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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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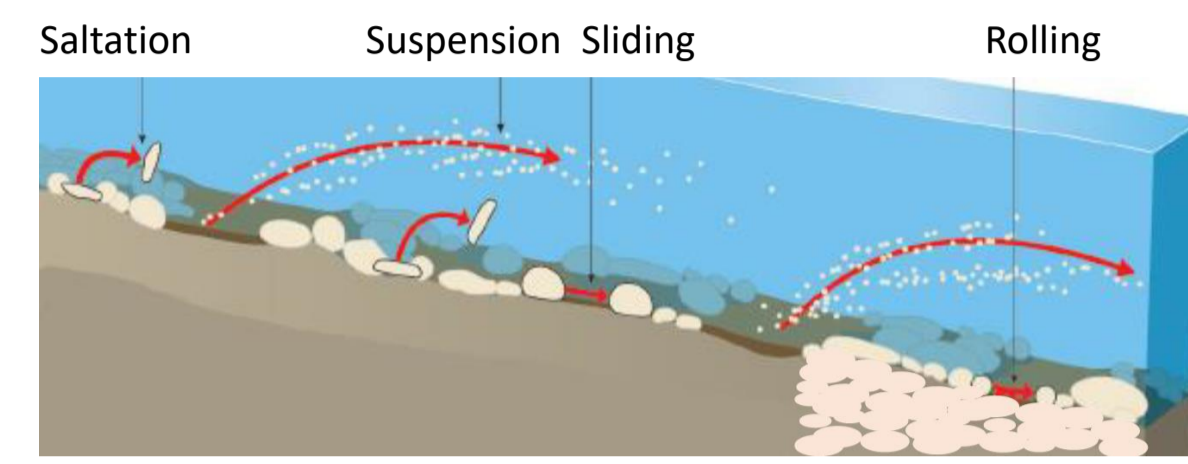
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Introduction

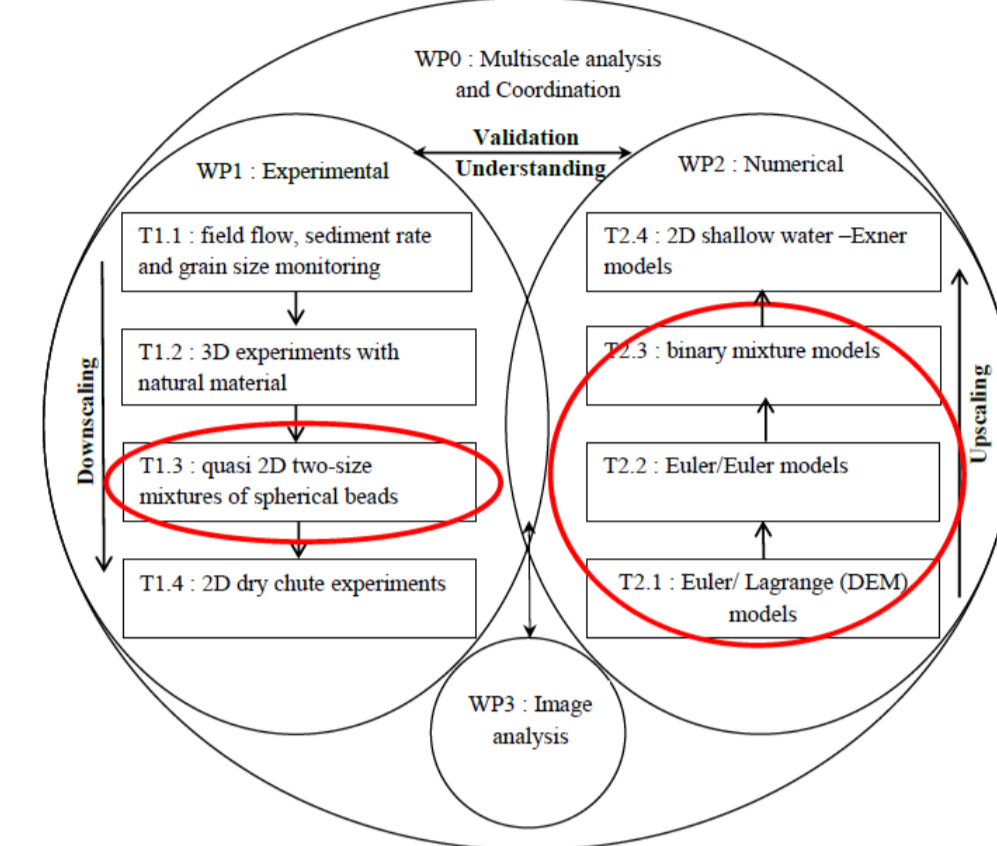
- Bedload has been investigated mostly from the fluid perspective as if the bed were immobile



