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Numerical method for porous sediments simulation

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Motivation

- To understand the influence of highly porous aggregates on the mass transport in ecosystems

- Simulating the scale larger than primary particles substantially decreases computational costs but still captures porosity effects

- Microflocs could be reasonably represented as porous spherical objects
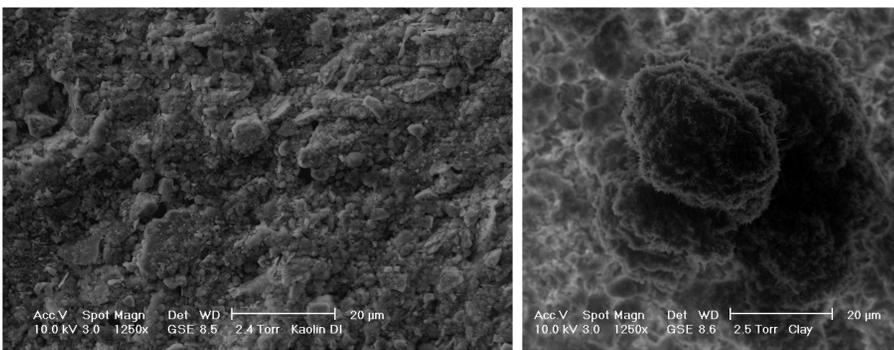
Electron microscope images of Kaolin clay submereged in deionized water (left) and Kaolin clay aggregates formed in salt water (right)

Modeling approach

Fluid solver

$$\frac{\partial \vec{u}}{\partial t} + \nabla \vec{u}\,\vec{u} = -\frac{1}{\rho_f}\nabla\,p_f + \nu_f \nabla^2 \vec{u} + \underbrace{M\,\frac{\nu_f}{K}\left(\vec{u} - \vec{U}_p\right)}_{Darcy\ term}$$

$$\nabla \vec{u} = 0$$

Particle motion

$$m_p \frac{d\vec{u}}{dt} = \underbrace{\oint_{S_p} \vec{n}\,p\,dA}_{Pressure\ force} + \underbrace{\oint_{S_p} \mu_f \frac{\partial \vec{u}}{\partial n} dA}_{Viscous\ force} + \underbrace{\int_{V_p} K\,dV}_{Darcy\ force} + \underbrace{F_c}_{Collision\ force} + \underbrace{F_{coh}}_{Cohesive\ force}$$

Force integration

$$\oint_{S_p} \vec{n}\,p\,dA = \sum_i^n p_i\,\vec{n}_i\,S_i$$

$$\oint_{S_p} \mu_f \frac{\partial \vec{u}}{\partial n} dA = \sum_i^n \mu_f \left(\frac{\partial \vec{u}}{\partial n}\right)_i S_i$$

$$\int_{V_p} K\,dV = \sum_j^m K_j\,V_j$$

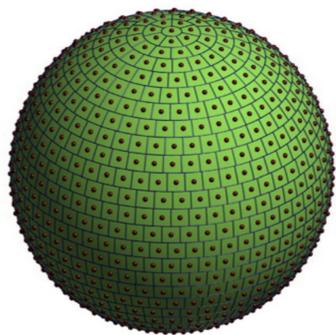$i - surface\ marker\ index$
$j - computational\ cell\ index$

Illustration of the surface markers and the surface area assigned for a certain marker

Kempe, T., & Fröhlich, J. (2012). An improved immersed boundary method with direct forcing for the simulation of particle laden flows. Journal of Computational Physics, 231(9), 3663-3684.

