Micro-scale modelling of internally unstable soils

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Outline

- Internal instability
- Micro-scale modelling
- Hydromechanical criteria for erosion:
  - Stress reduction in finer particles
  - Coupled DEM-CFD Analysis

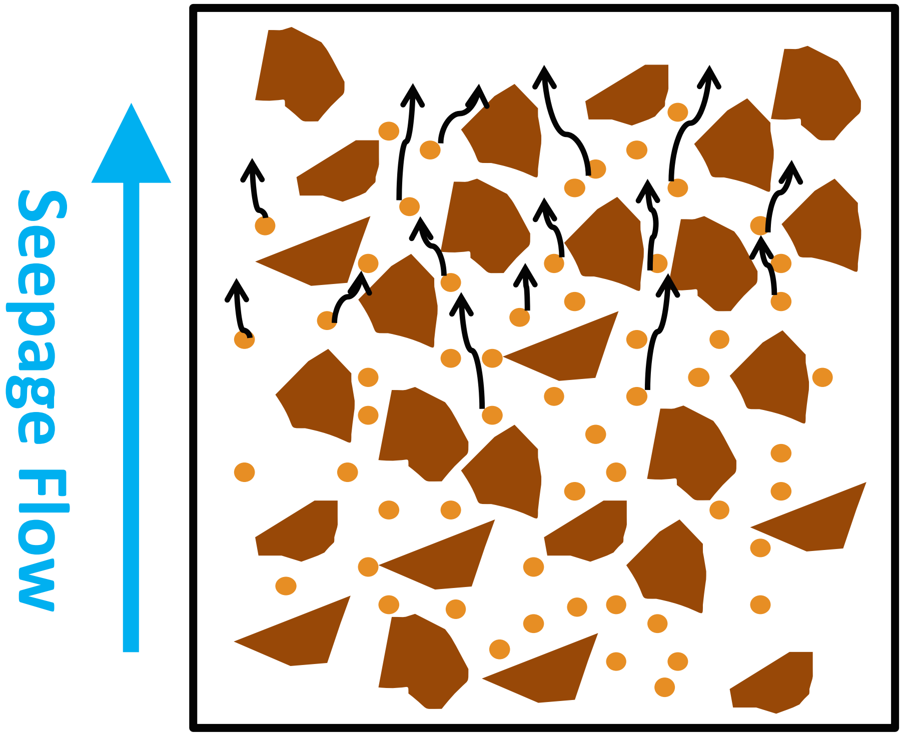
Internal Instability

Gap/broadly graded soils: Fine fraction preferentially eroded

Erosion of fines at **low hydraulic gradients** (i < 0.3)

Prerequisites:

- Cohesionless fines
- Load carrying matrix of coarse particles
- Fines under low stress
- Fines small enough to pass between coarse



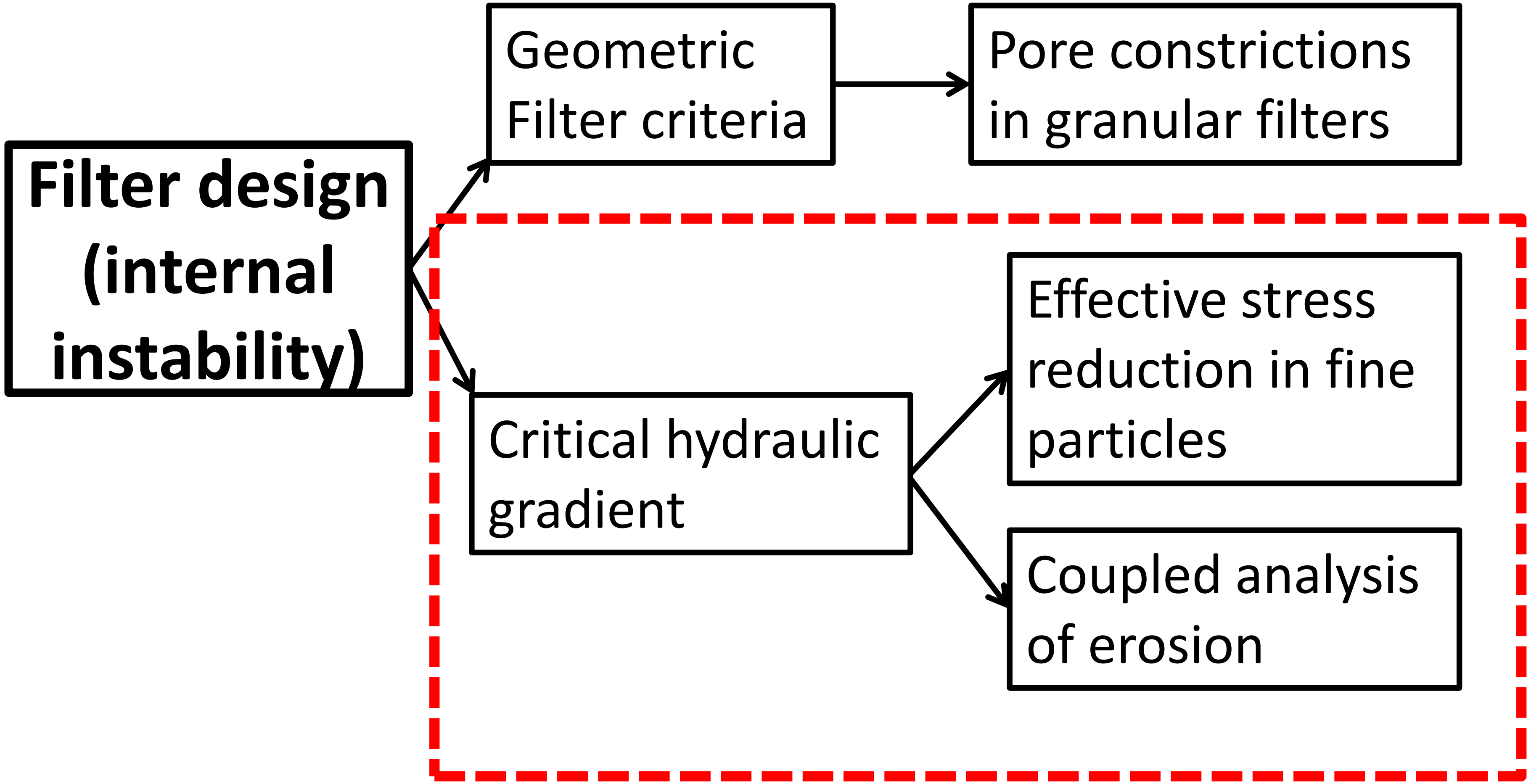
Eurocode 7: Hydraulic Failure

“[Geometric] **Filter criteria** shall be used to limit the danger of material transport by internal erosion.”

“If the filter criteria are not satisfied, the **hydraulic gradient** should be well below the critical gradient at which soil particles begin to move.”

Aim of micro-scale analysis

Examine both elements of filter design:



Filter design (internal instability)

Geometric Filter criteria

Pore constrictions in granular filters

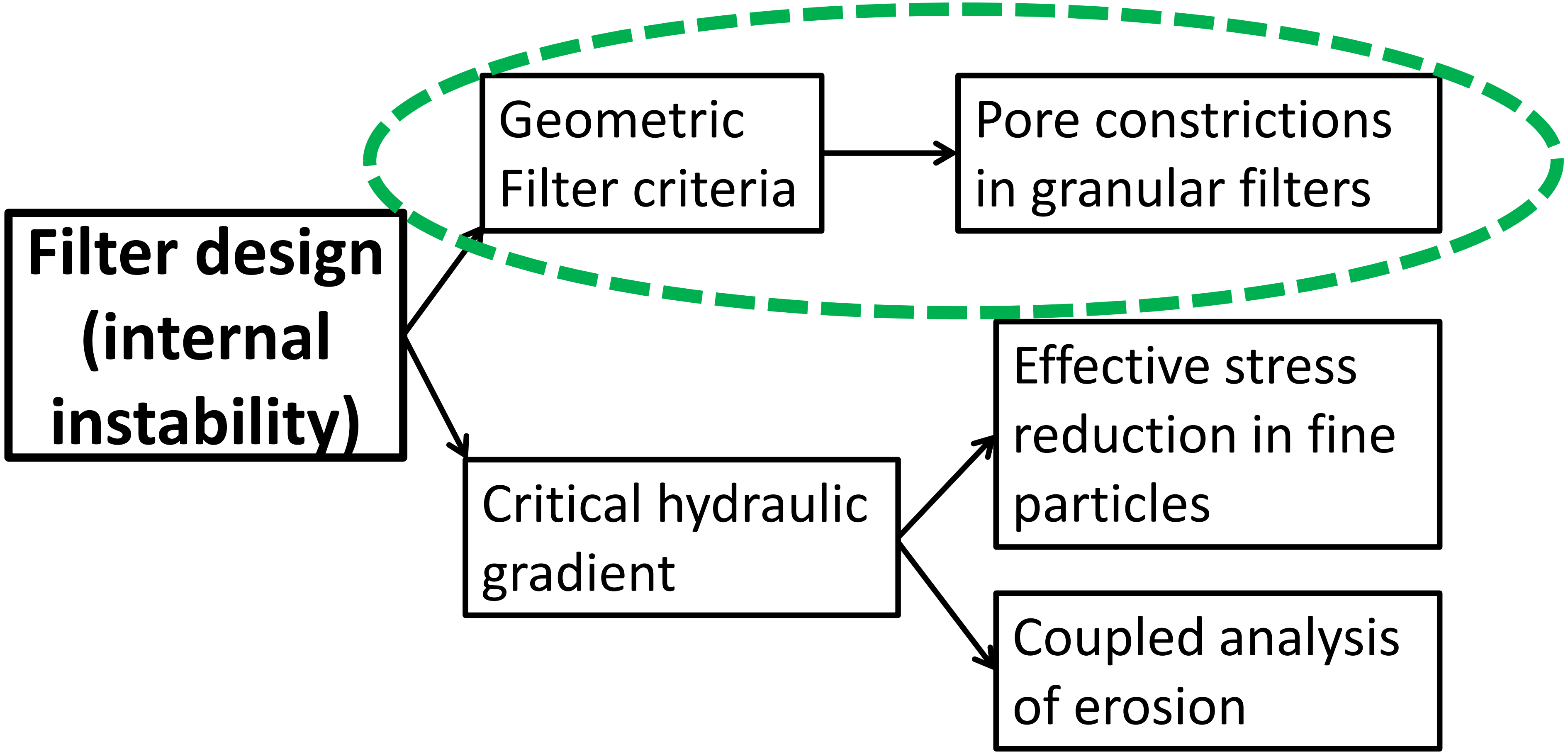
Critical hydraulic gradient

Effective stress reduction in fine particles

Coupled analysis of erosion

Aim of micro-scale analysis

Examine both elements of filter design:



Filter design (internal instability)

Geometric Filter criteria

Pore constrictions in granular filters

Critical hydraulic gradient

Effective stress reduction in fine particles

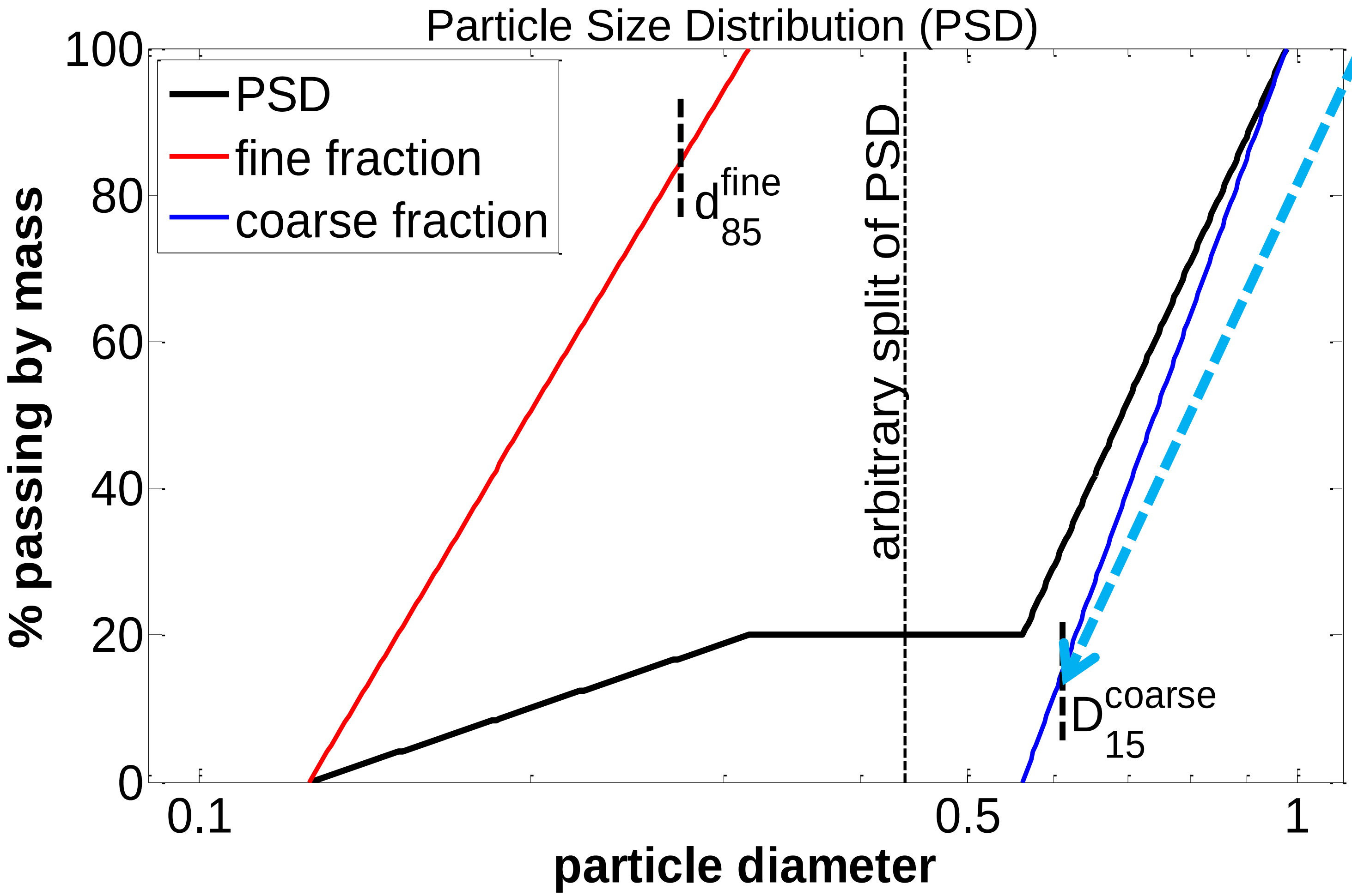
Coupled analysis of erosion

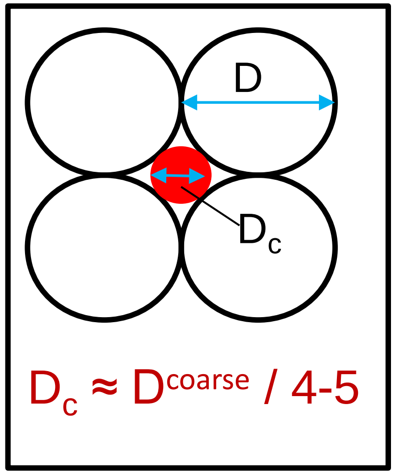
Geometric Filter Criteria: Kézdi (1979)

Split Gap-graded PSD into coarse and fine "PSDs"

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

$(D_{15}^{coarse} / 4)$ proxy for 'pore size'





Micro-scale modelling:

Discrete Element Modelling

Micro-scale modelling

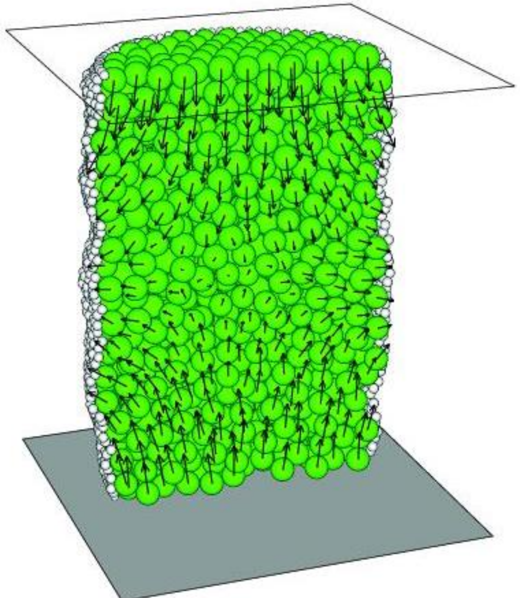
https://twiki.auscope.org/wiki/pub/EarthSim/ExistingInfrastructure/CollapsingBlock3.png

- DEM: Discrete Element Modelling

- Each element is a single soil particle

- Generally used for coarse-grained soils >100µm: Body forces dominate

- Used for virtual laboratory experiments

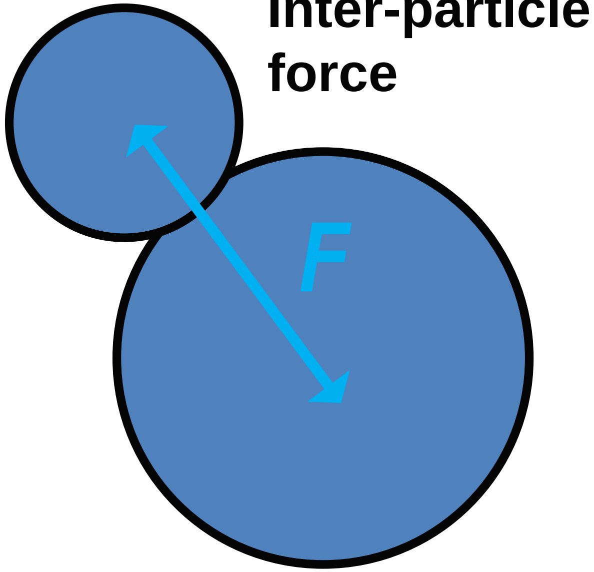


http://web.utk.edu/~alshibli/research/MGM/DEM.php

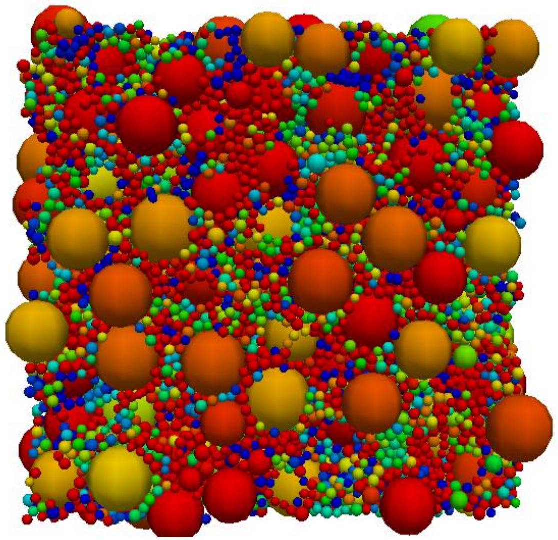
Discrete element method (DEM)

- Rigid particles which can overlap at contacts
- Overlap proportional to force acting at contacts
- Particles move at each timestep and make / break contact with neighbours

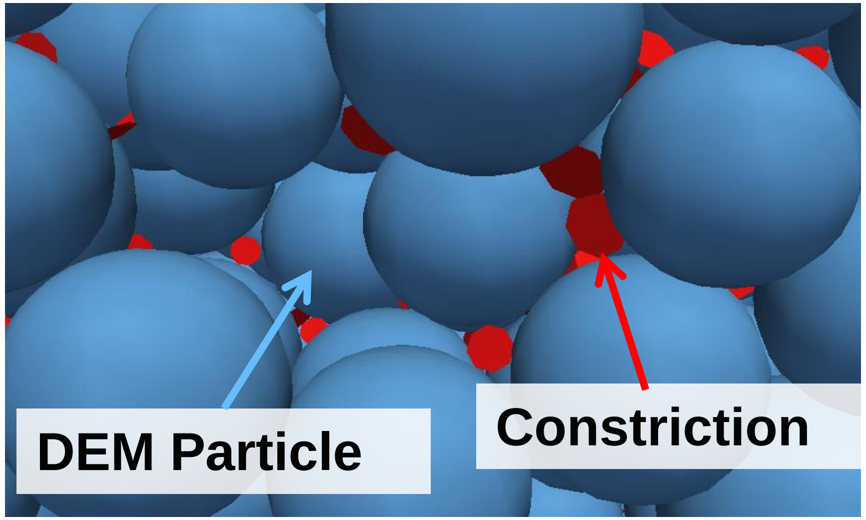
Measure variables unavailable in lab:


Inter-particle force

Particle stress



Void size

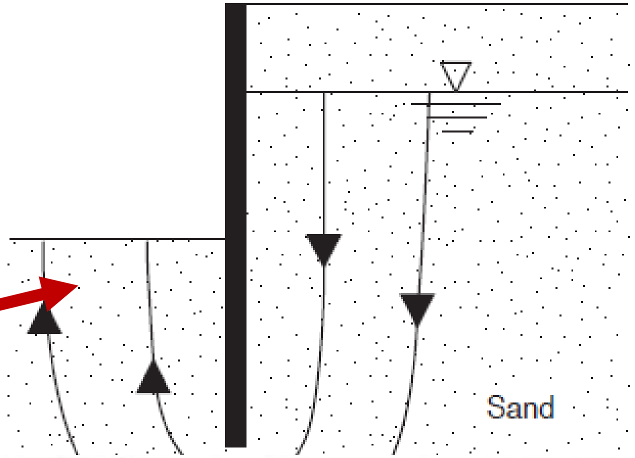


Hydromechanical potential for erosion : Stress reduction in finer particles

Critical hydraulic gradient and stress

For internally stable soils:

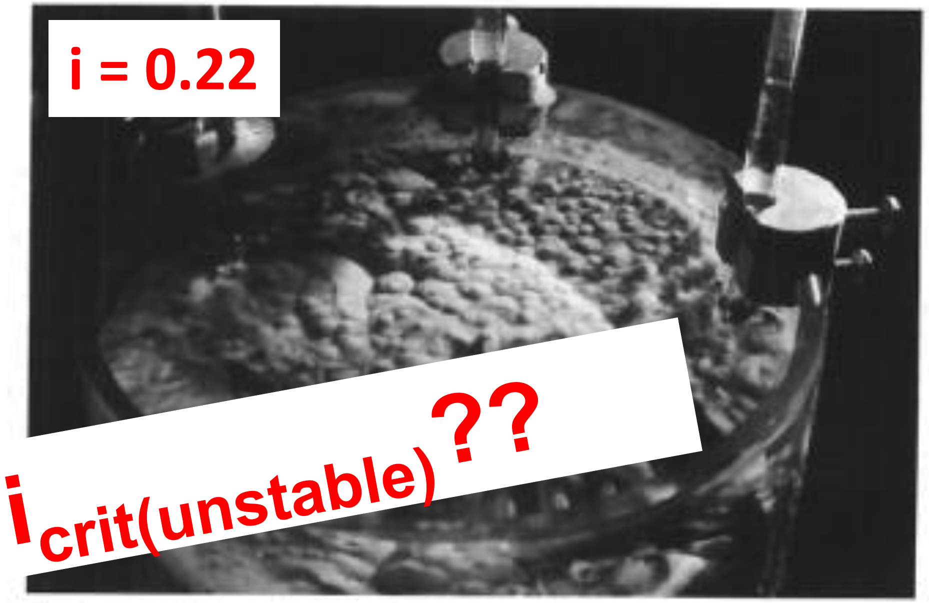
$i_{crit(heave)}$: hydraulic gradient at which $\underline{\sigma_v' = 0}$



$i_{crit(heave)} = \gamma'/\gamma_w \approx 1.0$ (Terzaghi, 1925)

For internally unstable soils:

$i_{crit(unstable)} < 1$ (as low as 0.2)



How to predict $i_{crit(unstable)}$??

Fig. 9. Material A: strong general piping of fines ($i = 0{\cdot}22$, $v = 0{\cdot}27$ cm/s)

Skempton and Brogan (1994)

Hydromechanical criterion

Skempton and Brogan (1994):

Coarse particles transfer overburden

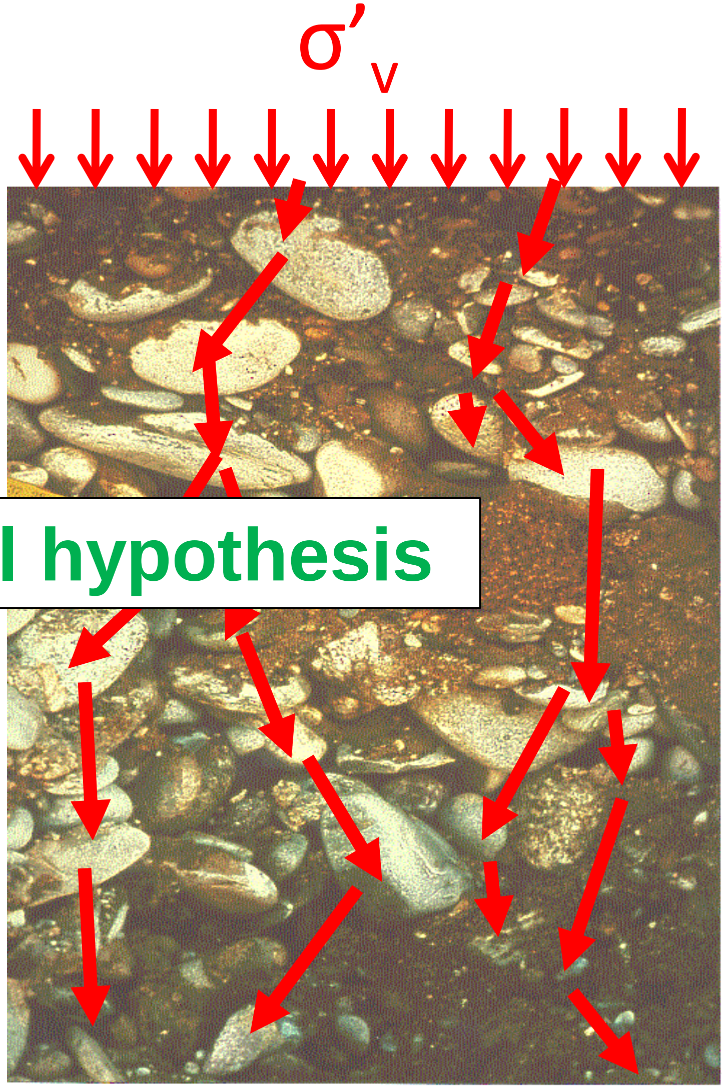
Fines carry reduced effective stress:

$$\sigma'_{fine} = \alpha \ \sigma'$$

Micromechanical hypothesis

Critical gradient to reach $\sigma' = 0$

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

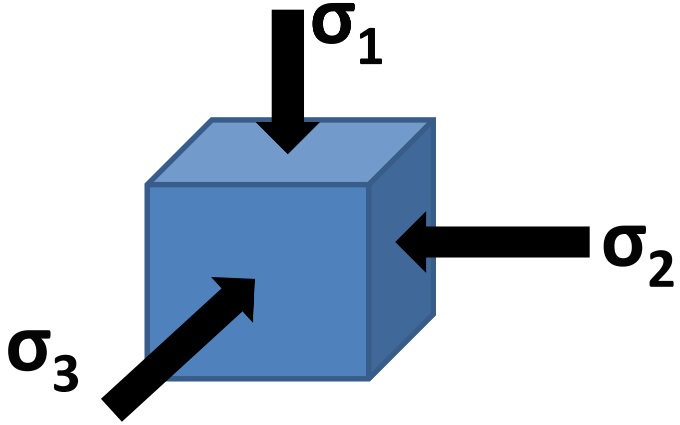


DEM Simulations

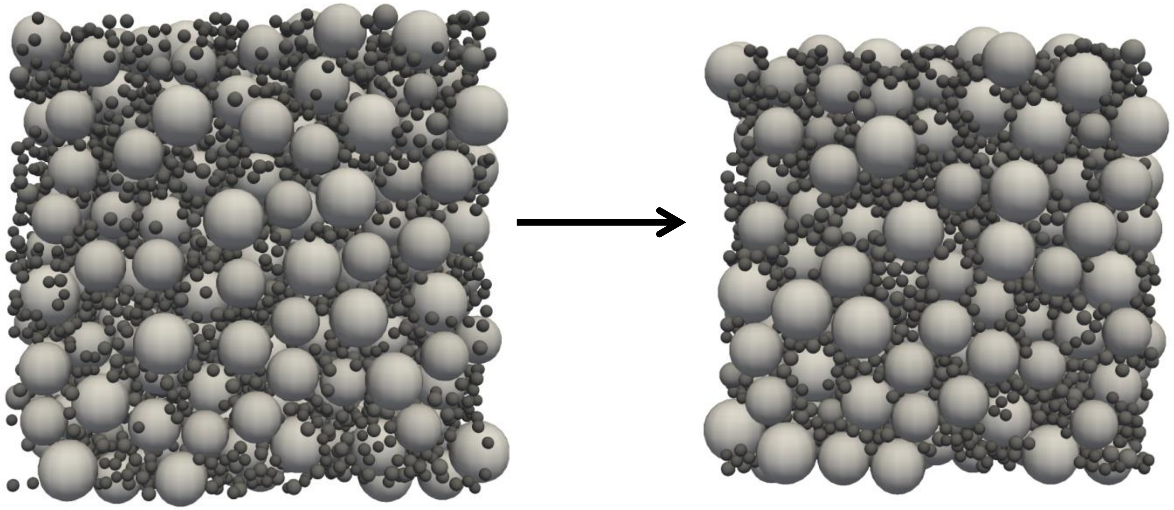
> 300,000 particles for large simulations

Servo-controlled **isotropic compression** to p' = 50kPa

Periodic cell – no boundary effects



Sample **density controlled** using interparticle friction:
μ = 0.0 (Dense), μ = 0.1 (Medium dense), μ = 0.3 (Loose)



Samples tested

Gap-graded samples

Study effect of:

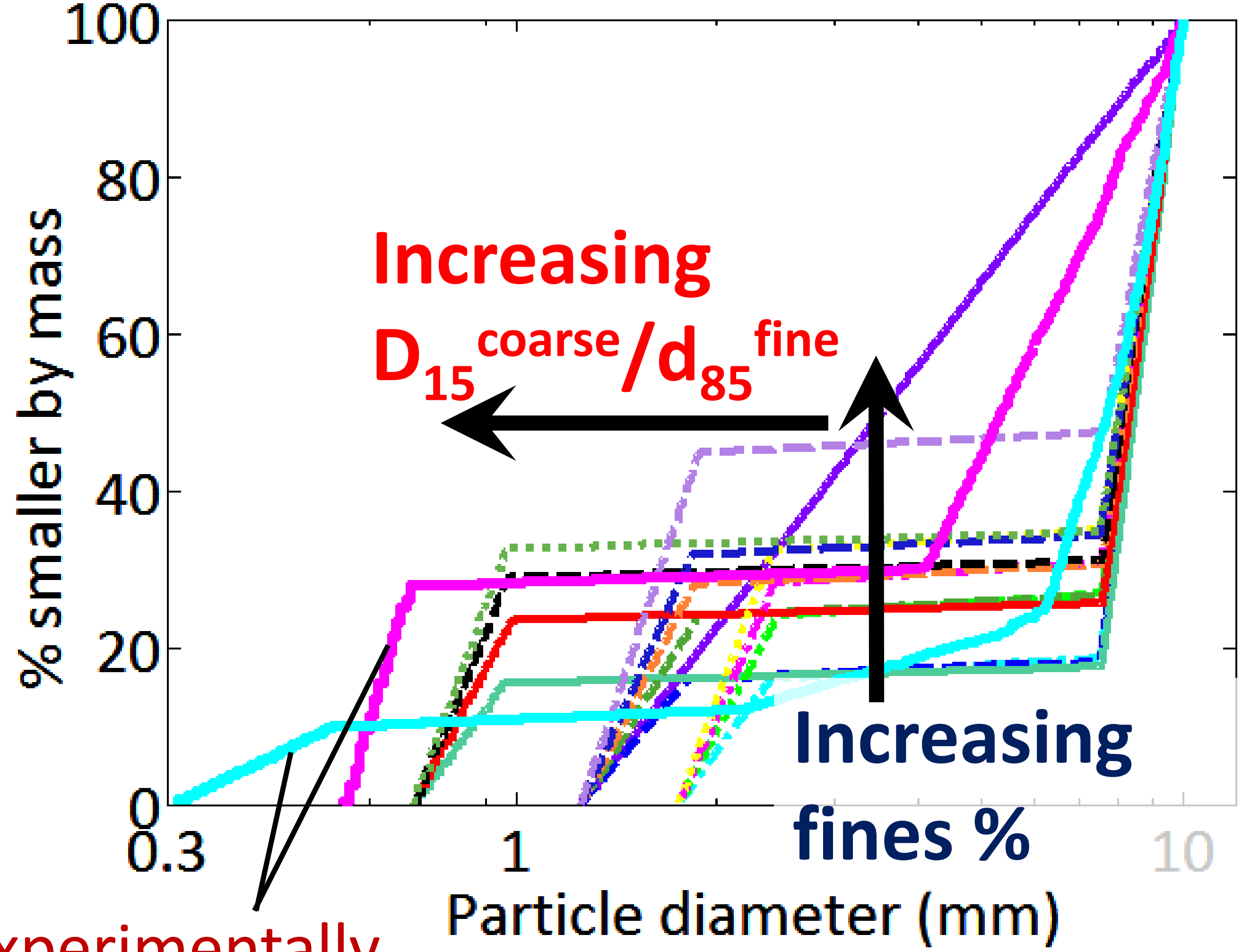
- **PSD (gap-ratio + fine-content)**
- **Relative density**

DEM: Measurement of α-factor:

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

Mean stress in finer particles

Mean stress in all particles



Increasing $D_{15}^{coarse}/d_{85}^{fine}$

Increasing fines %

Two experimentally tested PSDs

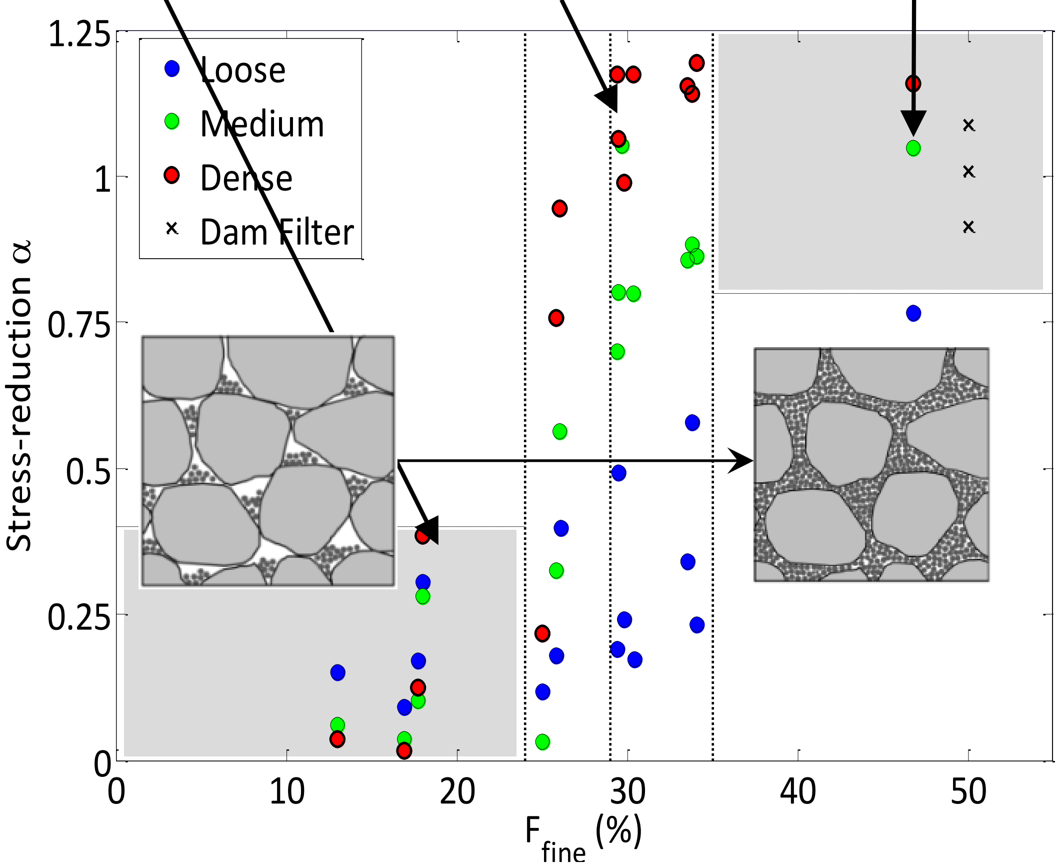
Results

Effect of % fines and density

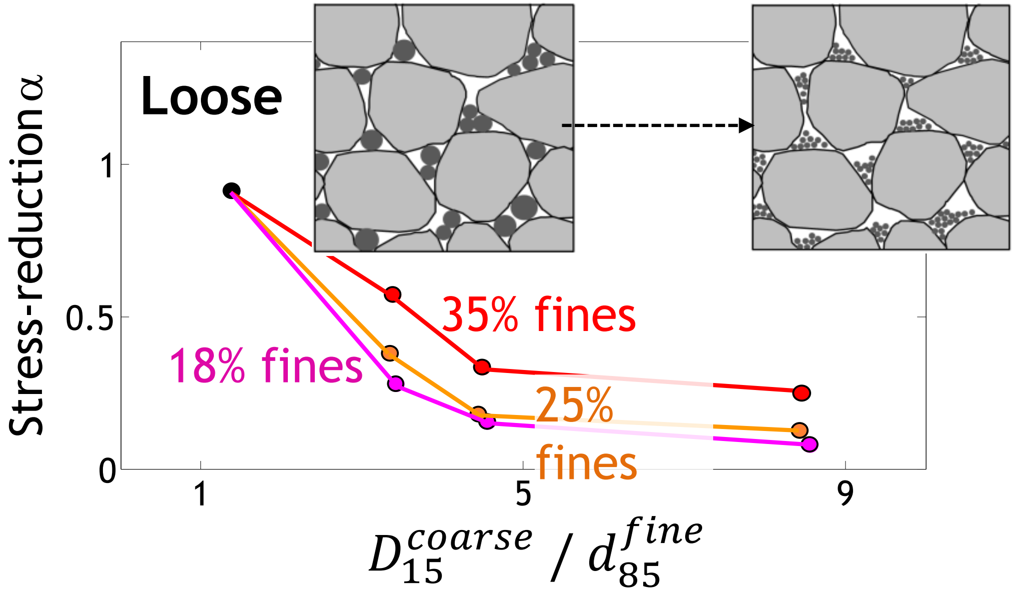
Low fines (<25%)
α < 0.4
Fines don’t fill voids

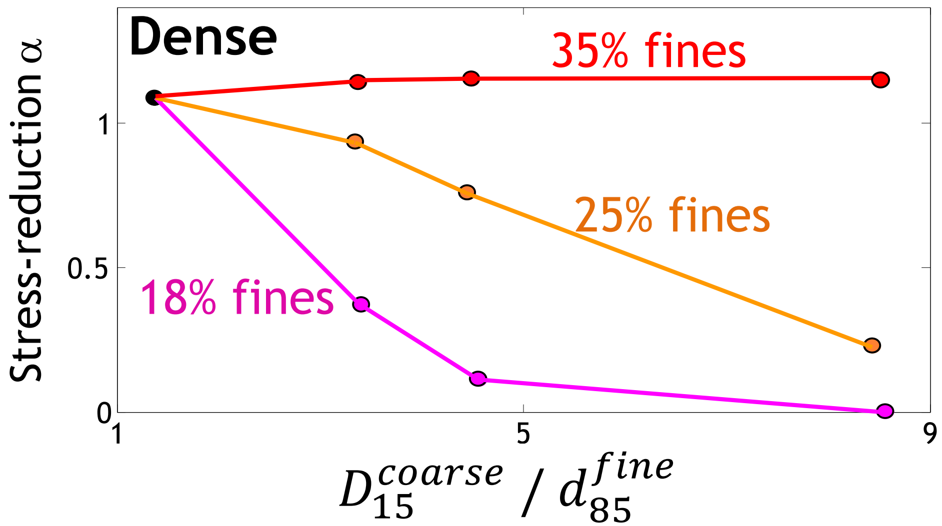
High fines (>35%); α ≈ 1
Fines separate coarse particles

