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Microscopic mechanism of grain detachment in suffusion

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Outline

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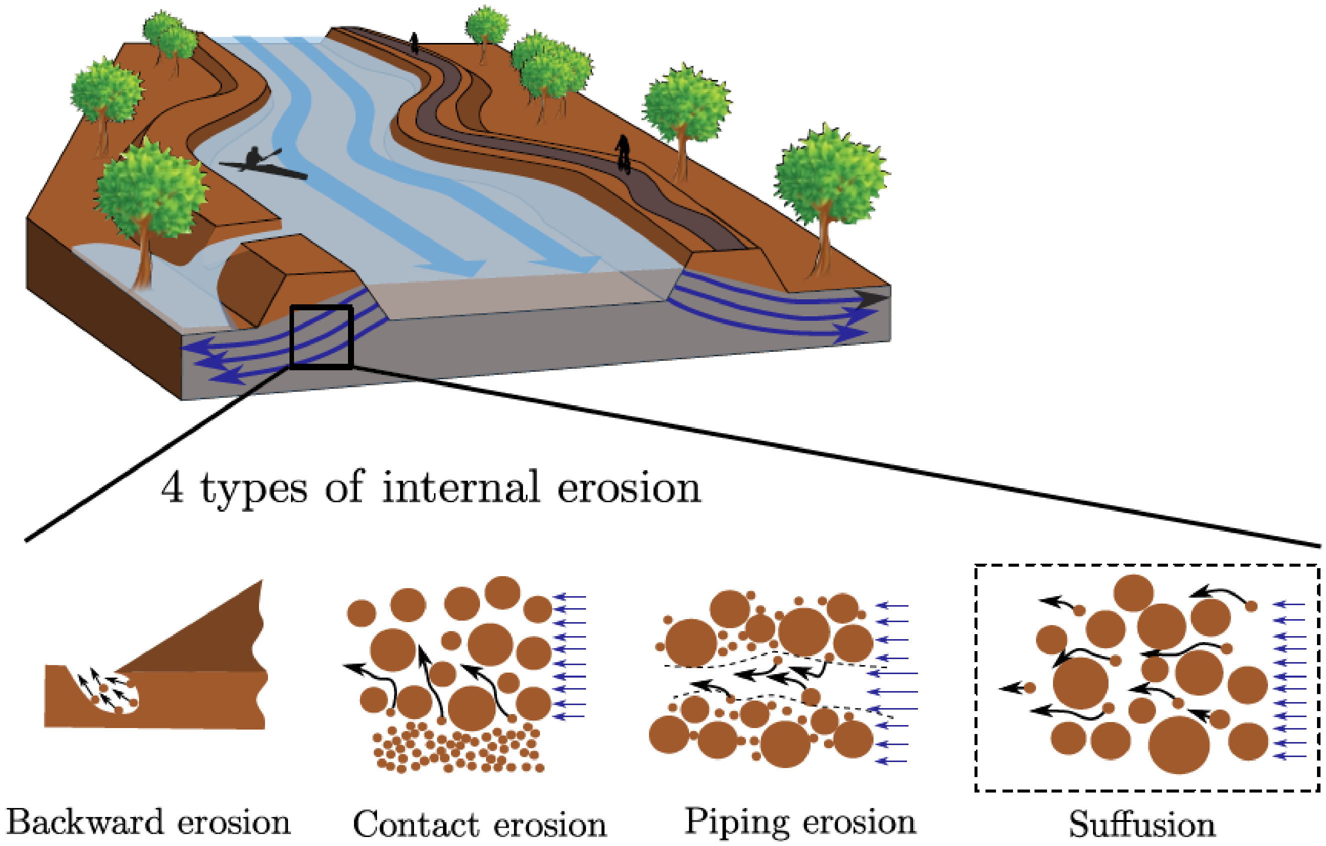
Research background

46% of earth rock dam damage is originated from internal erosion

(Foster,2000)

Research background



(Wautier,2018)

Suffusion: coupled process of detachment–transport–filtration of a part of the finest fraction within the porous network

Experimental investigation

PSD(Particle size distribution):
(Kenney & Lau,1986;Burenkova,1993; Kézdi, 2013)

Stress state:
(Chang & Zhang, 2013; Bendahmane et al., 2008; Sibille et al., 2015)

Plane Laser-Induced Fluorescence (PLIF) (Hunter & Bowman, 2018) and micro-CT techniques (Nguyen et al., 2019)(Taylor, 2016)

Numerical simulation

DEM without fluid (Particle removal):
(Scholtès et al., 2010;Wood & Maeda, 2008;Muir Wood et al., 2010)

PSD(Particle size distribution):
(Shire et al., 2014;Hicher, 2013; Nguyen et al., 2020; Zou et al., 2020)

