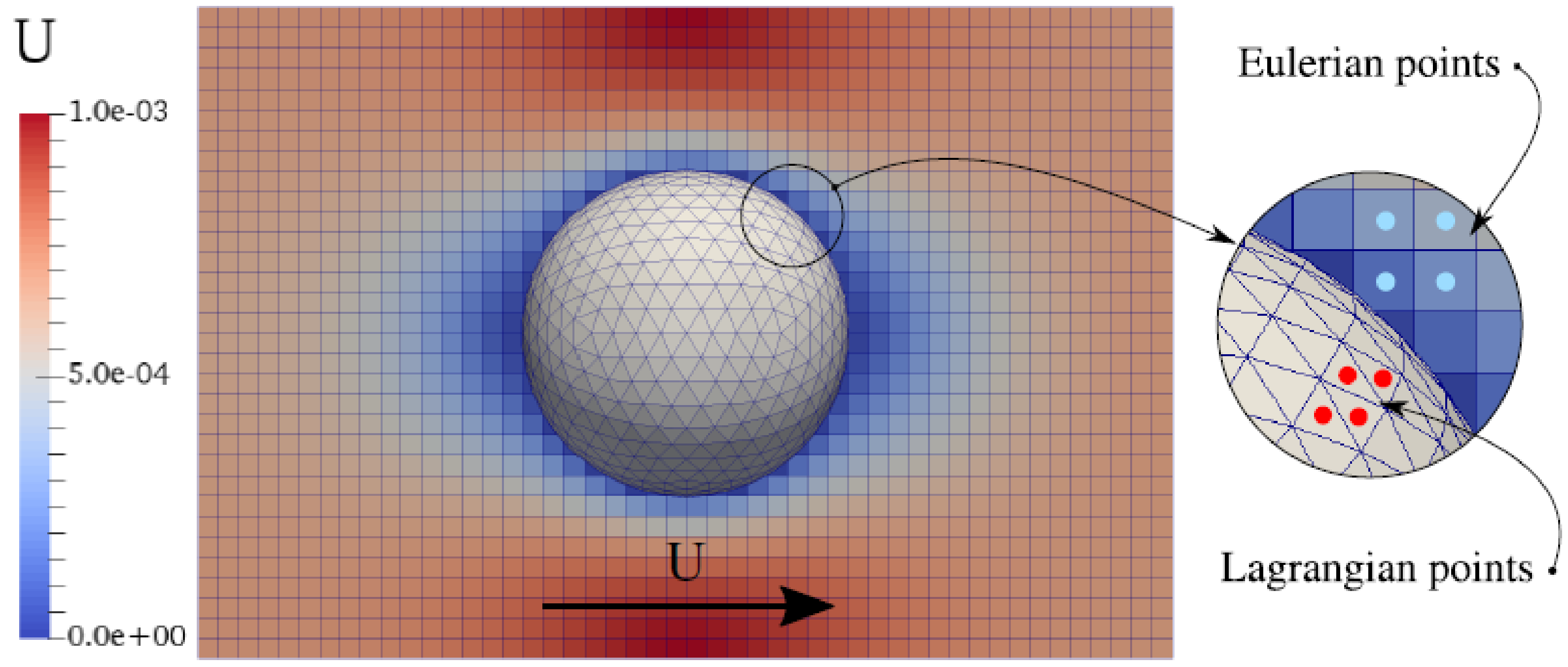
MPhil research of Kenichi Kawano

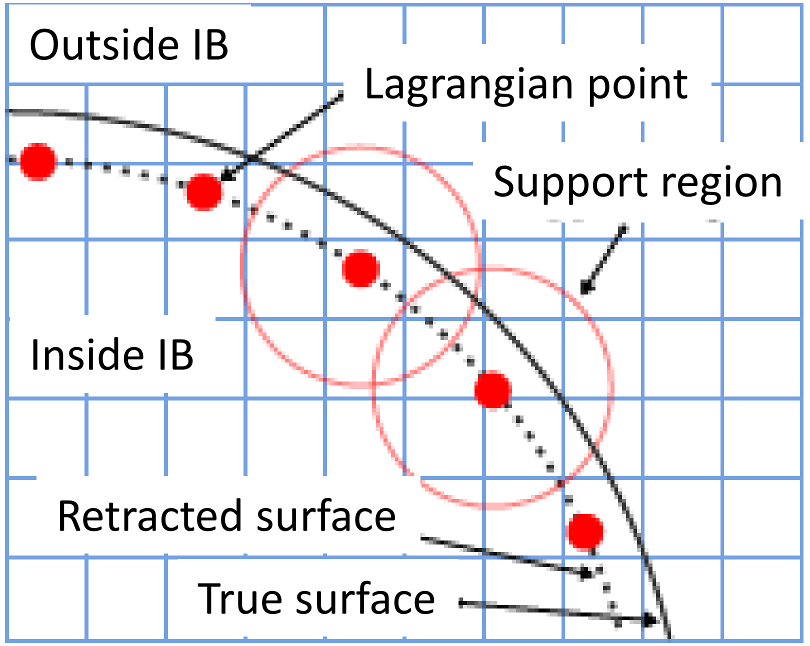
Immersed boundary method (IBM)

Allows simulation of fluid flow in void space (fixed, regular, Eulerian grid)

Fluid-particle interaction force can be determined

MultiFlow – B. van Wachem et al.

