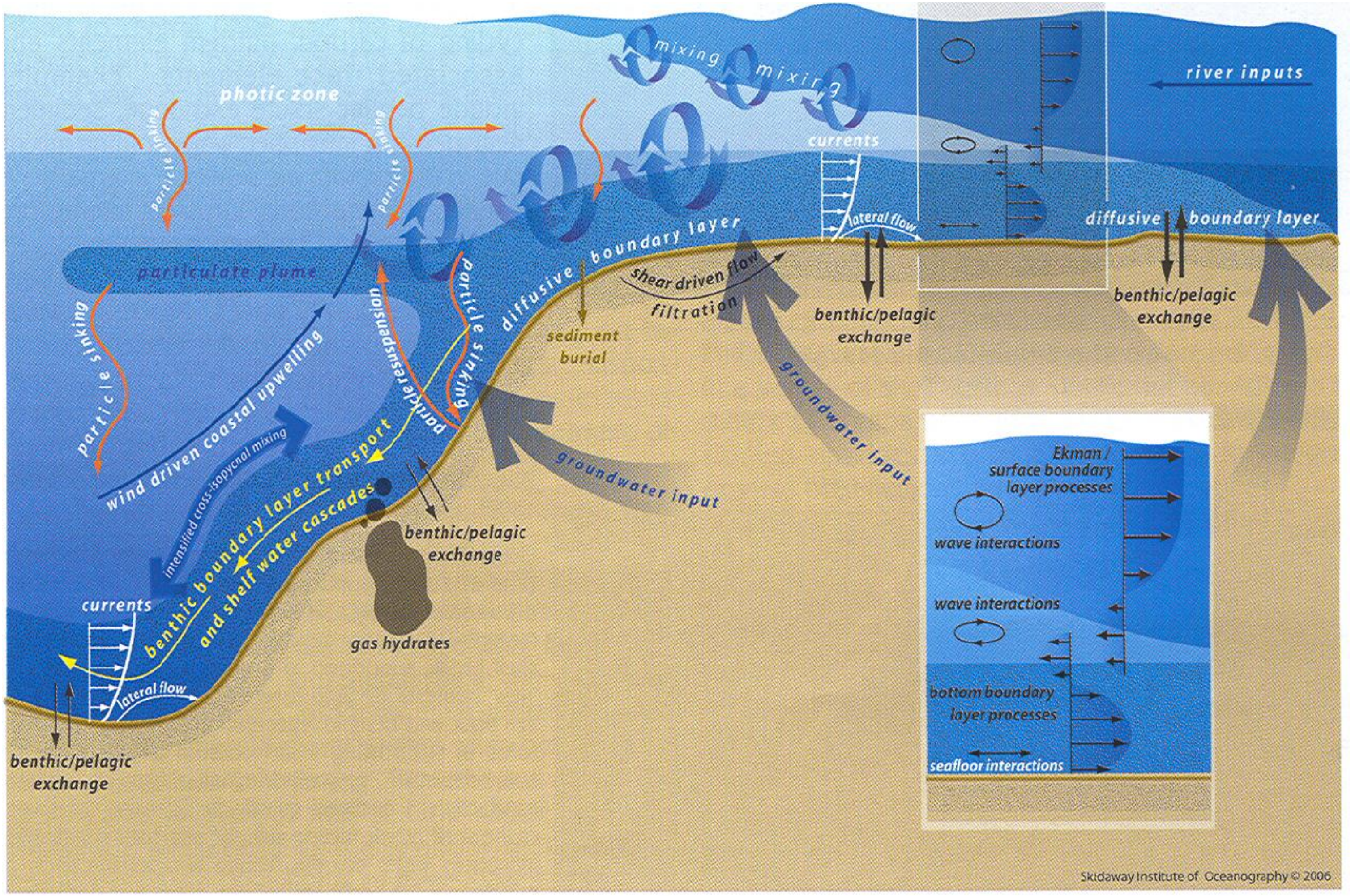
Oceanic sediment transport processes

Eckart Meiburg
UC Santa Barbara

- *Motivation*
- *Sedimentation from buoyant river plumes*
- *Turbidity currents*
- *Erosion from mobile sediment beds*

Near-coastal sediment transport

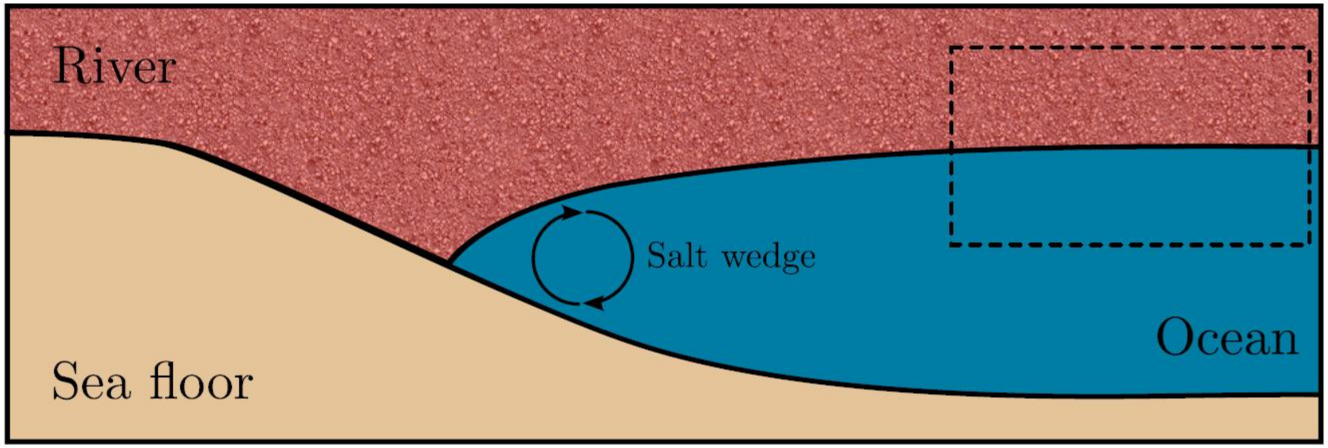


Sedimentation from buoyant river plumes: Configuration

Hypopycnal river plumes:

density of the river (fresh water + sediment) < density of ocean (water + salinity)

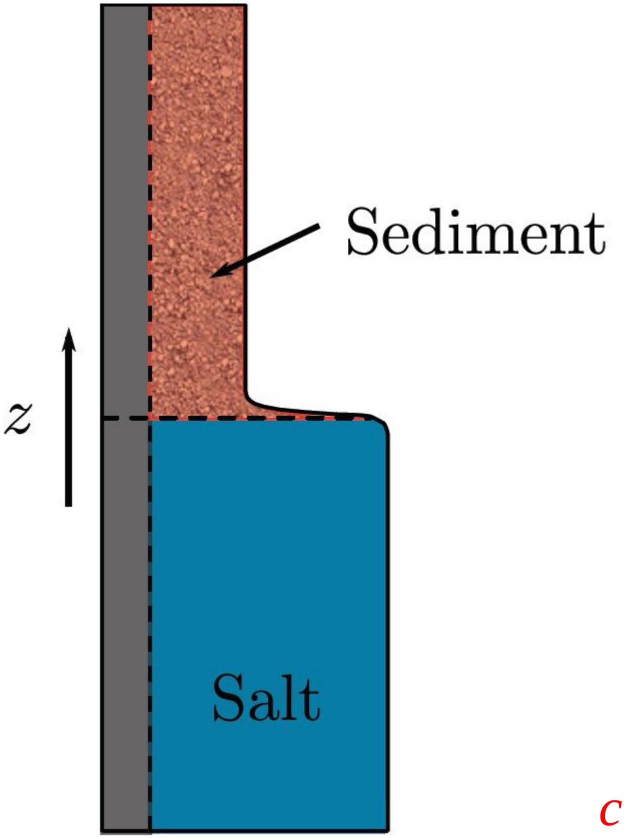
→ *river outflow propagates along the ocean surface*

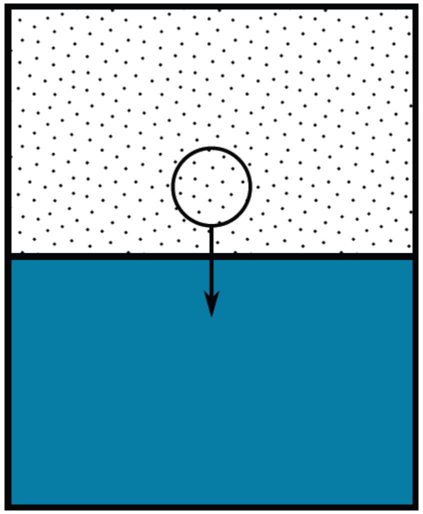


- *focus on the downstream density stratification*

Sedimentation from river plumes: Double-diffusion

Base density profile:

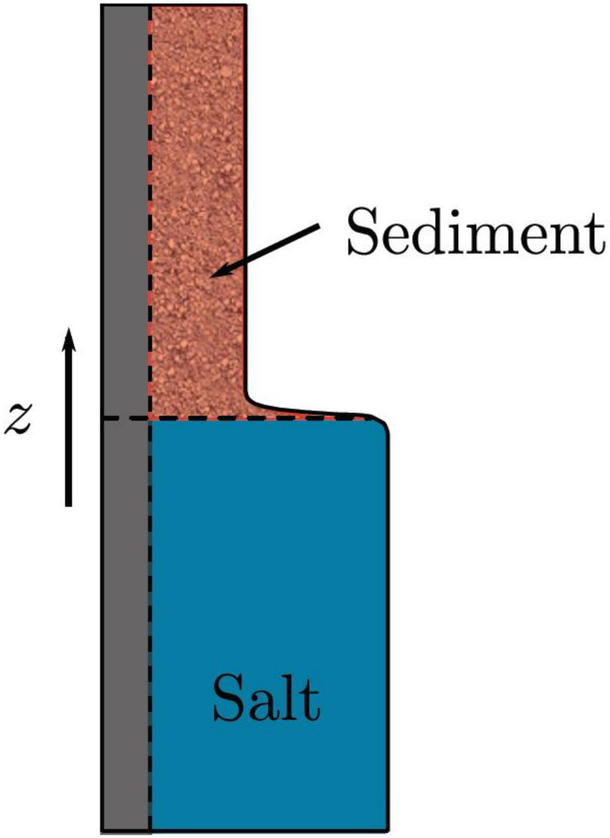


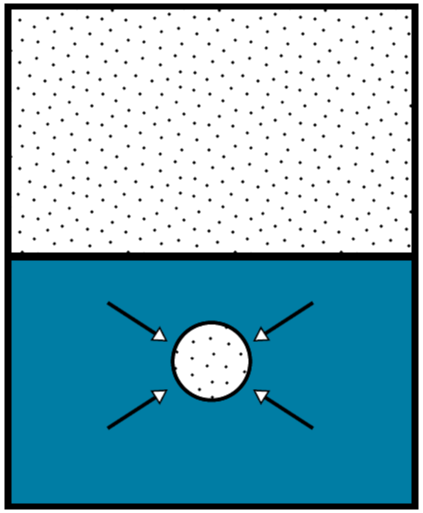


consider local downward perturbation of fluid element across opposing gradients

Sedimentation from river plumes: Double-diffusion

Base density profile:

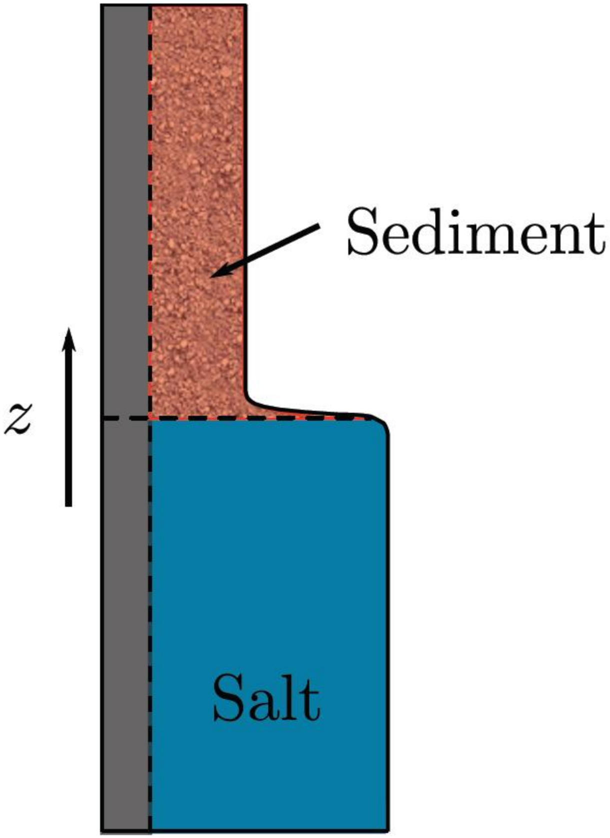


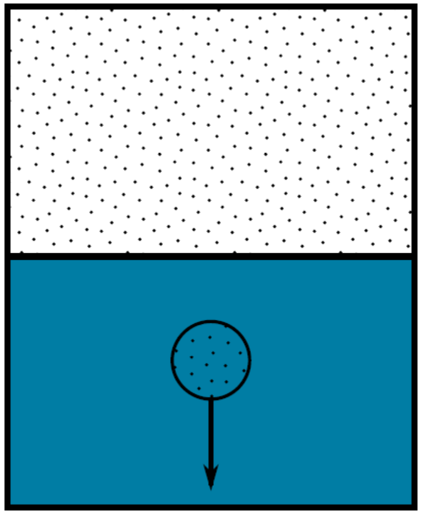


salinity diffuses inward more rapidly than particles diffuse outward

Sedimentation from river plumes: Double-diffusion

Base density profile:



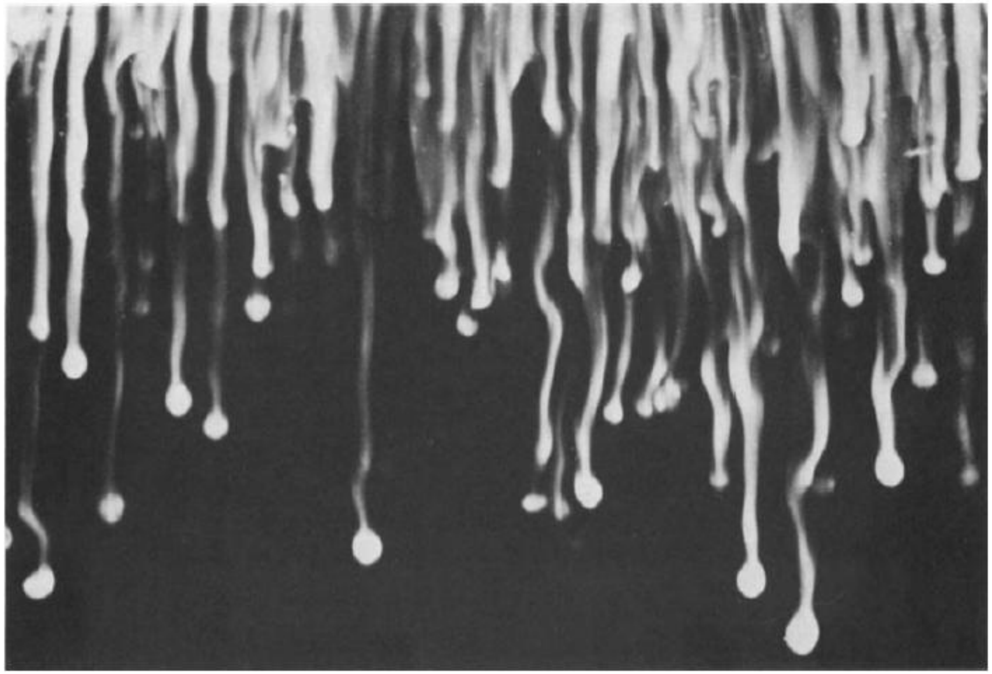


→ *fluid element will continue to sink*

- *potential for double-diffusive instability*

Traditional case: Salt fingers

- *warm, salty water above cold, fresh water:*



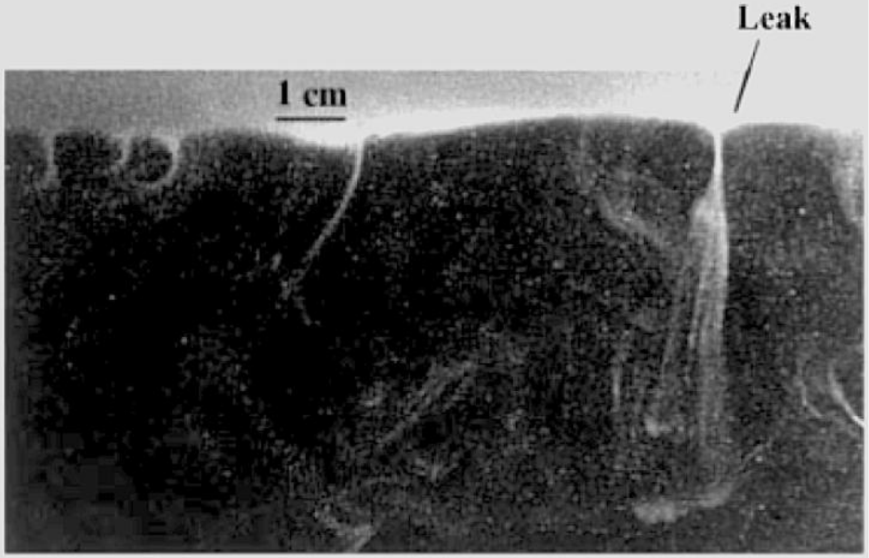
Huppert and Turner (1981)

- *dominant process for the vertical flux of salt in the ocean*
- *robust against shear*
- *believed to be responsible for the formation of the thermohaline staircase*

→ *for salt/sediment system, how does double-diffusion affect sedimentation?*

Sedimentation from river plumes: Experiments

- *previous experimental work by Parsons et al. (2001):*



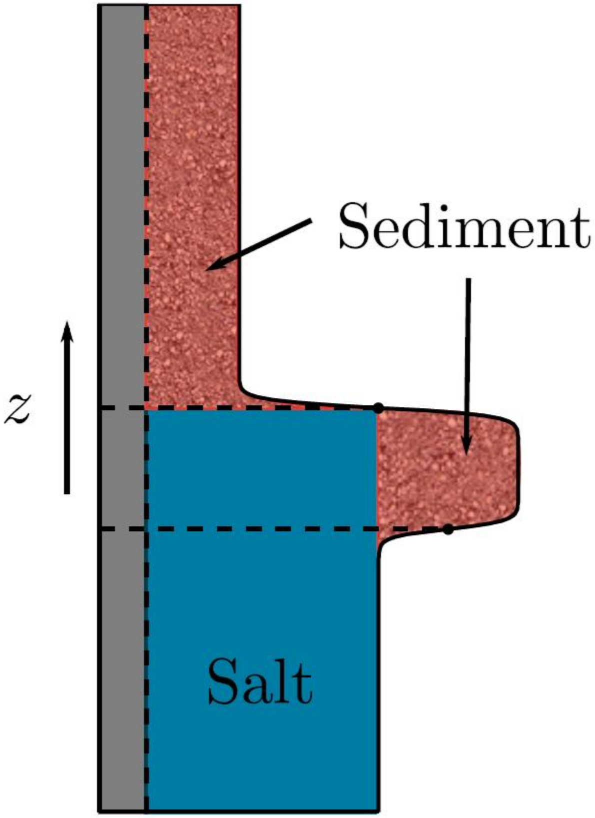
convective 'fingering' mode
space filling

'leaking' mode
localized, structures move along interface

→ *goal: understand mechanisms driving these modes, and their influence on the effective particle settling velocity*

Sedimentation from river plumes

Effect of settling velocity:



nose height H

density profile

- *settling process creates potential for Rayleigh-Taylor instability*

Framework: Dilute flows

Assumptions:

- *volume fraction of particles* $< O(10^{-3})$
- *particle radius « particle separation*
- *small particles with negligible inertia*

Dynamics:

- *effects of particles on fluid continuity equation negligible*
- *coupling of fluid and particle motion primarily through momentum exchange, not through volumetric effects*
- *particle loading modifies effective fluid density*
- *particles follow fluid motion, with superimposed settling velocity*

Moderately dilute flows: Two-way coupling (cont'd)

Governing dimensionless eqns:

$$\rho - 1 = \alpha S + \gamma C$$

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = \nabla^2 \mathbf{u} - \nabla \mathcal{P} + \rho' \frac{\mathbf{g}}{g'}$$

$$\frac{\partial S}{\partial t} + \mathbf{u} \cdot \nabla S = \frac{1}{Sc} \nabla^2 S$$

$$\frac{\partial C}{\partial t} - V_p \frac{\partial C}{\partial z} + \mathbf{u} \cdot \nabla C = \frac{1}{\tau Sc} \nabla^2 C$$