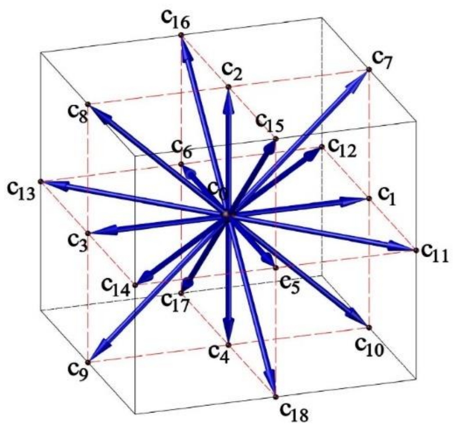
Fines content :
(Kawano et al., 2018; Hu et al., 2019)

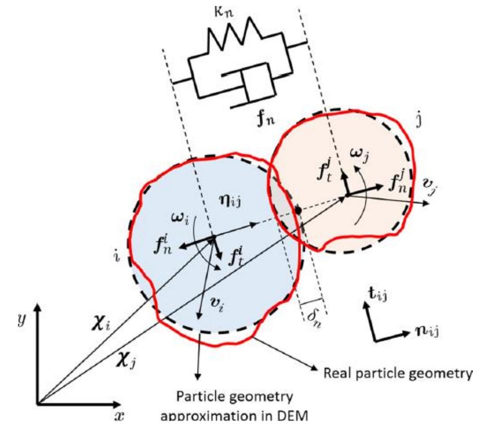
However, elementary mechanisms investigations are scarce, and often focus more on transport than detachment and clogging

Outline

1. Research background
2. Simulation method and process
3. Results and discussions
4. Conclusions

LBM-DEM method





Lattice Boltzmann Method (Palabos)
(Latt et al., 2020)

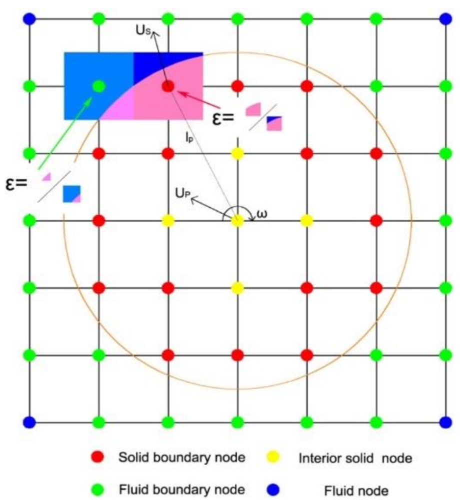
$$f_i(\mathrm{x}+\mathbf{c}_i\delta_t, t+\delta_t)-f_i(\mathrm{x},t)=-\frac{1}{\tau}[f_i(\mathrm{x},t)-f_i^{eq}(\mathrm{x},t)]$$

Discrete element method (LIGGGHTS)
(Kloss et al., 2012)

$$m_i\mathbf{a}=\mathbf{F}_c+\mathbf{F}_{fluid}+m_i\mathbf{g}$$

$$I_i\dot{\boldsymbol{\omega}}=\mathbf{T}_c+\mathbf{T}_{fluid}$$

(Owen et al. 2011)



Coupled LBM-DEM method

Immersed moving boundary (Noble & Torczynski,1998)

