# Precision powder feeding

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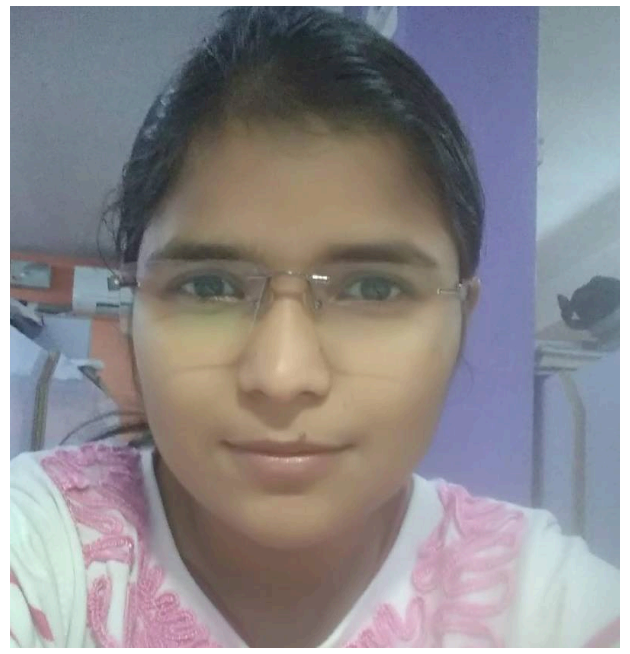

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IFPRI
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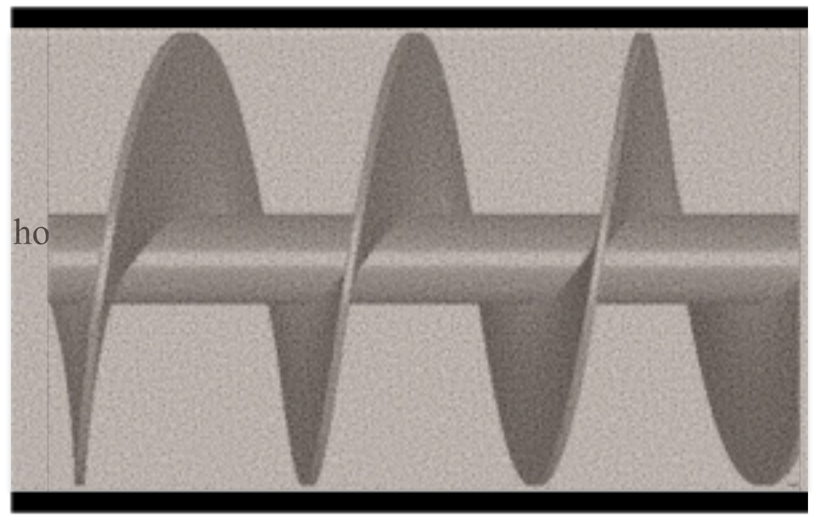
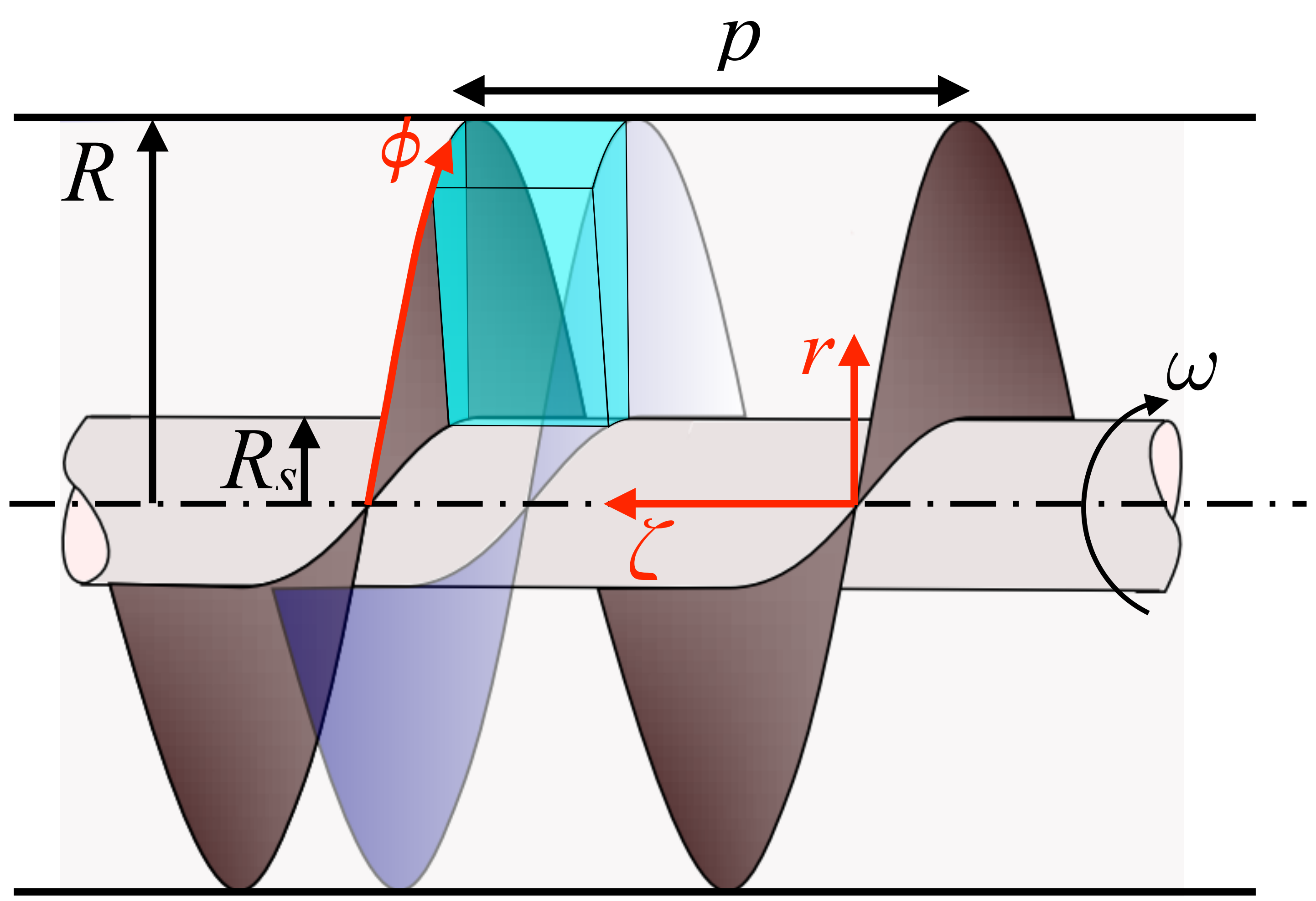


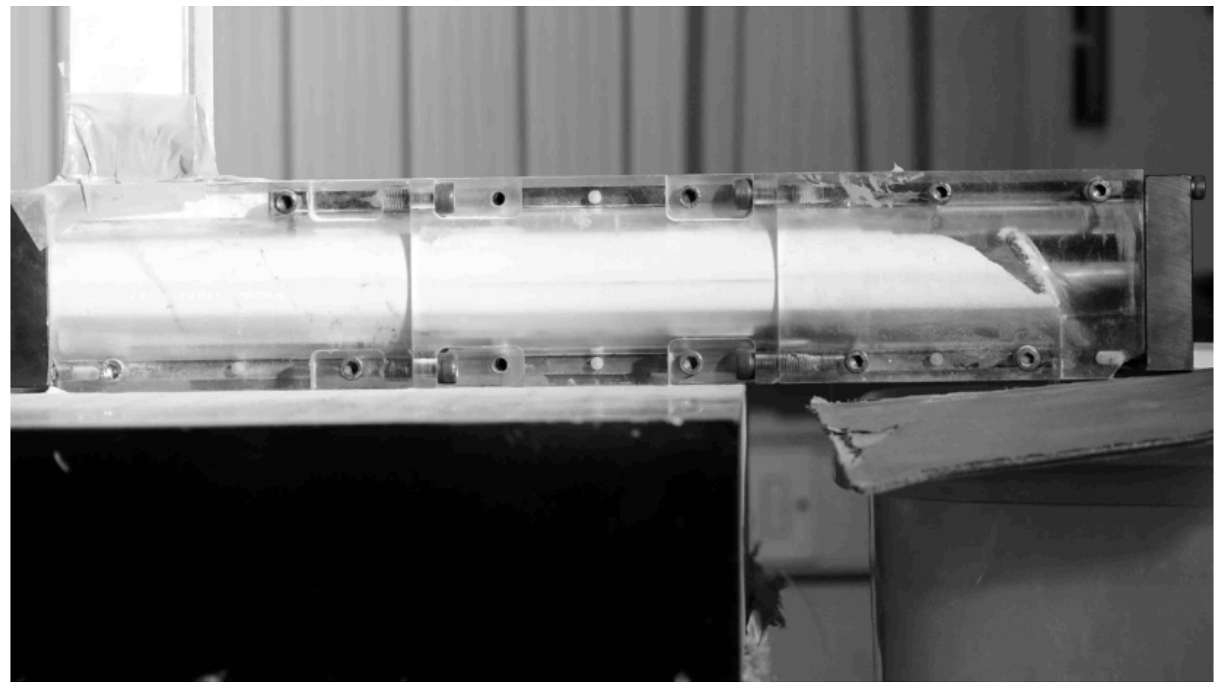
## Objectives

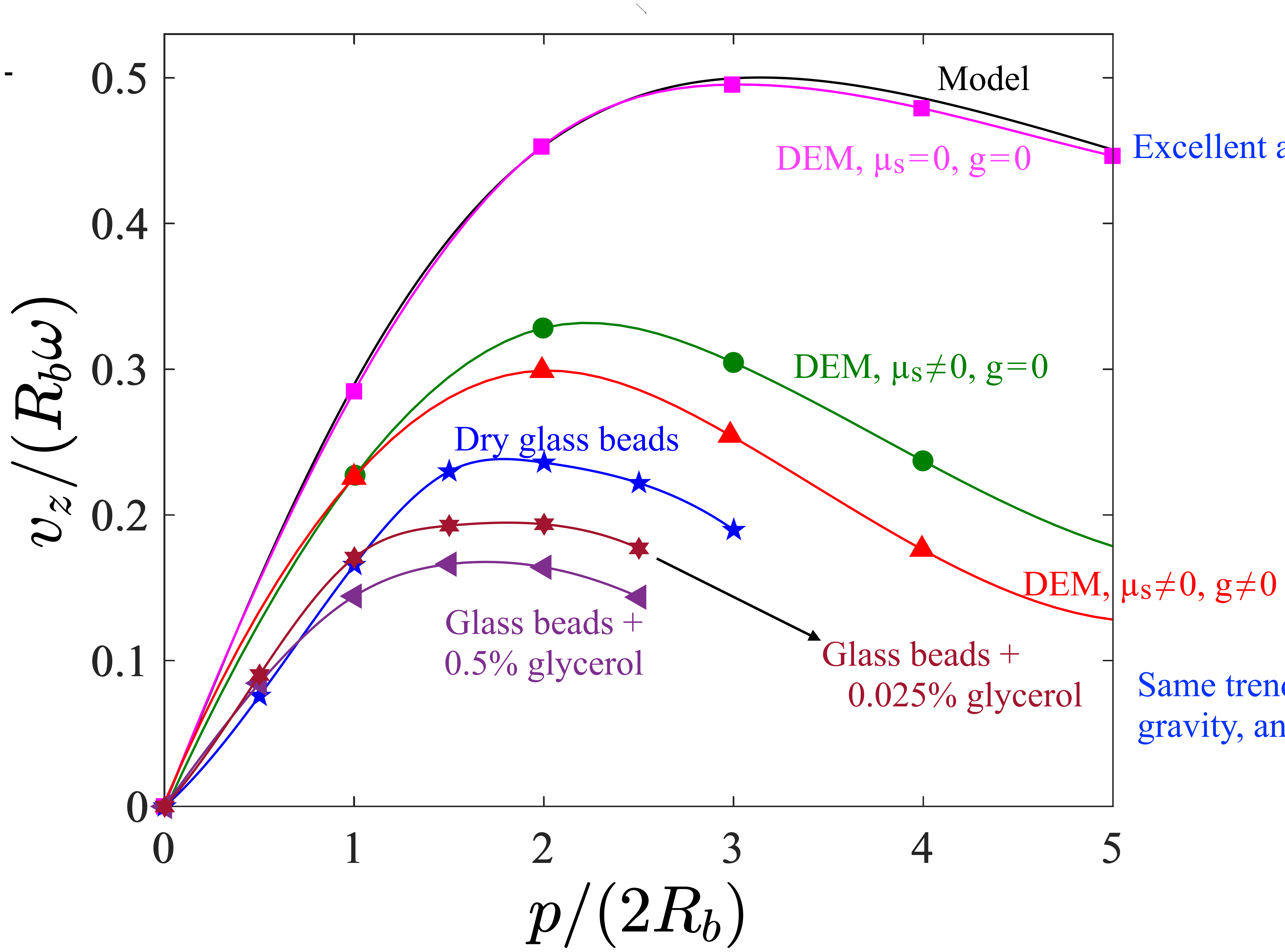
- Develop a theoretical model for flow through screw feeders
- Conduct experiments and DEM simulations to test and help refine the model
- Extend model to cohesive powders.

