TECHNISCHE UNIVERSITÄT DRESDEN

41ST IAHR WORLD CONGRESS SINGAPORE
22 – 27 JUNE 2025
INNOVATIVE WATER ENGINEERING FOR SUSTAINABLE DEVELOPMENT

Small is Beautiful:

What we can learn from grain-scale processes about sediment transport

Bernhard Vowinckel

24th Arthur Thomas Ippen Award
41st IAHR World Congress
June 26, 2025, Singapore

About me

Diploma
Hydrology

PhD
Fluid Mechanics
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Vlad Nikora

Postdoc on geophysical flows

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Starting grant research group:
Cohesive sediment dynamics
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LWI Leichtweiß-Institut

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2009 — 2015 — 2020 — 2023

IAHR AIRH

Journal of Hydraulic Research

Started reviewing

Joined editorial
board in 2024

Harold Jan
Schoemaker prize

9th Gerhard Jirka Summer School

Three types of grain-scale processes

Flocculation of fine-grained sediments

- Flocculation experiments of real clays onboard the International Space Station (ISS)
- Focus on cohesive forces of clay minerals
- Long term observations that are not possible on Earth

Satellite image of the Mississippi estuary

Flocculation under microgravity

Cape Canaveral, FL, June 29, 2018

Focus on

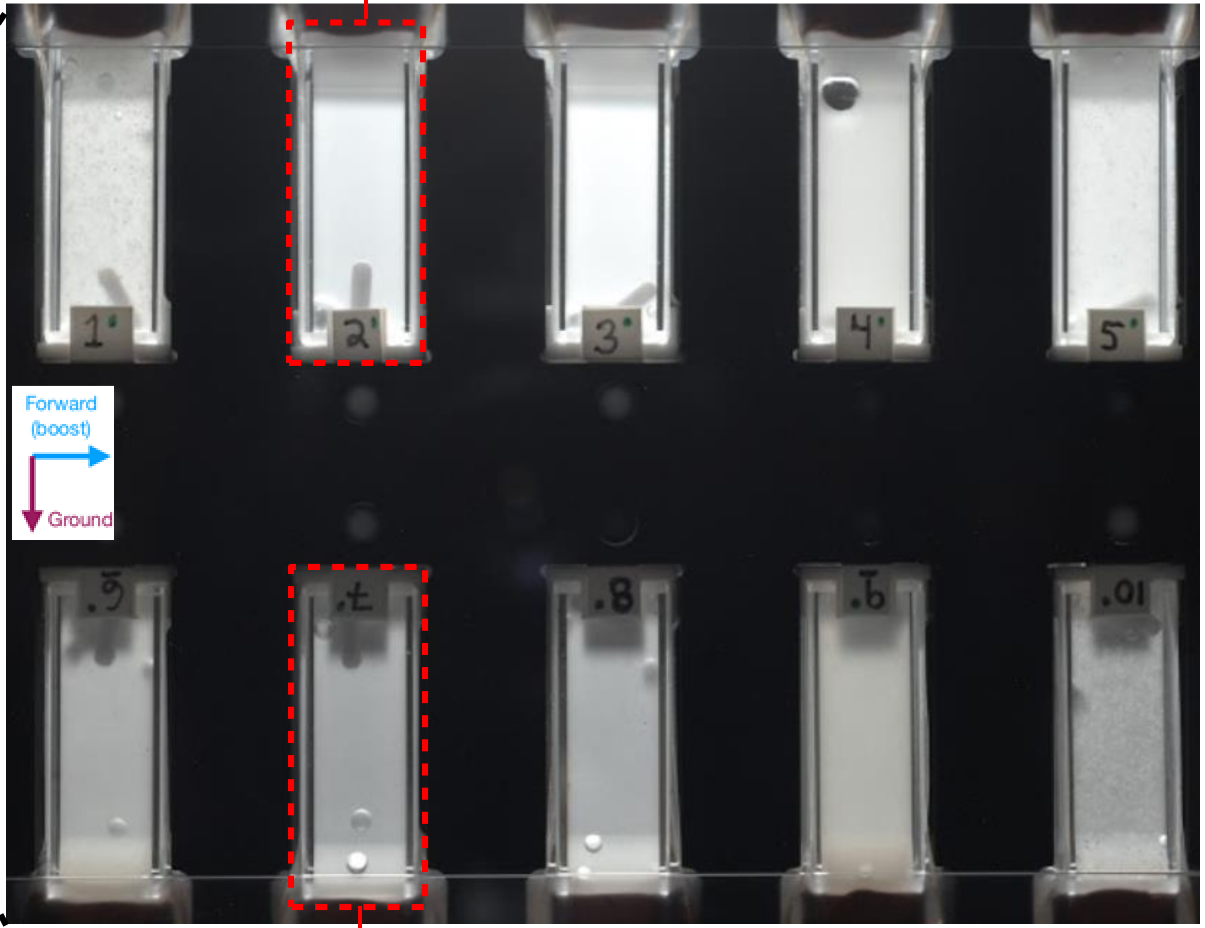
- Salinity comparable to ocean water
- Kaolinite, Montmorillonite and sand

[Krahl et al., 2022; Rommelfanger et al., 2022]

Experimental setup

- Constant monitoring
- Observation time: 99 days

Cuvette no. 2: 8 ppt Kaolinite

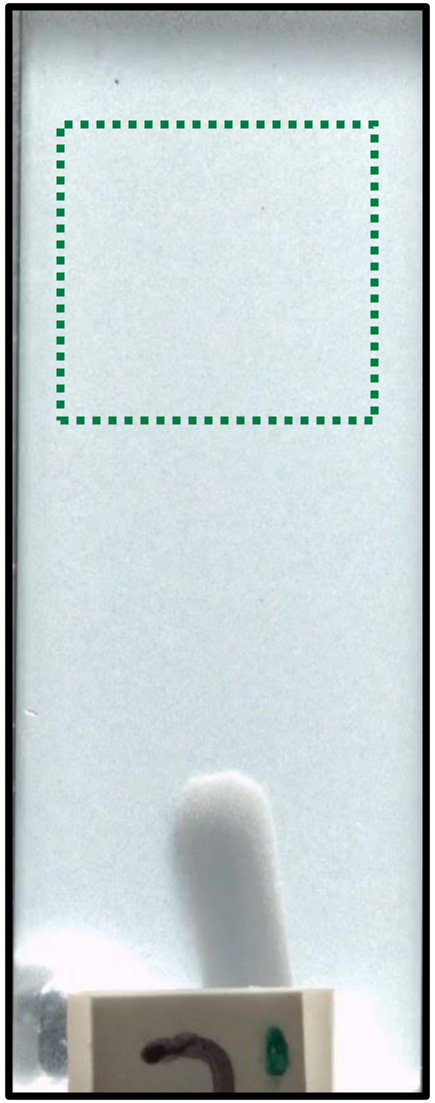


Cuvette no. 7: 4 ppt Kaolinite
4 ppt Montmorillonite

Binary Colloidal Alloy Test (BCAT) apparatus with magnetic bead for stirring

Image recordings

With Fabian Kleischmann



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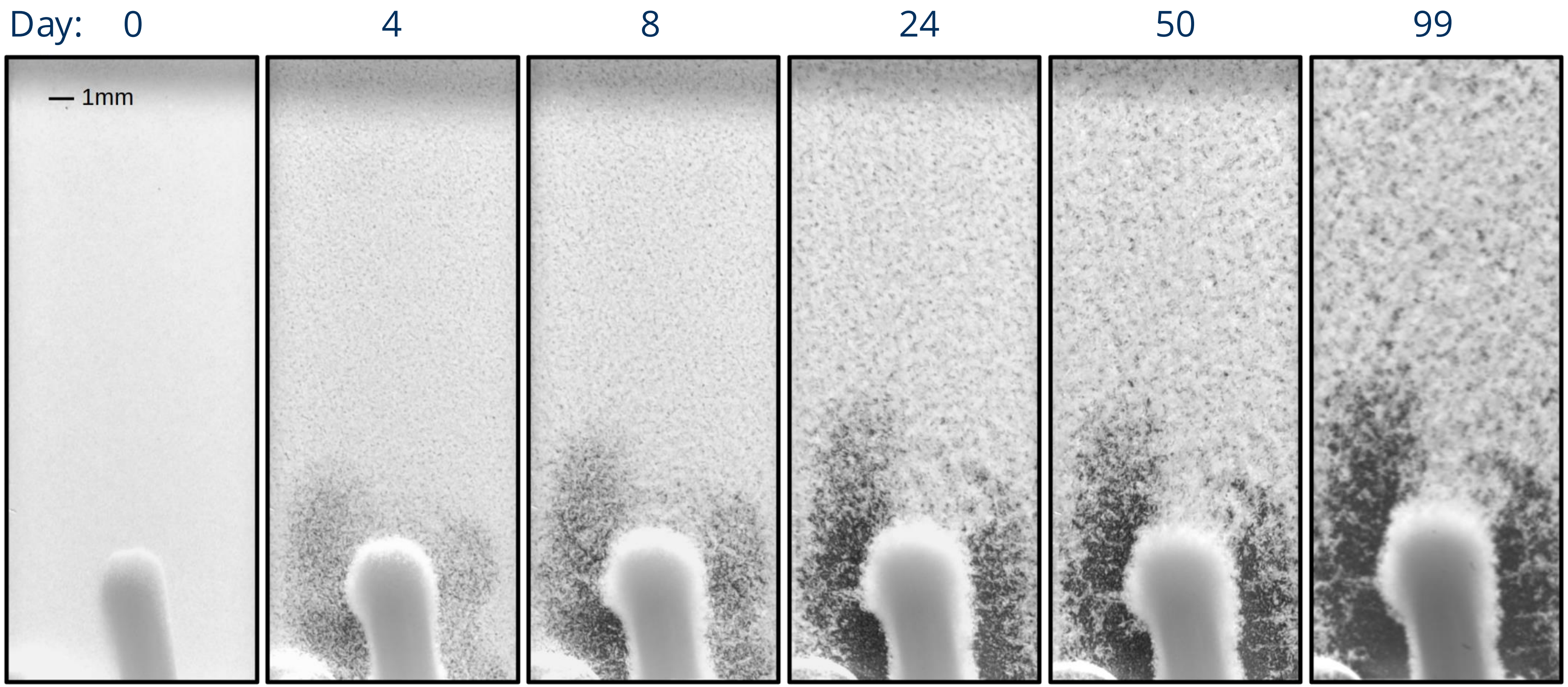
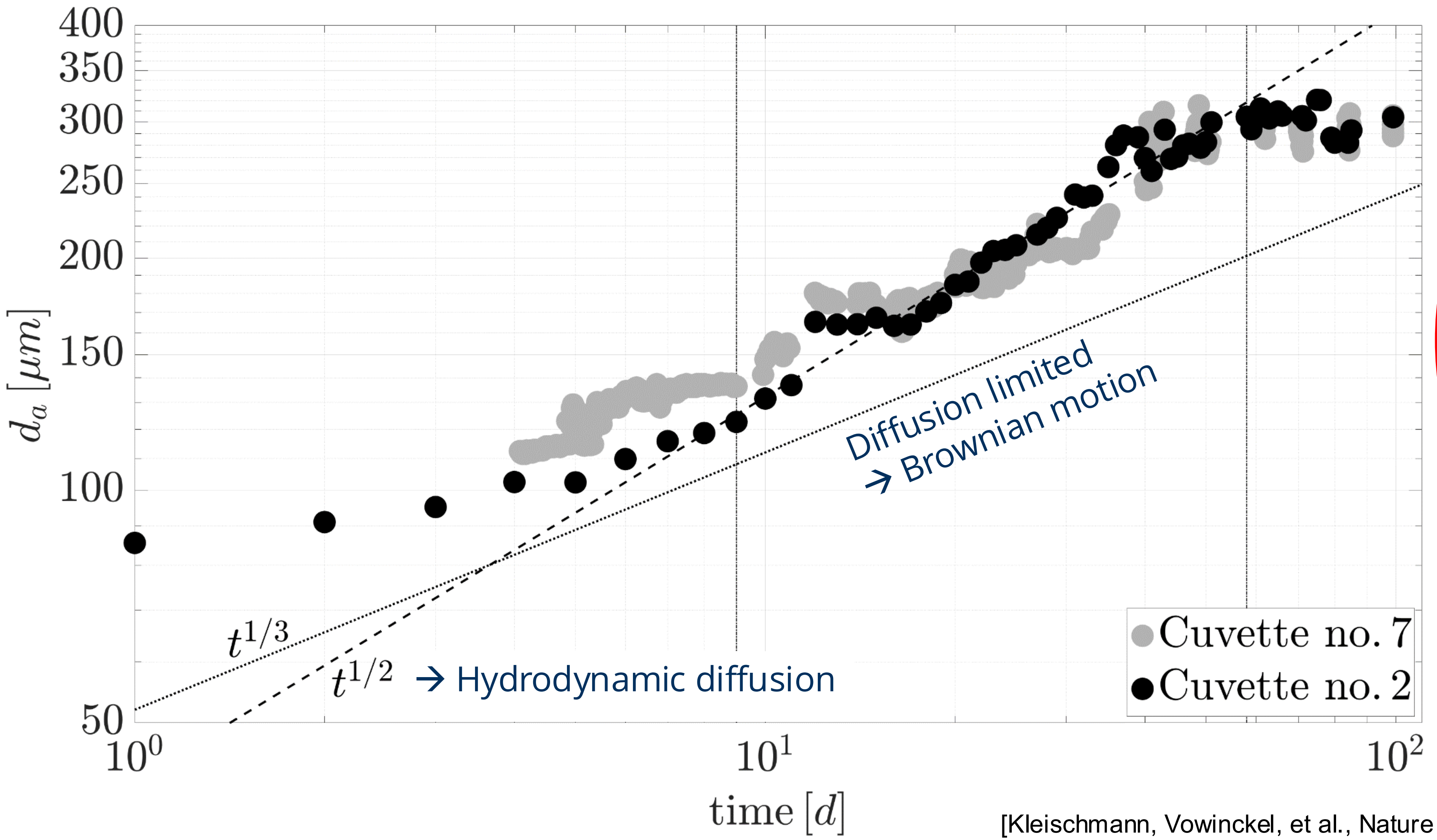