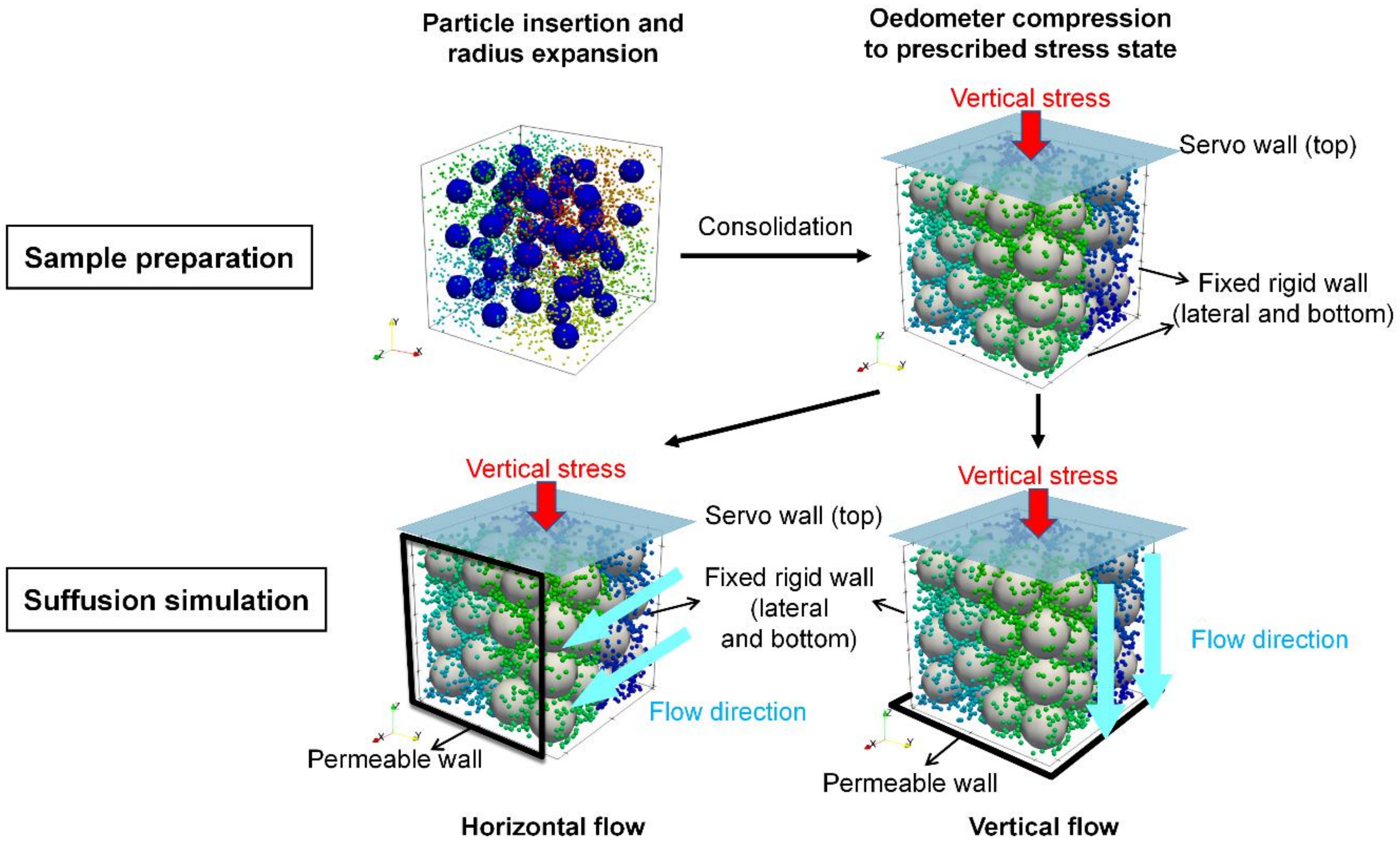
$$f_i(\mathrm{x}+\mathbf{c}_i\delta_t, t+\delta_t)-f_i(\mathrm{x},t)=-\frac{1}{\tau}[f_i(\mathrm{x},t)-f_i^{eq}(\mathrm{x},t)](1-B)+B\Omega_i^s$$

$$\Omega_i^s=f_{-i}(\mathrm{x},t)-f_{-i}^{eq}(\rho_f,\mathbf{u}_f)+f_i^{eq}(\rho_f,\mathbf{u}_s)-f_i(\mathrm{x},t)$$

$$B=\frac{\varepsilon(\tau-0.5)}{(1-\varepsilon)+(\tau-0.5)} \quad \varepsilon=V_{solid}/V_{cell}$$

Simulation process

- The sample is simplified as a binary mixture with a size ratio of 10, fines content 30% by mass.
- The binary packing is compressed vertically to prescribed stress levels with a servo-controlled boundary condition.



Parameters

Simulation conditions

Conditions	Vertical stress, σ_v (MPa)	Stress ratio, $\eta=q/p$	Hydraulic gradient, I	Flow direction
Case 1	0.1	0.7	1.0	Horizontal
Case 2	0.5	1.1	0.1	Horizontal
Case 3	0.5	1.1	1.0	Horizontal
Case 4	0.5	1.1	1.0	Vertical

Detailed parameters

	Parameters	Units	Values
DEM	Particle density	kg/m^3	2600
	Particle number （Coarse/Fine）		60（Coarse） /26728（Fine）
	Contact model		Hertz-Mindlin
	Young’s module	GPa	25
	Poisson ratio		0.3
	Maximum diameter	mm	30
	Minimum diameter	mm	3
	Particle size ratio		10
	Sliding friction		0.5
	Rolling friction		0.1
	DEM timestep	s	4.45×10^{-8}
LBM	Fluid density	kg/m^3	1000
	Kinematic viscosity	m^2/s	1.01×10^{-6}
	LBM timestep	s	4.45×10^{-7}
	Every coupling Period		10