Second year of renewed project

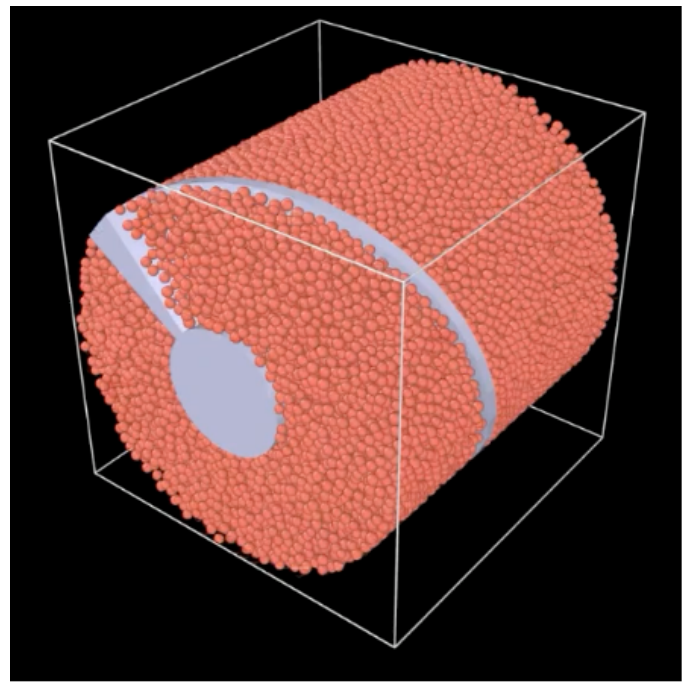
# Quick summary of work in previous years



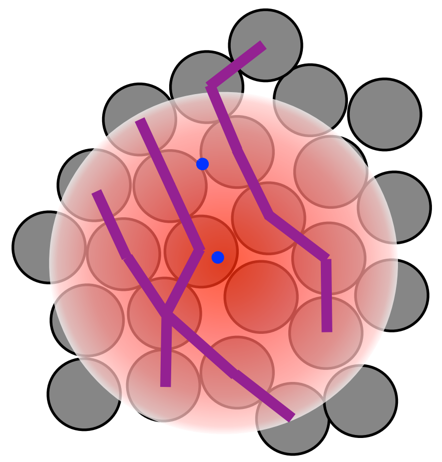



Excellent agreement



Same trend when friction, gravity, and cohesion are present

# Model that incorporates dilatancy and resolves kinematic interminacy

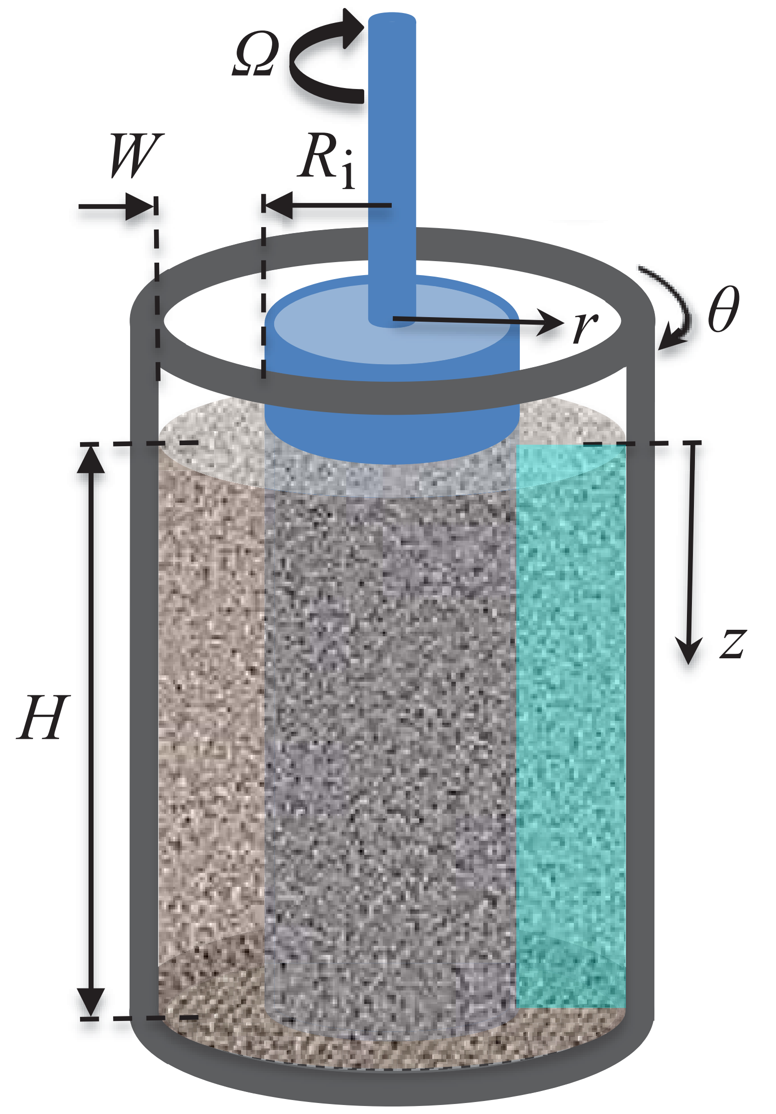


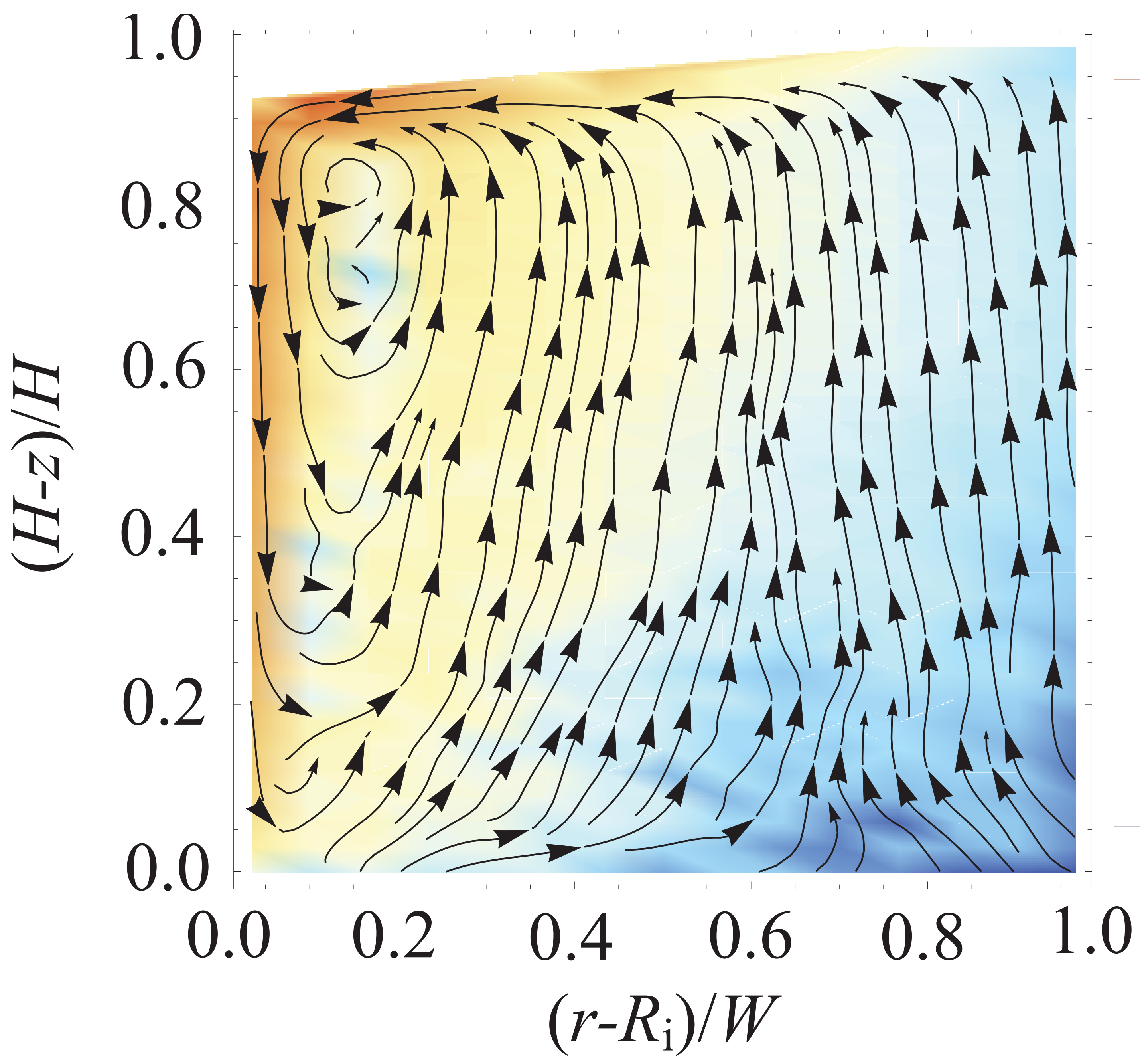
$$\boldsymbol{\sigma} = -p\,\boldsymbol{\delta} + \frac{2\mu}{\dot\gamma}\left(p_c\,\boldsymbol{D}' - \underline{\ell^2\,\Pi\,\nabla^2\boldsymbol{D}'}\right), \qquad p = p_c\left(1 - \frac{\mu_b}{\dot\gamma}\boldsymbol{\nabla}\cdot\boldsymbol{u}\right) - \underline{\ell^2\,\Pi\,\frac{\mu_b}{\dot\gamma}\nabla^2\boldsymbol{\nabla}\cdot\boldsymbol{u}}$$

$$p_c = \Pi - \underline{\ell^2\,\frac{d\Pi}{d\phi}\,\nabla^2\phi},$$

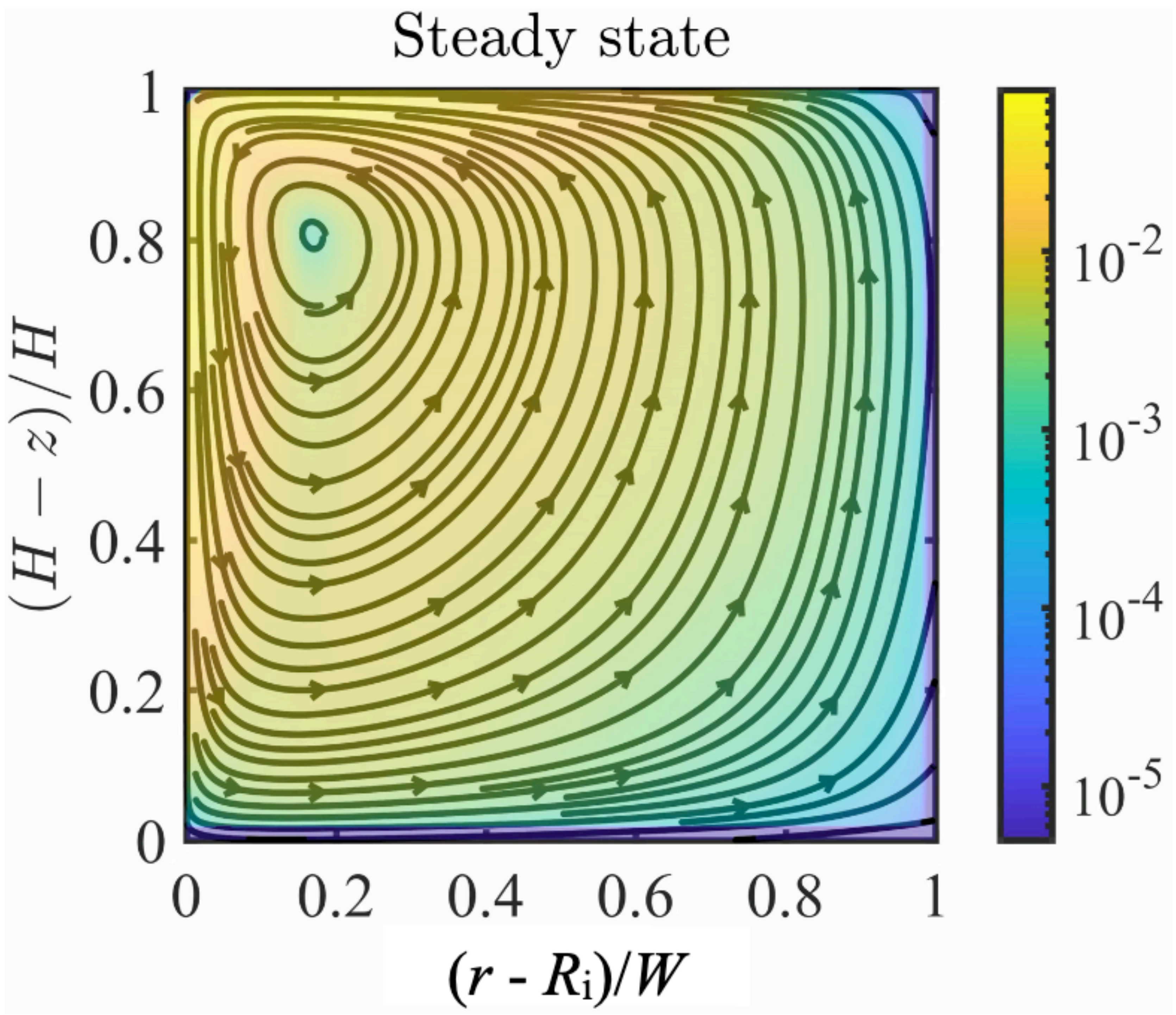
Dsouza & Nott (*J. Fluid Mech.* 2020)