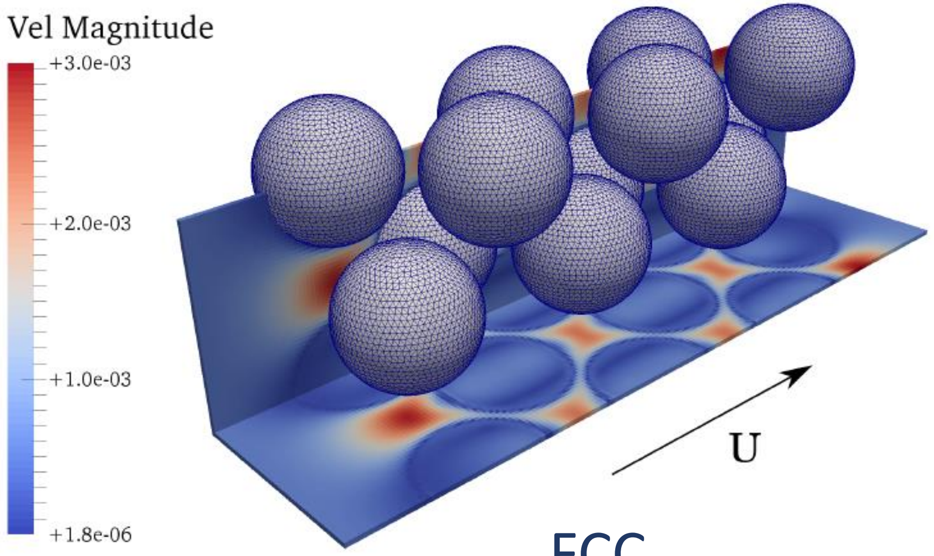




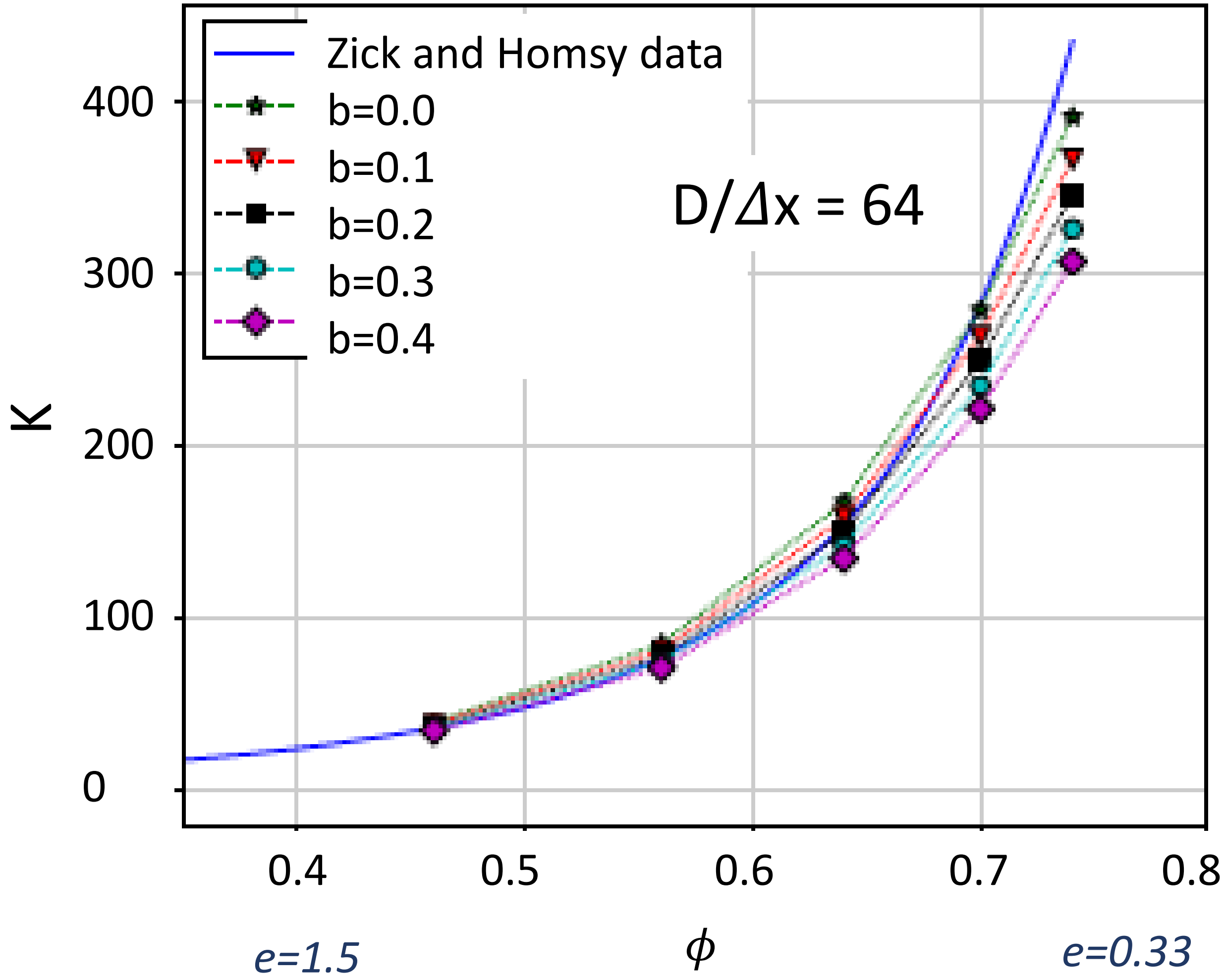
PhD research of Chris Knight

Verification simulations

Zick and Homsy – boundary integral method data



FCC



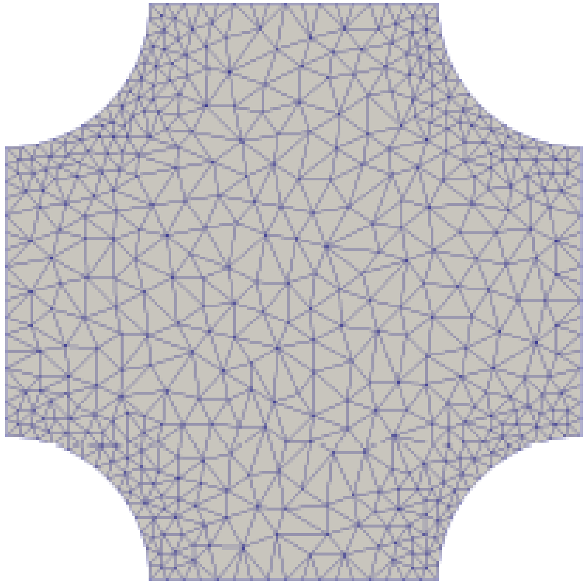
ϕ = solids fraction = V_{solids} / V_{total}

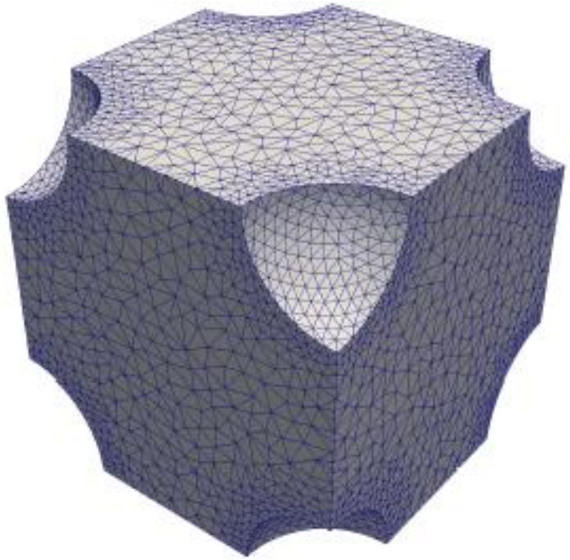
b = radius retraction parameter

(retraction = bΔx)

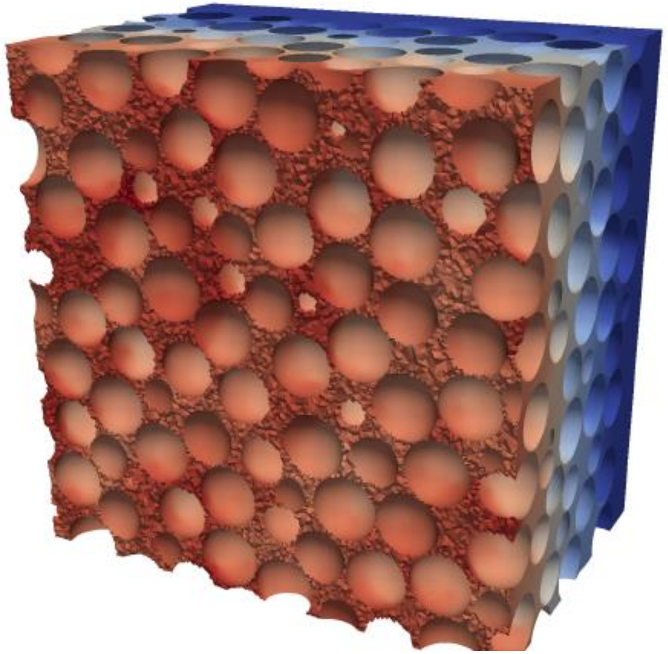
K = fluid particle interaction force / Stokes drag