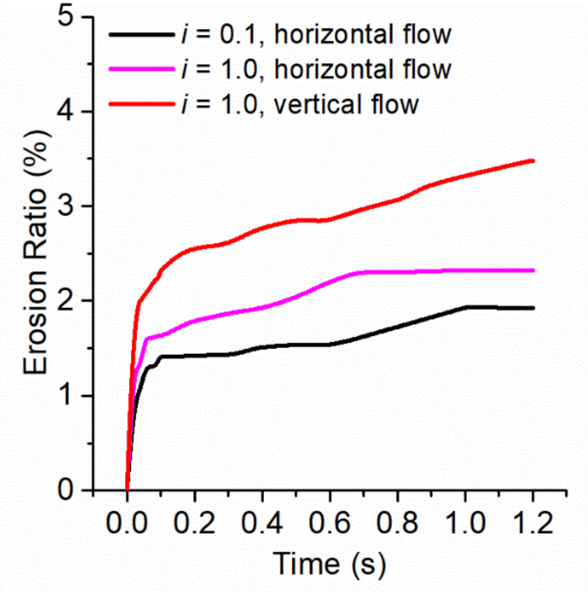
Outline

Results and discussions

Macro characteristics

Erosion ratio = $Mass_{erosion}$/ $Mass_{total}$

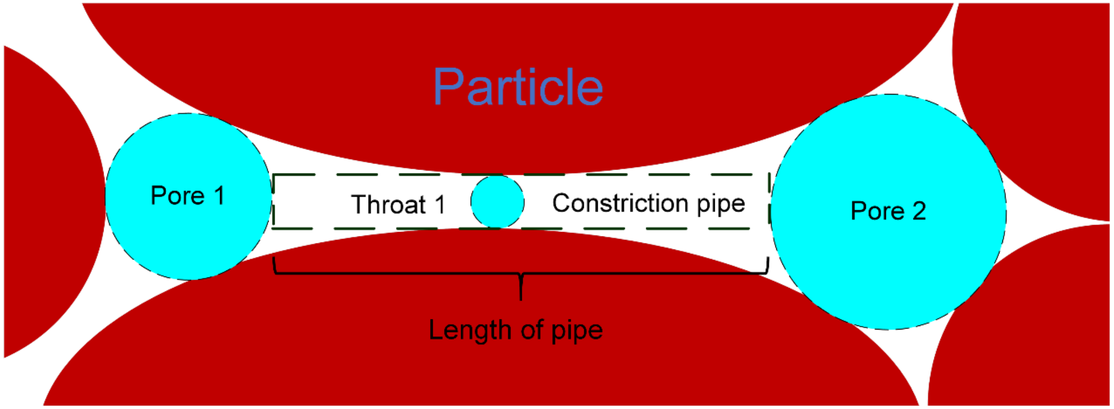
(i =1.0,σ_v=0.5 MPa)



- larger erosion with increased flow intensity
- larger erosion for vertical flow aligned with principal compression direction

Results and discussions

Directional porosity



$$\boldsymbol{\varphi} = \frac{1}{V_{\text{total}}} \sum_{i \in \text{constriction}} V_i \, \mathbf{m}_i \otimes \mathbf{m}_i$$

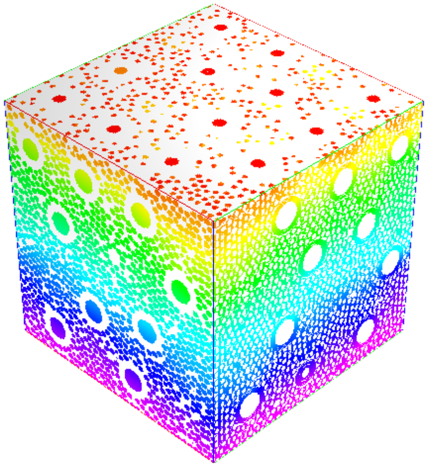
where $\mathbf{m}_i$ is the vector of *i*-th pipe direction, V_i is the volume of *i*-th pipe.

When $\sigma_v = 0.5\text{MPa}$

$$\boldsymbol{\varphi} = \begin{pmatrix} 0.5025 & & \\ & 0.5031 & \\ & & 0.5121 \end{pmatrix} * 10^{-3}$$

Directional permeability

Finite-difference method stokes solver (FDMSS) (Gerke et al. 2018)



