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Discrete element methods and continuum models in bedload transport

Philippe Frey, Hugo Rousseau, Rémi Chassagne, Raphaël Maurin, Julien
Chauchat

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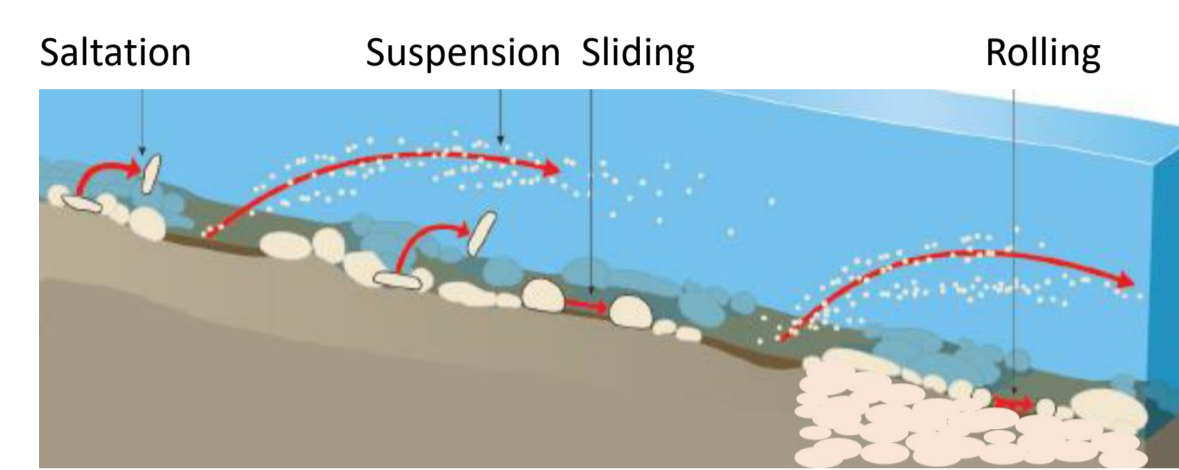
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Introduction

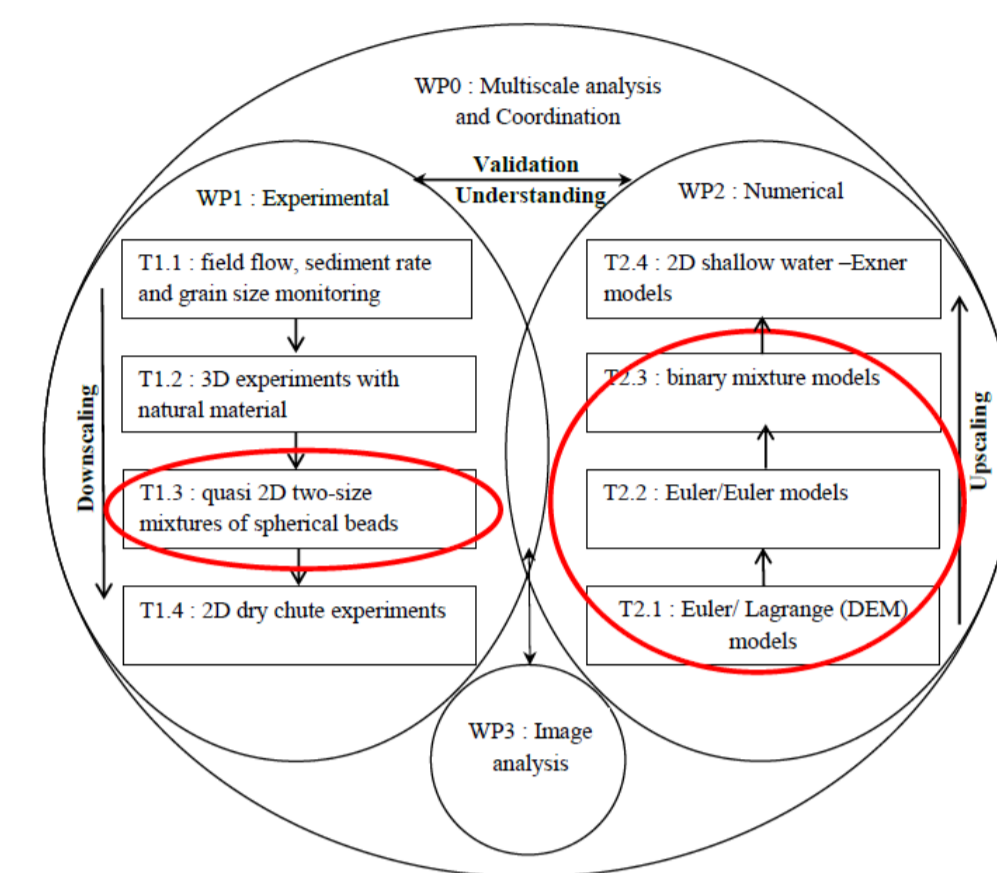
- Bedload has been investigated mostly from the fluid perspective as if the bed were immobile



