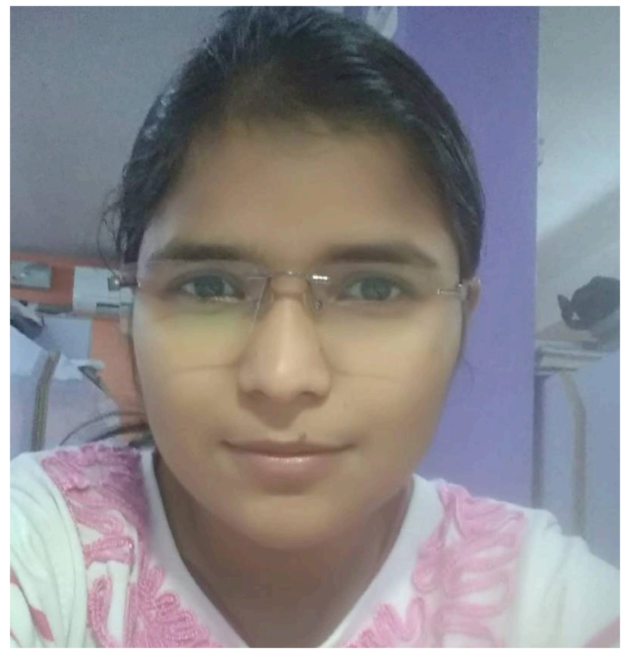
Precision powder feeding

Prabhu Nott

Gautam Vatsa



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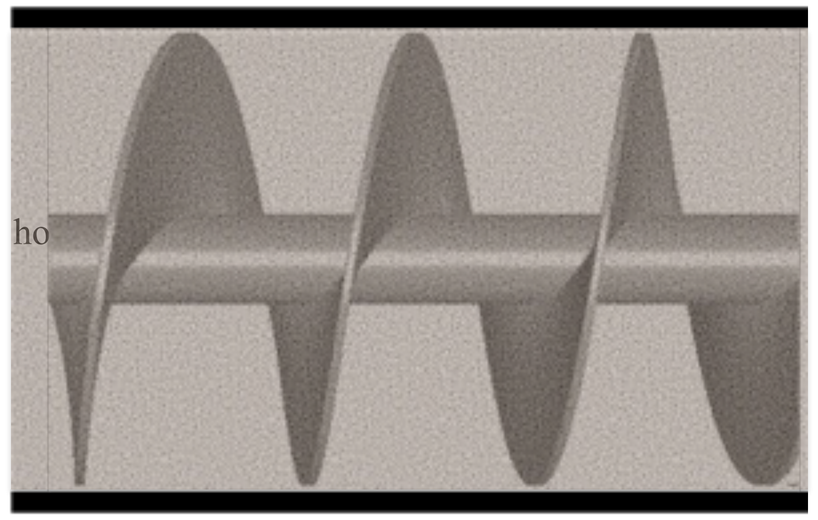


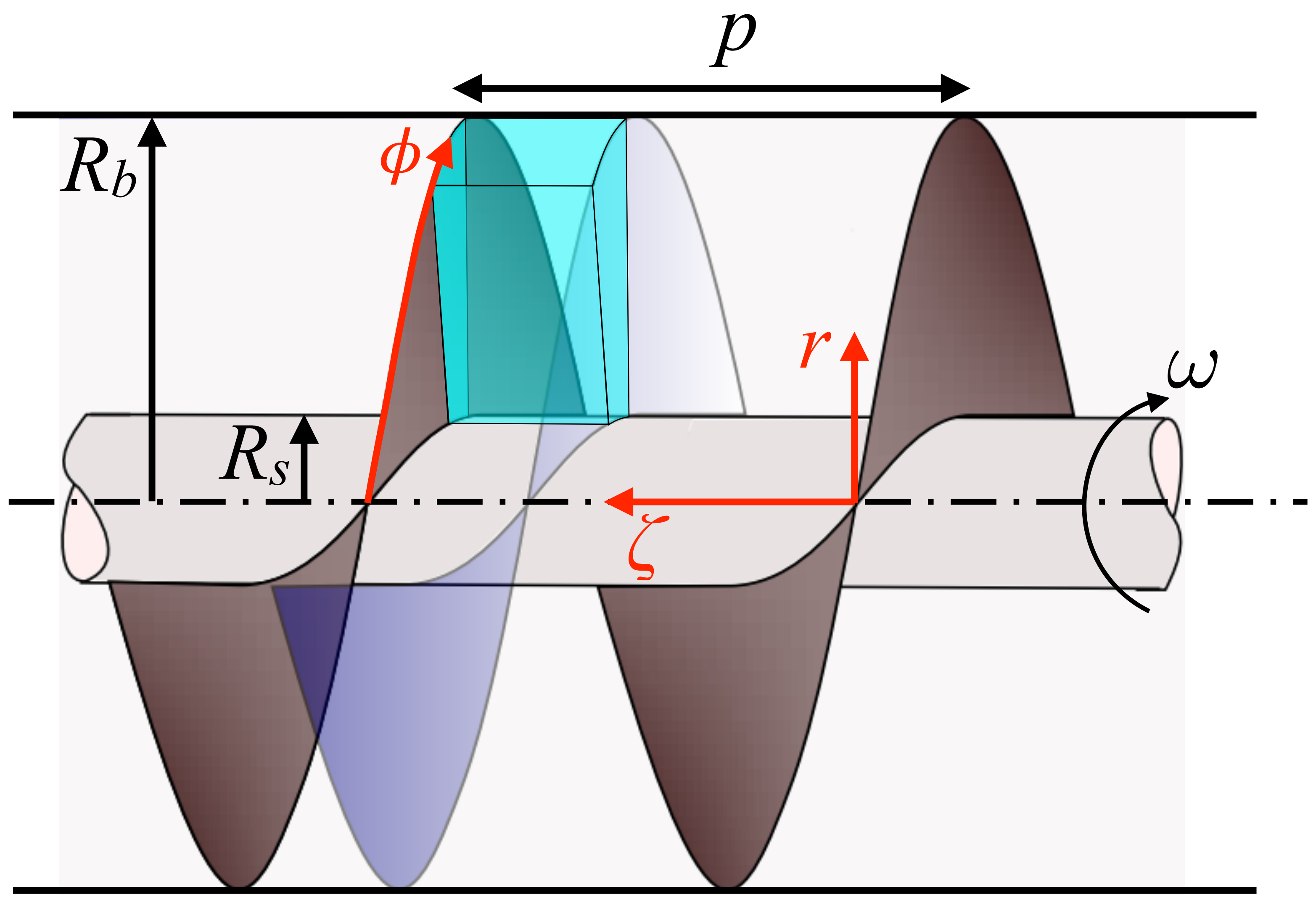
Objectives

- Develop a theoretical model for flow through screw feeders
- Test model predictions against experiments and DEM simulations
- Extend theory and experiments to cohesive powders.

First year of renewed project

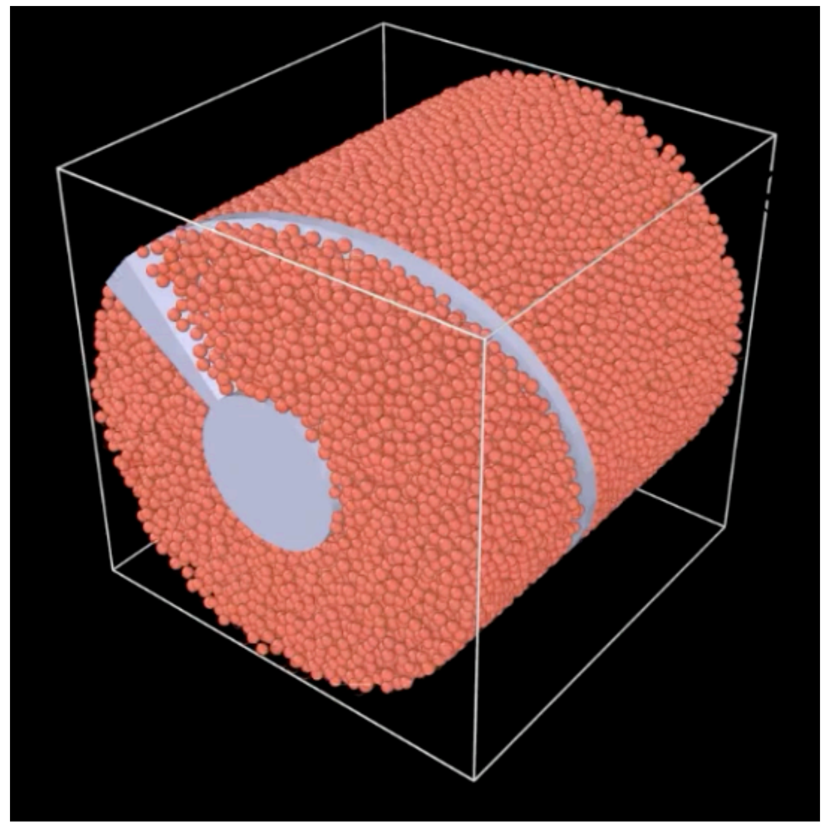
Quick summary of work in previous years

Simple model



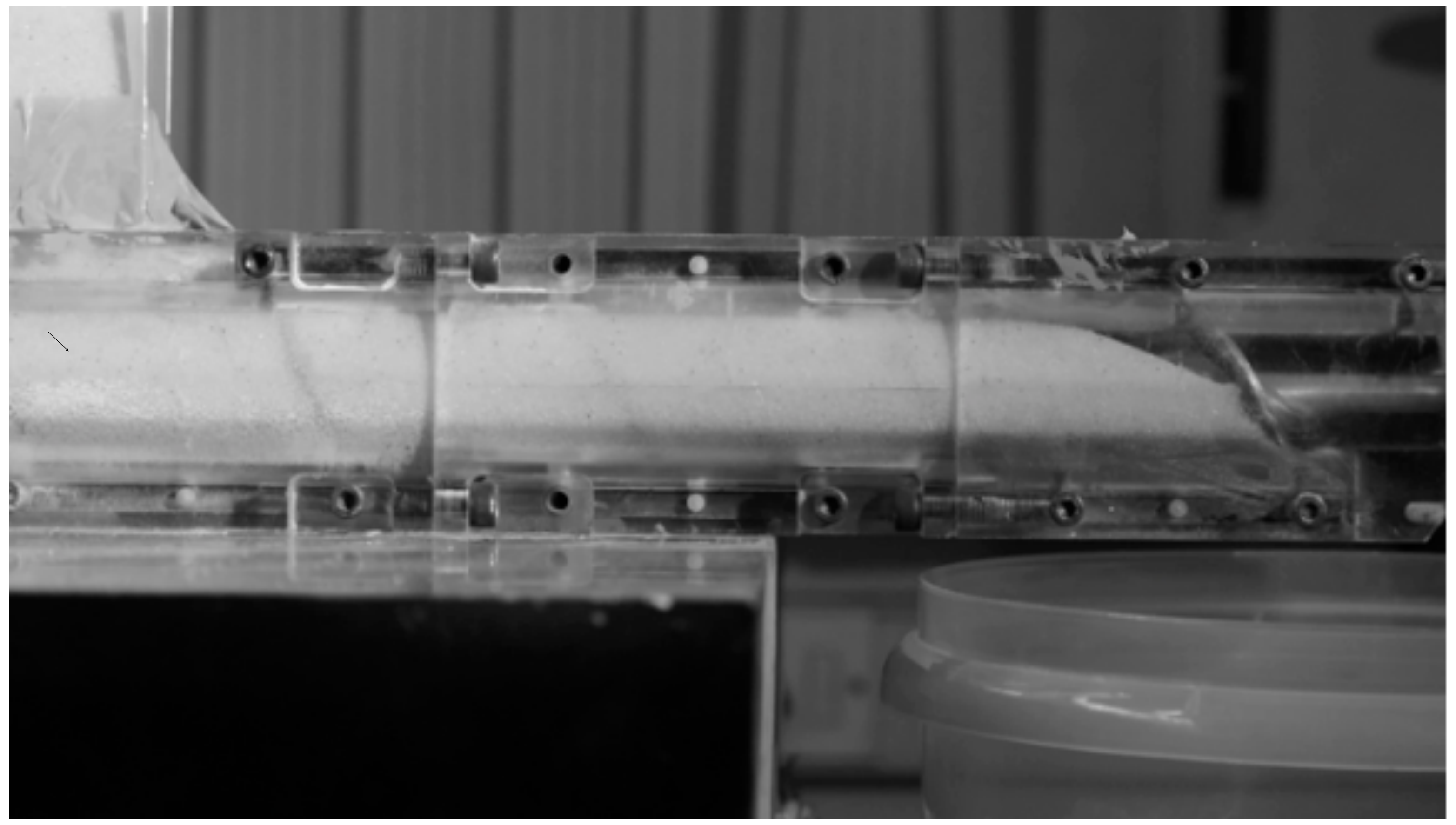
Assuming screw and shaft are *frictionless*, feeder is *fully filled*, and powder flows as a *plug*, the feed rate is