Characteristic quantities:

$$L^c = (\nu^2/g')^{1/3} \; , \qquad T^c = (L^{c2}/\nu) \; ,$$

$$U^c = (\nu \, g')^{1/3} \; , \qquad g' = \frac{\Delta \rho_c}{\rho_0} g \; ,$$

$$V_{st} = \frac{g \, d_p^2 \, (\rho_p - \rho_f)}{18 \, \mu_f}$$

Dimensionless parameters:

settling velocity $V_p = \dfrac{V_{st}}{(\nu g')^{1/3}}$

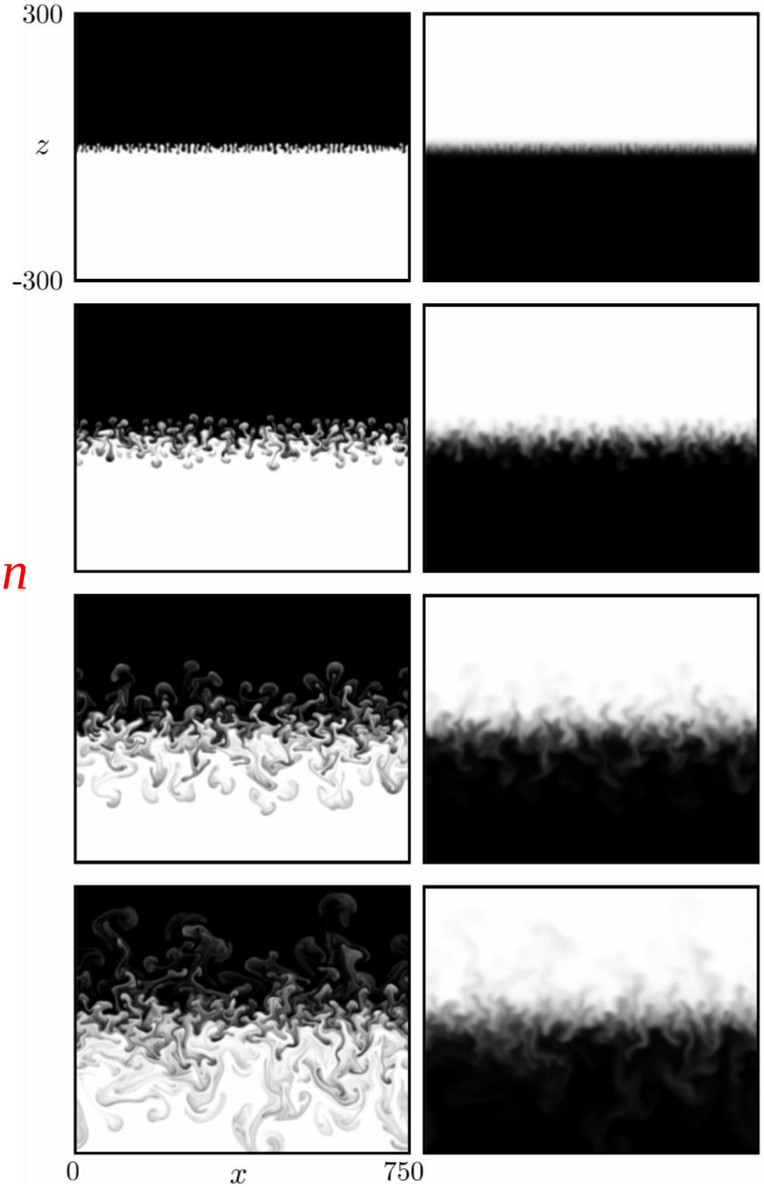
Schmidt number $Sc = \dfrac{\nu}{\kappa_s}$

stability ratio $R_s = \dfrac{\alpha}{\gamma}$

diffusivity ratio $\tau = \dfrac{\kappa_s}{\kappa_c}$

Sedimentation from river plumes: Numerical simulations

$$\begin{aligned} V_p &= 0.04 \ , \\ Sc &= 0.7 \ , \\ R_s &= 2 \ , \\ \tau &= 25 \end{aligned}$$



sediment concentration

salinity

Sedimentation from river plumes: Numerical simulations

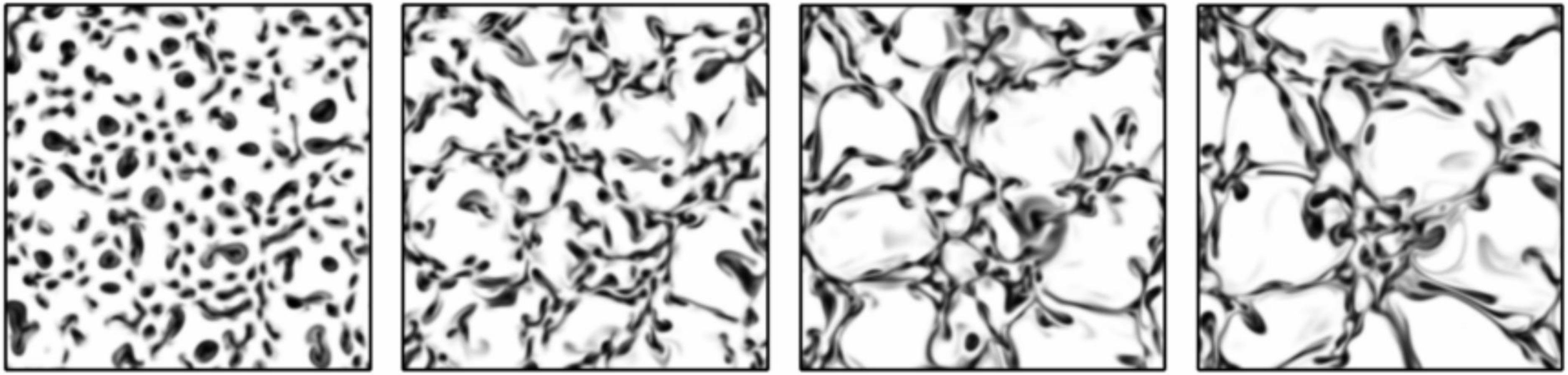
Mammatus clouds

Volcanic ash plume

Sedimentation from river plumes: Leaking mode (higher Sc)

Sedimentation from river plumes: Leaking mode

horizontal cross-cuts through sediment concentration field:

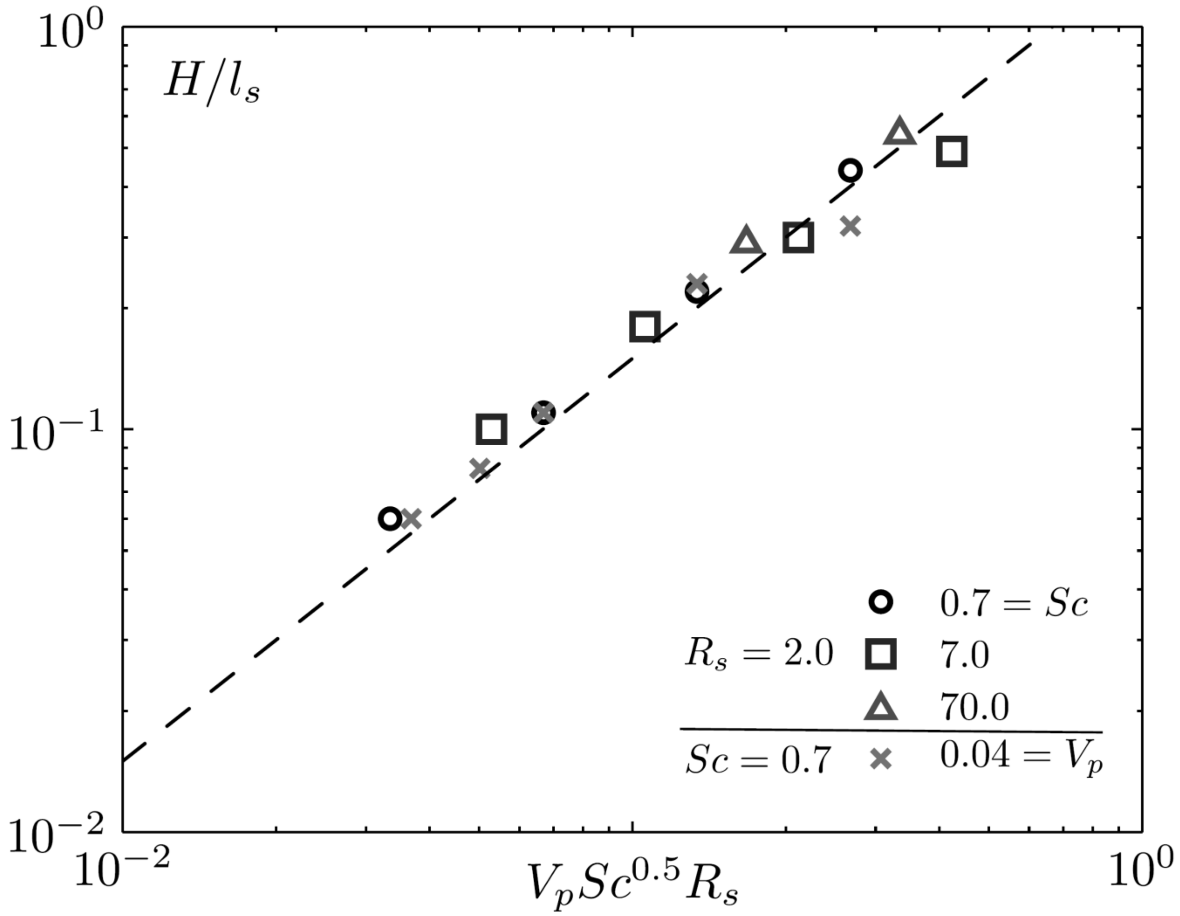


→ *time increases*

- *nonlinear evolution of initial, localized plumes results in web-like structure*
- *characterized by sheets, rather than plumes*

Sedimentation from river plumes: Scaling

Scaling of nose height with in-/outflow ratio:



→ quasisteady ratio of nose height to salinity interface thickness scales with ratio of sediment inflow into nose region to sediment outflow from nose region

Sedimentation from river plumes: Parametric study

Physical interpretation:

- *for small settling velocity, the rate of sediment inflow from above is low →*
  this low rate of sediment inflow can be balanced by conventional double-diffusive outflow of sediment below → there is little accumulation of sediment in the nose region → height of nose region remains small

- *for large settling velocity, the rate of sediment inflow from above is high →*
  this high rate of sediment inflow cannot be balanced by traditional double-diffusive sediment outflow below → sediment accumulates in the nose region → height of nose region increases until it is thick enough for Rayleigh-Taylor instability to form, which leads to increased sediment outflow below → new balance between in- and outflow into the nose region is established

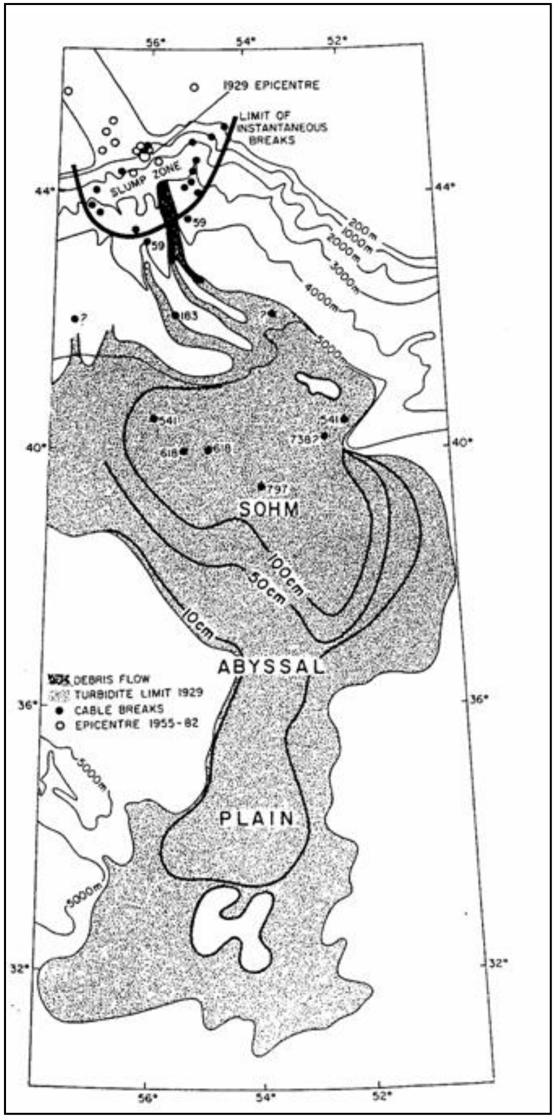
Turbidity current

- *Underwater sediment flow down the continental slope*
- *Can transport many km^3 of sediment*
- *Can flow O(1,000)km or more*
- *Often triggered by storms or earthquakes*
- *Repeated turbidity currents in the same region can lead to the formation of hydrocarbon reservoirs*
- *Properties of turbidite:*
  - *particle layer thickness*
  - *particle size distribution*
  - *pore size distribution*

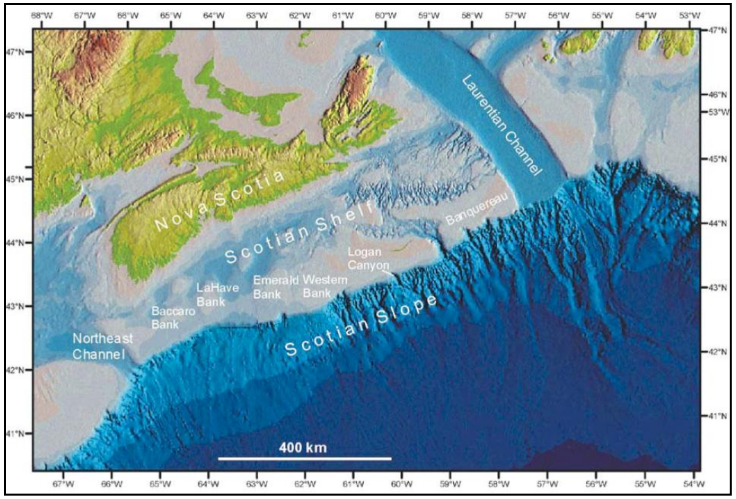
Turbidity current.

http://www.clas.ufl.edu/

Turbidity current (cont'd)



From Piper et al., 1984



Grand Banks turbidite

historical event, Nov 18 1929 (M7.2)

Length scale = 10^6 m

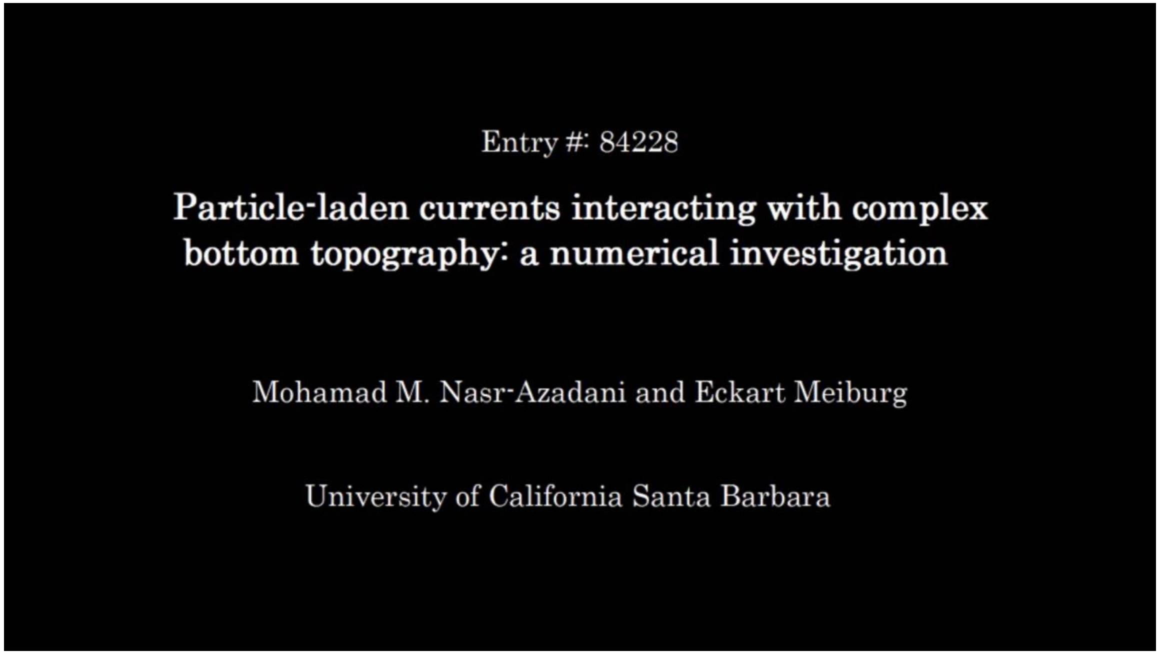
Grain size = $\leq 10^{-1}$ m

Volume of deposit = 1.8×10^{11} m^3

Re = O (10^9)

Lock exchange configuration (with M. Nasr-Azadani)

Flow of turbidity current around localized seamount



Entry #: 84228

Particle-laden currents interacting with complex bottom topography: a numerical investigation

Mohamad M. Nasr-Azadani and Eckart Meiburg

University of California Santa Barbara

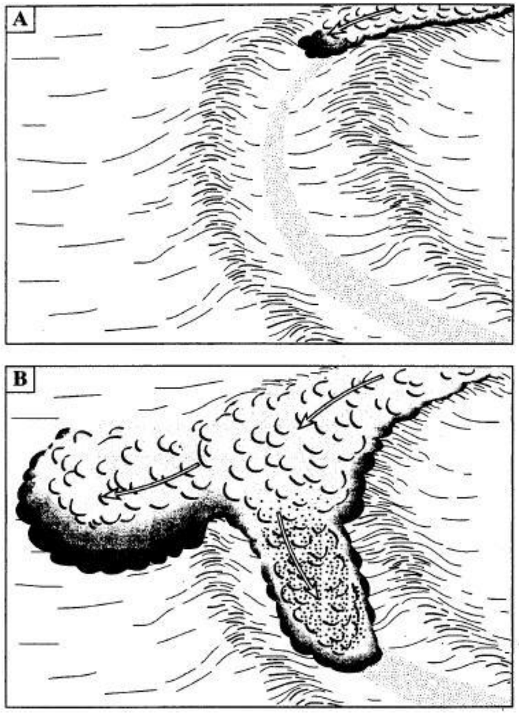
- *turbidity current develops lobe-and-cleft instability of the front*
- *current dynamics and depositional behavior are strongly affected by bottom topography*

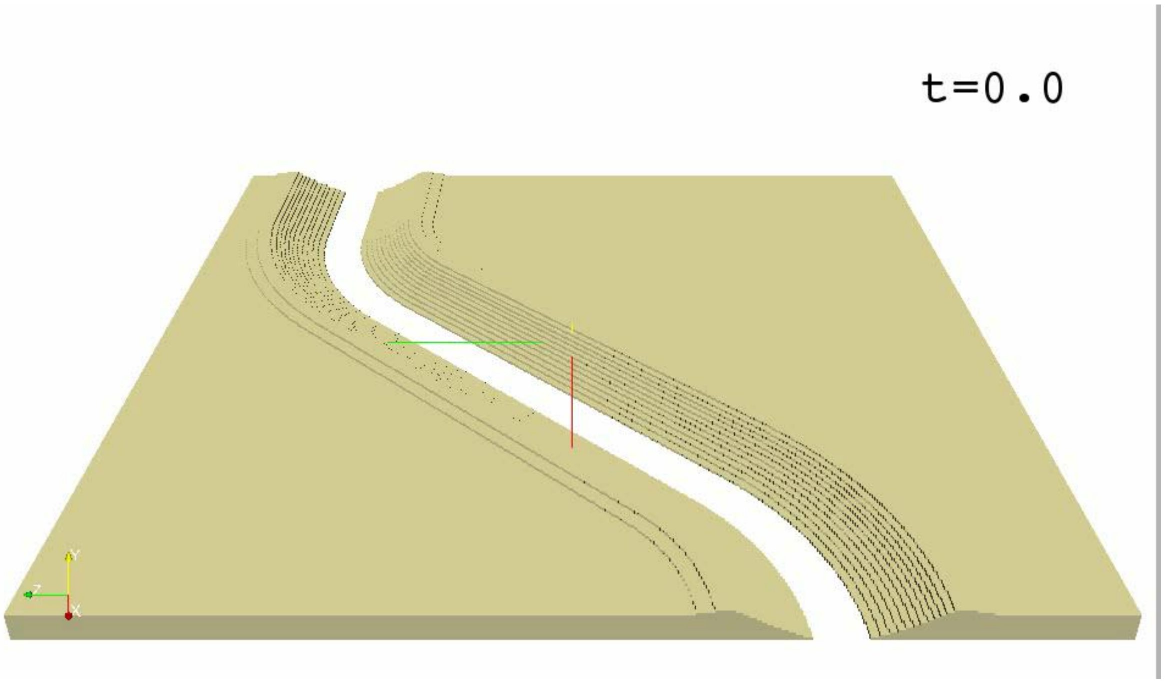
$$Re_{sim} = 2,000 : \; u_b \approx 2cm/s \; , \; L \approx 10cm \; , \; \nu \approx 10^{-6} m^2/s$$

→ *simulation corresponds to a laboratory scale current, not field scale!*

Turbidity current/sediment bed interaction (w. M. Nasr)

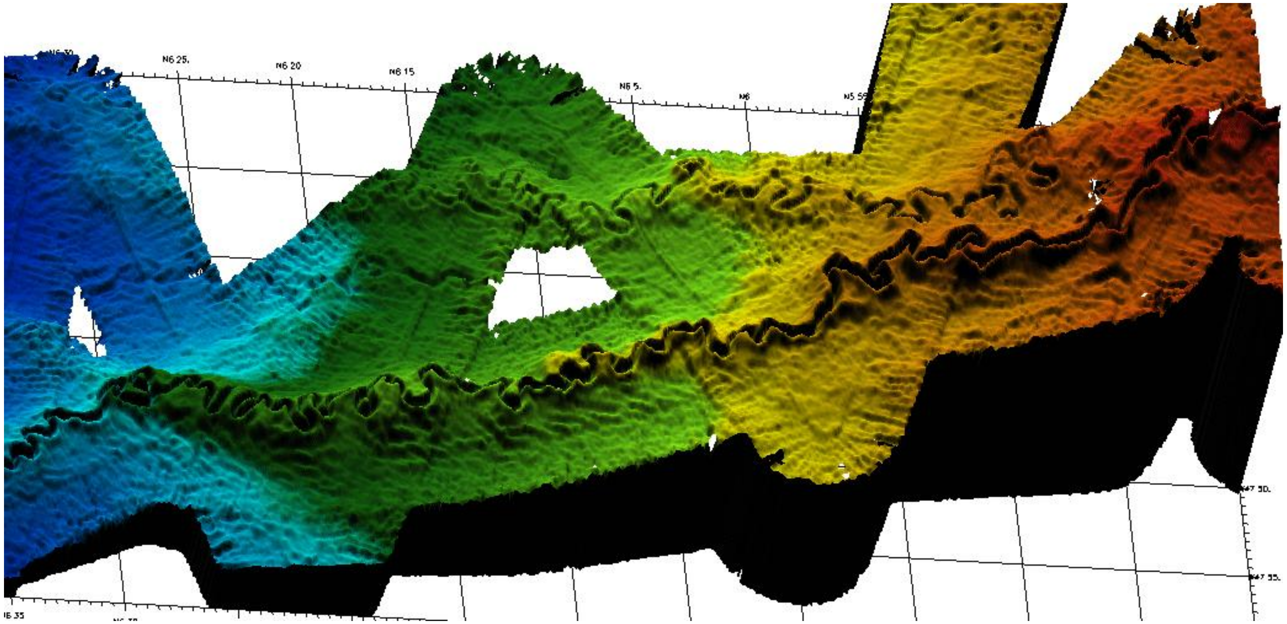
‘Flow stripping’ in channel turns: lateral overflows