Sediment transport = bedload (rolling, sliding, saltation) + suspension

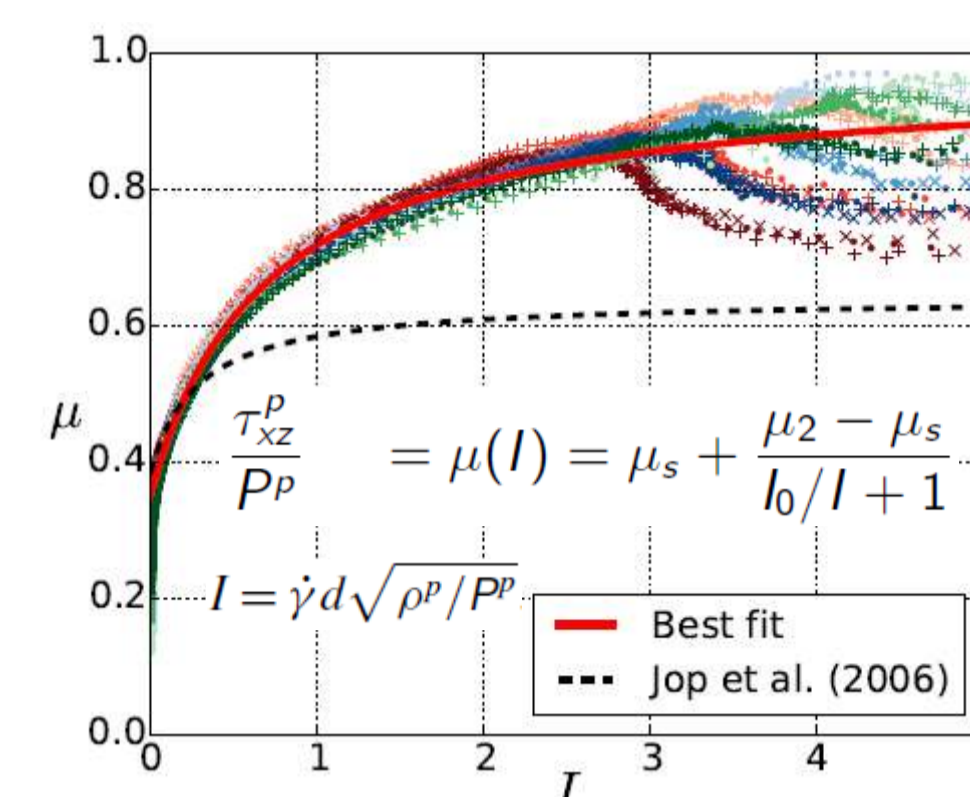
- Yet grain-grain interactions are important (Frey & Church 2009, 2011)
- Warrants:
 - Use of discrete element models (DEM)
 - Upscaling in continuum models

- Objective of this poster**
 - report globally on an ongoing research effort on **sediment transport multi-scale modelling** within the framework of the ANR project SegSed 'Size segregation in sediment transport'
 - Draw materials from PhDs by R. Maurin, R. Chassagne and H. Rousseau



Philosophy and workflow of the SegSed project
 Tasks reported in this poster are circled in red

Granular rheology $\mu(I)$ for upscaling



Maurin et al. JFM 2016

- Phenomenological constants μ_s, μ_2, I_0 derived from DEM
- Fed into a two phase continuous (Euler-Euler) model (Revil-Baudard and Chauchat 2013; Chauchat 2018)

$$0 = \frac{\partial \tau_{xz}^p}{\partial z} + \rho^p \phi g \sin \alpha + n \langle f_x \rangle^p \quad \text{Solid phase equation}$$

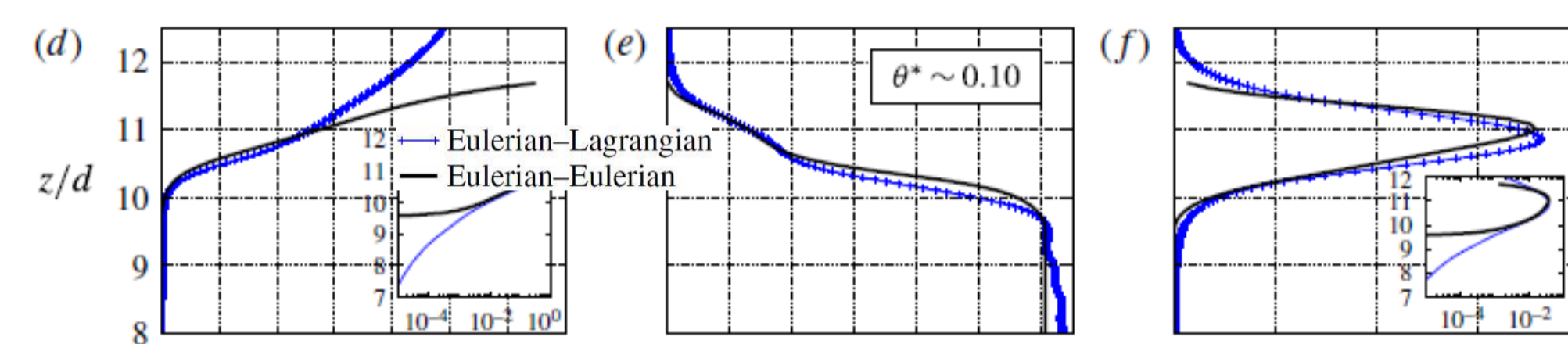
$$0 = -\frac{\partial P^p}{\partial z} + \rho^p \phi g \cos \alpha + n \langle f_z \rangle^p \quad \text{Fluid-DEM model}$$