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

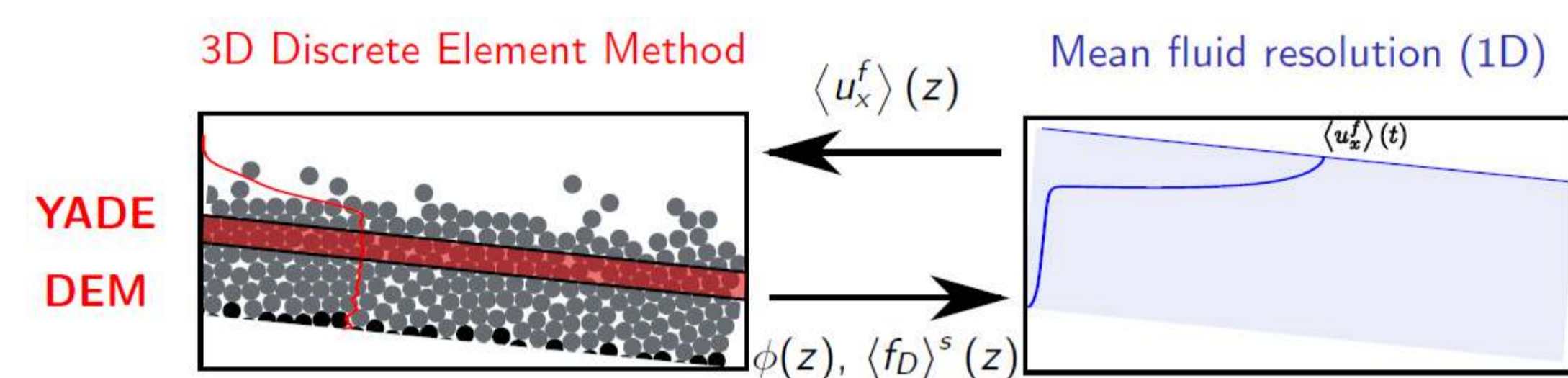
- Yet grain-grain interactions are important (Frey & Church 2009, 2011)
- Warrants:
 - Use of discrete element models (DEM)
 - Upscaling in continuum models

- 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



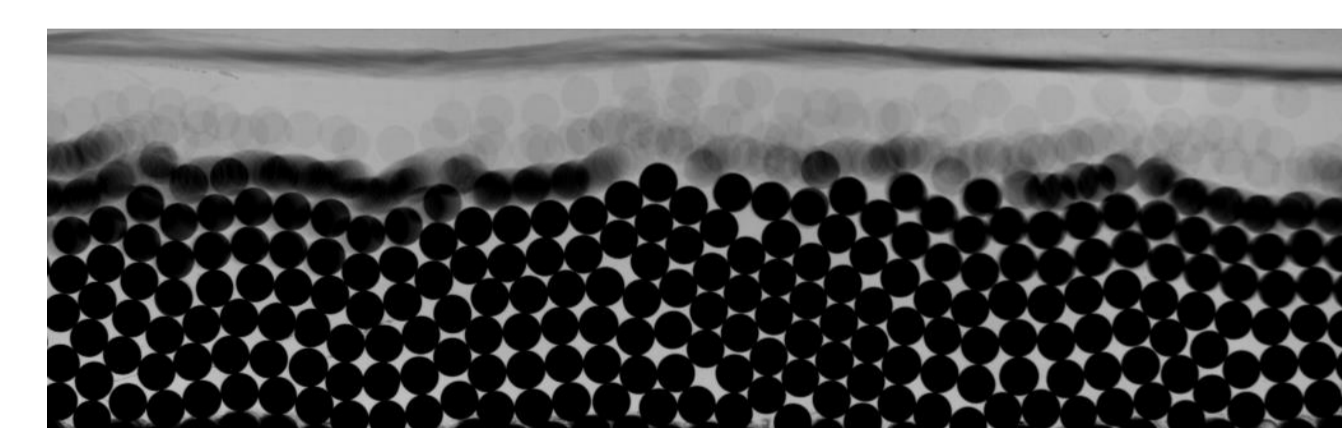
Philosophy and workflow of the SegSed project
 Tasks reported in this poster are circled in red