Turbidity current/sediment bed interaction

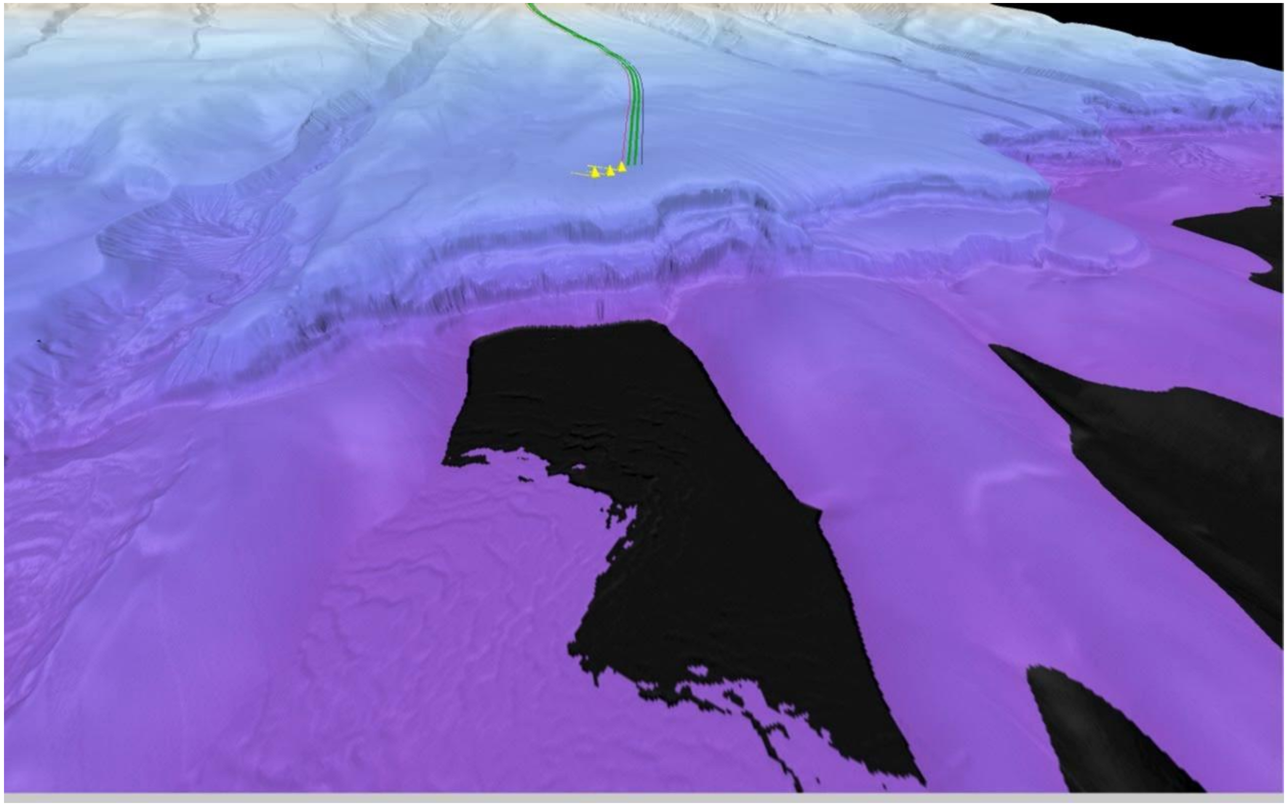
Formation of submarine channel-levee systems



Amazon submarine channel

Hazards posed by gravity and turbidity currents (with E. Gonzales, T. Tokyay, G. Constantinescu)

*Gravity currents may encounter underwater marine installations,
Such as pipelines, wellheads etc.:*



Erosion, resuspension of particle bed (with F. Blanchette, M. Strauss, B. Kneller, M. Glinsky)

Experimentally determined correlation by Garcia & Parker (1993) evaluates resuspension flux at the particle bed surface as function of:

- *bottom wall shear stress*
- *settling velocity*
- *particle Reynolds number*

Here we model this resuspension as diffusive flux from the particle bed surface into the flow

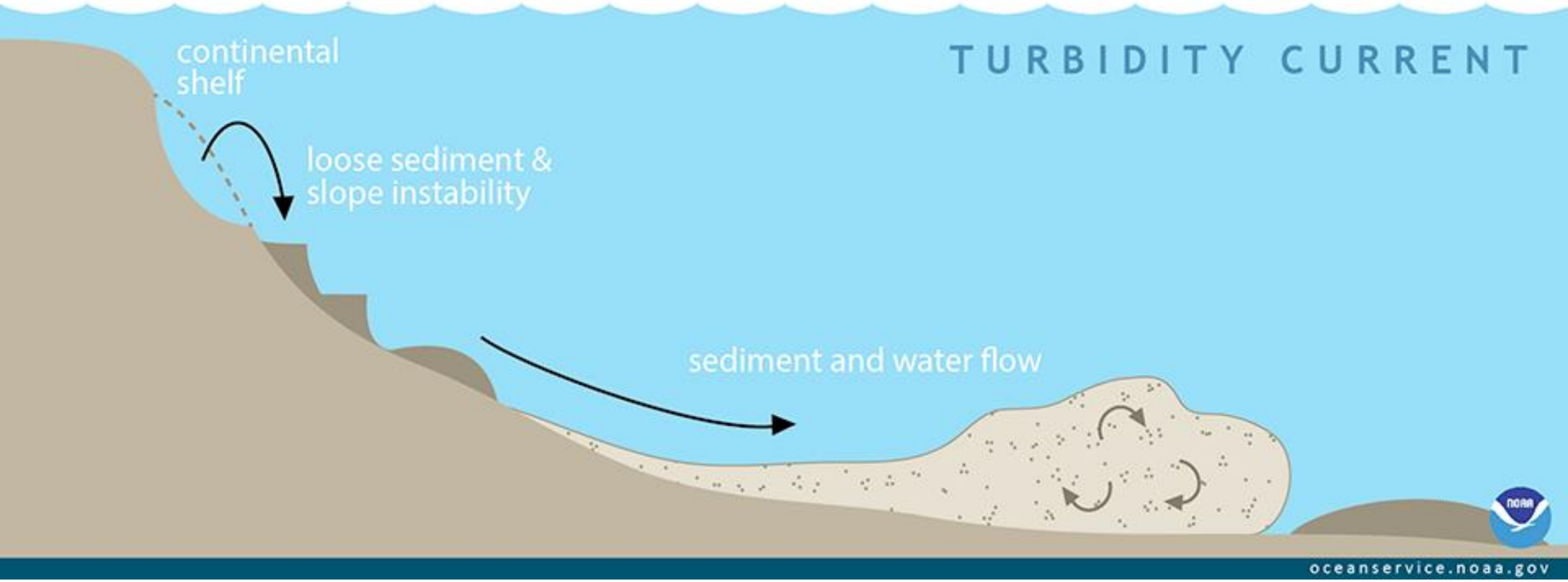
Eroding uncertainty:

Phase-resolved simulations of shear flows over mobile sediment beds

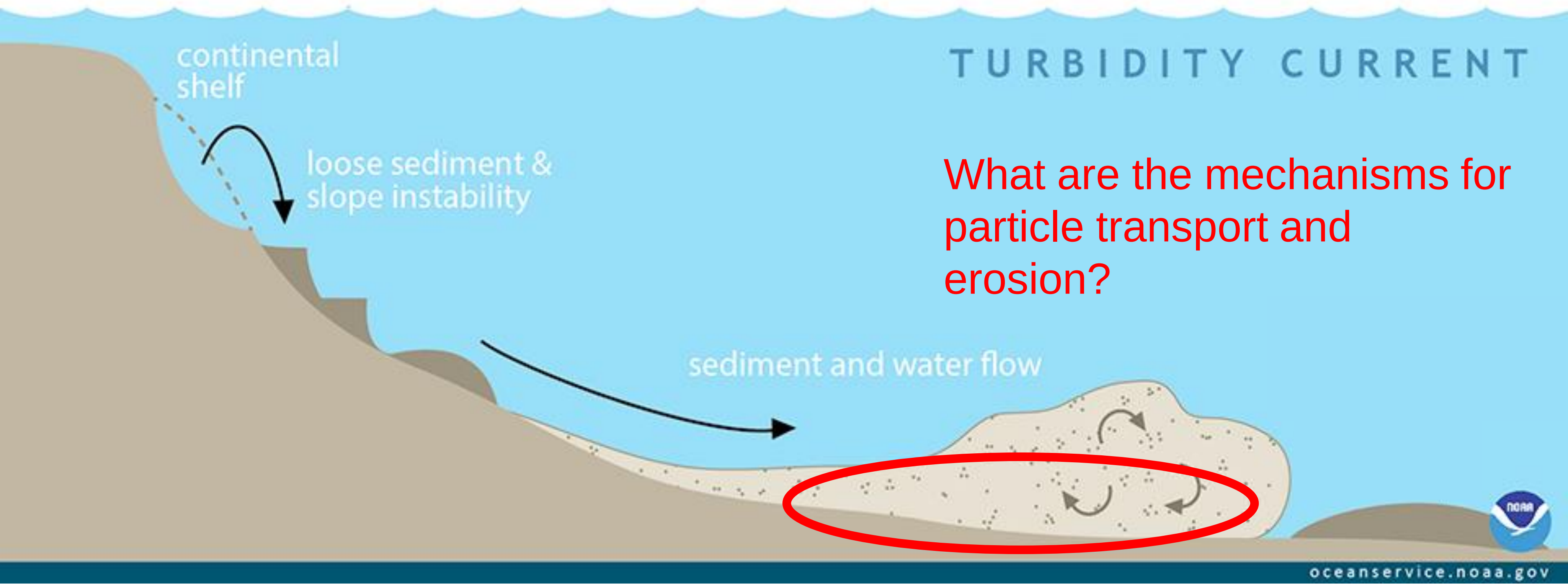
Edward Biegert, Bernhard Vowinckel, Eckart Meiburg

Physics of Dense Suspensions
KITP, UC Santa Barbara
14. March, 2018

Motivation and goals



Motivation and goals



What are the mechanisms for particle transport and erosion?

Particle-resolving simulations

Immersed Boundary Method (IBM)

- Solves full Navier-Stokes equations

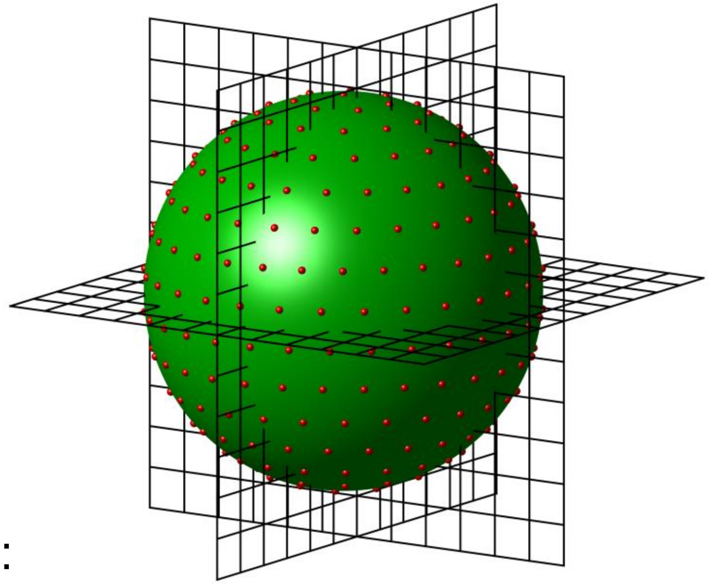
$$\rho_f \left[\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u})\right] = -\nabla p + \mu_f \nabla^2 \mathbf{u} + \mathbf{f}_{IBM}$$

$$\nabla \cdot \mathbf{u} = 0$$

- $\mathbf{f}_{IBM}$ enforces no-slip at Lagrangian Markers
- Fully-coupled with particle equations of motion:

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = \underbrace{\int_{\Gamma_p} \rho_f \, \boldsymbol{\tau} \cdot \mathbf{n} \, \mathrm{d}A}_{\text{Hydrodynamic forces}} + \underbrace{V_p(\rho_p - \rho_f)\mathbf{g}}_{\text{Buoyancy}} + \underbrace{\mathbf{F}_c}_{\text{Collisions}}$$

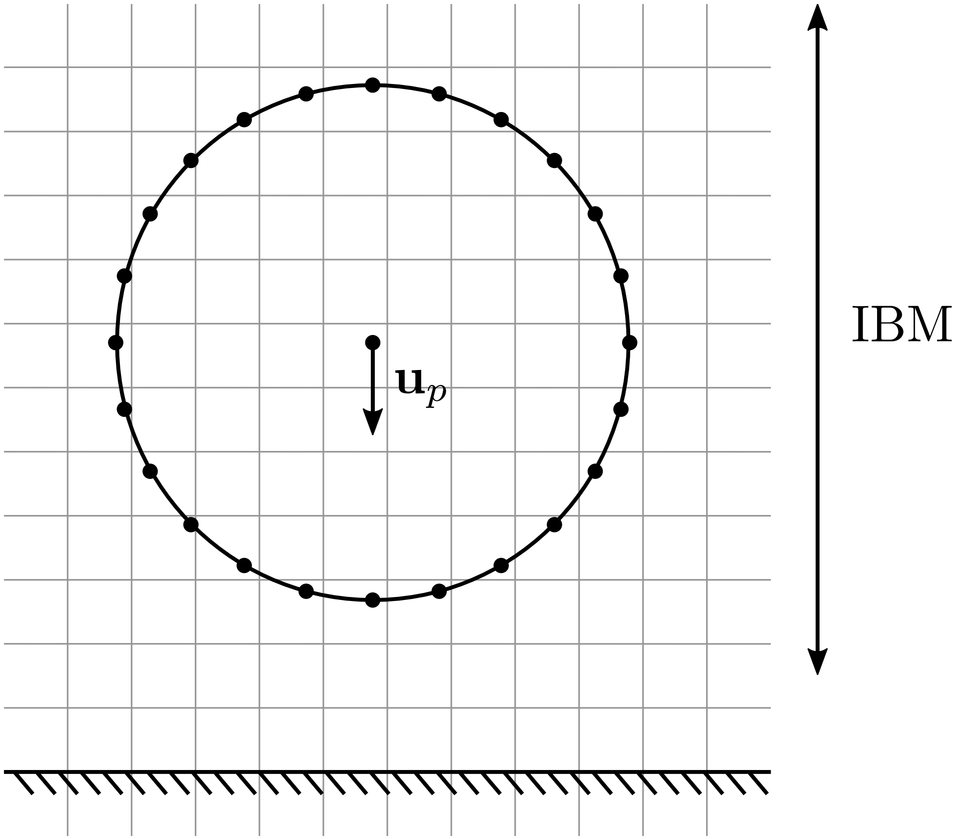
- Described in Biegert, Vowinckel, Meiburg [*JCP* 2017]



Lagrangian mesh (red markers) and Eulerian mesh (black lines)

Collision model – far from wall

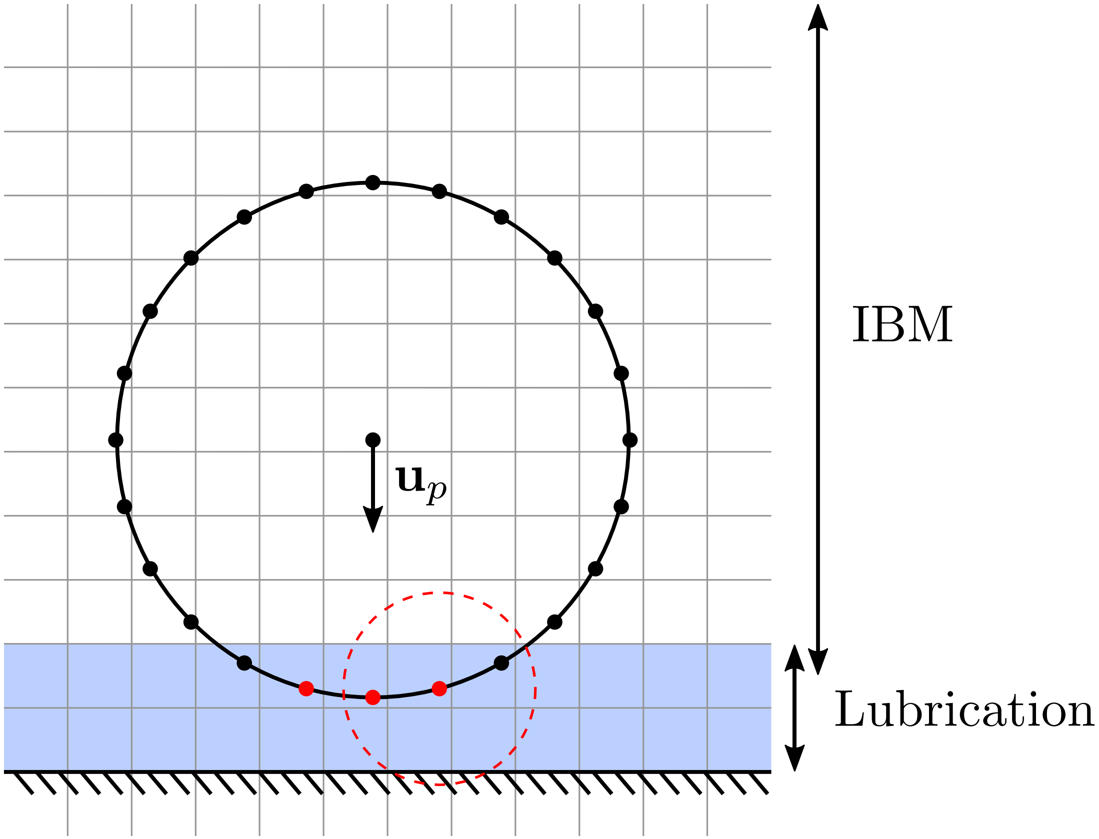
Described in Biegert, Vowinckel, and Meiburg [*JCP* 2017]



Collision model – near wall

- Turn off overlapping Lagrangian markers (red)
- Lubrication force

$$F_c = -\frac{6\pi\mu\dot{\zeta}_n R_p^2}{\max(\zeta_n, \zeta_{n,min})}$$



Collision model – contact with wall

Contact force

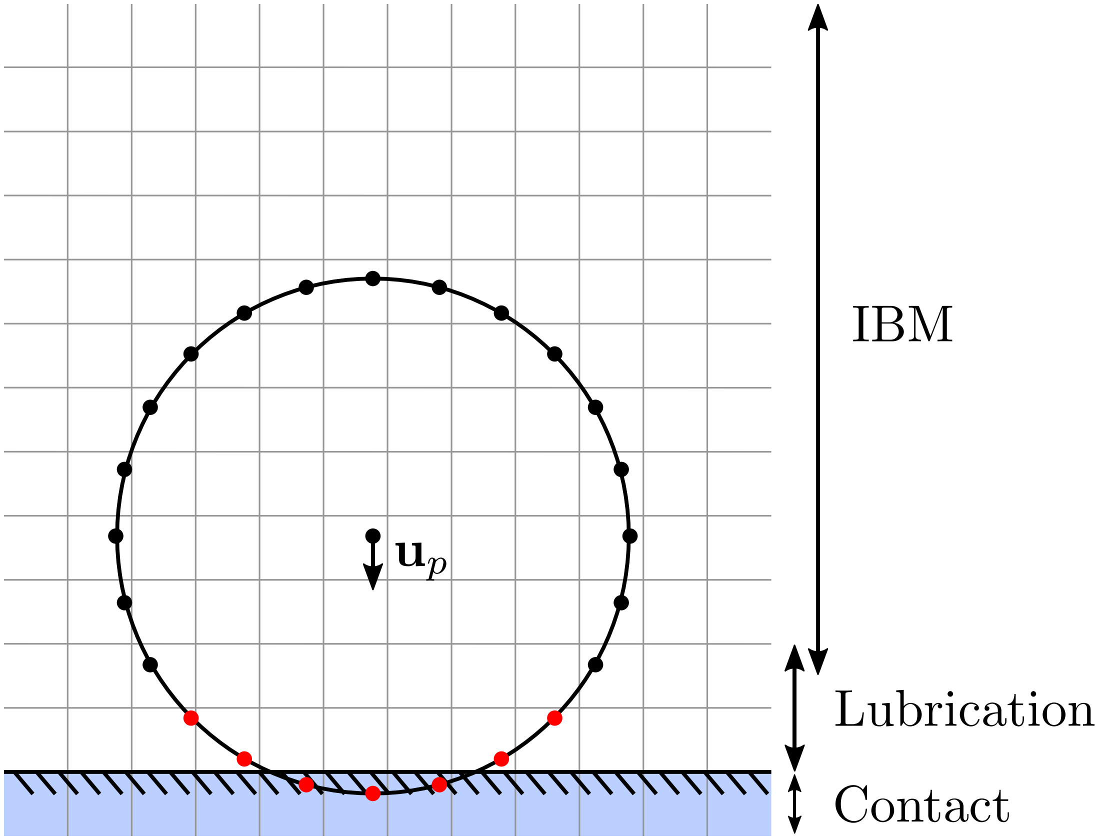
$$\mathbf{F}_c = \mathbf{F}_n + \mathbf{F}_t$$

- Normal component

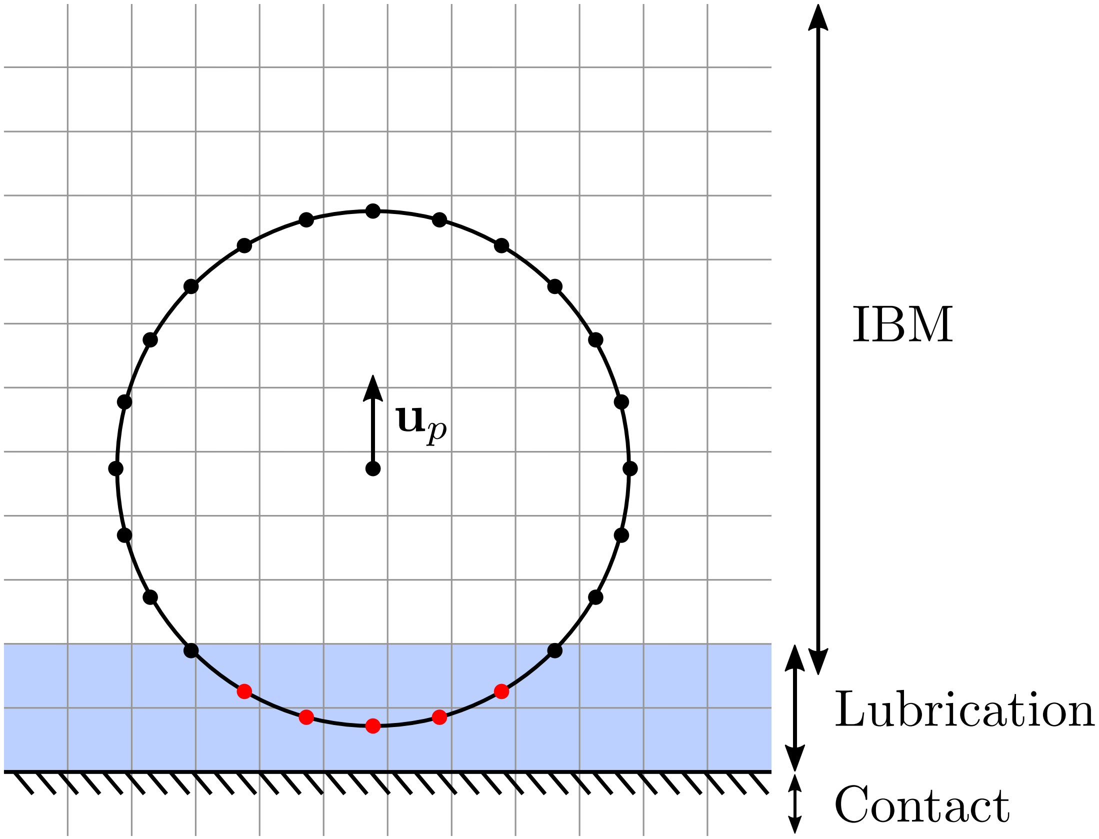
$$\mathbf{F}_n = -\left(k_n|\zeta_n|^{3/2} - d_n\dot{\zeta}\right)\mathbf{n}$$