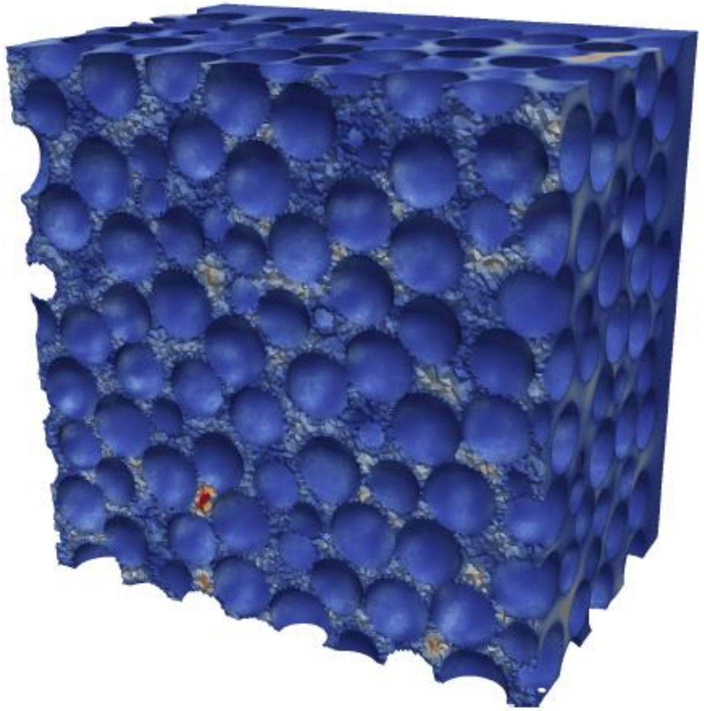
Verification simulations





Dense
monodisperse
sample
Low Re

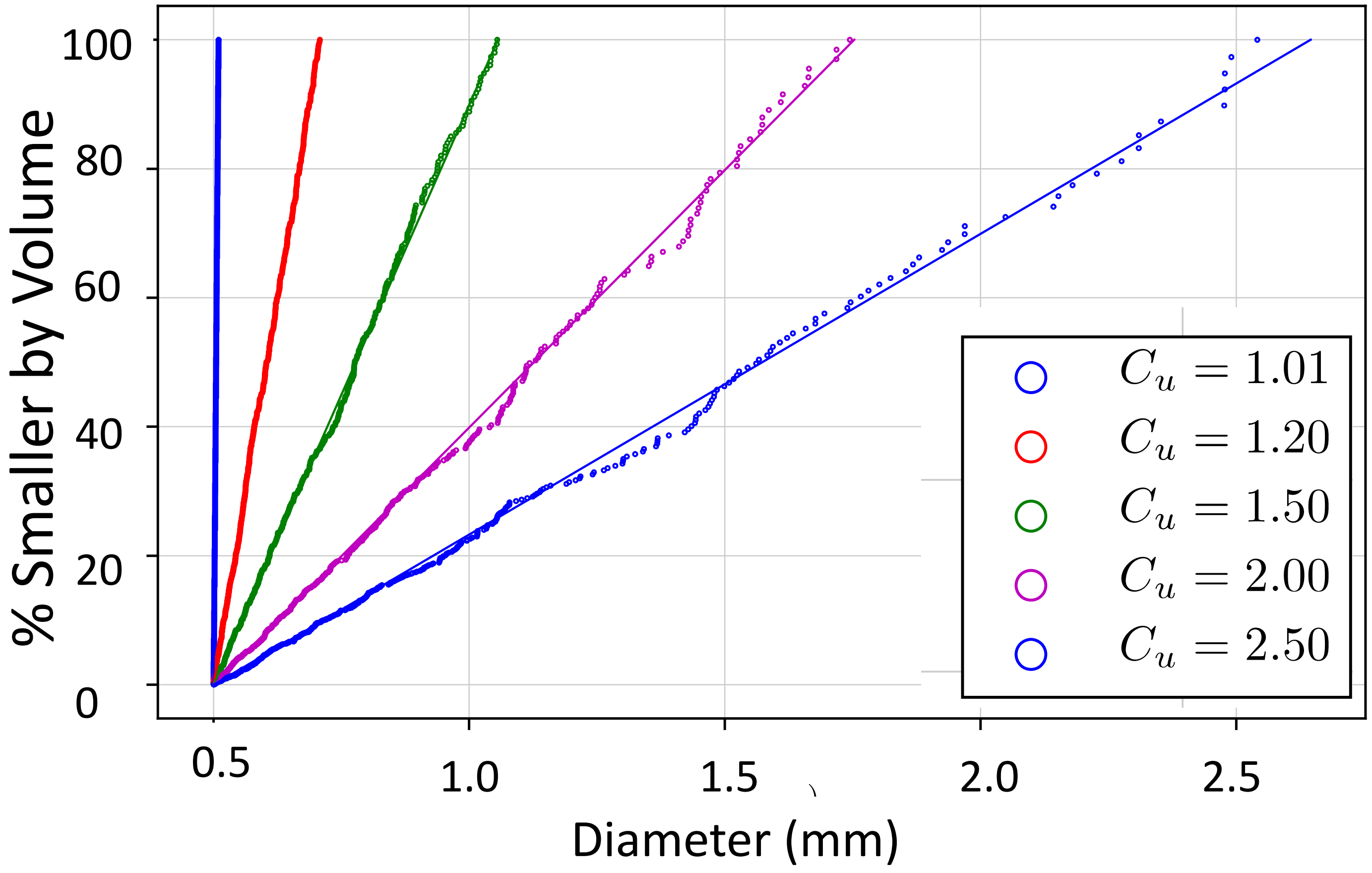


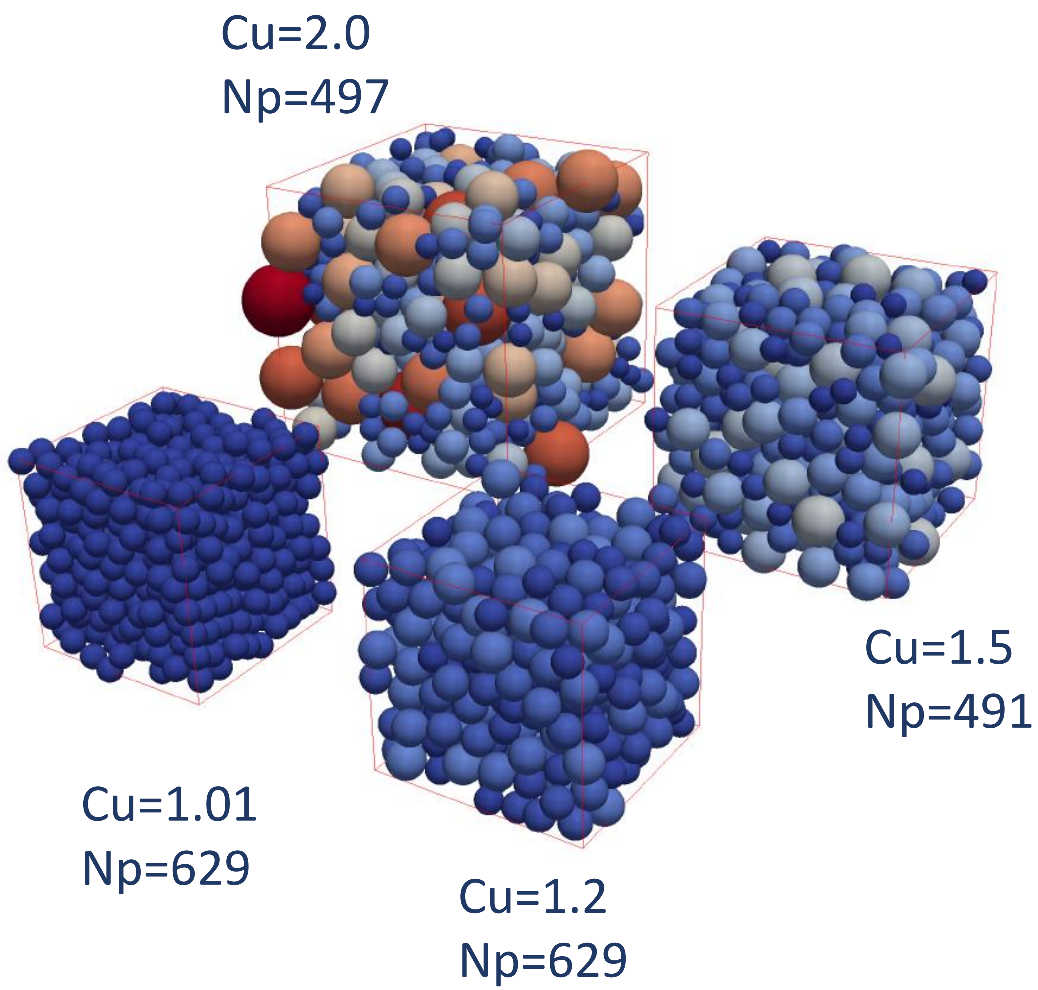


Body fitted mesh

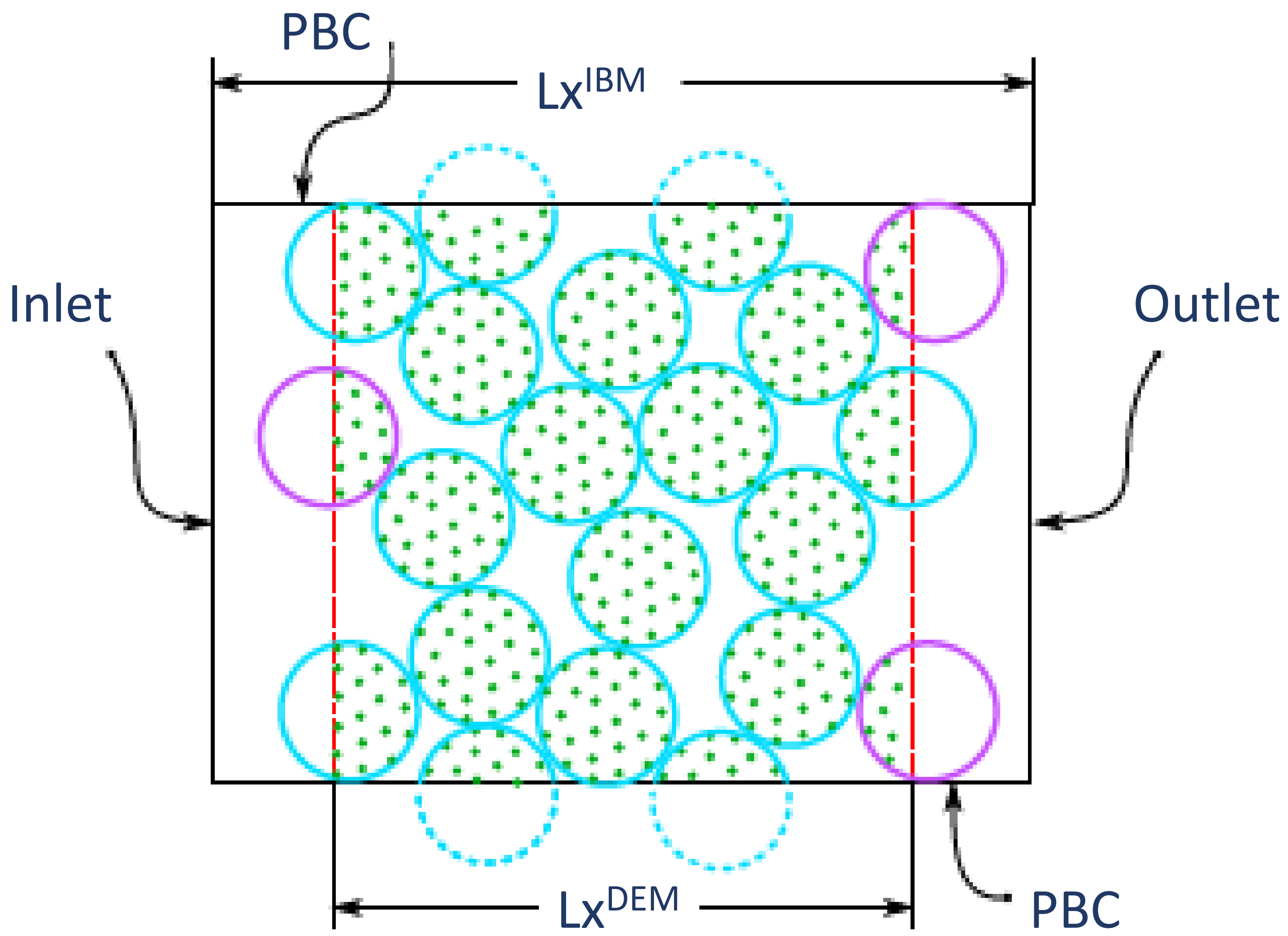
Particles a boundary to fluid flow

IBM Simulations – linear gradings





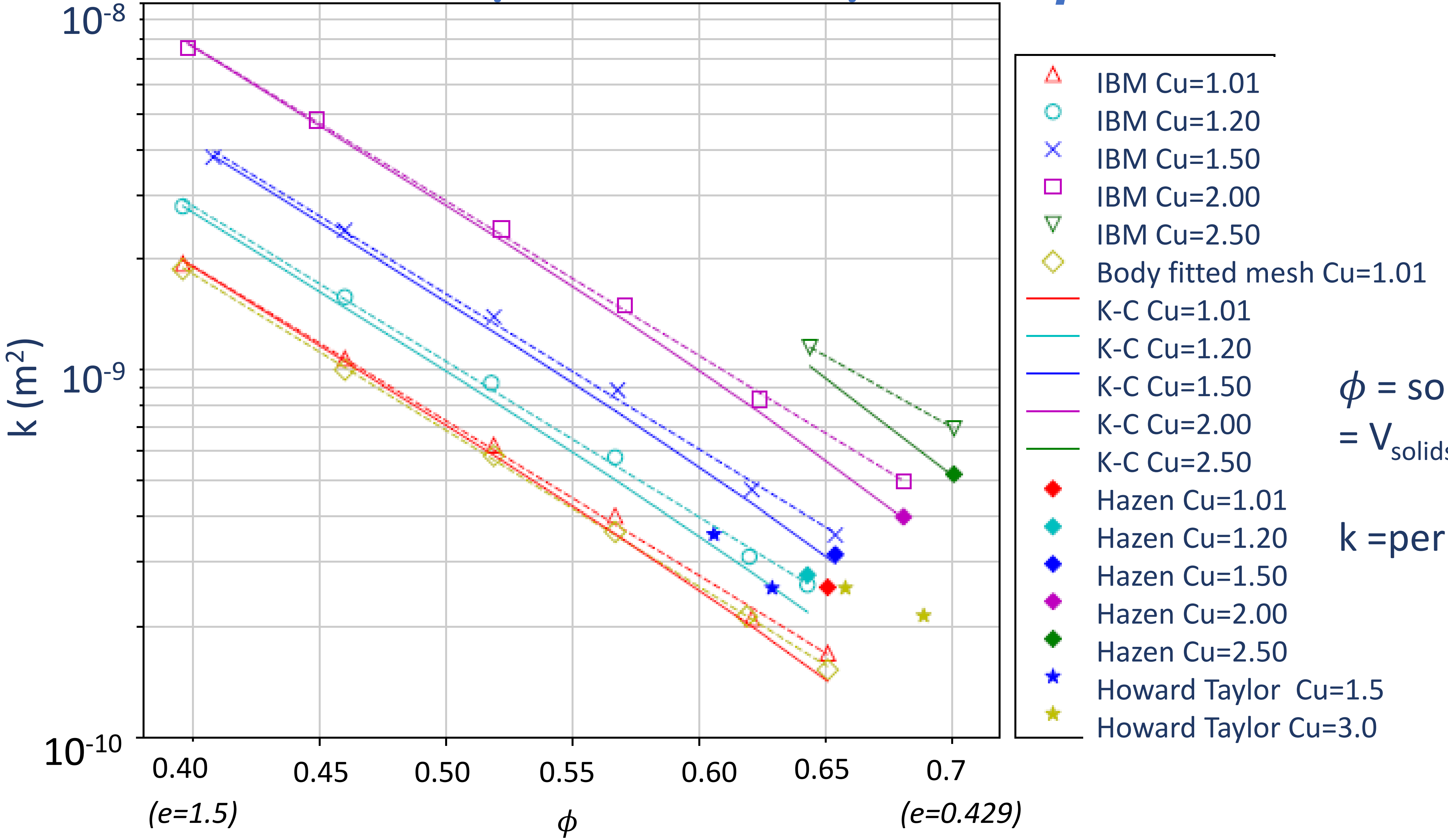