Coupled fluid discrete element model

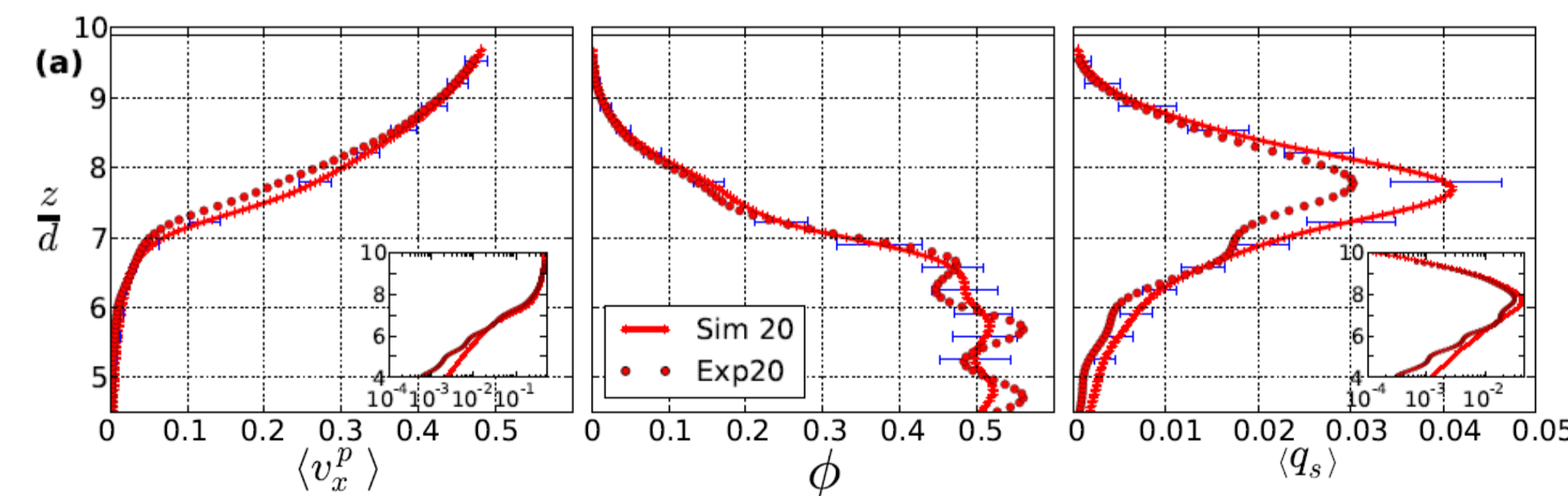


$$m_p \frac{dv^p}{dt} = \underbrace{f_c^p}_{\text{Contact}} + \underbrace{f_g^p}_{\text{Gravity}} + \underbrace{f_b^p}_{\text{Buoyancy}} + \underbrace{f_D^p}_{\text{Drag}}$$