First 8 days

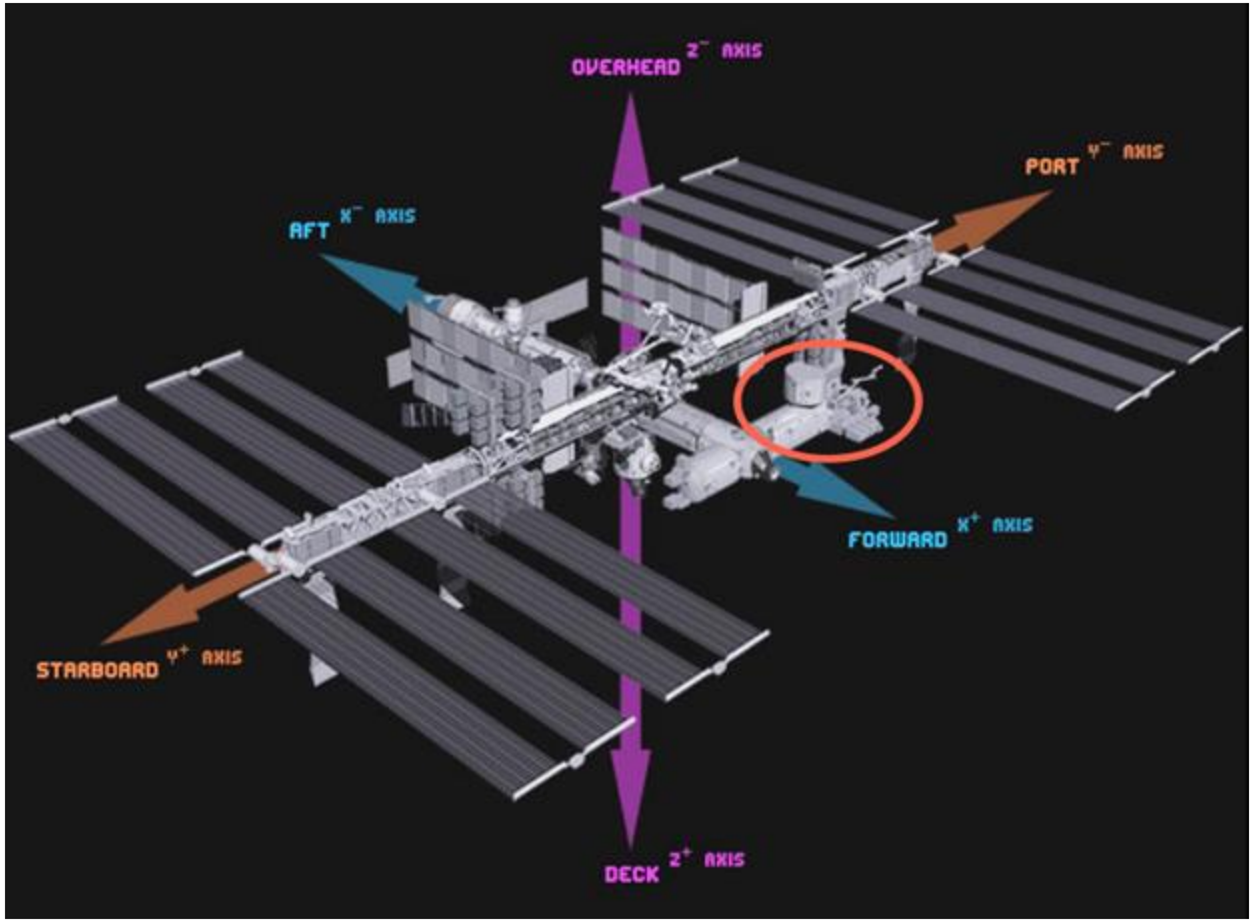
Aggregate growth



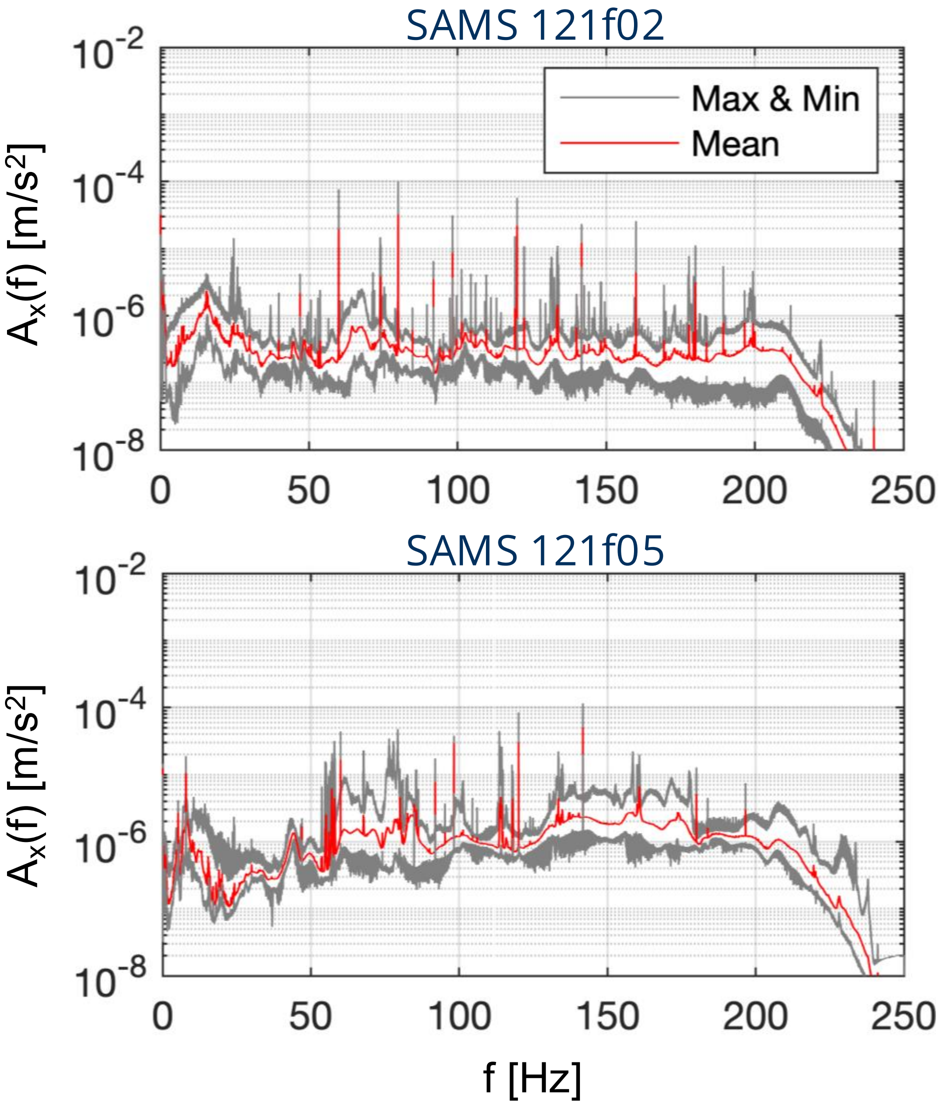
What is causing the prolonged hydrodynamic diffusion?

[Kleischmann, Vowinckel, et al., Nature Microgravity, in revision, arXiv:2505.13467]

Oscillations (g-jitter)



(NASA, 2018)



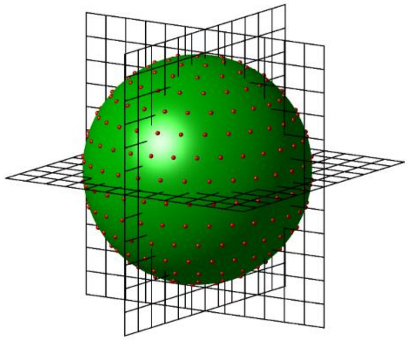
Particle-resolved Direct Numerical Simulations

Basic Fluid Solver

$$\frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{u}) + \frac{1}{\rho}\nabla p = \nu \nabla^2 \mathbf{u} + \mathbf{f}_{drag}$$

Fully-resolved [Uhlmann, 2005]

→ Particle larger than grid cell size



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

Immersed Boundary Method (IBM)

$$m_p \frac{\mathrm{d}\mathbf{u}_p}{\mathrm{d}t} = \mathbf{F}_h + (\rho_p - \rho_f)V_p\mathbf{g} + \mathbf{F}_c$$

Hydrodynamic forces | buoyancy | Collision/ contact

Particle-resolved Direct Numerical Simulations

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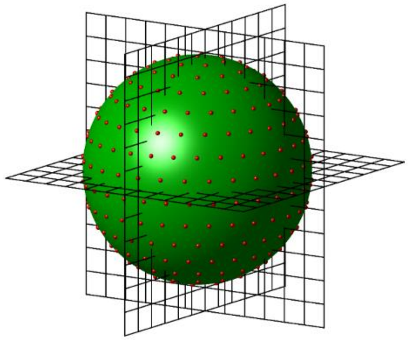

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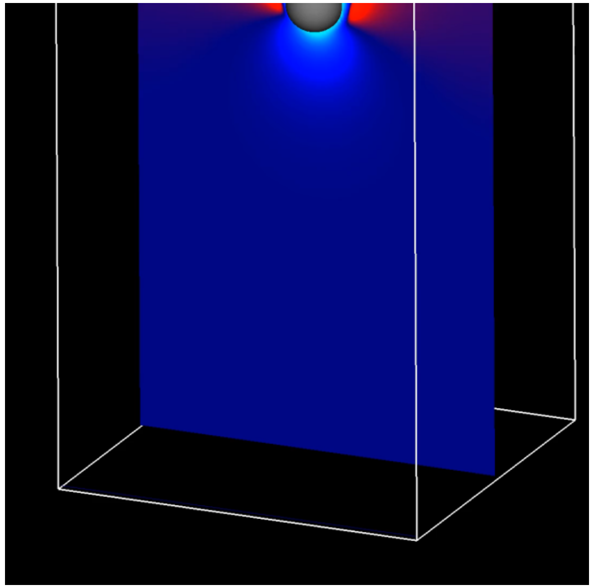
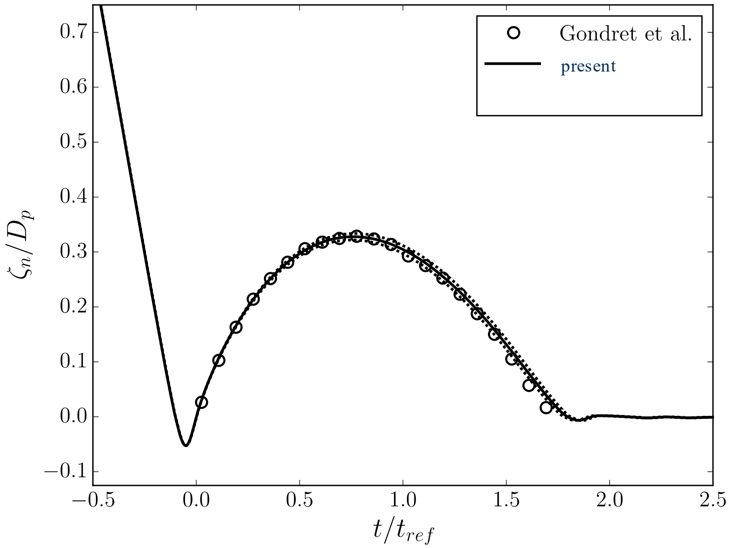
Hydrodynamic forces | buoyancy | Collision/ contact

Collision model for non-cohesive sediment

→ Excellent agreement with experiments



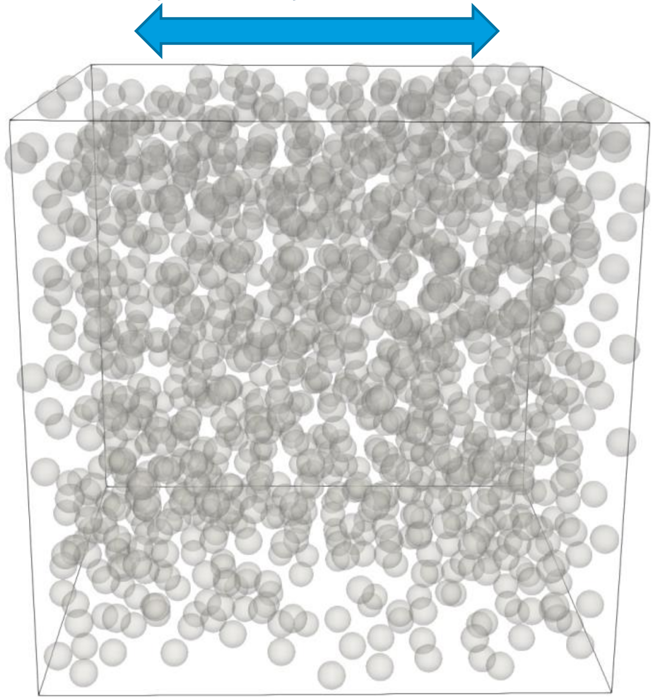


Effects from
- contact,
- friction,
- lubrication
- cohesion

[Biegert, Vowinckel & Meiburg, JCP, 2017]
[Vowinckel et al., JFM, 2019]

Numerical Setup

$u_f = -A_f \Omega \sin \Omega t$



- $L_{x,y,z} = 20\, d_p$
- $d_p / h = 20$
- Periodic boundary conditions
- 25,000 oscillations
- No gravity!