Intermediate:
Influence of relative density

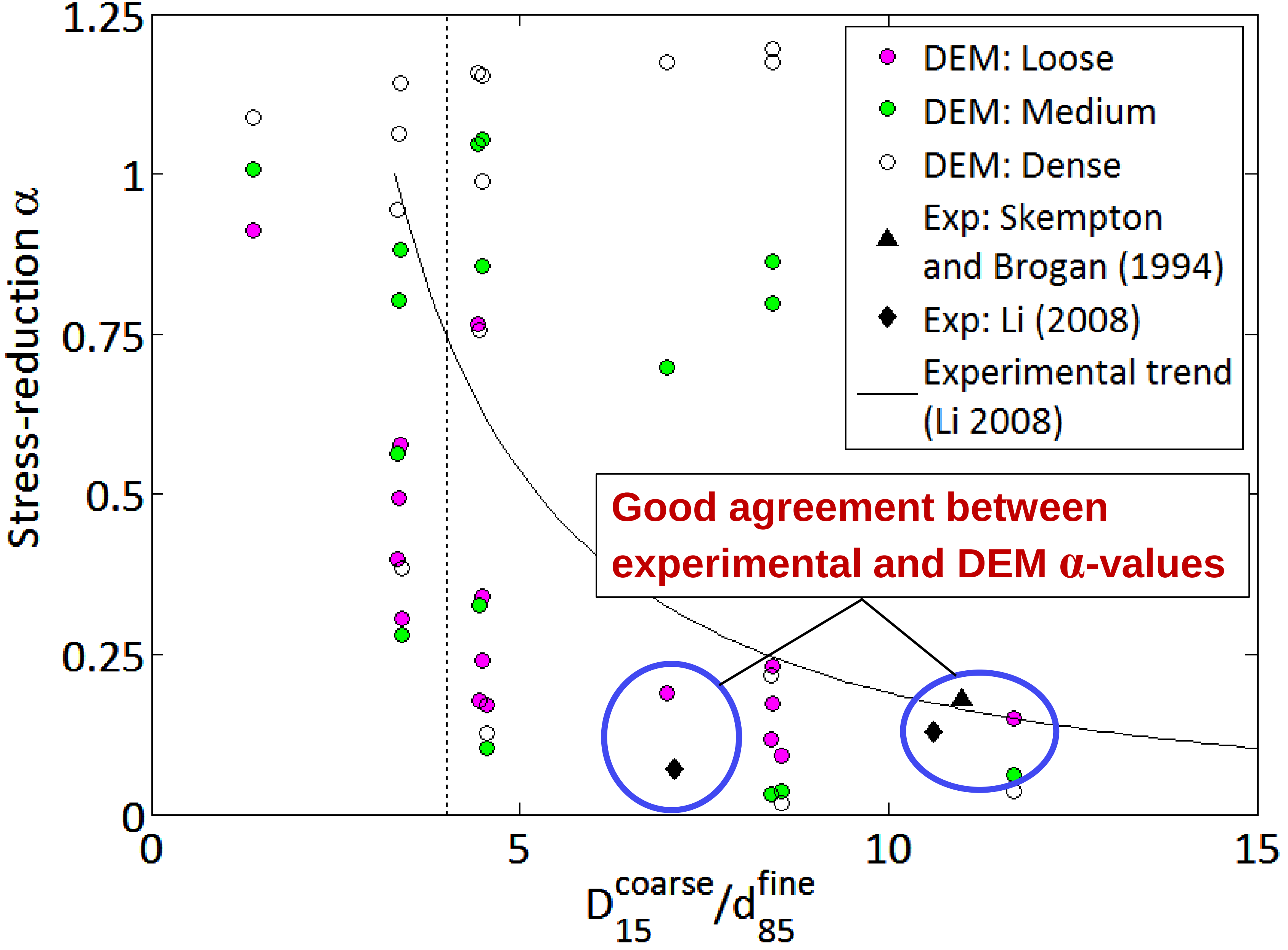


Effect of gap-ratio





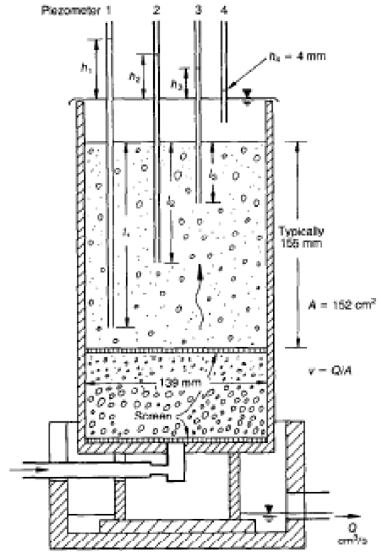
All Results



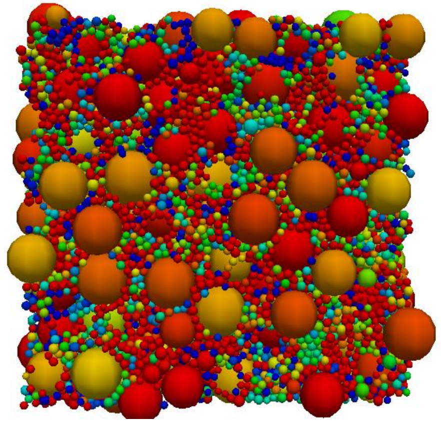
Good agreement between experimental and DEM α-values

Experimental: Permeameter

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



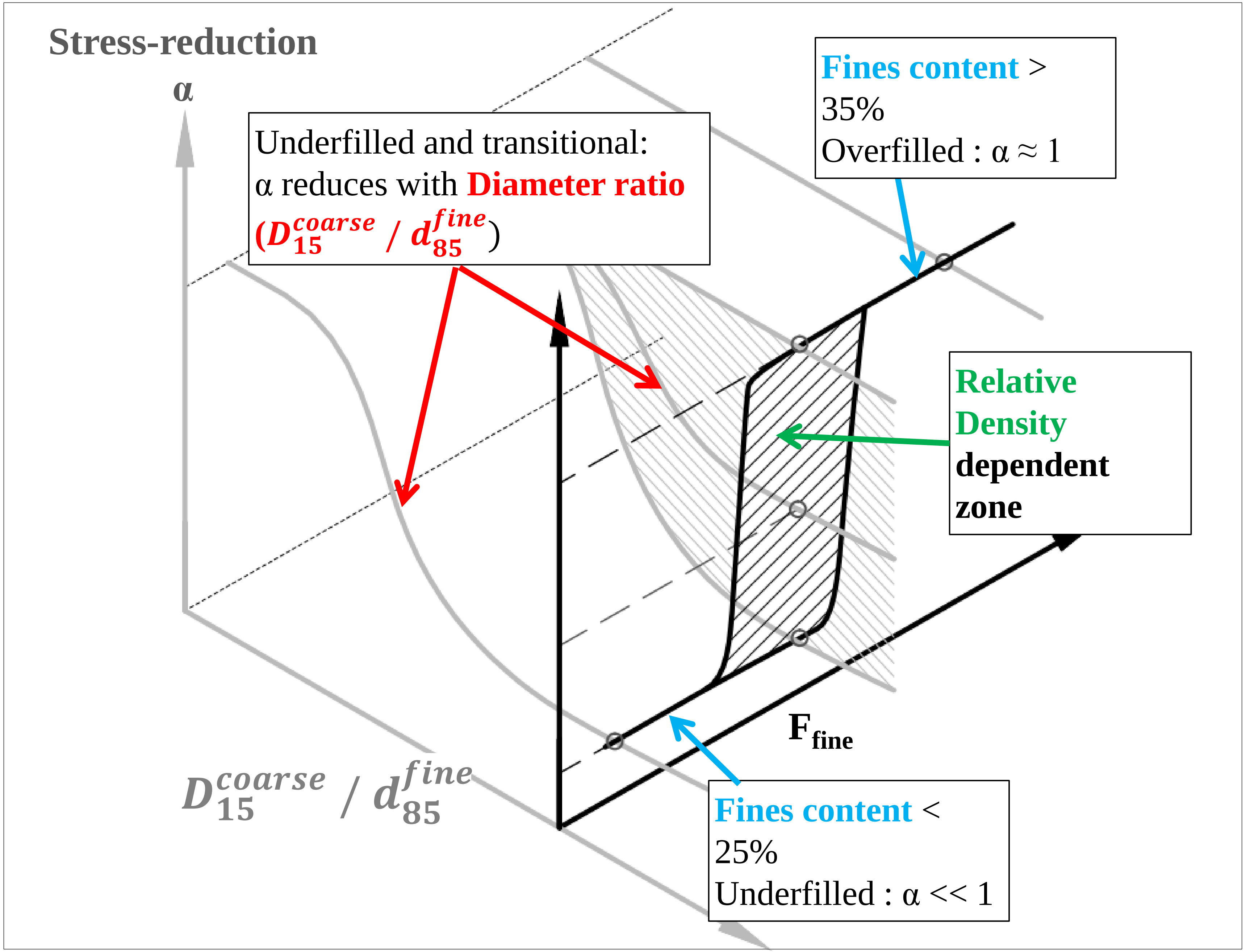
DEM: $\alpha = p'_{fine} \; / \; p'$



Stress reduction in fines : Summary

Three important factors:

- **Fines content,**
- **Relative density**
- **Diameter ratio**



Underfilled and transitional:
α reduces with **Diameter ratio ($D_{15}^{coarse} / d_{85}^{fine}$)**

Fines content > 35%
Overfilled : α ≈ 1

Relative Density dependent zone

Fines content < 25%
Underfilled : α << 1

Hydromechanical potential for erosion :

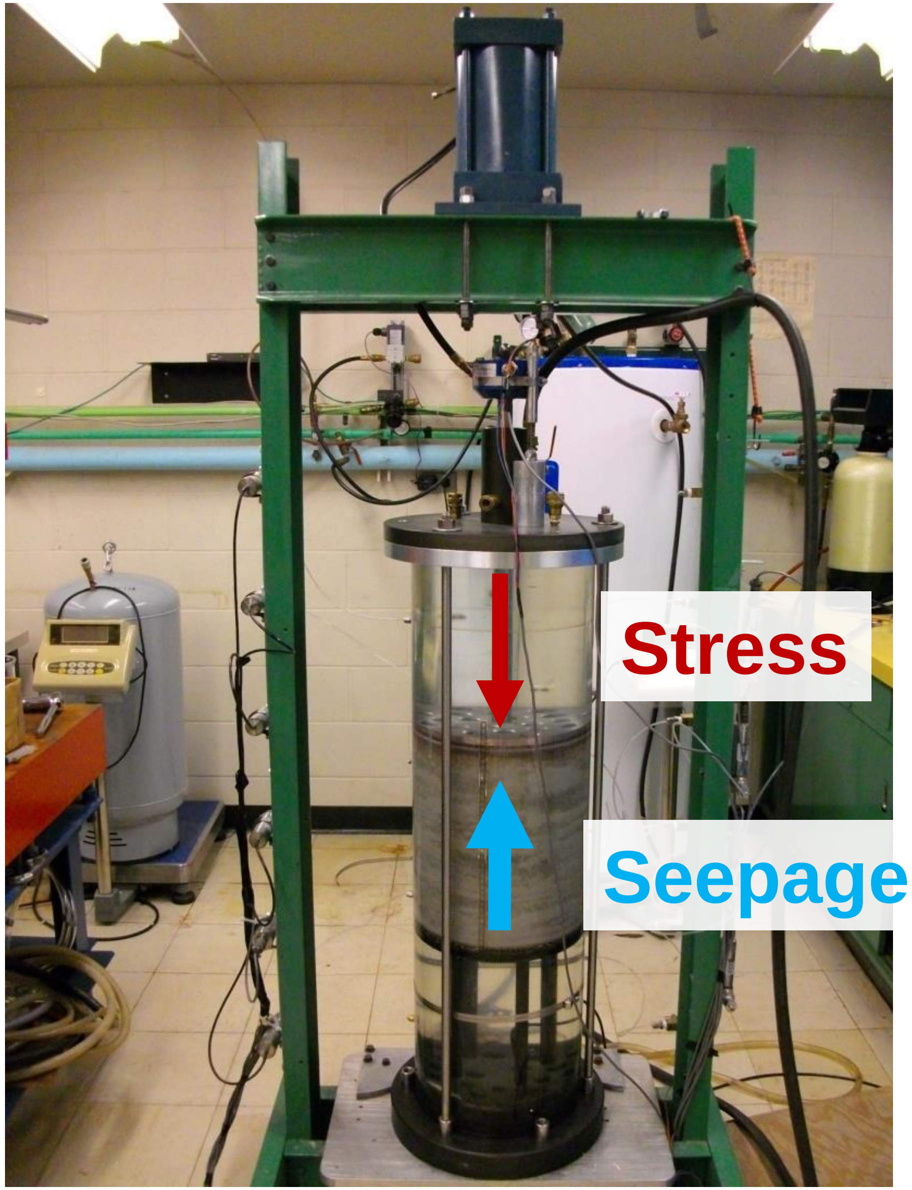
Coupled DEM-CFD analysis

Coupled DEM-CFD

Aim: model permeameter at micro-scale

Large permeameter for studying suffusion:

- Can vary top stress and hydraulic gradient
- Macro-scale measurements:
  - Hydraulic gradient (local)
  - Change in permeability
  - Visual observation of suffusion



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Coupling DEM + Computational Fluid Dynamics

Soil-fluid interaction

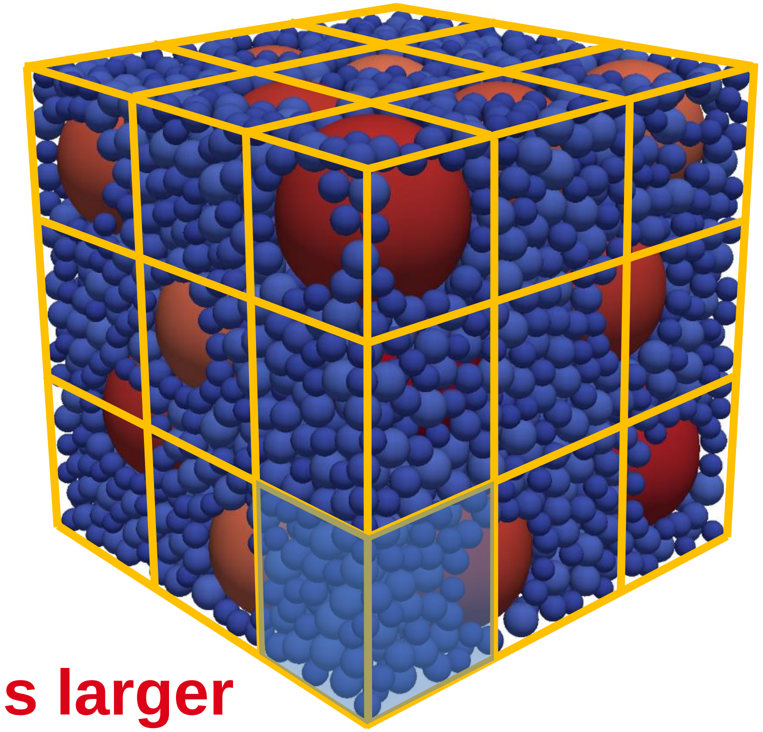
- DEM: soil particles
- CFD: water seepage

Data exchange

-Fluid velocity
-Fluid pressure
gradient

-Porosity
-Drag force

Coarse grid method
proposed by Tsuji



Fluid cells larger than particles

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

Coarse grid method

Averaged Navier-Stokes equation

$$\overbrace{\underbrace{\frac{\partial n v_f}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{v_f \nabla\left(n v_f\right)}_{\text{Convective acceleration}}}^{\text{Inertia force}} = \underbrace{\frac{u_f}{\rho_f}\nabla\left(n \nabla v_f\right)}_{\text{Viscosity}} - \underbrace{\frac{n}{\rho_f}\nabla p}_{\text{Pressure gradient force}} + \frac{\overbrace{f_{drag}}^{\textbf{Fluid-particle interaction force}}}{\rho_f}$$

n: porosity

v_f: fluid velocity

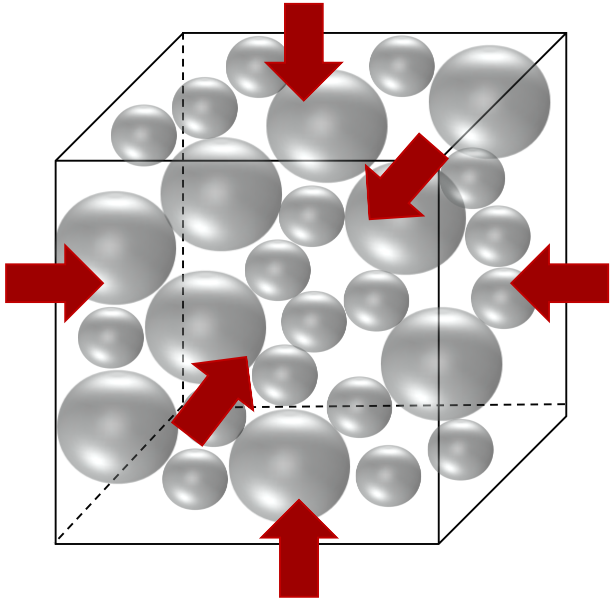
μ_f: fluid viscosity

ρ_f: fluid density

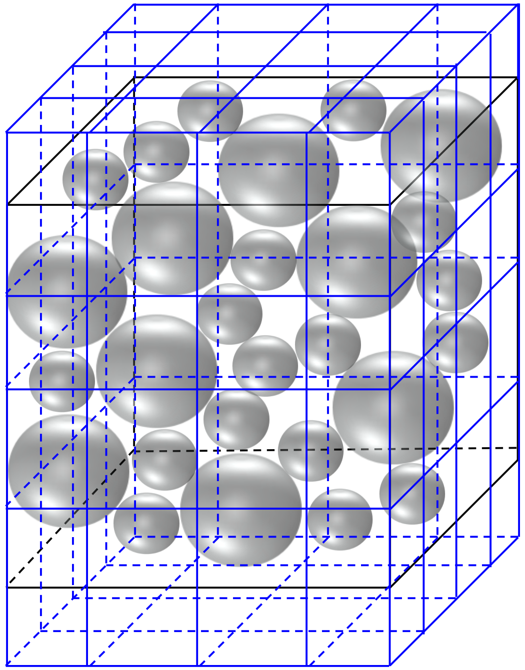
f_{drag} calculated using empirical equation based on fluid velocity, porosity and particle diameter (Di Felice, 1994)

Simulating permeameter tests

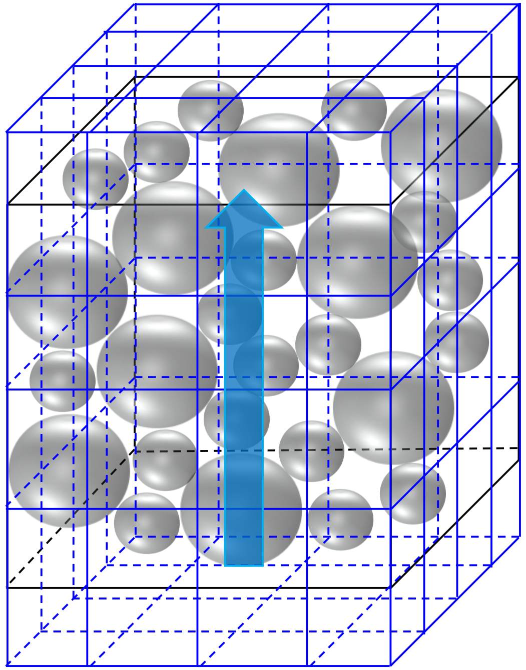
- Virtual stress-controlled permeameter



Compress to 50kPa,
Apply gravity



Create fluid mesh,
Fix boundaries,

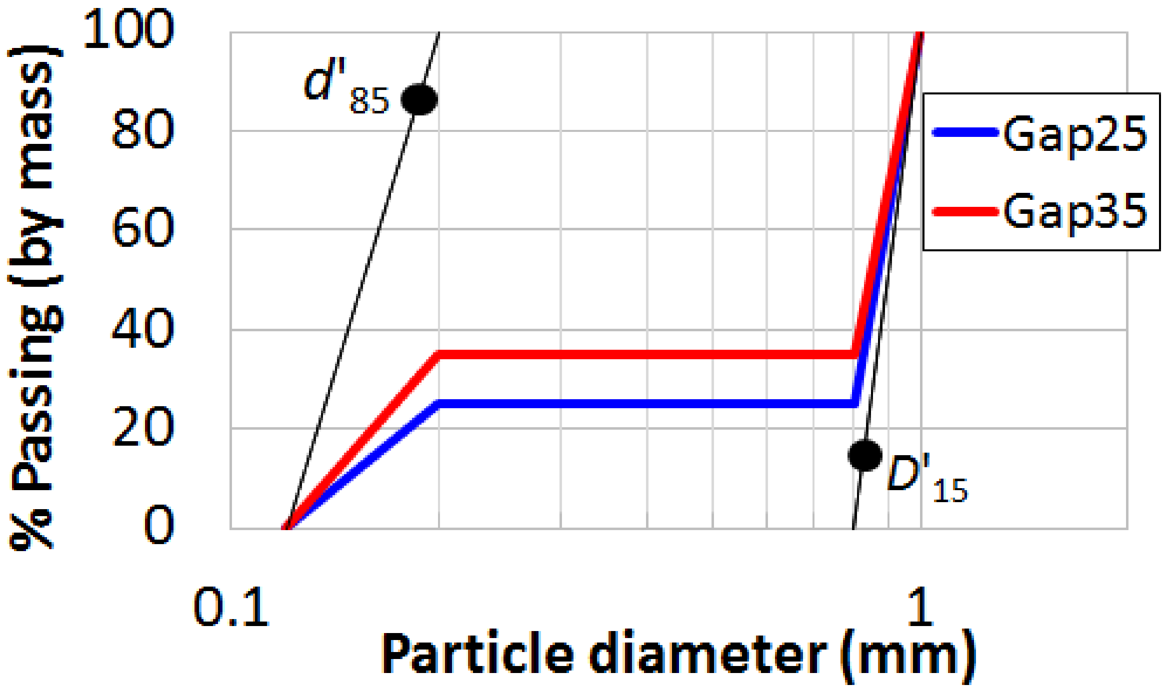


Apply pressure gradient,
Monitor steady state response

Virtual permeameter simulations

- 4 Samples tested: Up to 35000 particles
- D^{coarse}_{15} / d^{fine}_{85} = 4.6 : Borderline unstable (Kezdi, 1979)
- 25% and 35% fines
  - Each Loose and Dense
- Hydraulic gradient, *i* = 1, 2, 5, 10
- k ≈ 1.0×10^{-4} m/s to 2.3×10^{-4} m/s

