3 rd Iberian Congress Advances on SPH

A SPH-DEM solver for the interaction of large-scale particles with irregular shape and fluid

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Background—Fluid-particle interaction

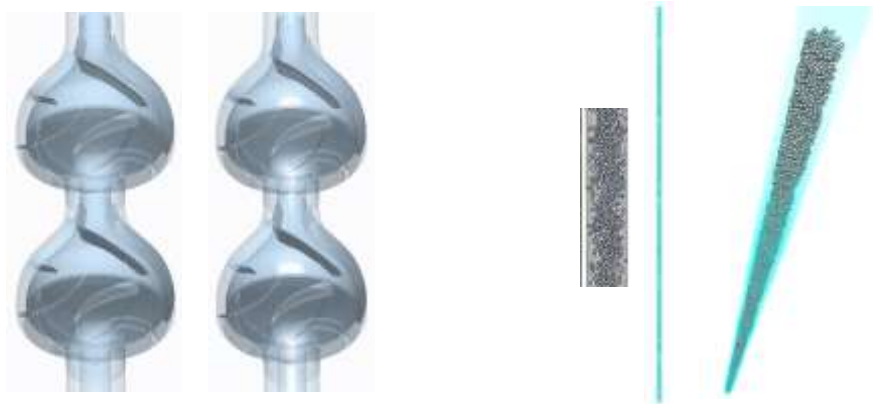
Particle-fluid two-phase flow is a research hotspot and frontier problem in the field of science and engineering

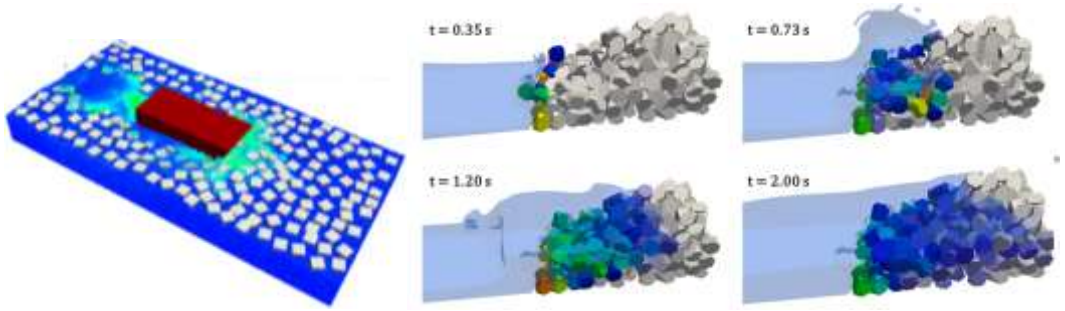
Natural phenomenon

- Landslide
- Sedimentation
- Estuarine gravel transport
- Marine biological particle

Engineering applications

- deep-sea mining pipelines
- Ice floe dynamics
- Interaction of wave with coastal rocks
- Rock dumping process in water
- Sediment erosion
- Granular fluidized bed
- ……





Simulating these complex processes shows great challenges:

- *Multi-scale modeling*
- *Particle system contact*
- *Fluid-solid coupling force modeling*
- *Particle shape in real world*
- *Huge computing cost*
- *….*

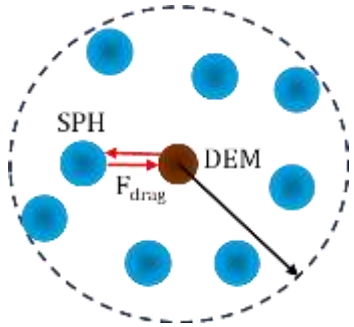
Fluid-particle interaction modeling

For free surface flow and complex moving interface problems, meshless methods such as SPH and MPS are widely used:

Unresolved SPH-DEM:

DEM objects: Spheres

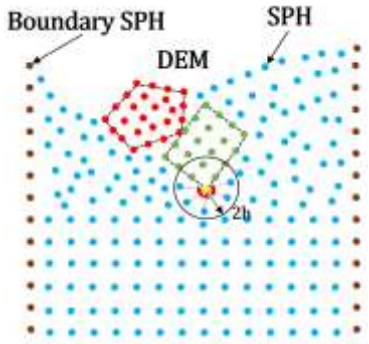
Coupling force: empirical formulas

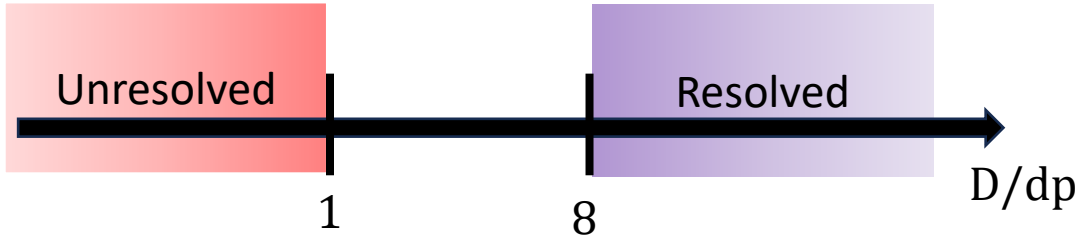


Resolved SPH-DEM:

DEM objects: Irregular shape…

Accurately solve the coupling force





GOAL:

Accurately modeling particle-fluid and particle-particle with complex shape interaction:

I. Develop a GPU-based meshless solver for solid-fluid two-phase flow based on SPH-DEM method

II. Couple two high-performance open source platforms: DualSPHysics and Blaze-DEM

III. Case verification and application extension

DualSPHysics

DualSPHysics:

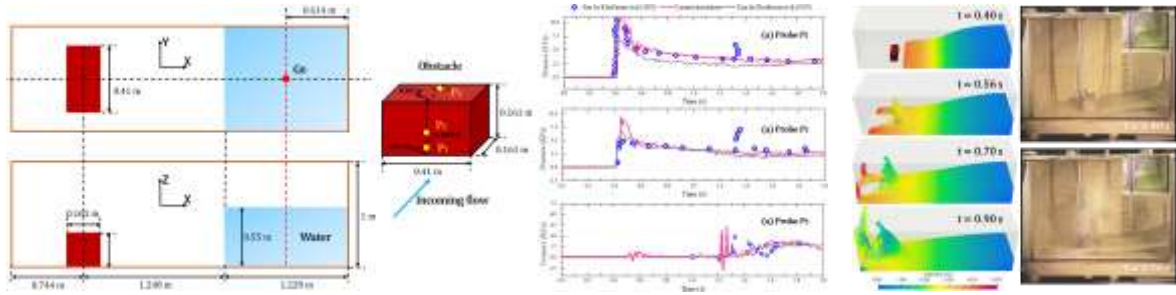
SPH based solver, widely used in various 3D fluid-structure coupling simulations.

Robust and efficient.

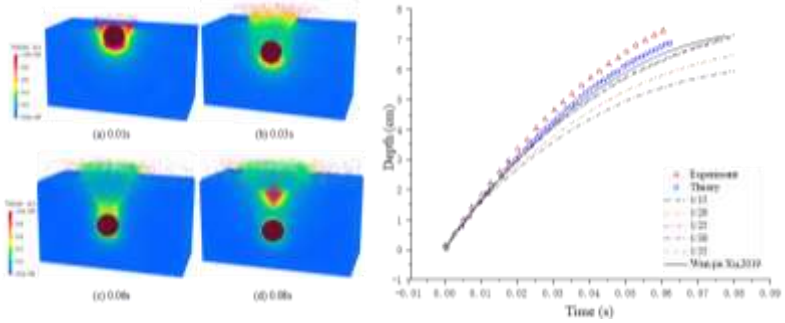
Many great features:

free-surface flow solver
Discrete element method coupled with SPH
Coupled with Project Chrono
Coupled with MoorDyn
Multi-phase gas-liquid solver
Three smoothing kernel functions
Advanced density dissipation terms
Two time integrators
Three smoothing kernel functions
GPU acceleration
MDBC
Periodic conditions
……

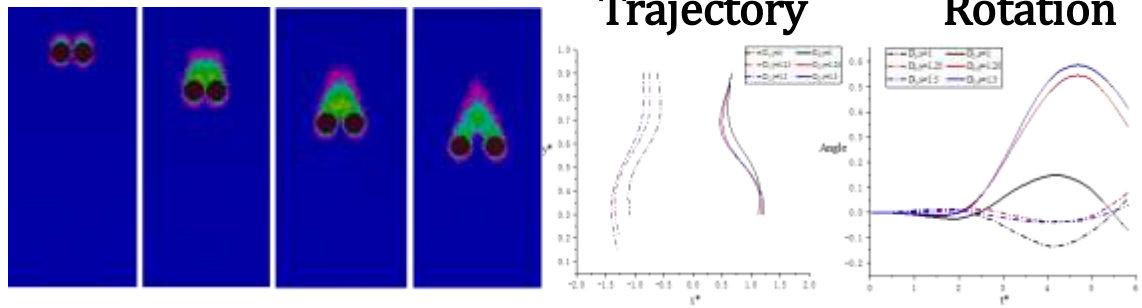
1). Dam-break flow with the obstacle



2). Sphere entry

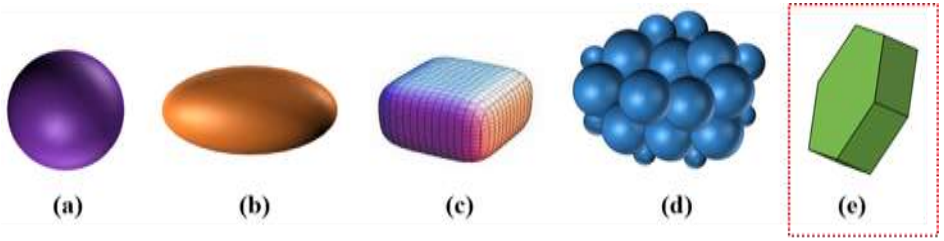


3). Two-sphere interaction



Blaze-DEM

Should we consider particle shape effects in the simulations?