Simulation – configuration



Samples subject to laminar flow

Wide range of packing densities

Variation in permeability with ϕ

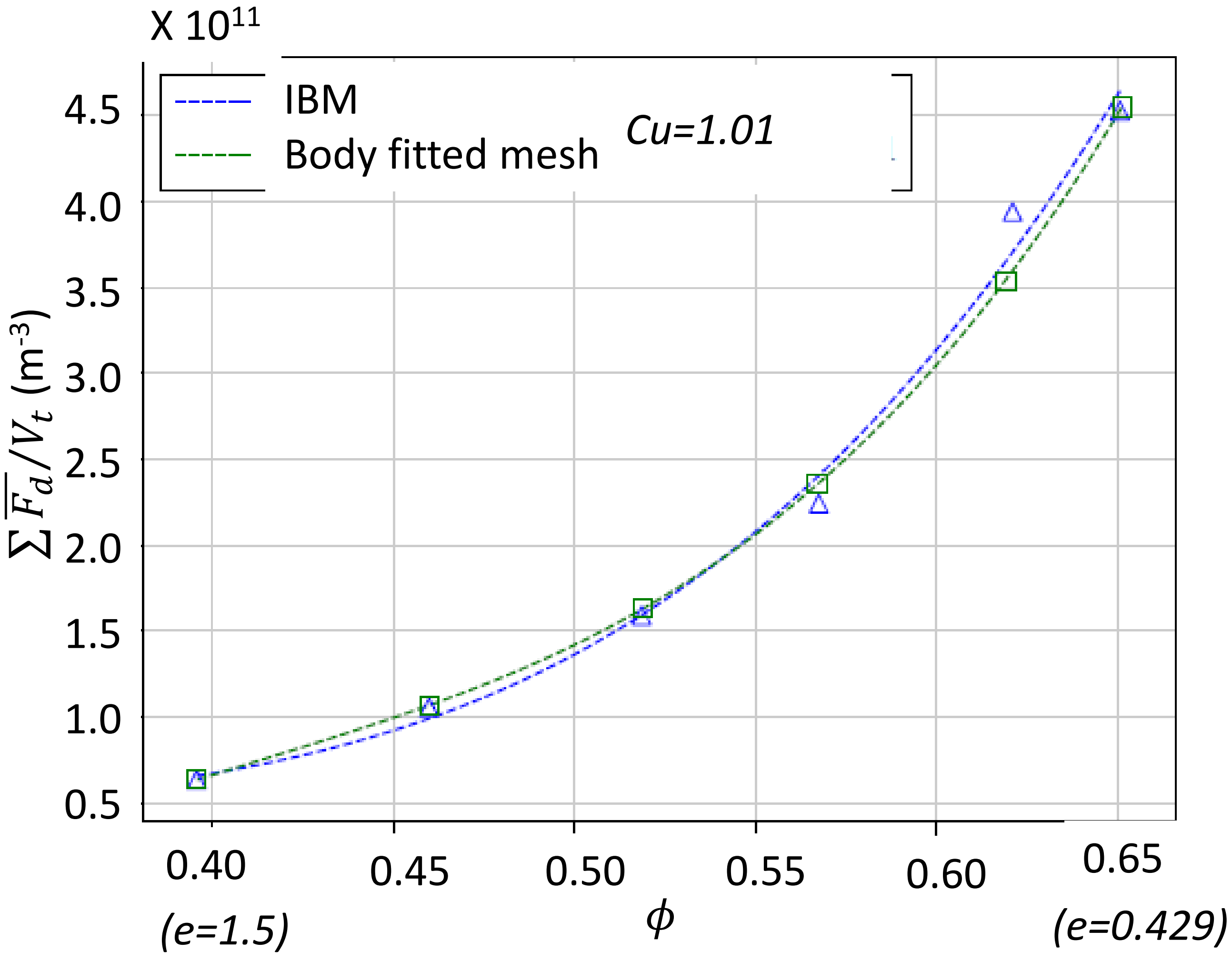


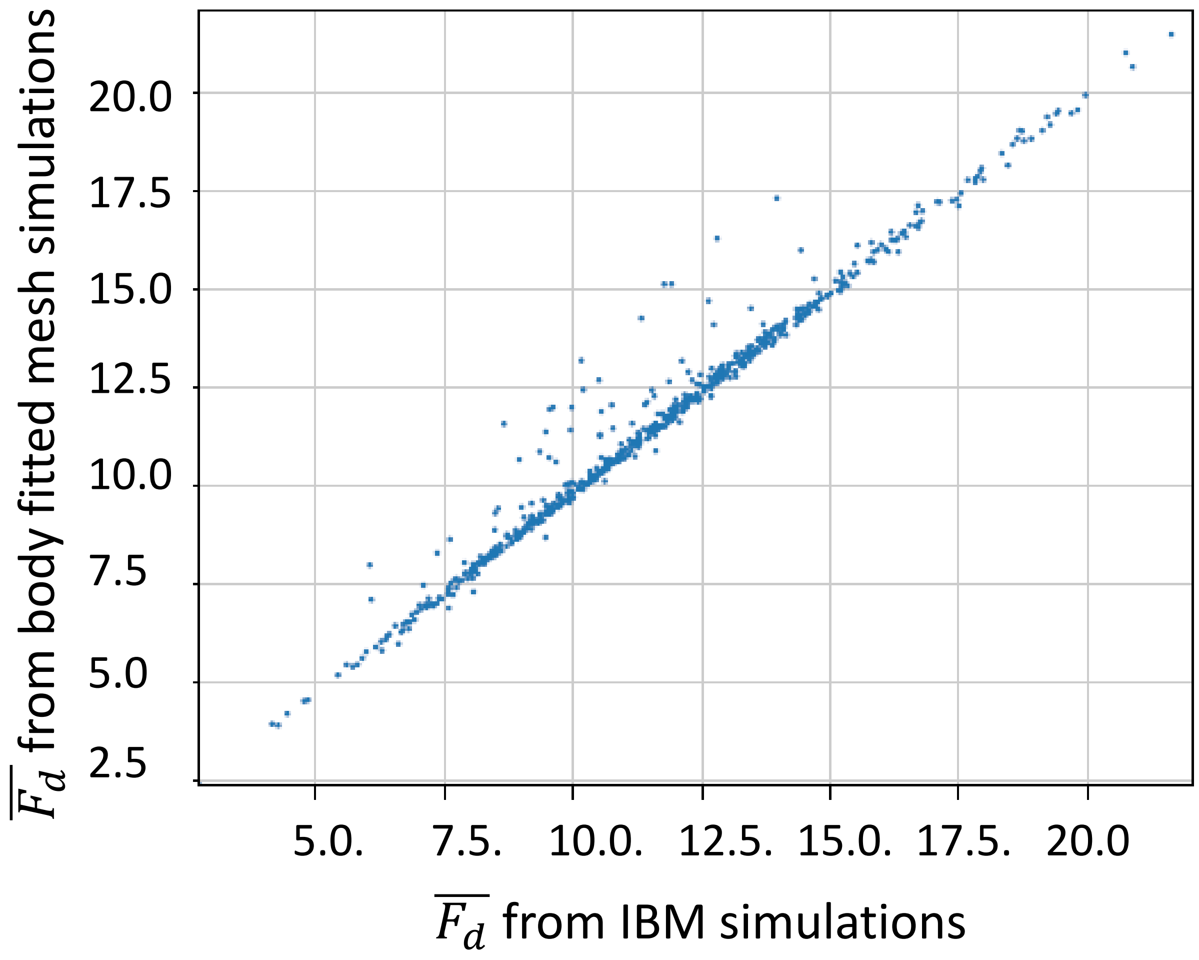
ϕ = solids fraction

$= V_{solids} / V_{total}$

k =permeability

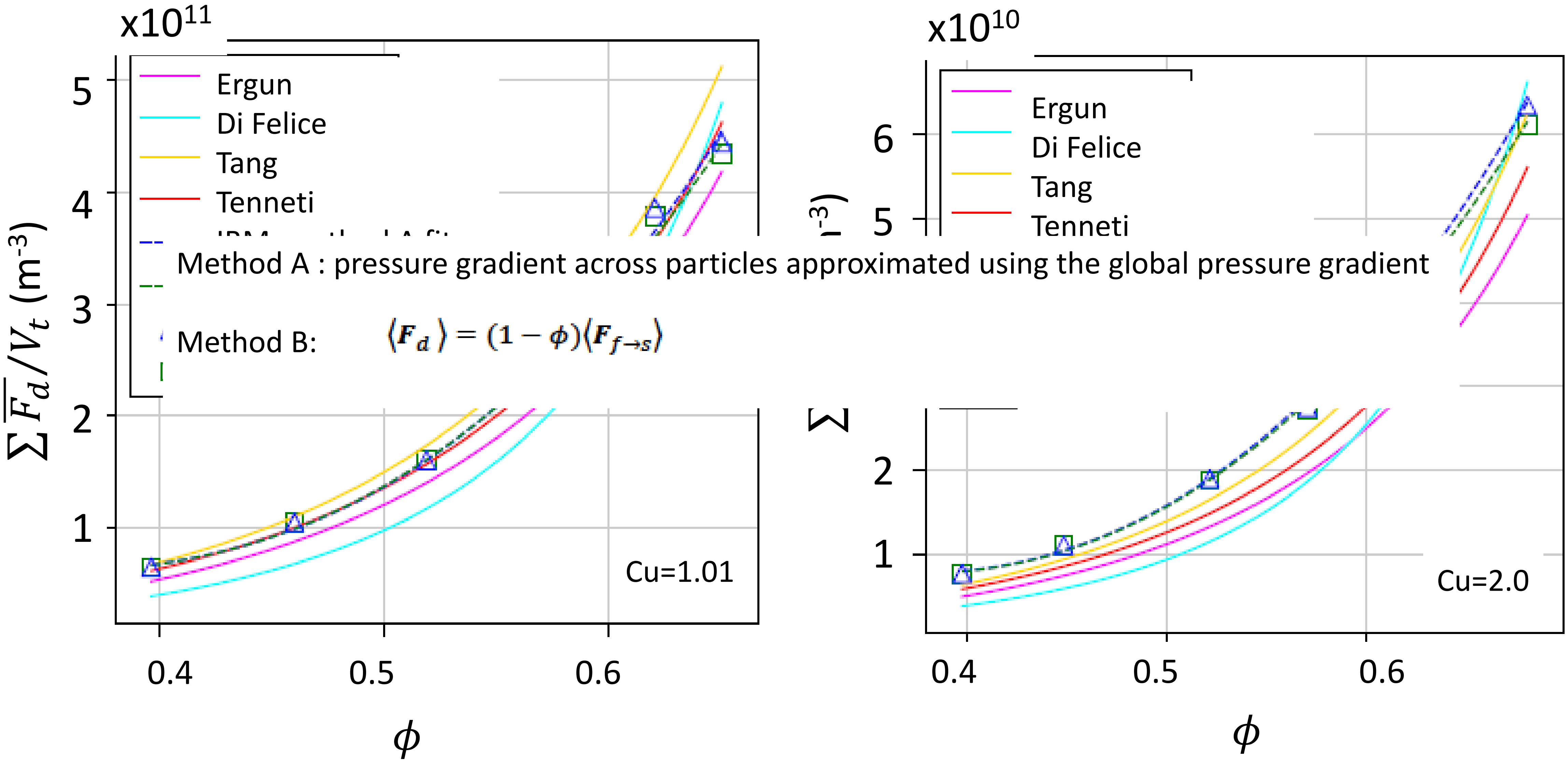
Variation in drag force with ϕ