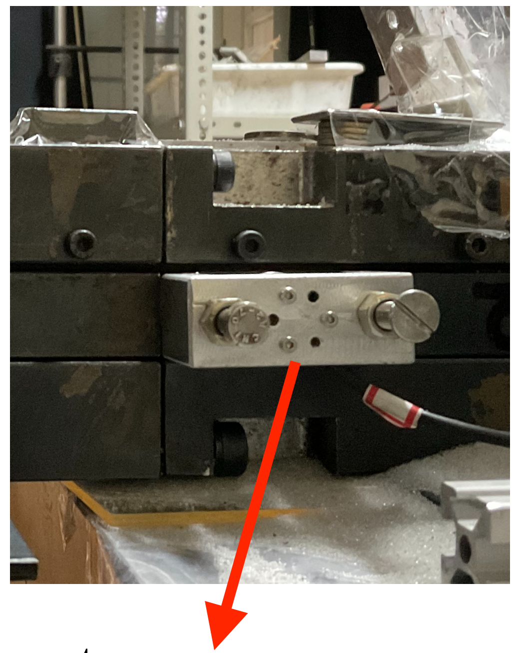
$$v_z = \omega R_b \frac{\pi\, p/(2R_b)}{\pi^2 + p^2/(2R_b)^2}$$

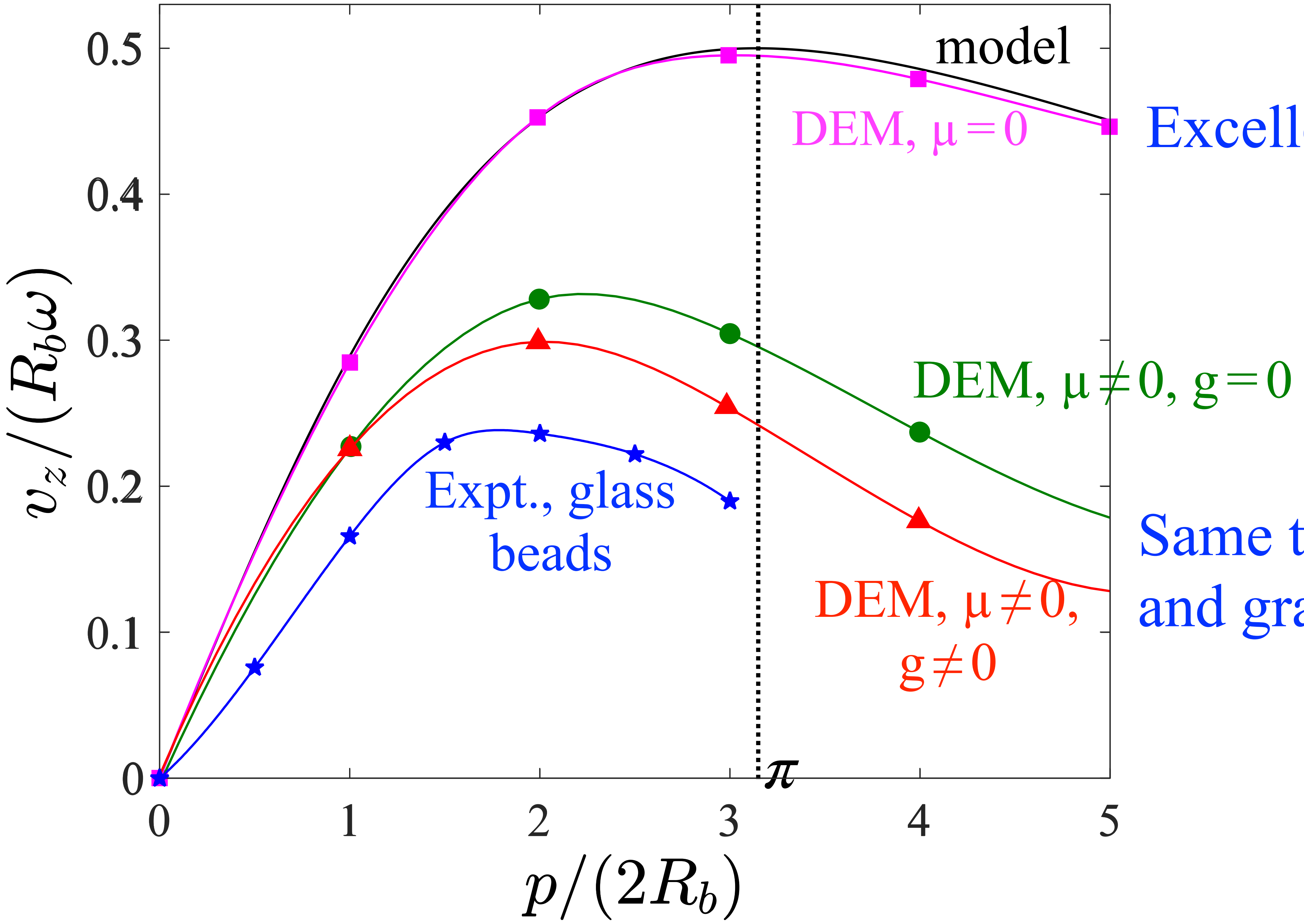


DEM simulations

Experiments



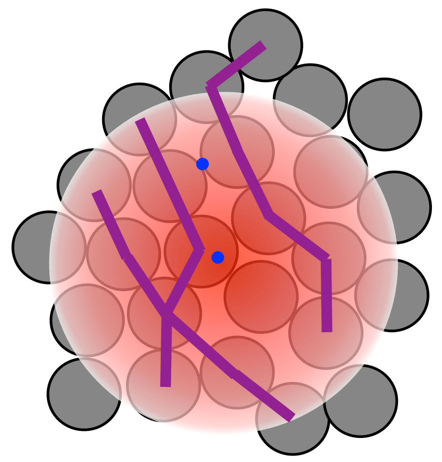




Excellent agreement

Same trend when friction and gravity are present

Non-local model that resolves kinematic indeterminacy and incorporates dilatancy



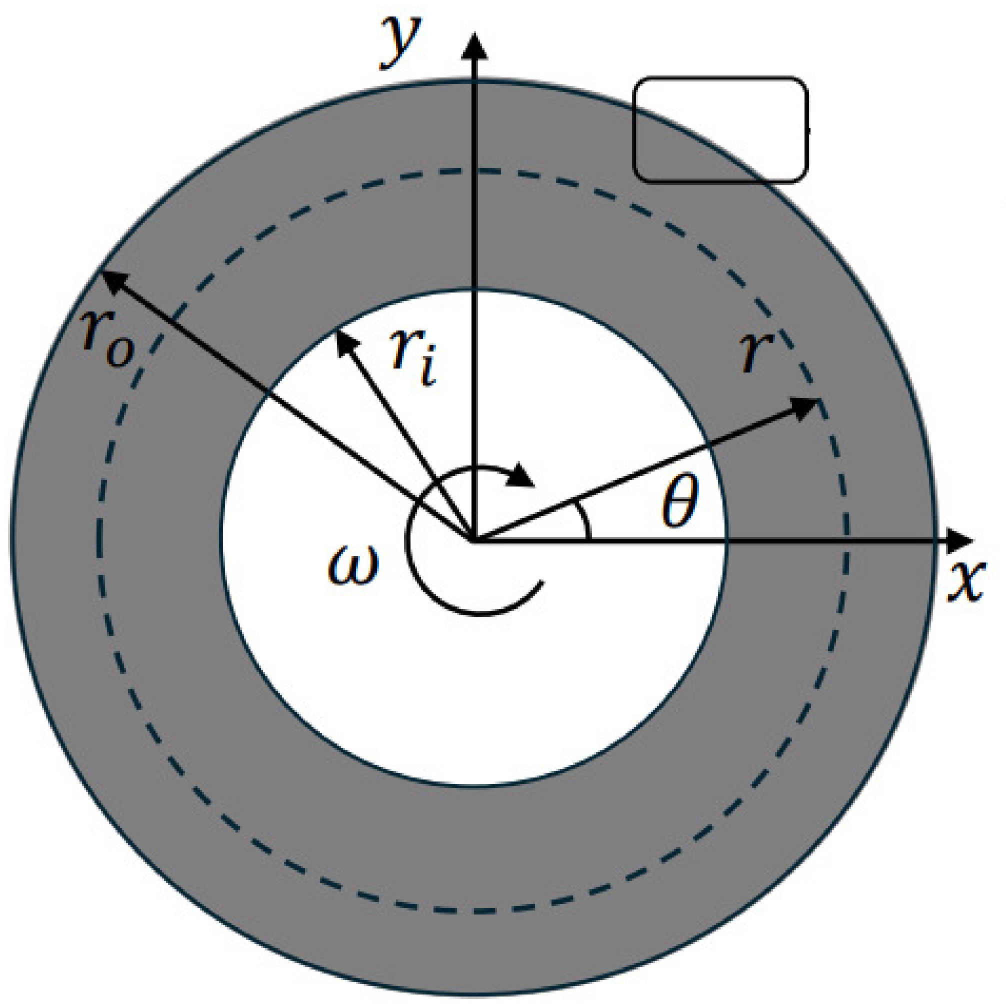
$$\boldsymbol{\sigma} = -p\,\boldsymbol{\delta} + \frac{2\mu}{\dot{\gamma}}\left(p_c\,\boldsymbol{D}' - \underline{\ell^2\,\Pi\,\nabla^2\boldsymbol{D}'}\right), \qquad p = p_c\left(1 - \frac{\mu_b}{\dot{\gamma}}\boldsymbol{\nabla\cdot u}\right) - \underline{\ell^2\,\Pi\,\frac{\mu_b}{\dot{\gamma}}\nabla^2\boldsymbol{\nabla\cdot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