## Model validation: secondary flow in cylindrical Couette device




Krishnaraj & Nott (*Nature Commun.* 2016)

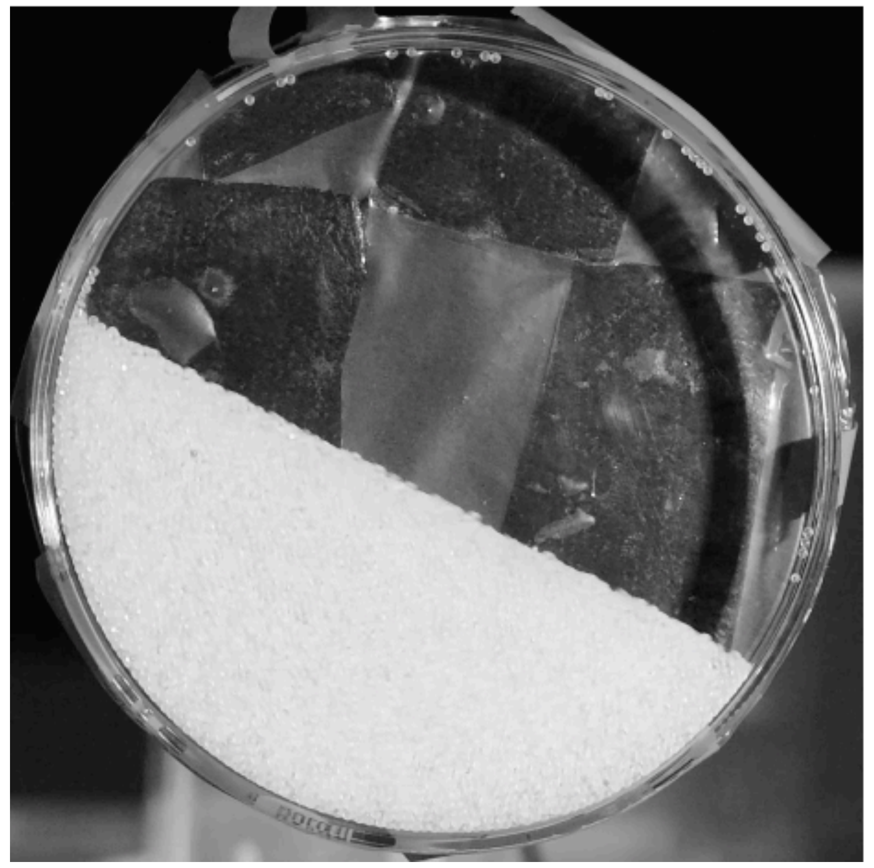



Vatsa & Nott (2025)

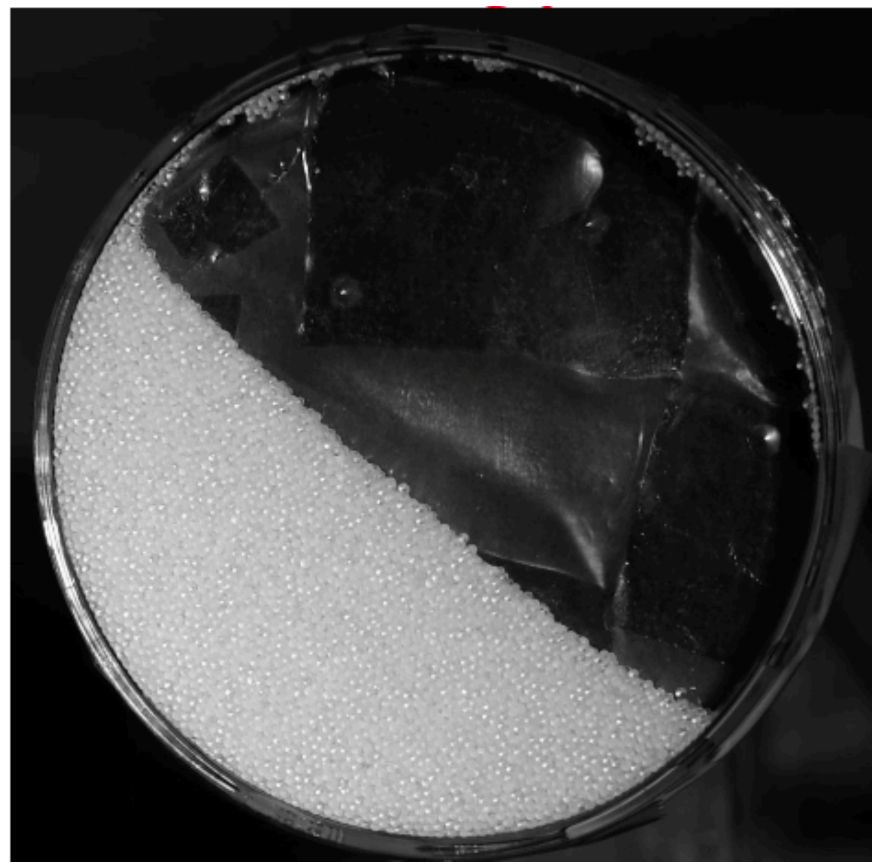
# Flow fluctuations in powders of controlled cohesion

