DualSPHysics Current Developments: SPH-DCDEM

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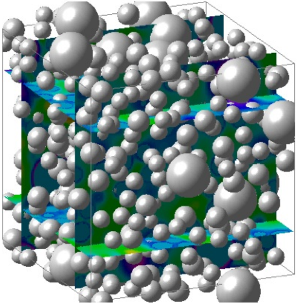
General motivation

- Common in **natural** and industrial processes, with dimensions ranging from $O(10^{-9})$ to $O(1)$ m.



Polydispersed flow. CBE-MFG, Princeton University

Debris flow in Switzerland, 2007.

Granular-fluid flows

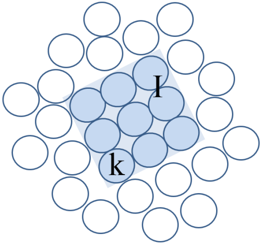
The motion of the granular phase is **difficult** to model:

- At **macro-scale**, complex rheologies requiring highly non-linear formulations with tuning parameters are required;
- At **grain-scale**, detailed description of particle-particle and fluid particle interactions induce high computational cost.

The proposed model will attempt a general **grain-scale** description, with the **potential** delivery of **phenomenological insight**.

Rigid bodies in DualSPHysics

Conserving the **relative positions** of a group of particles, these can be made to describe a solid body.



$$M_I \frac{d\mathbf{V}_I}{dt} = \sum_{k \in I} m_k \frac{d\mathbf{v}_k}{dt}$$

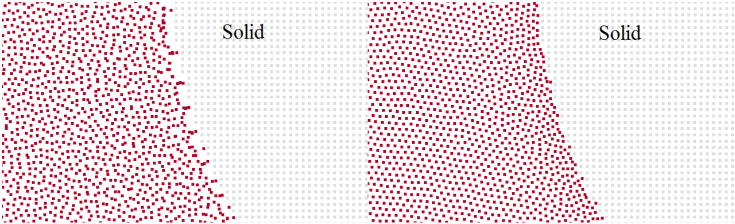
$$I_I \frac{d\mathbf{\Omega}_I}{dt} = \sum_{k \in I} m_k (\mathbf{r}_k - \mathbf{R}_I) \times \frac{d\mathbf{v}_k}{dt}$$

$$\mathbf{v}_k = \mathbf{V}_I + \mathbf{\Omega}_I \times (\mathbf{r}_k - \mathbf{R}_I)$$

The **inertia tensor** is computed for the fly for the system of material points, making no assumptions on shape, i.e. it **is exact for the discretized system**.

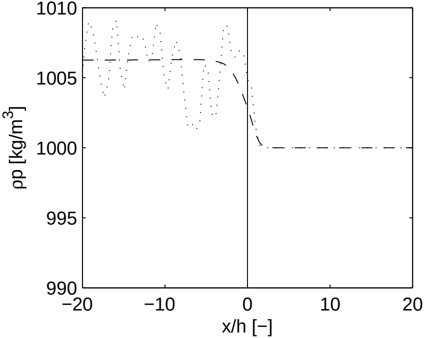
Resolving the interface

The force at every point of the interface is computed by the **momentum equation**. **Pressure** and **viscous** terms are computed for each particle, making the coupling seamless.
The **kernel sampling** across the interface is however **unbalanced**, since particles from the solid phase are kept in a rigid, **regular lattice distribution**.

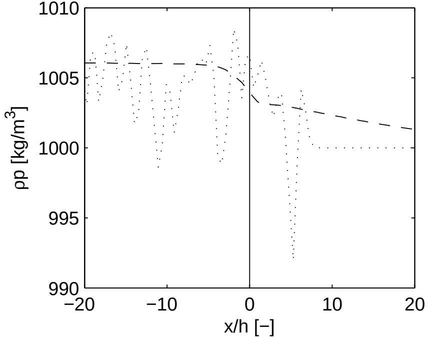


No δ terms. With δ terms.

Resolving the interface



Static interface.