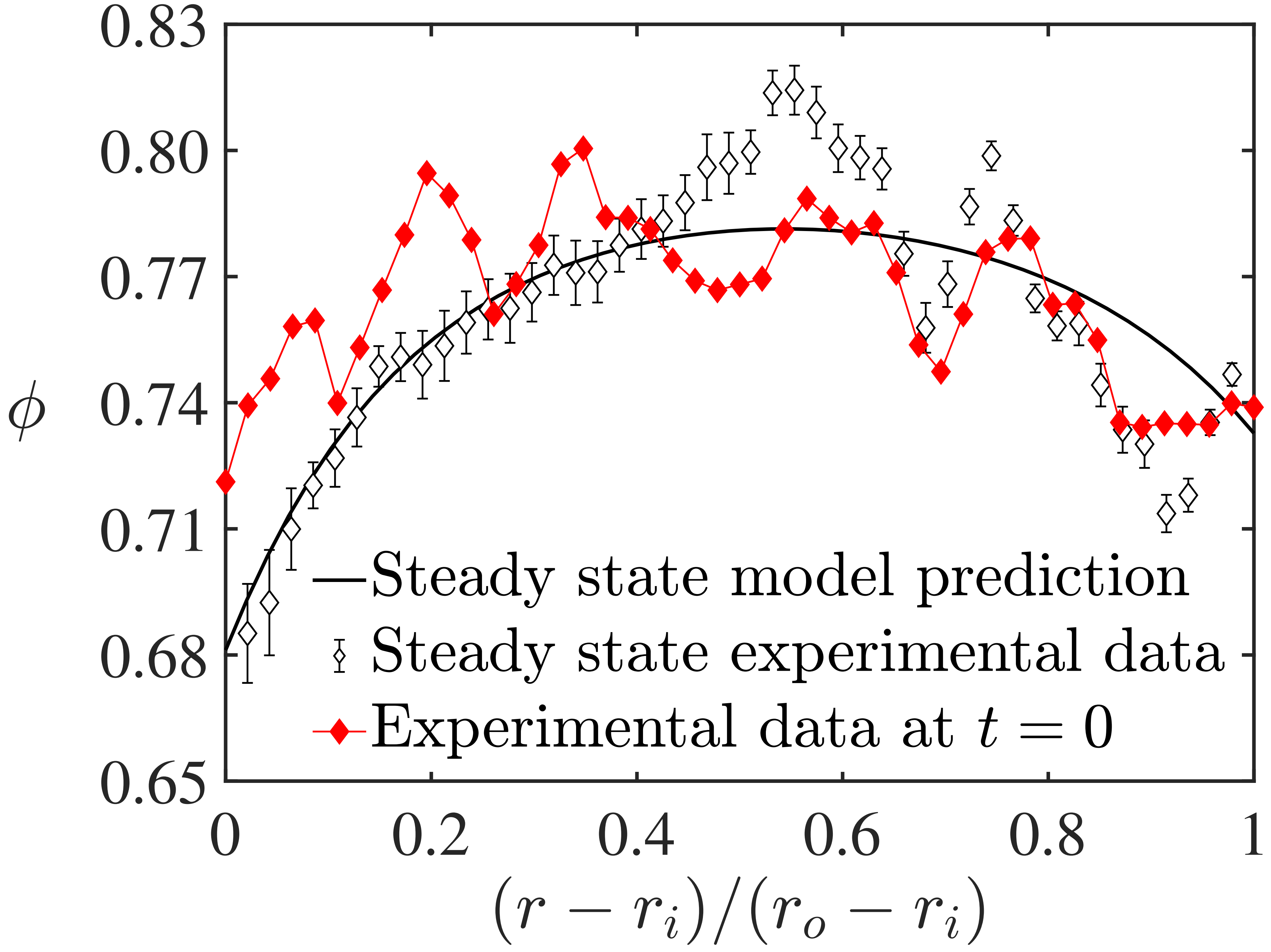
$$p_c = \Pi - \underline{\ell^2\,\frac{\mathrm{d}\Pi}{\mathrm{d}\phi}\,\nabla^2\phi},$$

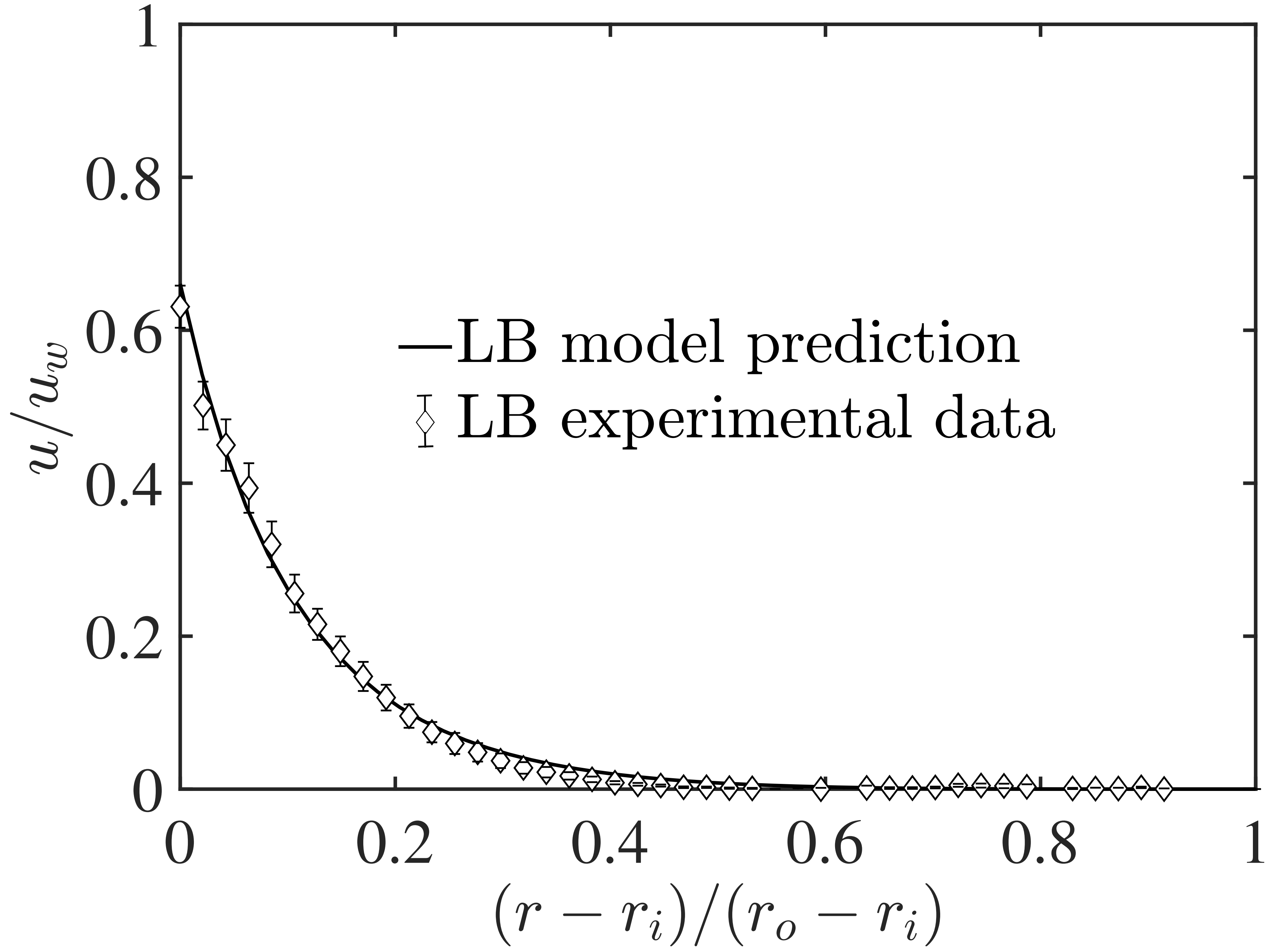
Model unconditionally well-posed

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

Validation in a cylindrical Couette shear cell: IISc-NCSU collaboration

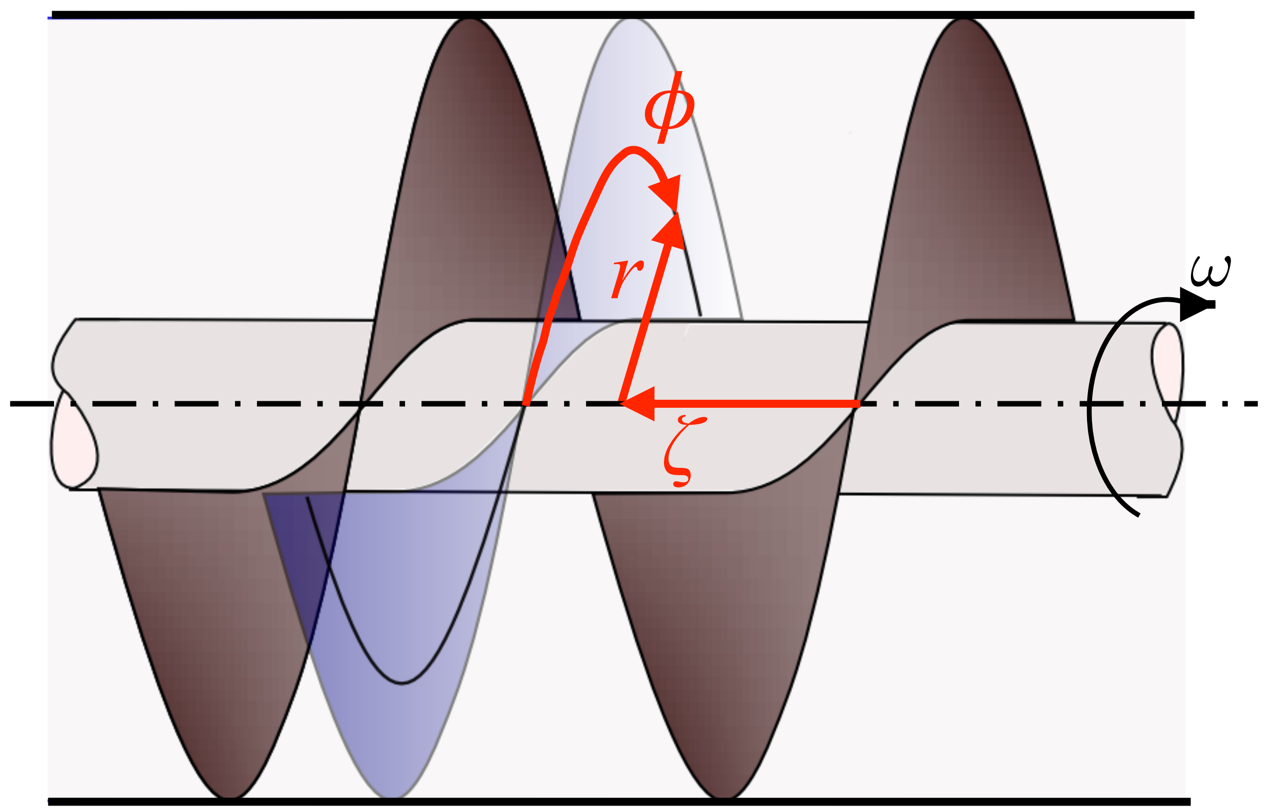




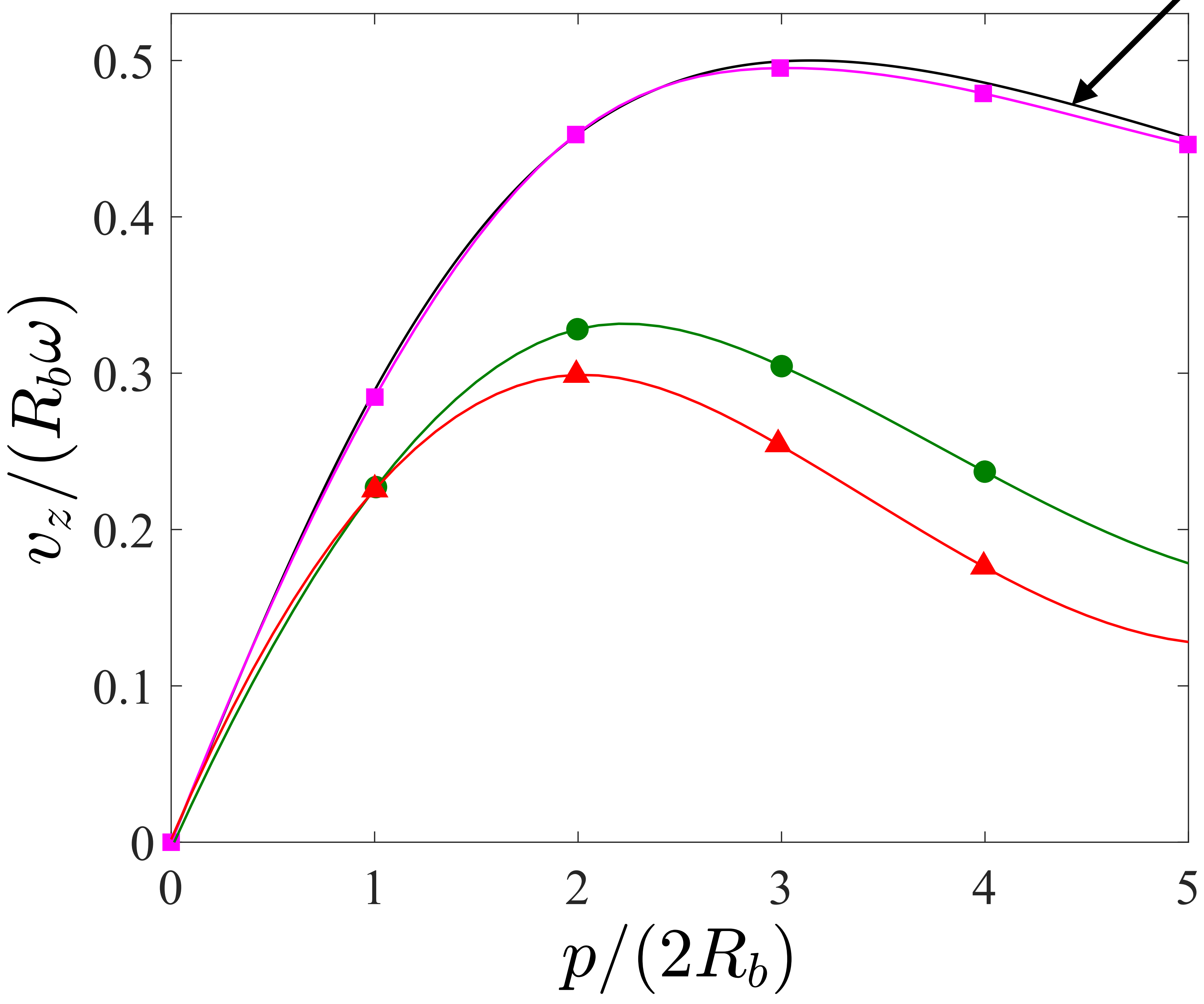


Vatsa *et al* (submitted, 2024)