## Cohesive powders created by mixing dry glass beads with a small amount of glycerol

0% glycerol

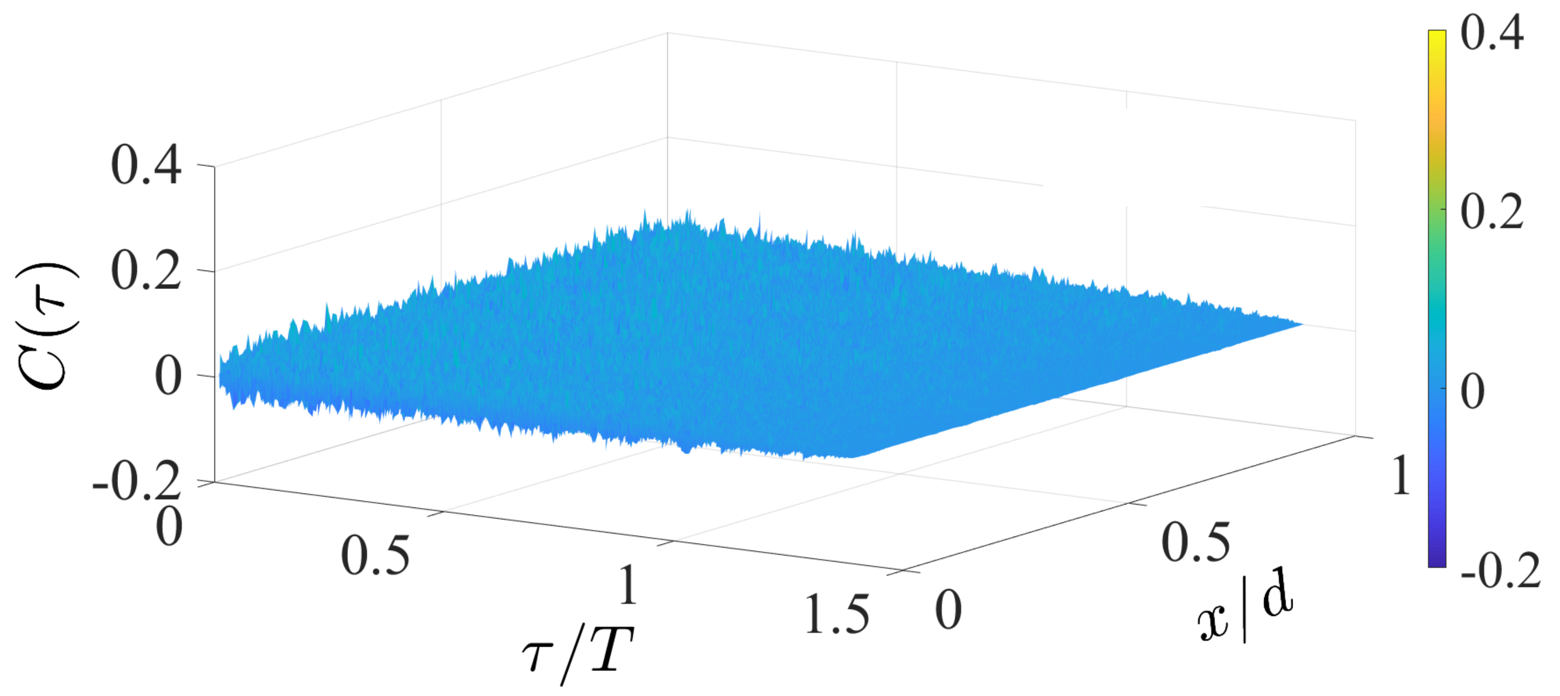


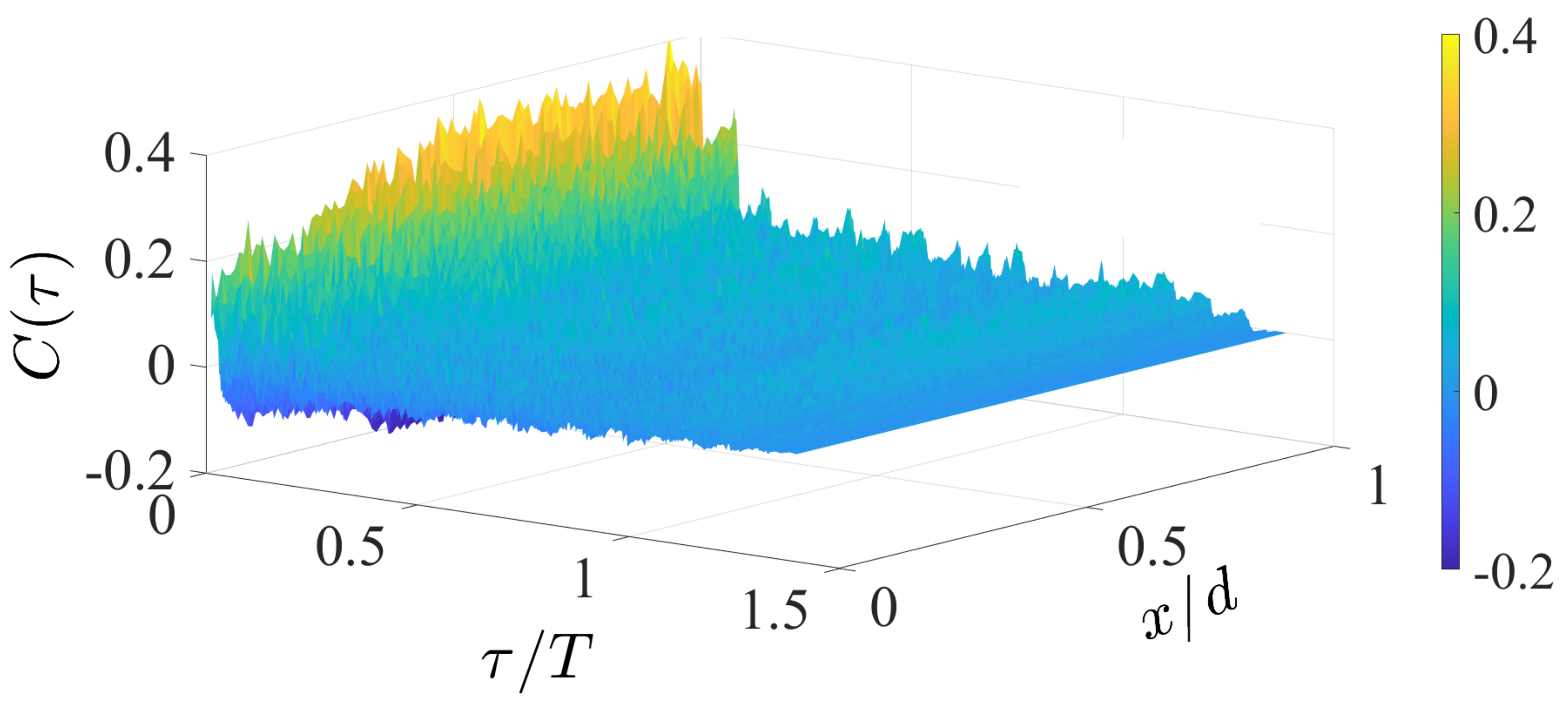
0.025% glycerol

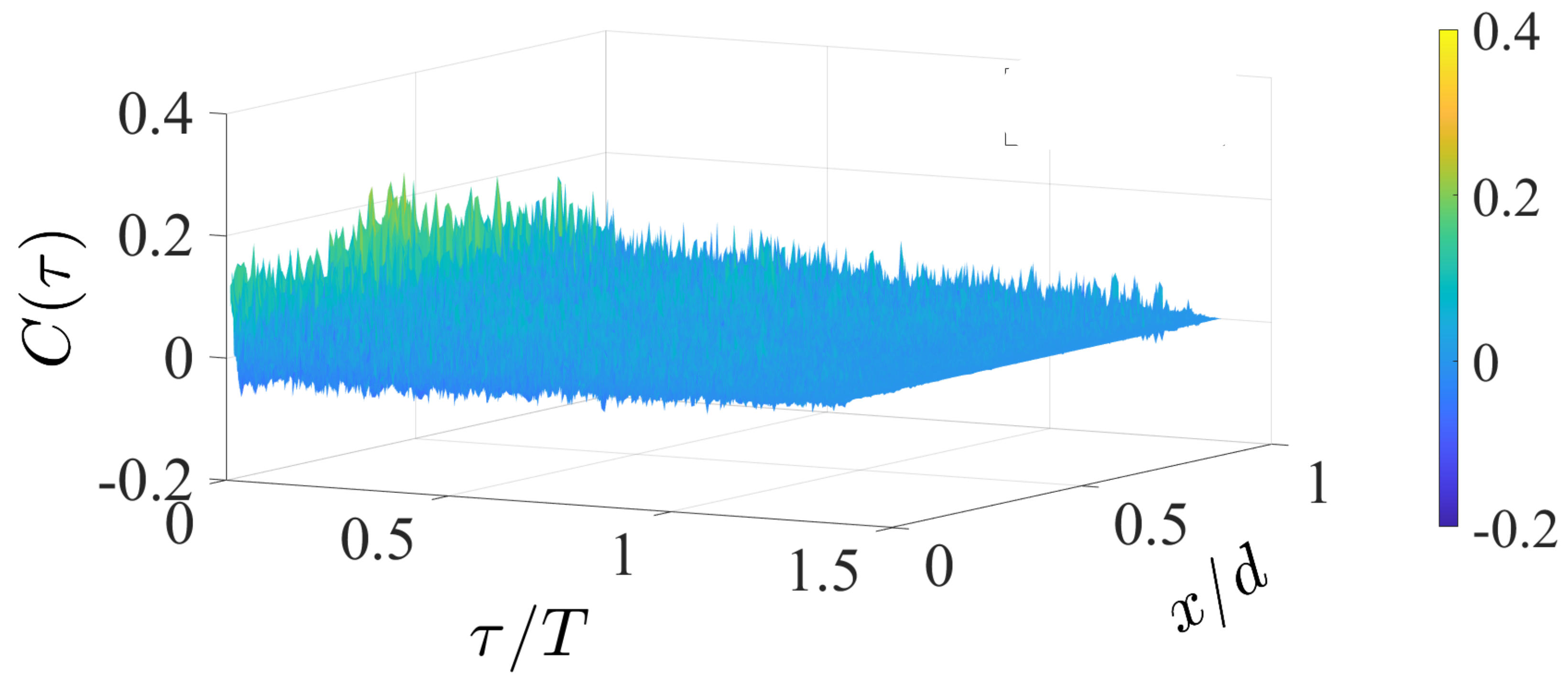


0.2% glycerol

$$C(\tau,\delta) = \langle \mathrm{u}(t,x)\, \mathrm{u}(t+\tau, x+\delta)\rangle$$ space-time velocity correlation



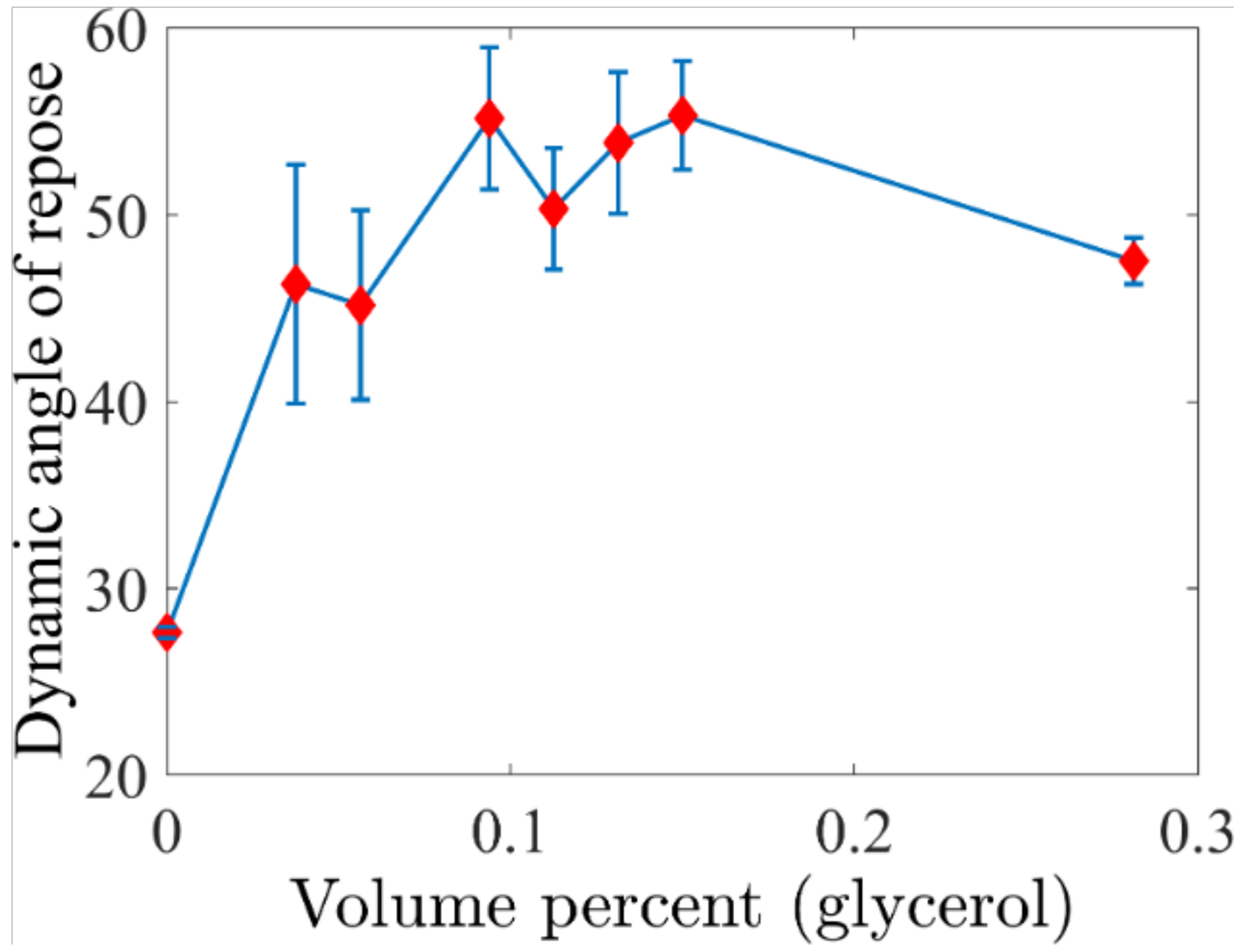




Dynamics modulated by cohesion, but largely driven by inertia.

Measurements in steady, non-inertial flows needed.

## What are the effects of inter-particle cohesion?

Cohesion modifies the yield condition: $F(\boldsymbol{\sigma}) = F_{\text{non-coh}}(\boldsymbol{\sigma}) - \tau_{\text{coh}}$