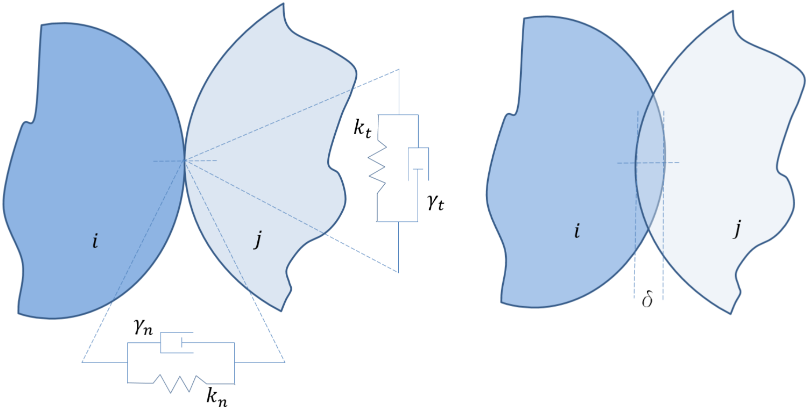


Moving interface.

Interface (— — —); No delta terms (· · ·); Delta terms (— — —).

DEM - Soft body model

Approximate contacts with a **spring model**:



Spring displacement is given by **body overlap**, δ, hence 'soft' body. This translates into a penalty method, solved with the same **explicit** schemes as the SPH equations.

DEM - Soft body model

Normal forces:

$$\mathbf{F}_{n,ij} = \mathbf{F}_n^r + \mathbf{F}_n^d = k_{n,ij}\delta_{ij}^{3/2}\mathbf{n}_{ij} - \gamma_{n,ij}\delta_{ij}^{1/2}\dot{\delta}_{ij}\mathbf{n}_{ij}$$

$$k_{n,ij} = \frac{4}{3}E^*\sqrt{R^*}; \quad \gamma_{n,ij} = -\frac{\log e_{n,ij}}{\sqrt{\pi^2 + \log^2 e_{n,ij}}}$$

$$\frac{1}{E^*} = \frac{1-\nu_I^2}{E_I} + \frac{1-\nu_J^2}{E_J}; \quad R^* = \frac{r_i r_j}{r_i + r_j}; \quad M^* = \frac{m_I m_J}{m_I + m_J}$$

Tangential forces:

$$\mathbf{F}_{t,ij} = \min(\mu_{IJ}|\mathbf{F}_{n,ij}|\tanh(8\dot{\delta}_{ij}^t)\mathbf{t}_{ij}; \;\; \mathbf{F}_t^r + \mathbf{F}_t^d)$$

$$\mathbf{F}_t^r + \mathbf{F}_t^d = k_{t,ij}\delta_{ij}^t\mathbf{t}_{ij} - \gamma_{t,ij}\dot{\delta}_{ij}^t\mathbf{t}_{ij}$$

DEM - adding stability constraints

$$\Delta t = \min \left[C \min_i \left(\sqrt{\frac{h}{|\mathbf{f}_i|}} \right); \right.$$

Force terms

$$C \min_i \left(\frac{h}{c_0 + \max_j \left| \frac{h \mathbf{u}_{ij} \mathbf{r}_{ij}}{\mathbf{r}_{ij}^2} \right|} \right);$$

CFL and viscosity terms

$$\left. \min_i \left(\frac{3.21}{50} \left(\frac{M^*}{k_{n,ij}} \right)^{2/5} u_{n,ij}^{-1/5} \right) \right]$$

DEM terms

Implementation

Computationally

- Forces per particle are computed during main interaction cycle - both SPH and DEM;
- Separate cycle across rigid bodies, to sum forces and update positions according to rigid body equations - main overhead.

For the user

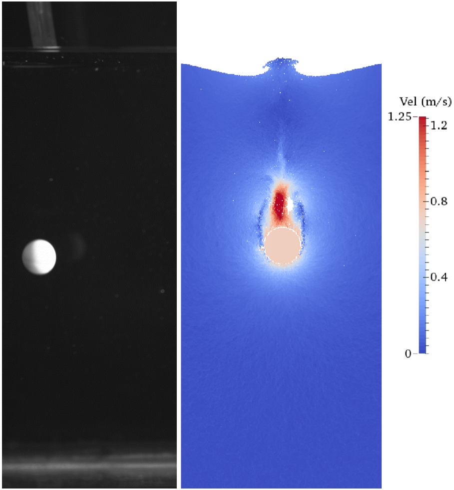
- Both SPH and DEM forces will be available on V4.0 vanilla release;
- Selecting materials is trivial with a xml list file.