Non-local model applied to the screw feeder



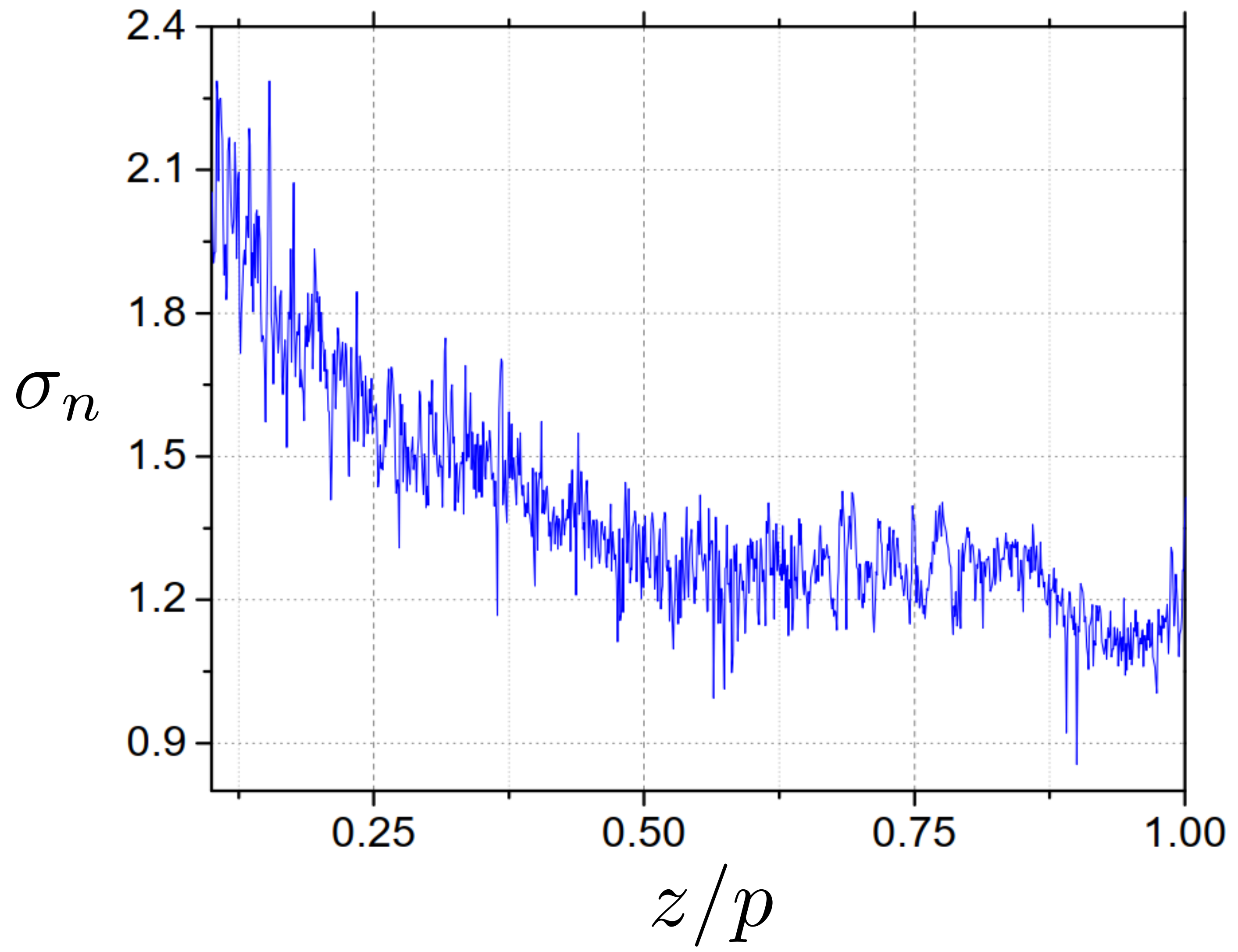
For fully filled feeder in the absence of gravity and a frictionless screw, we recover the plug flow solution of the simple model:



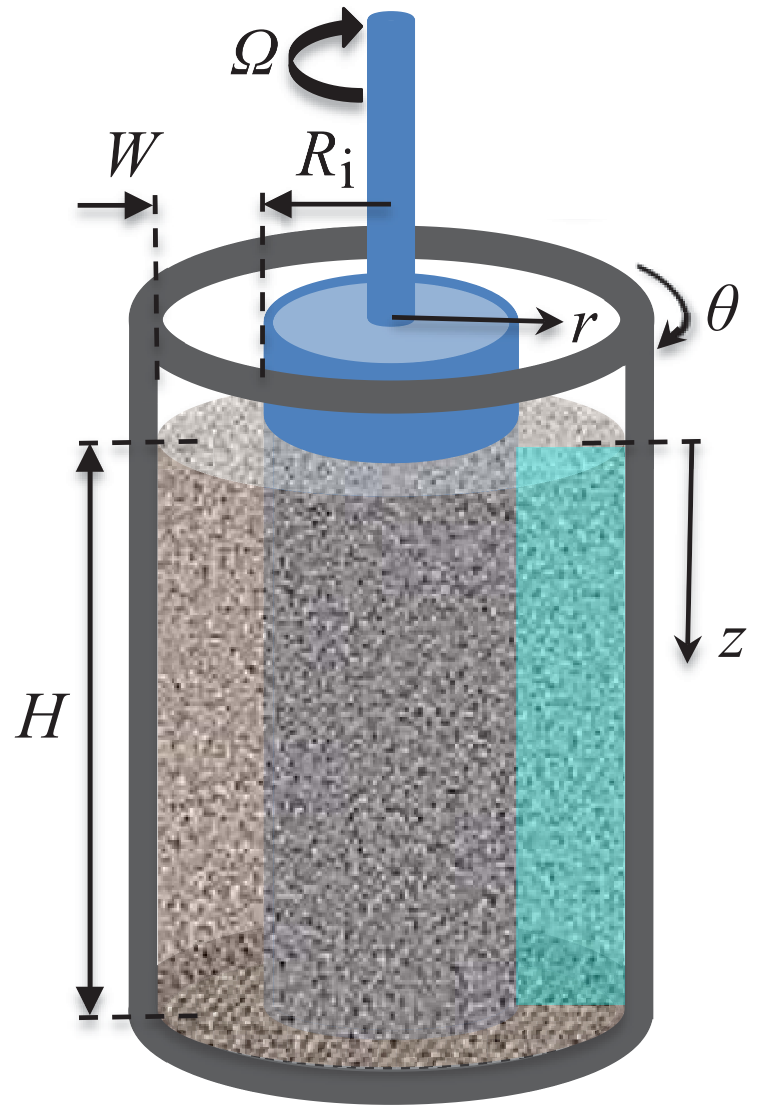
The model also yields the stress on the barrel,

$$\sigma_{rr} = \sigma_{rr0}e^{-K\zeta}$$

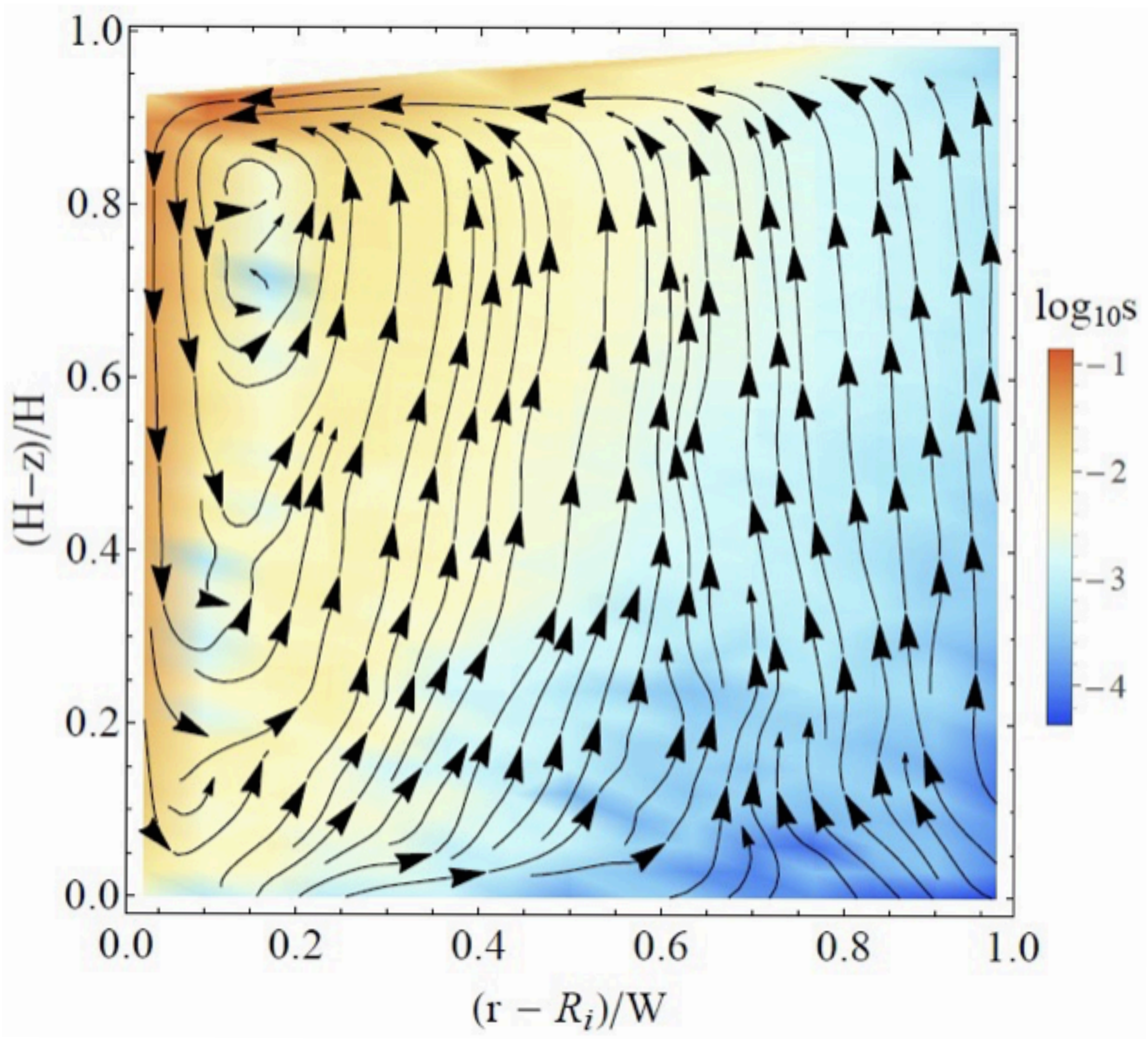
which agrees with the experimental data.