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

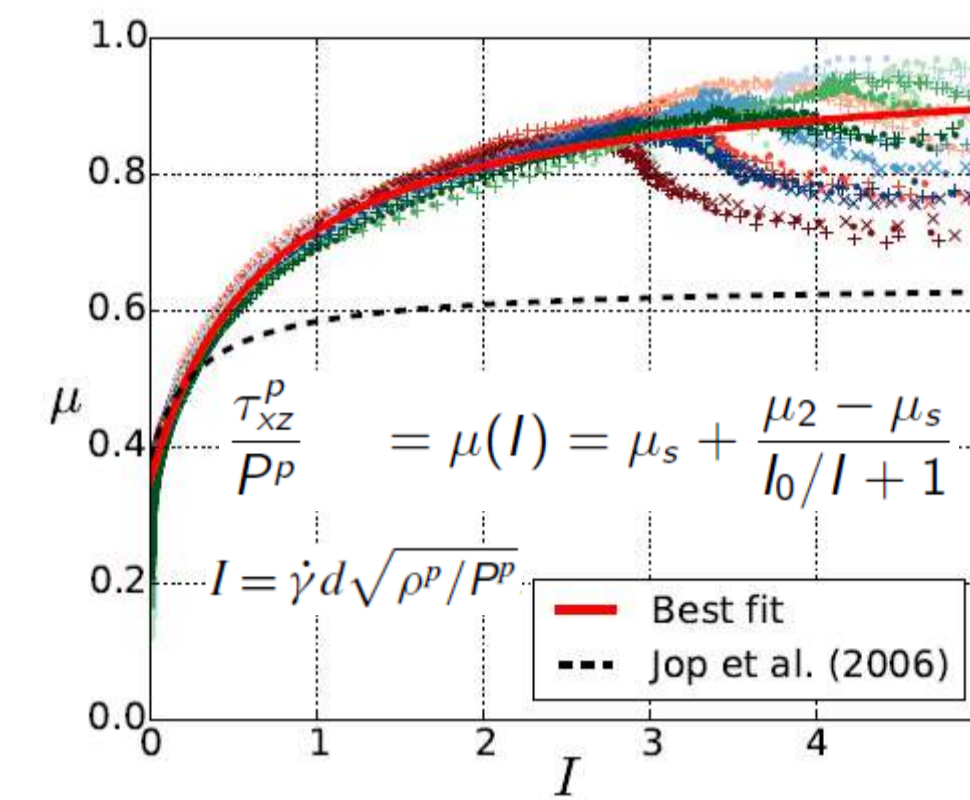


Experimental bedload dataset (Frey 2014): narrow flume, Slope 10%, glass beads 6mm, used to validate the fluid discrete model (cumulative image of 20 frames)



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

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)

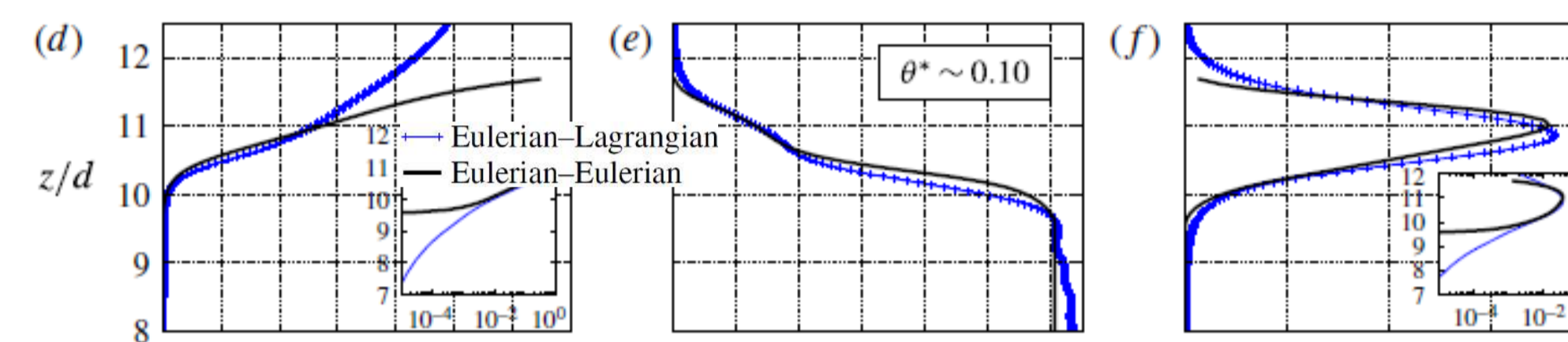
$$0 = \frac{\partial \tau_{xz}^p}{\partial z} + \rho^p \phi g \sin \alpha + n \langle f_x \rangle^p$$

