DEM-LBM method for the study of submerged and cohesive granular flows

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IRSTEA, Aix-en-Provence

Géosciences pour une Terre durable
Jianhua Fan, Gildas Noury
BRGM, DRP, Orléans

Project Research Region – **PERCIVAL** (2018-2020)

PErception des Risques effondrements liés aux Cavités associés aux Inondations en VAL de Loire

Outline

I) Context and motivations

II) Numerical Model

III) Submerged cohesive granular flow

1) Solid discharge rate
2) Pressure drop

IV) Conclusion and perspectives

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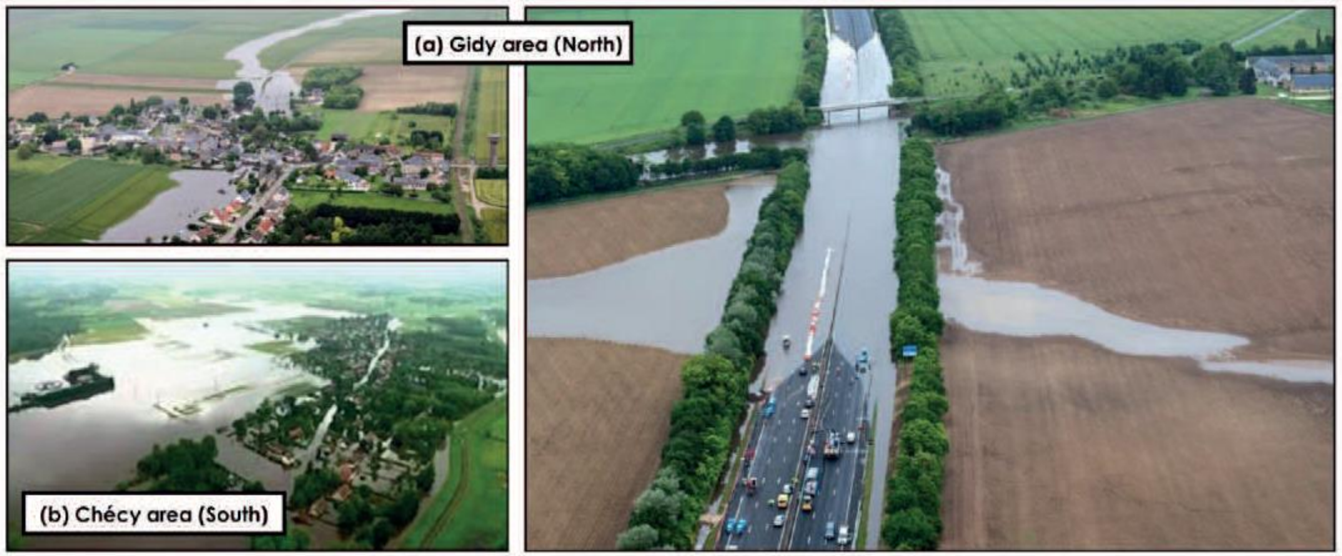
I - Context and motivation

Loire river floodplain around Orléans **-** Spring 2016 meteorological event



Geological survey

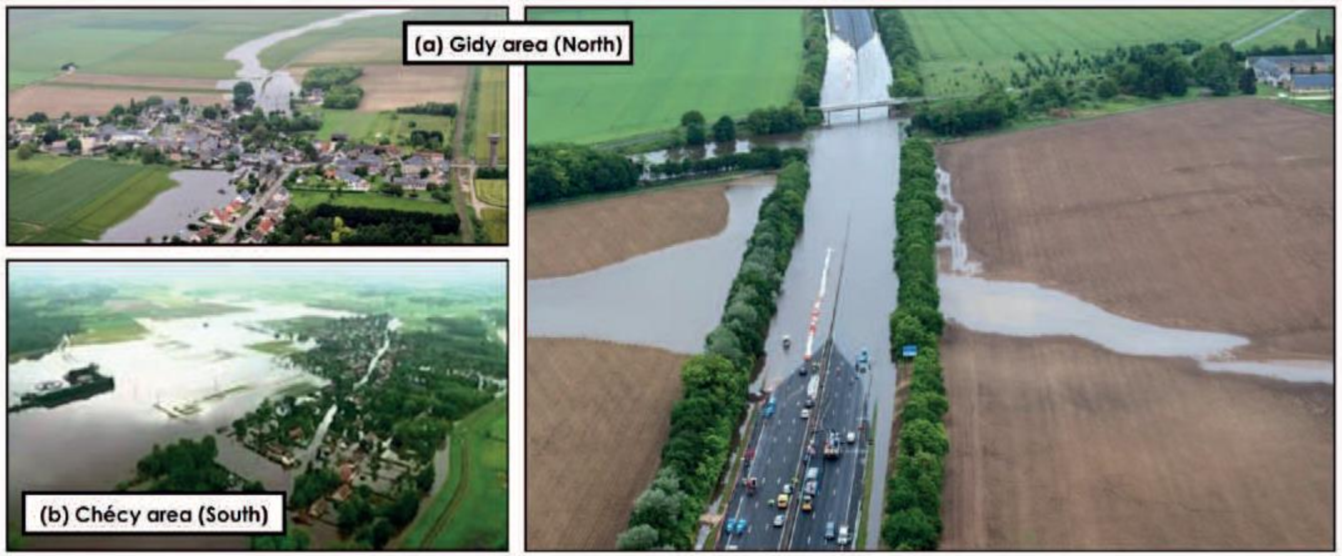
85 sinkhole formations

↓

Rainfalls, hydraulic load triggering their collapse

I - Context and motivation

Loire river floodplain around Orléans **-** Spring 2016 meteorological event



Géosciences pour brgm

Geological survey

85 sinkhole formations

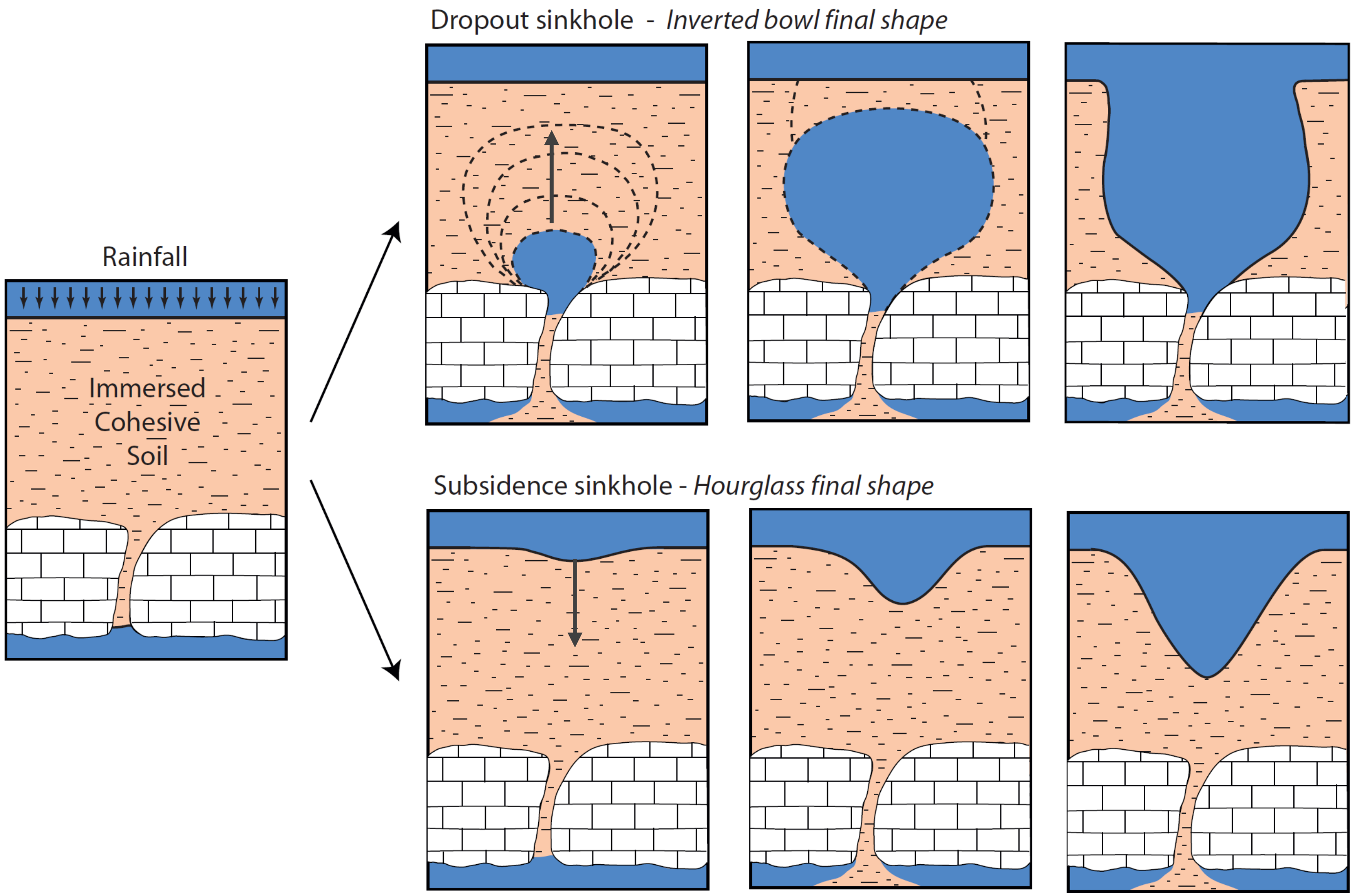
↓

Rainfalls, hydraulic load triggering their collapse

Sinkhole 1 | *Sinkhole 2*

I - Context and motivation

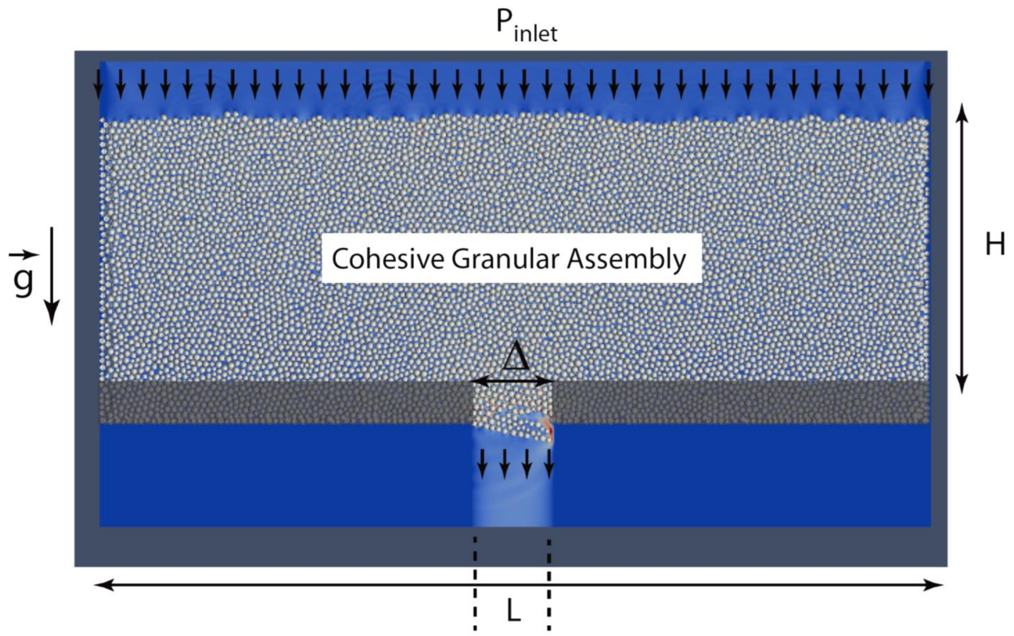
Cohesive soil discharge *through* ***submerged*** *karstic conduit*