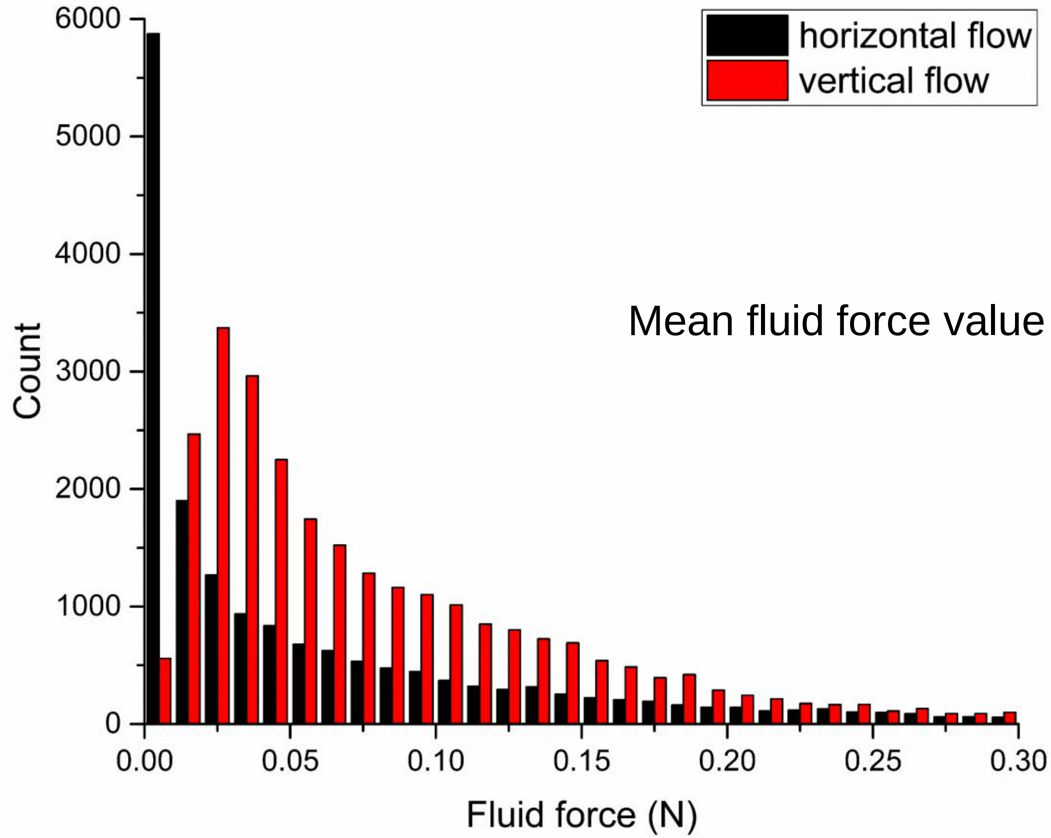
Permeability $\mathbf{K}$, μm^2

$K_x = 0.1499$
$K_y = 0.1501$
$K_z = 0.1661$

For eroded particles, the distribution of channels with more flowability is in the *z*-direction, which means that vertical erosion is more likely to occur.

Fluid force distribution

(I = 1.0, σ_v= 0.5MPa) t=0.6s (half of the simulation time)



Mean fluid force value :0.105 N (horizontal flow)
0.136 N (vertical flow)

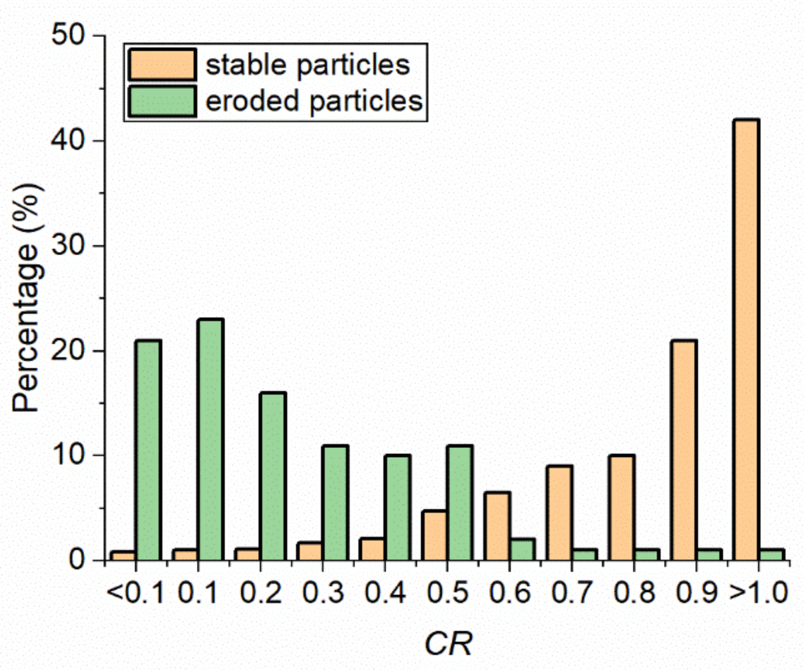
- In vertical flow, the larger fluid force obtained at the same hydraulic gradient, which makes the fine particles more easily to move.