$$\mu = \frac{\tau_{xz}^p}{P^p} = \mu(I) = \mu_s + \frac{\mu_2 - \mu_s}{I_0/I + 1}$$

$$I = \dot{\gamma} d \sqrt{\rho^p / P^p}$$

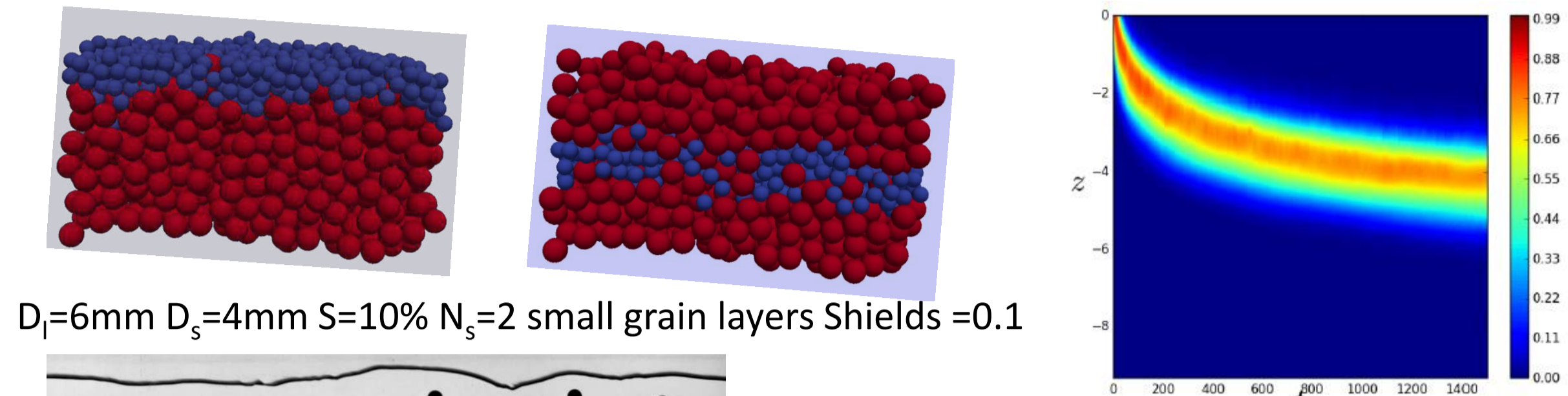
$$P^p = \frac{1}{I^2} \rho_p d^2 \left(\frac{d(v_x^p)}{dz} \right)^2$$

$$\tau^p = \frac{\mu(I)}{I^2} \rho_p d^2 \left(\frac{d(v_x^p)}{dz} \right)^2$$

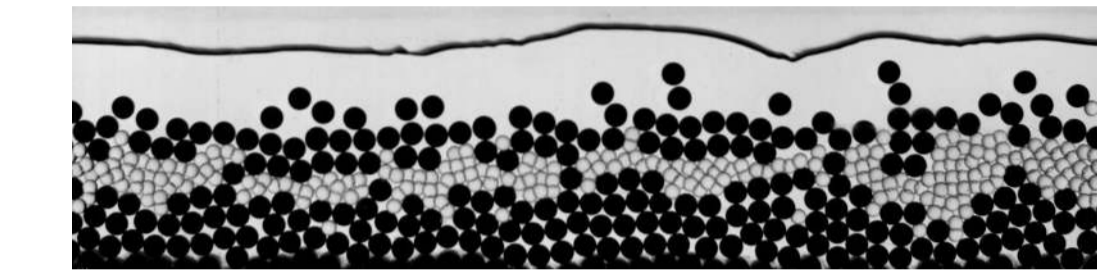


Solid depth profile comparison between the two-phase continuous model (Euler-Euler) and the coupled fluid-discrete-element model (Euler-Lagrange)