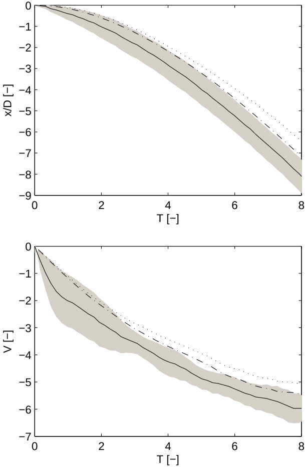
```
<property name="pvc">
<Young_Modulus value="90000000.0" comment="Young Modulus (N/m2)" />
        <PoissonRatio value="0.23" comment="Poisson Ratio (-)" />
        <Kfric value="0.45" comment="Kinetic friction coefficient" /
        <Restt value="0.80" comment="Restitution coefficient" />
</property>
```

Implementation advances

- Increased efficiency;
- Increased stability;
- Maximum number of bodies increased to 2048;
- Periodic conditions.

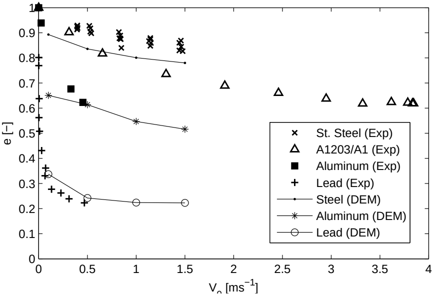
SPH - Buoyancy - Experimental





High speed camera with **object tracking algorithm**. Position (top) and velocity (bottom).

DCDEM - Normal Dry Collisions

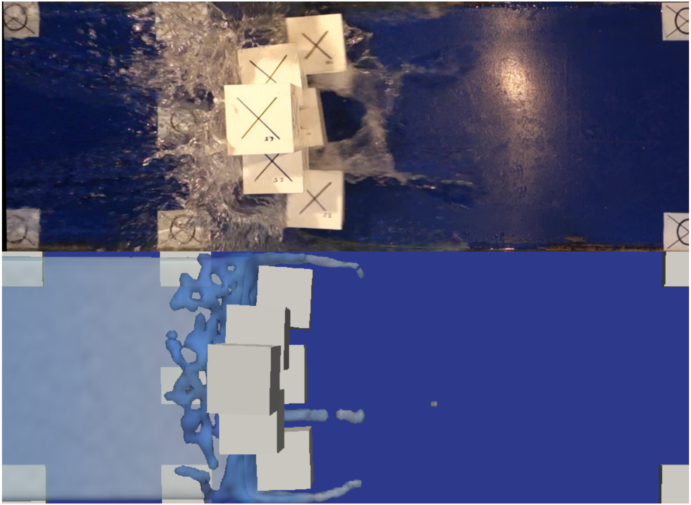


	$E\ [Nm^{-2}]$	$\nu_p\ [-]$	$e\ [-]$
Steel	200×10^9	0.30	0.85
Alum.	65×10^9	0.33	0.75
Lead	16×10^9	0.42	0.40

Reproducing **restitution coefficients** with changing **impact velocity**.

SPH-DCDEM - Complex interactions

Experimental work. Cubes in a flume with a dam-break wave.



Cubes were tracked and their pose estimated.

SPH-DCDEM - Complex interactions

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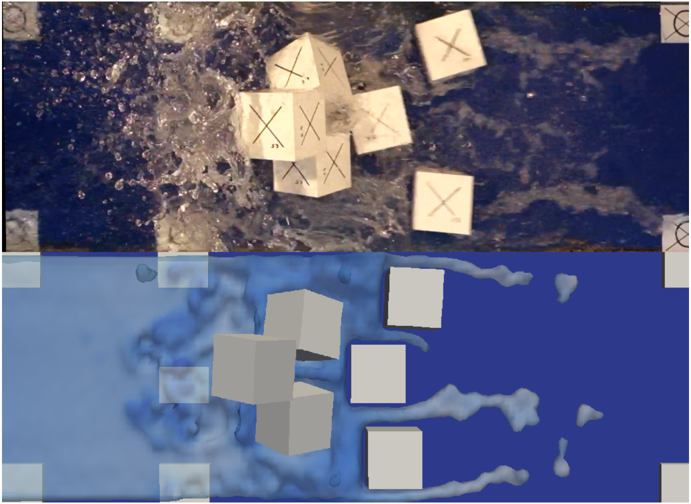

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SPH-DCDEM - Complex interactions