- Tangential component

$$\mathbf{F}_t = \min\left(\left\|-k_t\boldsymbol{\zeta}_t - d_t\mathbf{g}_{t,cp}\right\|, \left\|\mu\mathbf{F}_n\right\|\right)\mathbf{t}$$



Collision model – near wall



Collision model – far from wall

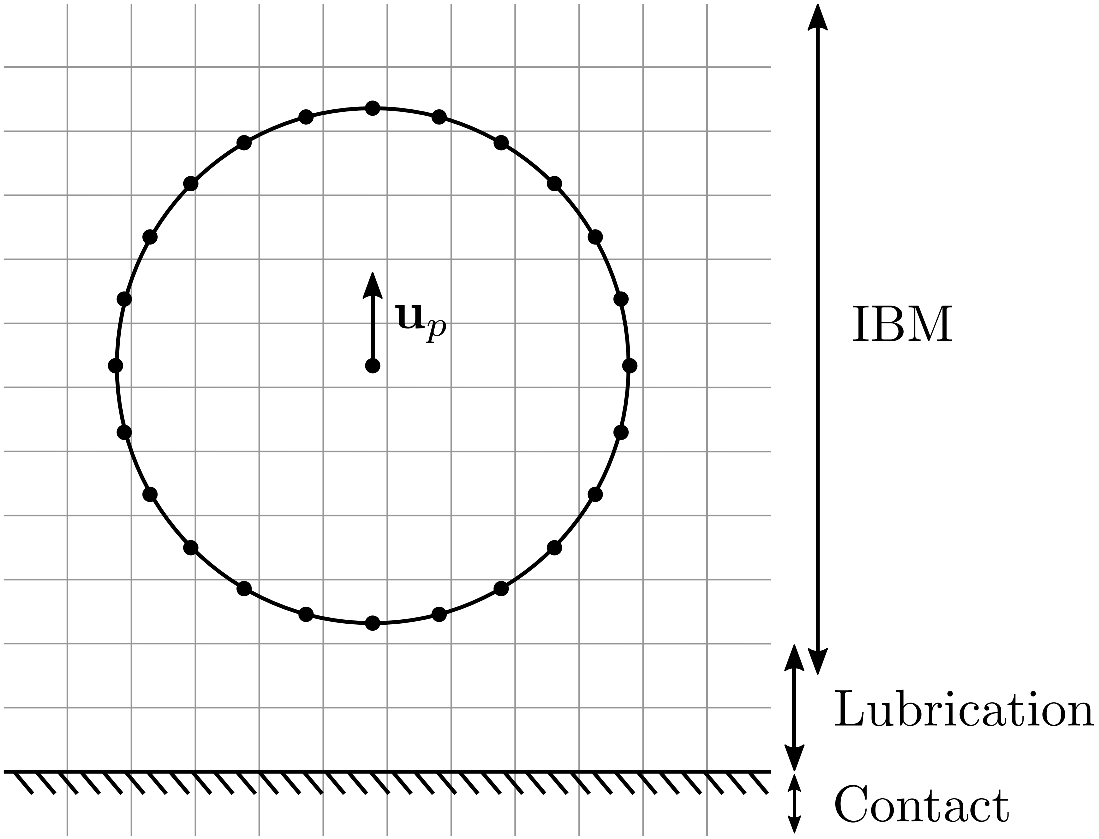
Generally accepted concept!

[Kempe & Fröhlich *JFM* 2012,

Izard et al. *JFM* 2014,

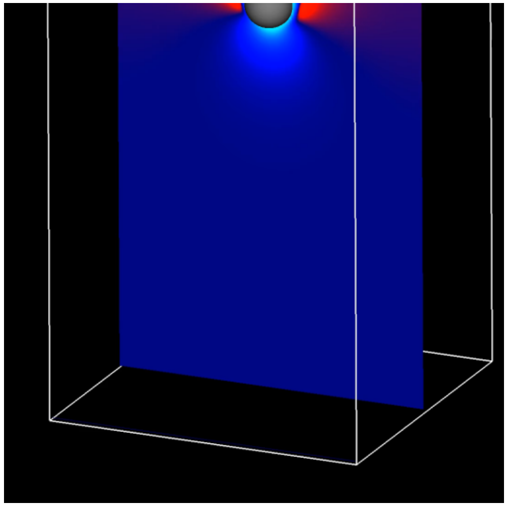
Costas et al. *PRE* 2015,

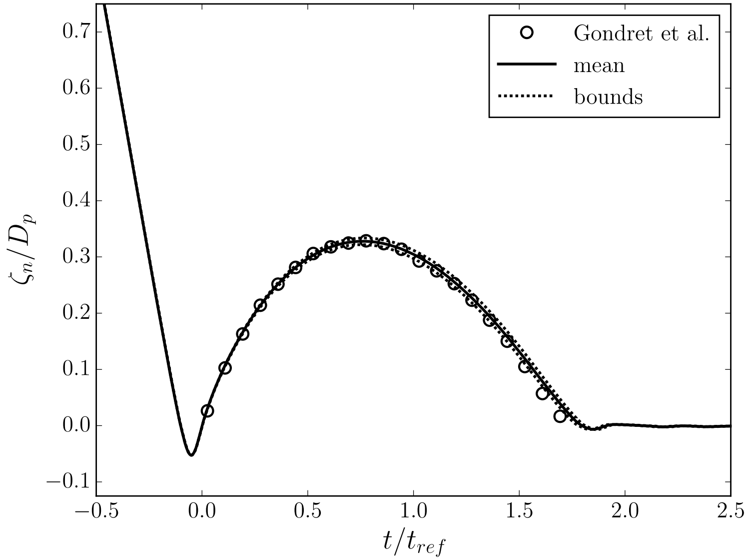
Sierakowski & Prosperetti *JCP* 2016]

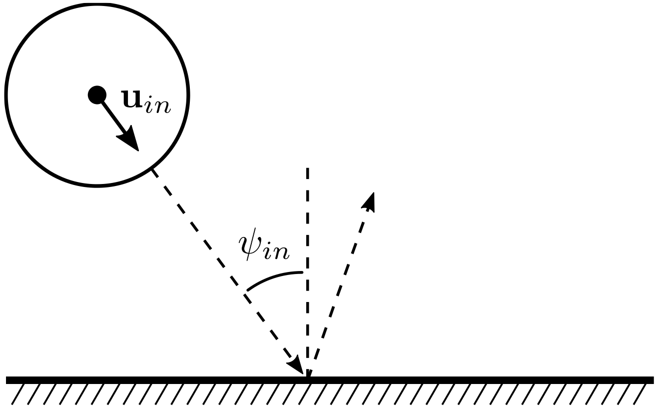


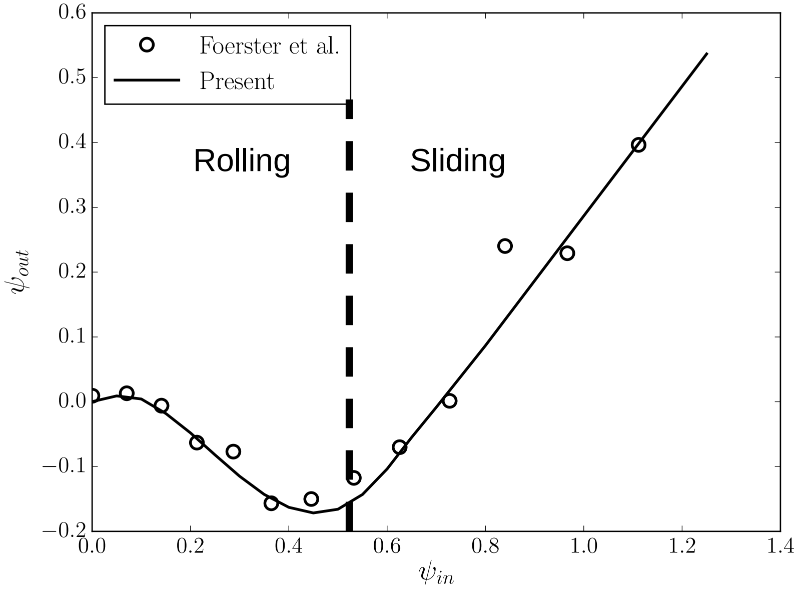
Validation

Excellent agreement with experiments of normal and oblique collision

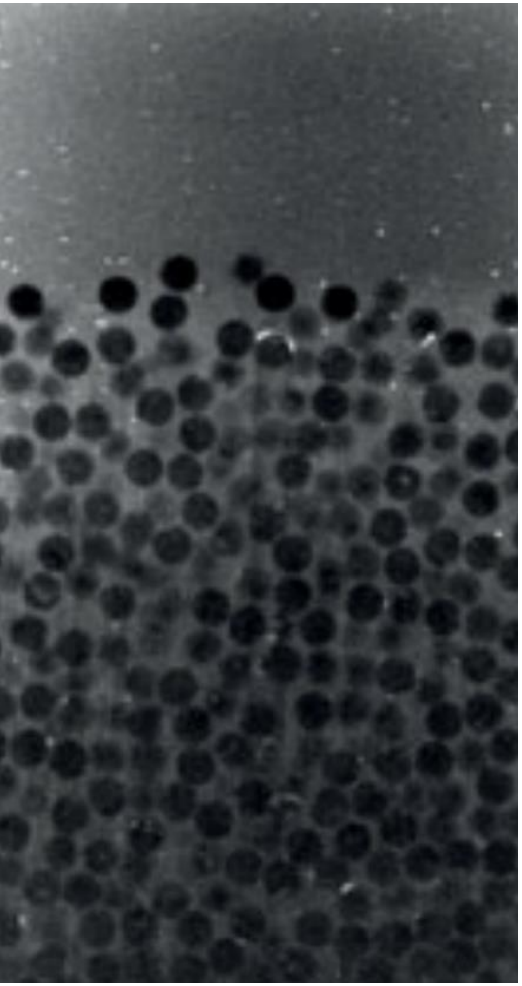








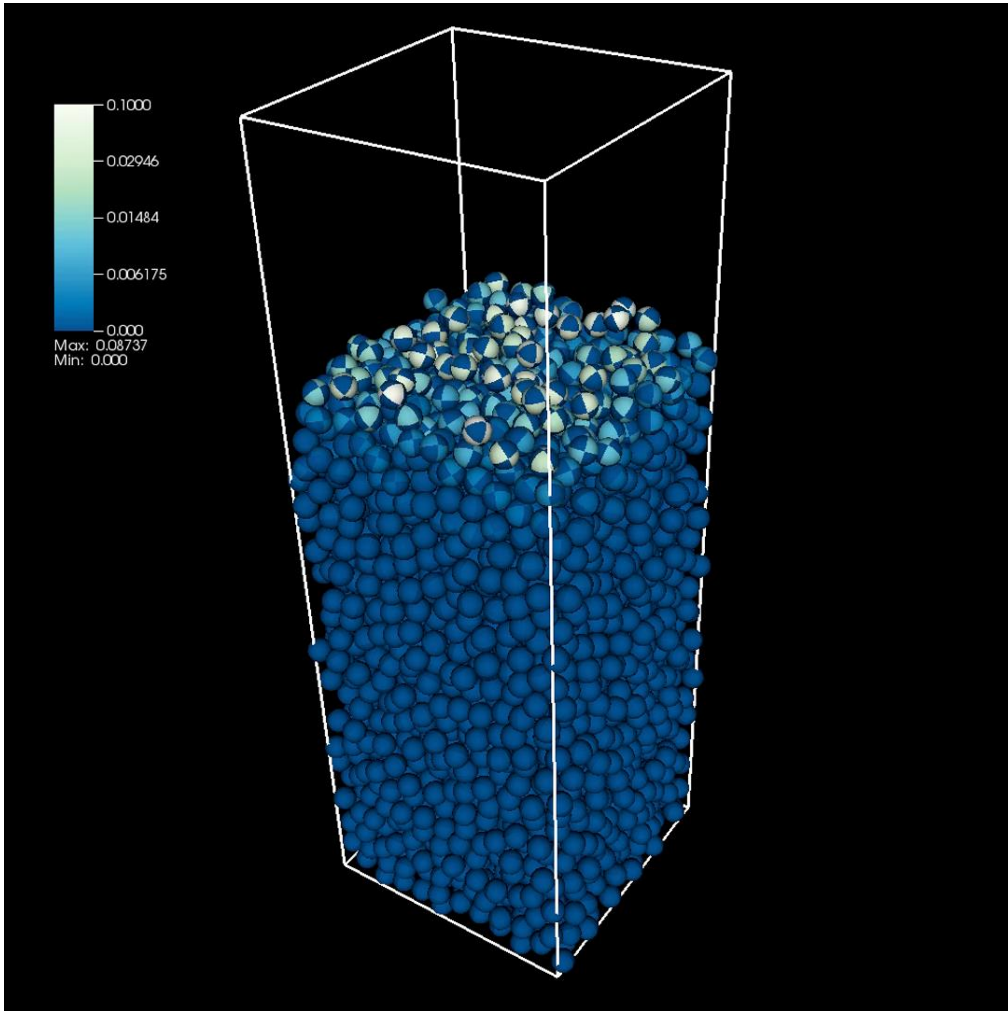
Comparison with experiments



[Aussillous et al. *JFM* 2013]

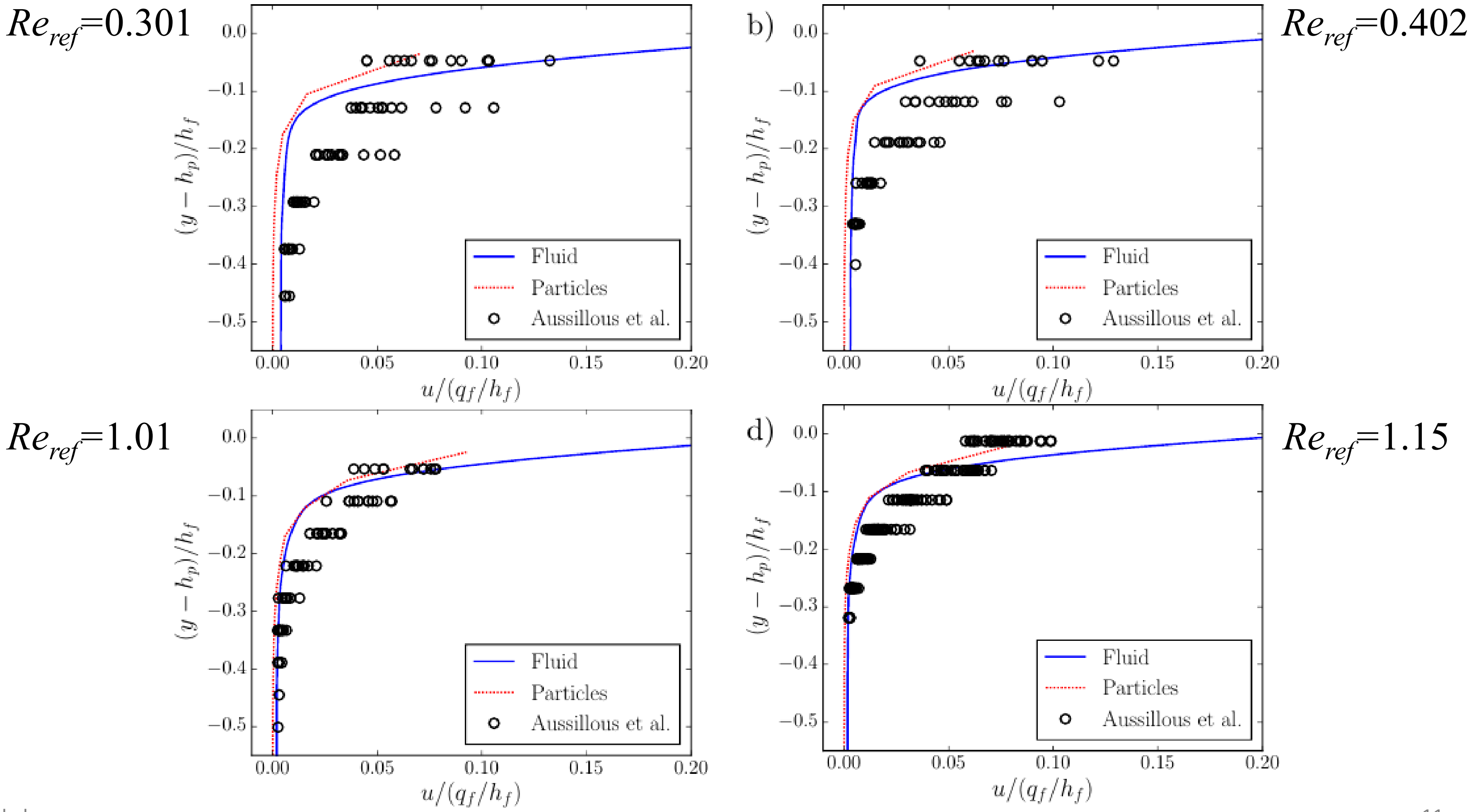
Sediment transport in laminar Poiseuille flow

- $Re = 1.11$
- $H/D = 11.3$
- $D/\Delta x = 22.7$



Bulk validation

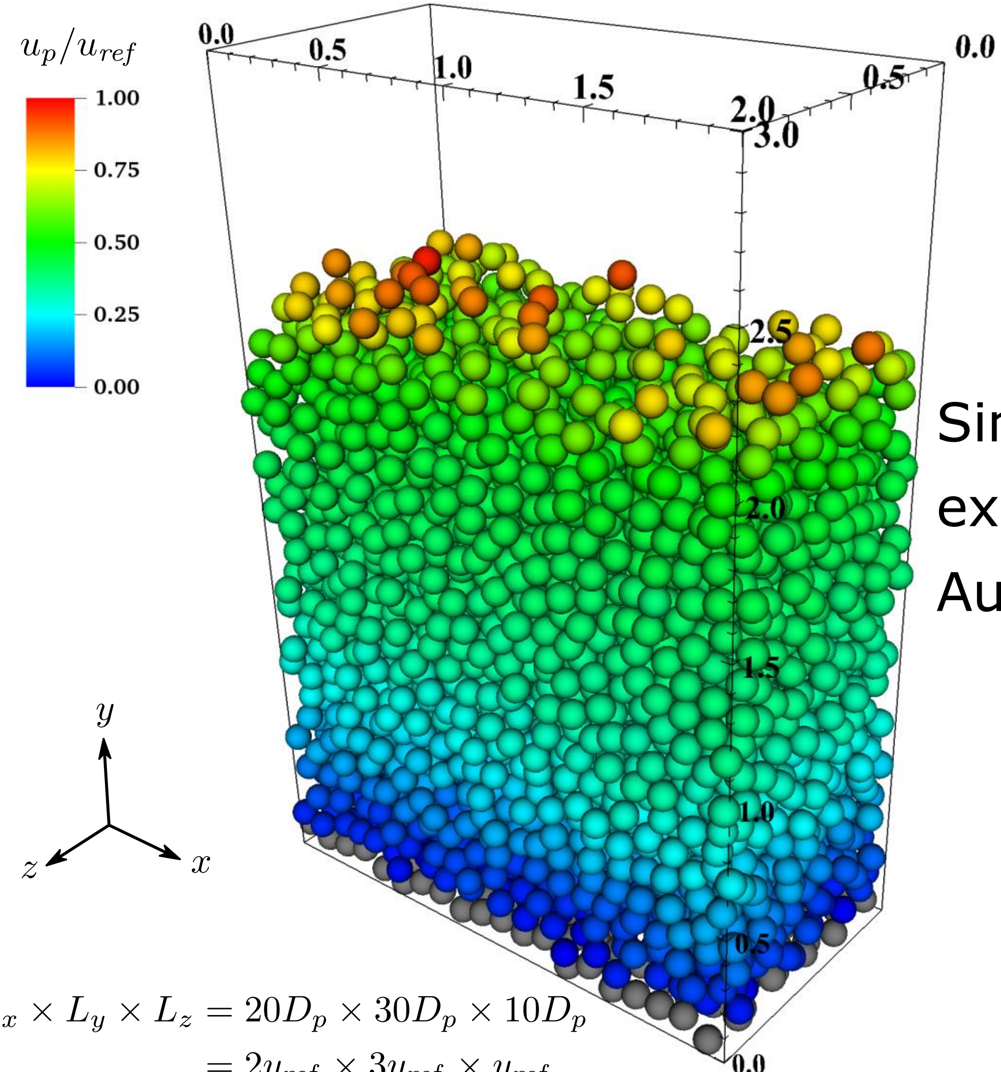
- Velocity profiles of Aussillous et al. [*JFM* 2013]