Stringent test of non-local model: secondary flow driven by dilatancy



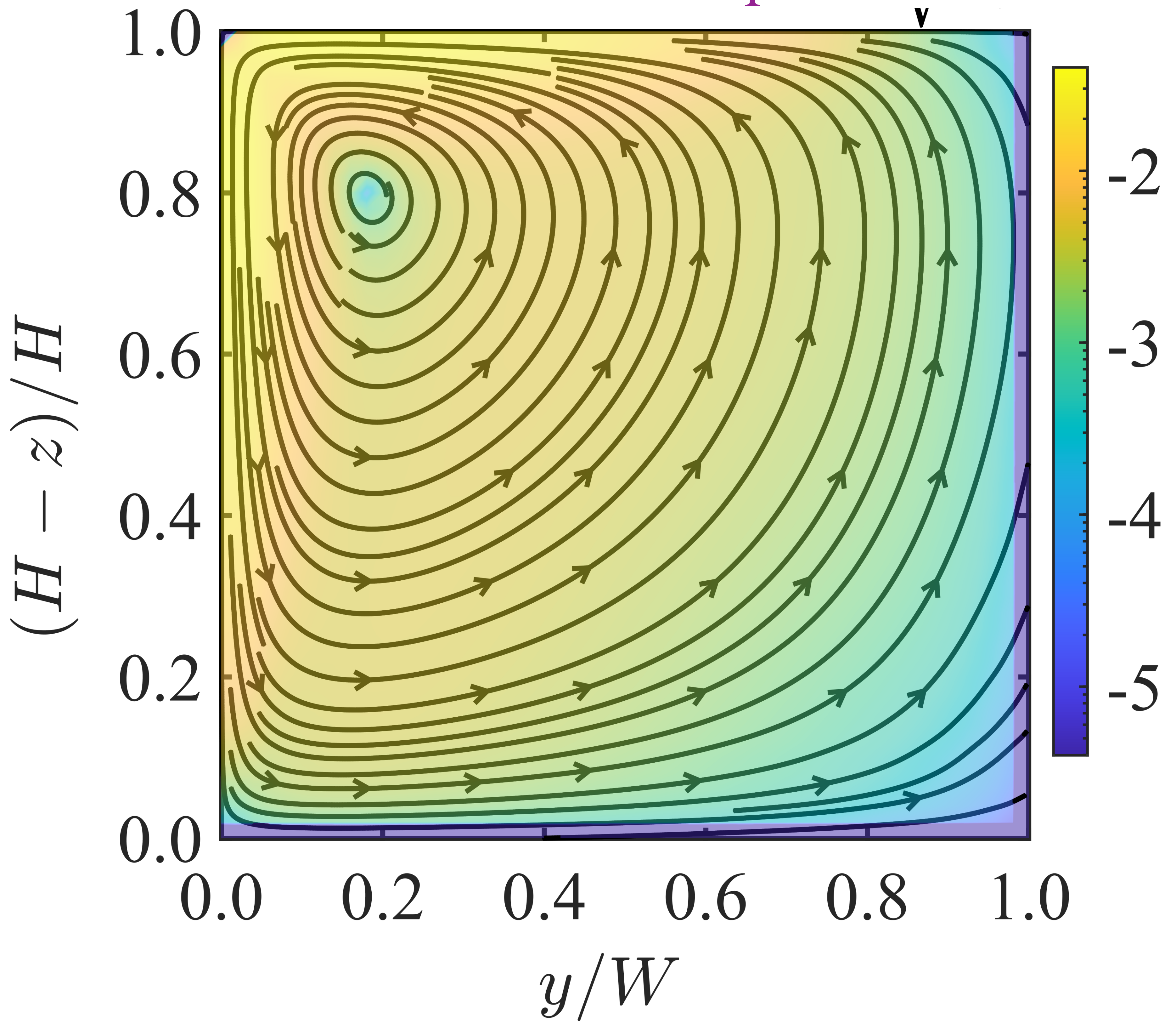
Streamlines: DEM simulations



$s \equiv (v_r^2 + v_z^2)^{1/2}$

Krishnaraj & Nott (*Nature Commun.*, 2016)

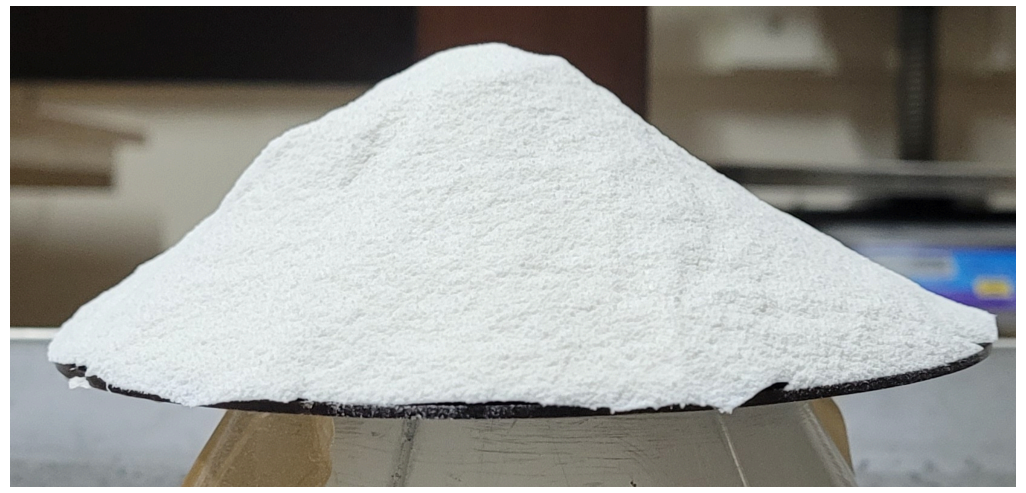
Streamlines: model prediction

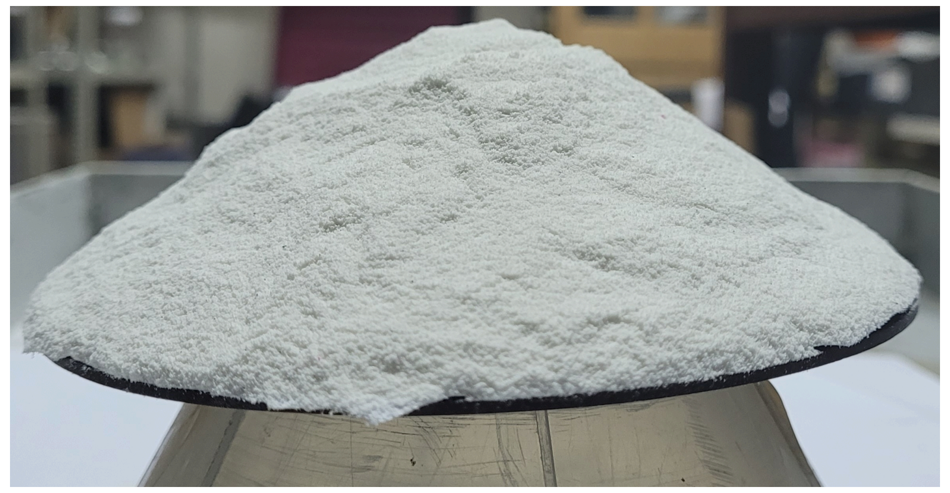


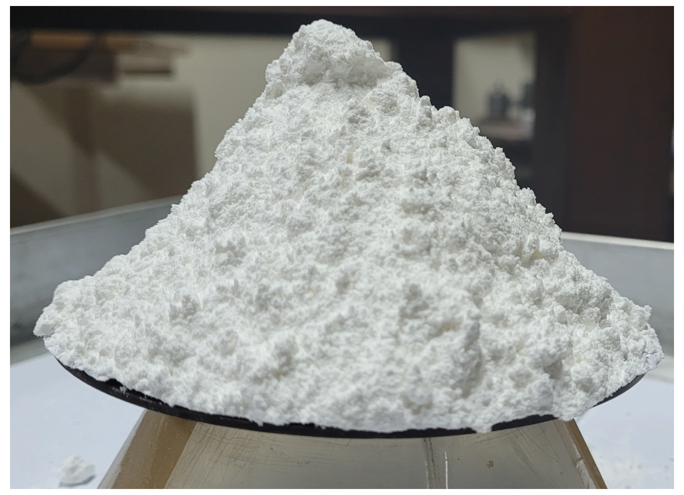
Vatsa & Nott (under preparation, 2024)

The model predicts the complex dilation-driven secondary flow, which requires the coupling between packing fraction and velocity fields to be captured.