Initial particle diameter: $d_p = 1.15 \cdot 10^{-4}\ [m]$
Density ratio: $\rho_s = \rho_p / \rho_f = 2.60\ [-]$
Kinematic fluid viscosity: $\nu_f = 10^{-6}\ [m^2/s]$
Oscillation frequency: $f = 60\ [Hz]$

based on ISS experiments

Oscillation amplitude: $A = \{0.05,\ \mathbf{0.1},\ 0.2\}\, d_p$
Solid volume fraction: $\phi = \{0.042,\ \mathbf{0.084},\ 0.164\}\ [-]$

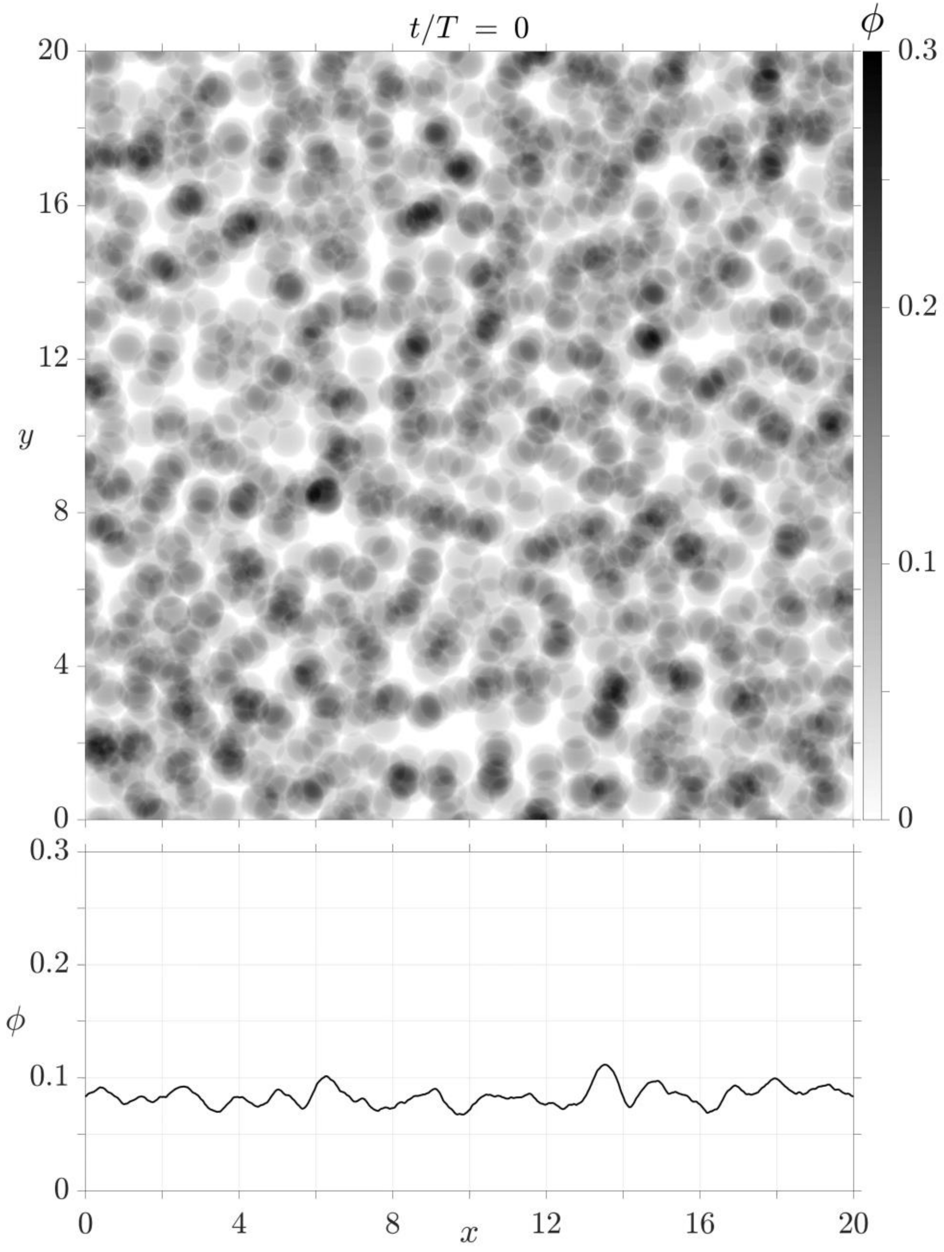
Reynolds Number: $Re = u_{f,max}\, d_p / \nu_f = \{0.25,\ \mathbf{0.5},\ 1.0\}$

with: $u_{f,max} = A_f \Omega$

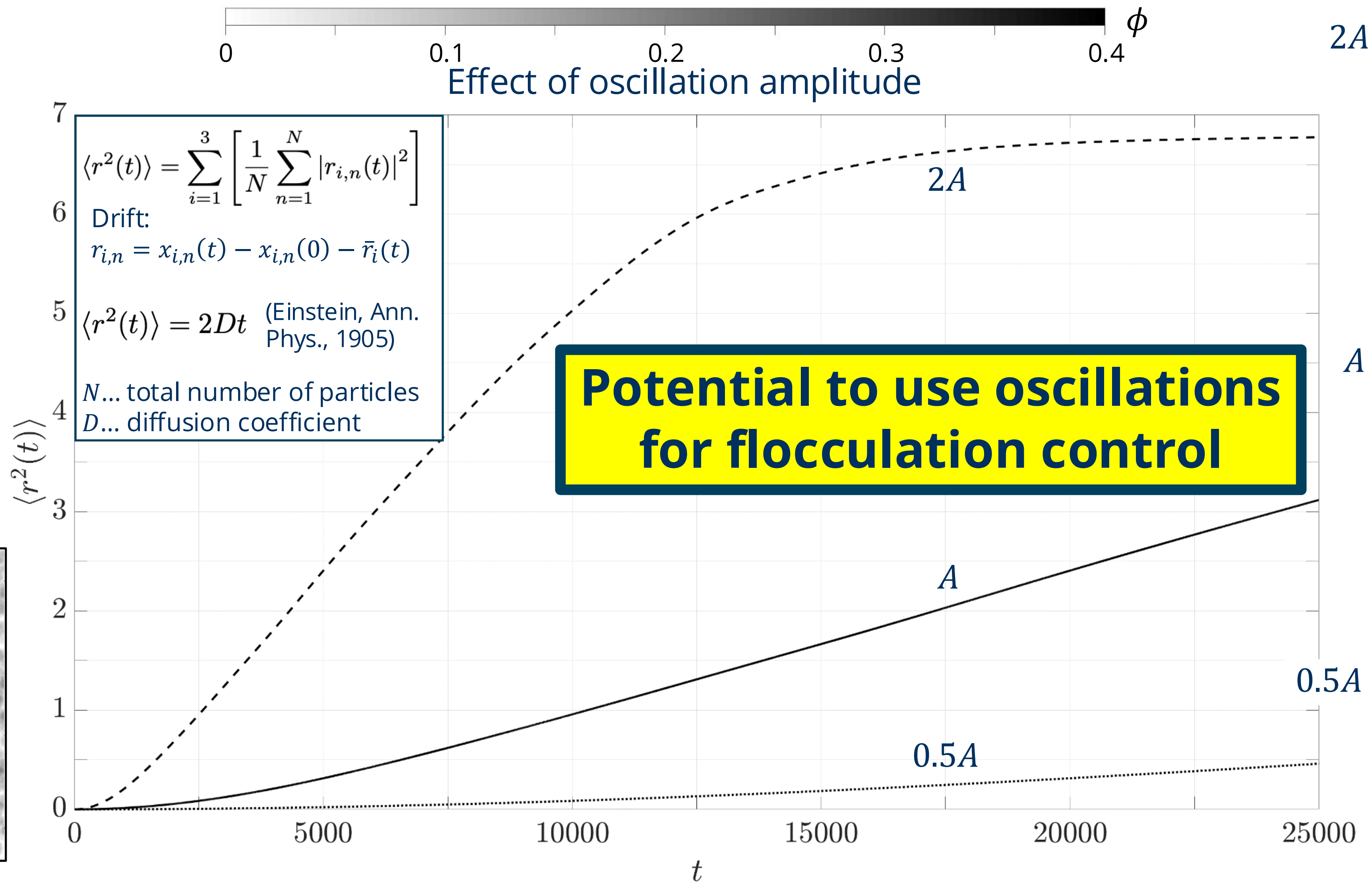
Non-dim. frequency: $S = d_p{}^2\, \Omega / (36\, \nu_f) = 0.14$

Stokes number: $St = \tau_p / \tau_f = |\rho_s - 1|\, 2\, S = 0.44$

Aggregation due to g-jitter



Particle diffusion: Mean square displacement



$$\langle r^2(t) \rangle = \sum_{i=1}^{3} \left[\frac{1}{N} \sum_{n=1}^{N} |r_{i,n}(t)|^2 \right]$$

Drift:

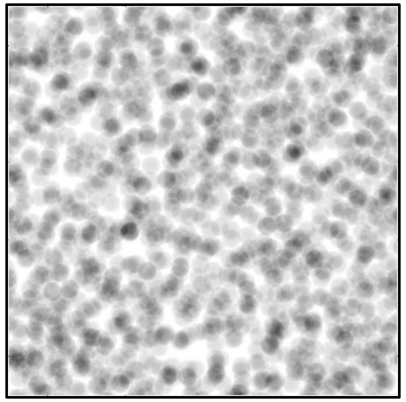
$r_{i,n} = x_{i,n}(t) - x_{i,n}(0) - \bar{r}_i(t)$

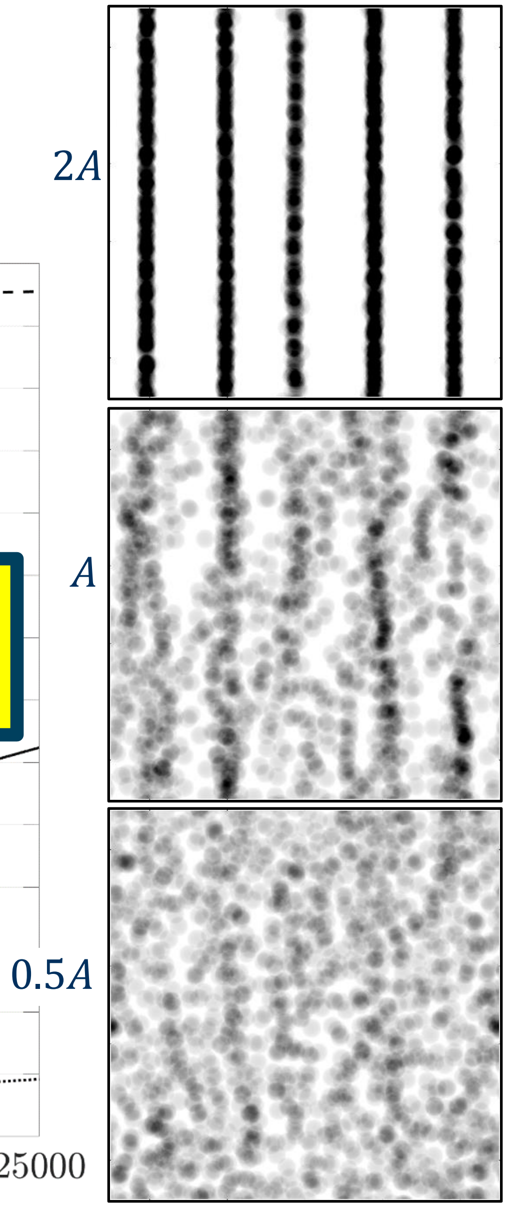
$\langle r^2(t) \rangle = 2Dt$ (Einstein, Ann. Phys., 1905)

N... total number of particles
D... diffusion coefficient

Potential to use oscillations for flocculation control

$0.5A, A, 2A$

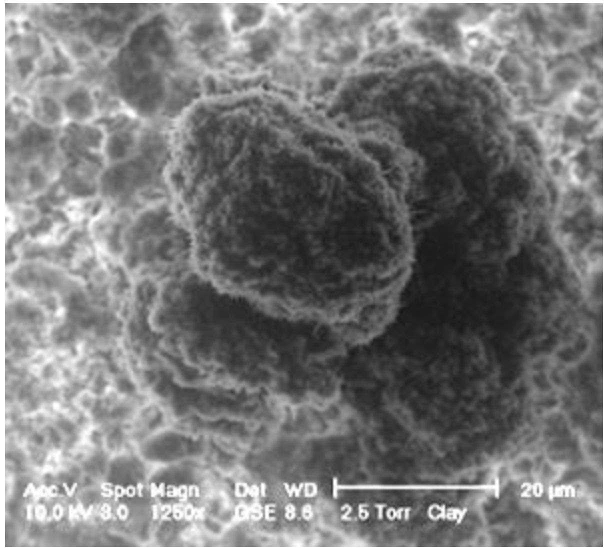




Three types of grain-scale processes

Flocculation and hindered settling

- Most mass of cohesive sediments is accumulated within flocs
- Marine snow – main contribution to vertical carbon flux
- Aggregates of cohesive sediments are small and fragile, hence **hard to measure directly**



Electron microscope images of Kaolin clay aggregates formed in salt water
[Vowinckel et al., Flow, 2023]

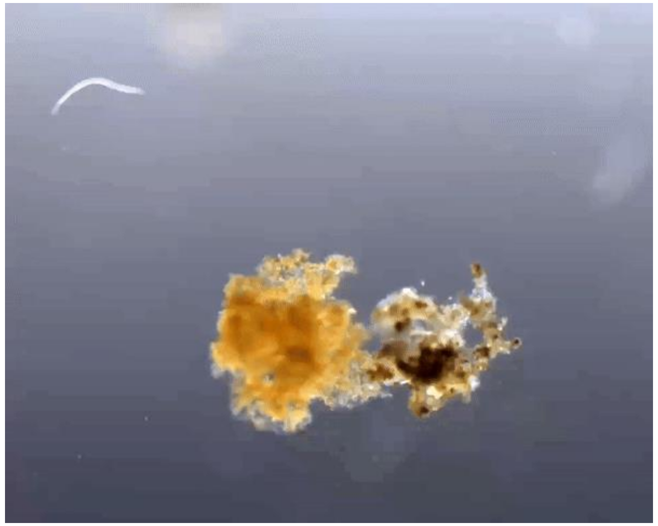


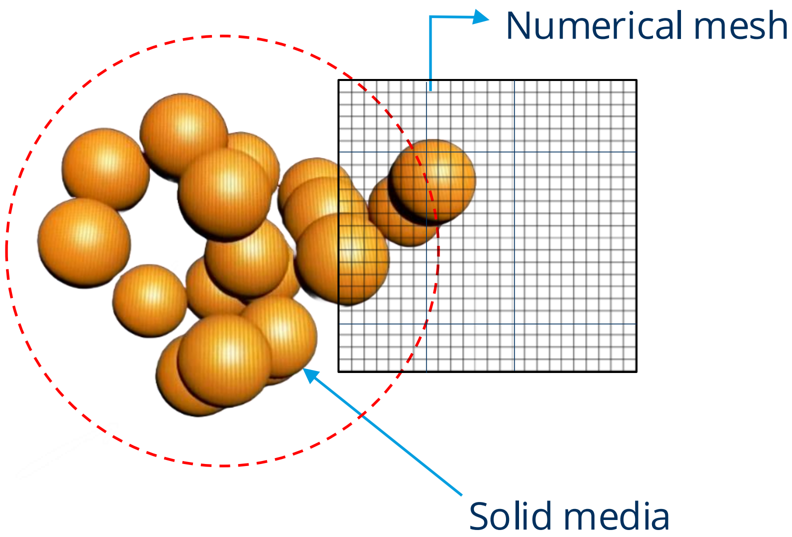
Illustration of marine snow floc
https://www.mbari.org/project/ecology-of-marine-snow/

Marine snow in the deep Gulf of Alaska
https://oceanexplorer.noaa.gov/facts/marinesnow.html

Motivation

With Alexander Metelkin

Geometrically resolved floc



[Maches et al., JFM, 2024]

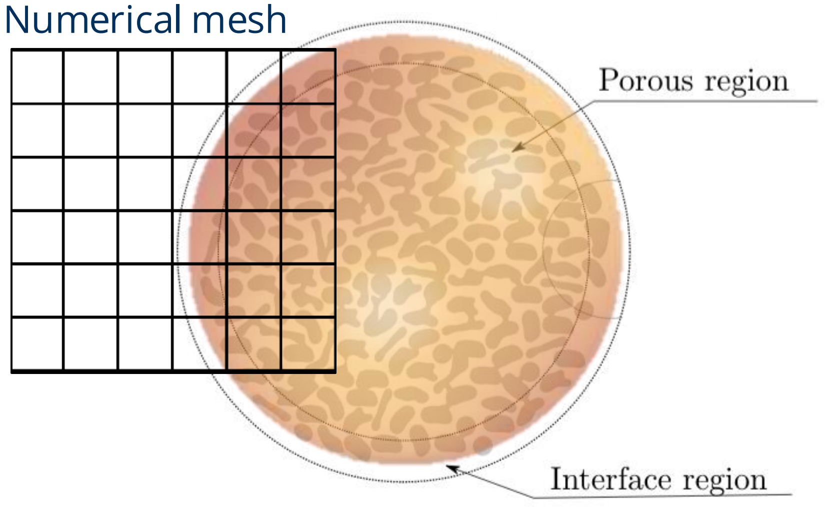
- High mesh resolution + High accuracy
- Each primary particle captured
- **Particle arrangement**
- **Density** of solid

Simulation parameter

Alternatively, approximate as **"sphere"**

? ? ?