Different particle shape models

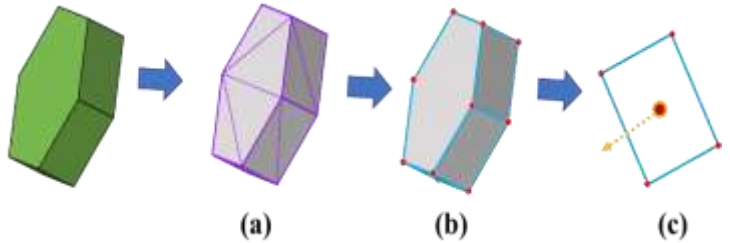
- ✓ Particle shape representation is one of the **key challenges**
- ✓ Most particles in real world are **non-spherical**, and **low fidelity results** in a lower value of the extracted information
- ✓ polyhedral shape is able to capture the particle angularity and aspect ratio as required, which can represent most particle shapes in ocean engineering.

For Blaze-DEM:

- ☐ **An efficient solver for DEM (Discrete Element Method)**
- ☐ **Spherical and polyhedral modeling**
- ☐ **Advanced neighbor particle search and contact algorithm**
- ☐ **Large-scale complex granular material interactions**
- ☐ **Perform millions of particle-scale simulations in a realistic computational runtime via GPUs**

Blaze-DEM

➢ Polyhedral geometry modelling



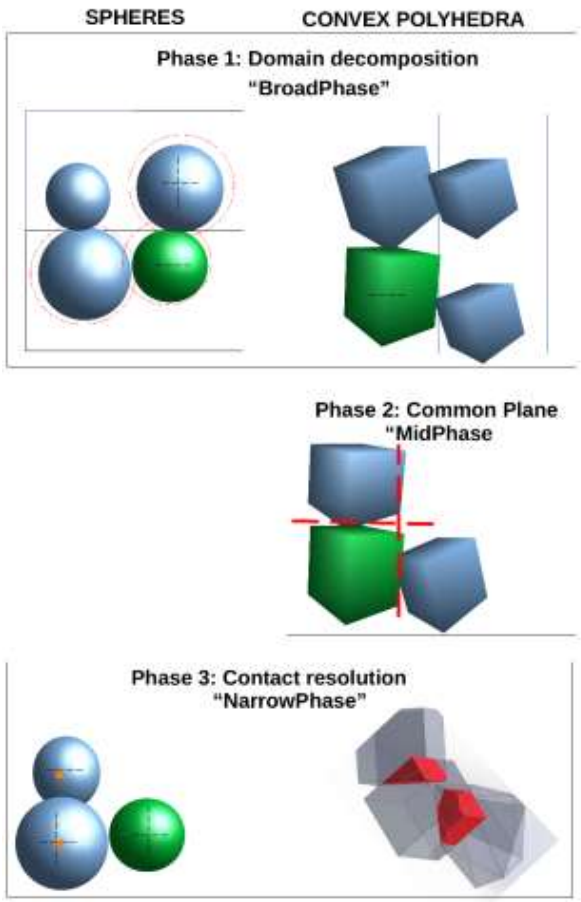
(a) Polyhedral geometry is imported as a **standard triangle list** (STL) mesh

(b) Triangles connected with similar orientations are merged to create feature edges and vertexes

(c) Finally, the unique polygon faces are defined, including the centre point and the normal direction

Using points, lines and faces to describe the polyhedral geometry

➢ DEM contact detection and collision model



Most time consuming:
about 90% in DEM simulations

Phase 1: Detect potential contact particles;