Simulation setup

$$\frac{\rho_p}{\rho_f} = 2.10$$

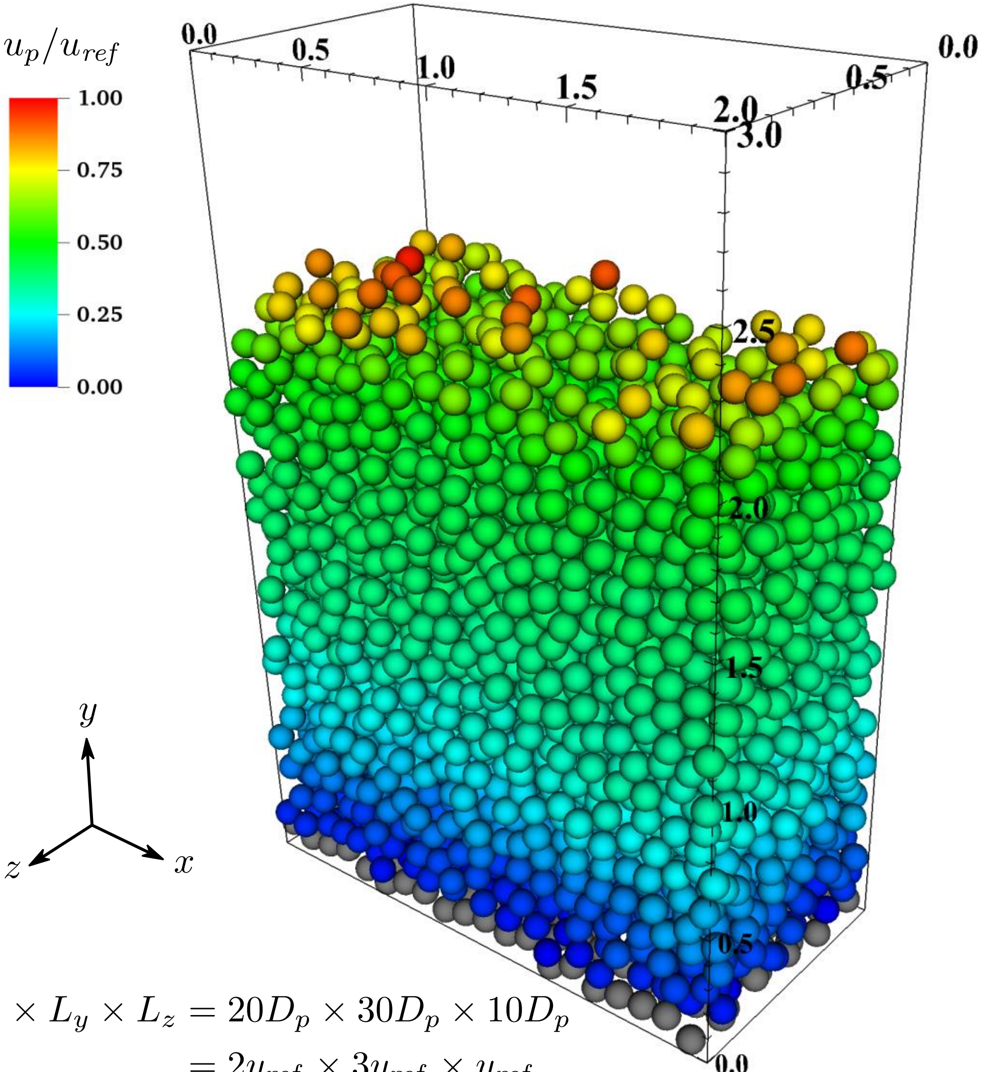
$$Re_{ref} = \frac{u_{ref}\, y_{ref}}{\nu_f} = 67$$



Similar to experimental setup of Aussillous et al. [*JFM* 2013]

$$L_x \times L_y \times L_z = 20D_p \times 30D_p \times 10D_p$$
$$= 2y_{ref} \times 3y_{ref} \times y_{ref}$$

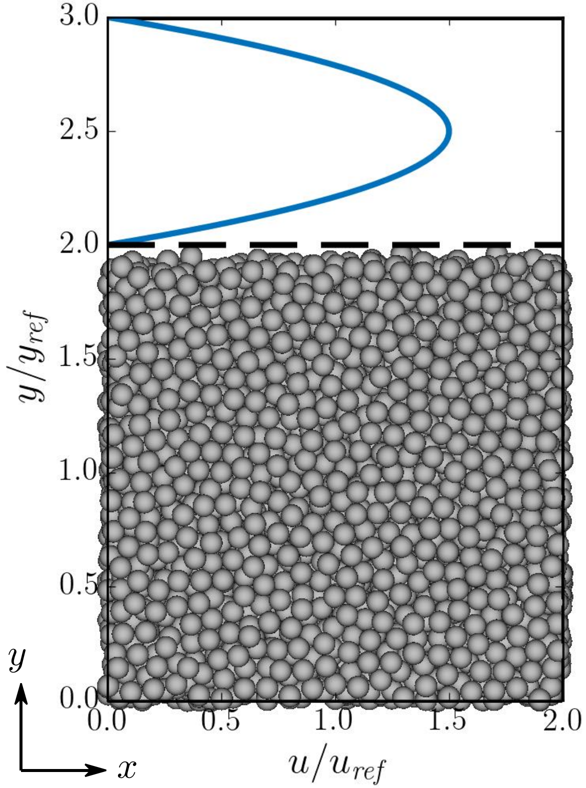
Simulation setup



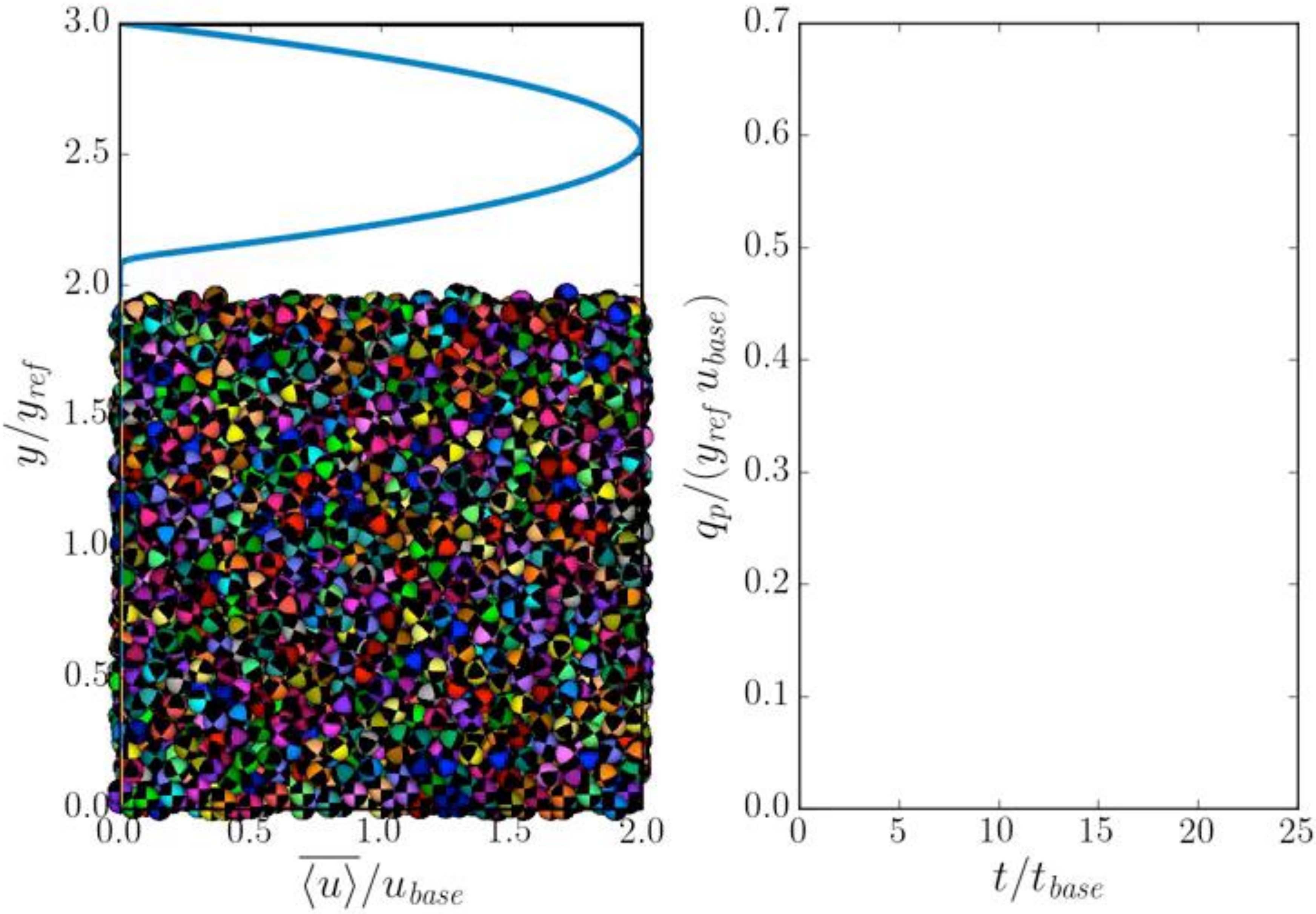
$$\frac{\rho_p}{\rho_f} = 2.10$$

$$Re_{ref} = \frac{u_{ref}\, y_{ref}}{\nu_f} = 67$$

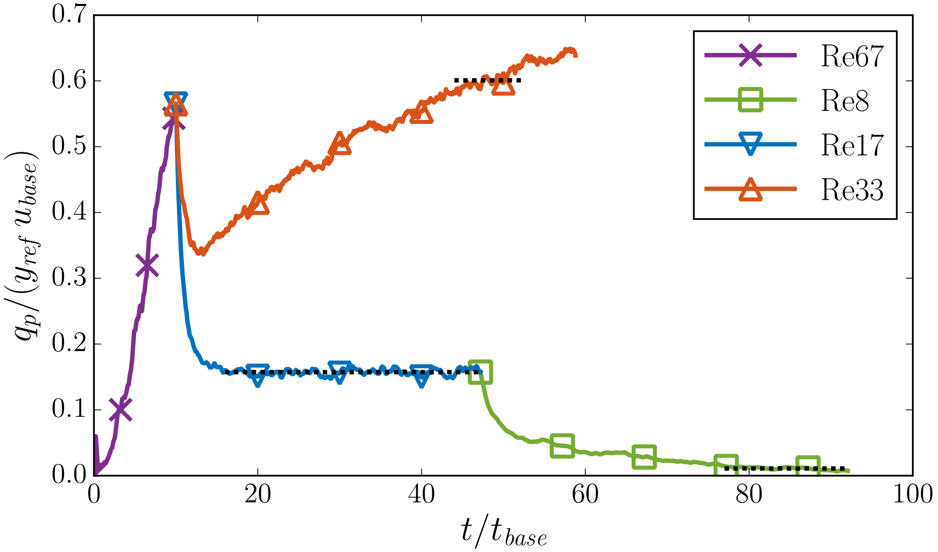
Reference Poiseuille flow:



$$L_x \times L_y \times L_z = 20D_p \times 30D_p \times 10D_p$$
$$= 2y_{ref} \times 3y_{ref} \times y_{ref}$$

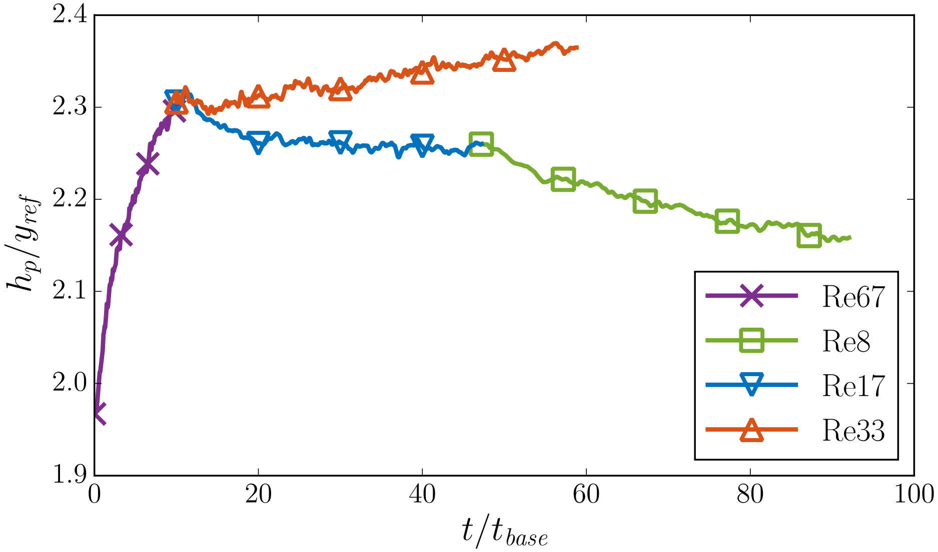

3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
y/y_{ref}
$\overline{\langle u \rangle}/u_{base}$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
5
10
15
20
25
$q_p/(y_{ref}\, u_{base})$
t/t_{base}

Transient behavior



Particle Flux

Bed Height



What is the rheology of a fluid/particle mixture?

Two constitutive model frameworks exist:

- Effective viscosity
  [Stickel and Powell, *ARFM* 2005]

$$\tau = \eta_s(\phi)\eta_f \frac{\mathrm{d}u}{\mathrm{d}y}$$

$$P^p = \eta_n(\phi)\eta_f \frac{\mathrm{d}u}{\mathrm{d}y}$$

where

$$\eta_s = 1 + \frac{5}{2}\phi_m\left(1 - \frac{\phi}{\phi_m}\right)^{-1} + K_s\left(\frac{\phi}{\phi_m - \phi}\right)^2$$

$$\eta_n = K_n\left(\frac{\phi}{\phi_m - \phi}\right)^2$$

- Macroscopic friction coefficient
  [Boyer et al., *PRL* 2011]

$$\tau = \mu(I_v)P^p$$

$$\phi = \phi(I_v)$$

where

$$I_v = \frac{\eta_f \,\mathrm{d}u/\mathrm{d}y}{P^p}$$

$$\mu(I_v) = \mu_1 + \frac{\mu_2 - \mu_1}{1 + I_0/I_v} + I_v + \frac{5}{2}\phi_m I_v^{1/2}$$

$$\phi = \frac{\phi_m}{1 + I_v^{1/2}}$$

What is the rheology of a fluid/particle mixture?

Two constitutive model frameworks exist:

- Effective viscosity
  [Stickel and Powell, *ARFM* 2005]

$$\tau = \eta_s(\phi)\eta_f \frac{\mathrm{d}u}{\mathrm{d}y}$$

$$P^p = \eta_n(\phi)\eta_f \frac{\mathrm{d}u}{\mathrm{d}y}$$

- Macroscopic friction coefficient
  [Boyer et al., *PRL* 2011]

$$\tau = \mu(I_v)P^p$$

$$\phi = \phi(I_v)$$

where

$$\mu(I_v) = \frac{\eta_s}{\eta_n}$$

We can directly measure

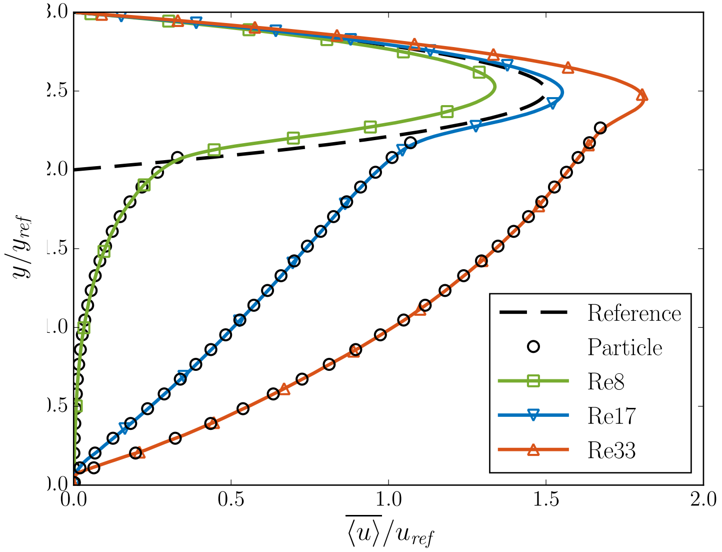
$$\mathrm{d}u/\mathrm{d}y,\ \ \phi,\ \ \tau,\ \ P^p$$

Then use the above relations to calculate

$$\eta_s,\ \ \eta_n,\ \ I_v,\ \ \mu$$

Establishing the rheology

Streamwise velocity

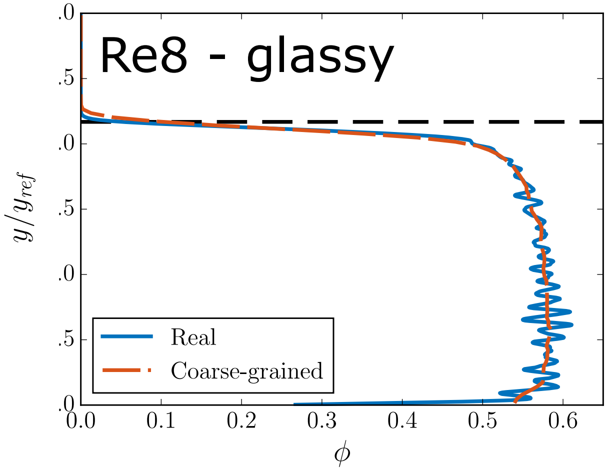


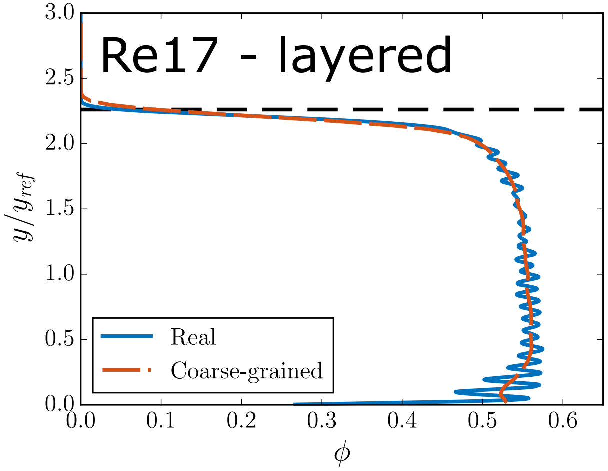
Still missing:

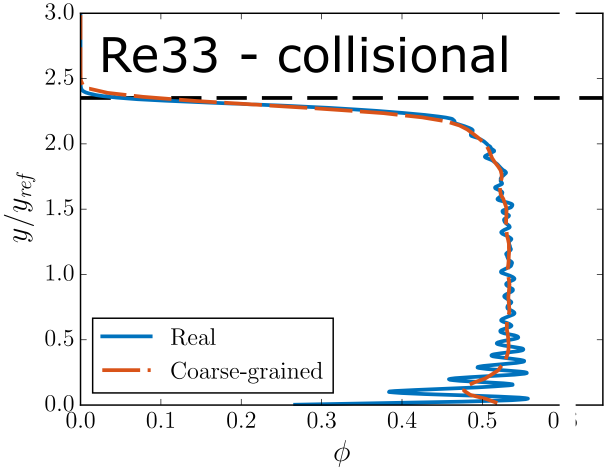
τ… Total shear

P^p… Particle pressure

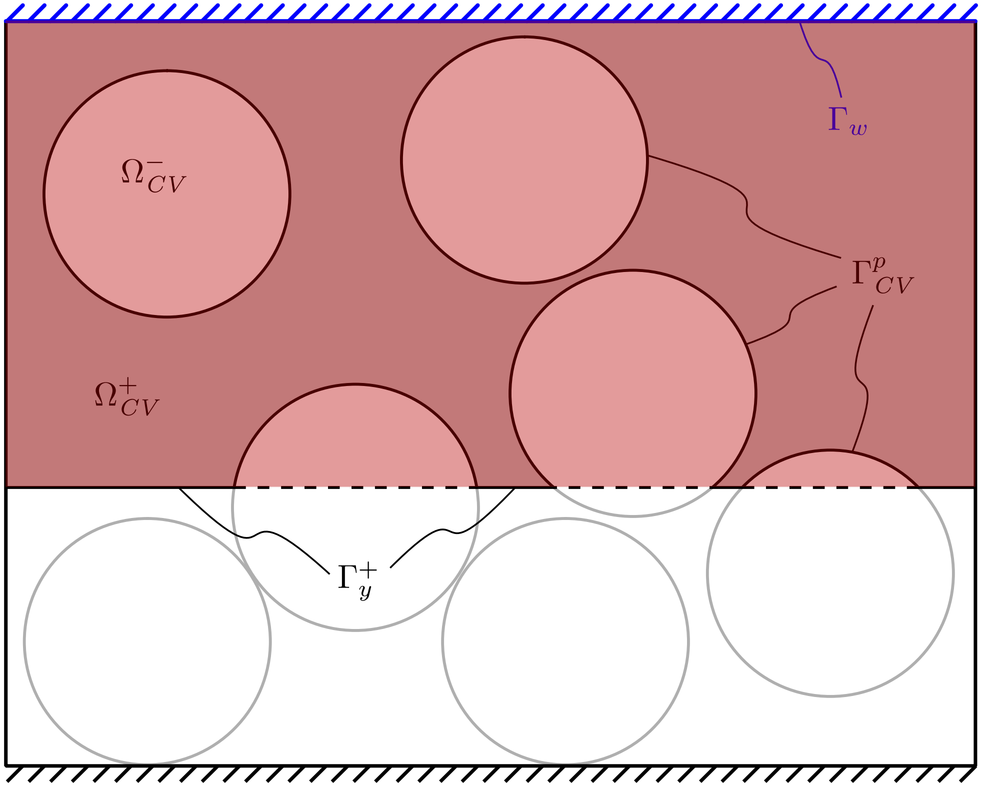
[Jenkins & Larcher, *PRF* 2017]