Sinkhole 1

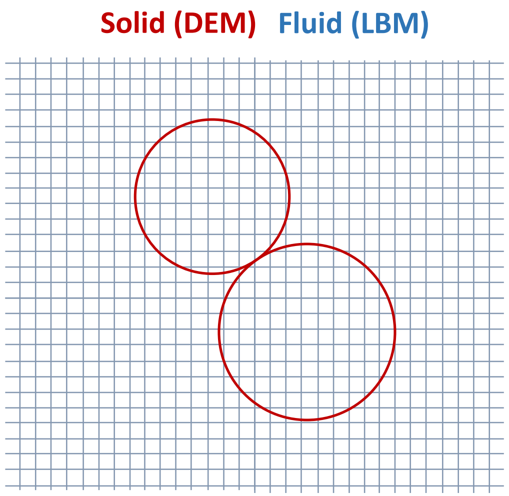
Sinkhole 2

I - Context and motivation



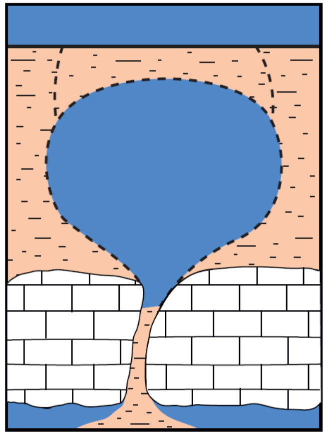
DEM-LBM Hydromechanical Modelling

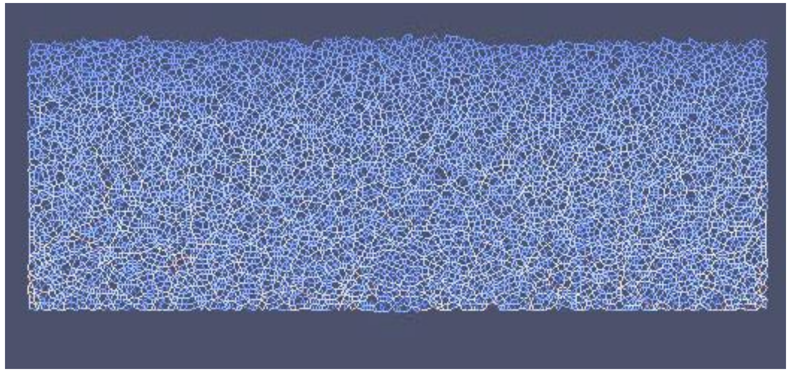
Luu *et al. (2019)*
Engineering Geology



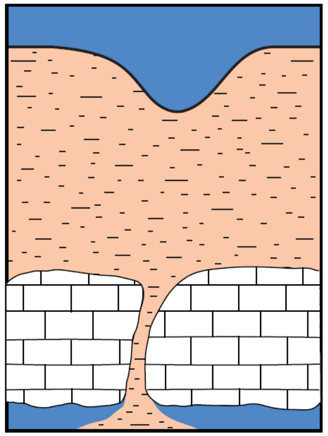
***Cohesive soil discharge** through **submerged** karstic conduit*

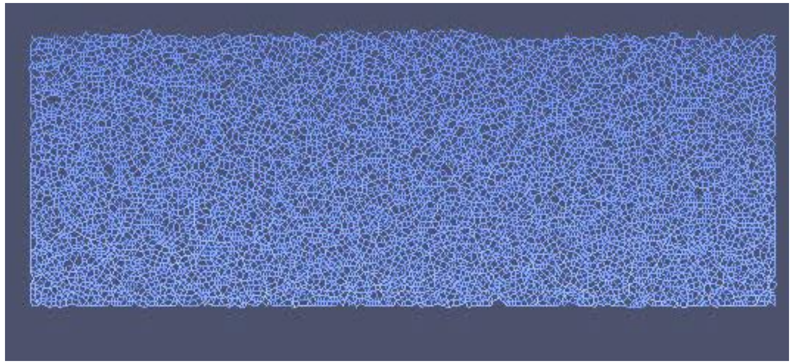
Scenario 1





Scenario 2





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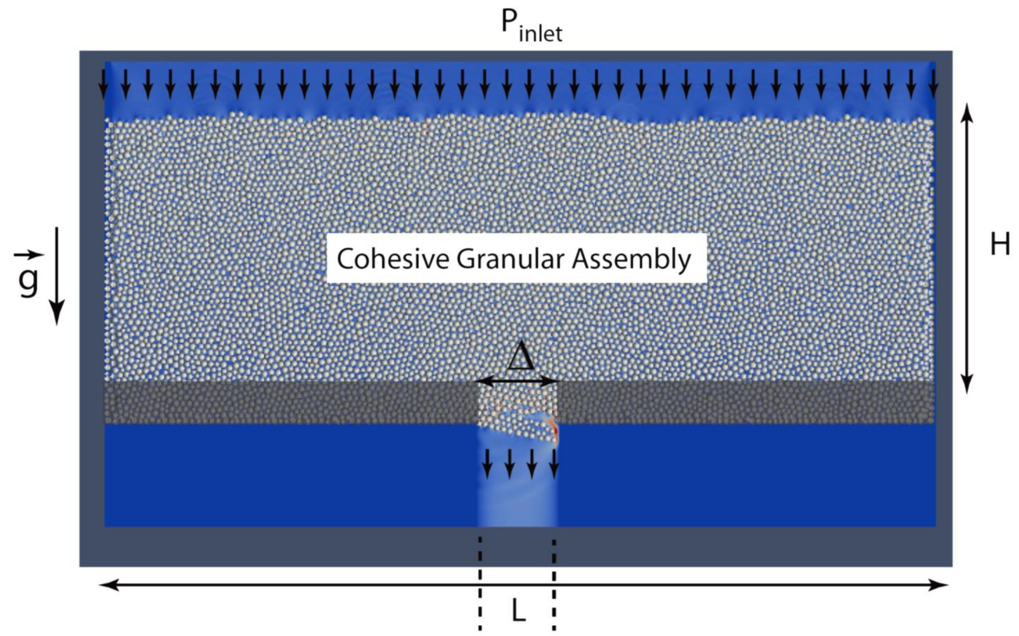

Cohesive soil discharge *through* ***submerged*** *karstic conduit*

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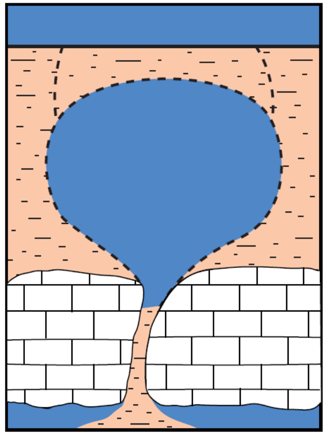

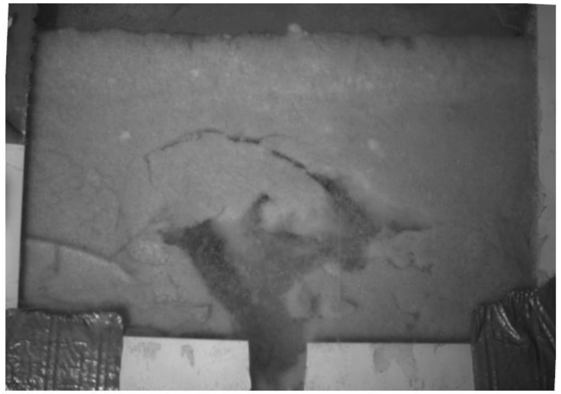

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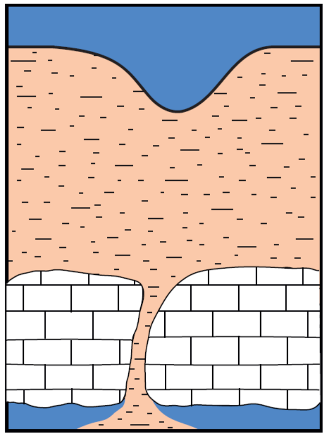
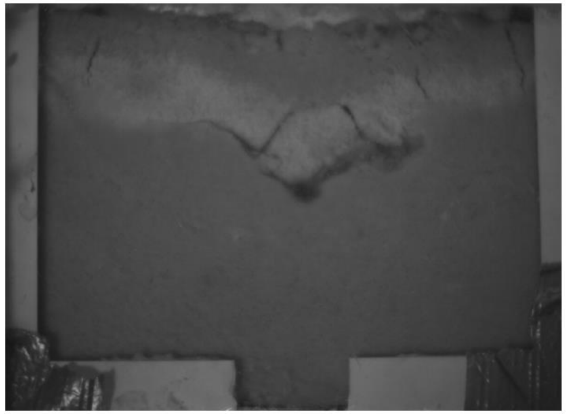
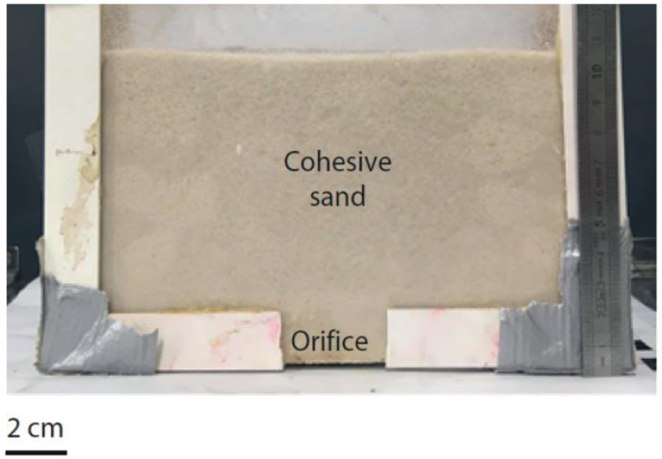
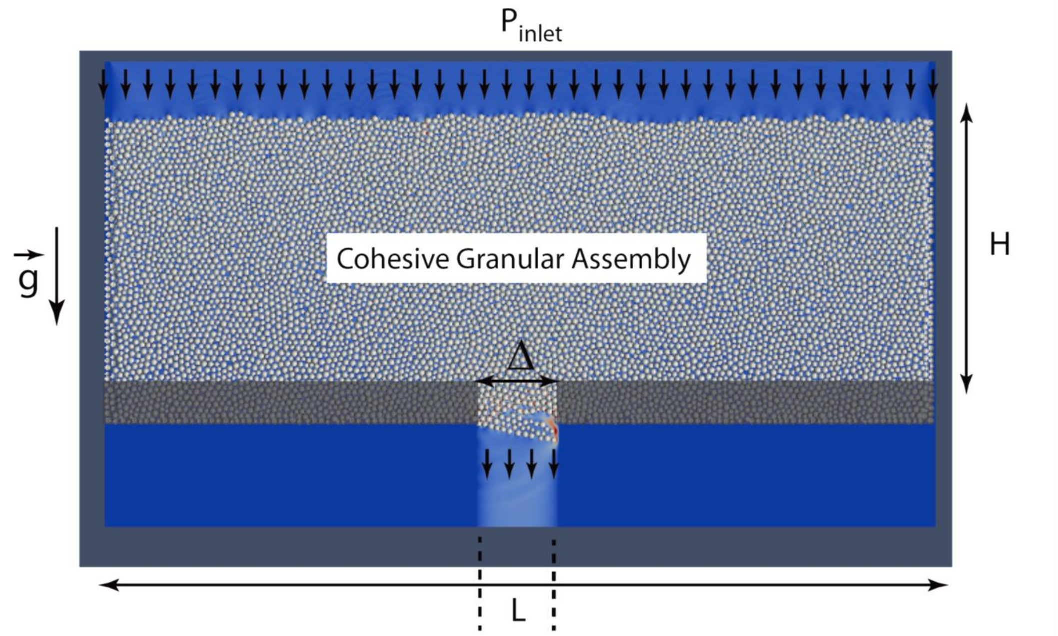




Experimental study

Luu *et al. (2019)*
Engineering Geology





Cohesive soil discharge *through* ***submerged*** *karstic conduit*

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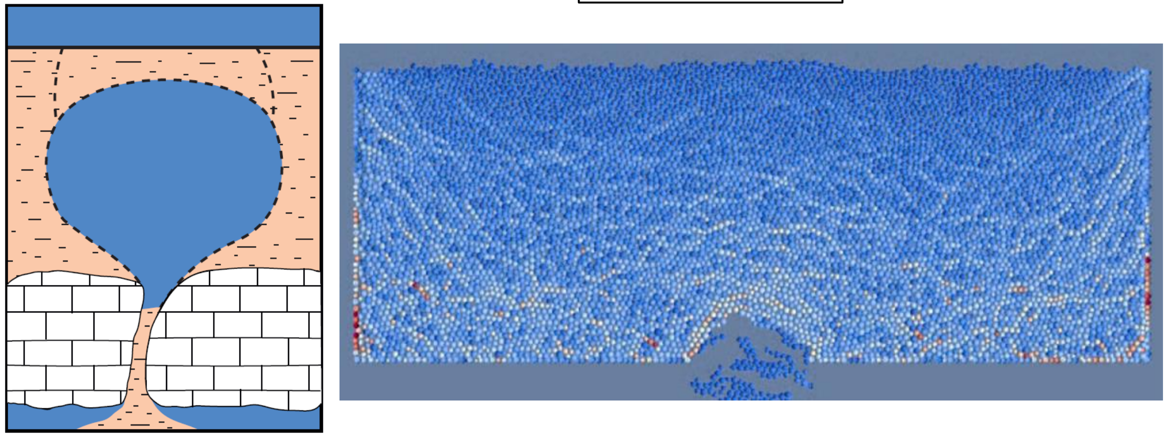
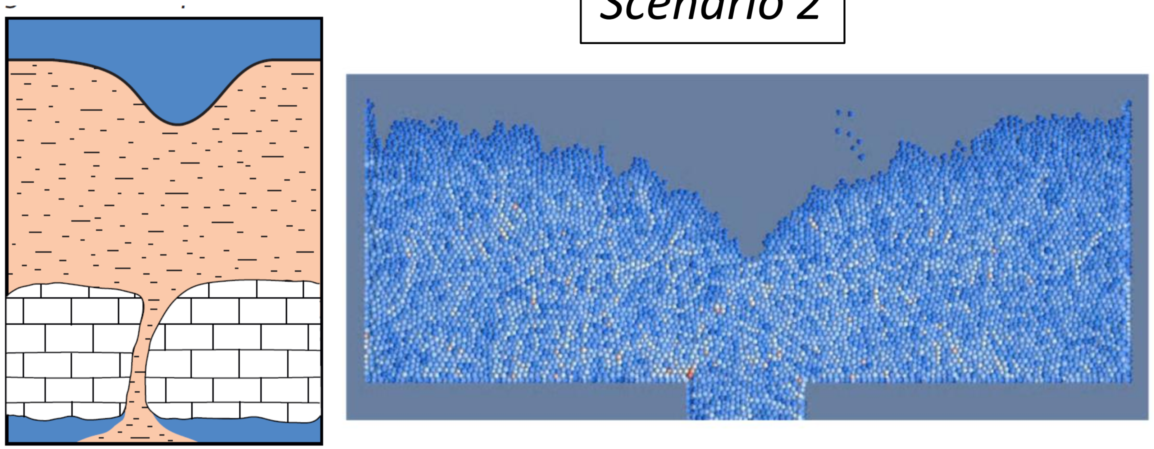
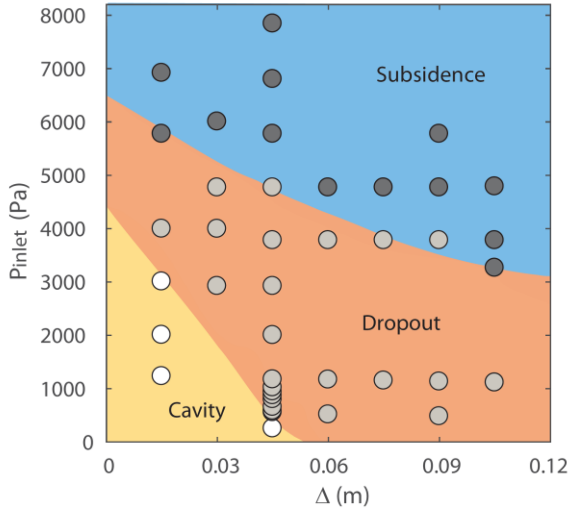