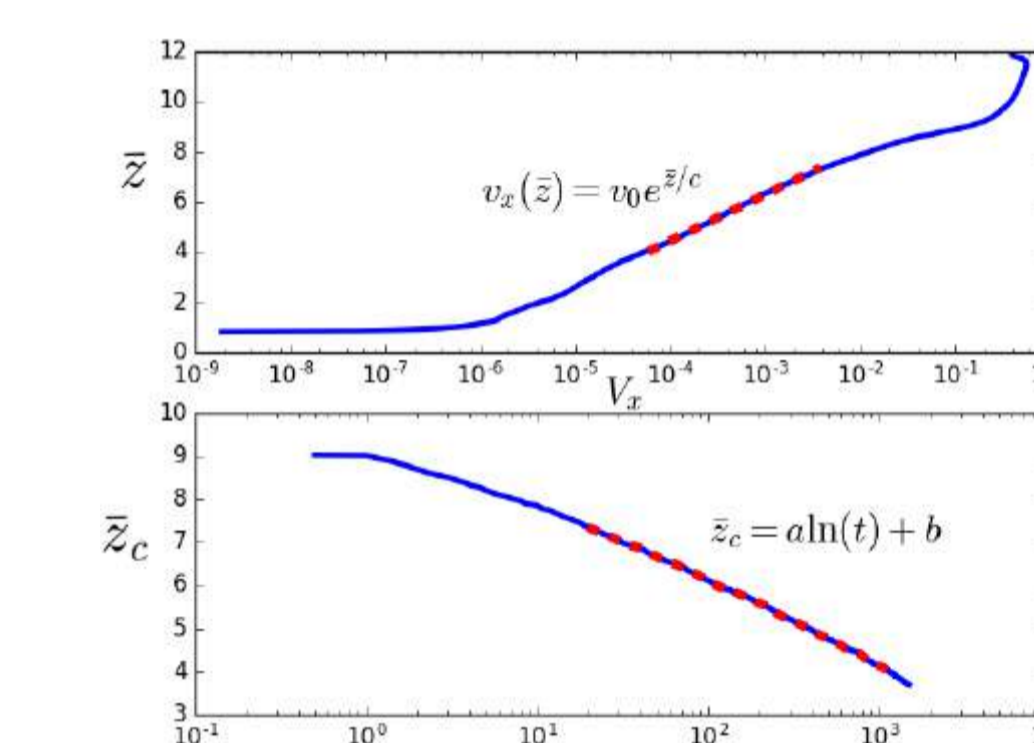
Size segregation – Kinetic sieving



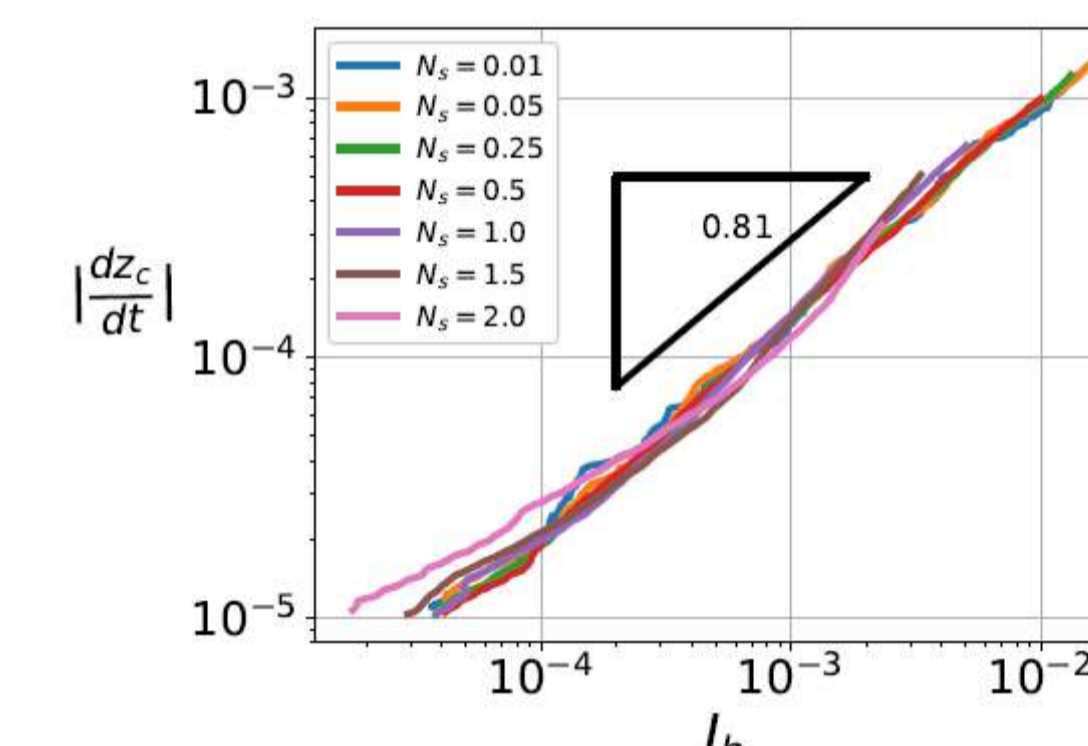
$D_1=6\text{mm}$ $D_2=4\text{mm}$ $S=10\%$ $N_s=2$ small grain layers Shields = 0.1