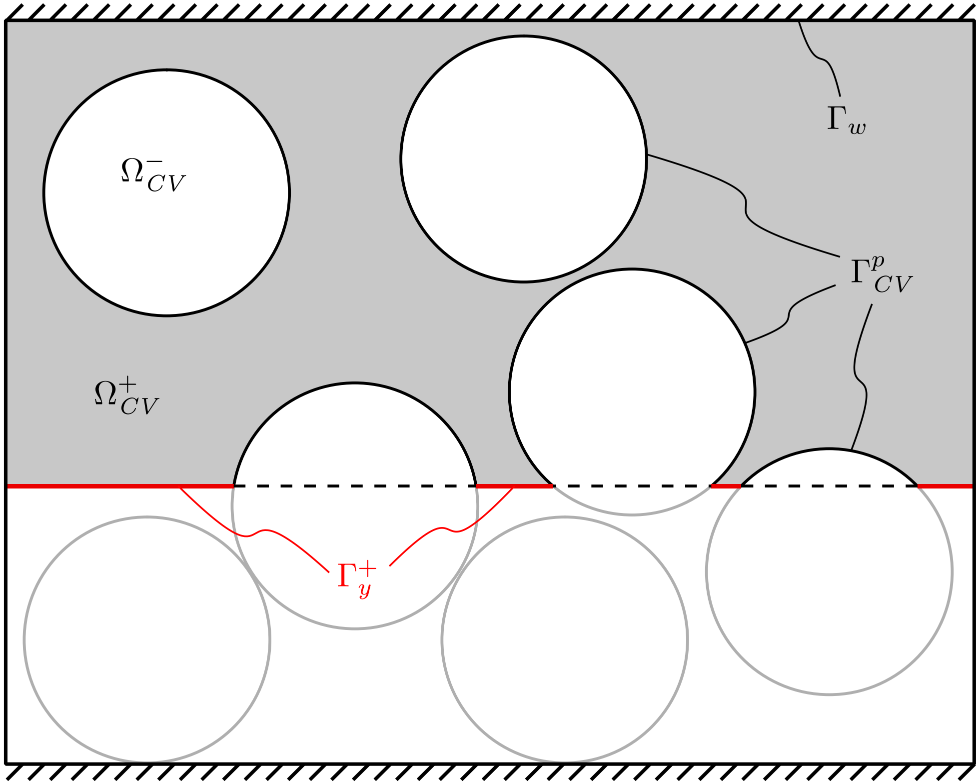


Control volume momentum balance



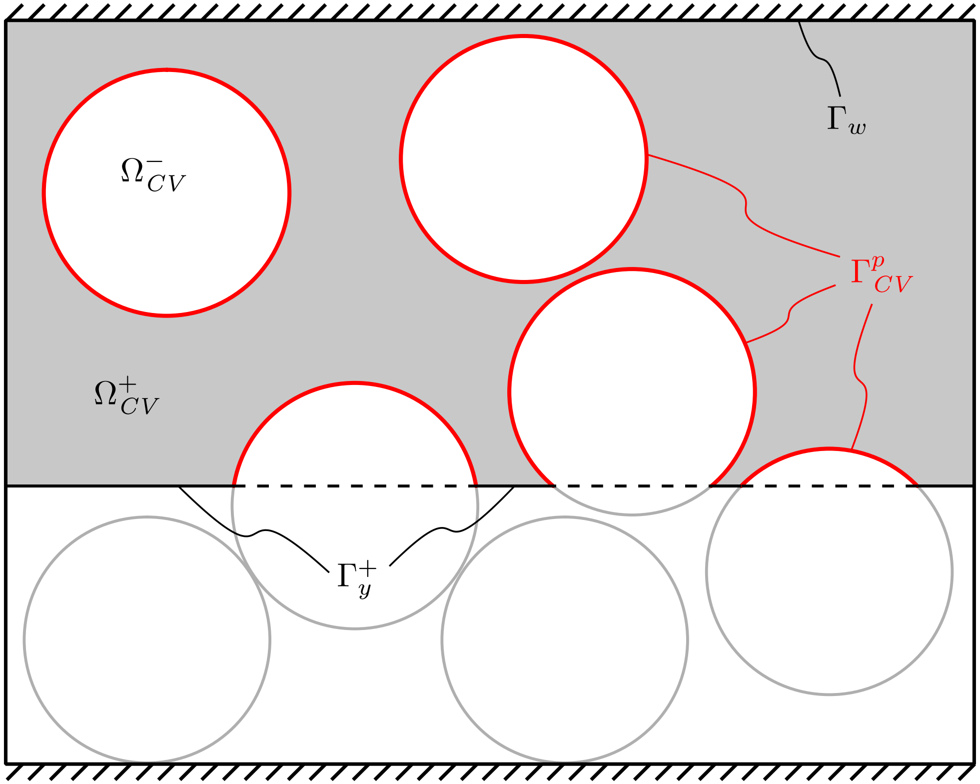
$$\underbrace{\int_{\Gamma_w} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Omega_{CV}} \mathbf{f}_b \,\mathrm{d}V}_{\text{External force}} = \underbrace{-\int_{\Gamma_y^+} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Gamma_y^+} \rho_f (\mathbf{uu}) \cdot \mathbf{n}^+ \,\mathrm{d}A}_{\text{Fluid force}} \underbrace{- \int_{\Gamma_{CV}^p} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Omega_{CV}^-} \mathbf{f}_b \,\mathrm{d}V}_{\text{Particle force}}$$

Control volume momentum balance



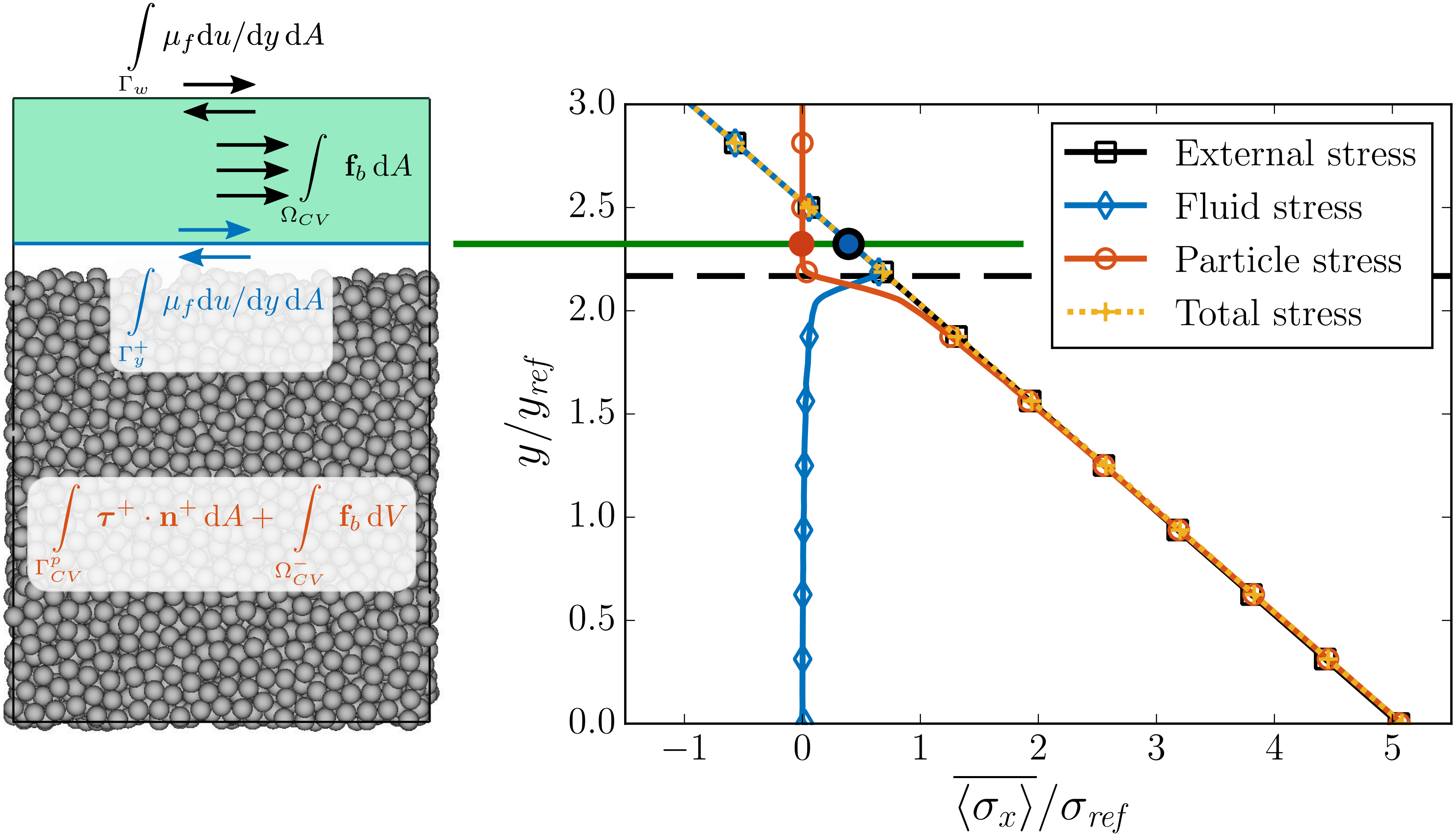
$$\underbrace{\int_{\Gamma_w} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Omega_{CV}} \mathbf{f}_b \,\mathrm{d}V}_{\text{External force}} = \underbrace{-\int_{\Gamma_y^+} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Gamma_y^+} \rho_f (\mathbf{uu}) \cdot \mathbf{n}^+ \,\mathrm{d}A}_{\text{Fluid force}} \underbrace{- \int_{\Gamma_{CV}^p} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Omega_{CV}^-} \mathbf{f}_b \,\mathrm{d}V}_{\text{Particle force}}$$

Control volume momentum balance

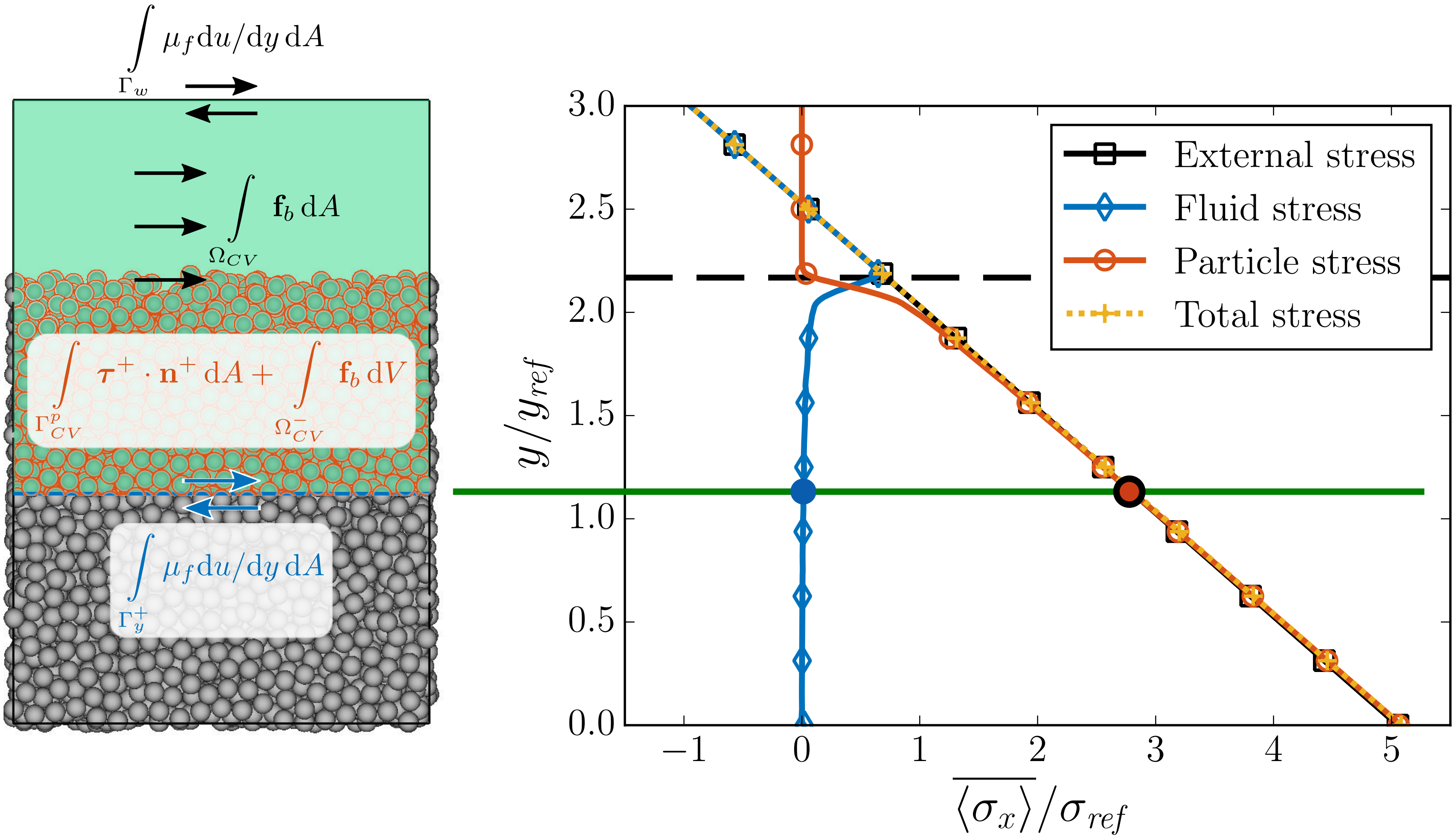


$$\underbrace{\int_{\Gamma_w} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Omega_{CV}} \mathbf{f}_b \,\mathrm{d}V}_{\text{External force}} = \underbrace{-\int_{\Gamma_y^+} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Gamma_y^+} \rho_f (\mathbf{uu}) \cdot \mathbf{n}^+ \,\mathrm{d}A}_{\text{Fluid force}} \underbrace{- \int_{\Gamma^p_{CV}} \boldsymbol{\tau}^+ \cdot \mathbf{n}^+ \,\mathrm{d}A + \int_{\Omega^-_{CV}} \mathbf{f}_b \,\mathrm{d}V}_{\text{Particle force}}$$

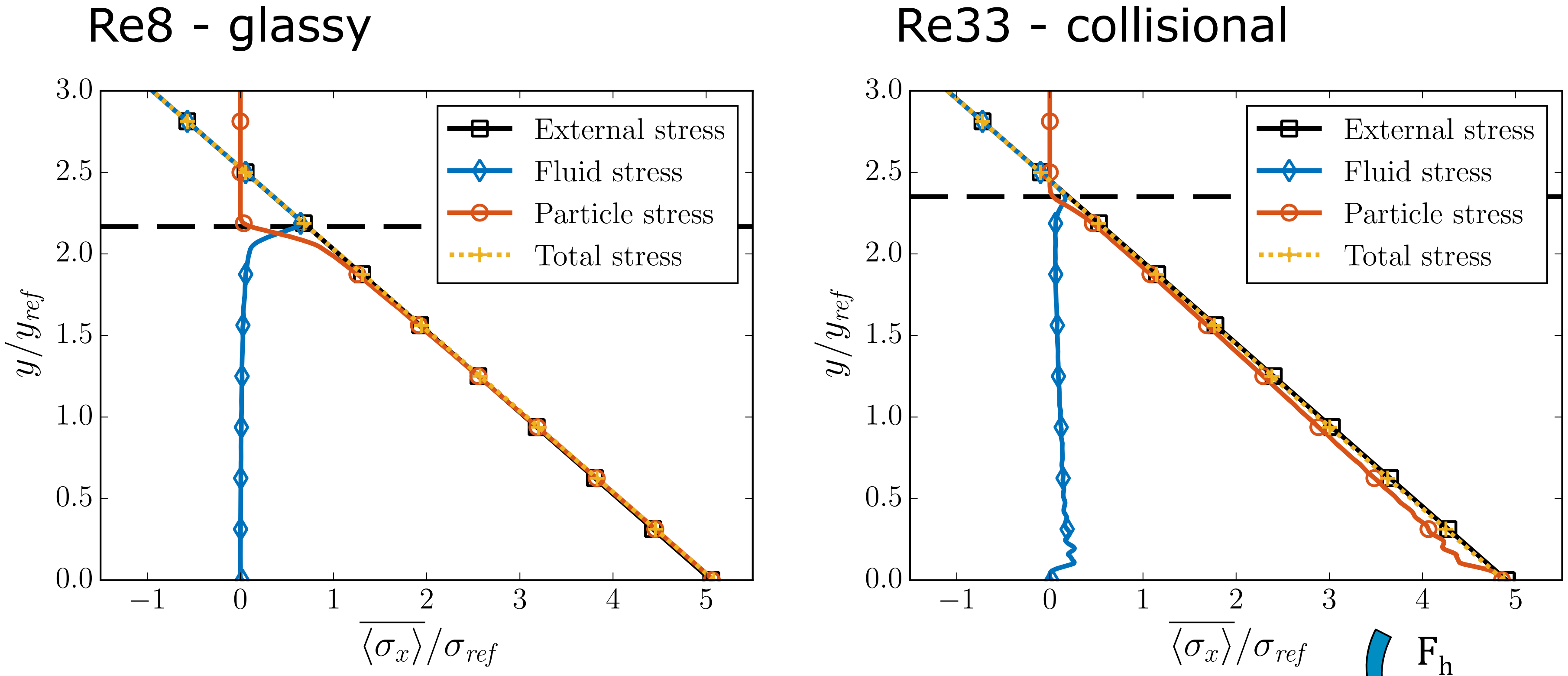
Fluid momentum balance in the x-direction



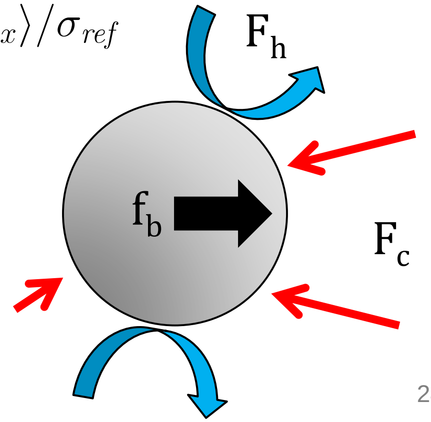
Fluid momentum balance in the x-direction