$\overline{F_d}$ = drag force normalized by Stokes drag

Assessment of semi-empirical expressions



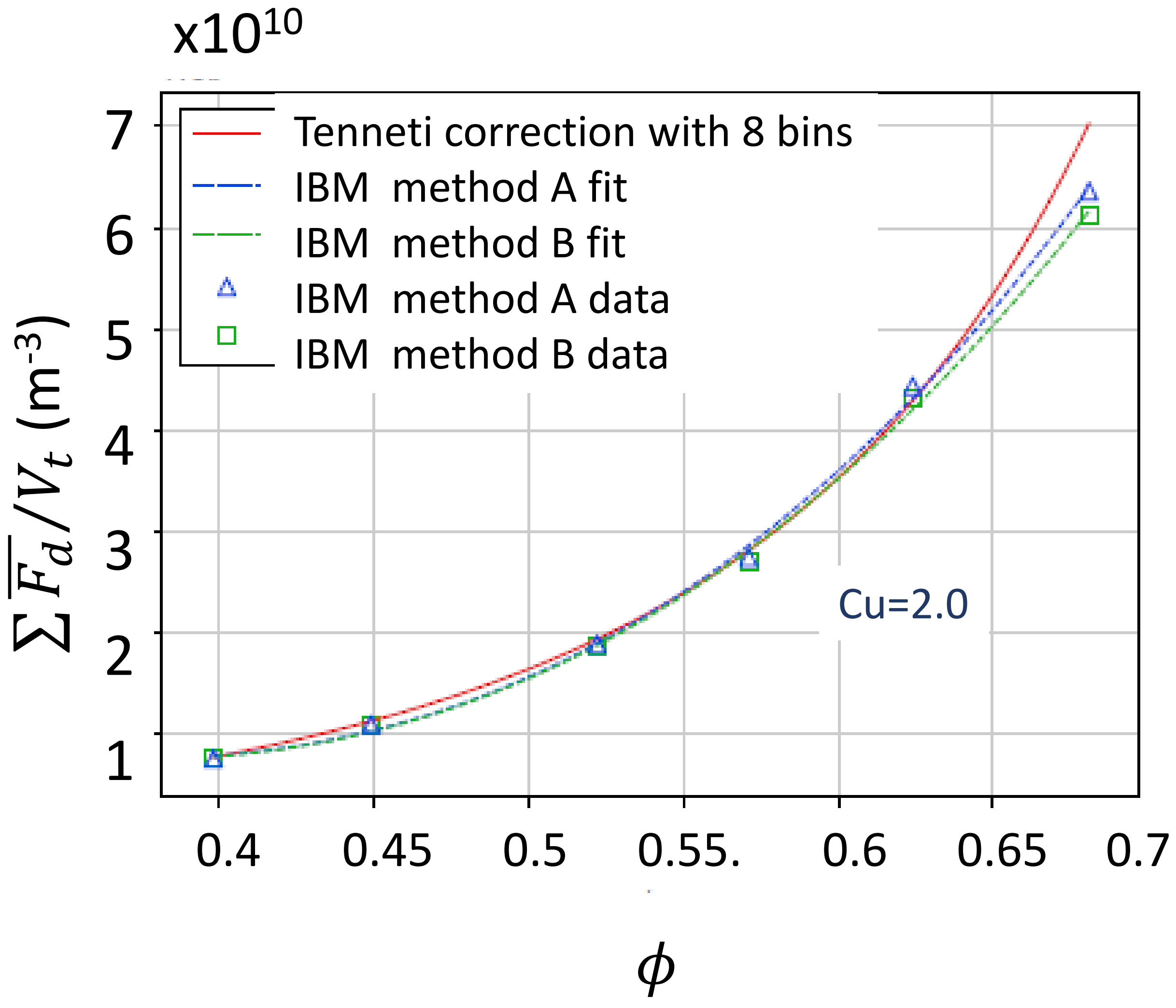
Method A : pressure gradient across particles approximated using the global pressure gradient

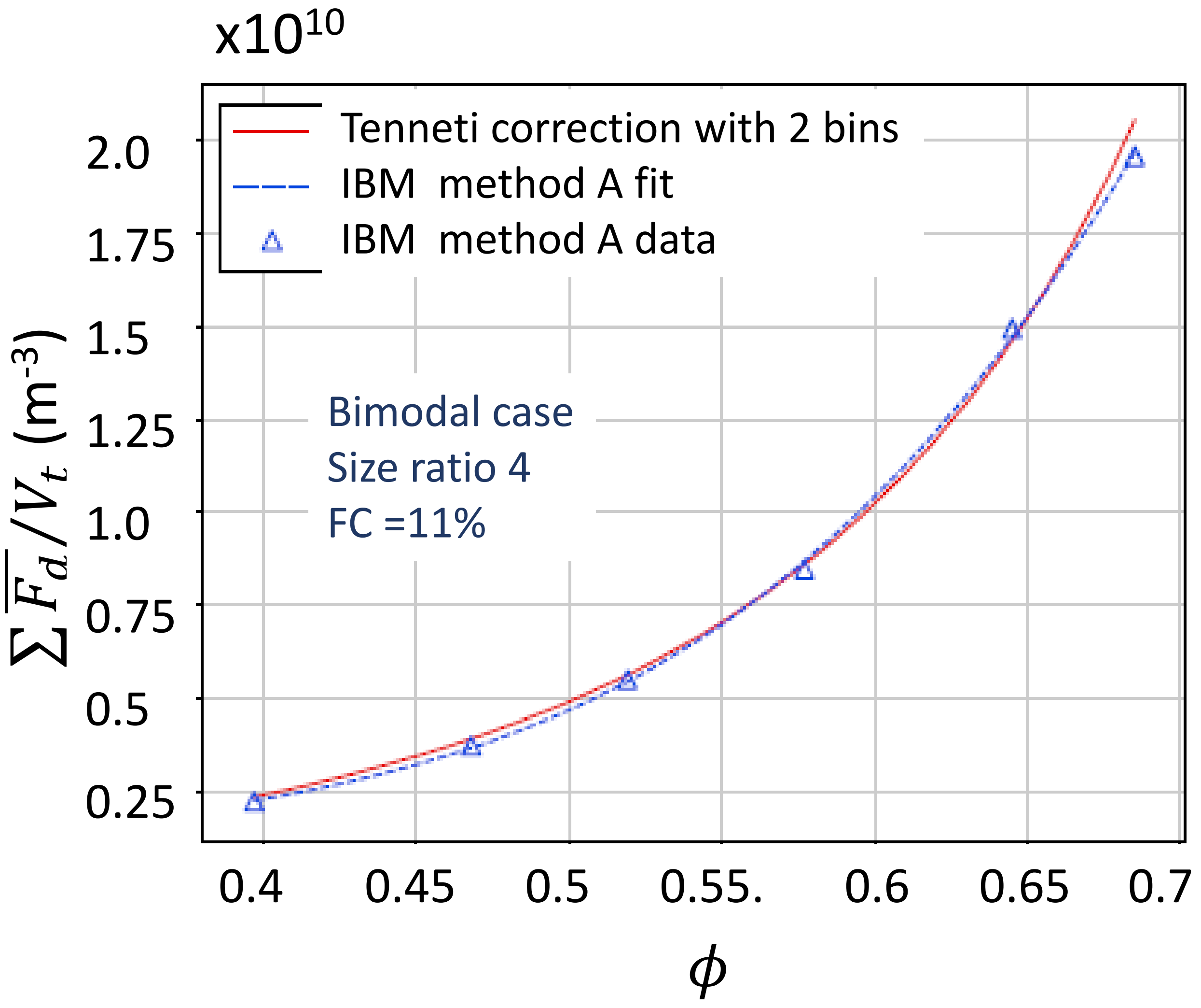
Method B: $\langle \boldsymbol{F_d} \rangle = (1-\phi)\langle \boldsymbol{F_{f\to s}} \rangle$