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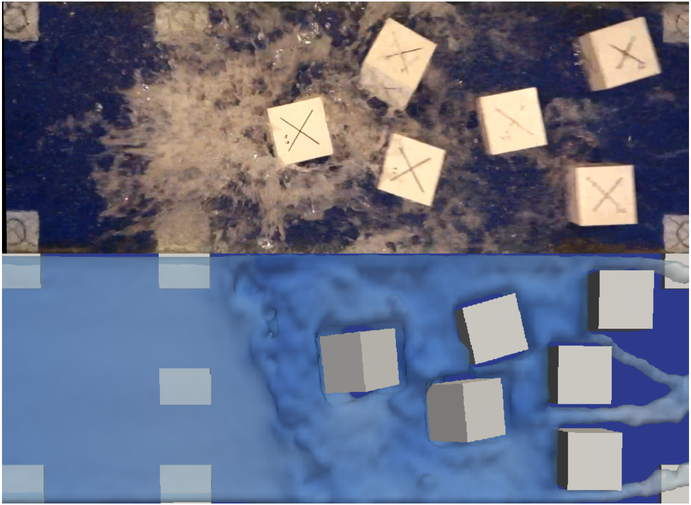

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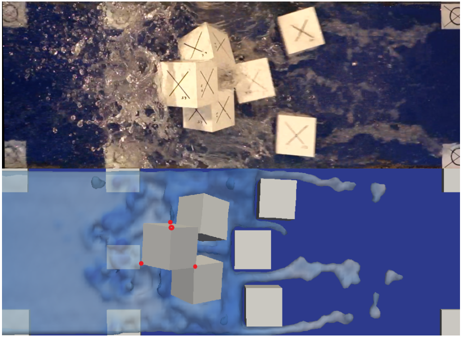
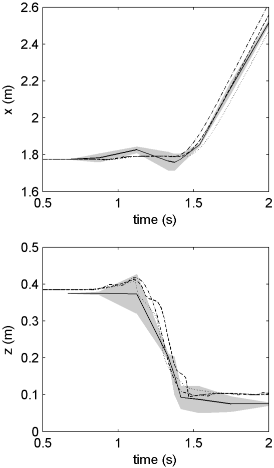
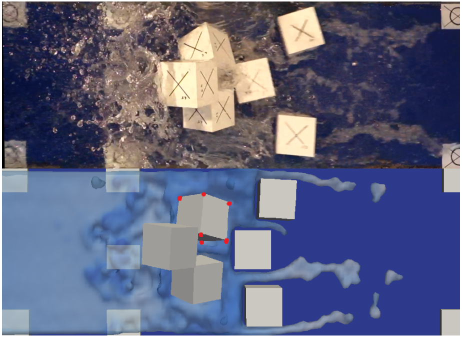
SPH-DCDEM - Complex interactions

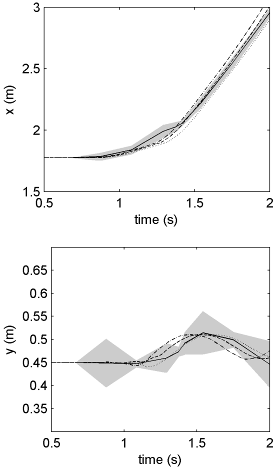




Experimental(· · ·)/numerical(–) barycenter coordinate positions over time for **top cube**.

SPH-DCDEM - Complex interactions

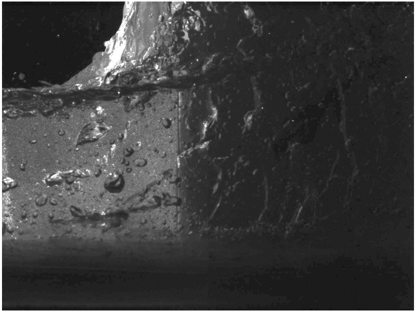


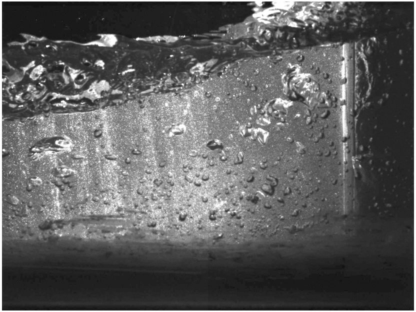


Experimental($\cdots$)/numerical(–) barycenter coordinate positions over time for **middle left cube**.

SPH-DCDEM - Complex interactions

Experimental work. **PIV** at the impact locus.