Results and discussions

Contact force ratio

$$CR = \frac{\frac{1}{N_{\text{contact}}}\sum_{i=1}^{N_{\text{contact}}}\left\|\boldsymbol{F}_{\text{contact}}\right\|}{\left\|\boldsymbol{F}_{\text{fluid}}\right\|}$$

The results are obtained by averaged methods in all time steps for stable particles.



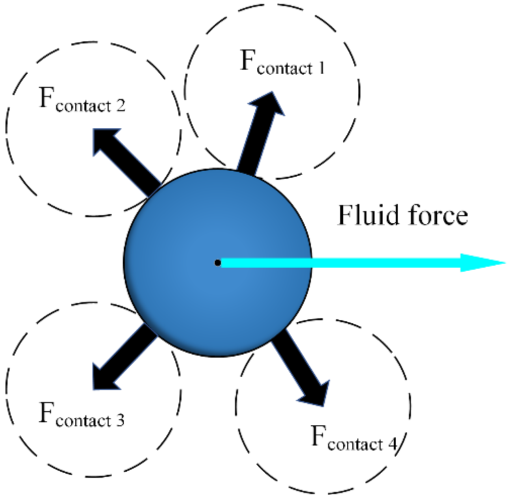
Most stable particles have a magnitude of *CR* larger than 1.0; whereas the leading proportions of eroded particles are smaller than 0.3.

- The dominant position of contact force for stable particles resist the fluid erosion, and the influence of the fluid prevails when the eroded particles are going to become free.

Results and discussions

Sliding index of contact pair at the critical time

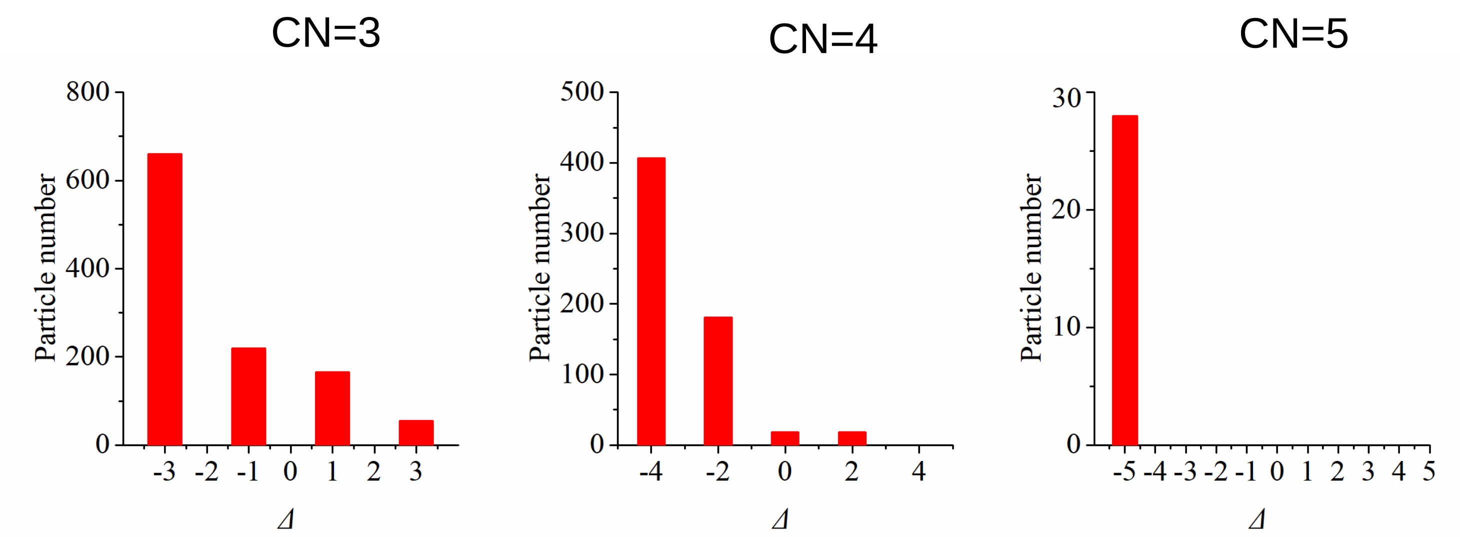
$$P^{(i)}(\boldsymbol{m}) = \frac{1}{\tan\varphi^{(i)}} \frac{\left\|\boldsymbol{F}_{\mathrm{t}}^{(i)}\right\|}{\left\|\boldsymbol{F}_{\mathrm{n}}^{(i)}\right\|} \left[\frac{k_{\mathrm{n}}^{(i)} \boldsymbol{n}^{(i)} \cdot \boldsymbol{m}}{\left\|\boldsymbol{F}_{\mathrm{n}}^{(i)}\right\|} - \frac{k_{\mathrm{t}}^{(i)} \boldsymbol{t}^{(i)} \cdot \boldsymbol{m}}{\left\|\boldsymbol{F}_{\mathrm{t}}^{(i)}\right\|} \right]$$