$\overline{F_d}$ = drag force normalized by Stokes drag – total for sample

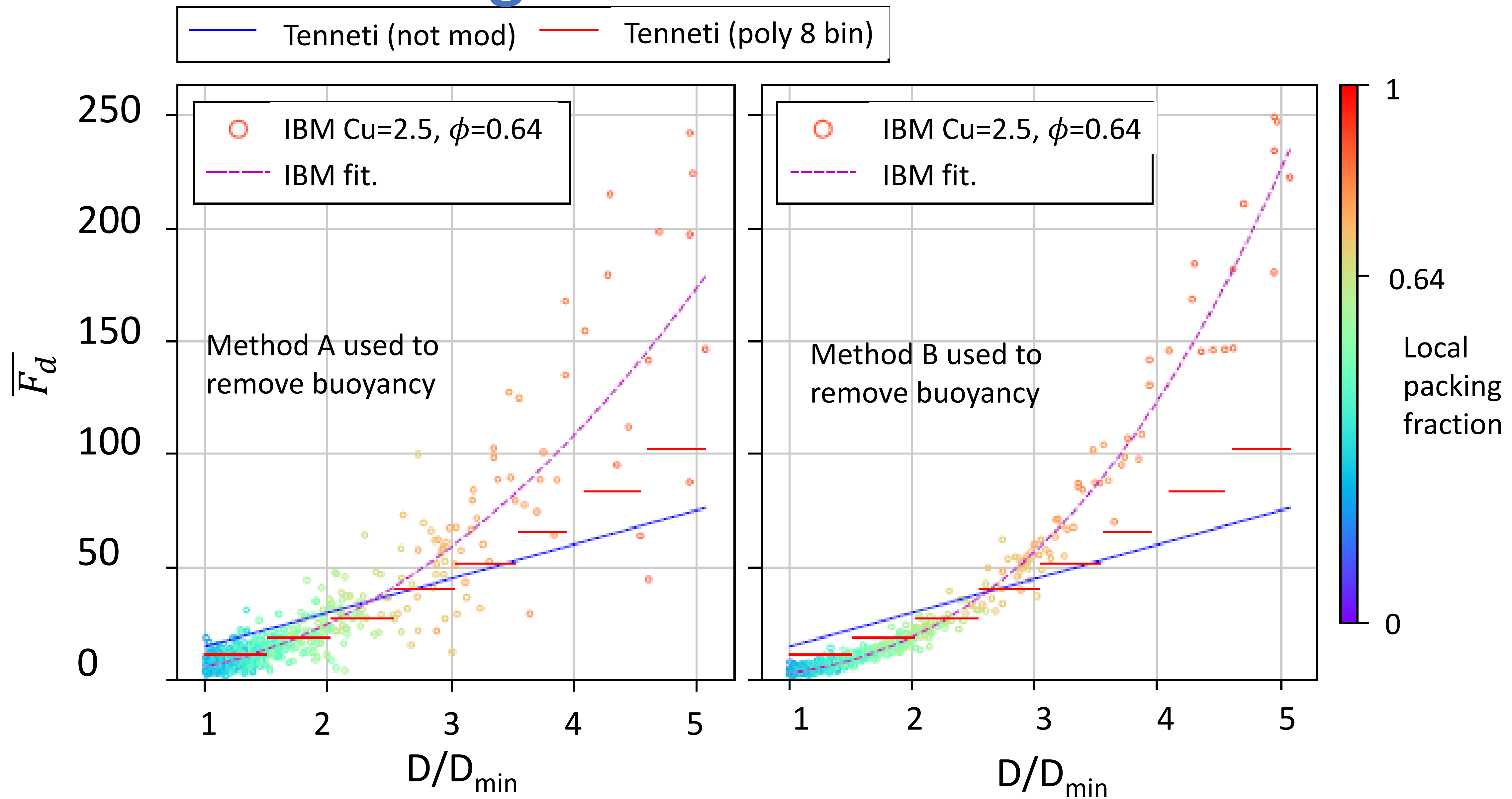
Method A/B – approach used to extract buoyancy

Assessment of polydispersity correction



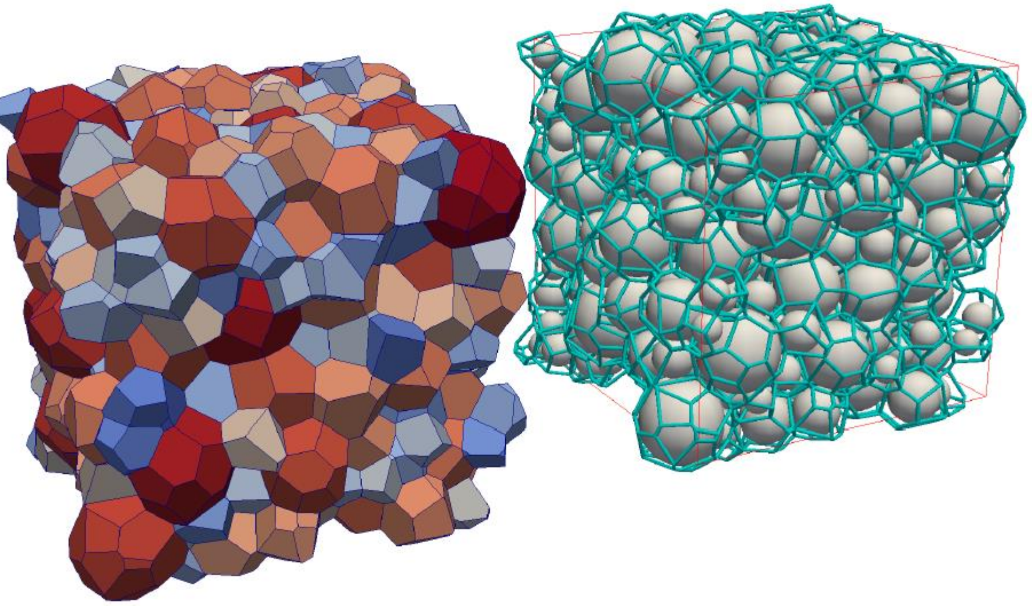


Individual drag forces versus diameter

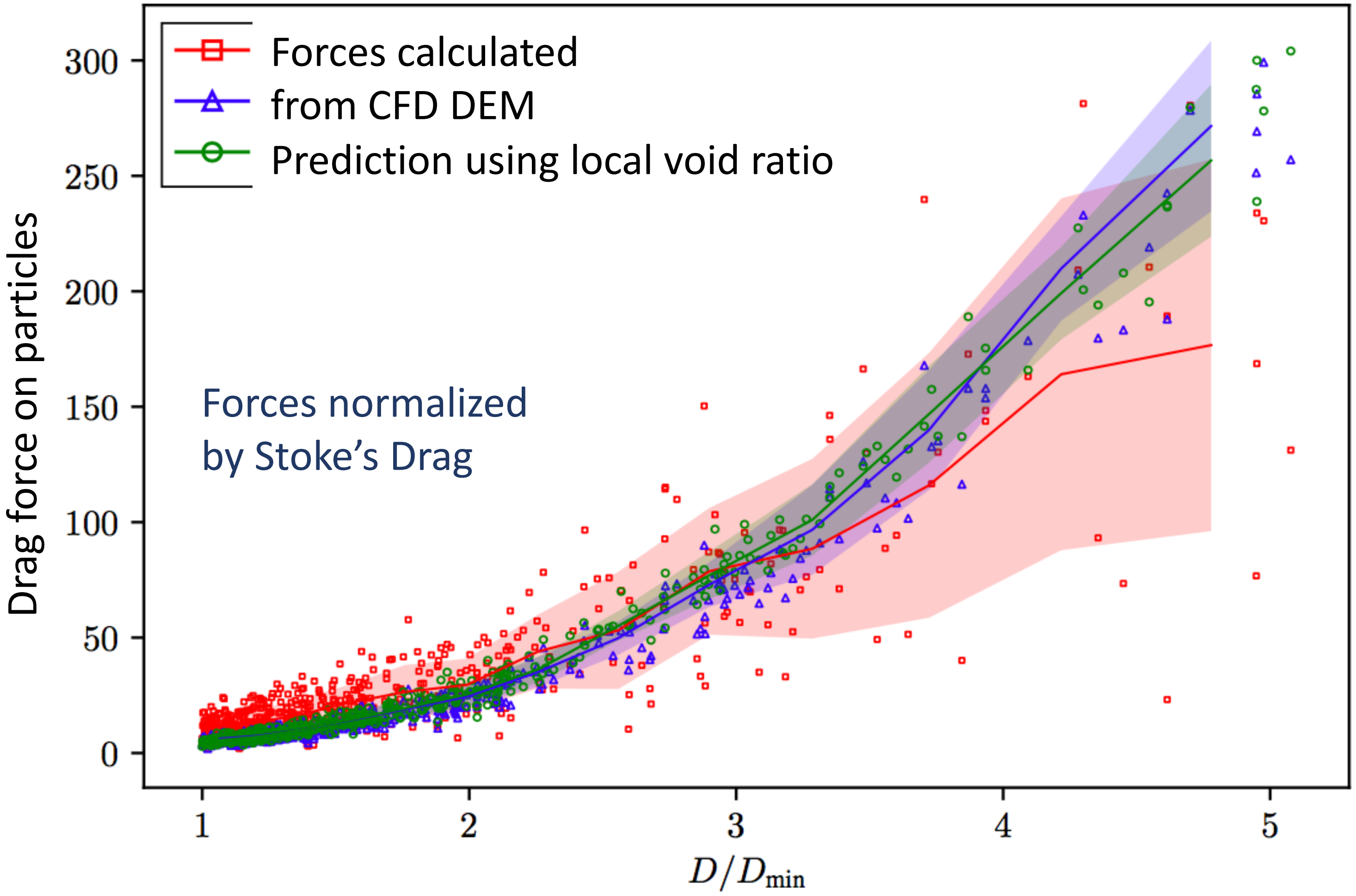


$\overline{F_d}$ = drag force normalized by Stokes drag – total for sample

Fluid particle interaction force : local void ratio



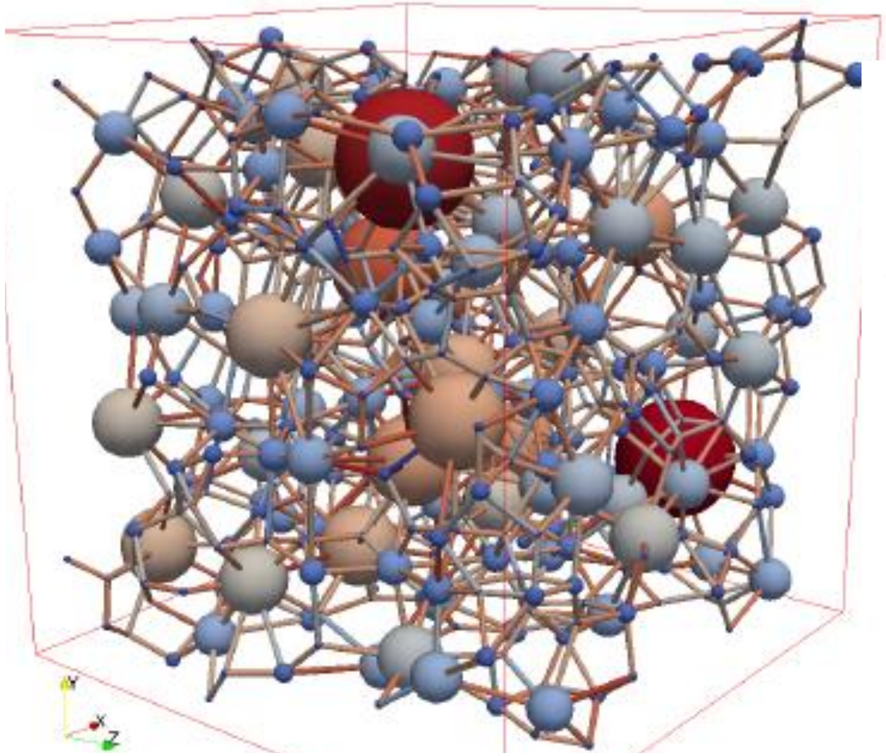
Tenneti et al. polydispersity correction also applied