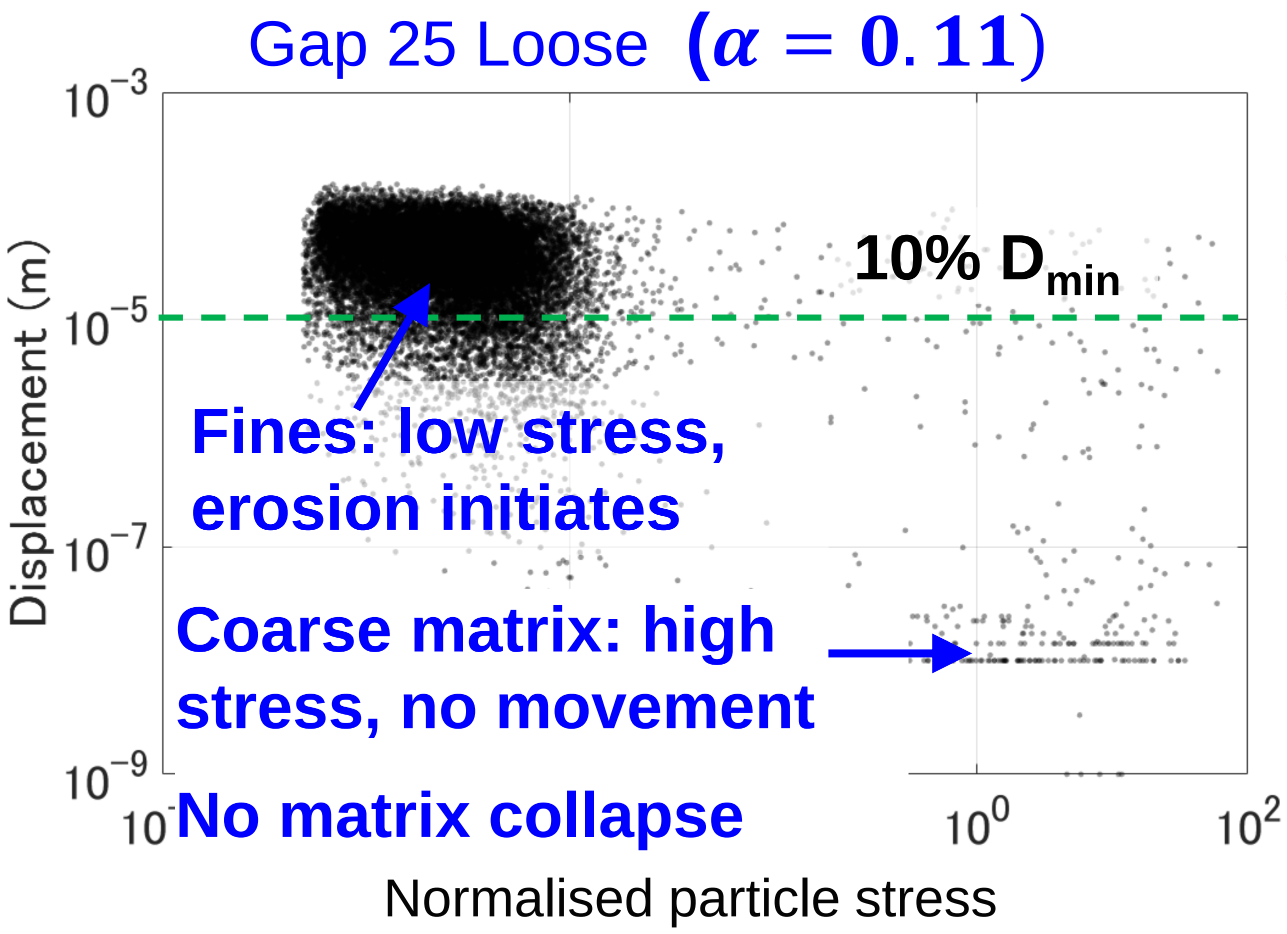
Similar to experimental data from UBC



Coupled analysis: typical micro-scale result

Hydraulic gradient: $i = 1$

Normalised particle stress = $\dfrac{\sigma^{part}}{\sigma'}$

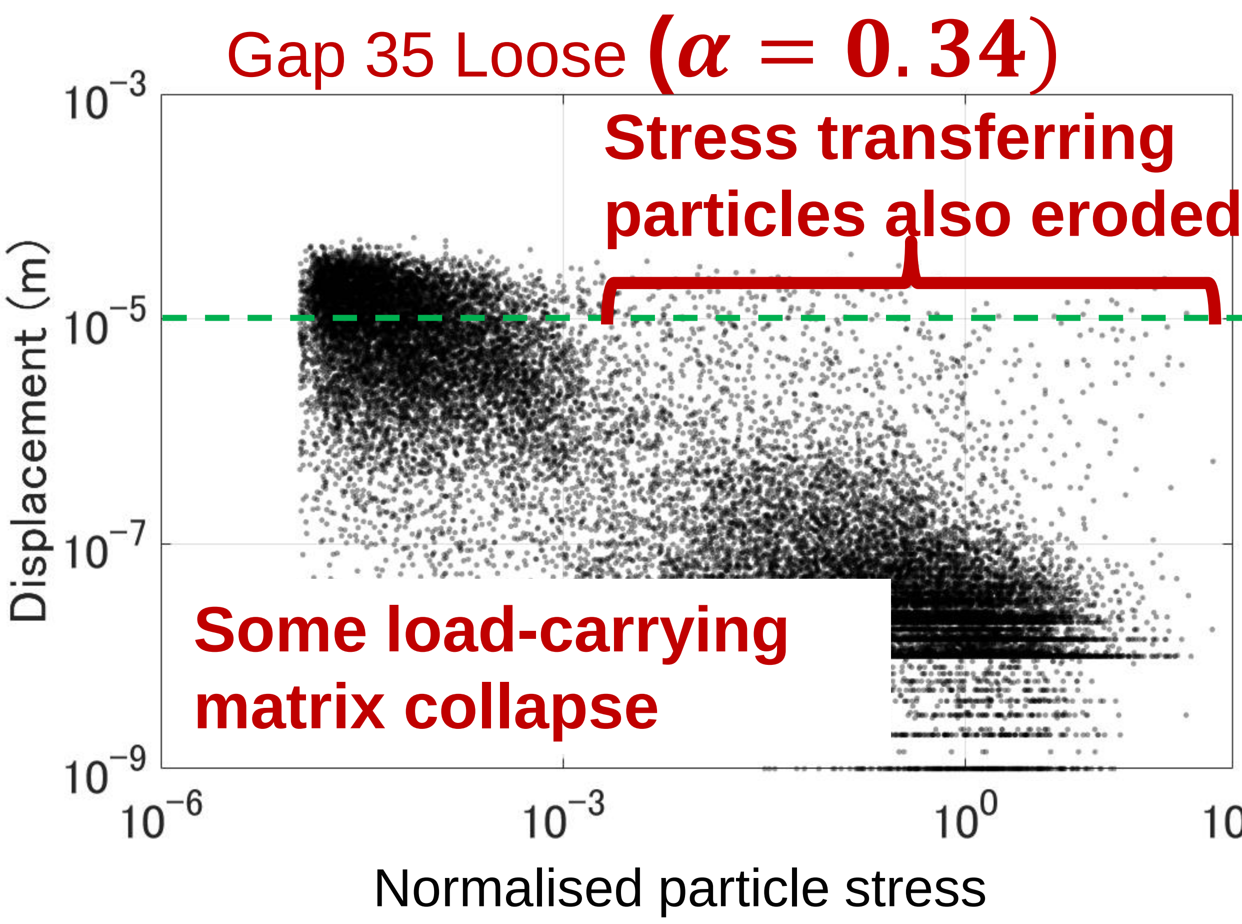


10% D_{min}

Fines: low stress, erosion initiates

Coarse matrix: high stress, no movement

No matrix collapse



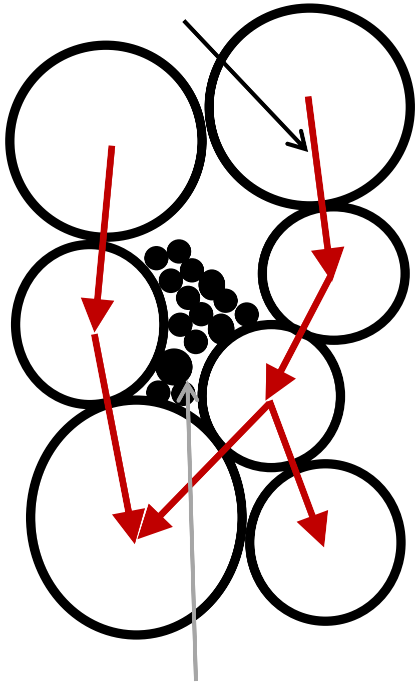
Stress transferring particles also eroded

Some load-carrying matrix collapse

Coupled analysis: typical micro-scale result

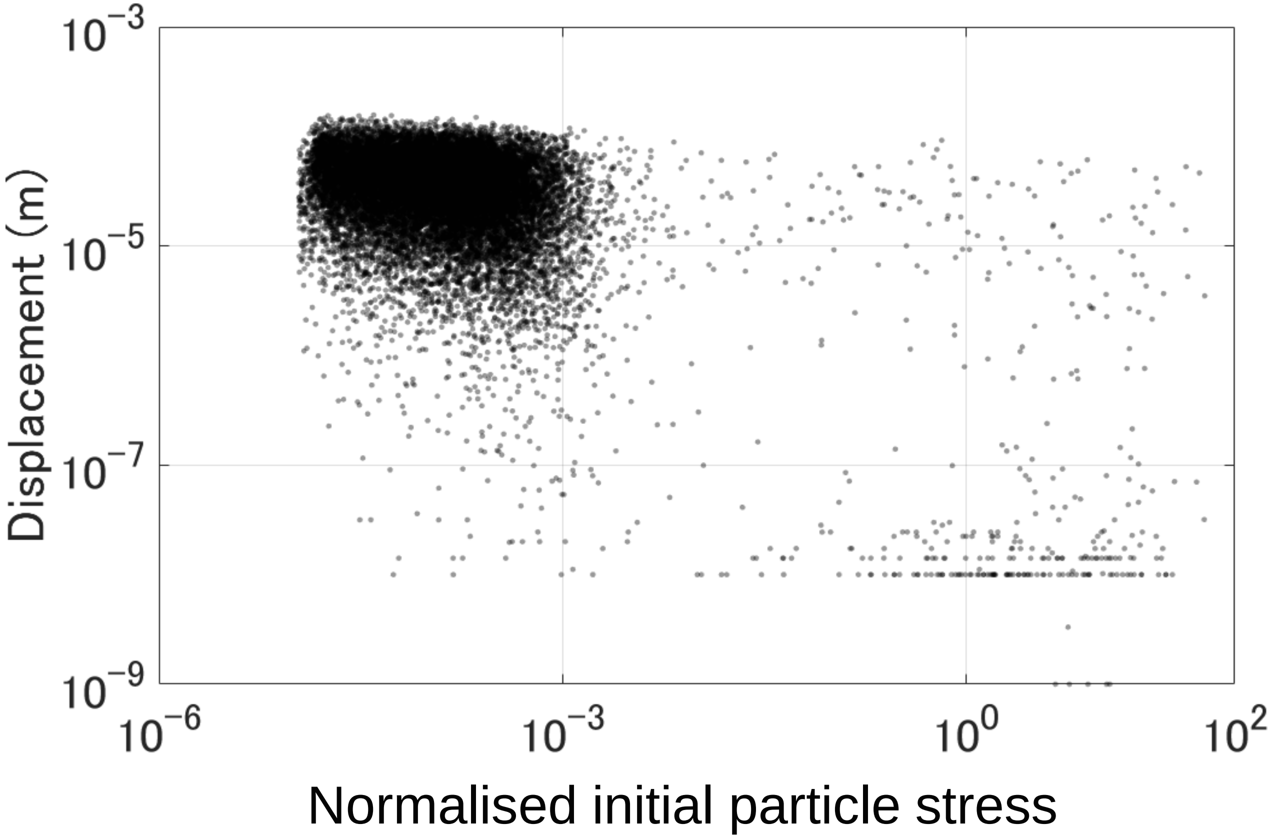
Results point towards different behaviour / fabric types:

Gap 25 Loose (α = 0.11)



Coarse matrix transfers stress

Fines do not participate in stress transfer: Eroded *en masse*

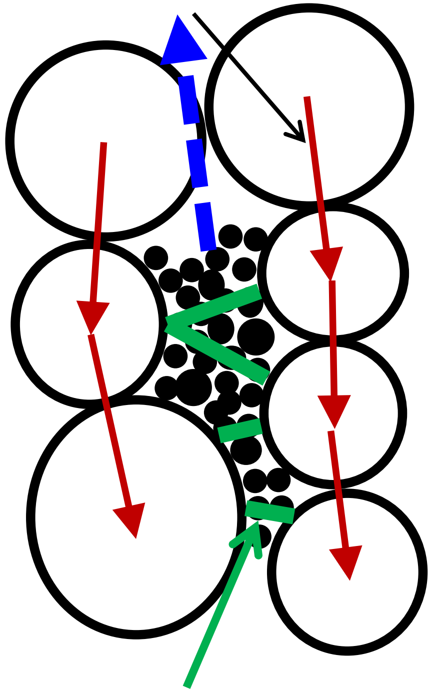


Coupled analysis: typical micro-scale result

Results point towards different behaviour / fabric types:

Gap 35 Loose ($\alpha = 0.34$)

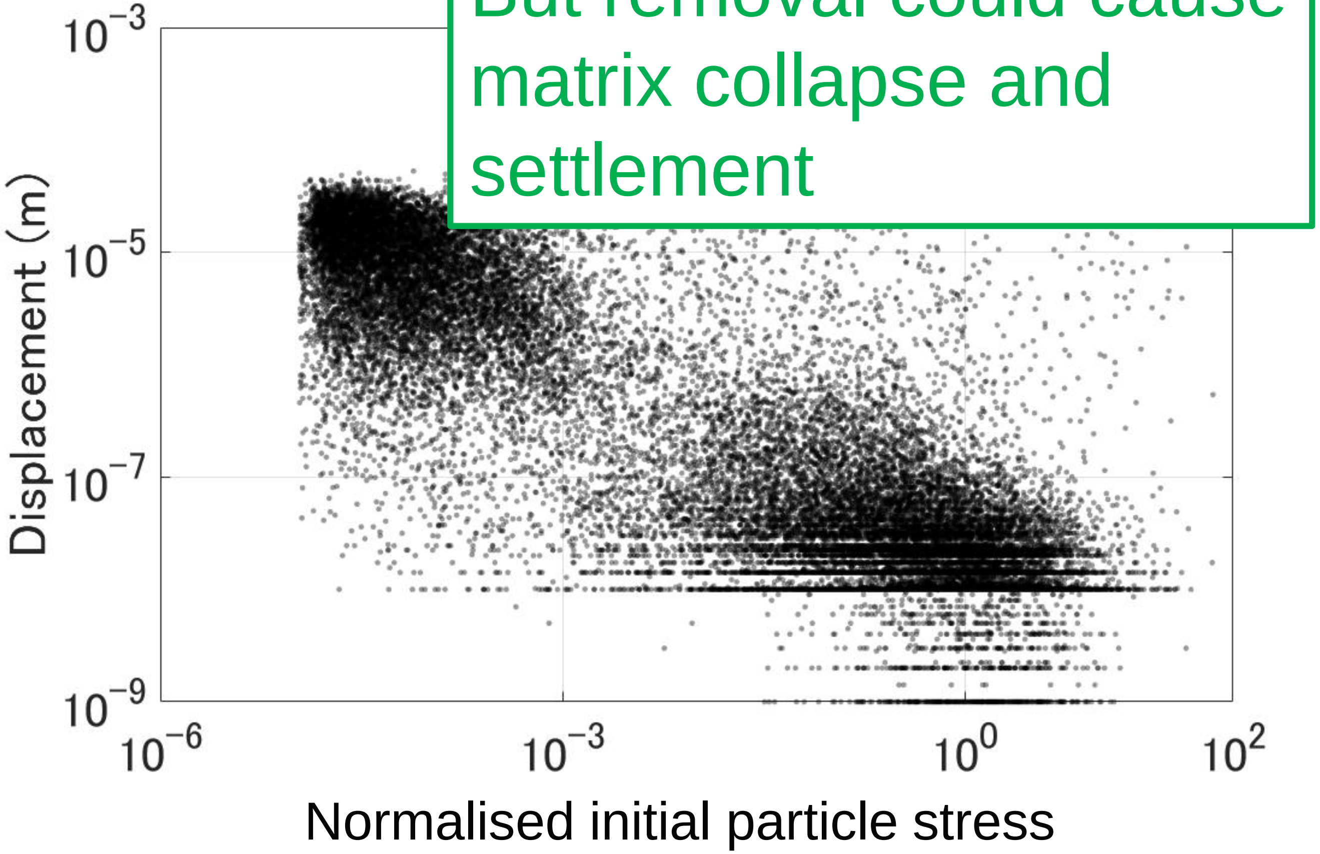
Coarse particles
dominate stress-transfer



Understressed fines provide
lateral support to coarse matrix

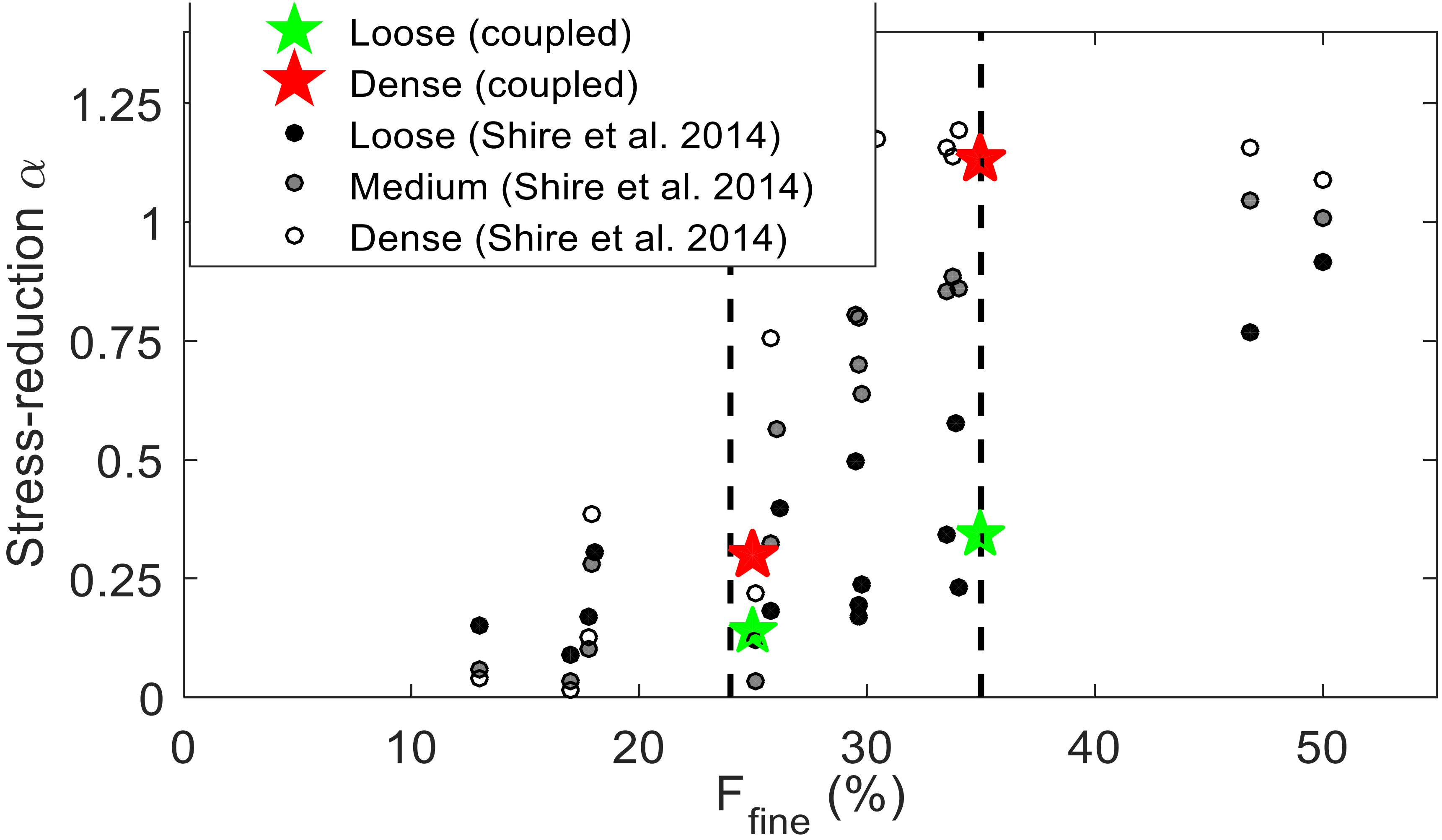
Fines harder to remove:

But removal could cause matrix collapse and settlement



Coupled analysis: typical micro-scale result

Coupled study examined only small range of possible states (due to computational expense of simulations)



Summary

- DEM can be used to study internal instability at micro-scale
- Stress controls initiation of erosion and is linked to PSD and relative density
- Coupled DEM-CFD can be used to study fluid-particle interactions

University of Glasgow

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