P<0 reflects that the contact pair is going to slide

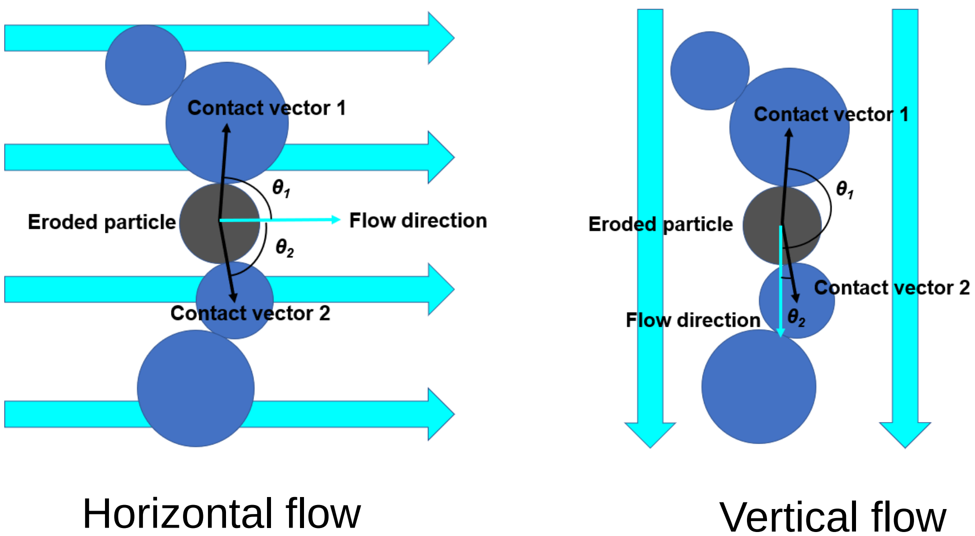
Δ=Number(*P*>0)-Number(*P*<0) stands for a detachment index

Critical time refer to the moment particle is going to detached (just before contact number=0)



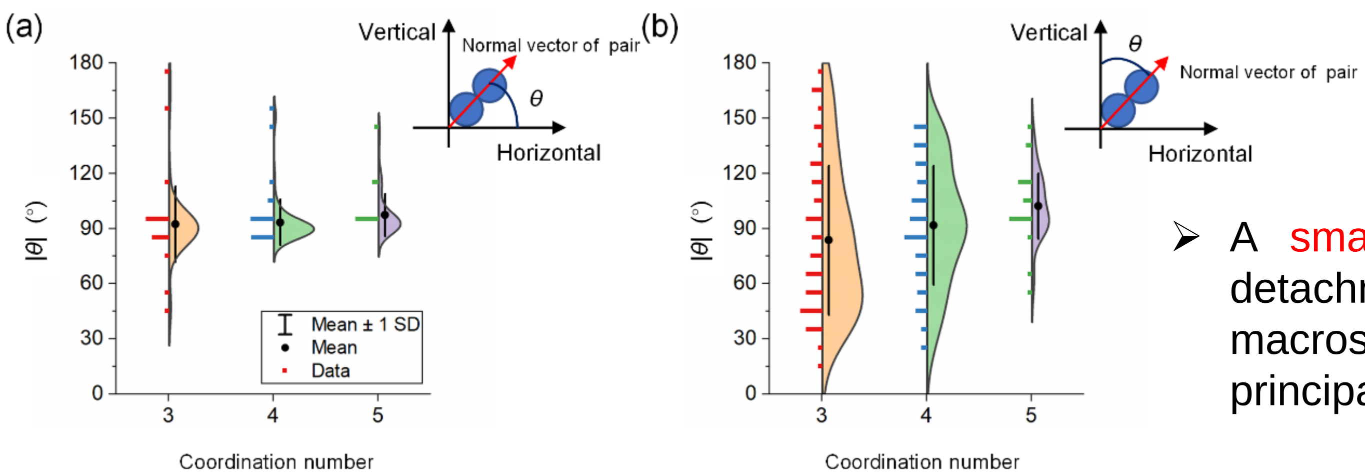
- the number of contact pairs of eroded particles exhibiting an absolute sliding trend

Angle distribution of contact pair at the critical time



The angle between the normal contact vector of eroded particle and macroscopic flow direction