Modelled porous floc



- Coarser mesh + higher efficiency
- Assumed homogeneous media
- **Density** of solid
- **Permeability**

Simulation parameter

Computing porous particle dynamics

Momentum equation for the fluid and porous particle

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla \cdot (\boldsymbol{u}\boldsymbol{u}) = -\frac{1}{\rho_f}\nabla p_f + \nu_f \nabla^2 \boldsymbol{u} + \nu_f \epsilon \kappa^{-1}(\boldsymbol{u} - \boldsymbol{U_p})$$

along with the continuity equation

Darcy's term

where,

ϵ ... porosity

κ ... permeability

ν_f ... kinematic viscosity

$\boldsymbol{U}_p$ ... Particle velocity

$\boldsymbol{r}$ ... Radial position vector

Equations of motion of porous particles

$$m_p \frac{\mathrm{d}\boldsymbol{u}_p}{\mathrm{d}t} = \int_{V_p} \nu_f \epsilon \kappa^{-1}(\boldsymbol{u} - \boldsymbol{U}_p)\, dV + (\rho_s(1-\epsilon) + \rho_f \epsilon) V_p \mathbf{g}$$

Drag

Weight

$$I_p \frac{\mathrm{d}\boldsymbol{\omega}_p}{\mathrm{d}t} = \int_{V_p} \boldsymbol{r} \times \left[\nu_f \epsilon \kappa^{-1}(\boldsymbol{u} - \boldsymbol{U}_p)\right] dV$$

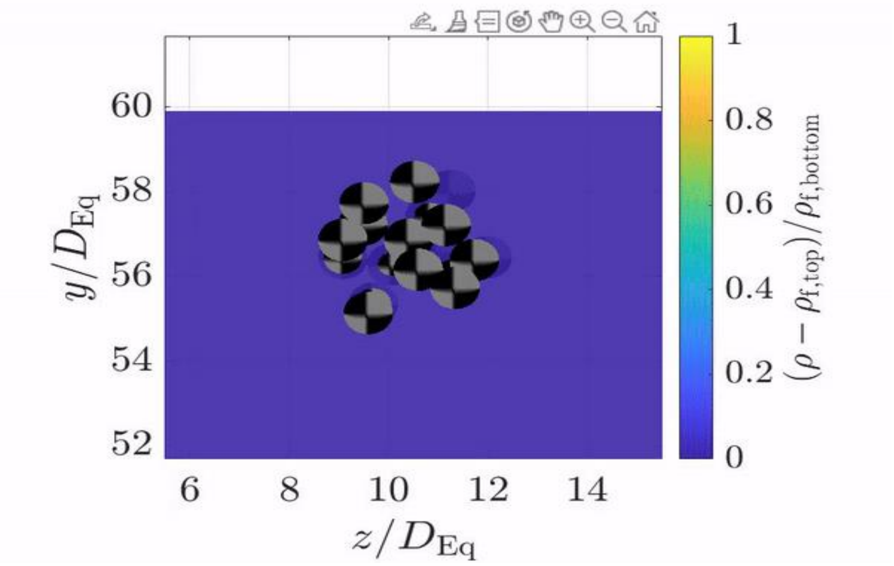
[Metelkin and Vowinckel, IJSR, 2025]

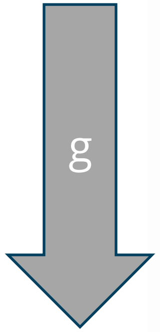
Settling in stratified fluids

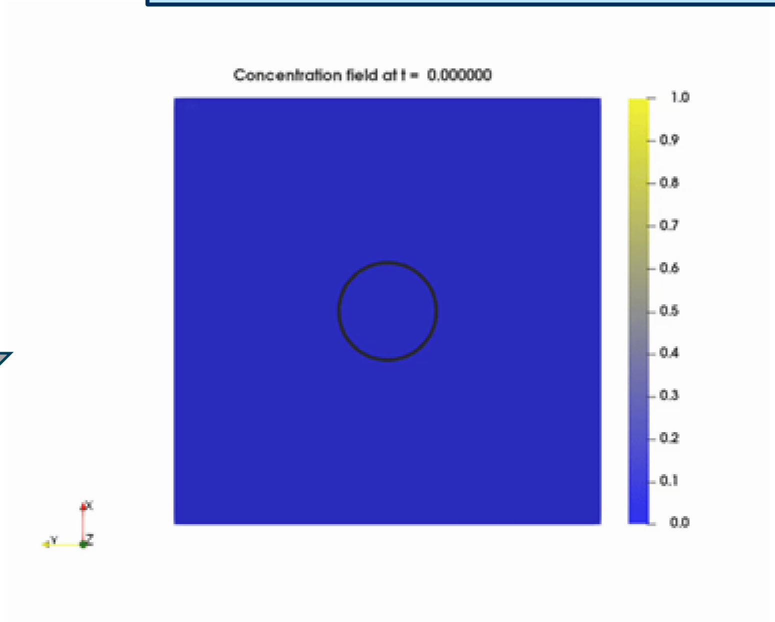
Moving frame of reference

Geometrically resolved (IBM)

Porous floc







Floc of resolved particles settling in densely stratified medium [Maches and Meiburg, private communication, 2024]

Porous aggregate settling in densely stratified medium

Simulation configuration

Simulation parameters:

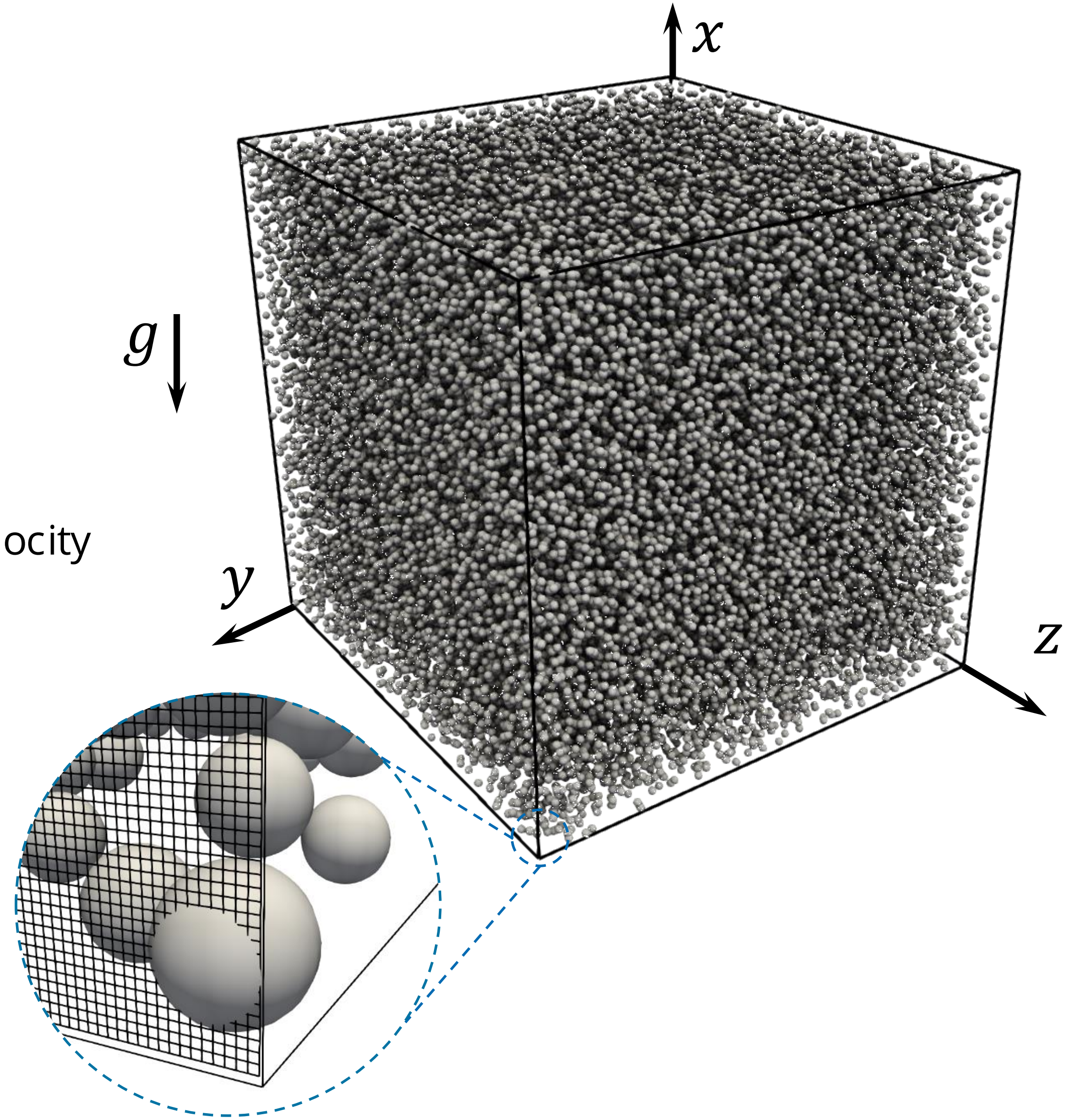
- $Re = u_{St} D / \nu = 1$
- $\frac{\rho_{agg}}{\rho_f} \approx 1.1$
- Volume fraction: $\phi \in \{0 \, .. \, 0.3\}$
- Drag reduction factor $\Omega \in \{0.95 \, .. \, 0.7\}$
- Permeability $\epsilon \in \{0.95 \, .. \, 0.966\}$

→ Three types of particles with same terminal settling velocity

Computational domain:

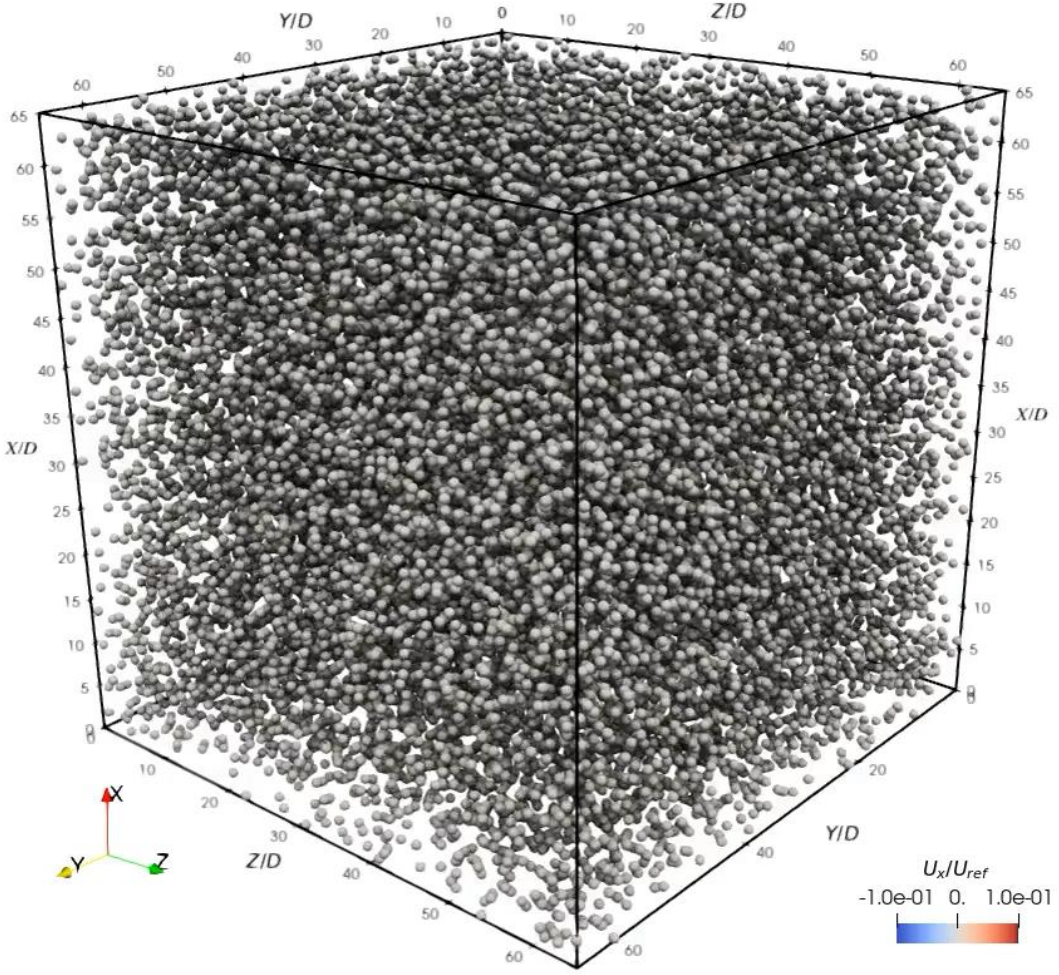
- $L_x \times L_y \times L_z = 65D \times 65D \times 65D$
- $N_x \times N_y \times N_z = 910 \times 910 \times 910$
- Triple periodic boundary conditions
- Artificial vertical pressure gradient