Experimental segregation pattern (Frey et al. 2020)



Streamwise velocity profile and time evolution of center of mass



Center of mass velocity vs. I at the bottom of the layer for varied numbers of layers N_s

Mixture model (Thornton et al. 2006)

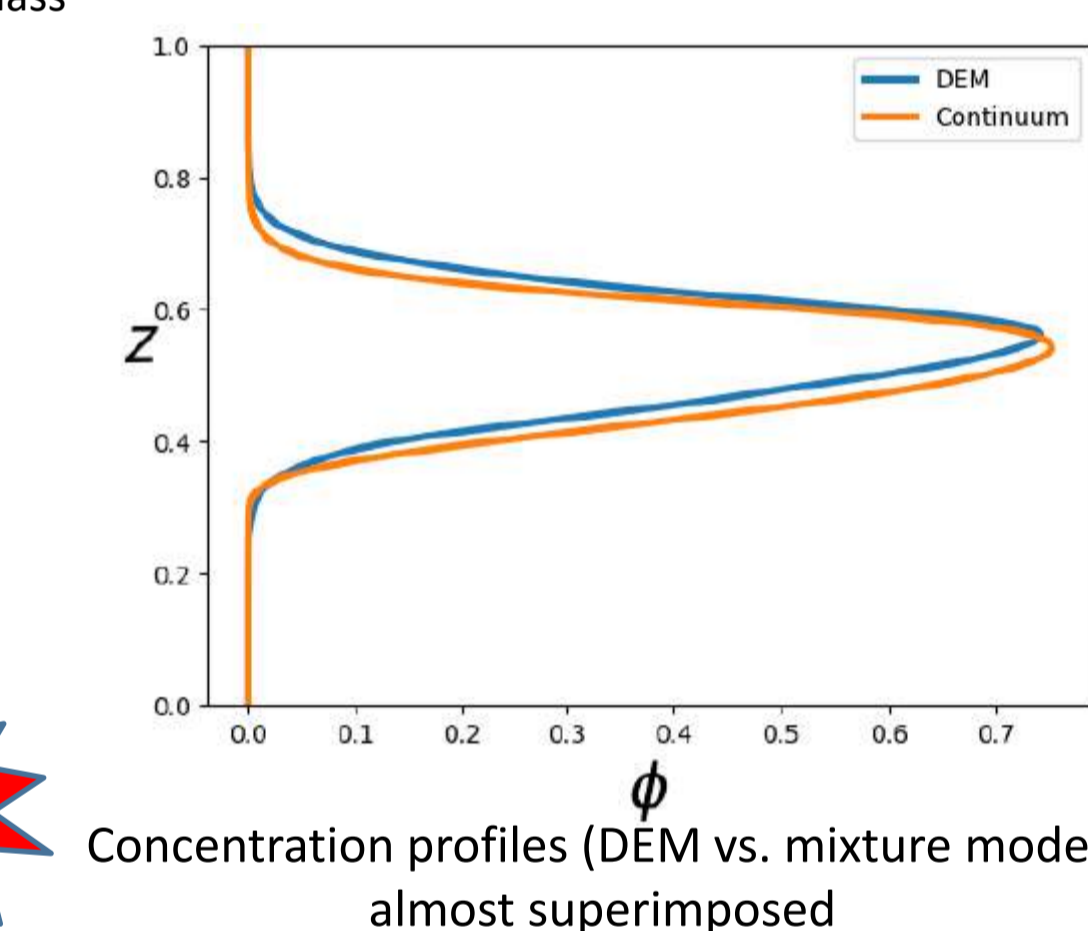
$$\frac{\partial \phi}{\partial t} - \frac{\partial}{\partial z} (S_{r0} e^{z/c} \phi (1 - \phi)) = \frac{\partial}{\partial z} \left(D(z) \frac{\partial \phi}{\partial z} \right)$$