Earlier experiments on cohesive powders used pharmaceutical powders


Spray dried lactose


Microcrystalline cellulose

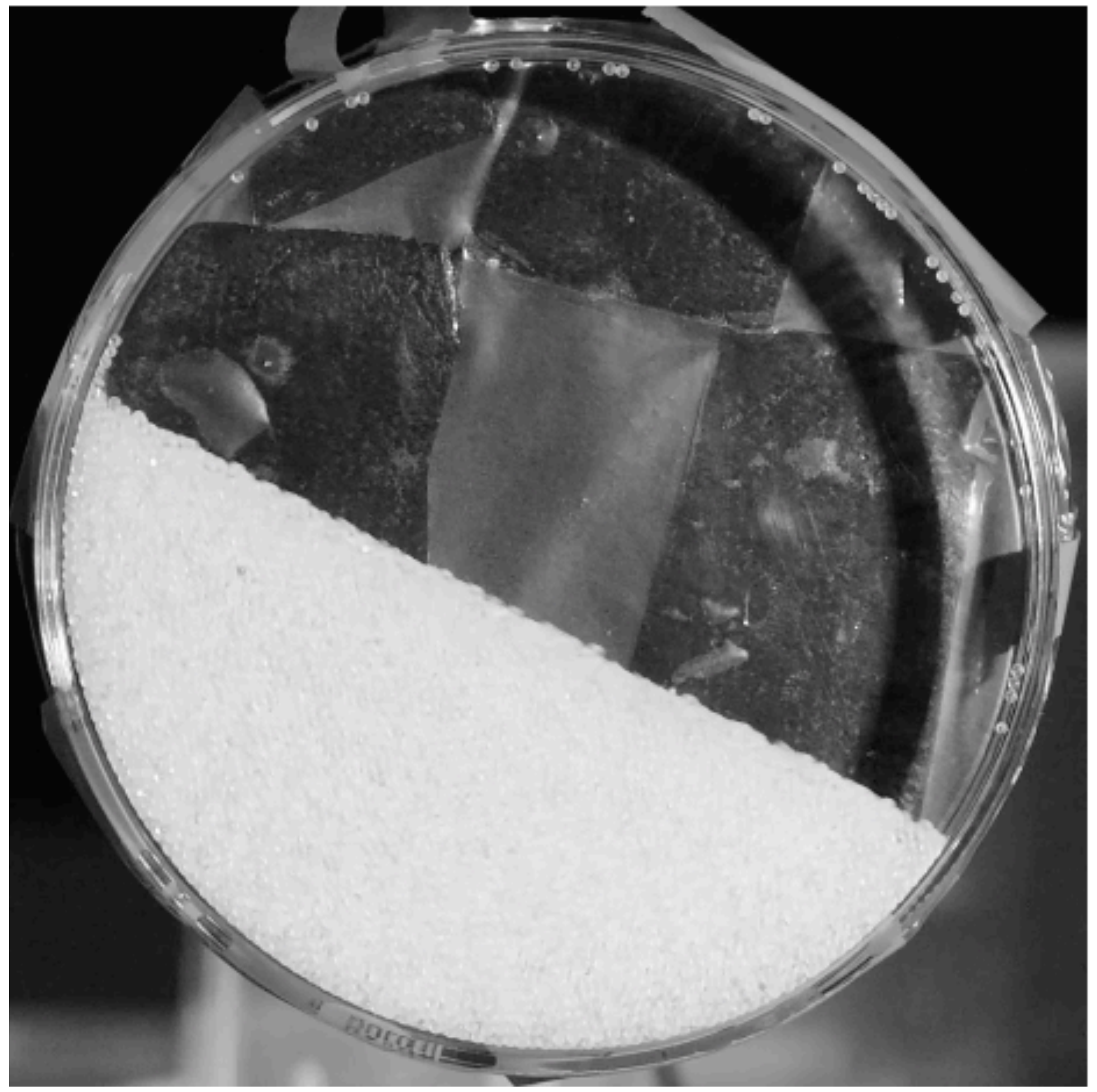

Anhydrous fine lactose

uncontrolled cohesion

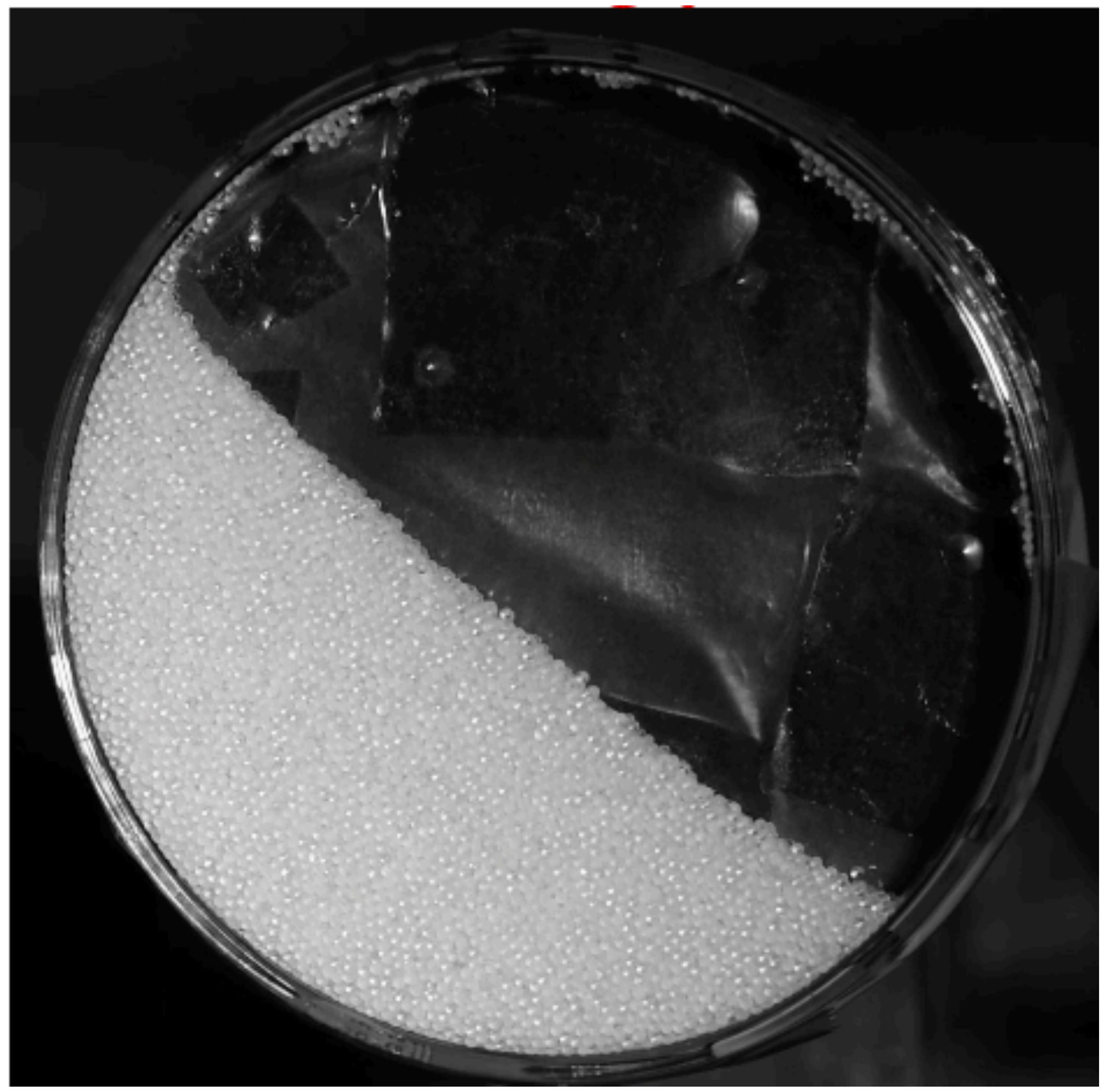
Experiments on cohesive powders with controlled cohesion

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

0% glycerol

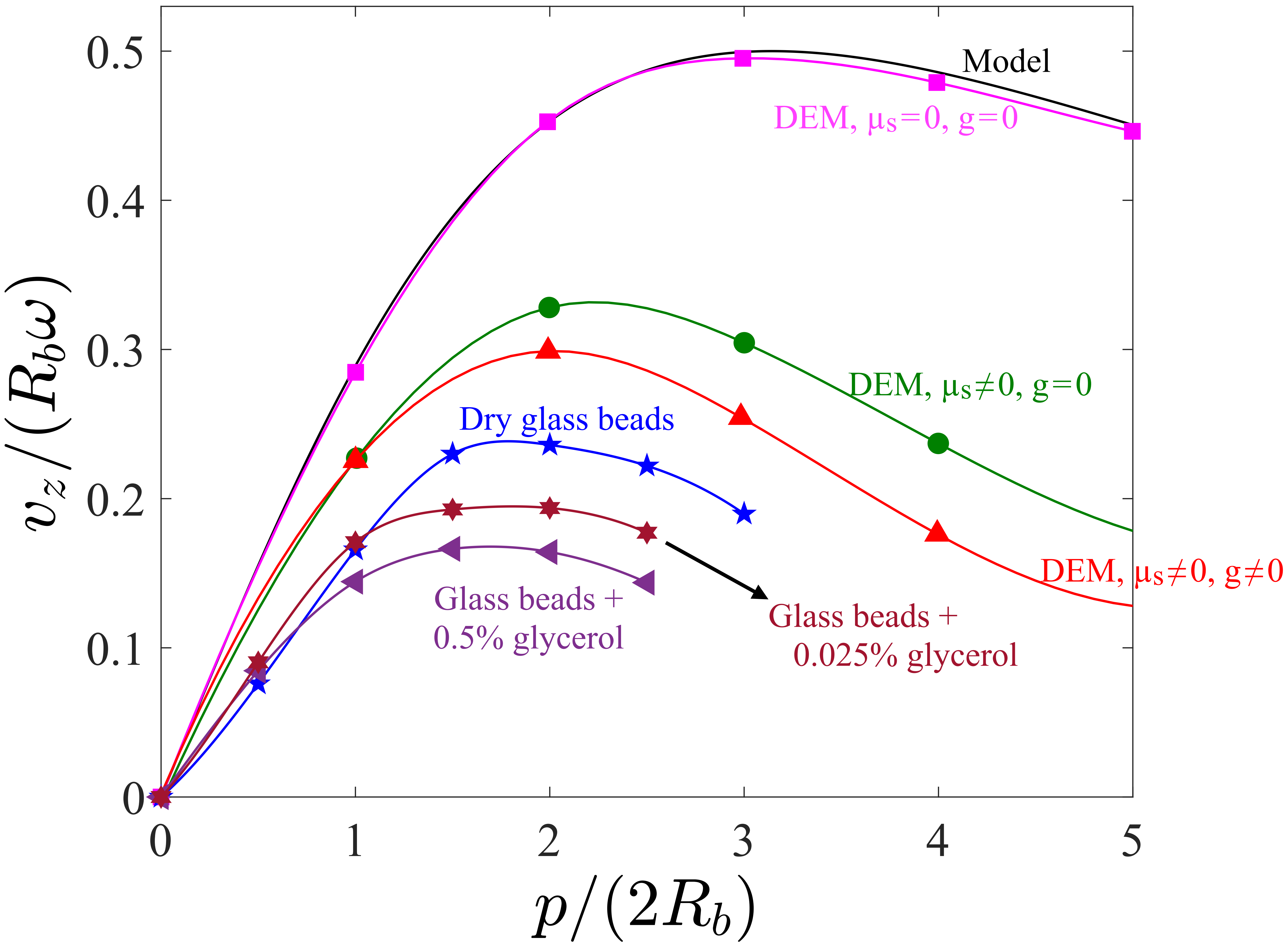


0.025% glycerol



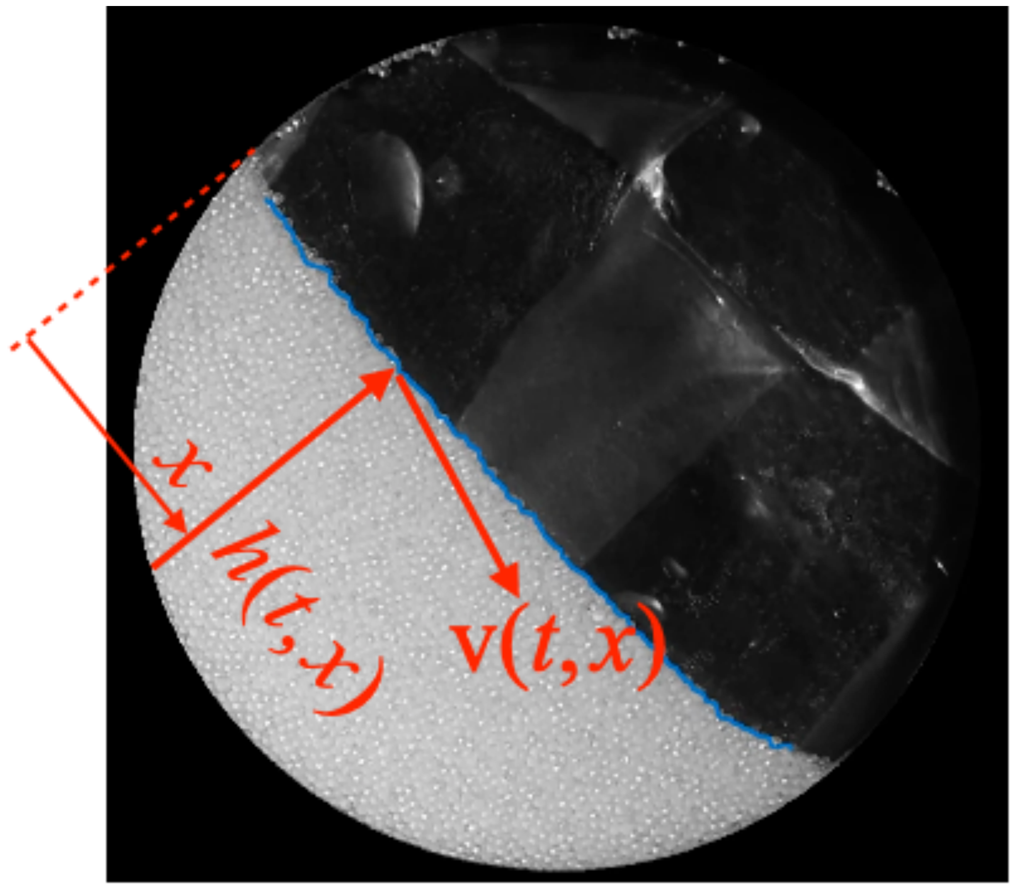
0.2% glycerol

Flow rate versus $p/(2R_b)$



For all powders, there is an optimum value of $p/(2R_b)$ at which flow rate is maximum