Fluid momentum balance in the x-direction

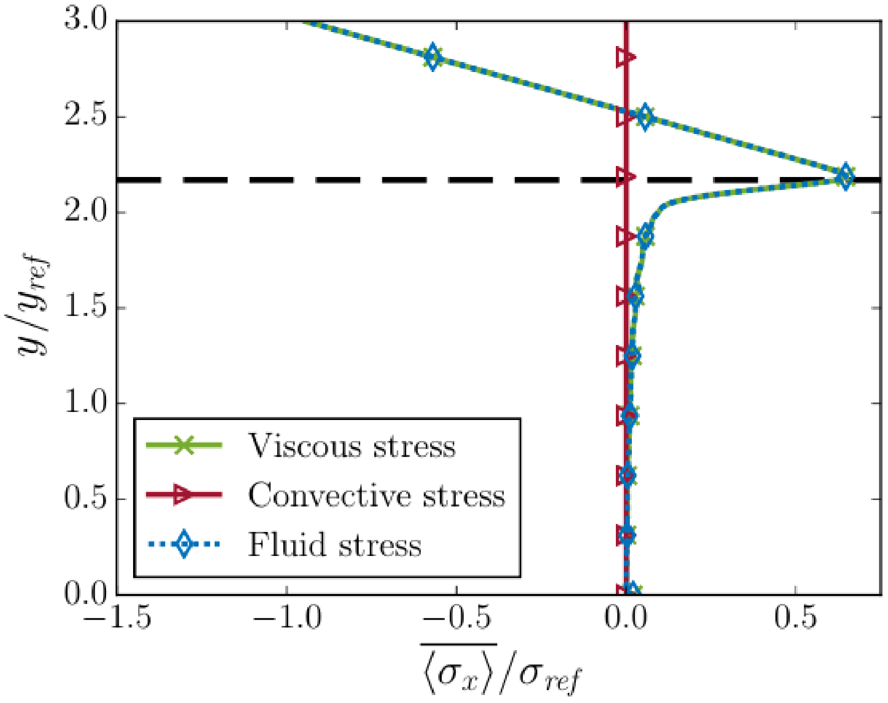


- Stress balance is in equilibrium
- Particles carry the stress within the bed

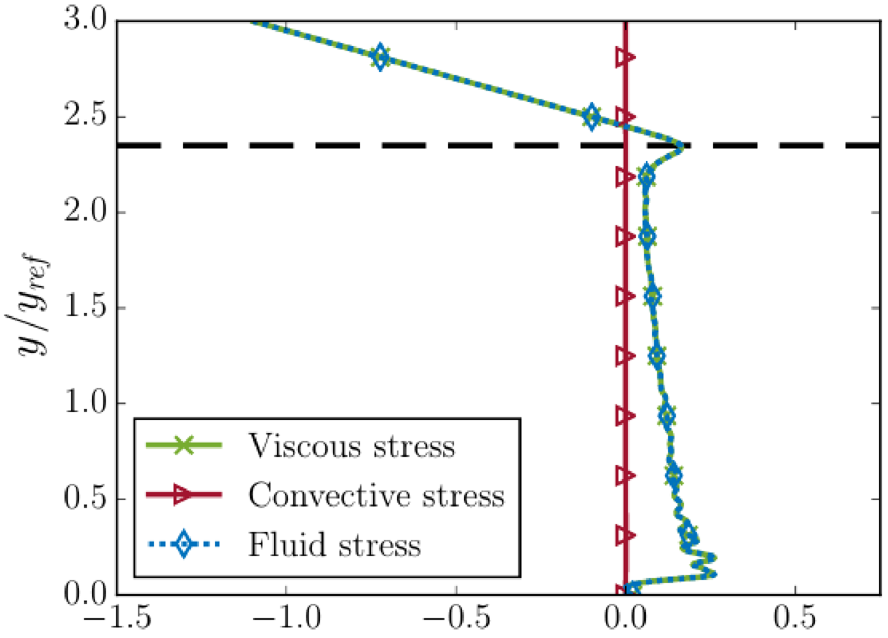


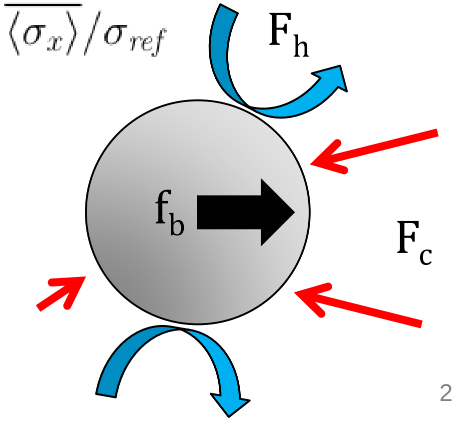
Fluid stress in the x-direction

Re8 - glassy



Re33 - collisional

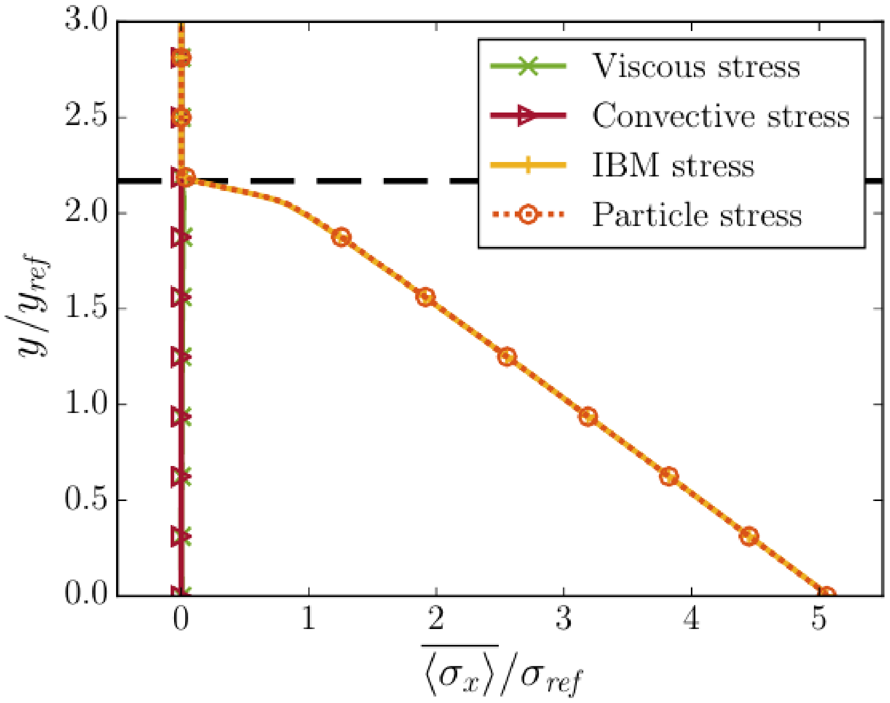




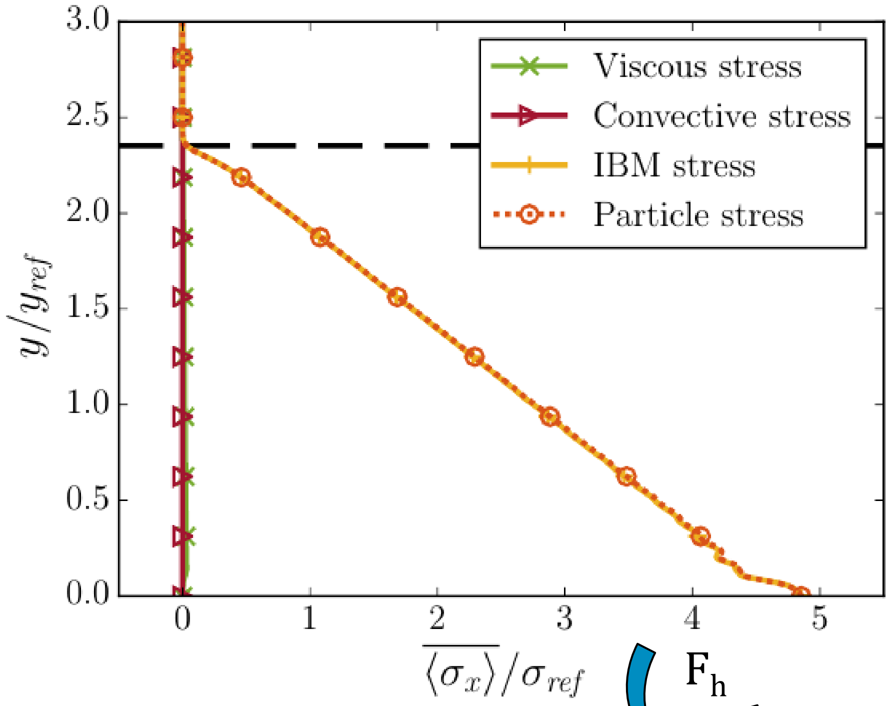
- Dominated by viscous stress

Particle stress in the x-direction

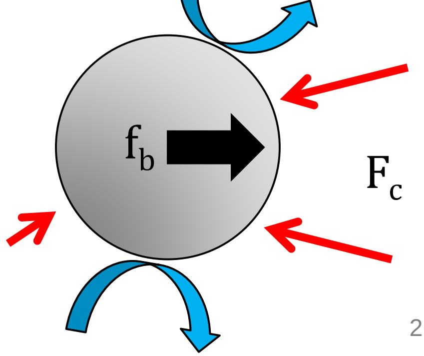
Re8 - glassy



Re33 - collisional

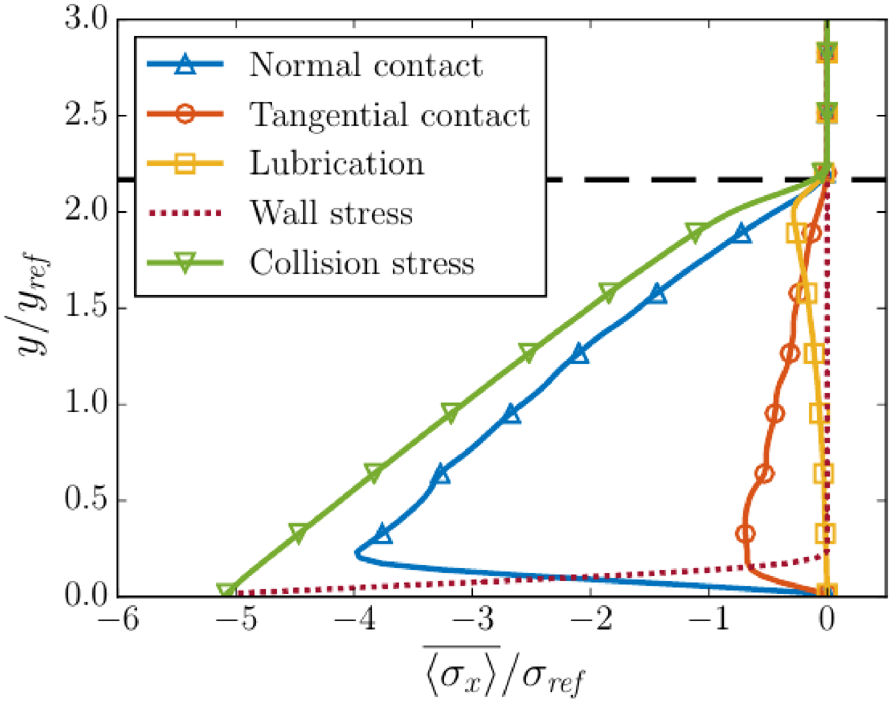


- Dominated by collision stress

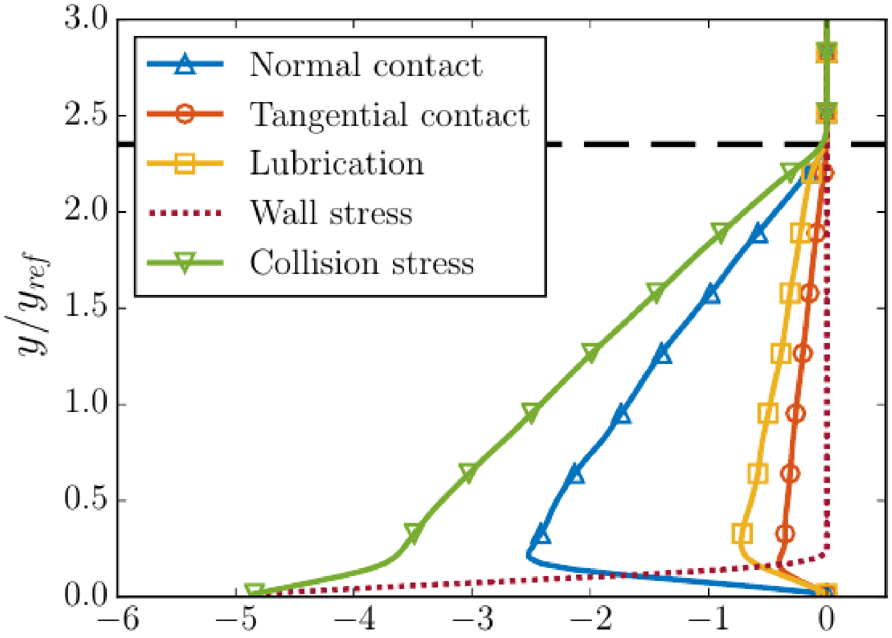


Collision stress in the x-direction

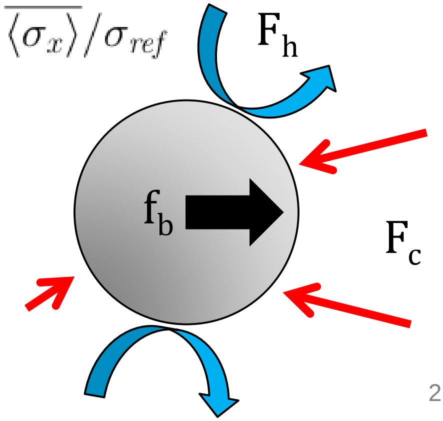
Re8 - glassy



Re33 - collisional

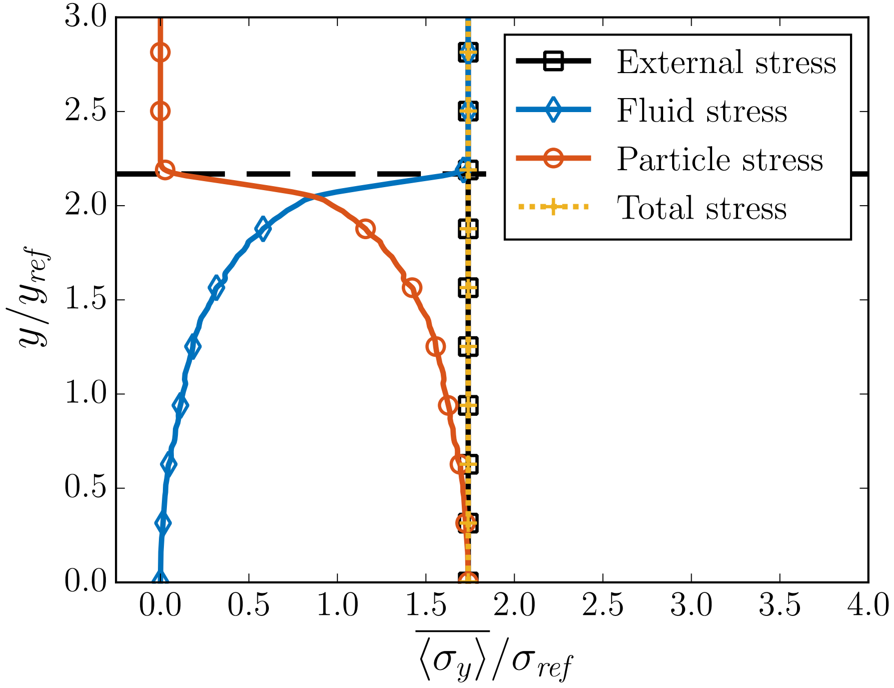


- Dominated by normal contact

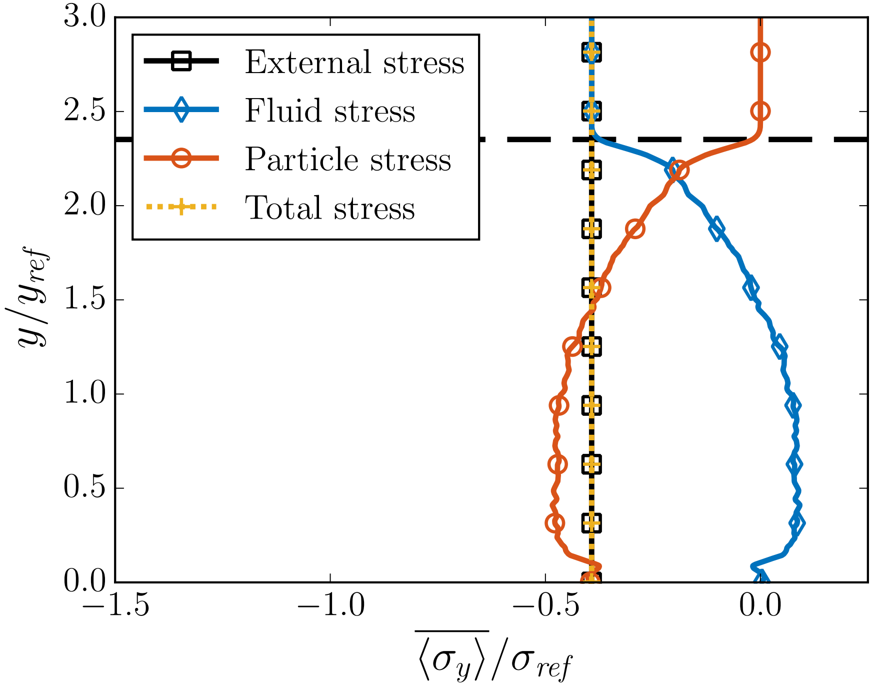


Fluid momentum balance in the y-direction

Re8 - glassy

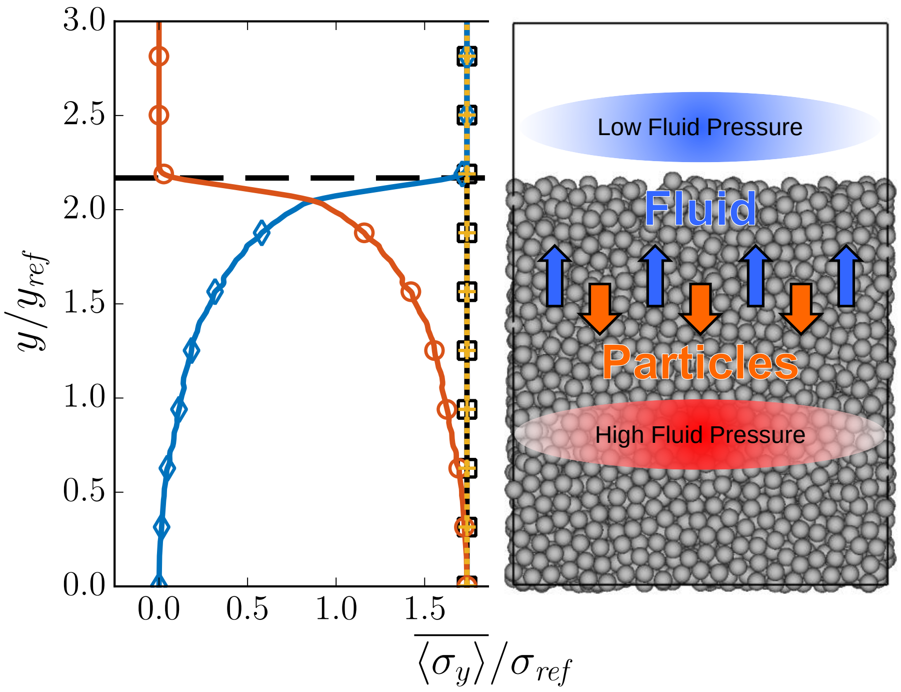


Re33 - collisional

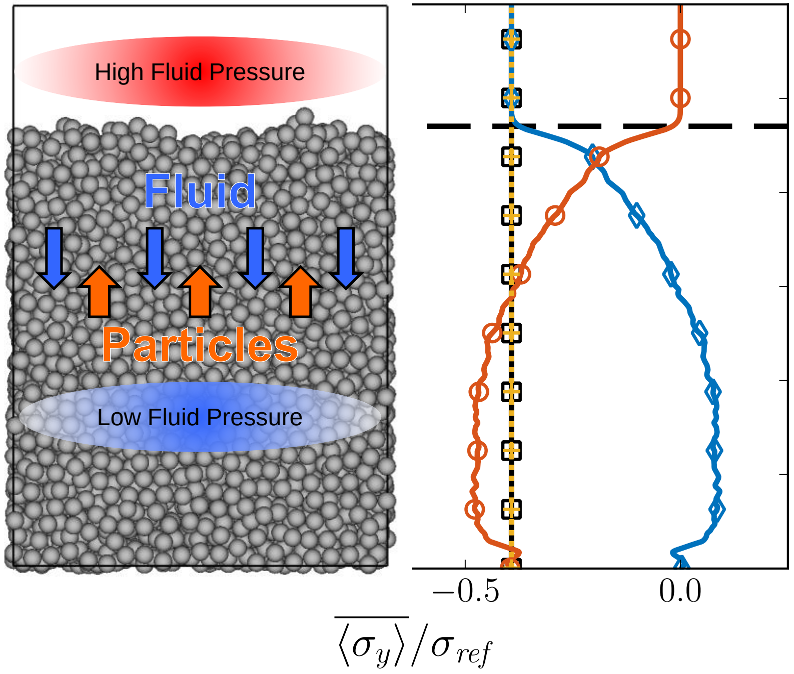


Fluid momentum balance in the y-direction

Re8 - glassy



Re33 - collisional



- Re8 contracting

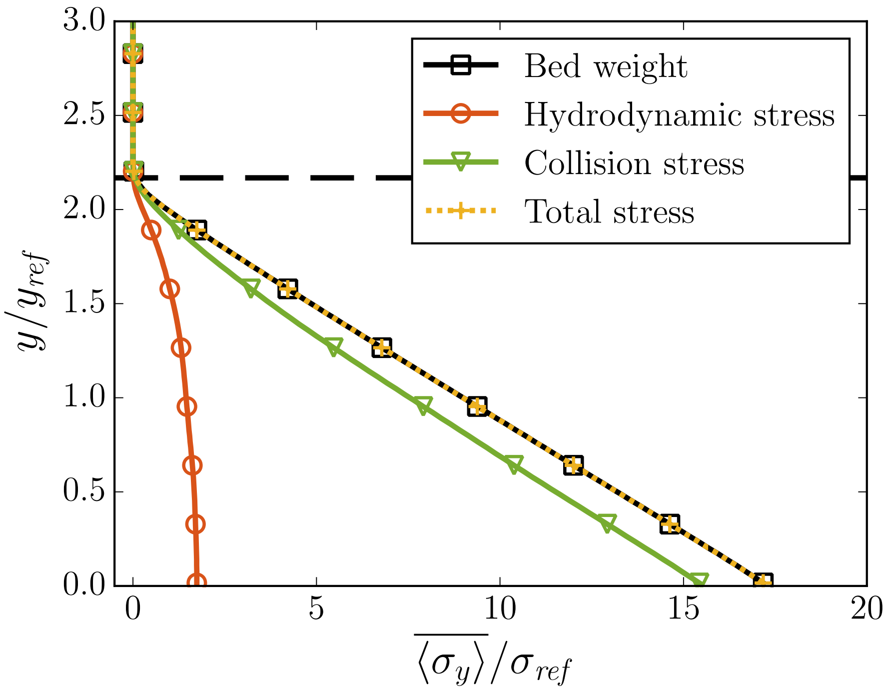
→ Dewatering

- Re33 dilating

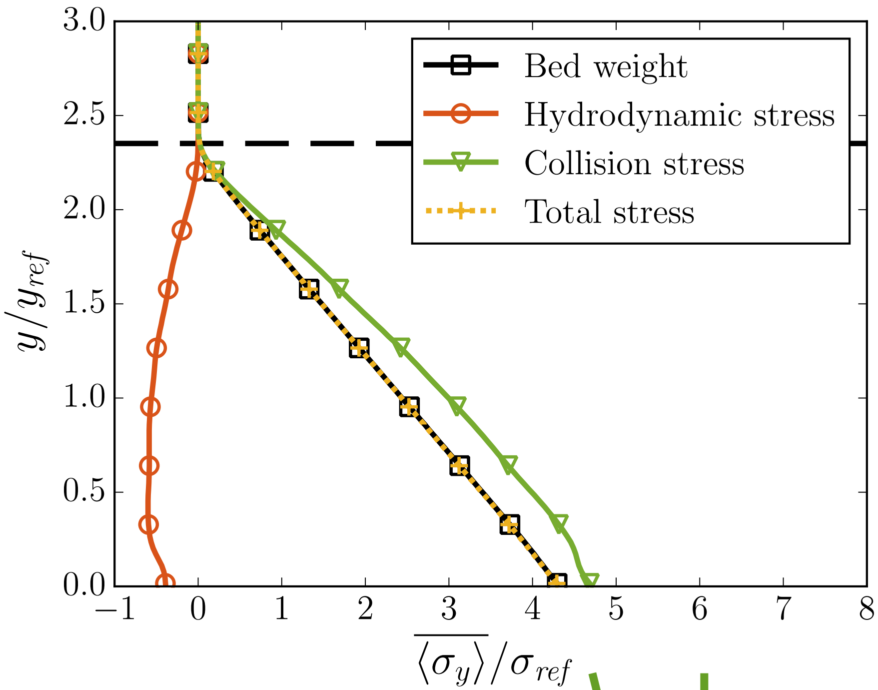
→ Fluidizing

Particle momentum balance in the y-direction

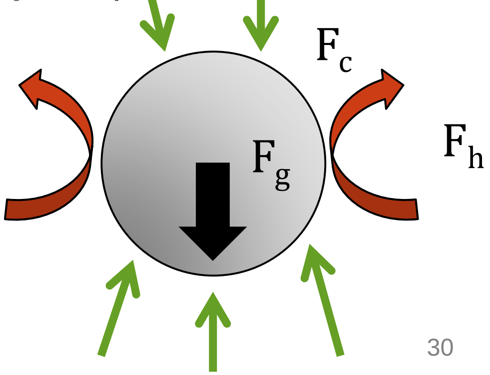
Re8 - glassy



Re33 - collisional

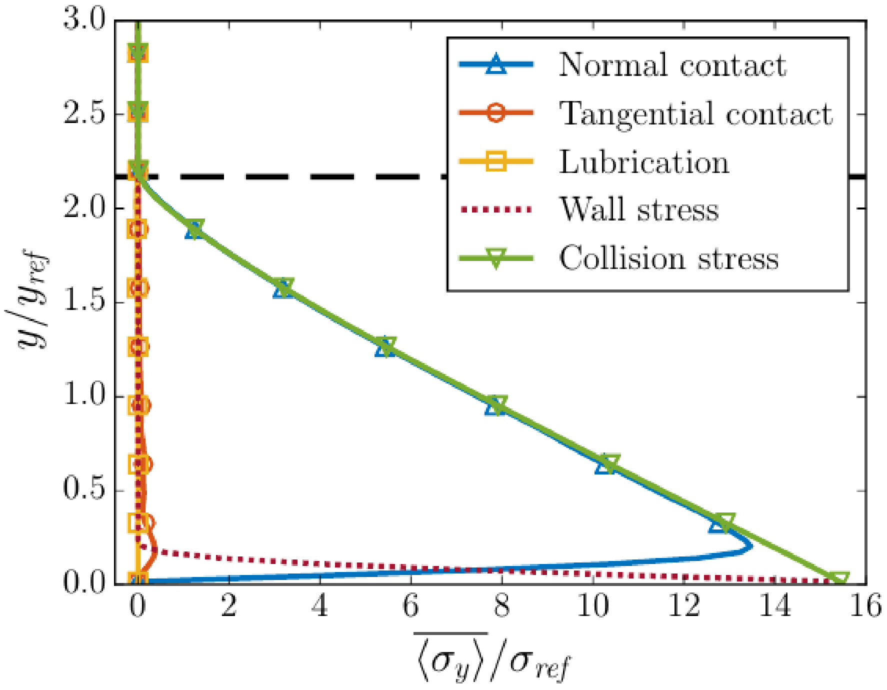


- Granular pressure = bed weight

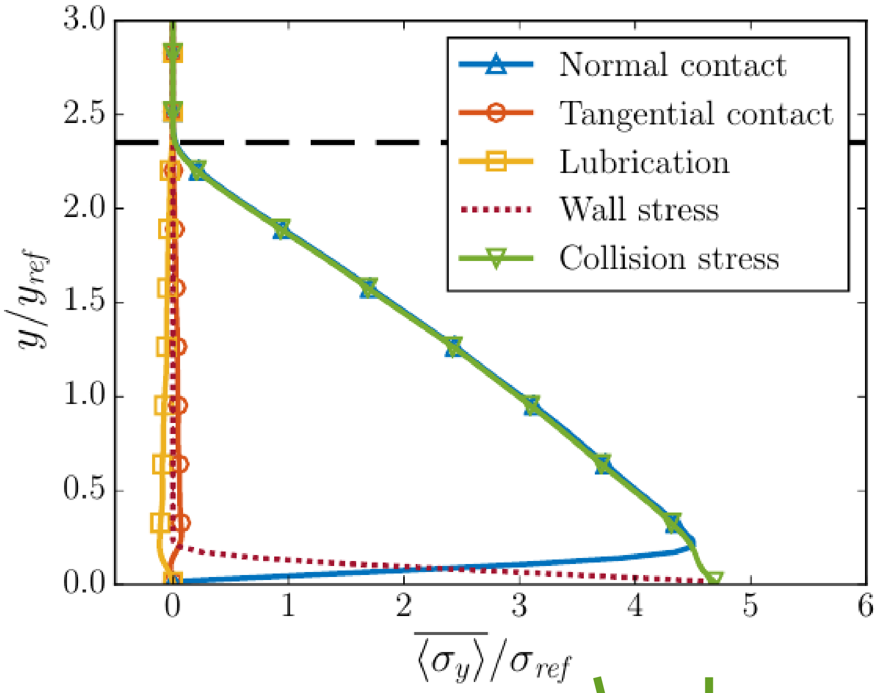


Collision stress in the y-direction

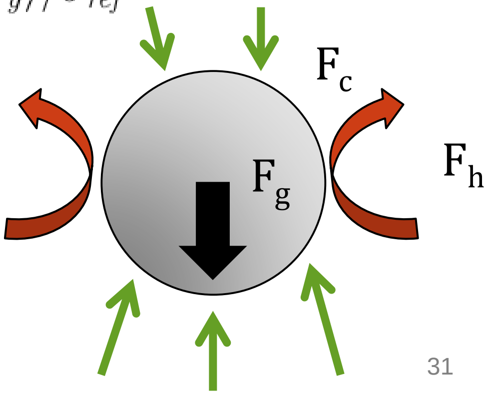
Re8 - glassy



Re33 - collisional

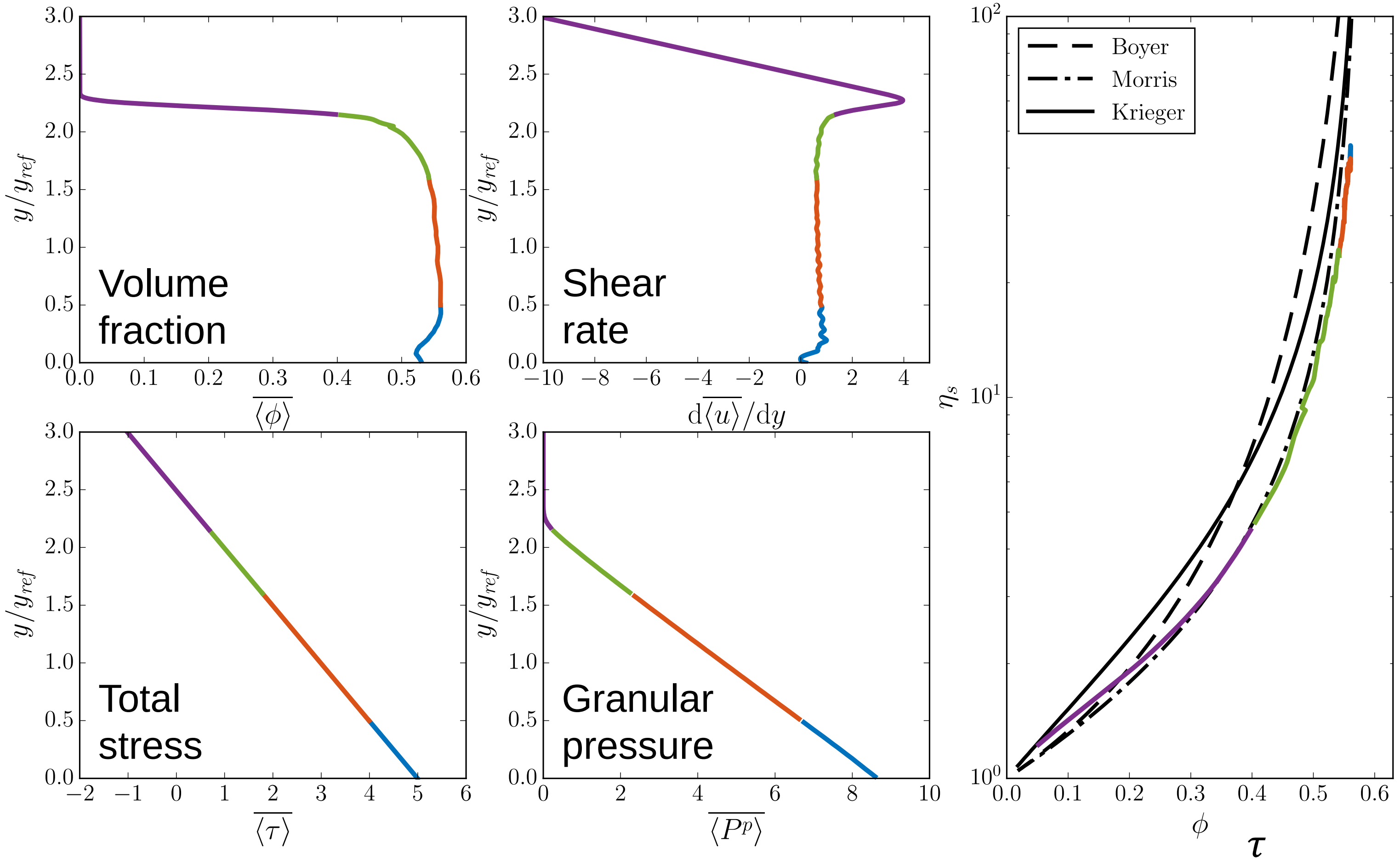


- Granular pressure = bed weight



Measuring the rheology of our simulations

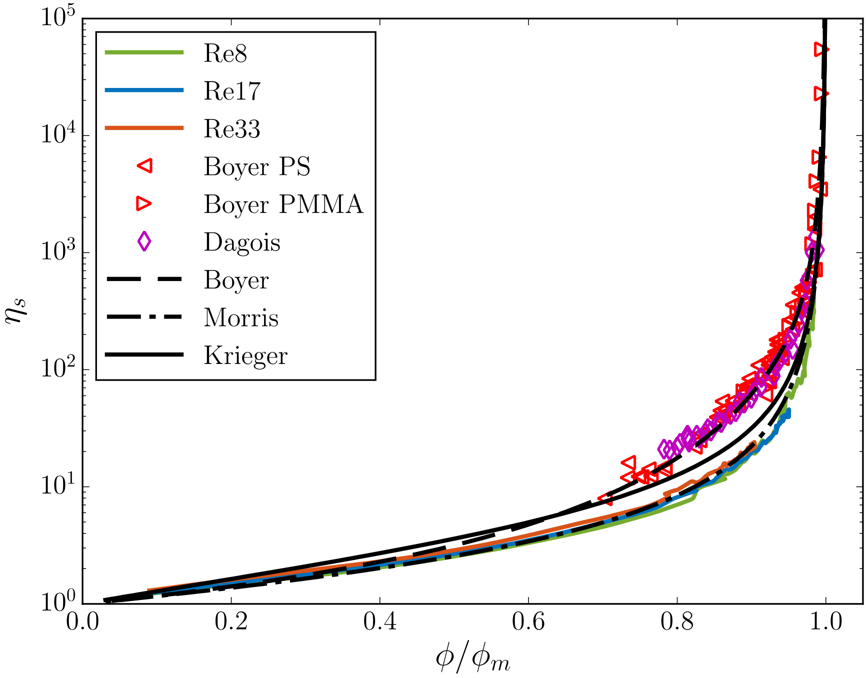
Effective shear viscosity



$$\eta_s(\phi) = \frac{\tau}{\eta_f \, \mathrm{d}u/\mathrm{d}y}$$

Effective shear viscosity results

$$\eta_s(\phi) = \frac{\tau}{\eta_f \mathrm{d}u/\mathrm{d}y}$$