Cohesive force

$$\vec{F}_{coh} = Co\,\frac{8\,R_{eff}}{\lambda^2}\left(\zeta_n^2 - \zeta_n \lambda\right)\vec{n}$$

$$Co = \frac{Cohesive\ forces}{Weight}$$
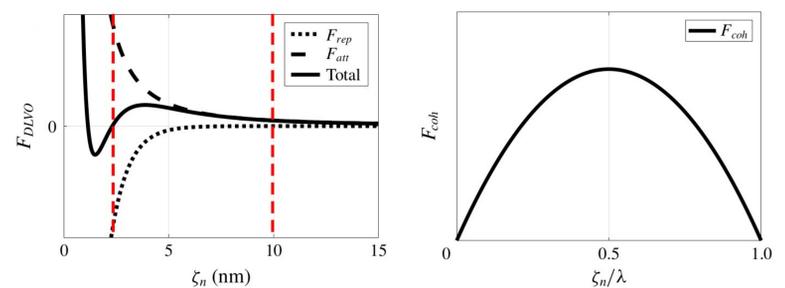
Attractive, repulsive and cumulative forces acting between two cohesive particles according to Derjaguin–Landau–Verwey–Overbeek theory (left) and resulting force used in the current model
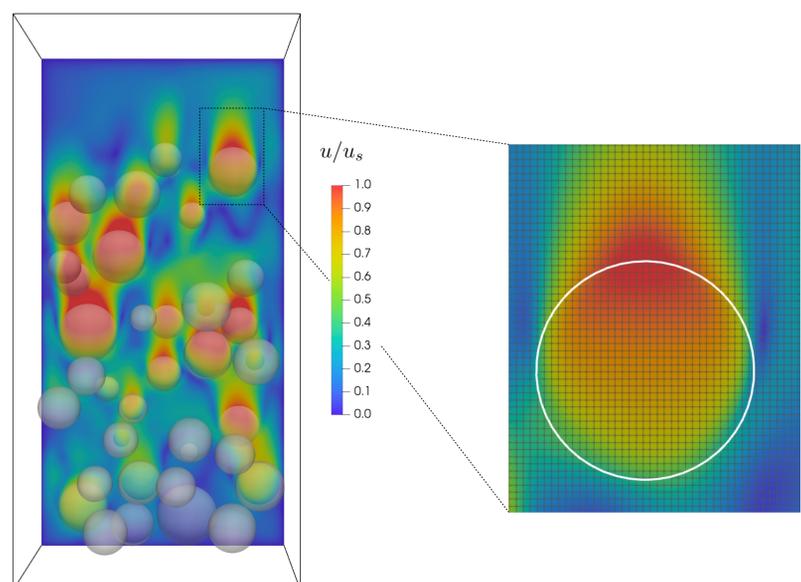
Vowinckel, B., et al. "Settling of cohesive sediment: particle-resolved simulations." Journal of Fluid Mechanics 858 (2019): 5-44.

Preliminary results

Flow over a single porous particle
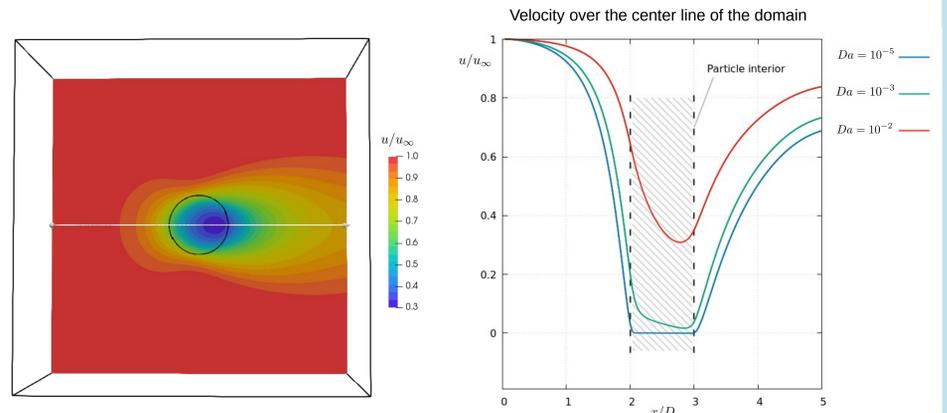
Sedimentation of polydisperse porous particles

Settling of randomly distributed porous particles. No-slip boundary conditions are chosen for the boundary frame. The average particle Reynolds number, Darcy number and global volume fraction of particles are 10, 10^{-2}, and 0.2, respectively.

Acknowledgments