Scenario 2

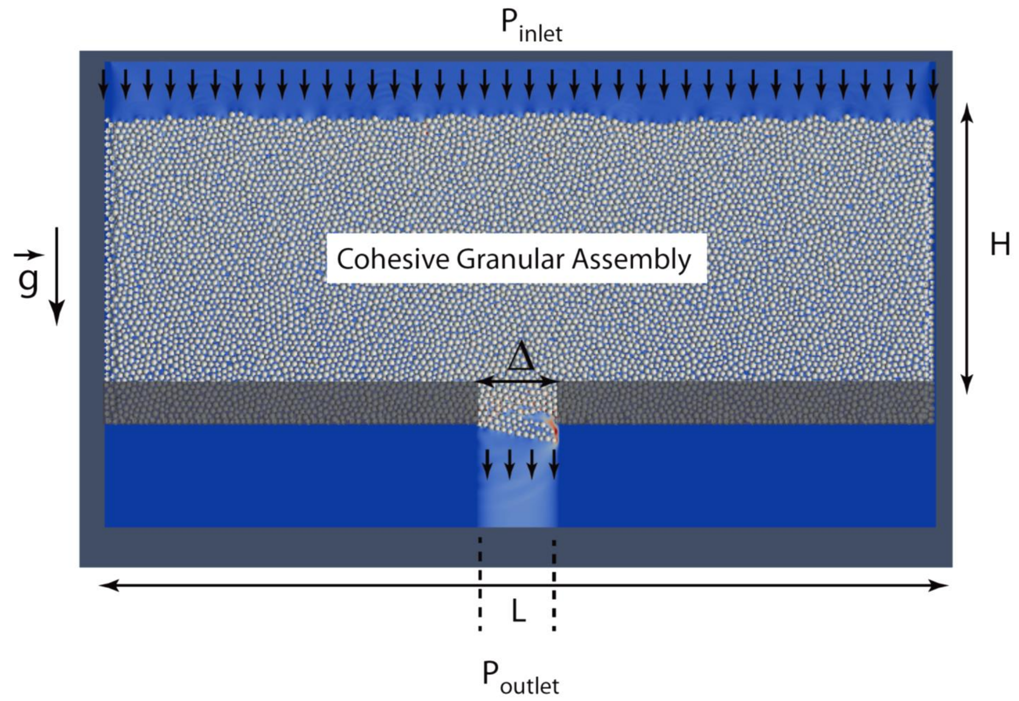


Phase diagram analysis

Luu *et al. (2019)*
Engineering Geology



I - Context and motivation



Cohesive soil discharge *through* ***submerged*** *karstic conduit*

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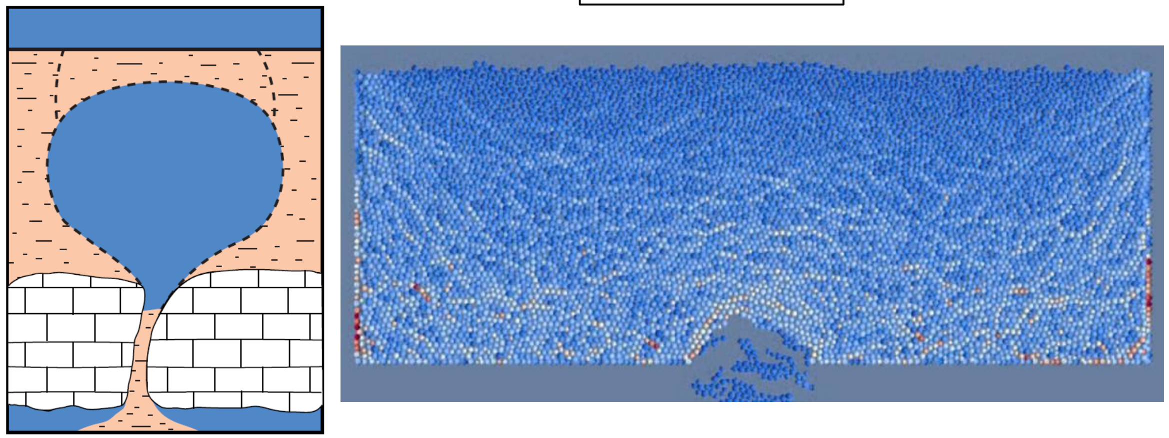
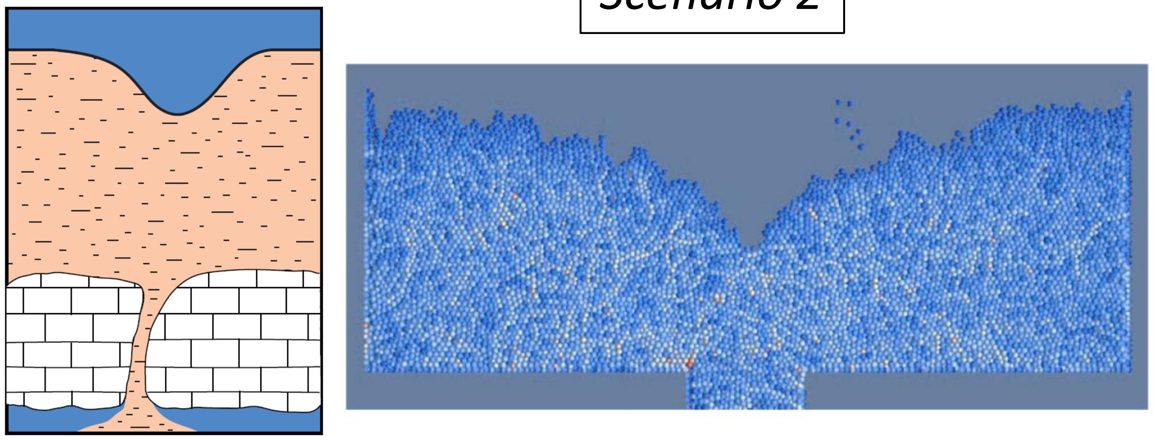


Scenario 2



→ **Granular flow rate ?**

I - Context and motivation

→ **Granular flow rate**

HOPPER / HOURGLASS

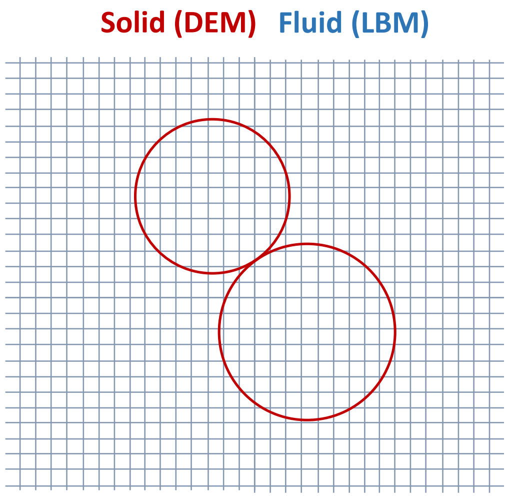
I - Context and motivation

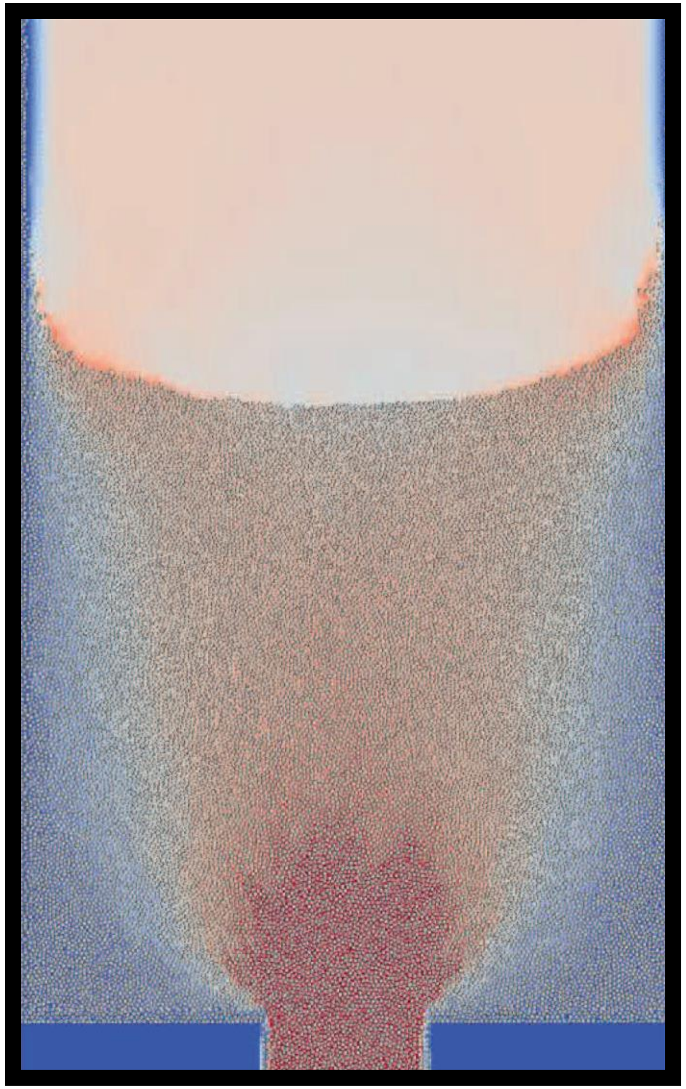
Granular flow rate

HOPPER / HOURGLASS

+ interstitial FLUID

+ grains COHESION





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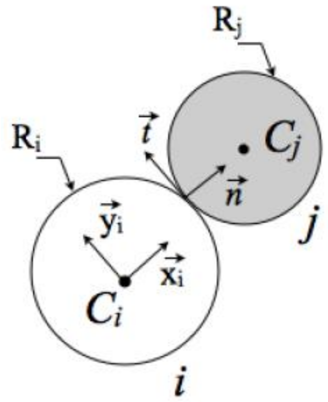
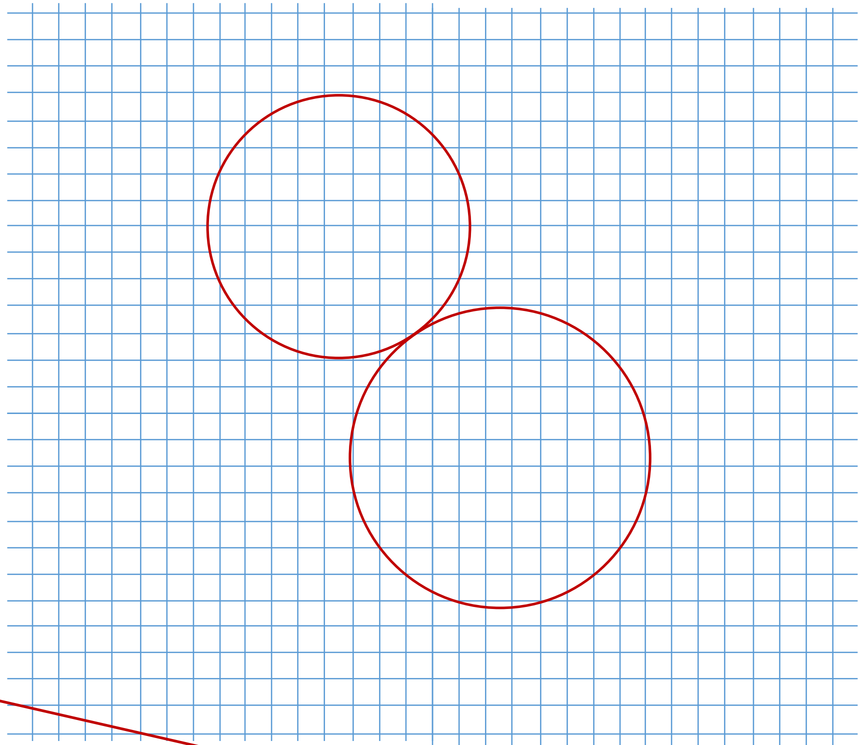
II - Numerical model