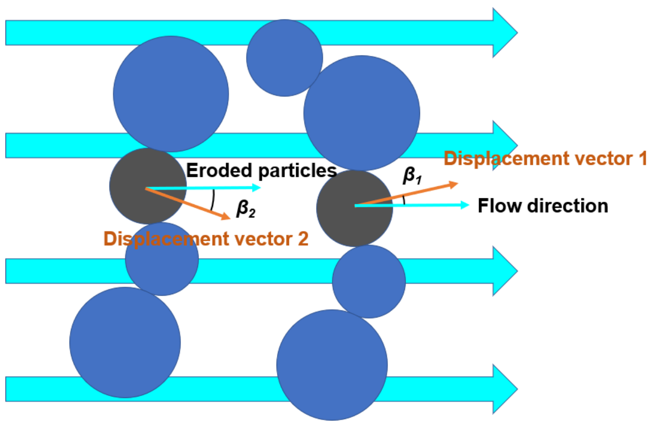
The angle θ distribution of the eroded particles with high contact number (CN>3) at the critical time.



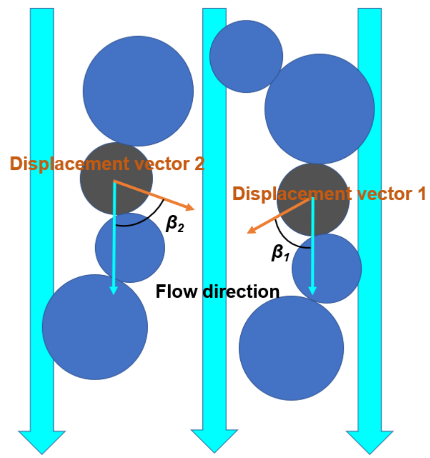
- A smaller sensitivity to grain detachment when the macroscopic flow aligns with the principal stress direction.

Results and discussions

Direction of displacement at the critical time



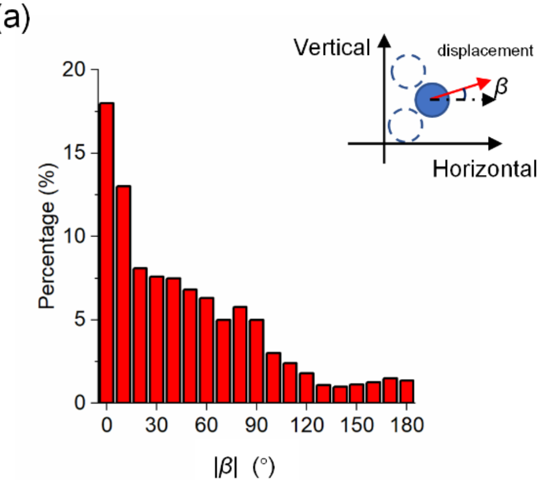
Horizontal flow



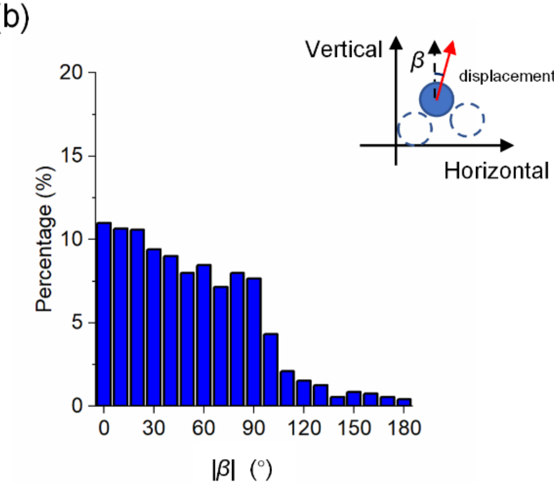
Vertical flow

β is the angle between the displacement of eroded particle at the critical time and macroscopic flow direction

(a)



(b)



- Most eroded particles detached in the direction of macroscopic flow in the horizontal case
- Grain detachment relies largely on local fluid force fluctuations when most of the contacts are aligned with the macroscopic direction in vertical flow.

Outline

Conclusions

- Compared with horizontal flow, the erosion rate and mean fluid force are greater in vertical flow. The larger directional porosity in the vertical direction also facilitate grain transport and subsequent erosion.

- Regardless of the initial state, the ratio between the fluid force and the contact force of the eroded particles displays a downward trend over time, reflecting the gradual dominance of the fluid force, which eventually leads to particle detachment and erosion.

- A contact sliding index P has been proposed to determine whether a given particle contact is going to slide or strengthen under the action of a fluid force.

- The majority of particle migration is directed by the fluid. When most of the contacts are aligned with the macroscopic direction in vertical flow, grain detachment relies largely on local fluid force fluctuations.

The End

Thanks for your attention!