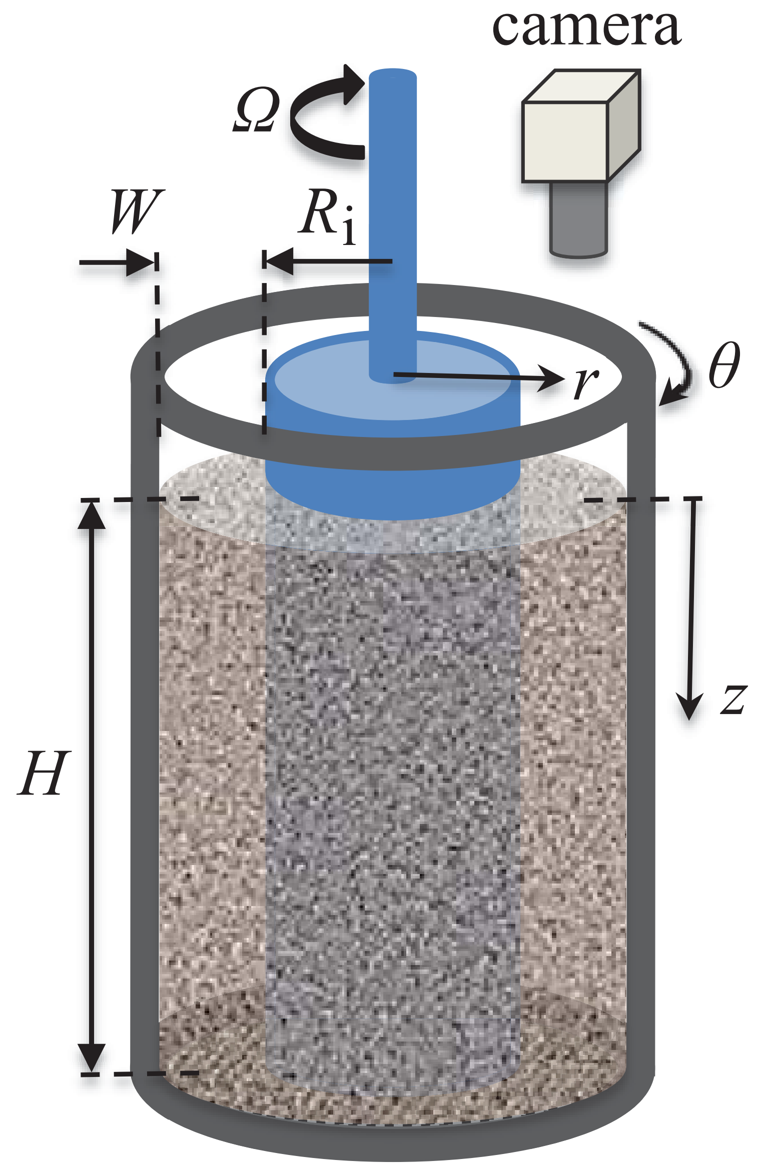


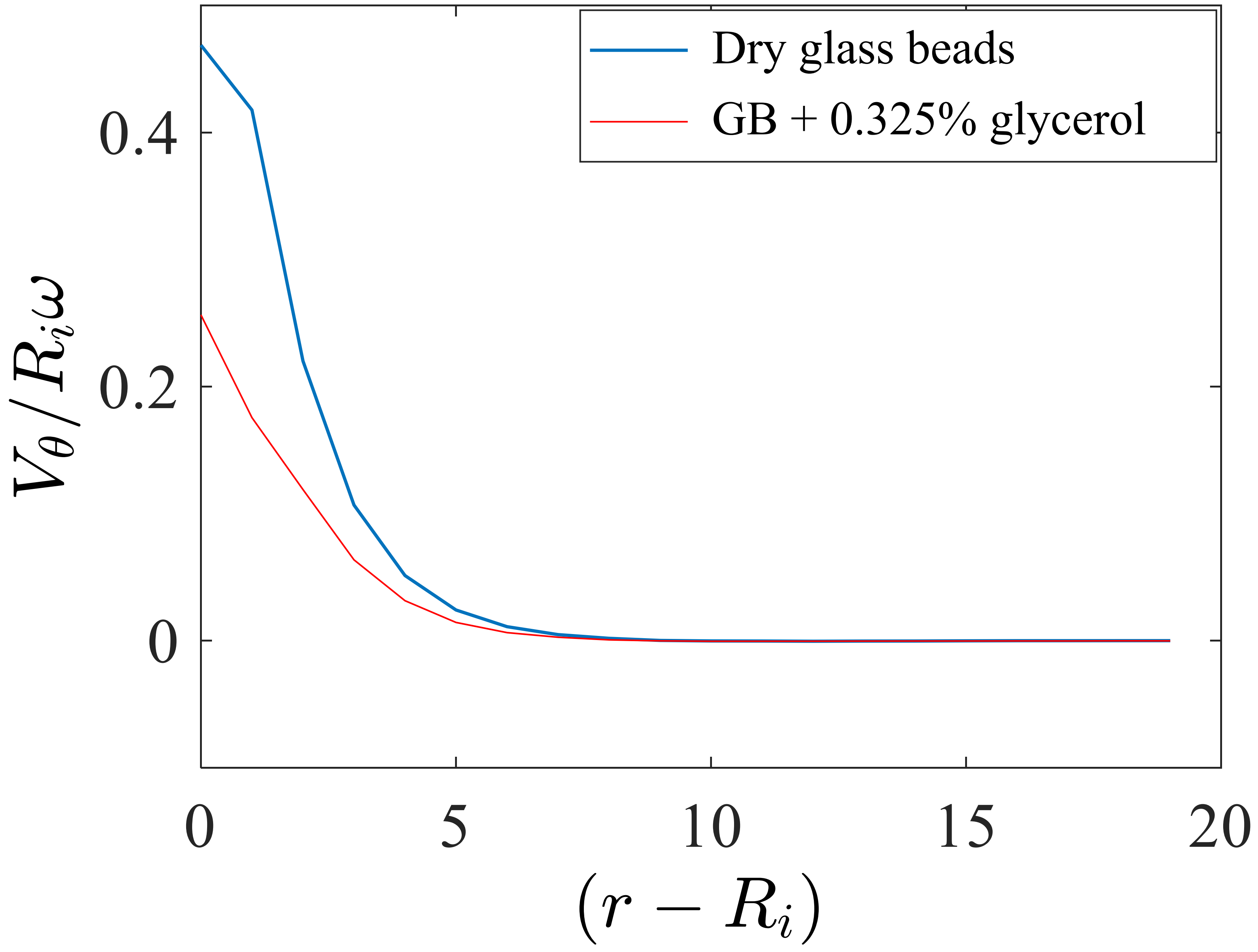

Our experiments show that cohesion also affects the post-yield kinematics, i.e. the **flow rule**: $D_{ij} = \dot{\lambda}\frac{\partial F}{\partial \sigma_{ij}}$