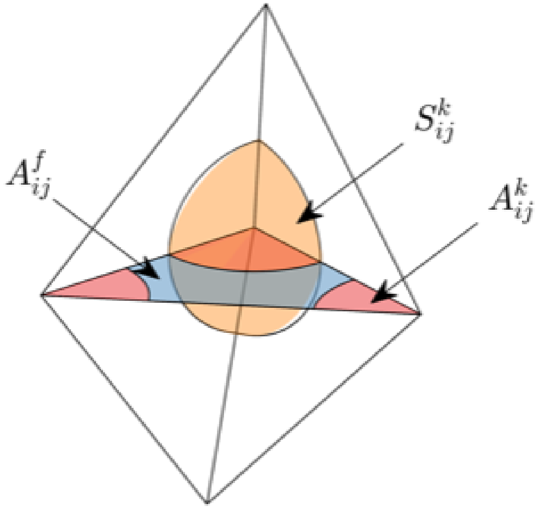


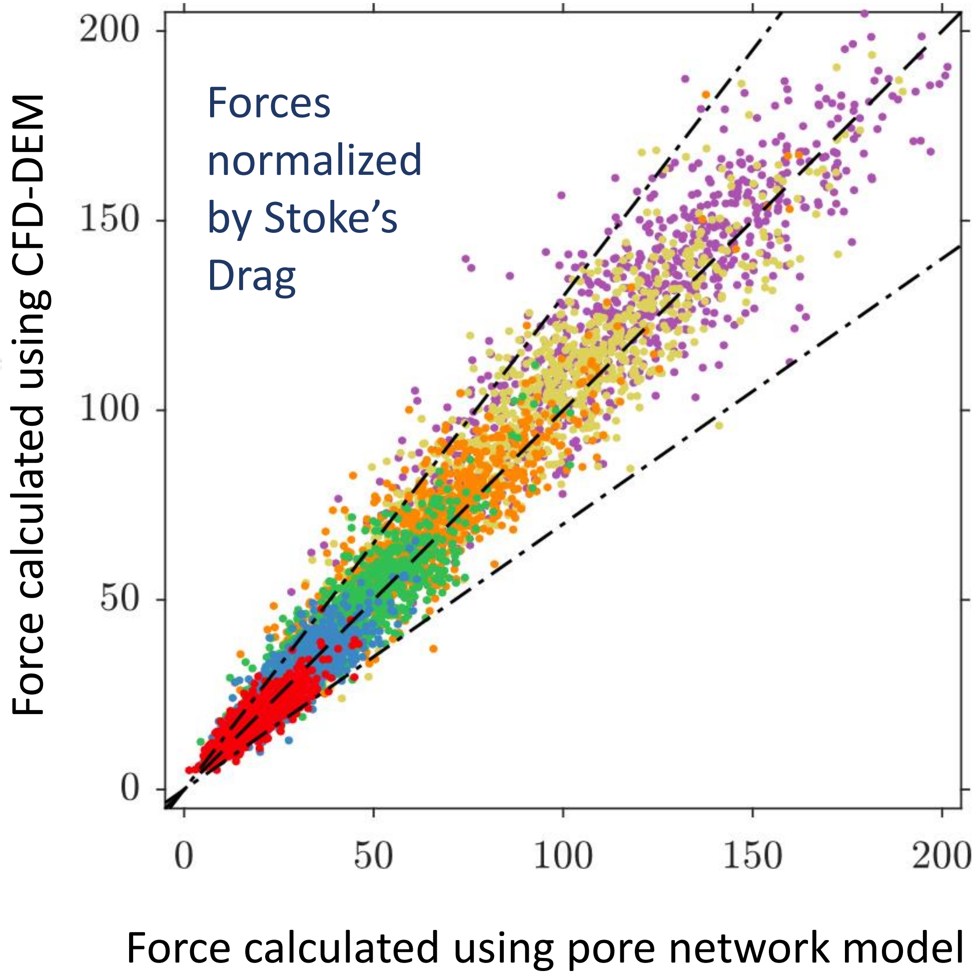
Cu=2.5, Solids fraction 0.701

Knight (2018)

Network based approach to determine forces

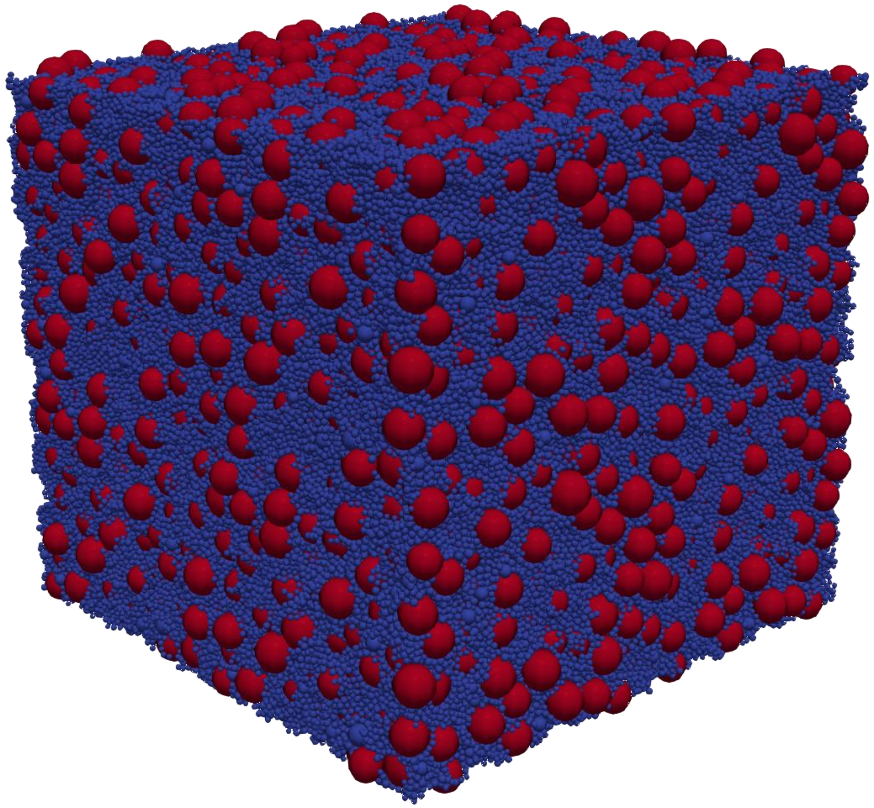




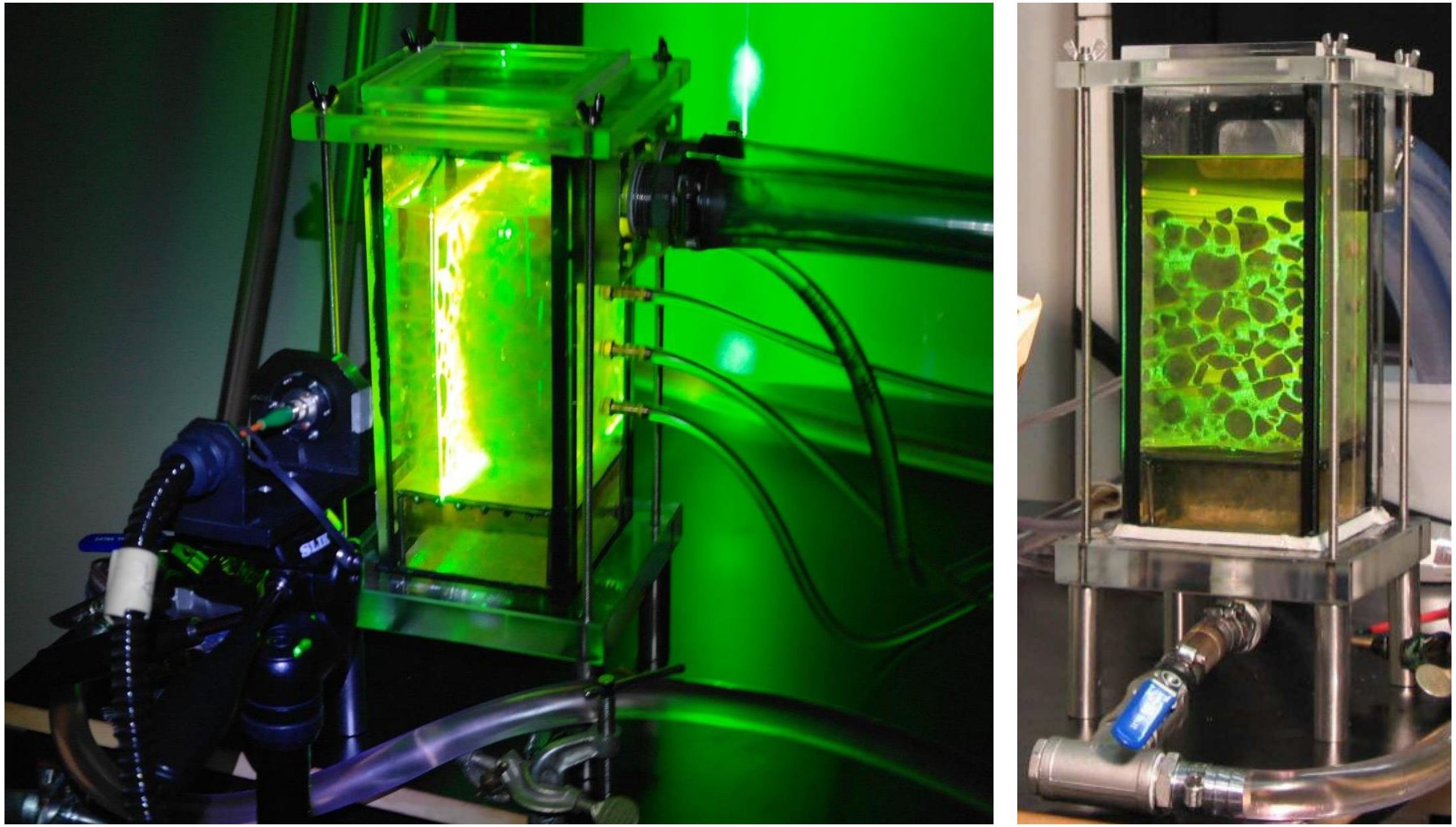


Sufian, Knight, et al. (2019)