Cohesion causes uneven/erratic flow: quantifying the fluctuations



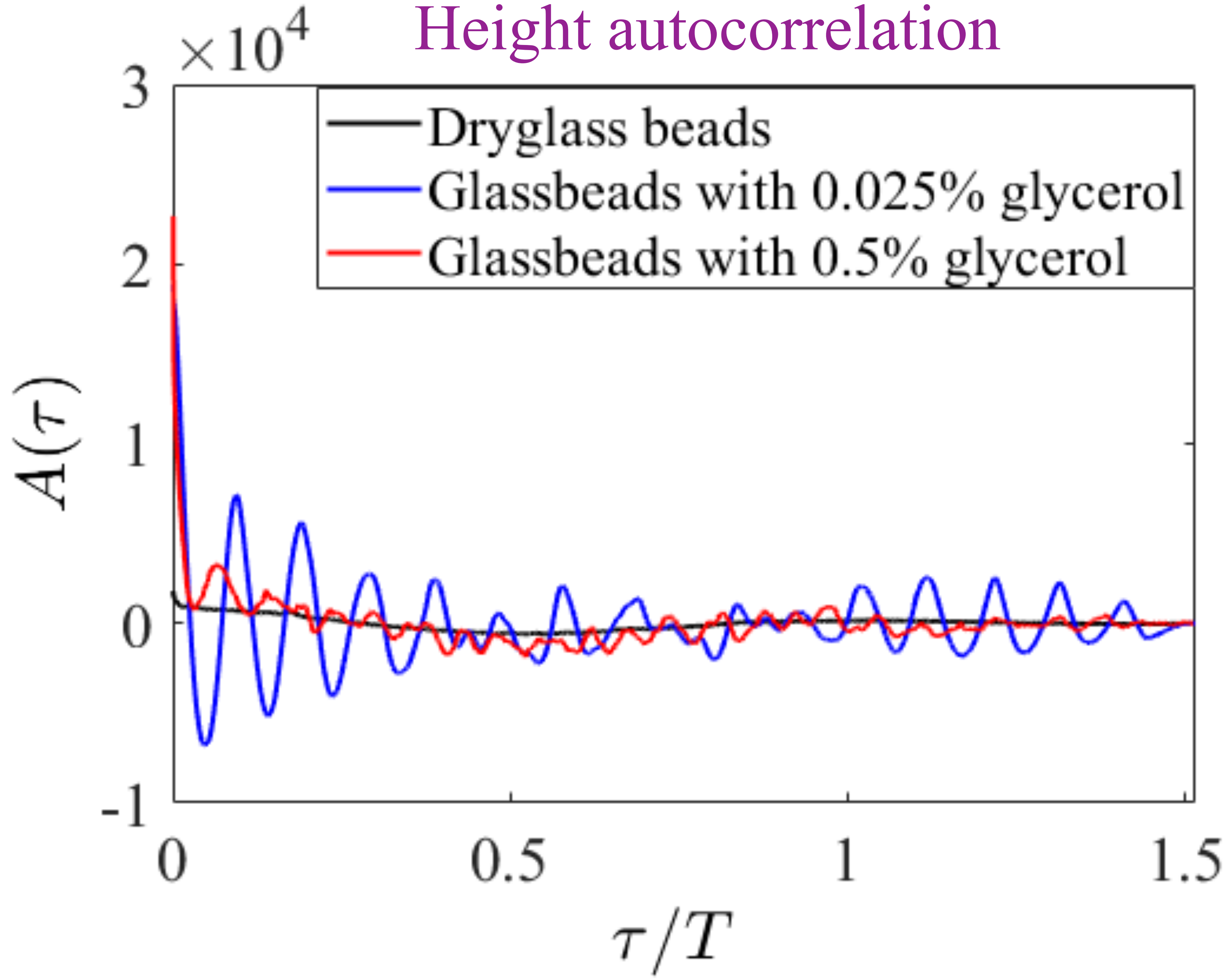
Determine temporal and spatial correlations of velocity and height <u>fluctuations</u>

$$A(\tau) = \langle \mathrm{v}(t,x)\,\mathrm{v}(t+\tau,x) \rangle$$

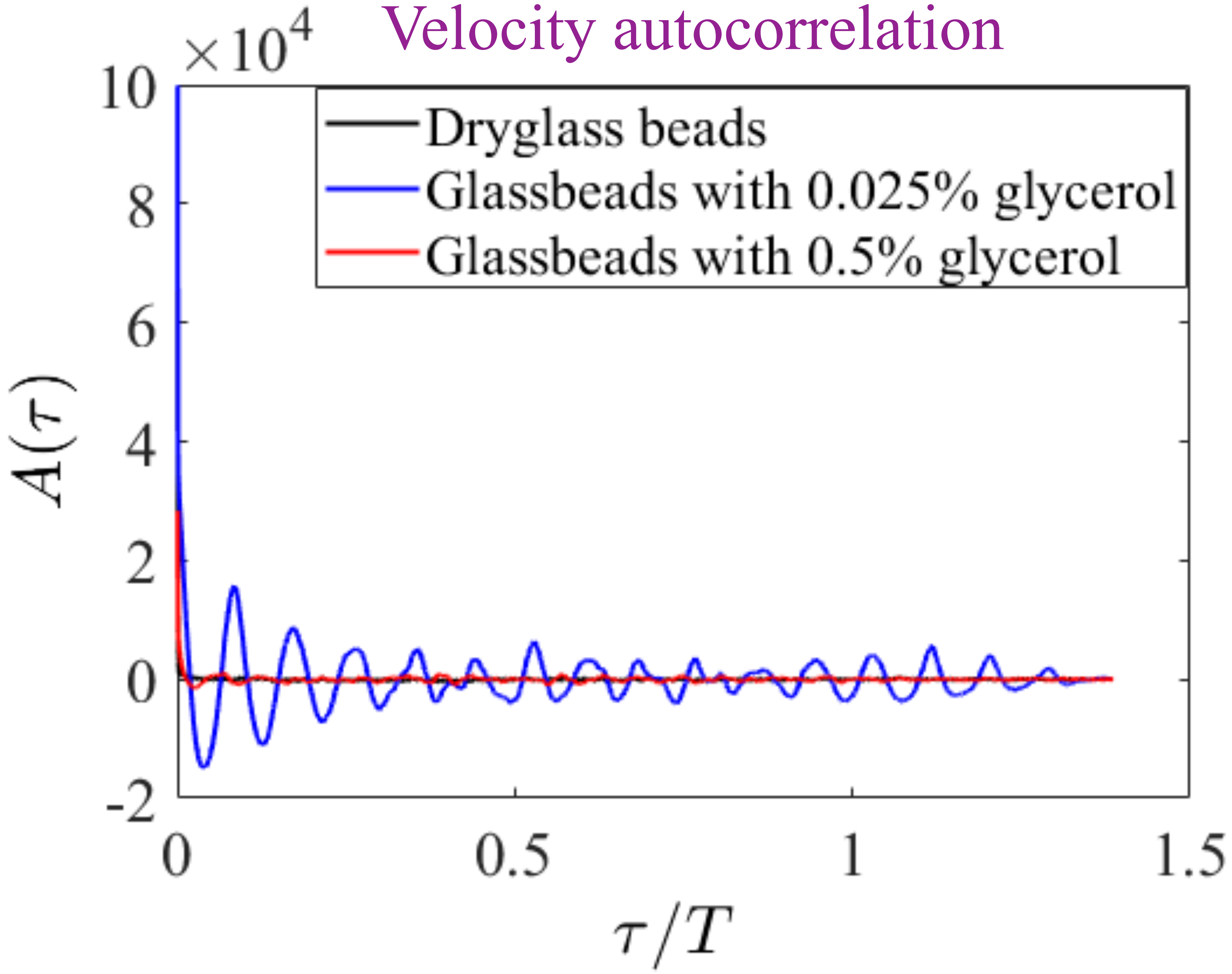
Autocorrelation

Similarly for height $h(t,x)$

Height autocorrelation



Velocity autocorrelation



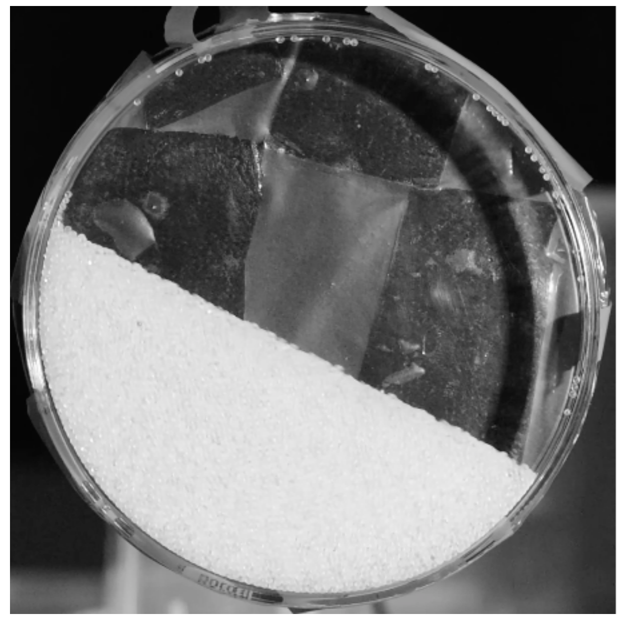
Space-time correlation of velocity

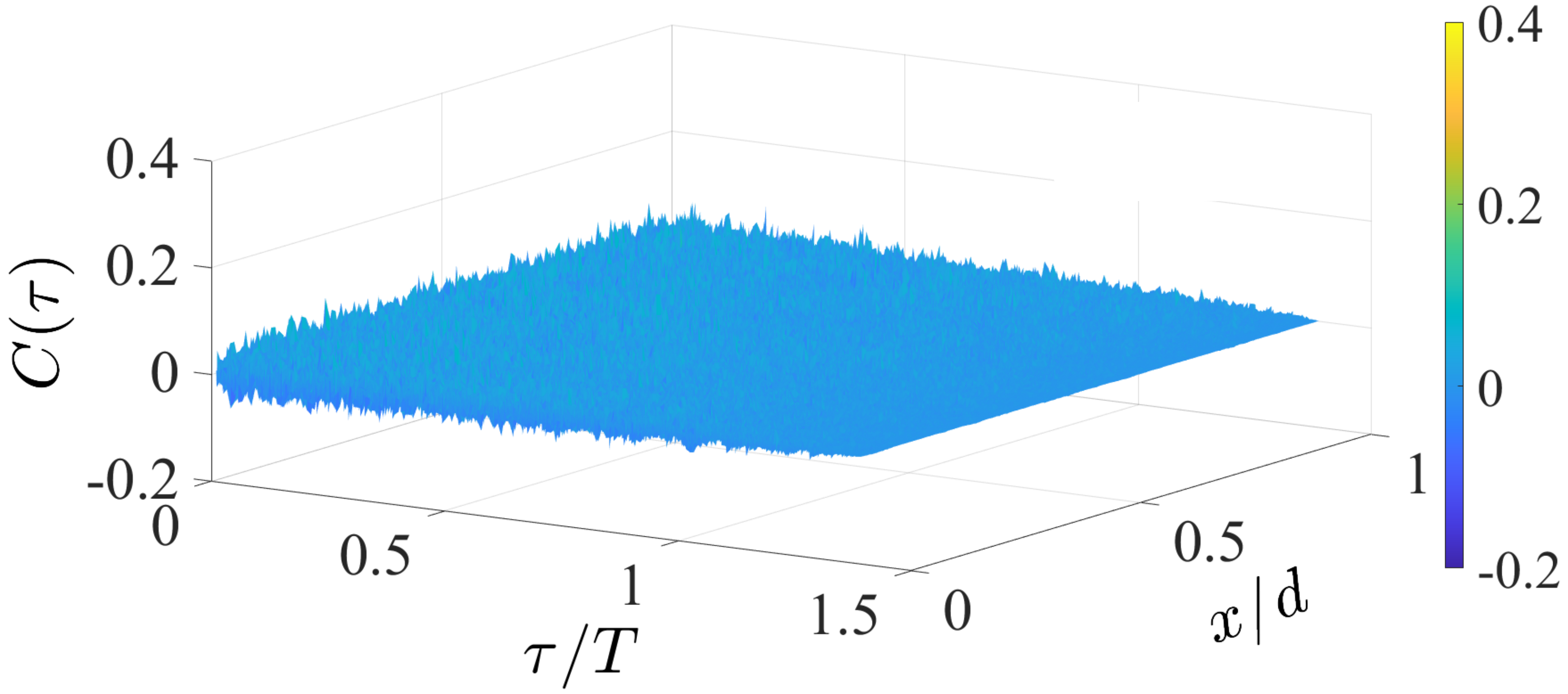
$$C(\tau,\delta) = \langle \mathrm{v}(t,x)\,\mathrm{v}(t+\tau,x+\delta)\rangle$$

$\delta = 0.2\ L$

When grains agglomerate, the ratio of the weight of the agglomerate to the cohesion force (Bond number) increases, which promotes free flow.