$$\text{DEM: } dz_c/dt = S_{r0} I_b^{0.81}$$

$$\text{Model: } w_p = S_{r0} I_b^{0.81} (1 - \phi)$$

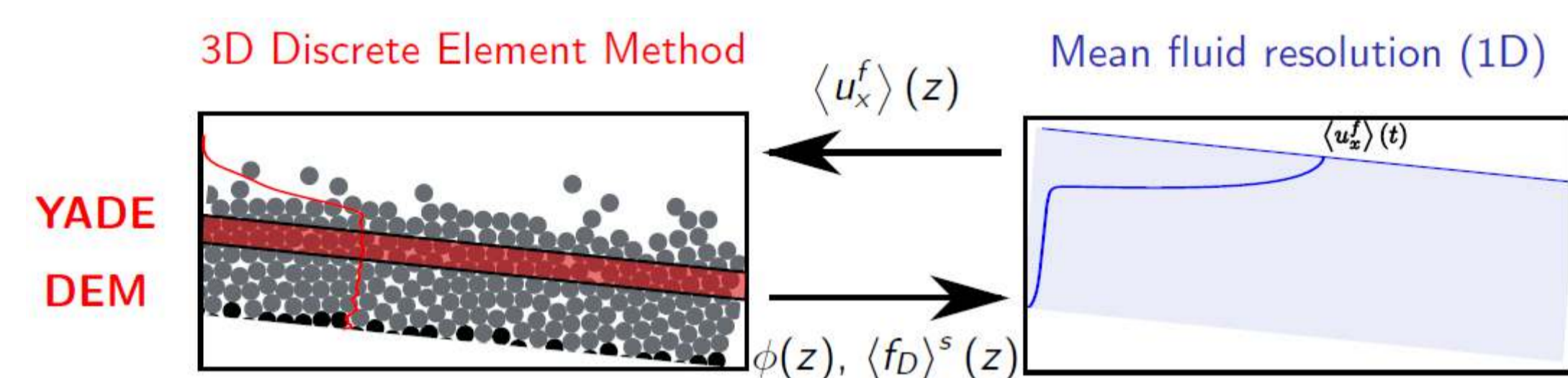
$$D(z) = D_0 I_b^{0.81} = D_0 e^{z/c}$$

Diffusion must have the same exponential dependency as segregation
 Chassagne et al. JFM In press



Concentration profiles (DEM vs. mixture model) almost superimposed

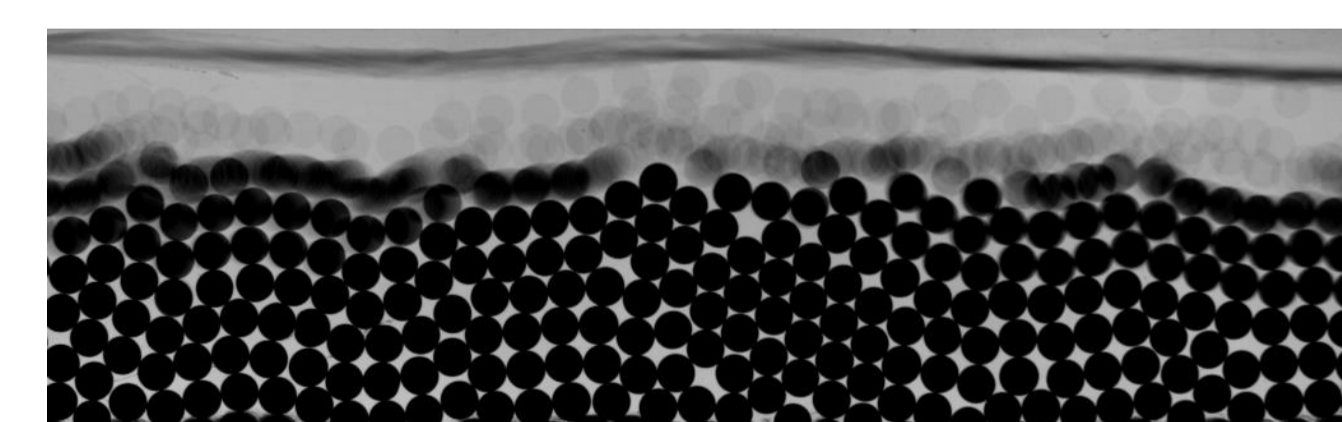
Coupled fluid discrete element model



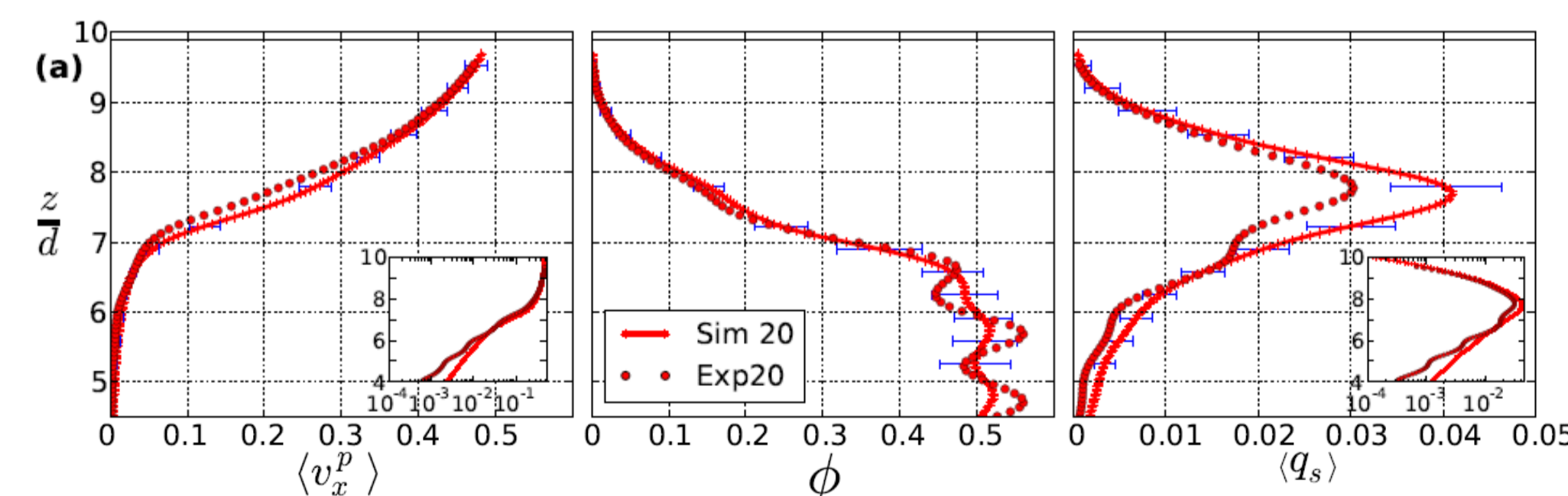
$$m_p \frac{dv^p}{dt} = \underbrace{f_c^p}_{\text{Contact}} + \underbrace{f_g^p}_{\text{Gravity}} + \underbrace{f_b^p}_{\text{Buoyancy}} + \underbrace{f_D^p}_{\text{Drag}}$$