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

Solid phase equation
 Fluid component is the same as in the fluid-DEM model

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

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

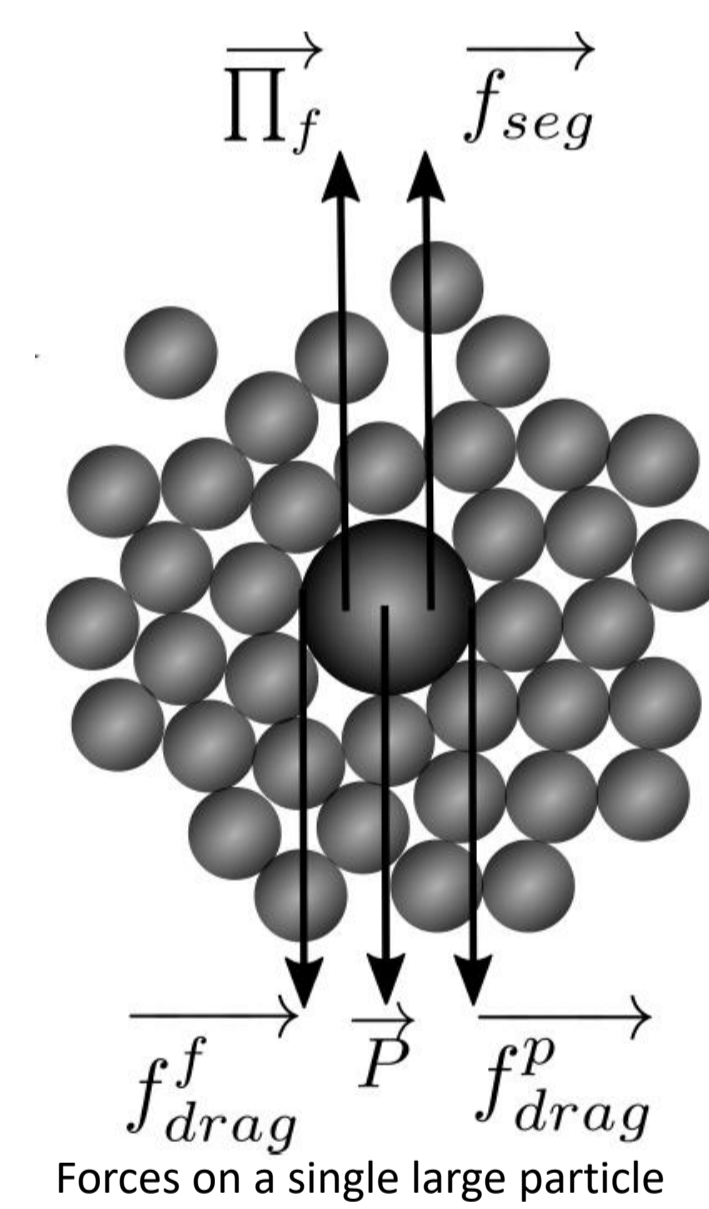


Solid depth profile comparison between the two-phase continuous model (Euler-Euler) and the coupled fluid-discrete-element model (Euler-Lagrange)