Discrete Element Method (DEM)
Solid phase



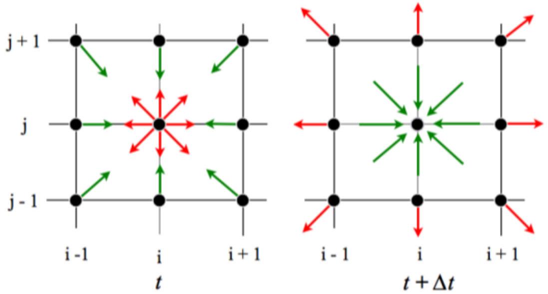
(Cundall & Strack, 1979)



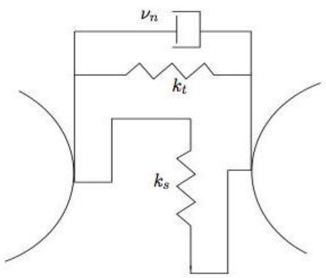
Lattice Boltzmann Method (LBM)
Fluid phase

$$\frac{\partial f_\alpha}{\partial t} + \vec{c}_{\alpha,i}\frac{\partial f_\alpha}{\partial x_i} = -\frac{1}{\tau}\left[f_\alpha(\mathbf{x},t) - f_\alpha^{eq}(\mathbf{x},t)\right]$$

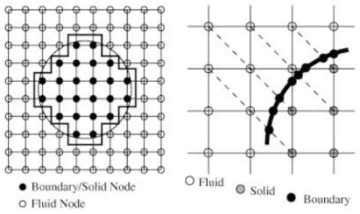
streaming — collision



Contact models



hydrodynamics

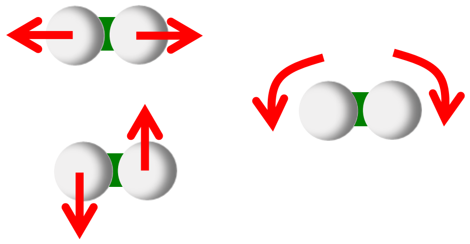


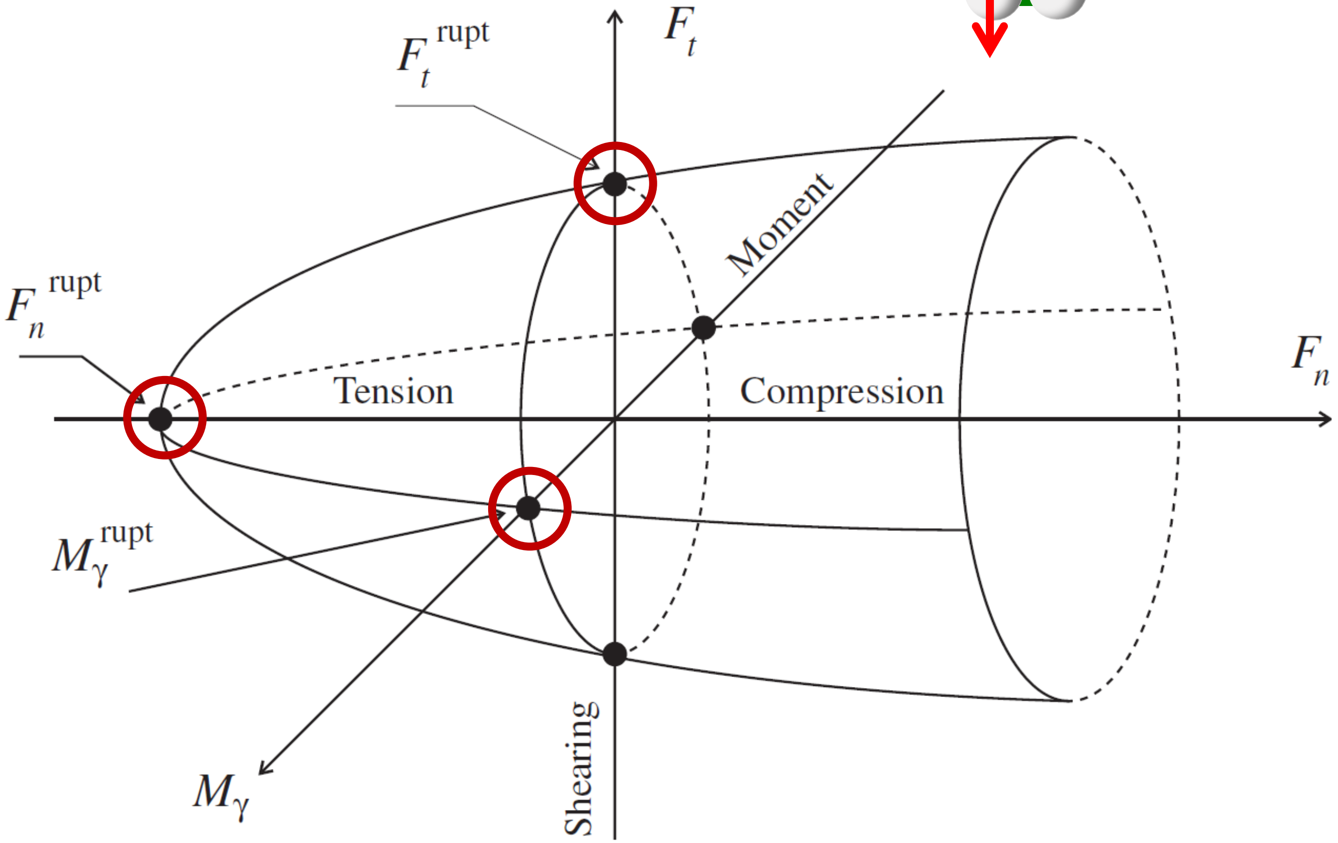
$ma=F+F_c+F_h$

$J\omega'=T+T_c+T_h$

II - Numerical model

Discrete Element Method (DEM)
Solid phase





$$\zeta = \left(\frac{F_n}{F_n^{rupt}}\right) + \left(\frac{F_t}{F_t^{rupt}}\right)^2 + \left(\frac{M_\gamma}{M_\gamma^{rupt}}\right)^2 - 1$$

[Delenne *et al.*, 2004]

Experimental data
with model material:

Loading paths	Yield load
Tension	$F_n^{rupt} = 1500$ N
Compression	No failure
Shearing	$F_t^{rupt} = 900$ N
Moment	$M_\gamma^{rupt} = 2.9$ N m

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1) Solid discharge rate
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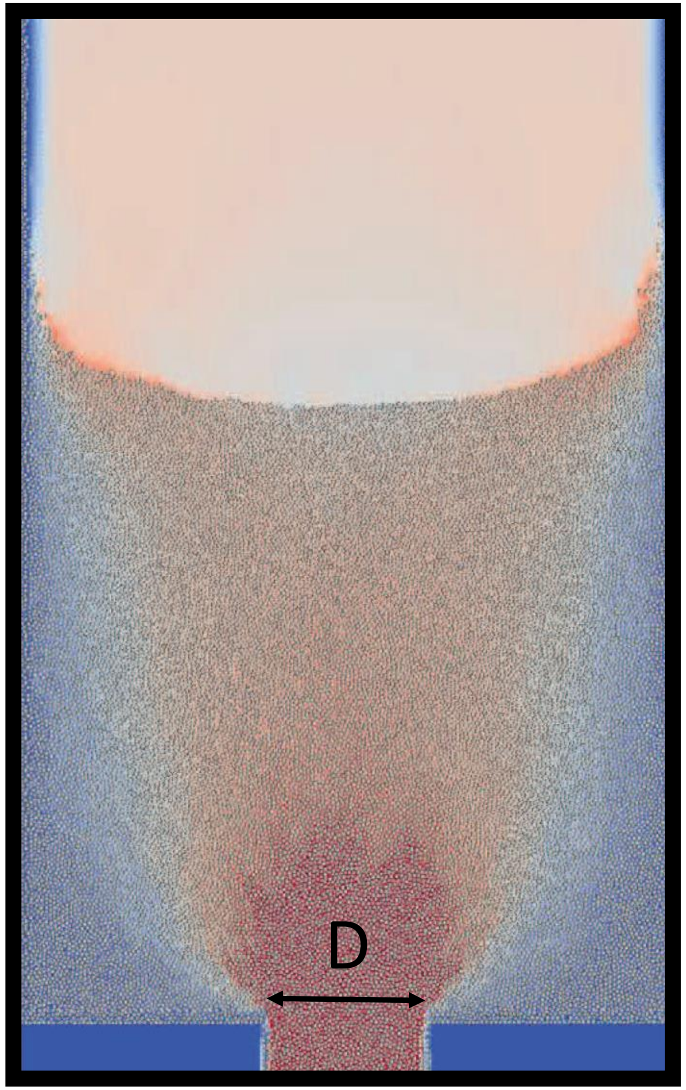
III – Submerged cohesive granular flow through an orifice

$P_{inlet} = 0$



Number of particles
N = 37 452
d = 3 mm

$\downarrow \vec{g}$

Parametric study

→ **From cohesionless to various cohesion**

Particle cohesion number

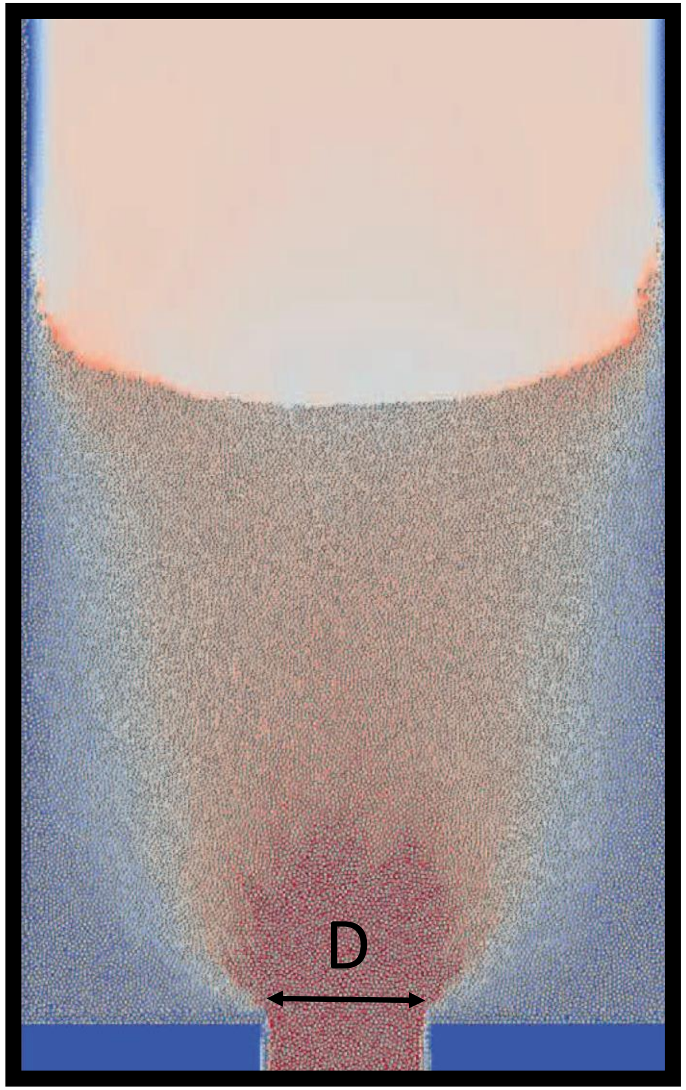
$$Coh = \frac{C}{(\rho_g - \rho_f) g S}$$

C : bond strength
ρ_g : particle density
ρ_f : fluid density
S : particle area

→ **Various orifice size D**

III – Submerged cohesive granular flow through an orifice

$P_{inlet} = 0$



Number of particles
N = 37 452
d = 3 mm

$\vec{g}$

Parallelized code

GPU (CUDA)

Benseghier *et al. (2019)*
Computers and Geotechnics
(submitted)