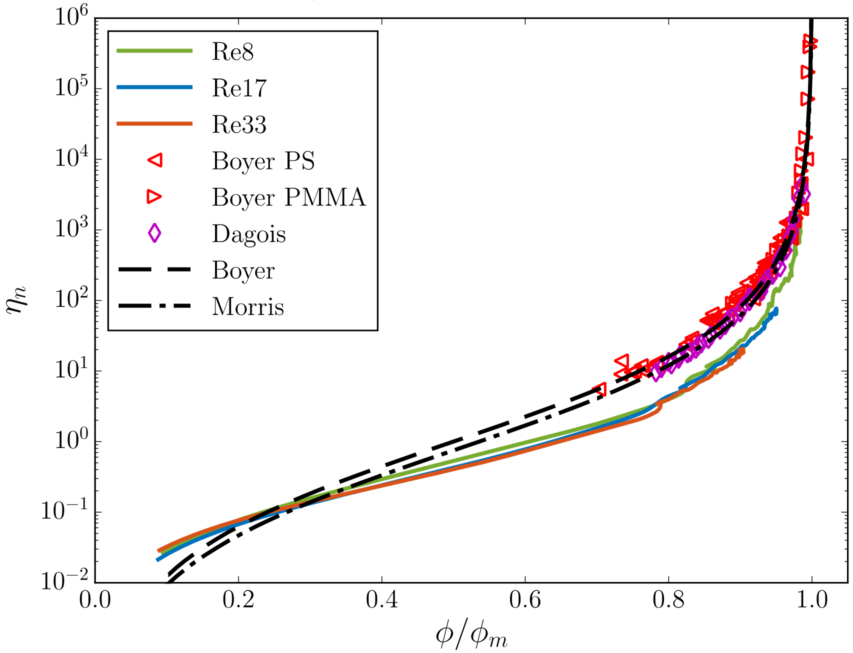


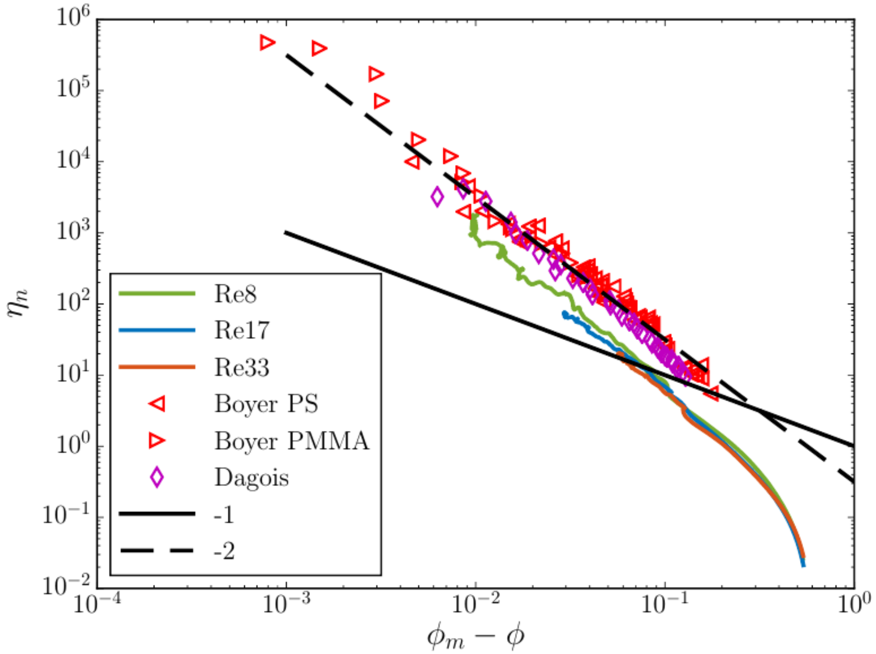
- Collapse for different Reynolds numbers
- Match Morris model well
- Underpredict experimental data
- Match expected behavior at low volume fractions

Models of Boyer et al. [*PRL.* 2011], Morris and Boulay [*JoR*1999], and Krieger and Dougherty [*Trans. Soc. Rheol.* 1959]
Experiments of Boyer et al. [*PRL* 2011] and Dagois-Bohy et al. [*JFM* 2015]

Effective normal viscosity results

$$\eta_n(\phi) = \frac{P^p}{\eta_f \mathrm{d}u/\mathrm{d}y}$$





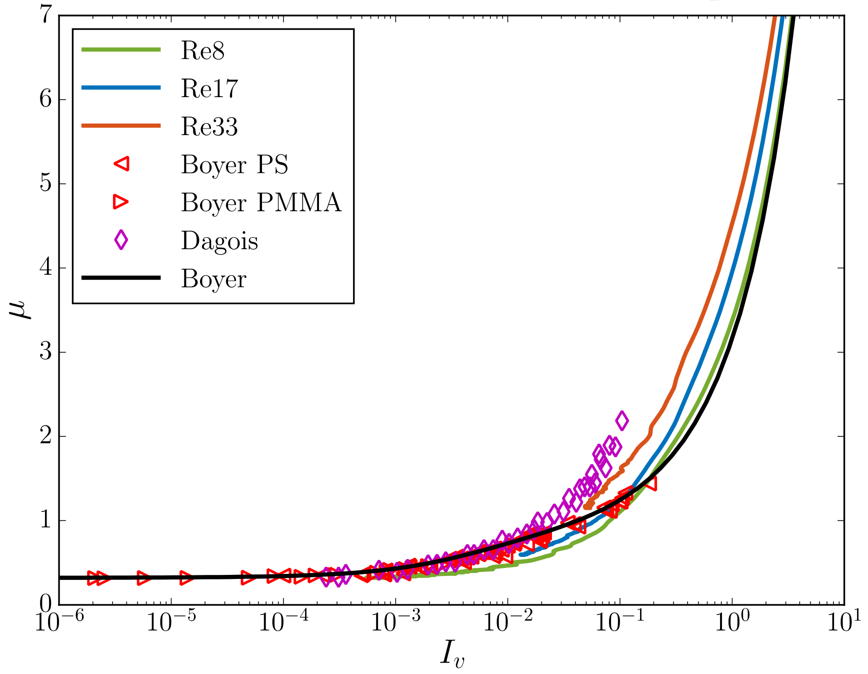
- Collapse for different Reynolds numbers
- Underpredict models and experimental data

- Nonlinear viscous scaling

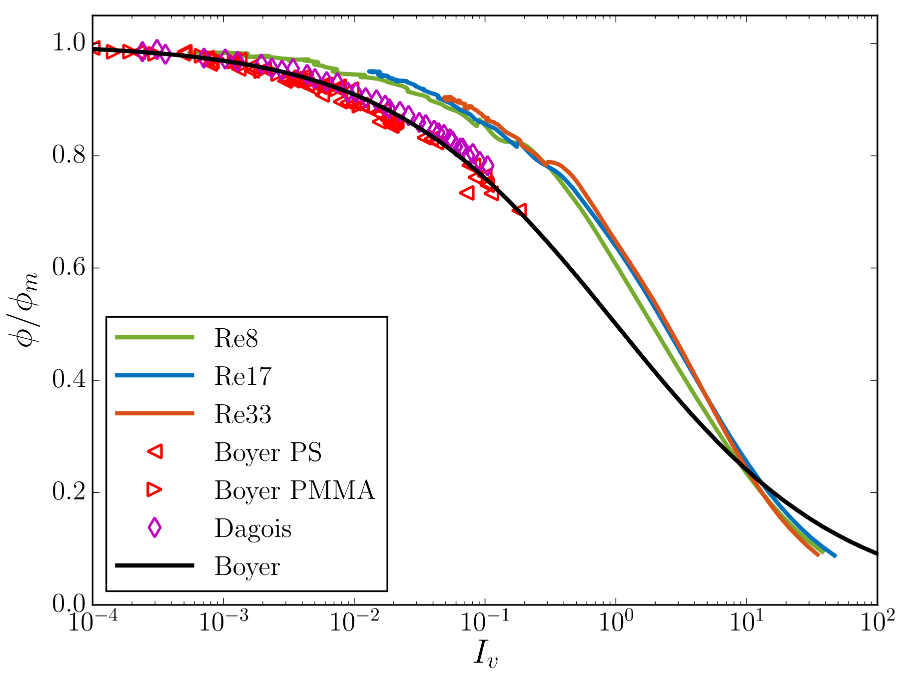
Models of Boyer et al. [*PRL* 2011] and Morris and Boulay [*JoR* 1999]
Experiments of Boyer et al. [*PRL* 2011] and Dagois-Bohy et al. [*JFM* 2015]

Macroscopic friction results

Friction coefficient $\mu(I_v) = \frac{\tau}{P^p}$



Volume fraction $\phi = \phi(I_v)$



$$I_v = \frac{\eta_f \mathrm{d}u/\mathrm{d}y}{P^p}$$

Model of Boyer et al. [*PRL* 2011]
Experiments of Boyer et al. [*PRL* 2011] and Dagois-Bohy et al. [*JFM* 2015]

Conclusions

- Equilibrium of particle and fluid stresses

  → even for dilating/contracting beds

- Lift forces indicate bed dilation/contraction

  → compensated by top wall fluid pressure

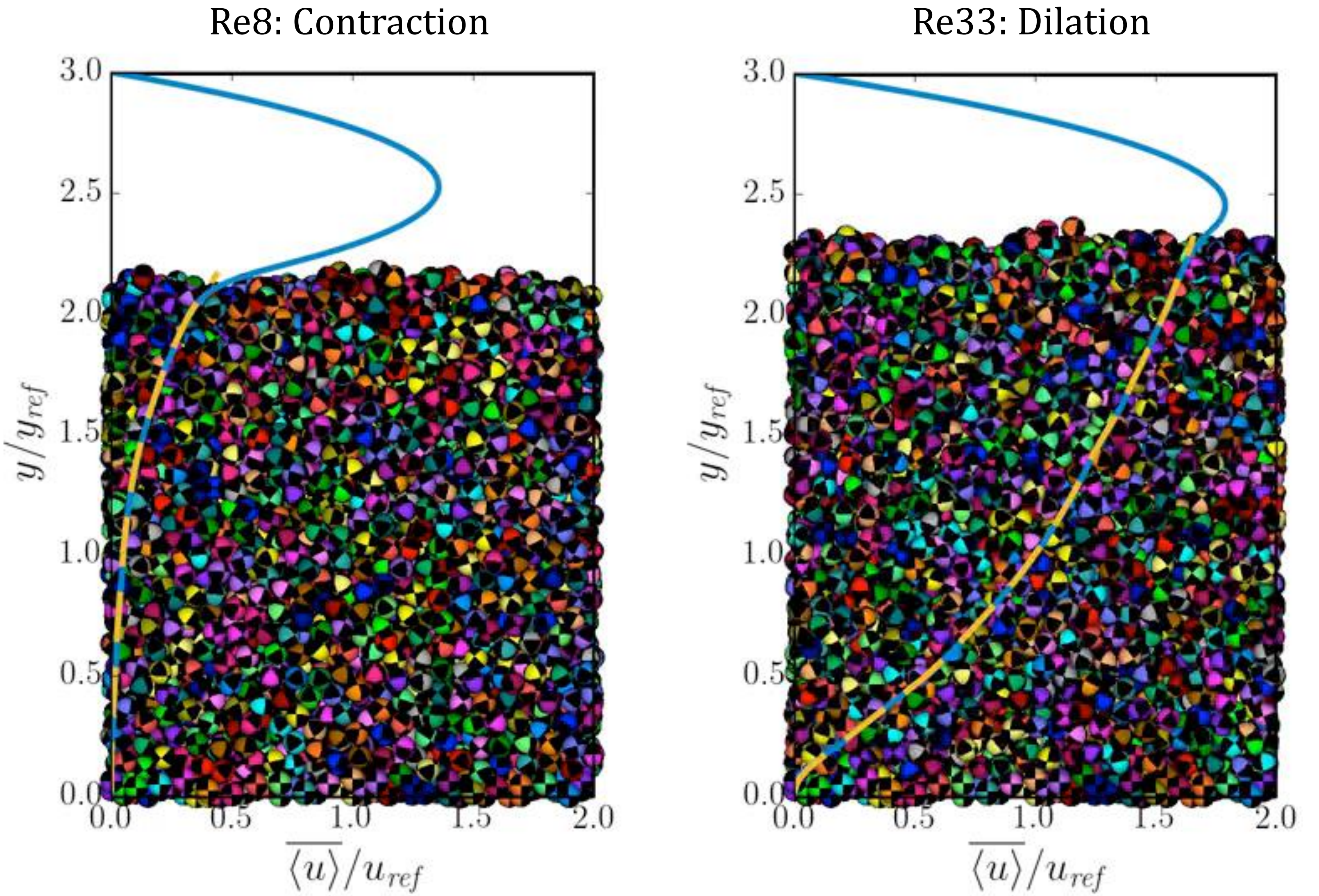
- Simulation results compare well to existing rheology models

  → predict shear stress of particle beds

- Models do not predict particle pressure of simulated beds
- Rheology frameworks might be applicable to this situation due to collapse of simulation data

Thank you!

Backup-slides


Re8: Contraction
Re33: Dilation
3.0
2.5
2.0
1.5
1.0
0.5
0.0
y/y_{ref}
0.0
0.5
1.0
1.5
2.0
$\overline{\langle u \rangle}/u_{ref}$

Particle momentum balance in the x-direction

- Hydrodynamic forces, F_h
  - Pressure gradient + fluid drag
- Collision forces, F_c