Multi-Phase Model

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

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

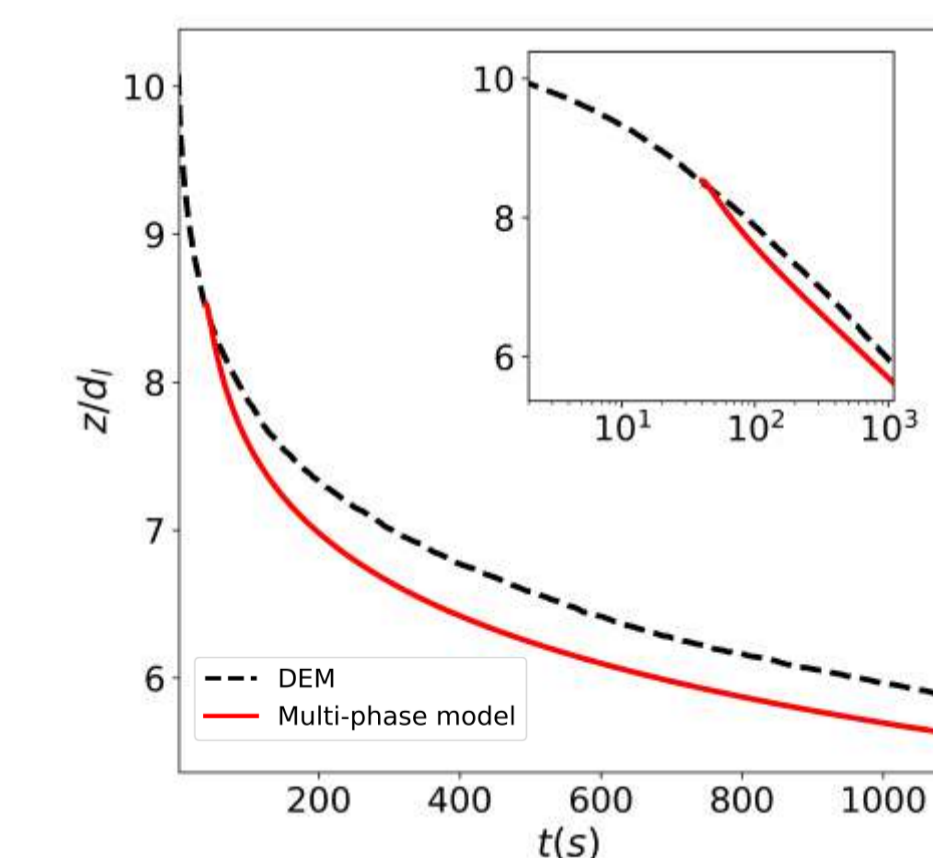


Rousseau et al. JFM submitted

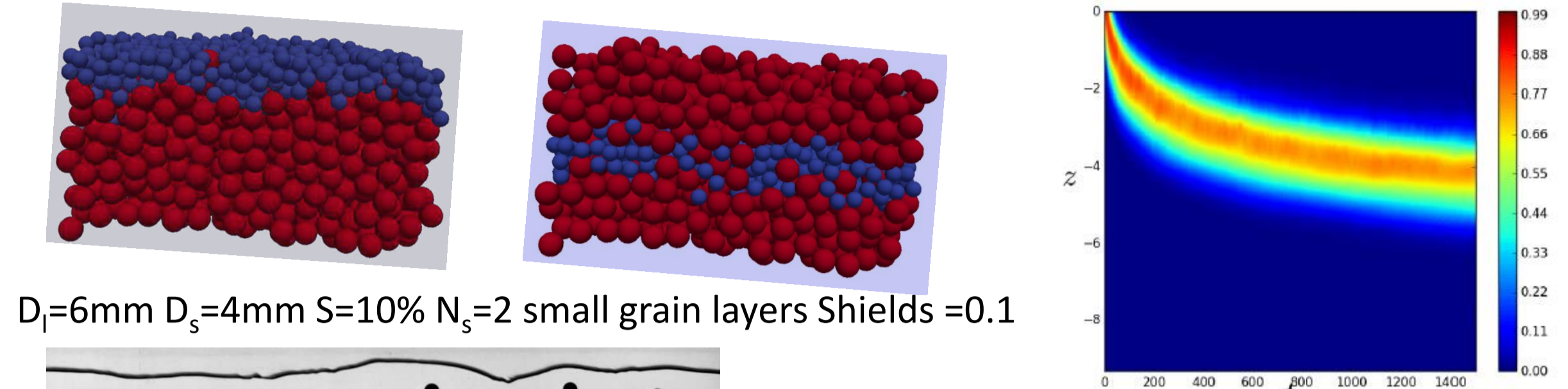
- Spatial Averaging by number density (Jackson 2000) of a large collection of coarse particles
- $\mathcal{F}(\mu)$ is initially taken from Guillard et al. 2016
- Then improved by DEM
- DEM is used for the particle viscosity η_p and friction factor μ

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

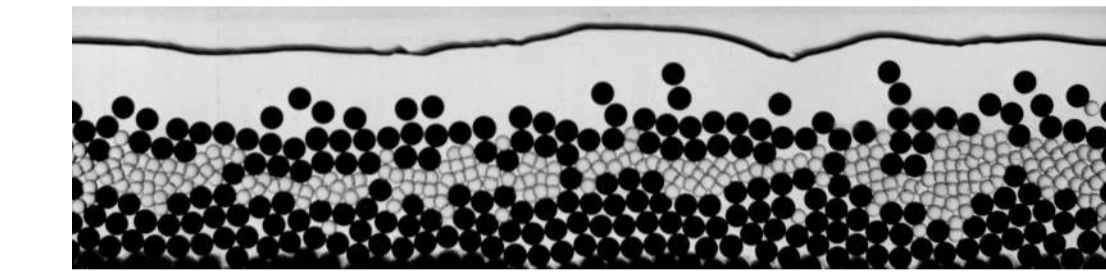
$$S_r = \mathcal{F}(\mu) \frac{\rho^p d_l \sqrt{d_l g} \partial p^m}{18 \eta^p \partial z} \quad \text{and} \quad D = \frac{\Phi^s}{\Phi^l} \frac{\rho^p d_l \sqrt{d_l g}}{18 \eta^p}$$