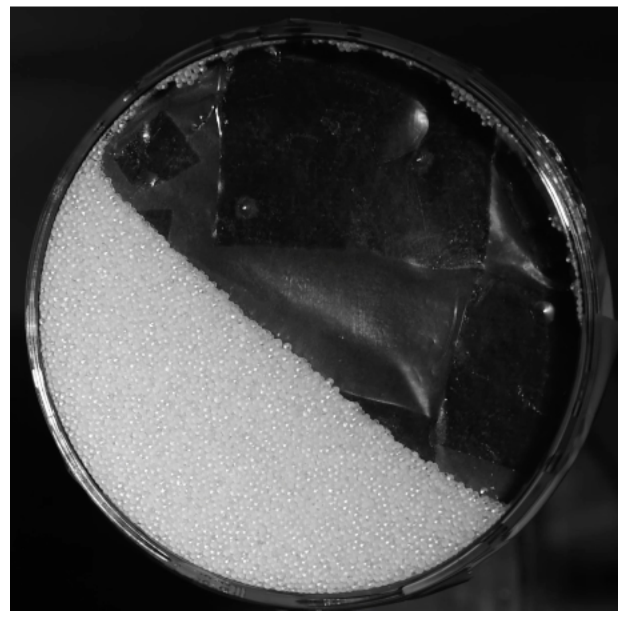
dry glass beads

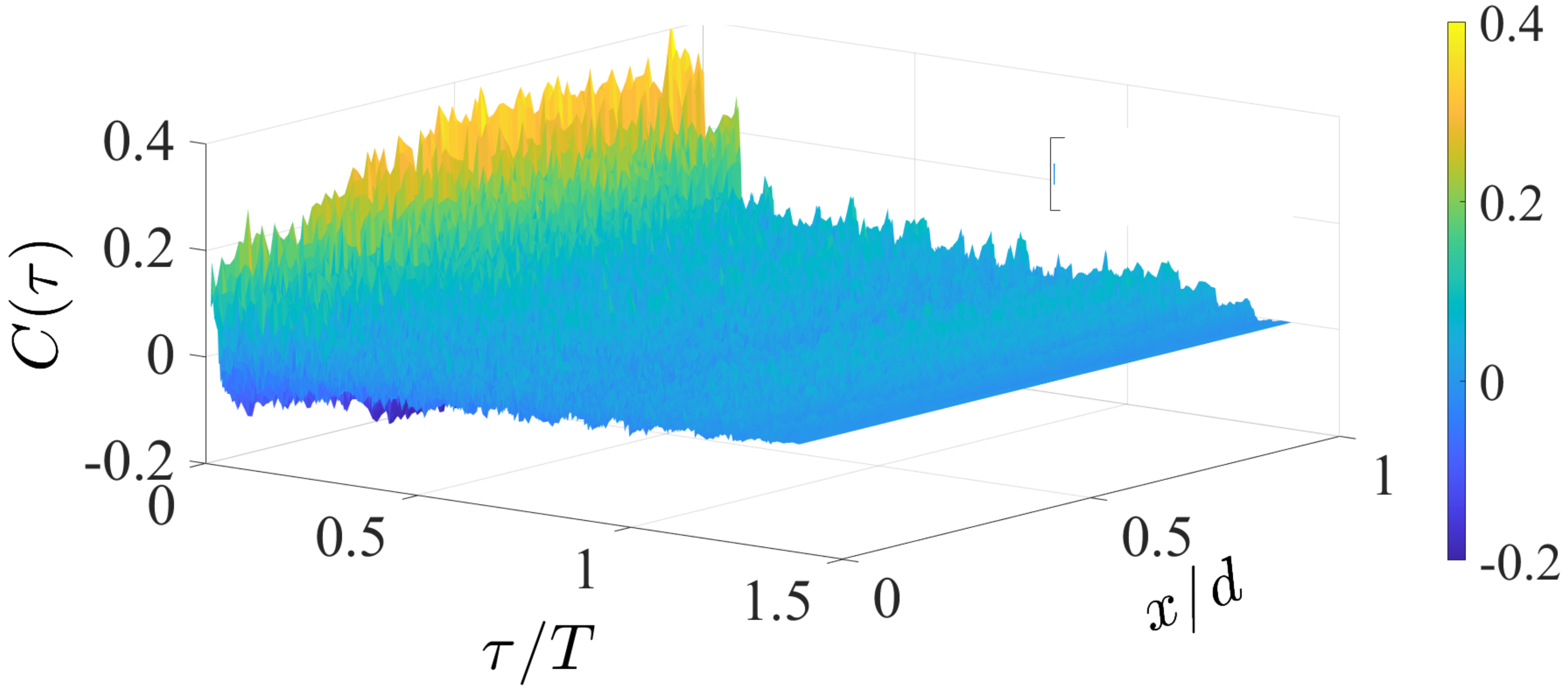


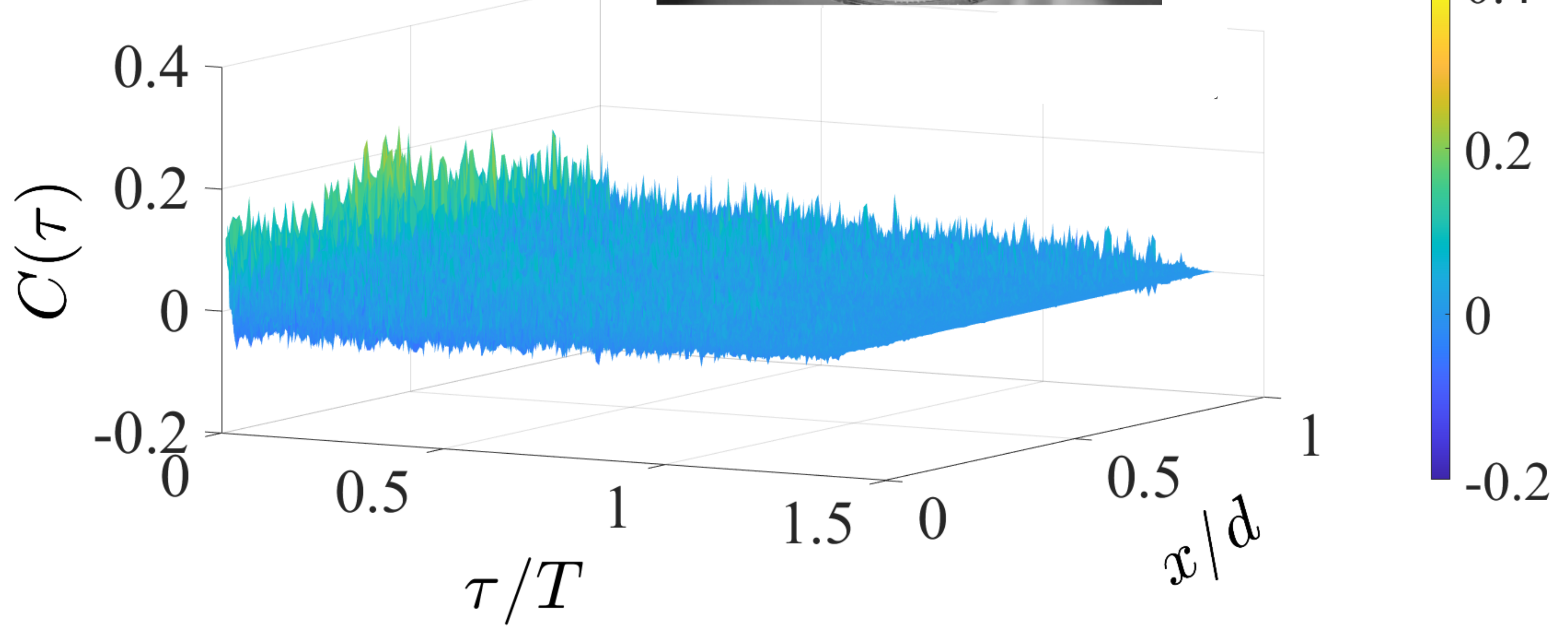


0.5% glycerol

0.025% glycerol







Above 0.2% glycerol, flows is more even – cohesion-induced agglomeration promotes free flow

How do we incorporate the fluctuations and correlations in a rheological model?

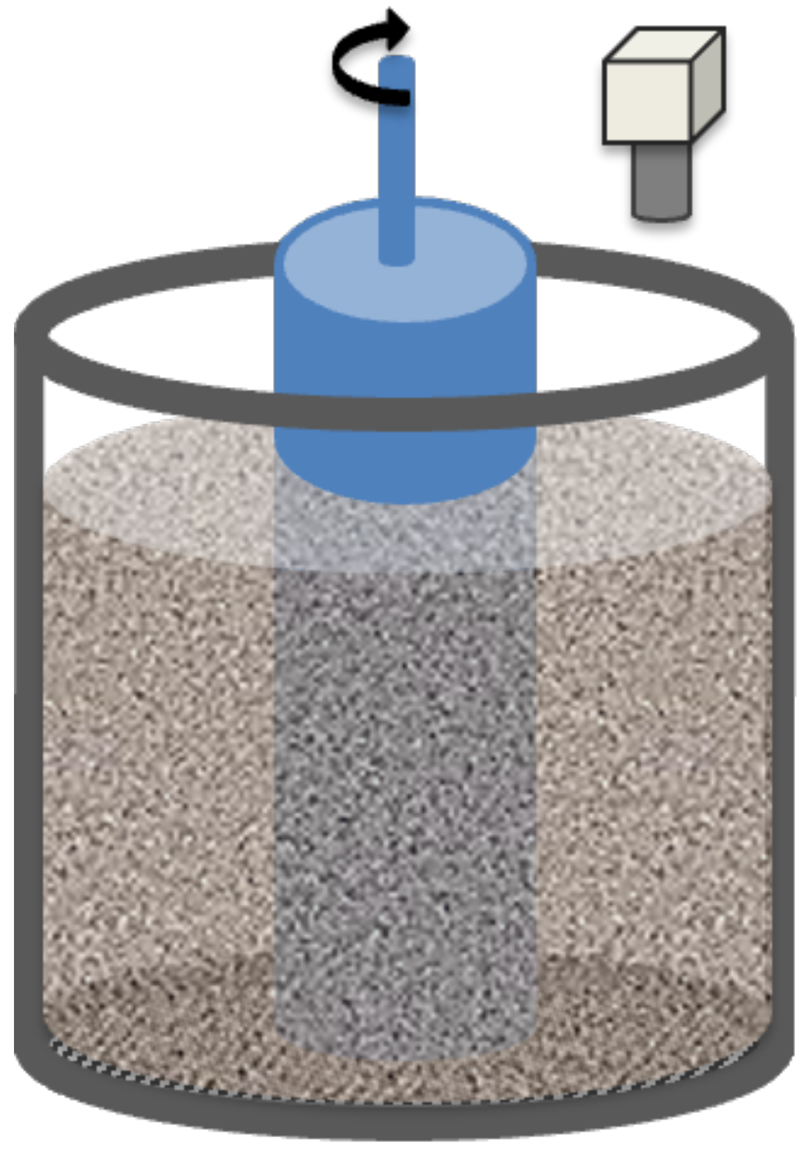
In classical plasticity, **flow rule** relates the strain rate to the stress:

$$D_{ij} = \dot{\lambda} \frac{\partial F}{\partial \sigma_{ij}} + \ell^2 \nabla^2 (\dot{\lambda} \frac{\partial F}{\partial \sigma_{ij}})$$

fluidity

Traditionally, cohesion only adds a term to the yield function: $F(\boldsymbol{\sigma}) = F_{\text{non-coh}}(\boldsymbol{\sigma}) - \tau_{\text{coh}}$

Our observations indicate that the fluidity too must depend on cohesion, through the degree of agglomeration.



We will soon begin an experimental study to quantify the effect of cohesion on agglomeration, flow, and the stress.

- Measure simultaneously the stress and kinematics in a cylindrical Couette cell.
- Velocity and microstructure (agglomeration) will be determined by imaging the free surface.

Conclusion

- Non-local model predicts a complex, dilatancy-driven secondary flow. Demonstrates the necessity for capturing the coupling between the velocity and packing fraction fields
- Model cohesive powders with controlled cohesion obtained by mixing dry glass beads with small amounts of glycerol.
- Intermittent flow and large fluctuations for a range of glycerol fraction. Beyond a critical glycerol fraction, cohesion-induced agglomeration promotes freer flow.
- A set up for simultaneously measuring the stress, kinematics and agglomeration is being constructed. Will help develop constitutive model for cohesive powders.