Computational domain illustration:



Simulation results: various aggregate concentration

$\Omega = 0.95, \qquad \phi = 30\%$
(almost impermeable)



$\Omega = 0.95, \qquad \phi = 30\%$
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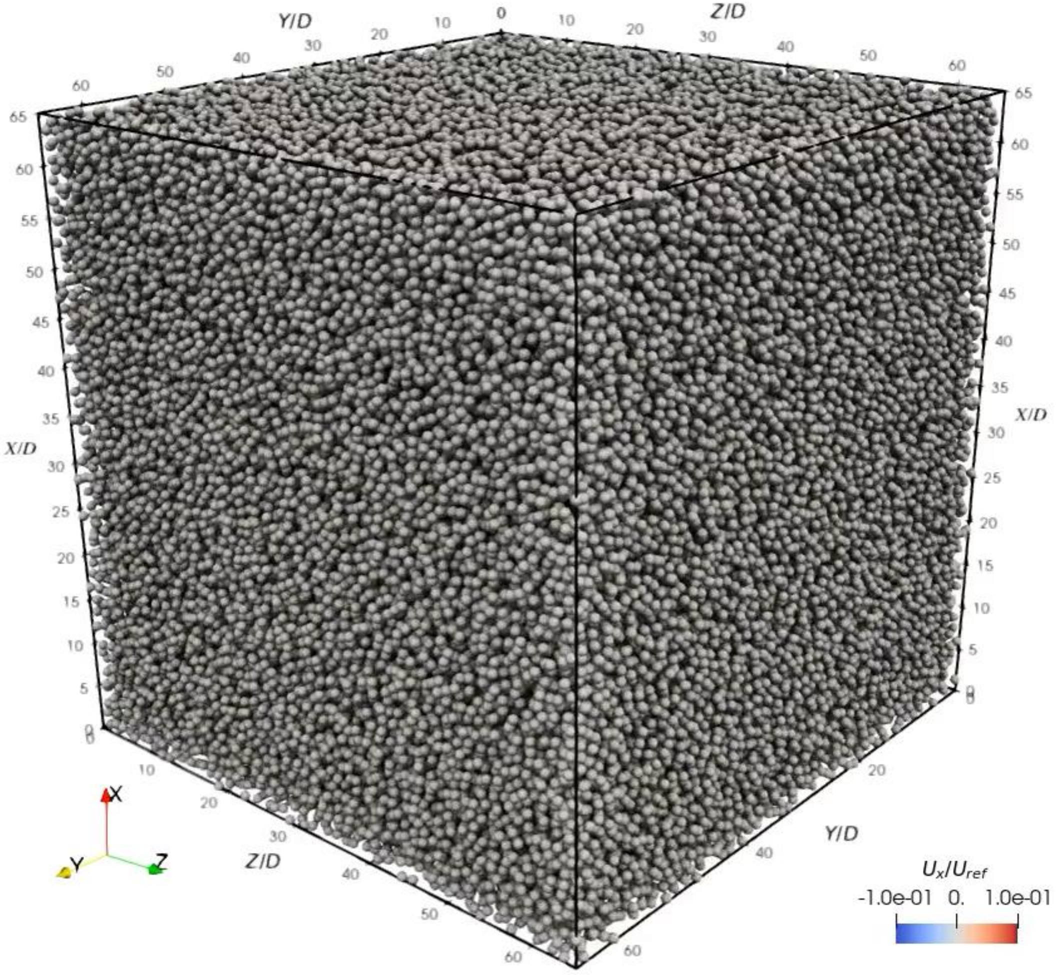
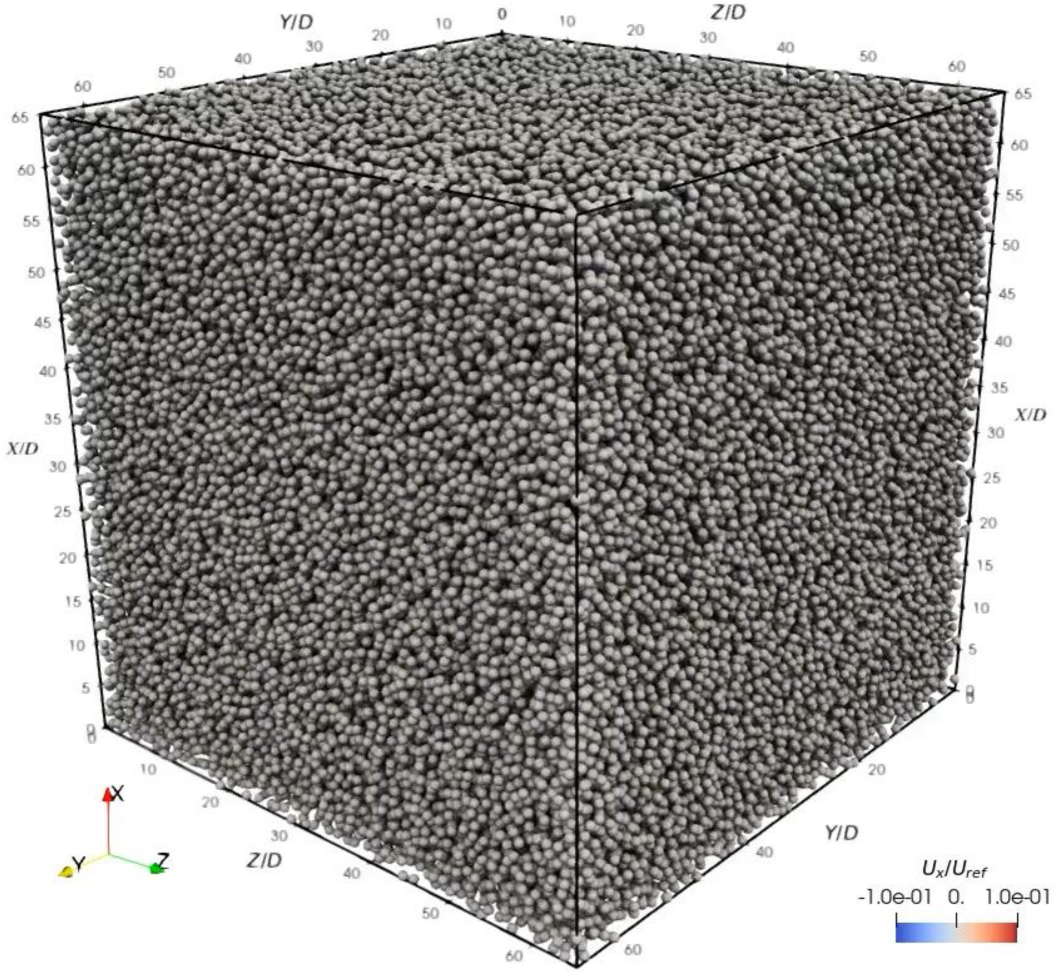
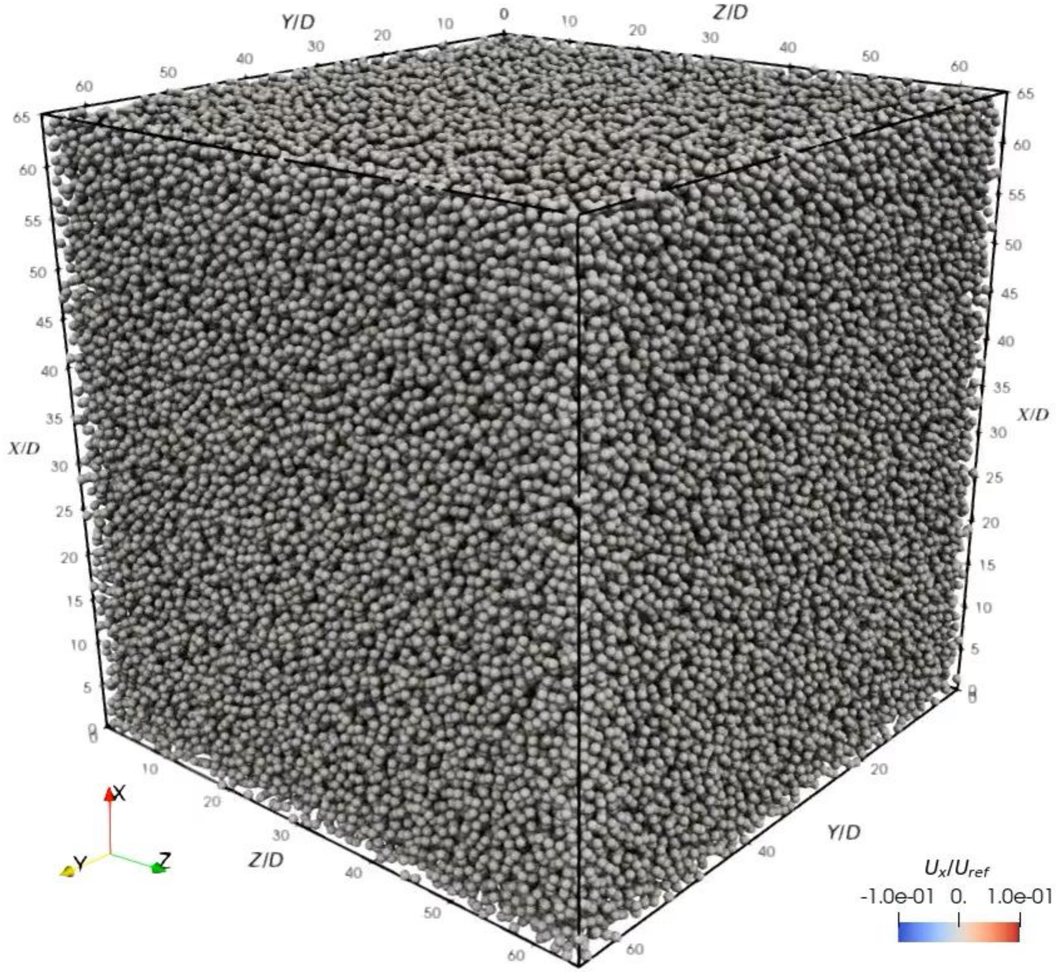


Simulation results: various drag reduction factor

$\Omega = 0.95, \qquad \phi = 30\%$
(almost impermeable)



$\Omega = 0.7, \qquad \phi = 30\%$
(impermeable)



Settling velocity as a function of concentration

Sedimentation of spheres in viscous flow:

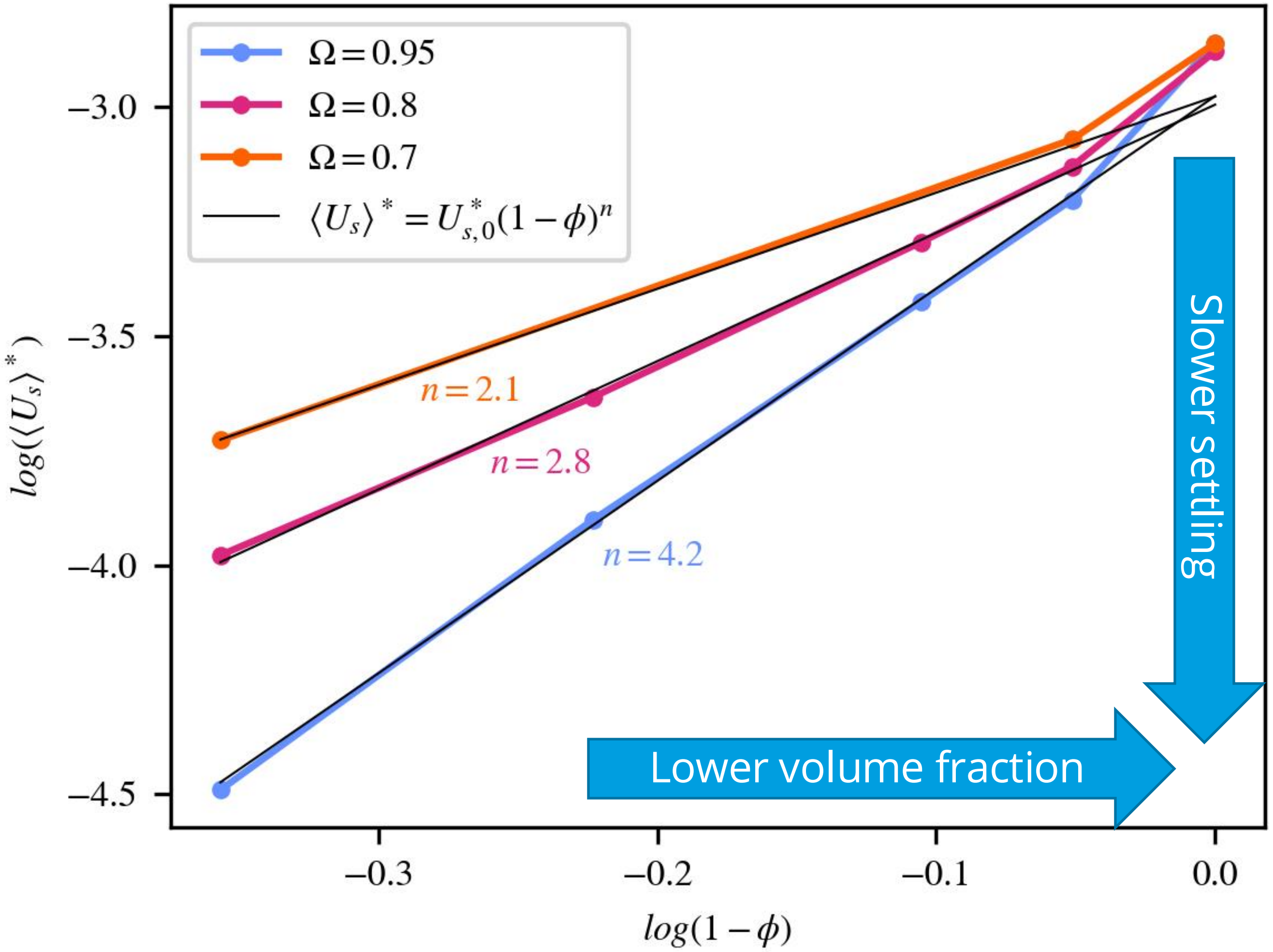
$$\langle U_s \rangle^* = U_{s,0}^* (1-\phi)^n$$