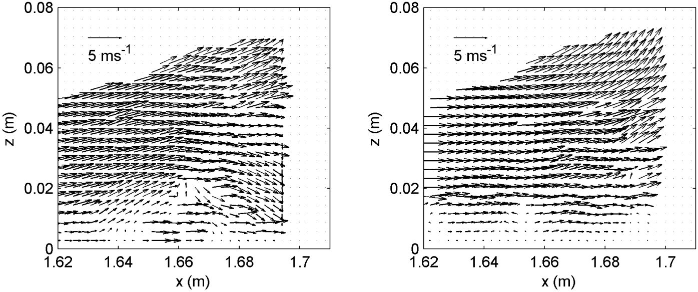




Very difficult conditions with free-surface splashing, air entrainment and large velocities.

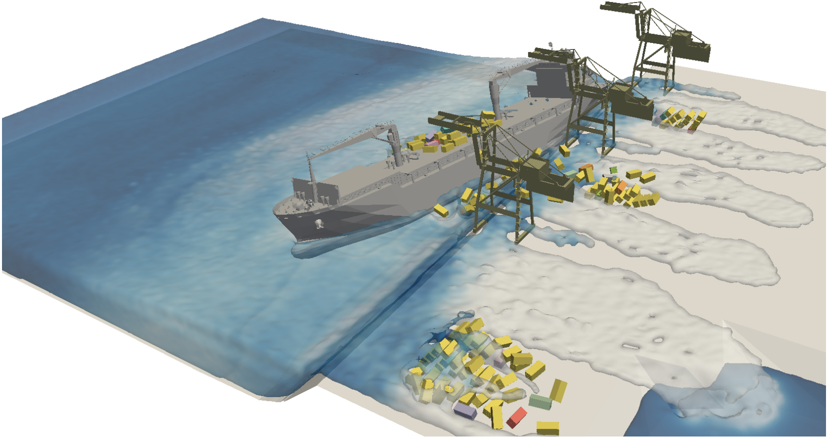
SPH-DCDEM - Complex interactions

Experimental work. **PIV** and SPH **velocity fields**.



Velocity fields on impact locus. Left - PIV; Right - SPH

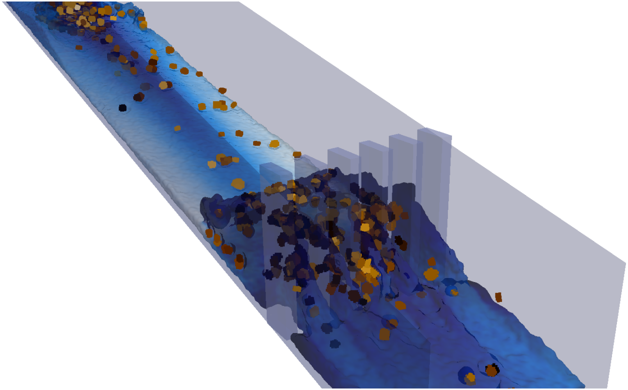
Large scenarios



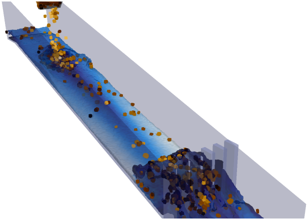
$Dp = 0.50$ m, 12×10^6 particles, 57 h computation.

Debris flows

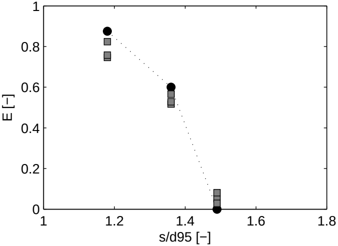
What do we need to start modeling a convincing debris flow? Reproduction of a given **granulometric curve**; **3D scans** of debris, a semi-random way to generate **initial conditions**.

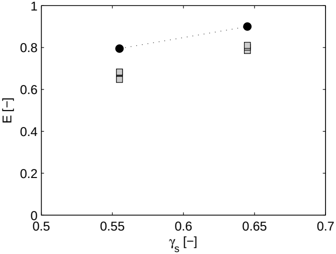


Resolved modeling of debris flows



$Dp = 0.008$ m, 1.6×10^6 particles, 280 h computation.





Conclusions and future work

- The model, together with an optimal implementation, allows for the **resolved** study of **scenarios in large scales**;
- **New classes of flows** are now within modeling capabilities: solid laden debris flows, massive rock slides, urban flooding; with a **minimal number of approximations**;
- As **high resolution** simulations become possible, **new research prompts** should be created;
- Implement **unresolved granular** phase models;
- Explore **adaptive** and **multi-resolution** formulations;
- Explore alternative, more robust turbulence models;
- Implement **elasto-plastic** constitutive equations for the bodies;

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