Seepage Induced Instability

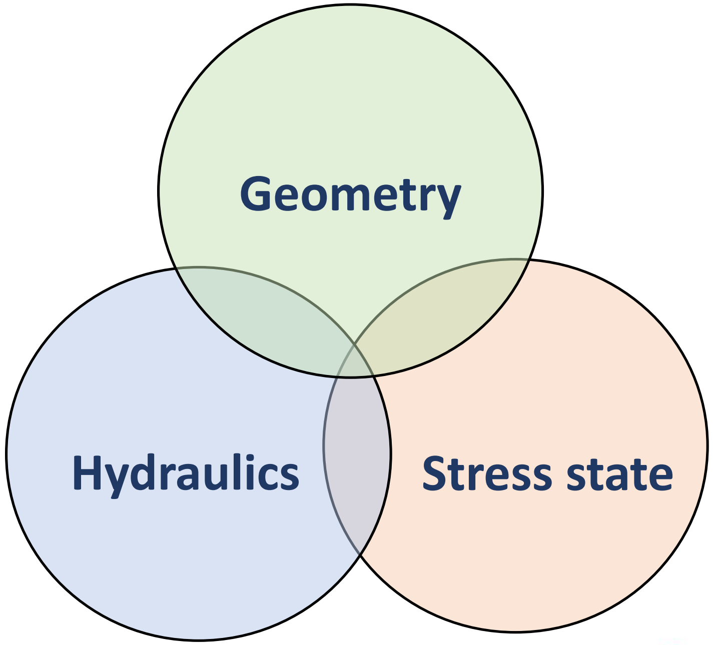


Discrete element method simulations at Imperial College London

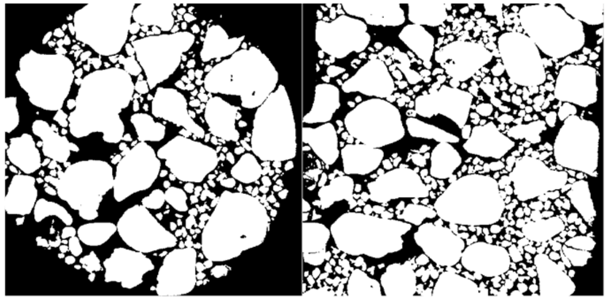


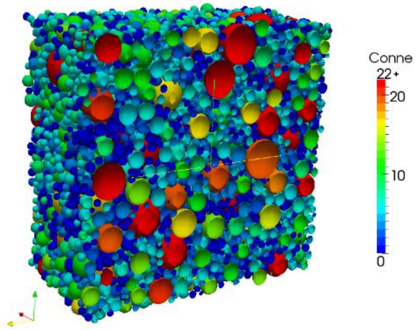
Transparent soil at the University of Sheffield

Conclusions



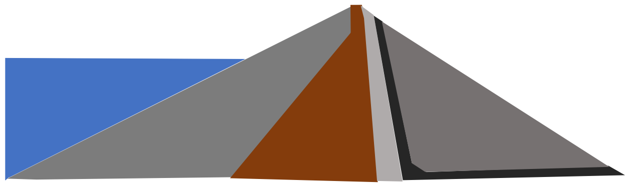
- Considerations of filter compatibility and internal instability are important in dam and embankment design and maintenance





- Geometry / particle scale topology of materials; stress state and fluid:particle interaction determine behaviour

- Particle-scale simulation can improve understanding leading to more robust design guidance

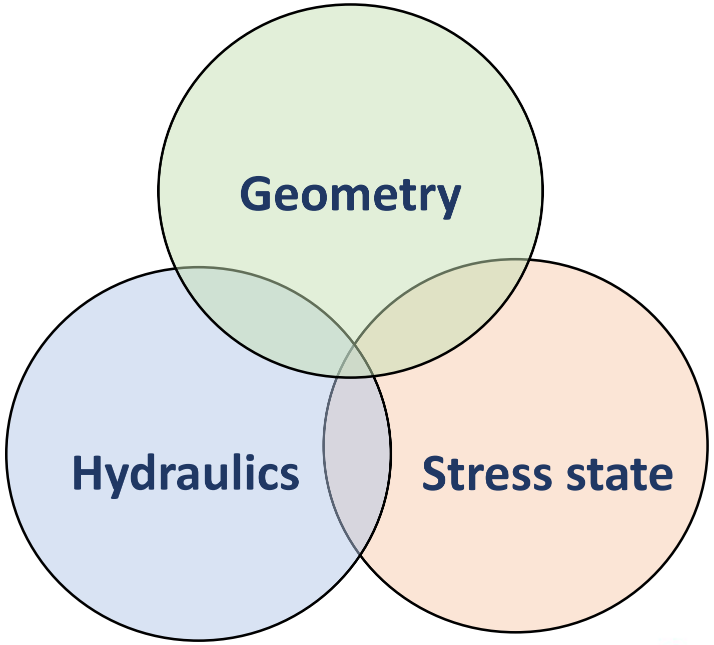


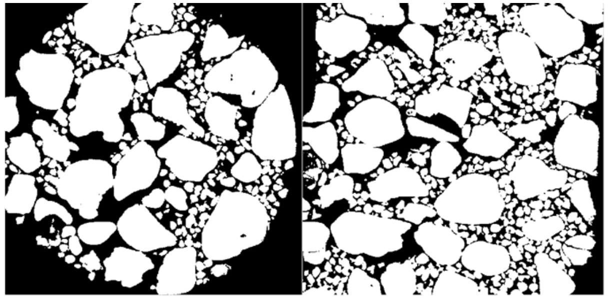
Conclusions

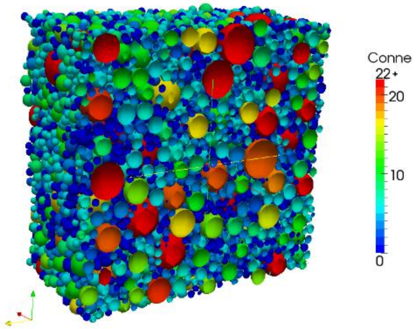
- Simulations with gap-graded materials are challenging – large numbers of particles are needed and low strain rates are required.

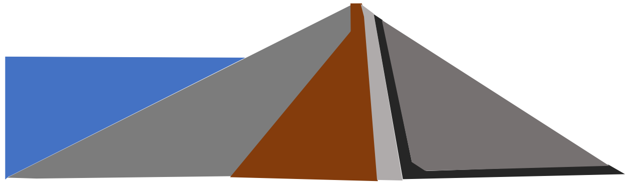
- Significant research effort needs to be put into developing accurate drag expressions to enable unresolved DEM-CFD to be used with confidence in geomechanics applications where polydispersity is always an issue.

- Combining network based approaches with DEM datasets can overcome some of the challenges associated with CFD-DEM

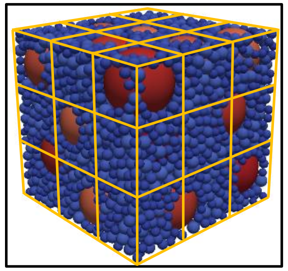




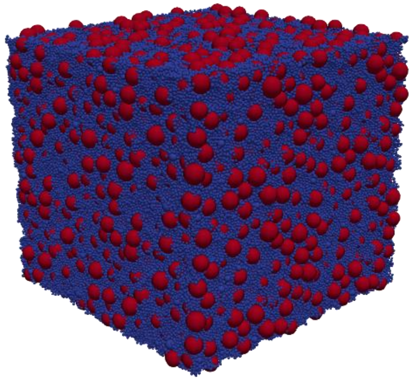




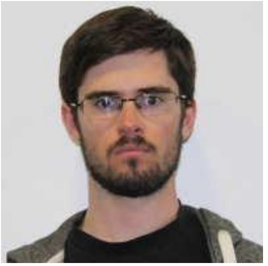
Acknowledgements

Kenichi Kawano

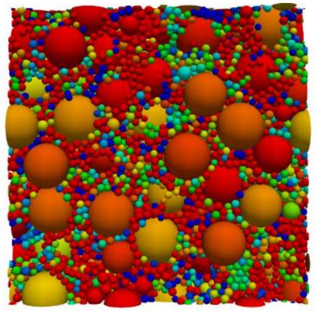



Adnan Sufian



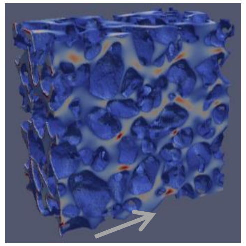
Chris Knight

Berend van Wachem

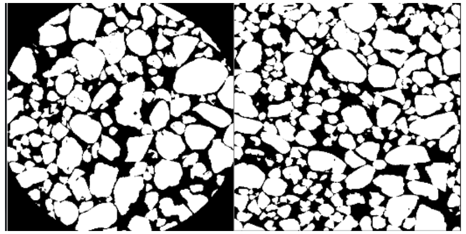

Tom Shire

Kevin Hanley

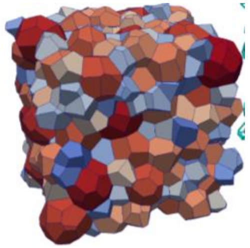




Howard Taylor

Way Way Sim

Joana Fonseca




Daniele Dini

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Key references

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