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

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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
Outline

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IV) Conclusion and perspectives
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

Geological survey
- 85 sinkhole formations
- Rainfalls, hydraulic load triggering their collapse

Sinkhole 1
- Inverted-bowl shape

Sinkhole 2
- Hourglass shape
I - Context and motivation

*Cohesive soil discharge* through *submerged* karstic conduit

Sinkhole 1

Sinkhole 2
I - Context and motivation

Cohesive soil discharge through submerged karstic conduit

DEM-LBM
Hydromechanical Modelling
Luu et al. (2019)
Engineering Geology
1 - Context and motivation

Cohesive soil discharge through submerged karstic conduit

Scenario 1

Scenario 2

Experimental study

Luu et al. (2019)
Engineering Geology
I - Context and motivation

Cohesive soil discharge through submerged karstic conduit

Scenario 1

Scenario 2

Phase diagram analysis

Luu et al. (2019)
Engineering Geology
I - Context and motivation

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

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

Solid (DEM)  Fluid (LBM)
I) Context and motivations

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IV) Conclusion and perspectives
II - Numerical model

Discrete Element Method (DEM)
Solid phase

Lattice Boltzmann Method (LBM)
Fluid phase

Contact models

(Cundall & Strack, 1979)

\[ ma = F + F_c + F_h \]

\[ J\omega' = T + T_c + T_h \]
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:

<table>
<thead>
<tr>
<th>Loading paths</th>
<th>Yield load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tension</td>
<td>( F_n^{rupt} = 1500 \text{ N} )</td>
</tr>
<tr>
<td>Compression</td>
<td>No failure</td>
</tr>
<tr>
<td>Shearing</td>
<td>( F_t^{rupt} = 900 \text{ N} )</td>
</tr>
<tr>
<td>Moment</td>
<td>( M_\gamma^{rupt} = 2.9 \text{ N m} )</td>
</tr>
</tbody>
</table>
I) Context and motivations

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III) Submerged cohesive granular flow through an orifice
   1) Solid discharge rate
   2) Pressure drop

IV) Conclusion and perspectives
Submerged cohesive granular flow through an orifice

$P_{\text{inlet}} = 0$

Number of particles
$N = 37\,452$
$d = 3\,\text{mm}$

Particle cohesion number

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

$C$: bond strength
$\rho_g$: particle density
$\rho_f$: fluid density
$S$: particle area

Parametric study

- From cohesionless to various cohesion
- Various orifice size $D$
III – Submerged cohesive granular flow through an orifice

\[ P_{\text{inlet}} = 0 \]

Number of particles
\[ N = 37452 \]
\[ d = 3 \text{ mm} \]

Parallelized code
GPU (CUDA)
Benseghier et al. (2019)
Computers and Geotechnics
(submitted)

Parametric study

→ From cohesionless to various cohesion

Particle cohesion number
\[ Coh = \frac{C}{(\rho_g - \rho_f)gS} \]

\( C \): bond strength
\( \rho_g \): particle density
\( \rho_f \): fluid density
\( S \): particle area

→ Various orifice size \( D \)
III – Submerged cohesive granular flow through an orifice

Particle + Fluid velocity

$Coh=0$

Interparticle force

$Coh=150$

$Coh=500$
III – Submerged cohesive granular flow

1) Solid discharge rate

Dry non-cohesive discharge

Gravitational flow
Beverloo et al. (1961)

Gravity-driven

\[ Q_s = C \sqrt[5]{g(D_0 - kd_p)^{2.5}} \]

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)
III – Submerged cohesive granular flow

1) Solid discharge rate

Submerged particles

Gravitational flow
Cohesionless

Experimental Study

Solid mass flow rate

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

Terminal falling velocity in fluid

Sphere drag force

Granular discharge rate for submerged hoppers

T. J. Wilson,^1,2 C. R. Pfeifer,^1,3 N. Meysingier,^1,4 D. J. Durian^1*
III – Submerged cohesive granular flow

1) Solid discharge rate

**Submerged particles**

Gravitational flow

Cohesionless

**Experimental Study**

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**

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

Cut-off due to the fluid

$k = 2.4 \pm 0.1$ instead of $k=1.5$ in air
III – Submerged cohesive granular flow

1) Solid discharge rate

![Graph showing the number of grains over time with different cohesive strengths.](image-url)
1) Solid discharge rate

**Solid discharge rate**

\[ Q_s = C'' \frac{4}{\pi d} v_t \left[ \frac{D}{d} - k \right] \]

**2D**

DEM-LBM sphere fall
Benseghier et al. (2019)
Solid discharge rate

\[ Q_s = C'' \frac{4}{\pi d} v_t \left[ D/d - \left( \frac{k}{2} \right) \right] \]

**2D**

Increase with particle cohesion

\[ k = 2.2 \pm 1 \]

Exp. : Wilson et al.
\[ k = 2.4 \pm 0.1 \]
III – Submerged cohesive granular flow

1) Solid discharge rate

**Solid discharge rate**

\[
Q_s = C'' \frac{4}{\pi d} v_t \left[ D/d - \frac{k}{C'} \right] \text{Cut-off}
\]

**Dry case**

DEM + cohesion

Capillary liquid bonds

Anand et al. (2009)

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**Similar behavior**

- Increase with particle cohesion
III – Submerged cohesive granular flow

2) Pressure drop

**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)
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**Air pressure-driven**

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

Apparent orifice (k=1.5)
Submerged cohesive granular flow

2) Pressure drop

Submerged granular flow

Gravitational
Cohesionless

Experimental Study

Solid mass flow rate

\[ Q_s = C(D_0 - k d_p) \sqrt{\frac{P_2 - P_1}{\rho_s}} \]

Pressure-driven

Water-submerged granular flow through a long efflux tube

Shuai Guo¹ · Tingchao Yu² · Yiping Zhang²

Pressure measurement
Above and Below the orifice

Guo et al. (2017)
III – Submerged cohesive granular flow

2) Pressure drop

Pressure « measurement »
Above and Below the orifice
III – Submerged cohesive granular flow

2) Pressure drop

![Graph showing pressure drop over time for different D/d ratios, with the legend indicating maximum (P_max) and minimum (P_min) pressure for each ratio. Agreement is marked with the text: Exp. : Guo et al. (2017).]
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IV) Conclusion and perspectives
IV - Conclusion

Micromechanical approach

Particle and fluid flow

Solid flow rate

- $Q_s$ 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

\[ P_{\text{inlet}} \neq 0 \]

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

**Solid bridges with resin**

Brunier-Coulin thesis (2017)
THANK YOU FOR YOUR ATTENTION