Parametric study

→ **From cohesionless to various cohesion**

Particle cohesion number

$$Coh = \frac{C}{(\rho_g - \rho_f) g S}$$

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S : particle area

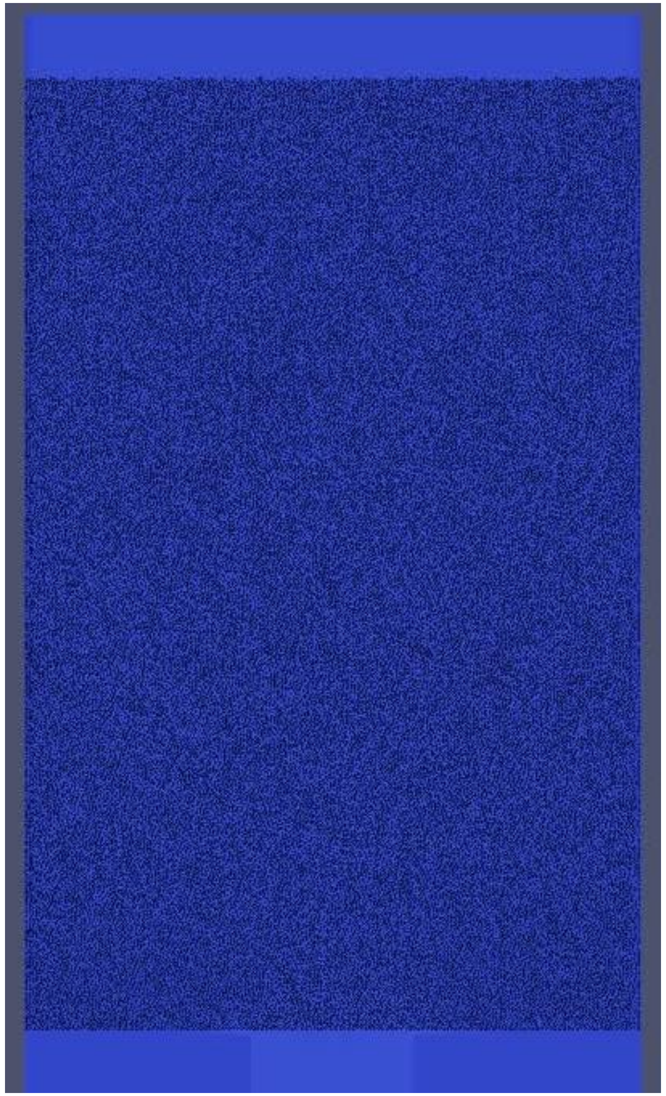
→ **Various orifice size D**

III – Submerged cohesive granular flow through an orifice

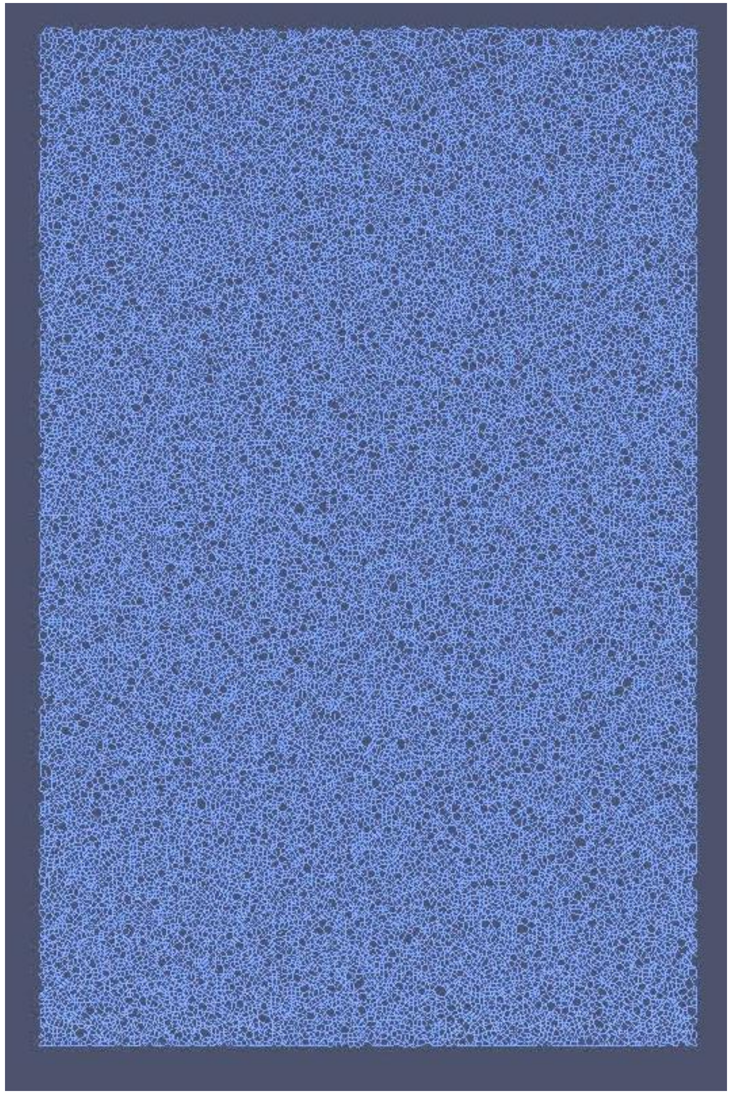
Particle + Fluid velociy

Interparticle force

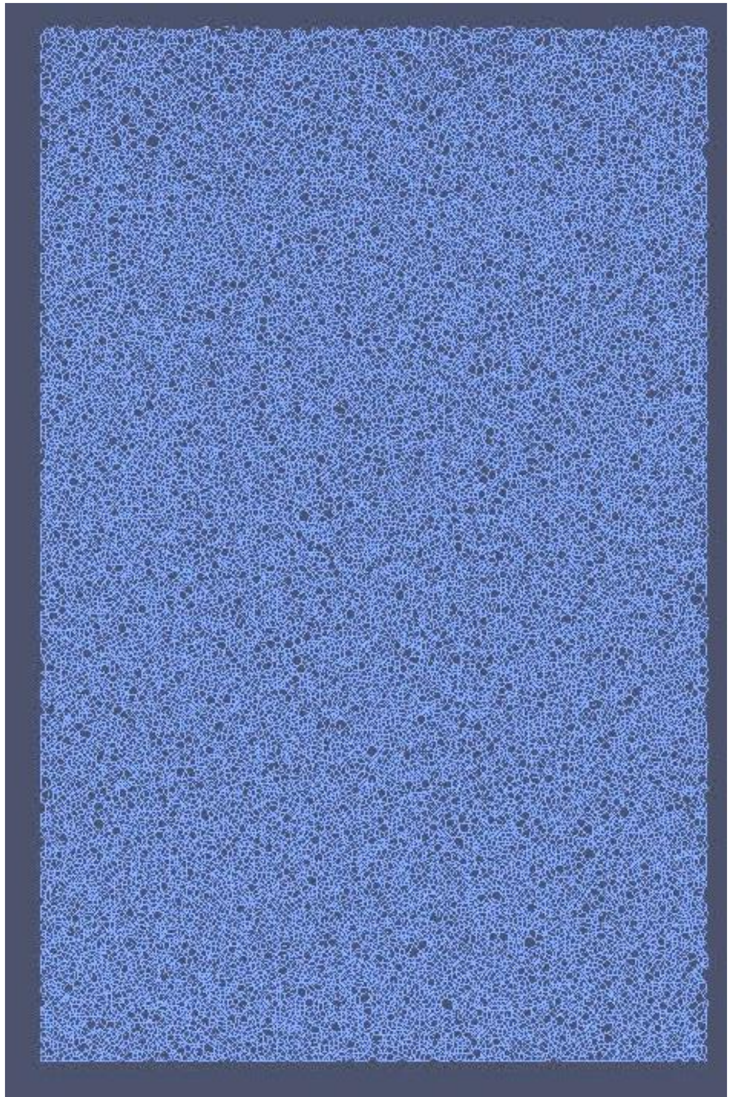
Coh=0



Coh=150



Coh=500



Dry non–cohesive discharge

Gravitational flow

Beverloo et al. (1961)

Gravity-driven

$$Q_s = C\sqrt{g}(D_0 - kd_p)^{2.5}$$

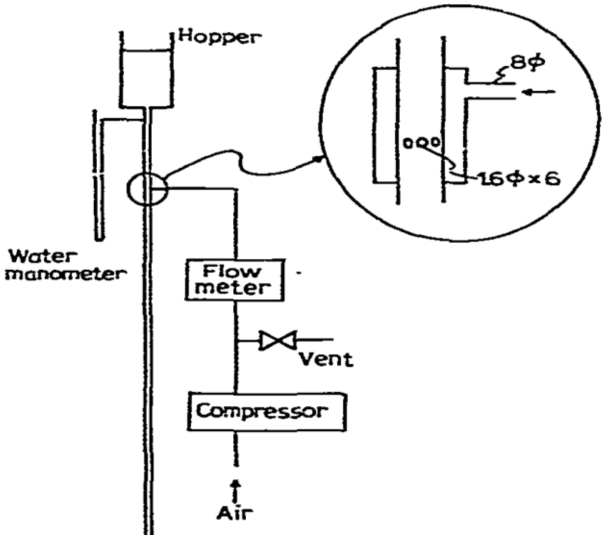
Apparent orifice (k=1.5)

Air-assisted powder flows

Bulsara et al. (1964)

De Jong & Hoelen (1975)

Lamptey & Thorpe (1991)



Air pressure-driven

$$Q_s = C(D_0 - kd_p)^2\sqrt{\frac{P_2 - P_1}{\rho_s}}$$

Apparent orifice (k=1.5)

Submerged particles

Gravitational flow

Cohesionless

Experimental Study

Papers in Physics, vol. 6, art. 060009 (2014)

www.papersinphysics.org

Received: 11 September 2014, Accepted: 10 October 2014
Edited by: L. A. Pugnaloni
Reviewed by: L. Staron, CNRS, Université Pierre et Marie Curie, Institut Le Rond d'Alembert, Paris, France.

DOI: http://dx.doi.org/10.4279/PIP.060009

ISSN 1852-4249

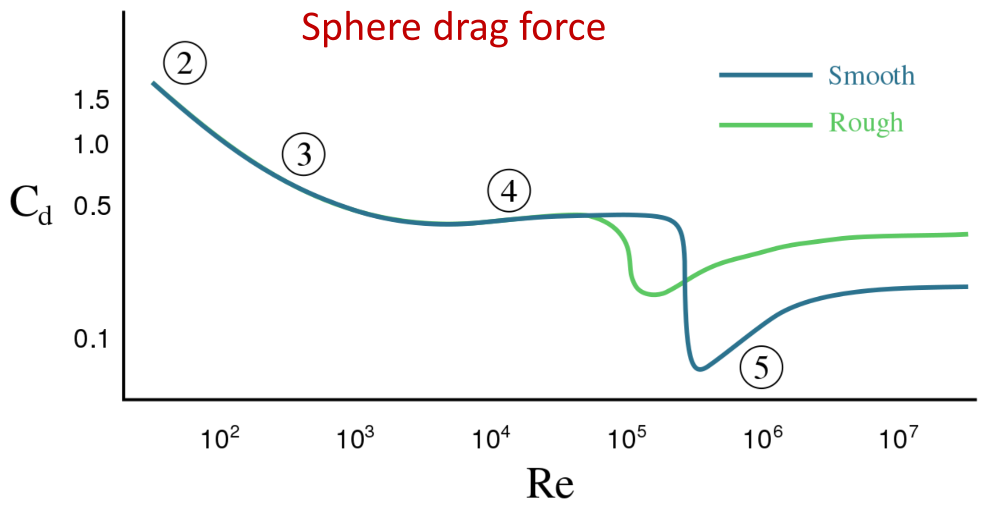
Granular discharge rate for submerged hoppers