fluidity

*Quantify the influence of cohesion on kinematics*

- Imaging experiments to measure kinematics and agglomeration

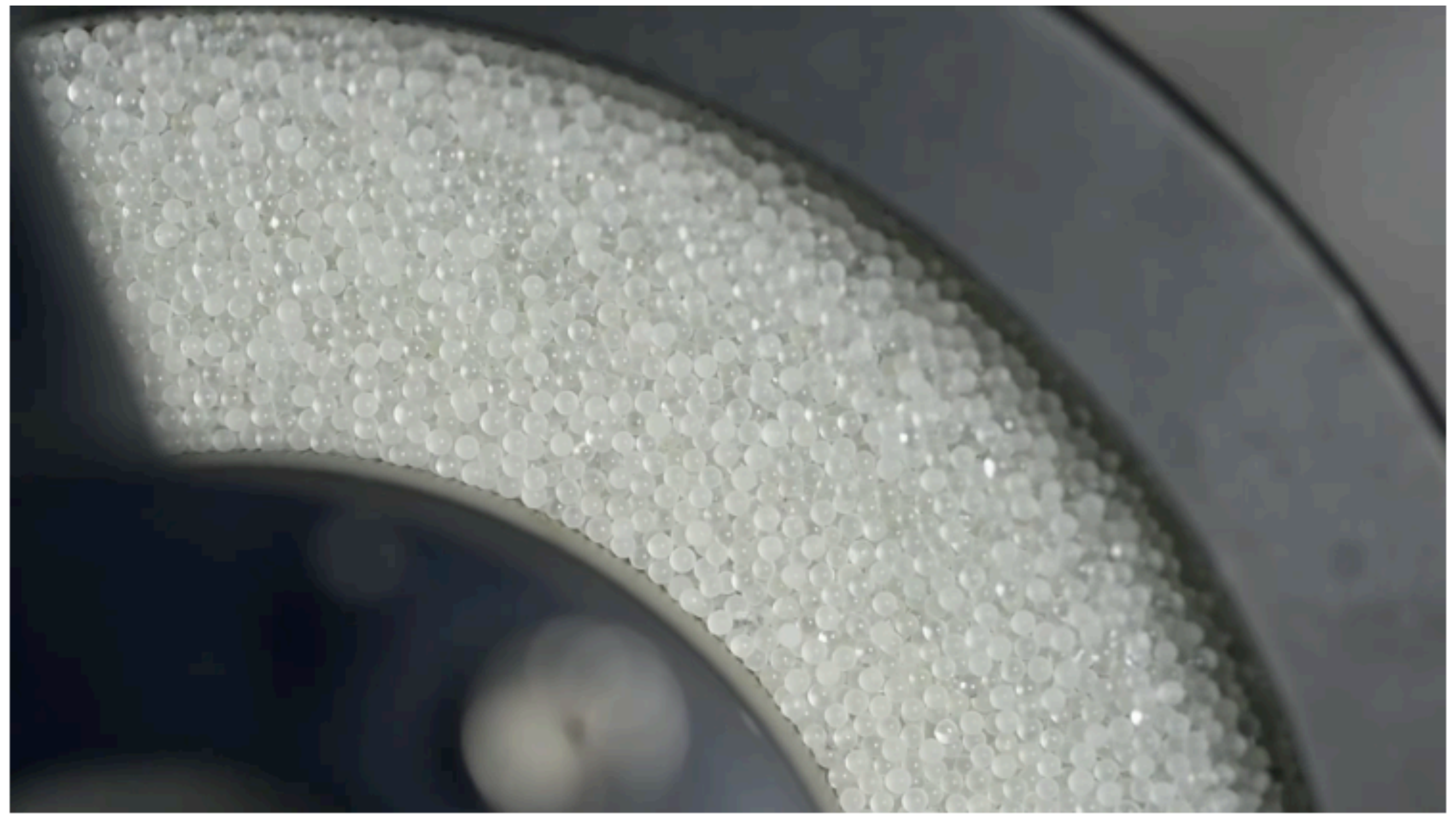


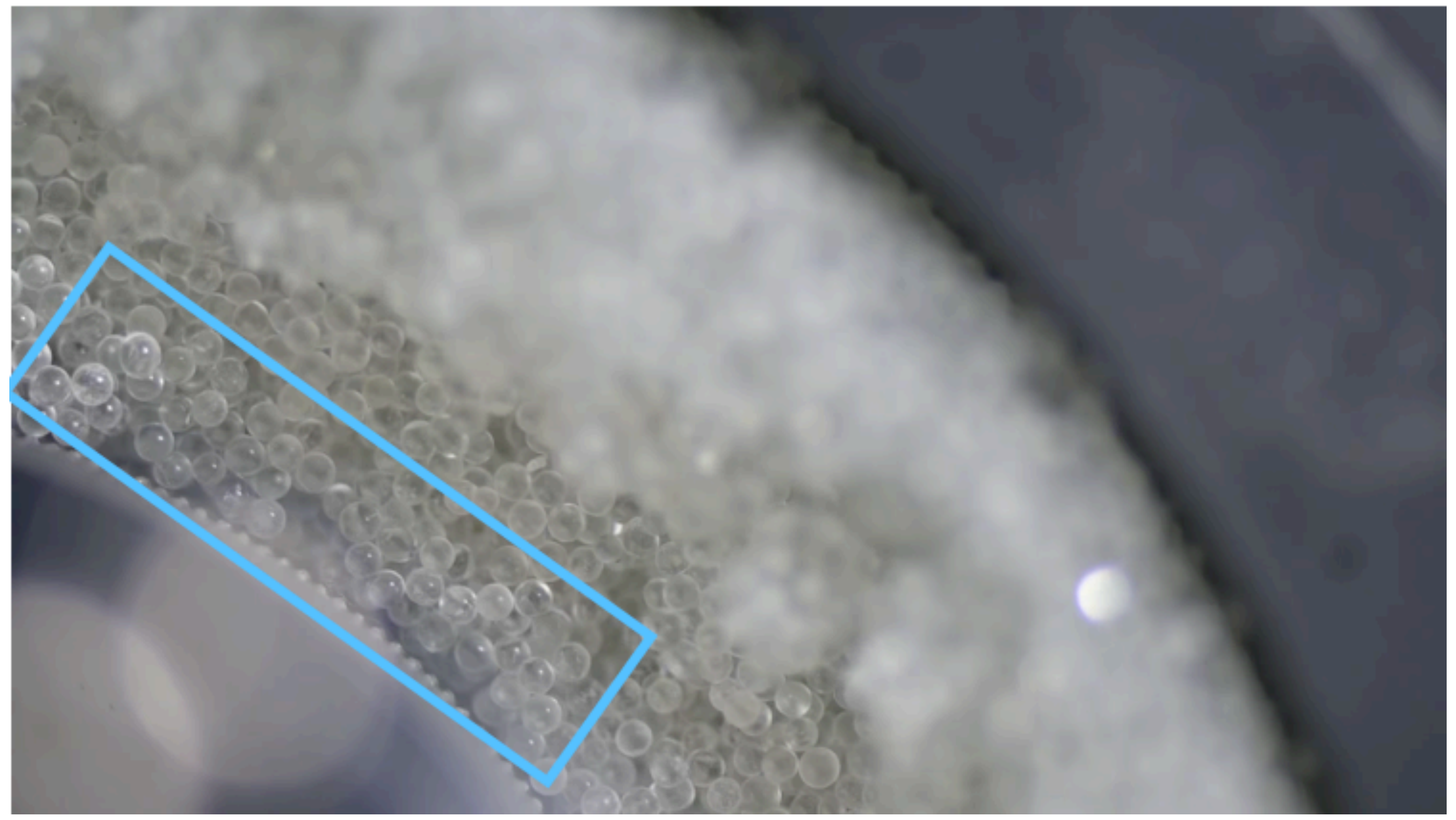
## *How does cohesion affect flow?*

- *Imaging experiments*

dry glass beads

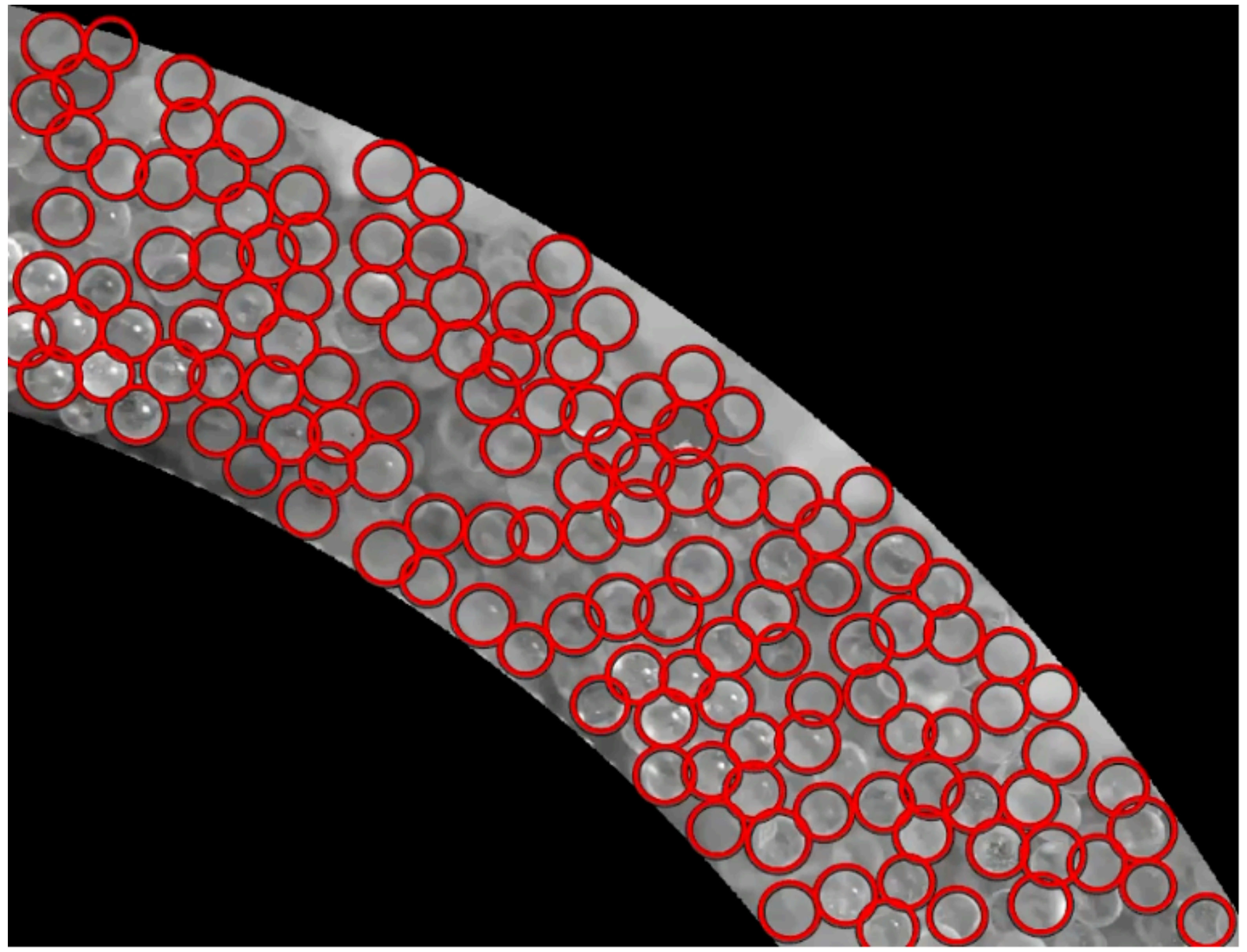


glass beads + 0.325% glycerol



The cohesive powder appears to form clusters

Quantification of cluster formation necessary

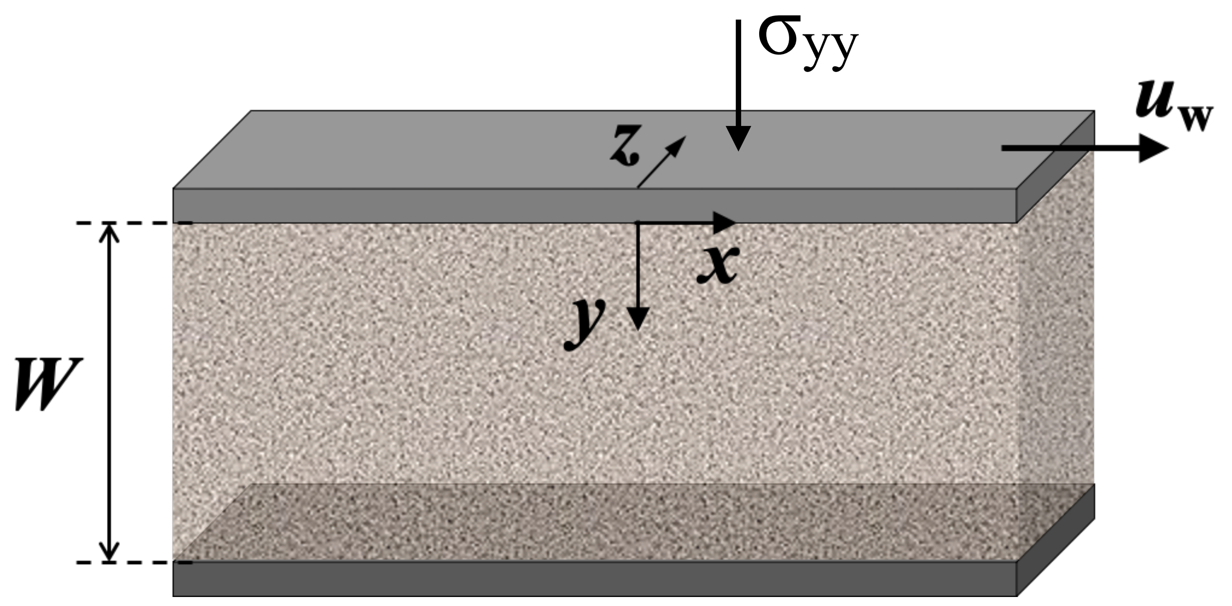


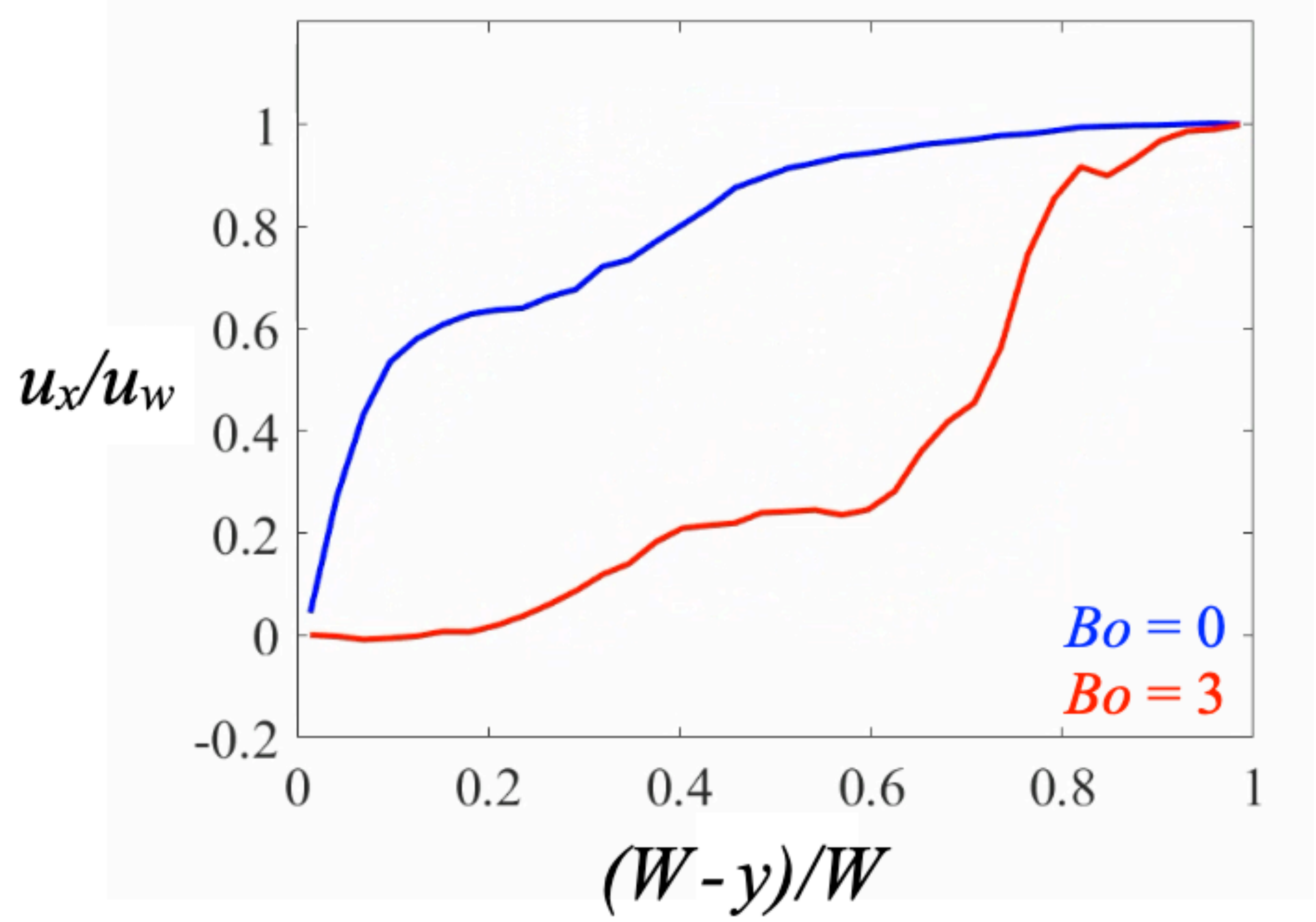
Unable to identify clusters by optical imaging

# *How does cohesion affect flow?*

- *DEM simulations with JKR model for cohesion*

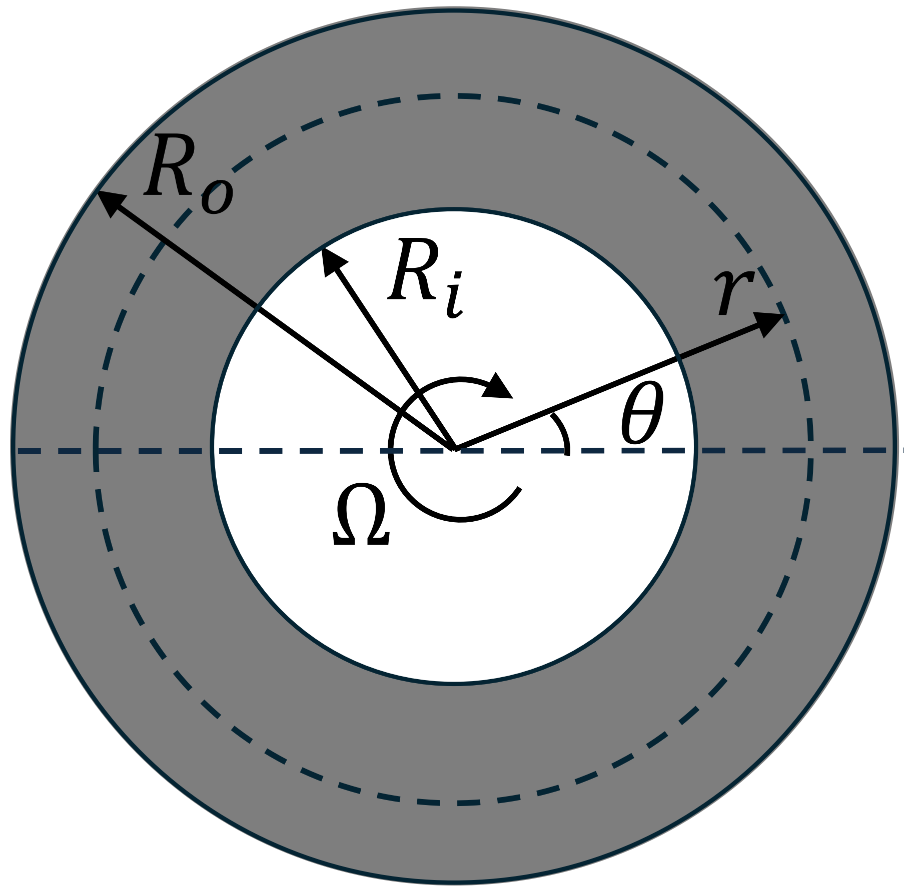
Bond number: $Bo = F_{coh}/(\sigma_{yy}\, d_p^{\,2})$