$\langle U_s \rangle^*$… converged settling velocity of suspension

$U_{s,0}^*$ … converged settling velocity with zero sediment concentration

n… empirically defined constant

[Richardson & Zaki, CES, 1954]



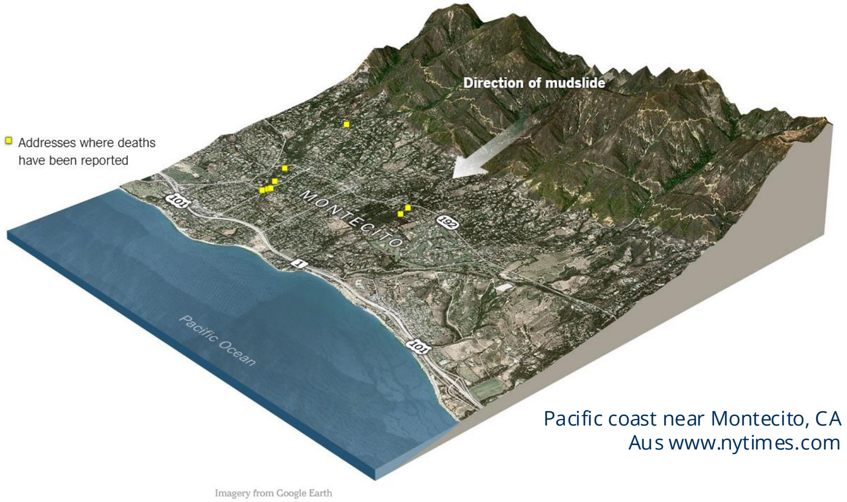
Very good agreement and potential to extend to porous particles

Three types of grain-scale processes

Mudslides as a natural hazard

Map of the US-Karte with California

CNN.com



Pacific coast near Montecito, CA
Aus www.nytimes.com

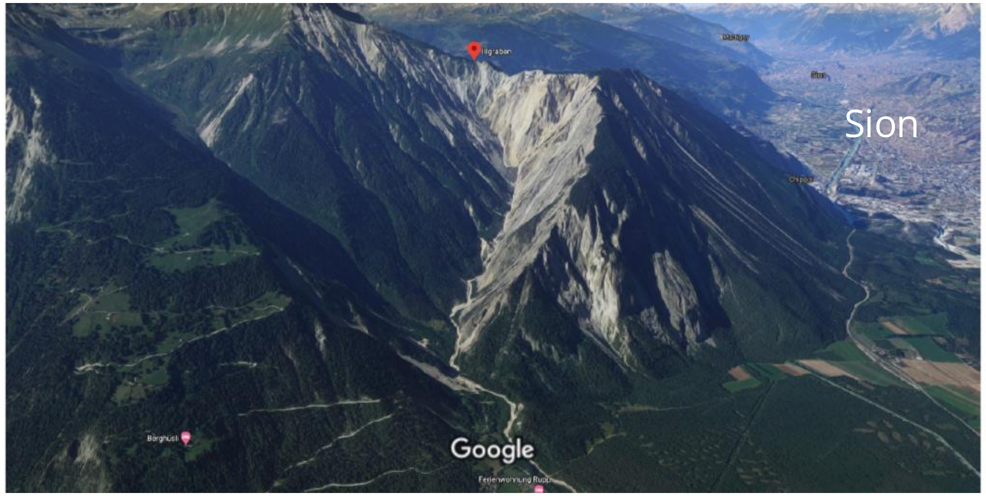
1. Drought

2. Wild fire (Thomas Fire, 2018)
   → Incineration of all vegetation

3. Intensive rainfall
   → mudslids
   → 23 casualties
   → >207 Million USD damage

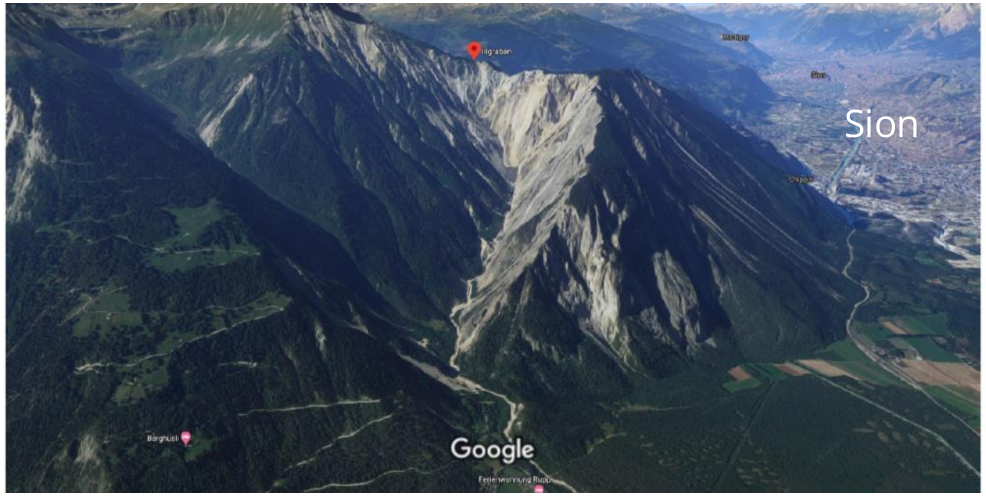
San Ysidro creek, CA, mudslide aftermatch

Dynamics of mudslides



Illgraben, Switzerland (source: youtube.com)

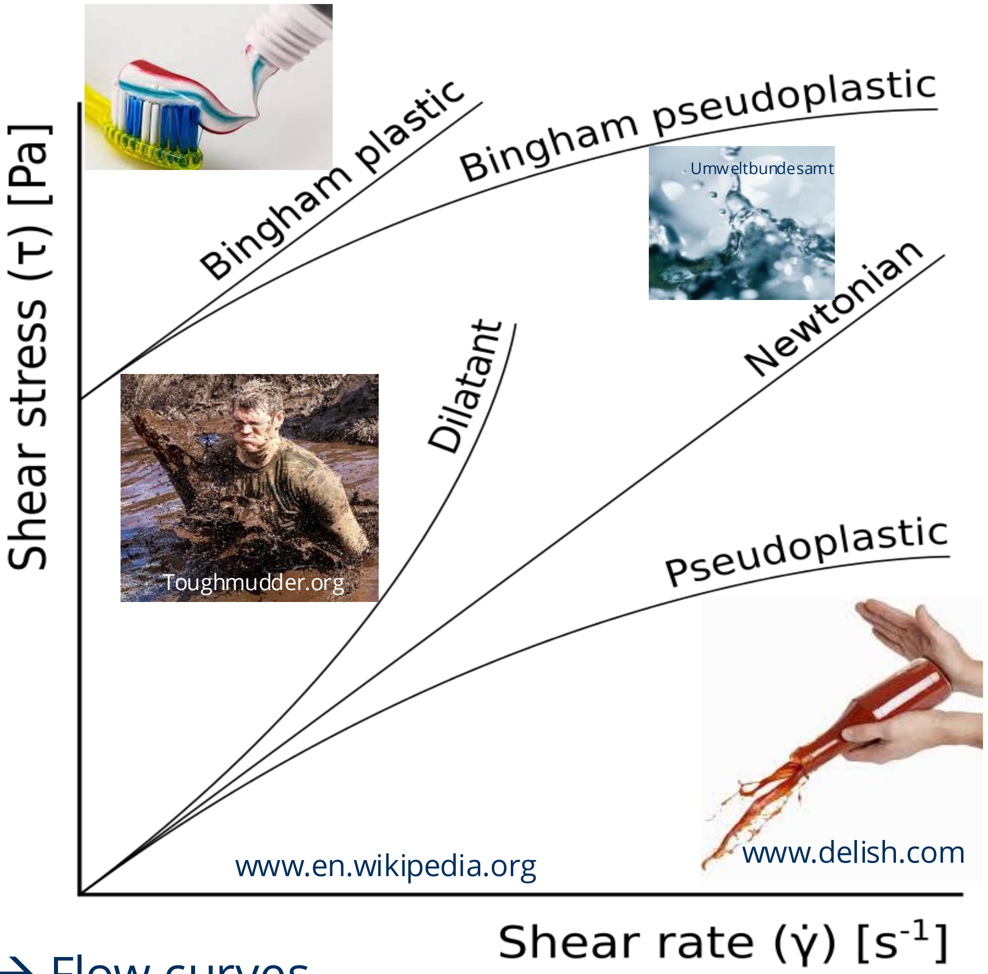
Dynamics of mudslides



Risk (frequency and magnitude) is going to increase due to climate change!

Rheology of sediment suspensions

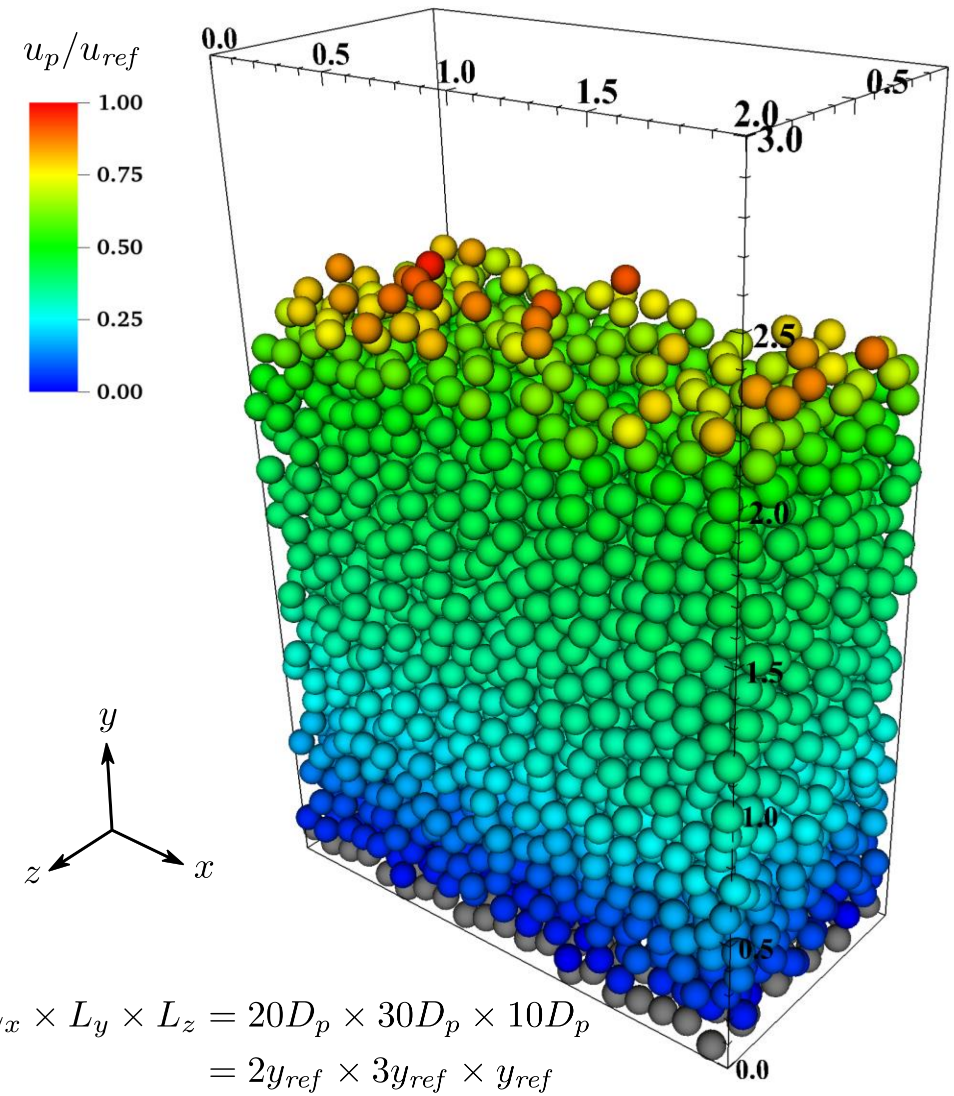
River of flowing rocks at Terrible Gully (Canterbury, New Zealand) in 2018



→ Rheology: study of the flow and deformation of matter → Flow curves

→ How does the sediment load alter the flow behavior of the river?