T. J. Wilson,[1,2] C. R. Pfeifer,[1,3] N. Meysingier,[1,4] D. J. Durian[1*]

Solid mass flow rate

$$W_o = C\rho_g v_t (D - kd)^2$$

Terminal falling velocity in fluid



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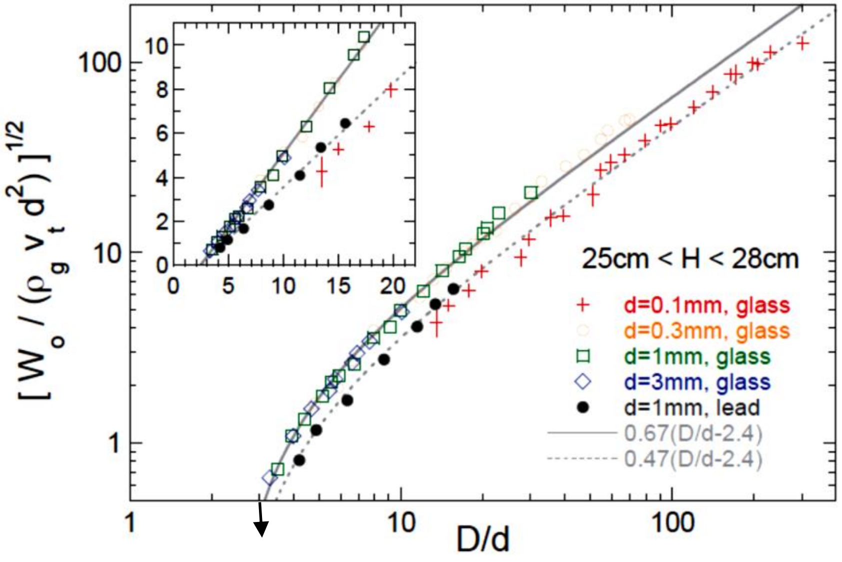
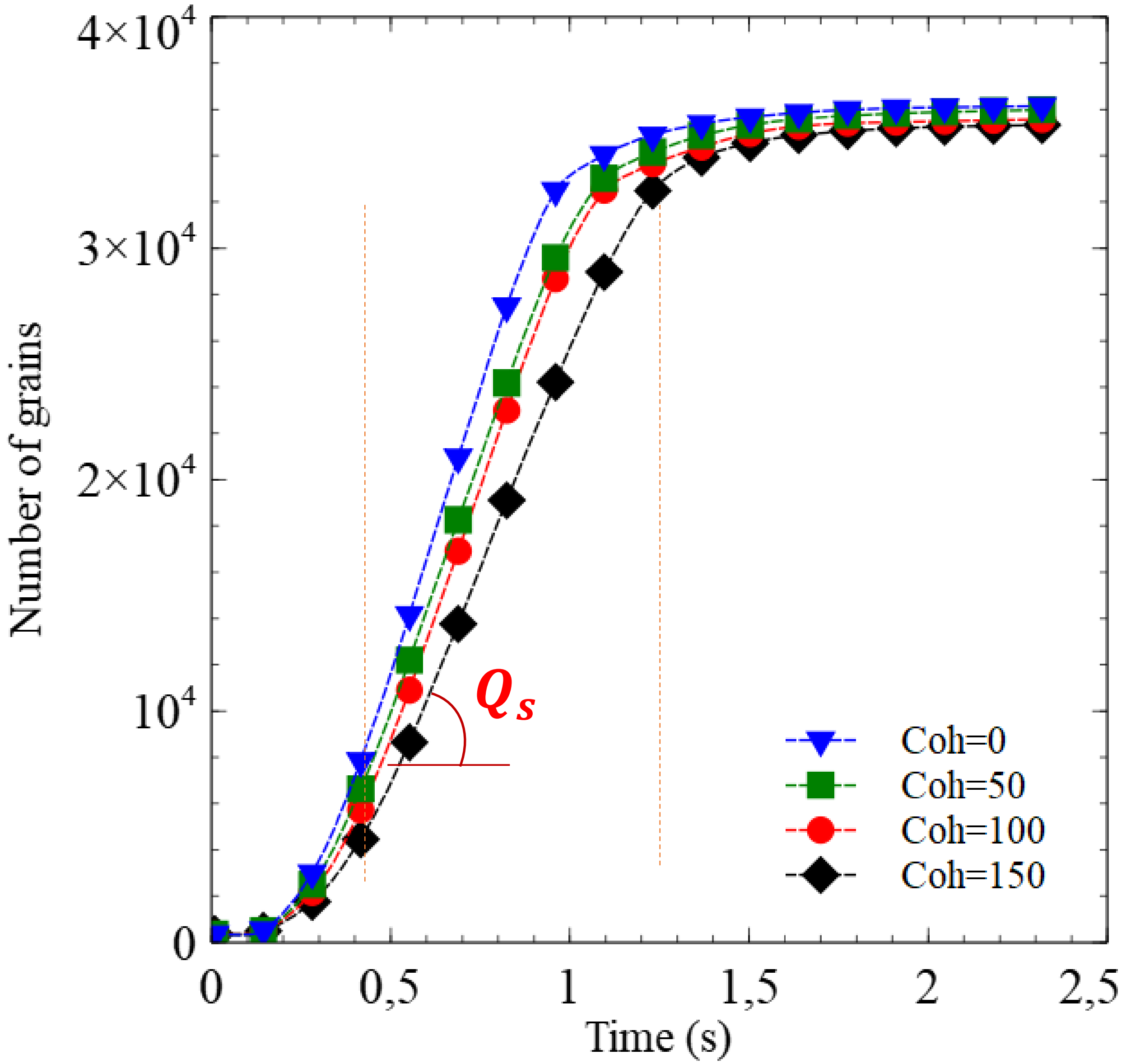
Cut-off due to the fluid



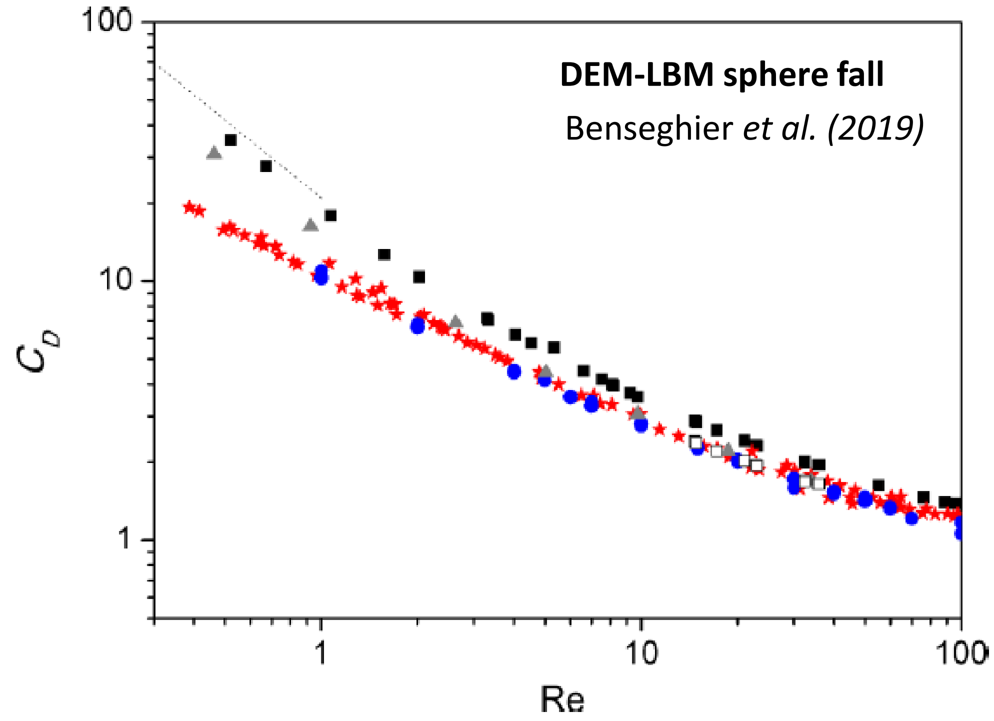
k =2.4 ± 0.1 *instead of k=1.5 in air*

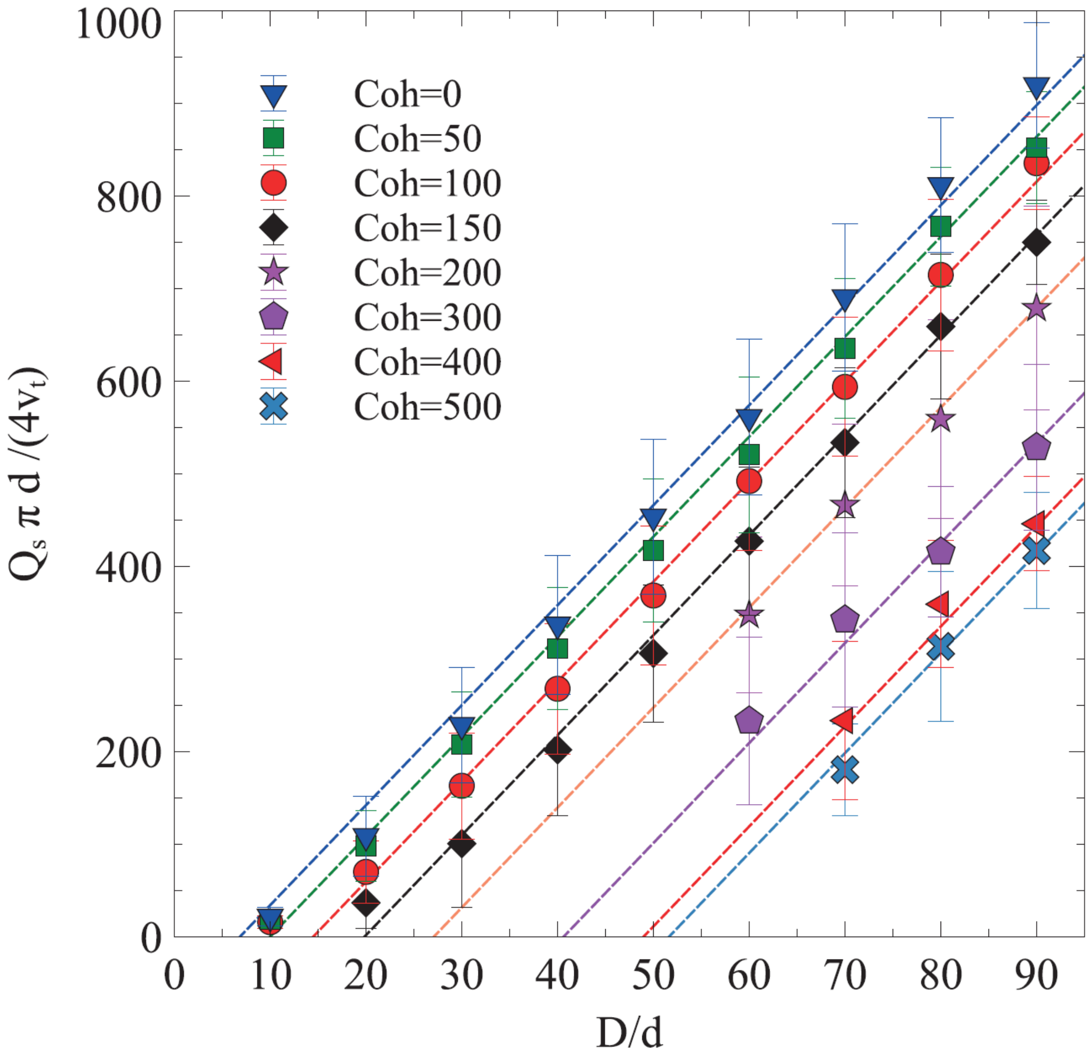


4×10^4
3×10^4
2×10^4
10^4
0
Number of grains
0
0,5
1
1,5
2
2,5
Time (s)
Q_s
Coh=0
Coh=50
Coh=100
Coh=150