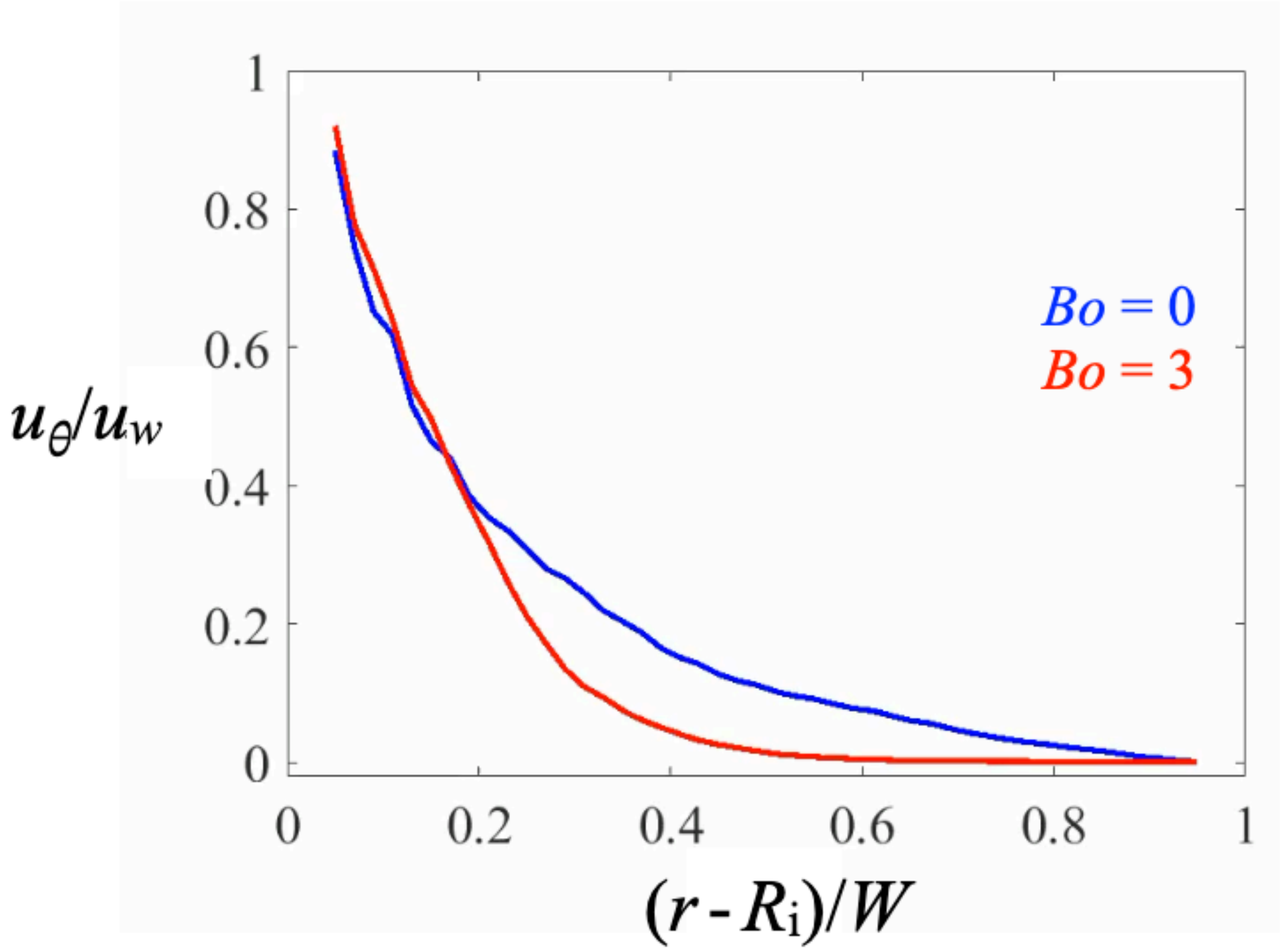



Large fluctuations in velocity profile make it difficult to quantify effect of cohesion.

Plane shear not suitable to study effect of cohesion on flow



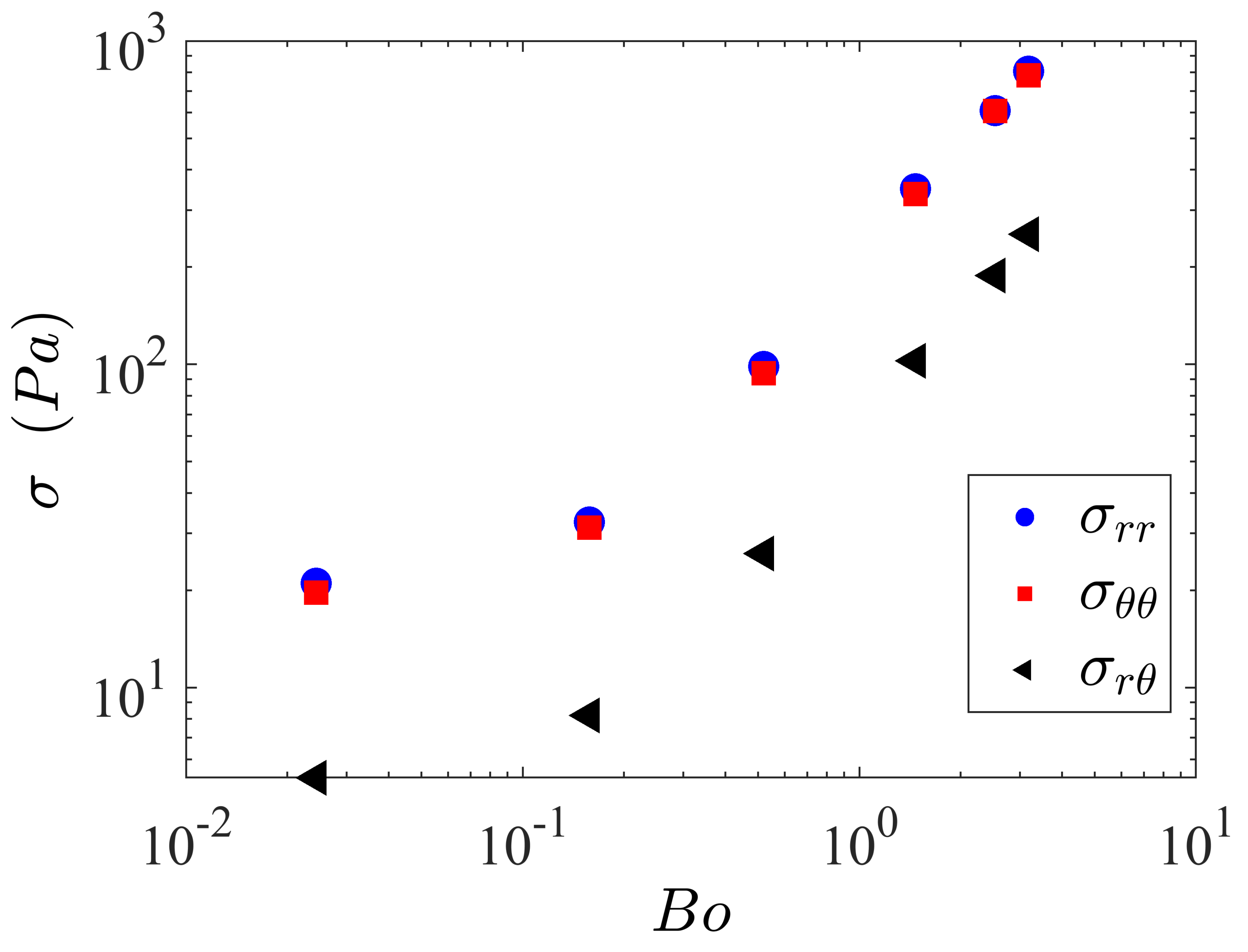




Shear layer always near inner cylinder.

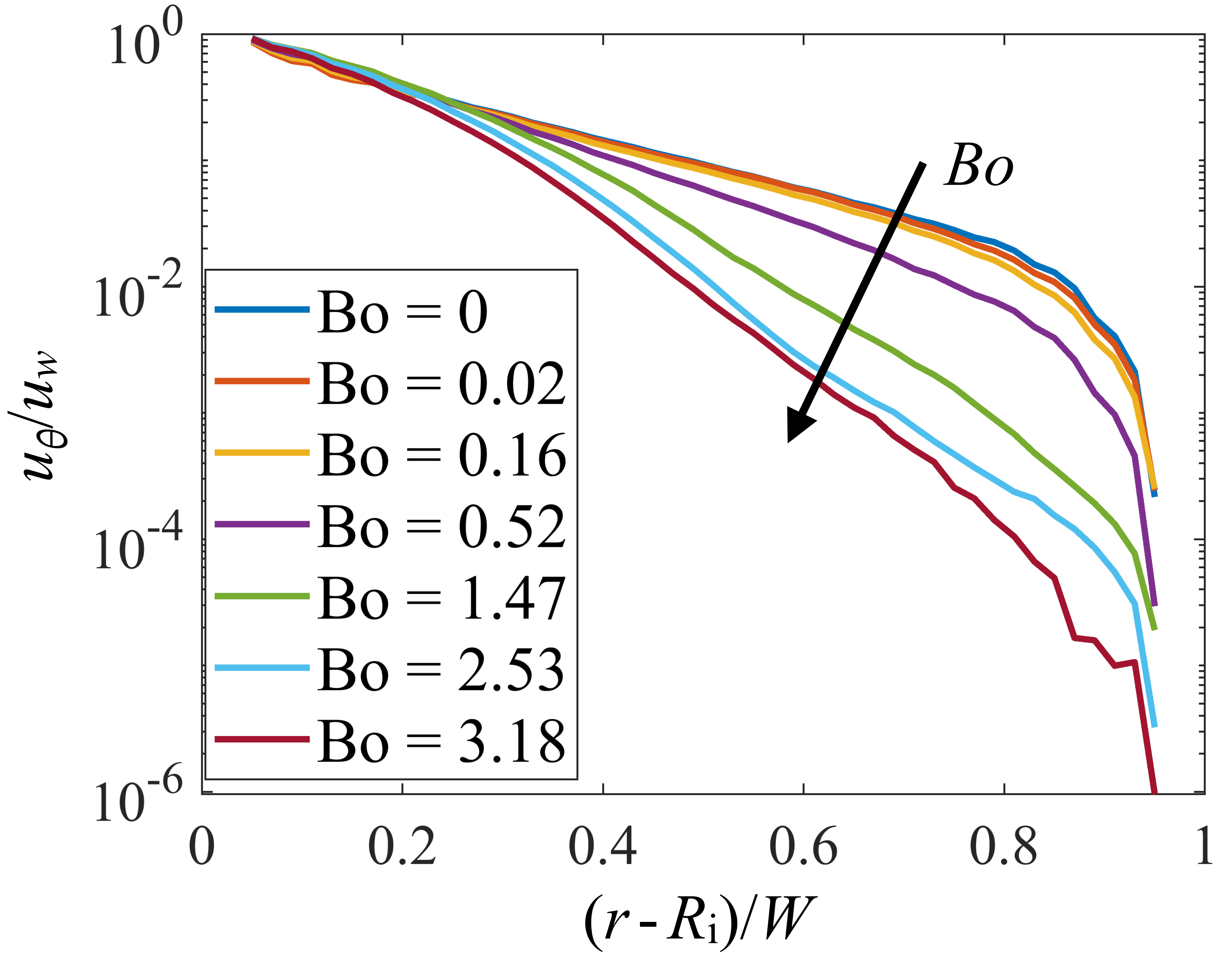
Cylindrical Couette flow suitable: effects of cohesion easier to distinguish

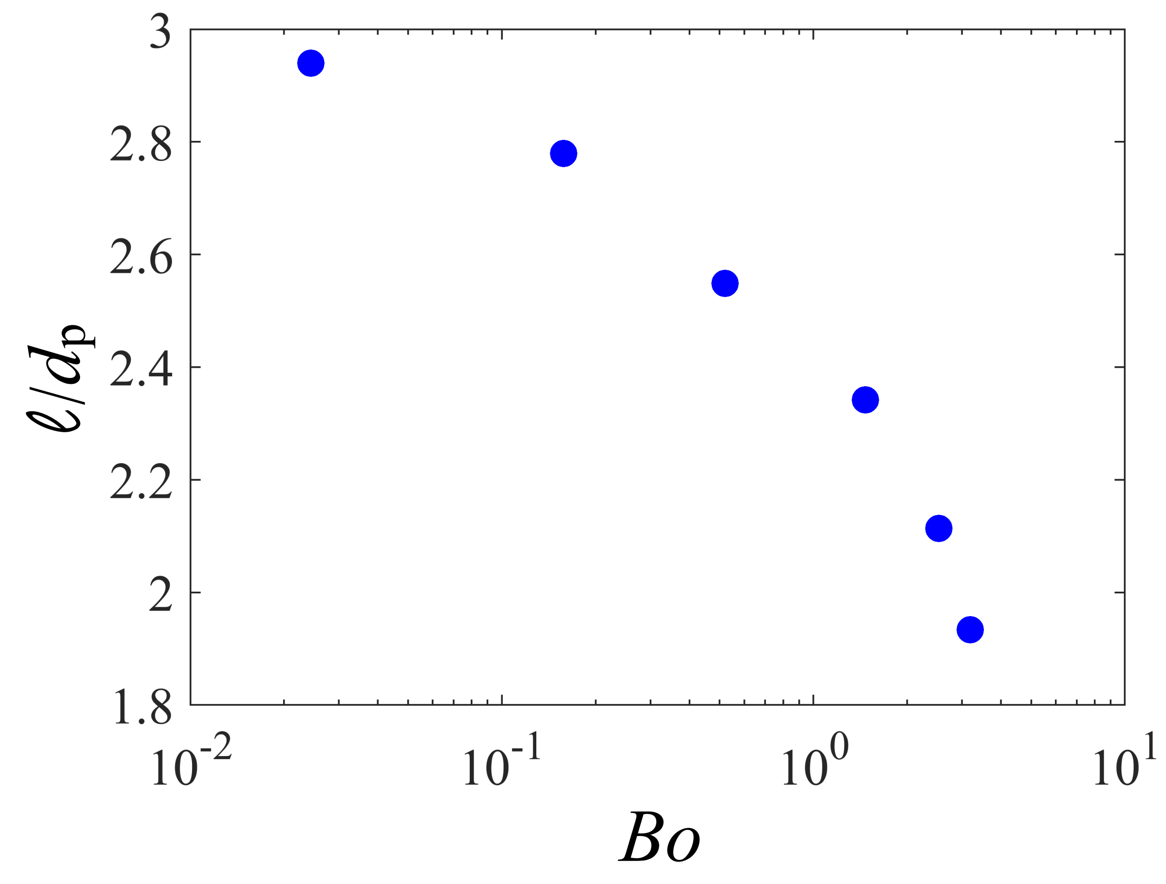
# *How does cohesion influence the stress and kinematics?*