Simulation setup



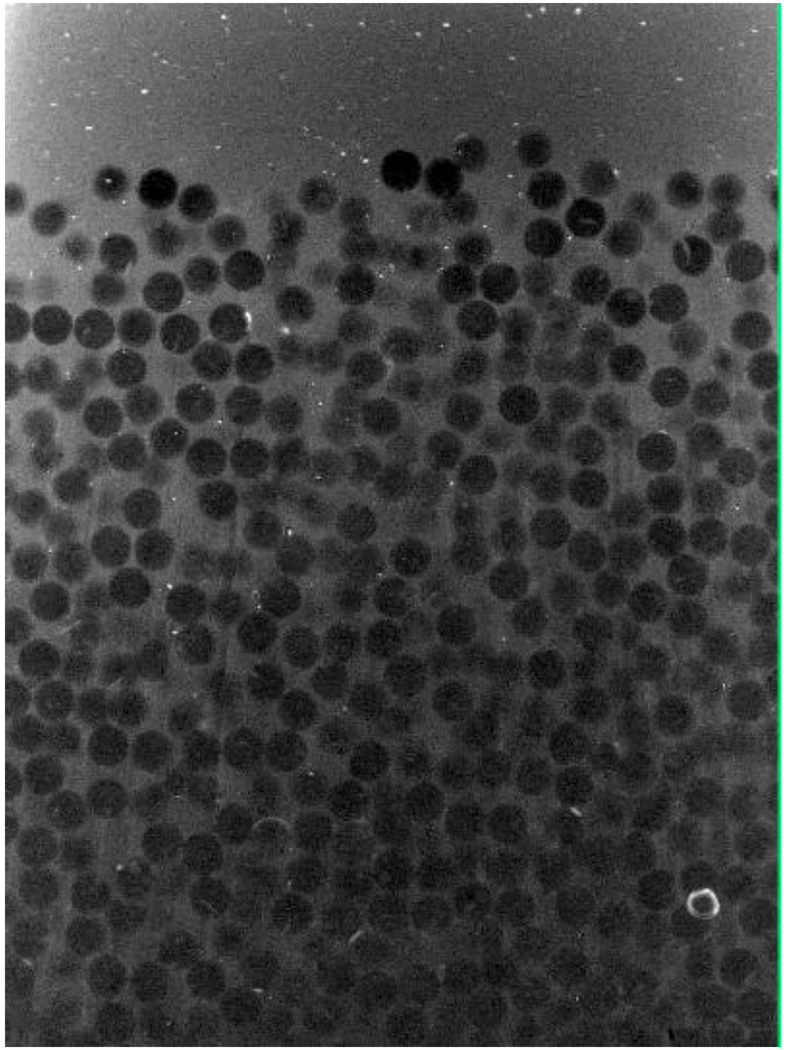
$$L_x \times L_y \times L_z = 20D_p \times 30D_p \times 10D_p$$
$$= 2y_{ref} \times 3y_{ref} \times y_{ref}$$

Number of particles:	4339
Galileo number $Ga = \nu_f^{-1}\sqrt{\rho' g D_p^3}$:	0.85
ρ_p/ρ_f:	2.1
$D_p/\Delta x$:	25.6
Initial h_f/D_p:	10

Boundary conditions:
→ periodic (x); no-slip (y); periodic (z)

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

Experiments by Aussillous et al. (JFM, 2013)



Brinkman equation:

$$\frac{\partial p^f}{\partial x} - \frac{\partial \tau^f}{\partial z} + \frac{\eta}{K}(U - u^p) = 0$$

Momentum equation for the mixture

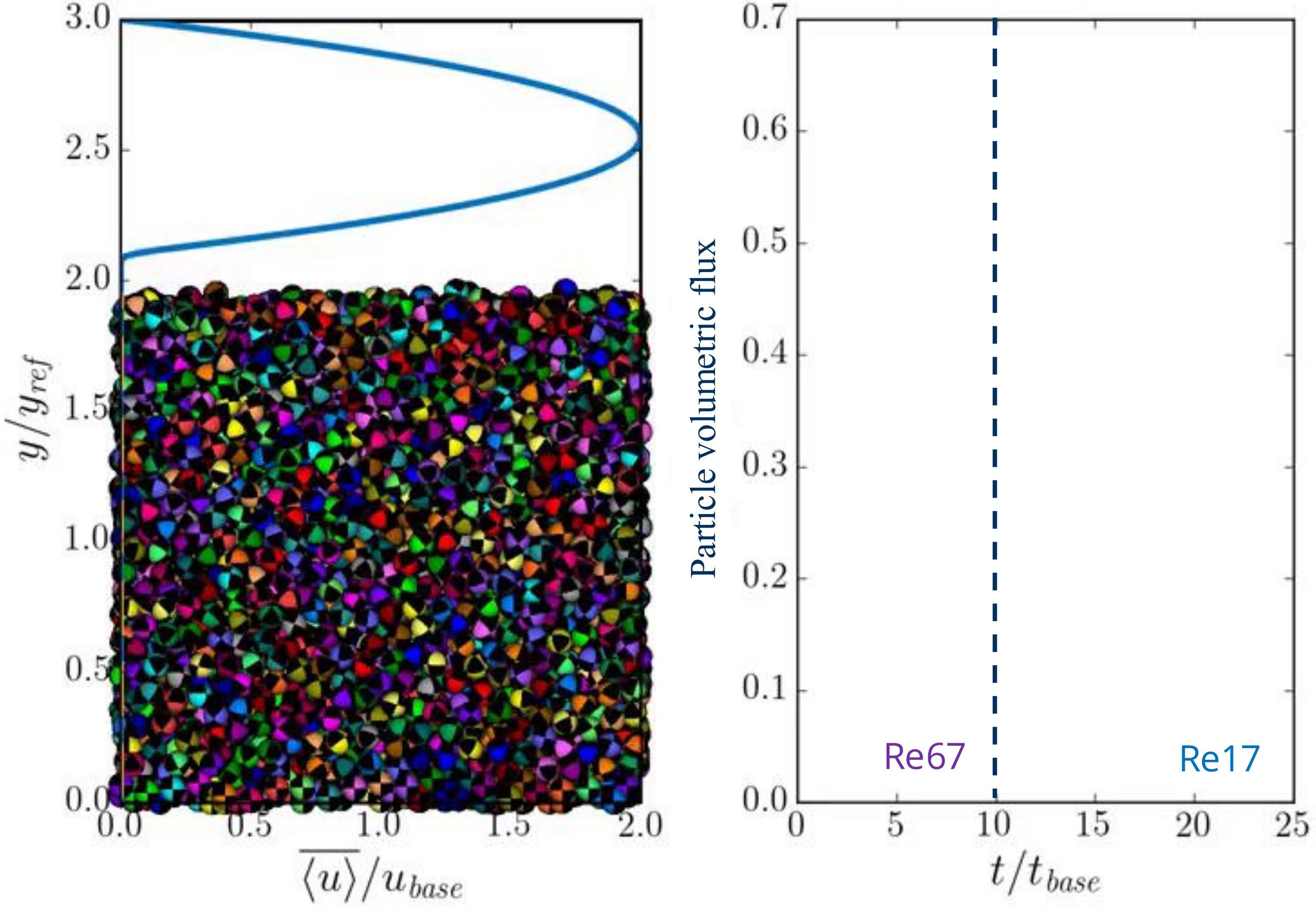
$$\tau^p(\mathrm{z}) + \tau^f(z) = \tau^f(h_p) - \frac{\partial p^f}{\partial x}(h_p - z)$$

where

$$\tau^f = \eta_e \left(\frac{dU}{dz}\right)$$

$$\tau^p = \mu p^p$$

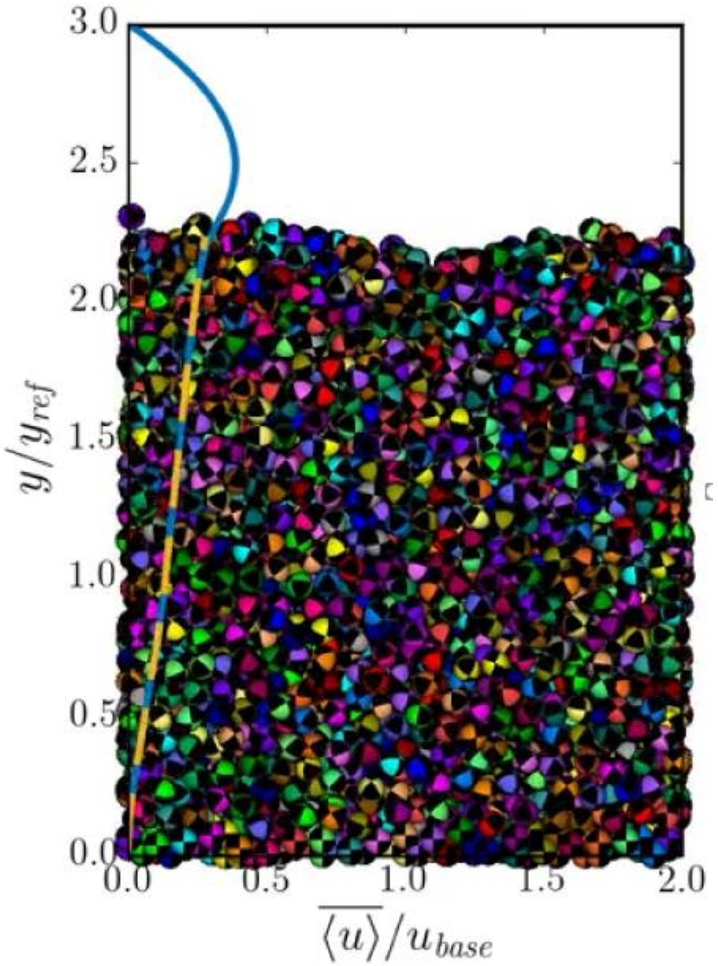
Simulation runs



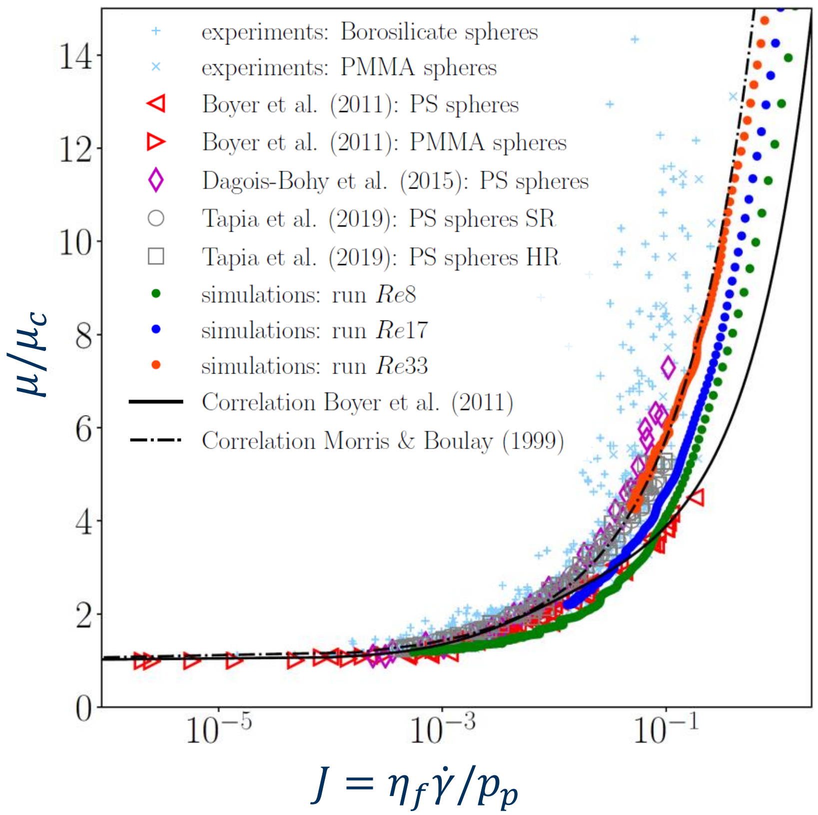
[Vowinckel et al., JFM, 2021]

Rheology of mobile sediment beds

Pressure driven flow



Macroscopic friction $\mu = \tau/p_p$

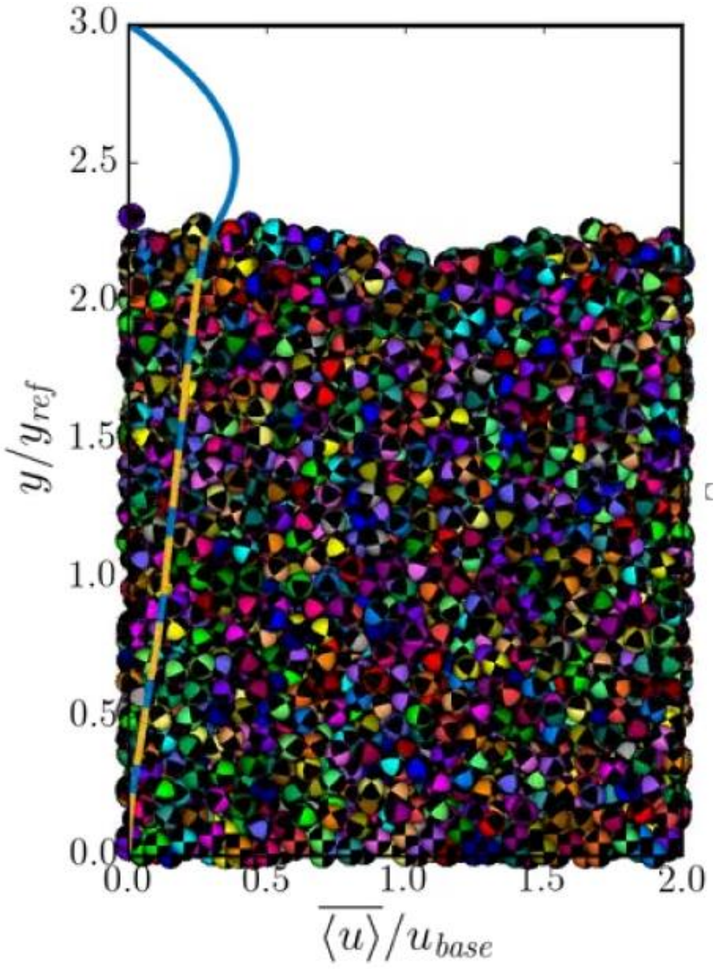


- Good agreement with experimental results

[Vowinckel et al., JFM, 2021]

Rheology of mobile sediment beds

Pressure driven flow



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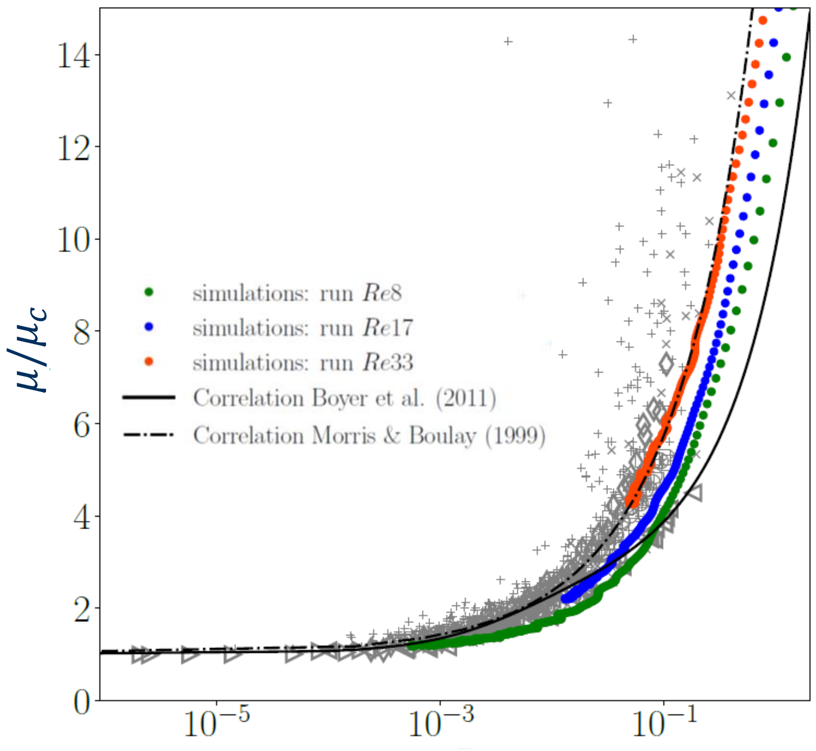
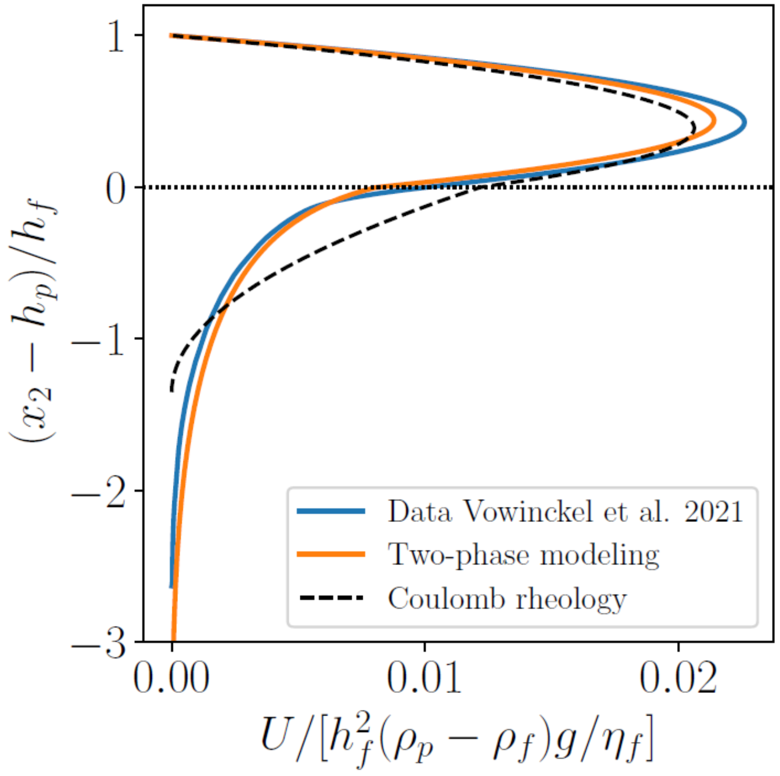