Solid discharge rate

2D $$Q_s = C' \frac{4}{\pi d} v_t [D/d - k]$$

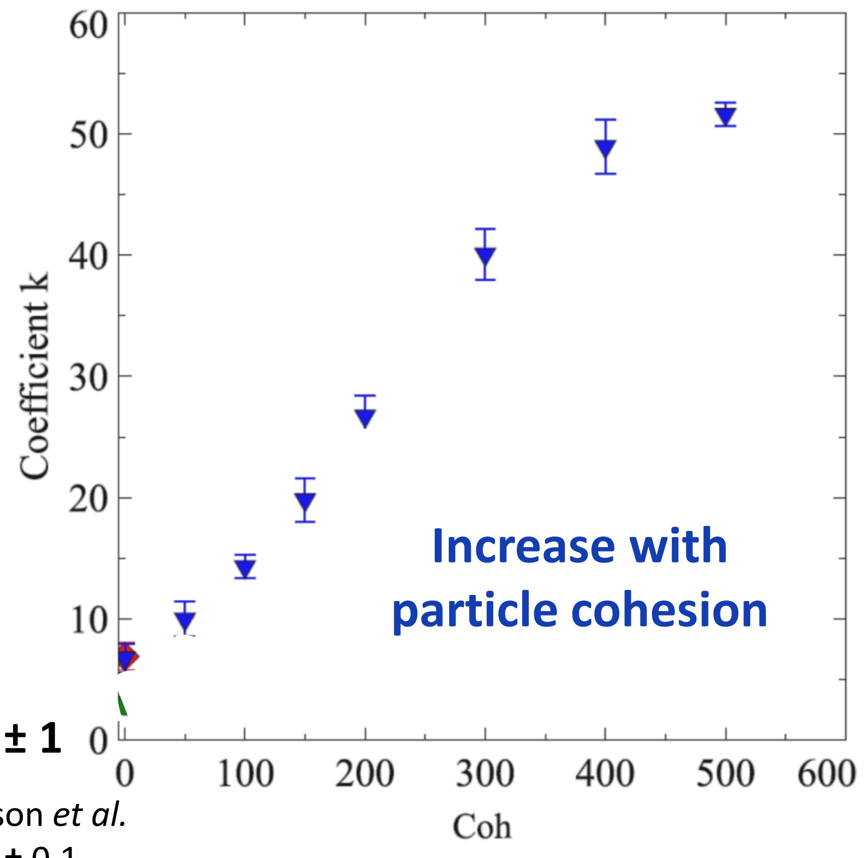




Solid discharge rate

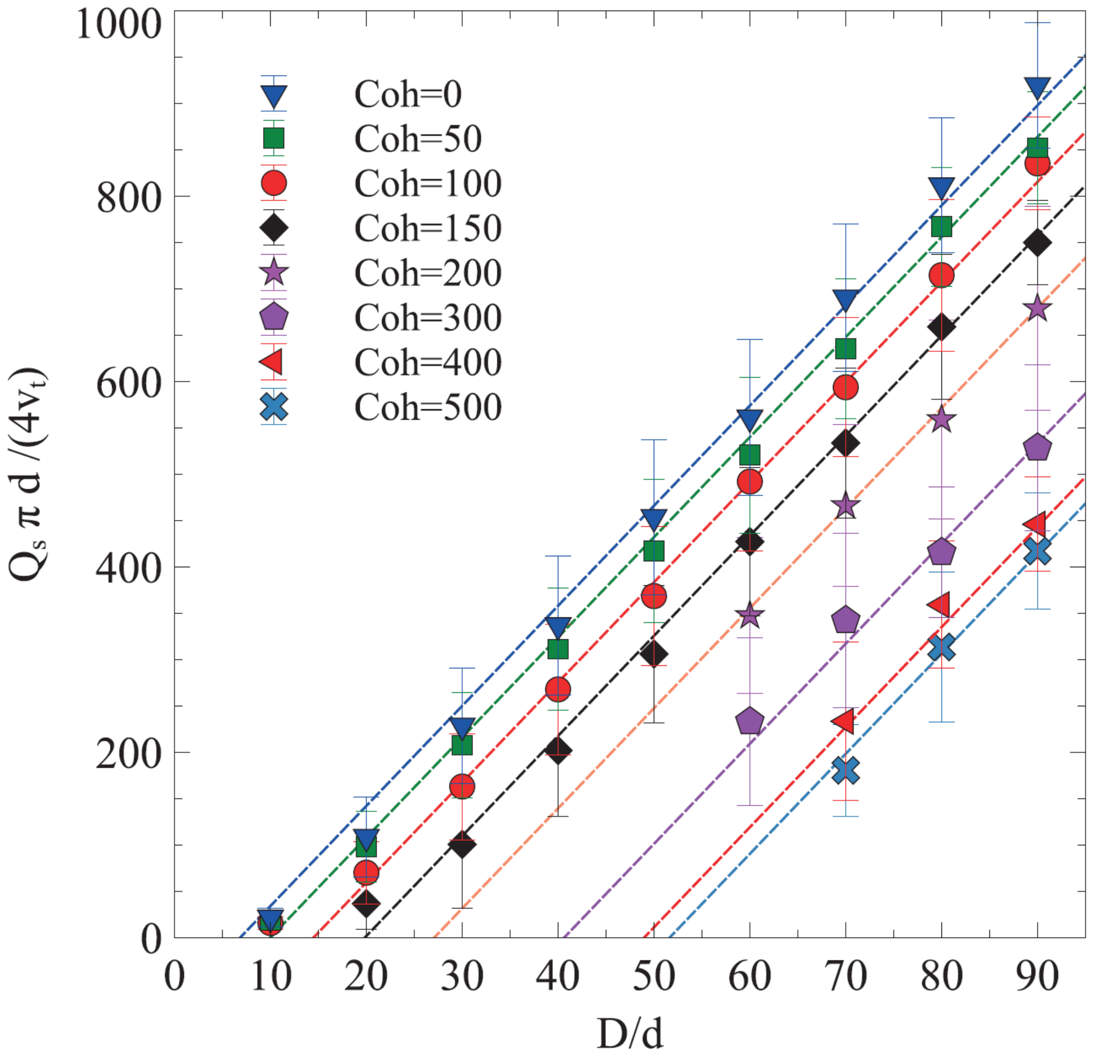
2D $$Q_s = C' \frac{4}{\pi d} v_t [D/d - k]$$

Apparent orifice *Cut-off*



***k* =2.2 ± 1**

Exp. : Wilson *et al.* k=2.4 ± 0.1



Solid discharge rate

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Apparent orifice

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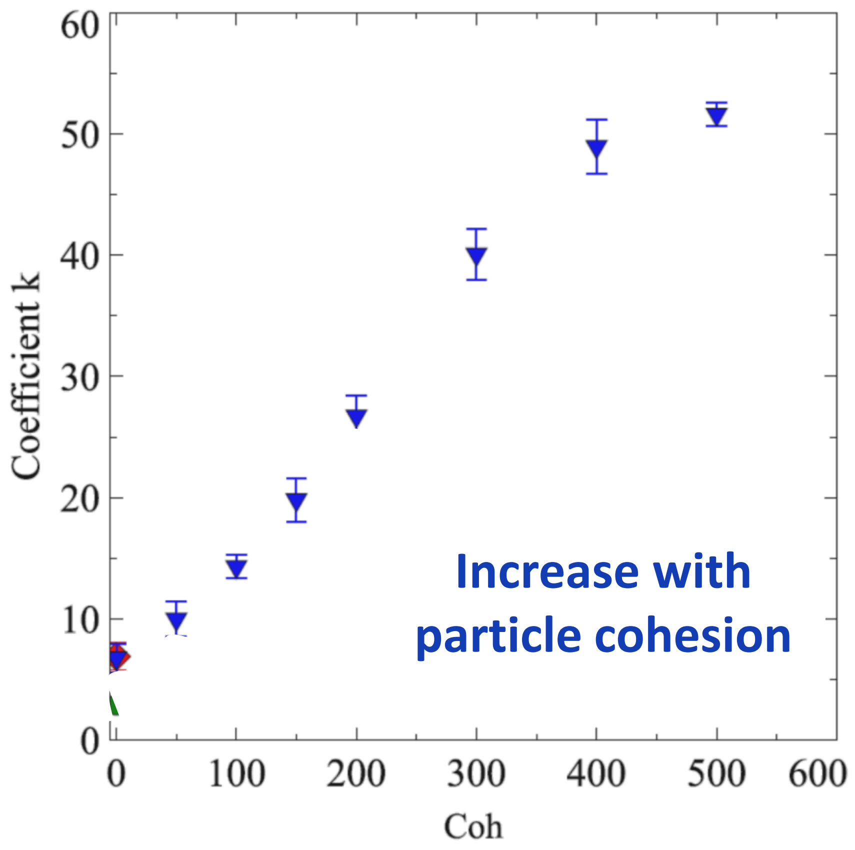
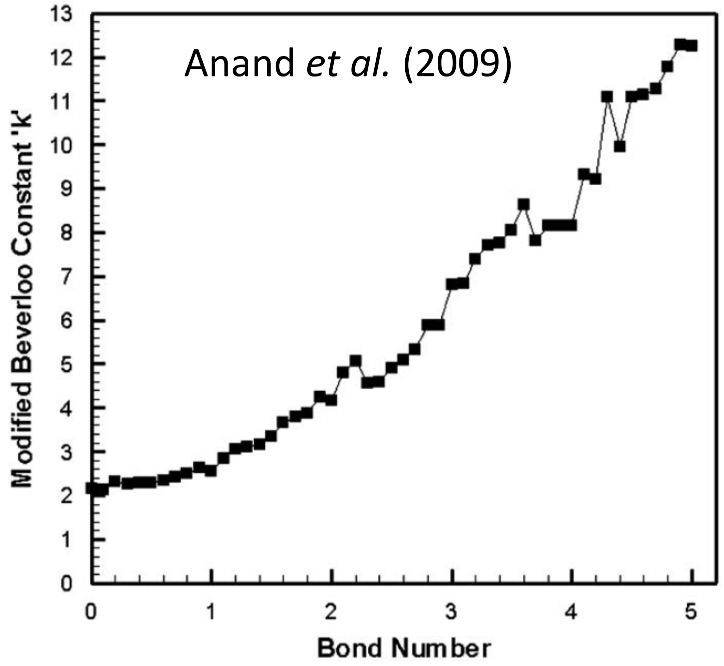


Similar behavior →

Dry case

DEM + cohesion
Capillary liquid bonds



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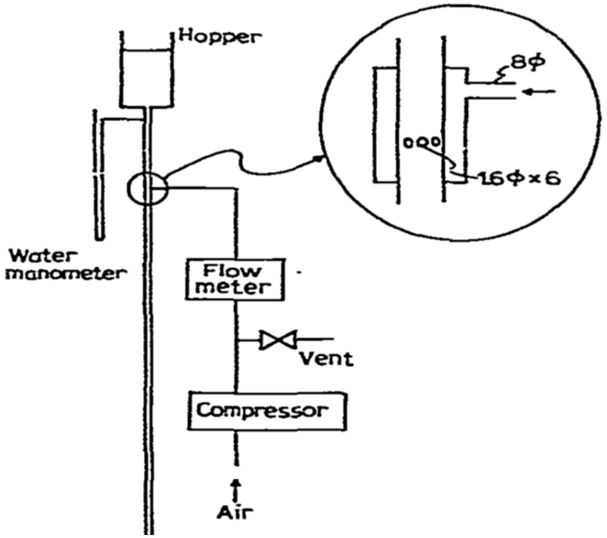


Gravity-driven

$$Q_s = C\sqrt{g}(D_0 - kd_p)^{2.5}$$

Apparent orifice (k=1.5)

Air pressure-driven

$$Q_s = C\,(D_0 - kd_p)^2\sqrt{\frac{P_2 - P_1}{\rho_s}}$$

Apparent orifice (k=1.5)

Submerged granular flow

Gravitational

Cohesionless

Experimental Study

Solid mass flow rate

$$Q_s = C\left(D_0 - kd_p\right)^2 \sqrt{\frac{P_2 - P_1}{\rho_s}}$$

Pressure-driven

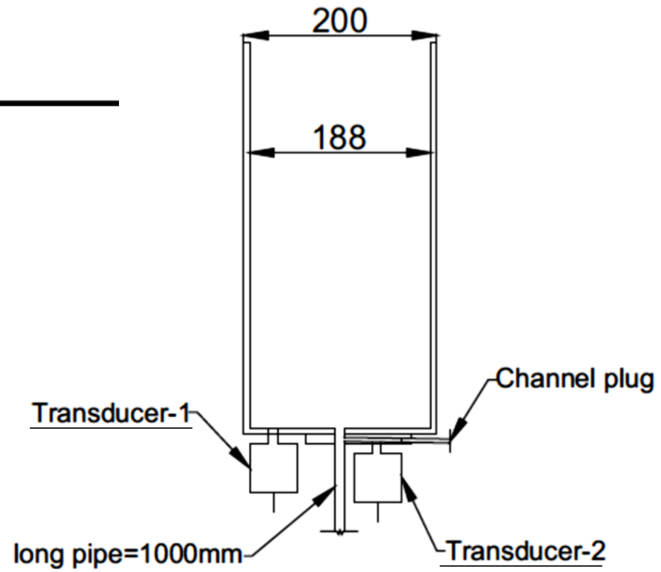
Granular Matter (2017) 19:45
DOI 10.1007/s10035-017-0732-7

ORIGINAL PAPER

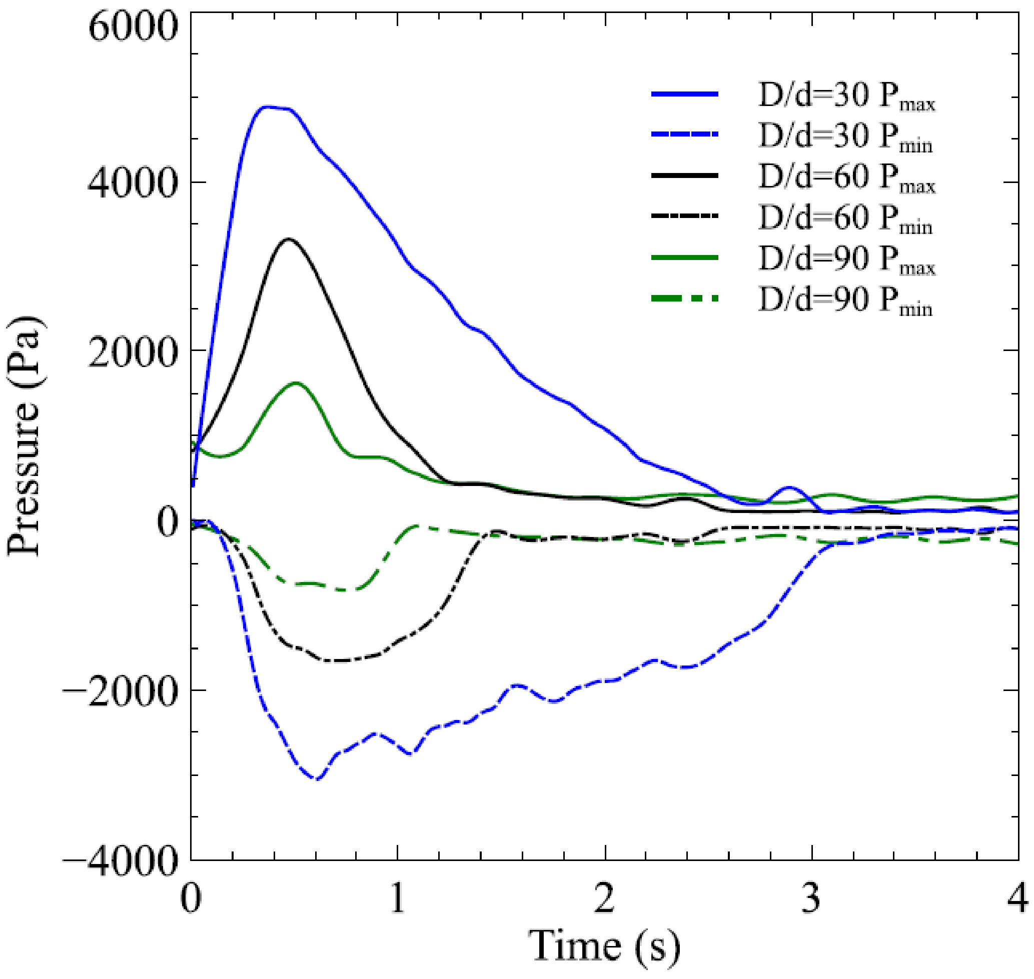
Water-submerged granular flow through a long efflux tube