$$(1 - \phi)^f \rho^f \frac{\partial \langle u_x^f \rangle}{\partial t} = \underbrace{\frac{\partial R_{xz}^f}{\partial z}}_{\text{Turb. stress}} + \underbrace{\frac{\partial \tau_{xz}^f}{\partial z}}_{\text{Visc. stress}} + \underbrace{(1 - \phi)^f \rho^f g S_0}_{\text{Gravity}} - \underbrace{n \langle f_{Dz} \rangle^s}_{\text{Drag}}$$

Integral Mixing length taking into account ϕ



Experimental bedload dataset (Frey 2014): narrow flume, Slope 10%, glass beads 6mm, used to validate the fluid discrete model (cumulative image of 20 frames)



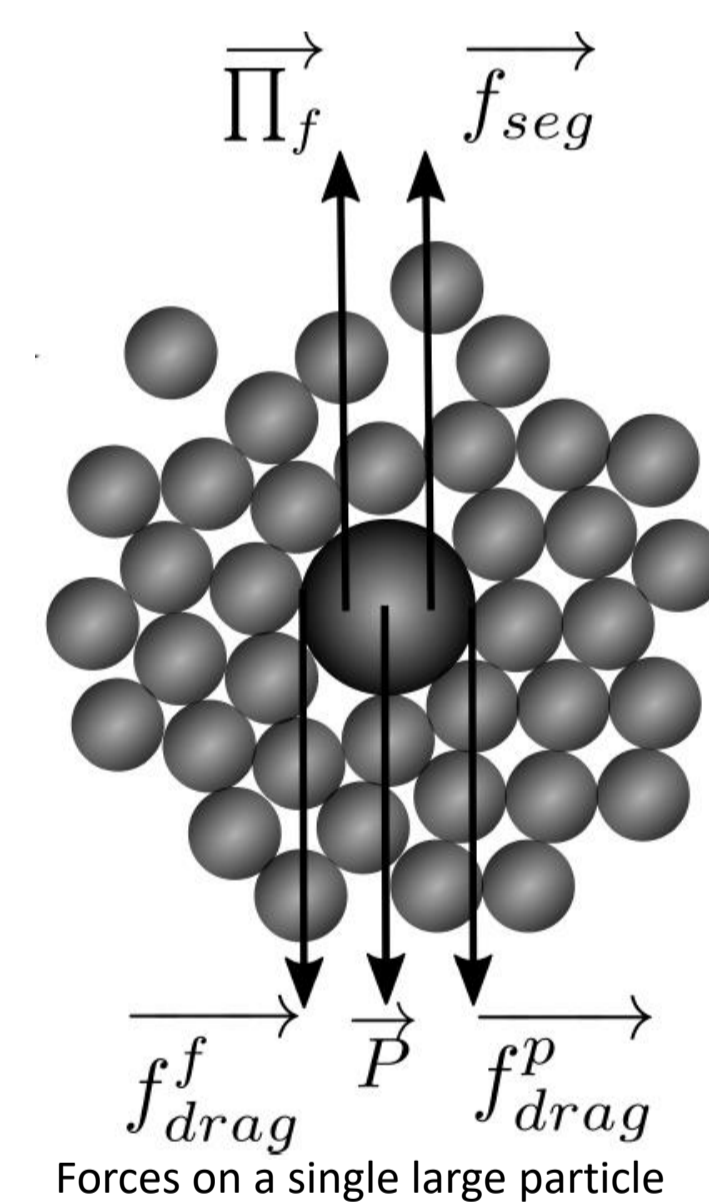
Depth profiles of the streamwise solid velocity v_x^p (m/s), solid volume fraction ϕ and sediment transport rate density q_s (m/s). Comparison with experiments by Frey 2014