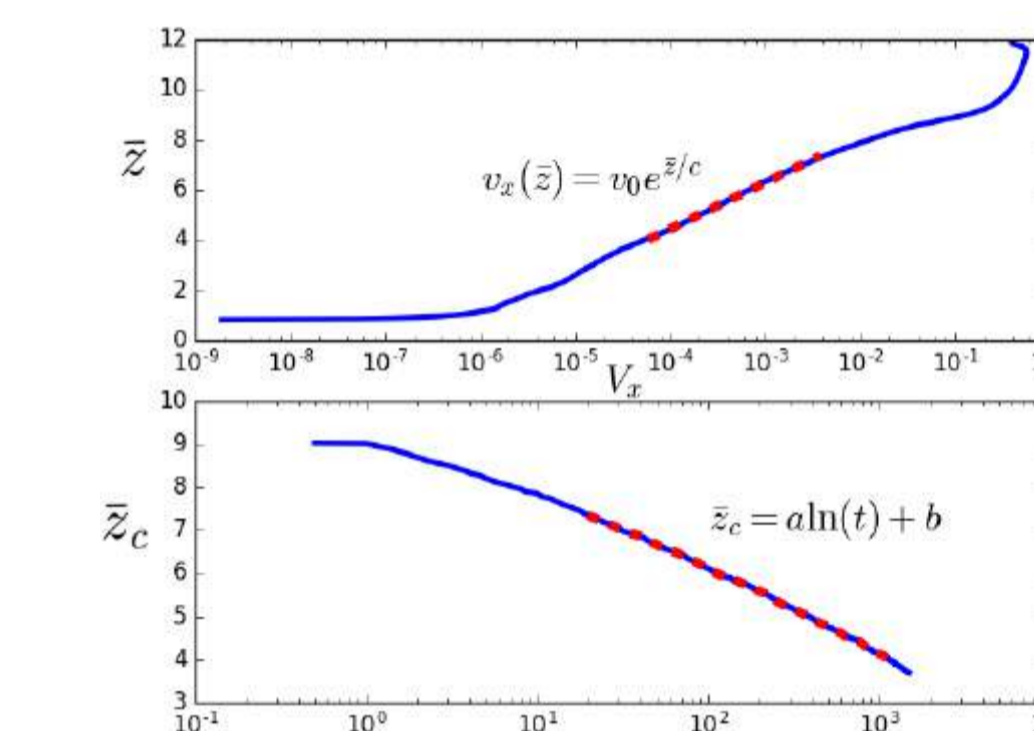
Size segregation – Kinetic sieving



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



Experimental segregation pattern (Frey et al. 2020)



Streamwise velocity profile and time evolution of center of mass

Mixture model (Thornton et al. 2006)

$$\frac{\partial \phi}{\partial t} - \frac{\partial (S_r \phi e^{z/c} (1-\phi))}{\partial z} = \frac{\partial (D(z) \frac{\partial \phi}{\partial z})}{\partial z}$$

DEM: $dz_c/dt = S_r \phi I_b^{0.81}$

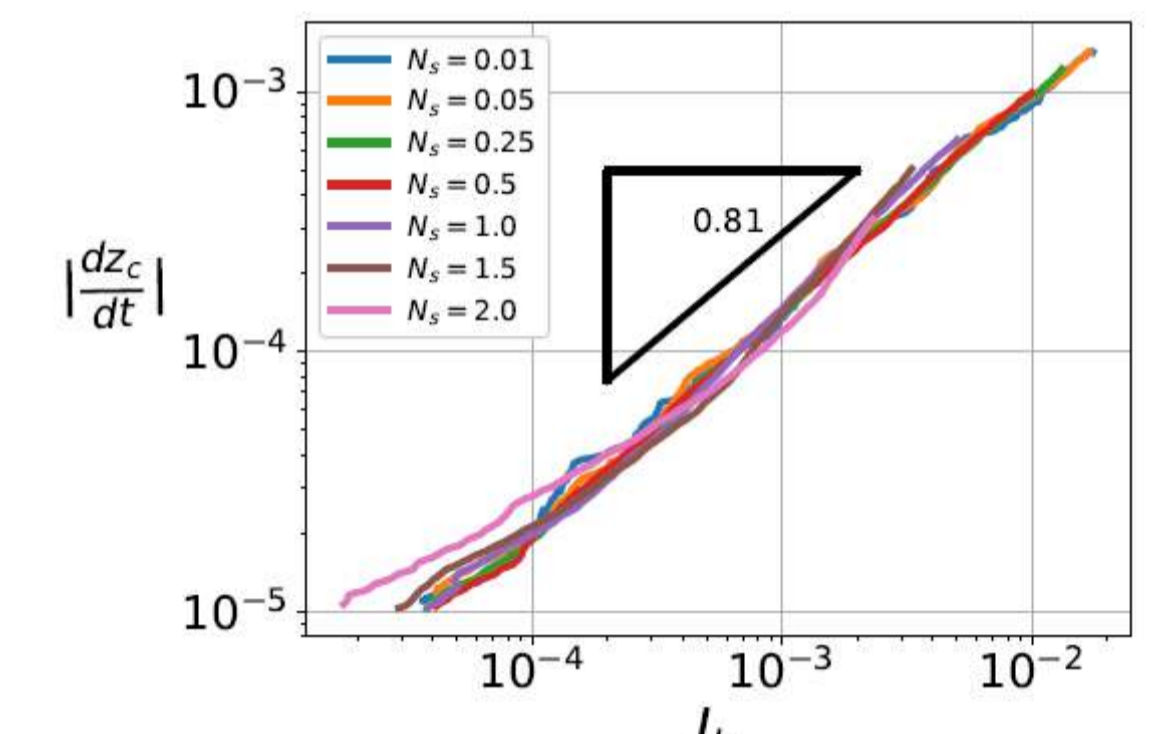
Model: $w_p = S_r \phi I_b^{0.81} (1-\phi)$