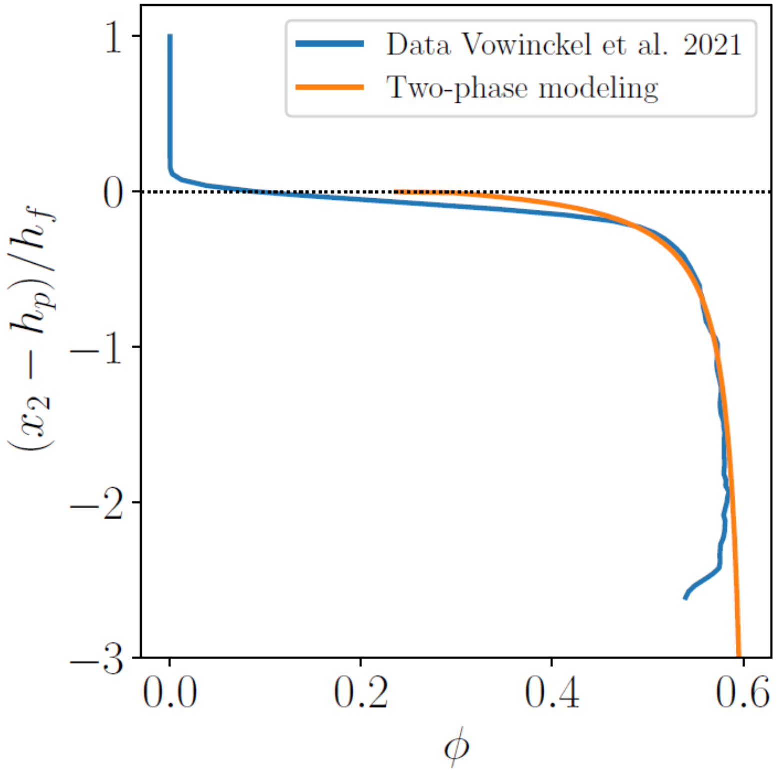
$J = \eta_f \dot{\gamma} / p_p$

- Good agreement with experimental results

[Vowinckel et al., JFM, 2021]

Comparison to two-phase modeling





Very good agreement without any further model tuning!

Momentum equation for the mixture

$$\mu p^p(z) + \tau^f(z) = \tau^f(h_p) - \frac{\partial p^f}{\partial x}(h_p - z)$$

Coulomb: $\mu = const$

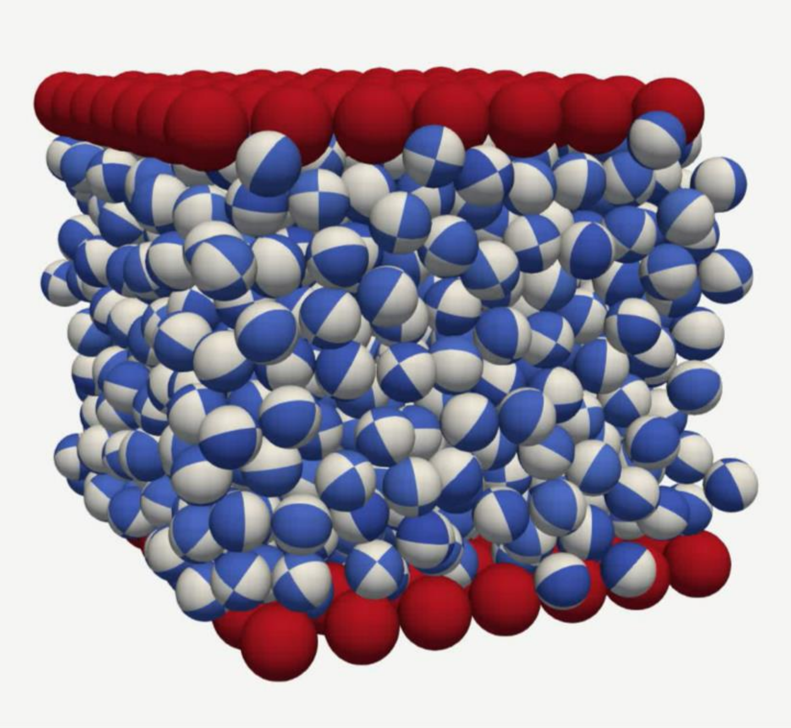
Two-phase: $\mu = \mu(J)$

[Aussillous et al. , *in press*, 10.22541/essoar.173557601.14442343/v1]

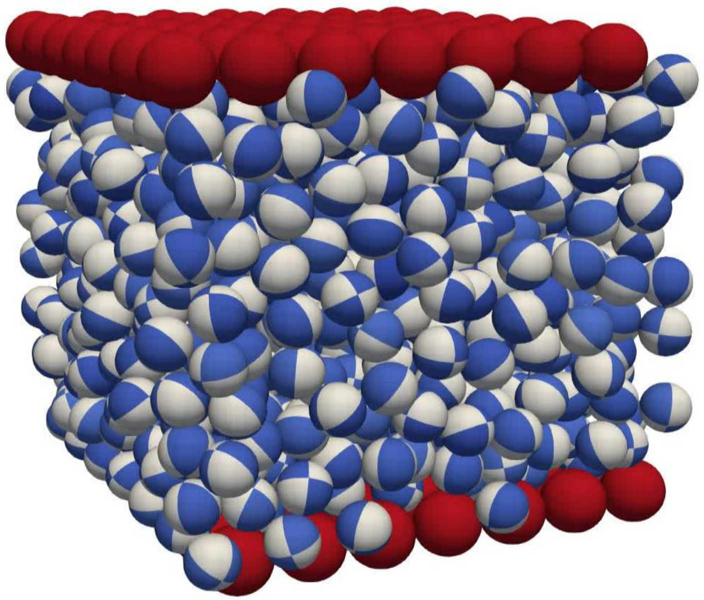
Towards more complicated flows

With Sudarshan Konidena and Alireza Khodabakhshi

$St = 0.065$
Viscous regime – low shear



$St = 120$
Inertial regime – high shear

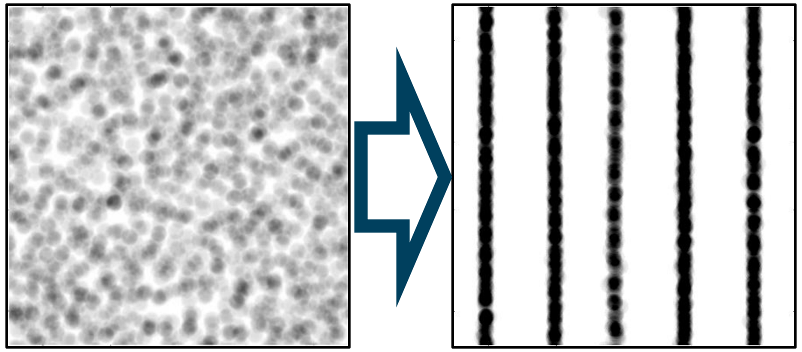


Rolling vs sliding

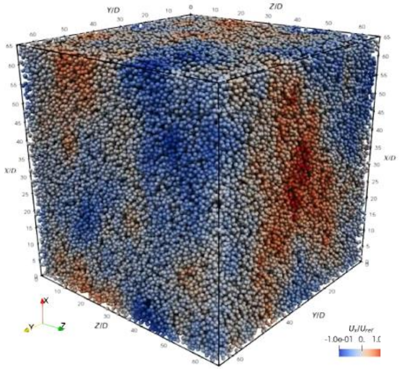
[Konidena, ..., Vowinckel, PRL, in revision, arXiv:2505.04242v1]

Conclusions

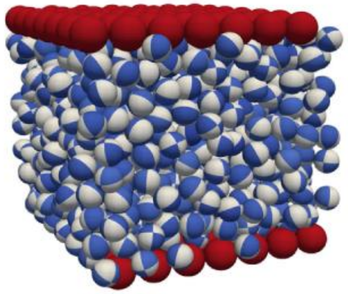
- Flocculation:
  Can be triggered and promoted by oscillations/j-gitter

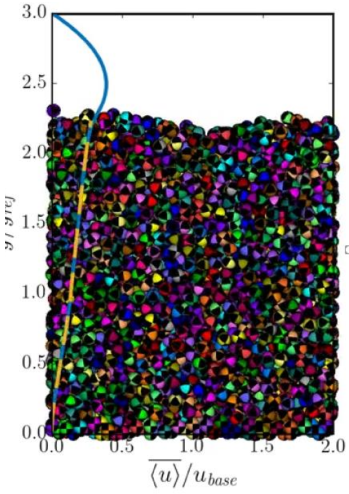


- Hindered settling:
  Applicable to porous particles, but weaker counter flows

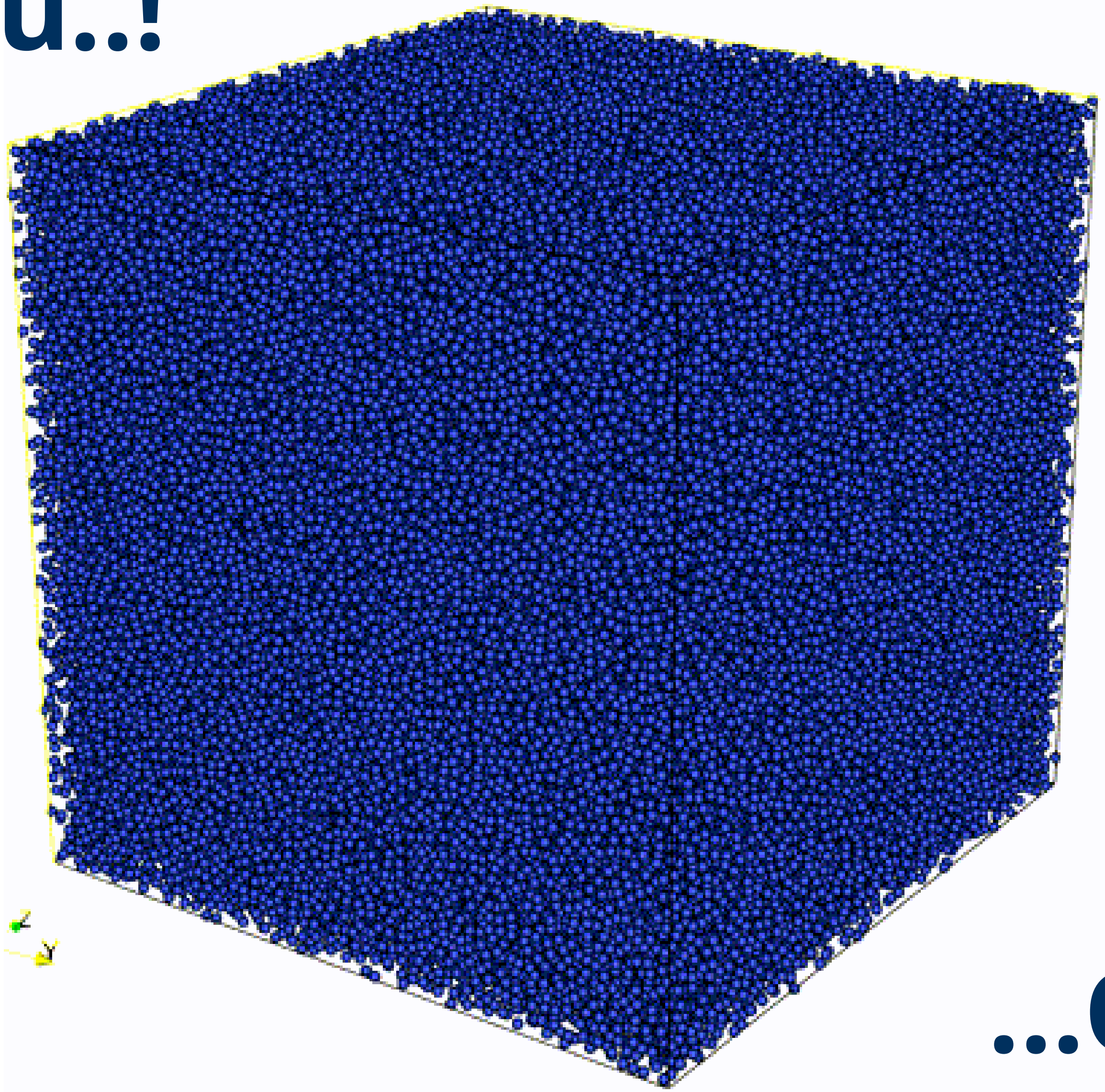


- Rheology of sediments:
  provides adequate closures for two-phase flow models





Thank you..!



...Questions?