## *DEM simulations of cylindrical Couette flow*




$u_\theta/u_w = \exp[-(r - R_\mathrm{i})/\ell]$



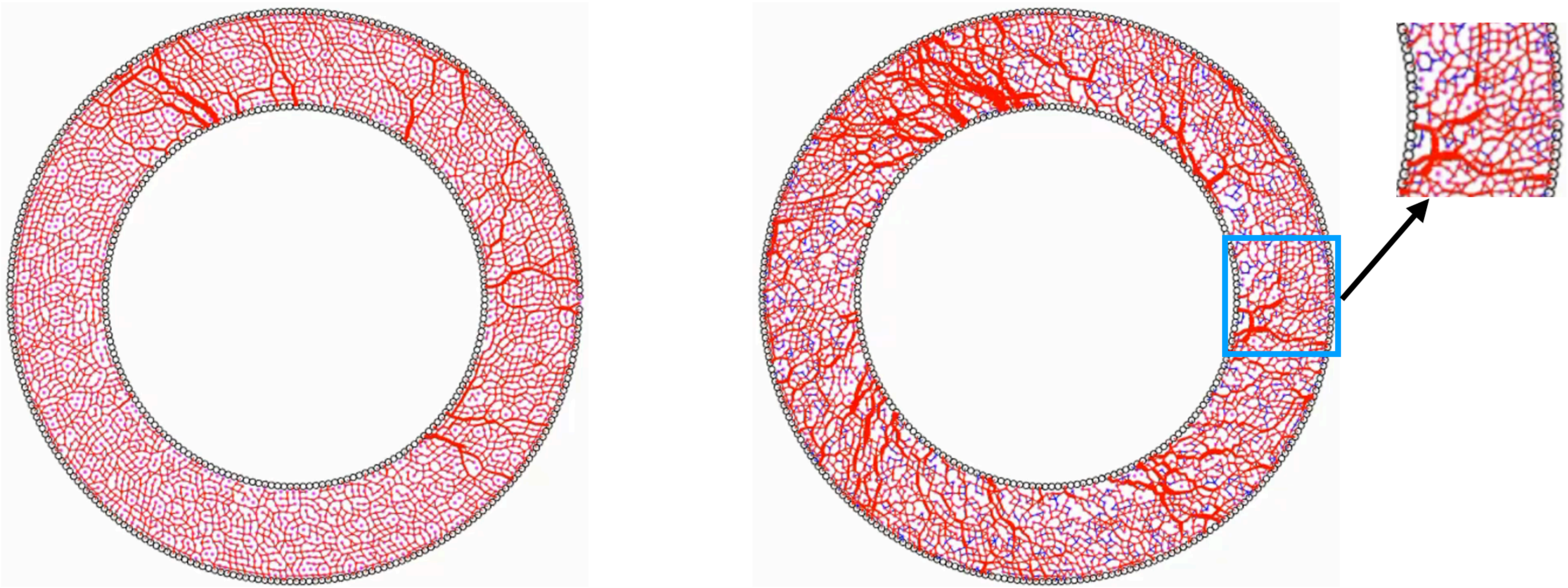




Substantial dependance of the stress and velocity fields on the Bond number *Bo*.

We need a micromechanical understanding of these effects.

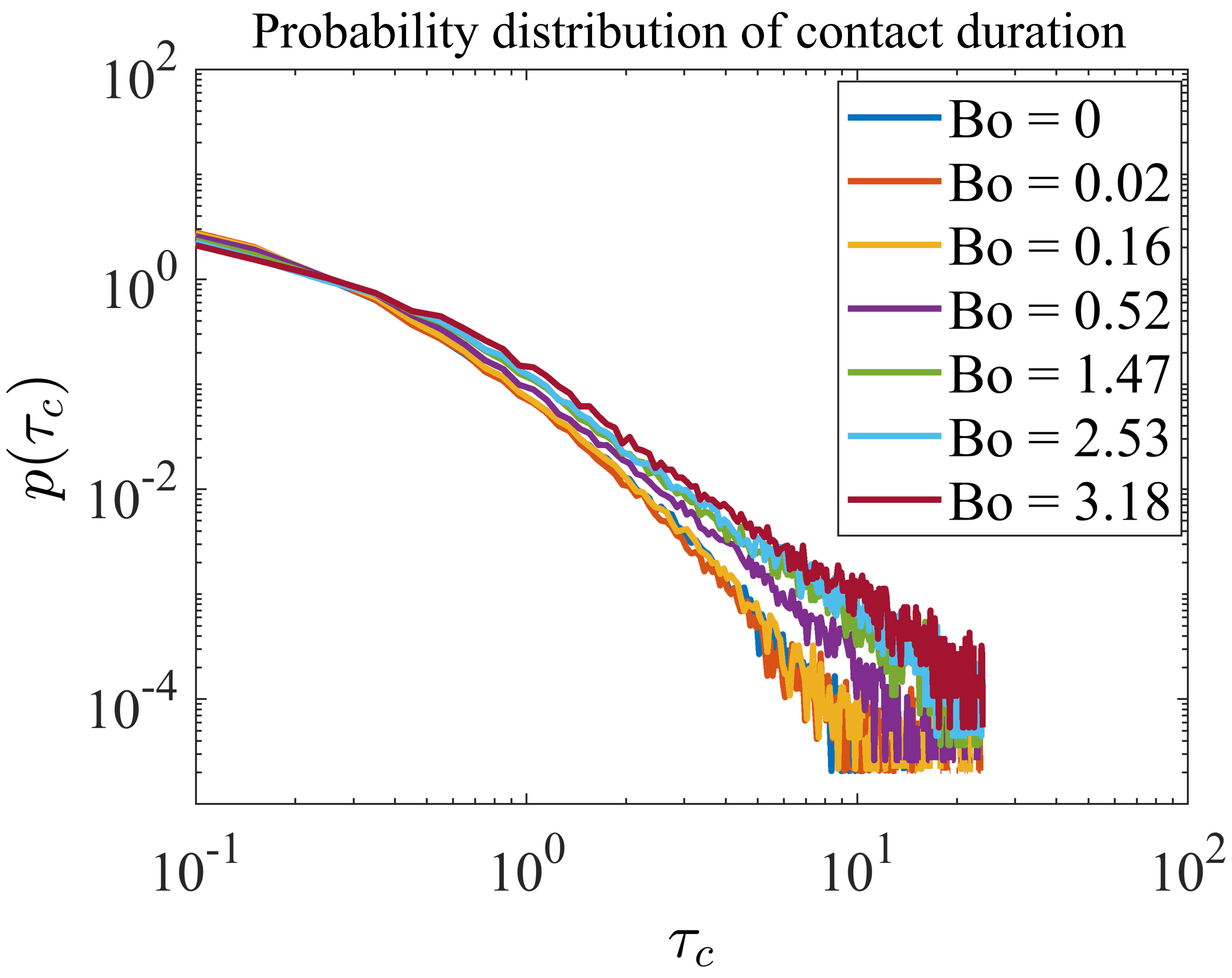
*How does cohesion alter the distribution of contact forces?*

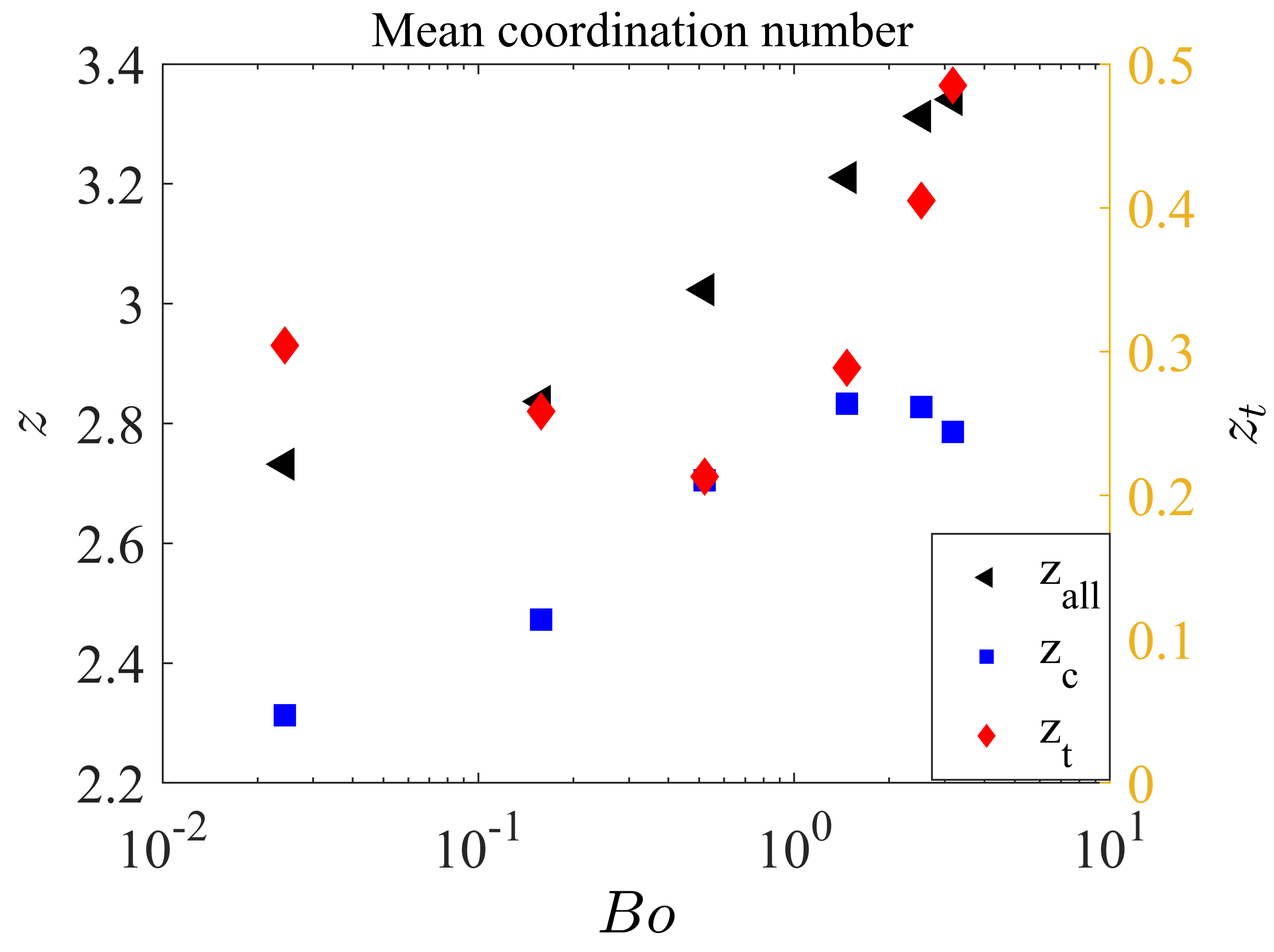
$Bo = 0$ $Bo = 3.18$



Small number of tensile contacts appear to support large compressive force chains

*Effect of cohesion on the statistics of contacts*




Cohesion increases overall duration of contacts, even though the fraction of tensile contacts is small.

DEM simulations provide useful information on the micromechanics and statistics. They must be used to build a continuum model.

# Conclusion

- Experiments on model cohesive powders, made by mixing dry glass beads with small amounts of glycerol, seemingly show formation of particle clusters. Optical imaging does not clearly identify clusters.

- DEM simulations of cylindrical Couette flow are useful to study the influence of cohesion. Cohesion strongly affetcs the stress and velocity fields. Length-scale in non-local model decreases with increasing Bond number.

- Tensile contacts bearing cohesive forces appear to stabilize force chains of compressive contacts. Mean contact duration increases substantially with increasing cohesive force.

- The challenge now is to make use of the micromechanics of particle interactions to build a continuum model for cohesive powders.