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

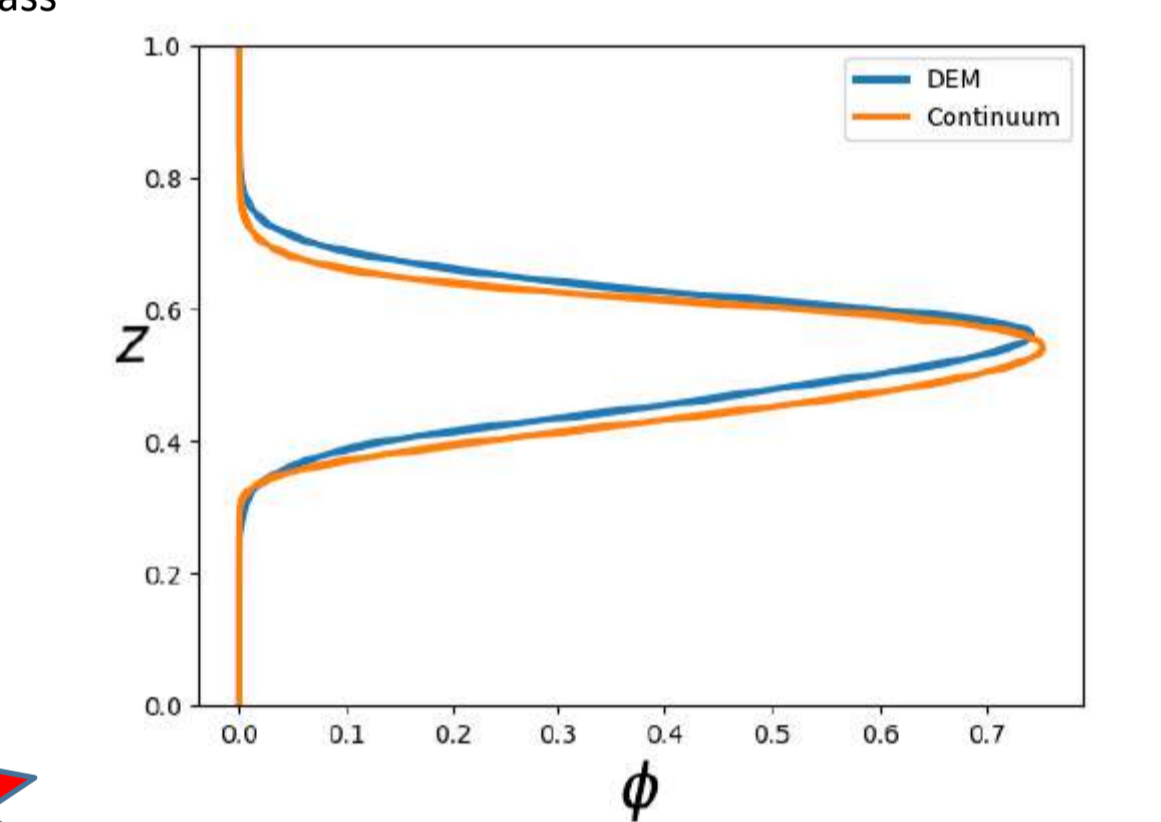
Diffusion must have the same exponential dependency as segregation



Chassagne et al. JFM In press



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



Concentration profiles (DEM vs. mixture model) almost superimposed

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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