Maurin et al. PoF 2015

Multi-Phase Model

$$\rho^p \left[\frac{\partial \Phi^s w^s}{\partial t} + \frac{\partial \Phi^s w^s w^s}{\partial z} \right] = -\frac{\partial p^s}{\partial z} - \Phi^s \frac{\partial p^f}{\partial z} - \rho^p g \cos \theta + n_s f_{drag}^{f \rightarrow s} - n_l f_{drag}^{p \rightarrow l} - n_l f_{seg}$$

$$n_l f_{drag}^p = \frac{6c\Phi^l \eta^p}{d_l^2} (w^s - w^l) \quad \text{and} \quad n_l f_{seg} = -\Phi^l \mathcal{F}(\mu) \frac{\partial p^m}{\partial z}$$



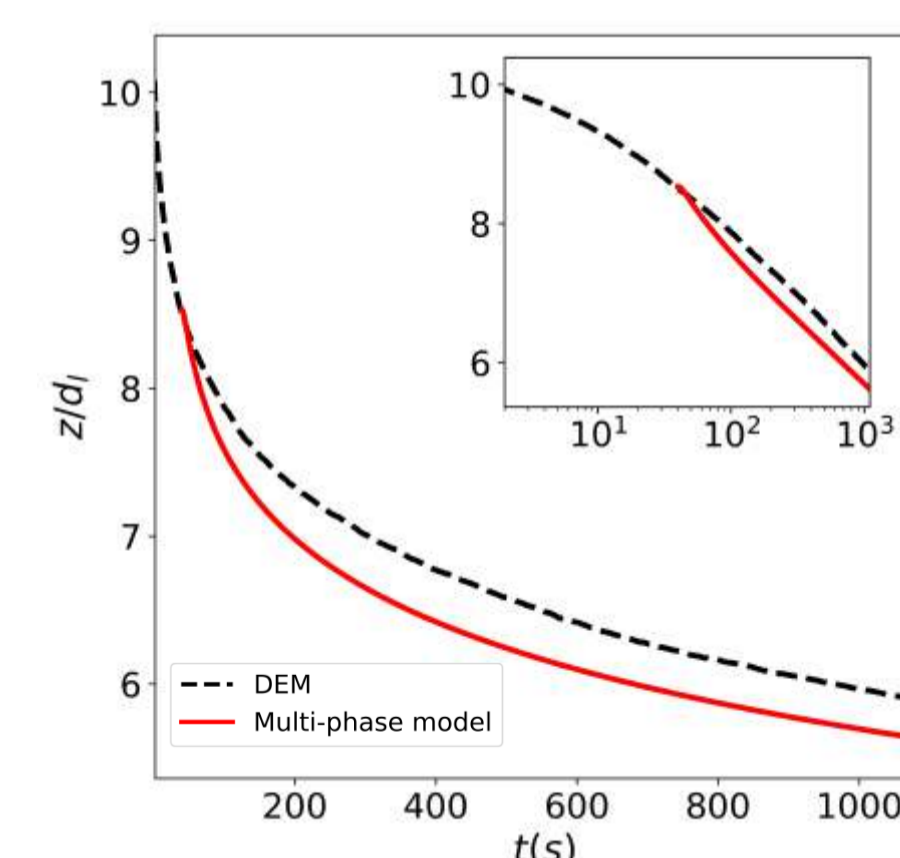
Forces on a single large particle



- Spatial Averaging by number density (Jackson 2000) of a large collection of coarse particles
- $\mathcal{F}(\mu)$ is initially taken from Guillard et al. 2016
- Then improved by DEM
- DEM is used for the particle viscosity η_p and friction factor μ

$$\frac{\partial \phi^s}{\partial t} + \frac{\partial}{\partial z} (\phi^s \phi^s S_r) = \frac{\partial}{\partial z} \left(D \frac{\partial \phi^s}{\partial z} \right)$$

$$S_r = \mathcal{F}(\mu) \frac{\rho^p d_l \sqrt{d_l g} \partial p^m}{18 \eta^p \partial z} \quad \text{and} \quad D = \frac{\Phi^s}{\Phi^l} \frac{\rho^p d_l \sqrt{d_l g}}{18 \eta^p}$$



Rousseau et al. JFM submitted

Conclusions and outlook

- Coupled fluid-discrete element model validated on experiments to:
 - gain access to grain scale physics (impossible to measure in the laboratory)
 - Confirm relevancy of the $\mu(I)$ rheology in bedload transport
 - Study segregation dynamics
 - Provide parametrizations for the grain-scale physics in continuum models
 - Upscaling for applications at larger scales
- Future work:**
 - Improve particle-particle interaction forces
 - drag (e.g. effect of small particle concentration)
 - segregation (e.g. scaling with size ratio)
 - Need of experimental data not only numerical DEM results

Contact

Philippe Frey
 Irstea, UR ETNA
 BP 76, 38402 St-Martin-d'Hères
 France
philippe.frey@inrae.fr
www.irstea.fr/en/frey

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