Shuai Guo[1] · Tingchao Yu[2] · Yiping Zhang[2]

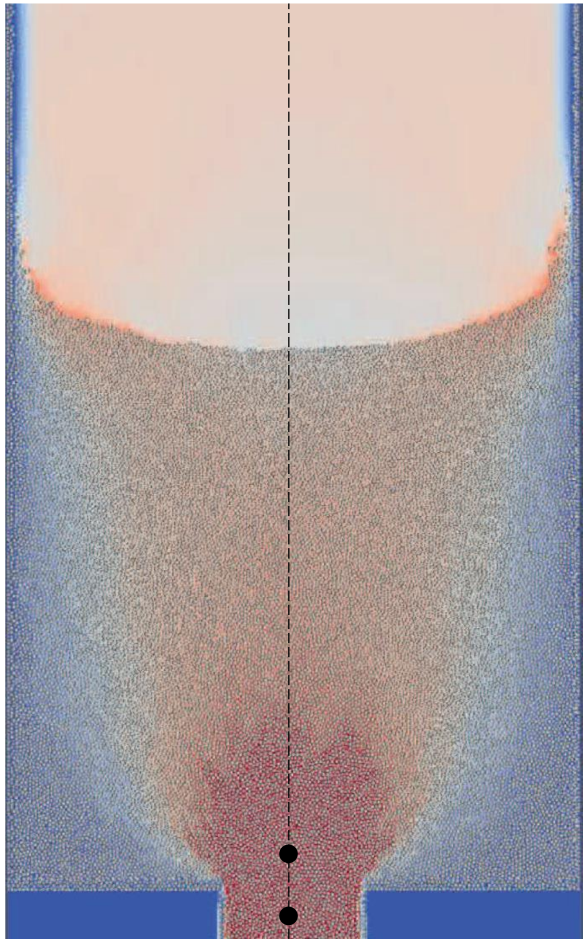
Pressure measurement
Above and **Below** the orifice

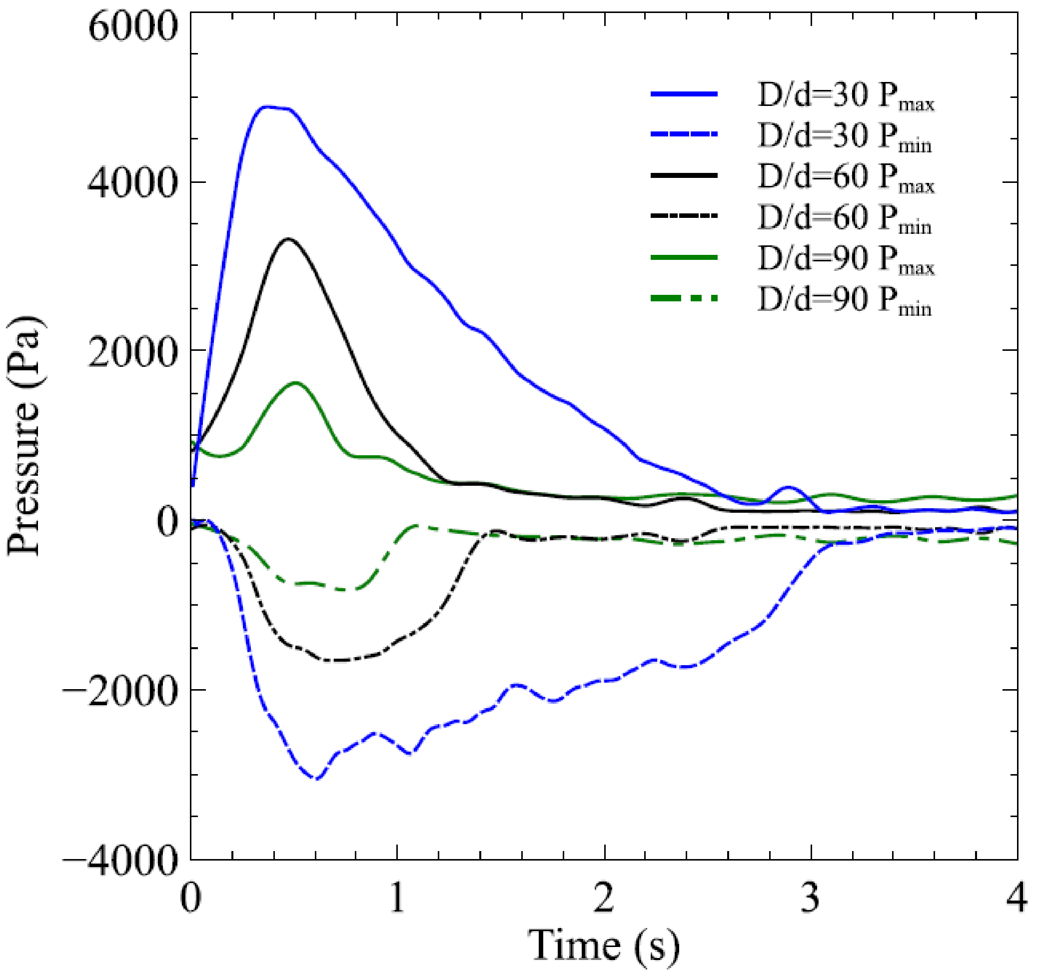


Guo *et al.* (2017)



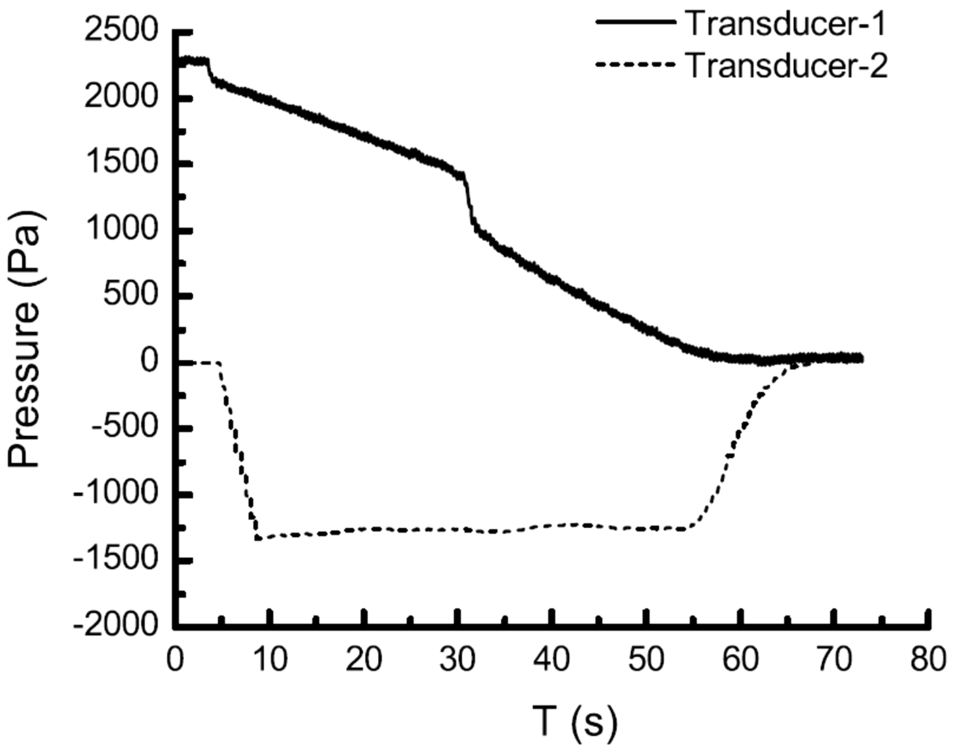
Pressure « measurement »
Above and **Below** the orifice





AGREEMENT

Exp. : Guo *et al.* (2017)



Outline

I) Context and motivations

II) Numerical Model

III) Submerged cohesive granular flow

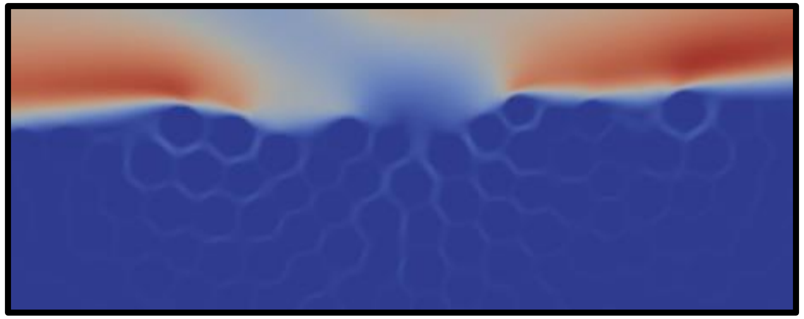
1) Solid discharge rate
2) Pressure drop

IV) Conclusion and perspectives

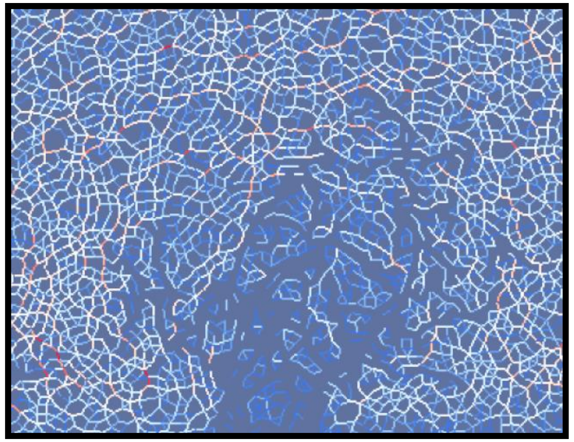
IV - Conclusion

Micromechanical approach

Particle and fluid flow



Bond network



Solid flow rate

- **Qs increases linearly with the orifice size D** *consistently with a 2D Beverloo law.*
- **Apparent orifice size k** is higher in the submerged case *consistently with experiments.* and increases with the particle cohesion.

Interstitial flow analysis

- **Fluid entrainment** by the particle motion.
- **Pressure drop** around the orifice *consistent with experiments.*

IV - Perspectives

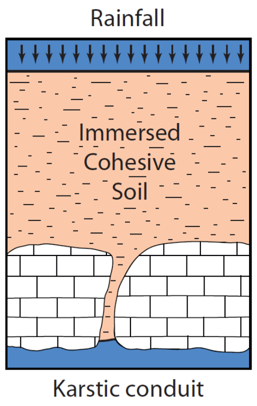
Work in progress

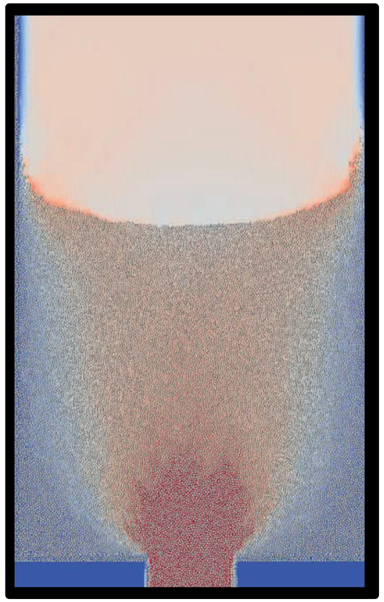
Gravitational flow

↓

Pressure-force flow

$P_{inlet} \neq 0$

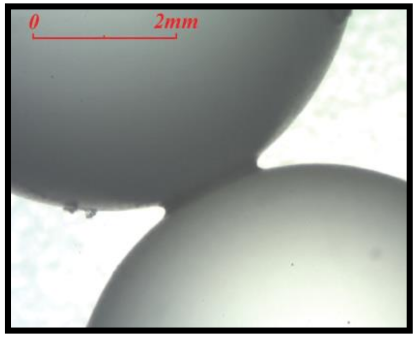




- What about the **particle-fluid interaction** ?
- Can we properly correlate the particle cohesion with the **agregate size** ?
- Calibration with **experiments on artificial cemented material**

Solid bridges with resin

Brunier-Coulin thesis (2017)



THANK YOU FOR YOUR ATTENTION

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