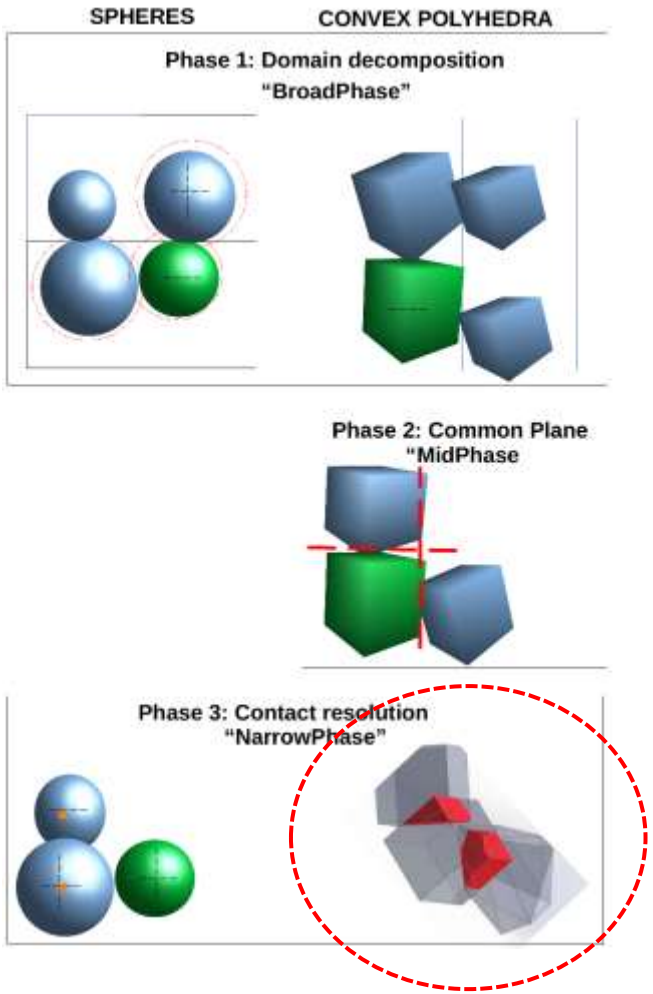
Phase 2: Only for polyhedral, detect contact more accurately but at a lower cost;

Phase 3: Determine the direction and magnitude of the contact pairs using the overlap volume method.

[1] Govender N. A DEM study on the thermal conduction of granular material in a rotating drum using polyhedral particles on GPUs. Chemical Engineering Science. 2022;252.
[2] Govender N. Study on the effect of grain morphology on shear strength in granular materials via GPU based discrete element method simulations. Powder Technology. 2021;387:336-47

Blaze-DEM

➢ Collision model



Phase 3: Calculated contact force between DEM objects

The overlap volume, rather than the depth, can estimate the contact force, which is more representative of how the granular material will contact in the real world

Normal force $\boldsymbol{F}_n = (K_n V_c)\boldsymbol{n} - C_n(\boldsymbol{v}_R \cdot \boldsymbol{n})\boldsymbol{n}$

K_n is the volumetric spring stiffness (N/m^3), V_c is the overlap volume and C_n is the damping coefficient (Ns/m), $\boldsymbol{v}_R$ is the relative velocity

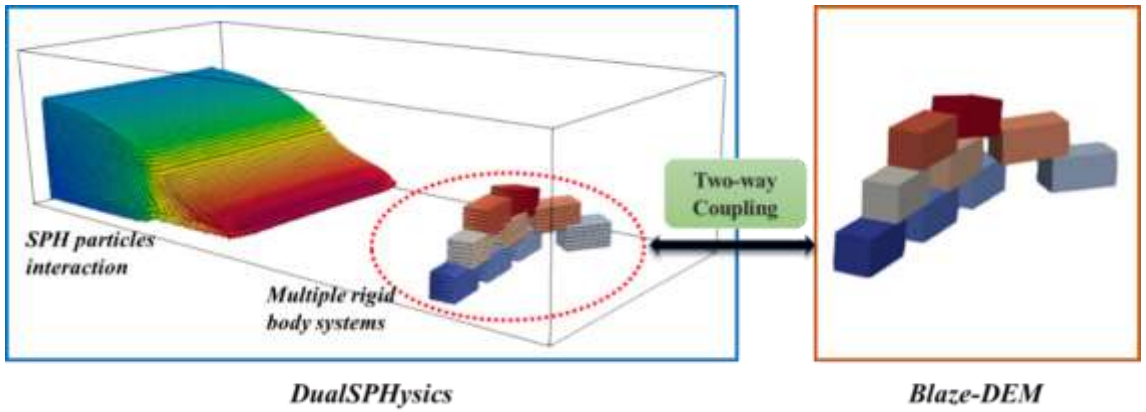
Tangential force $\boldsymbol{F}_T = -K_T(\boldsymbol{v}_T dt + \boldsymbol{L}) - C_T \boldsymbol{v}_T,$

K_T is the tangential spring stiffness (typically $K_T \geq K_n/2$), $\boldsymbol{v}_T$ represents the relative tangential velocity,

Contact force $\boldsymbol{F}^S = \boldsymbol{F}_n + \boldsymbol{F}_T,$

Torque $\boldsymbol{T}^S = (\boldsymbol{R} - \boldsymbol{R}_0) \times \boldsymbol{F}^S,$

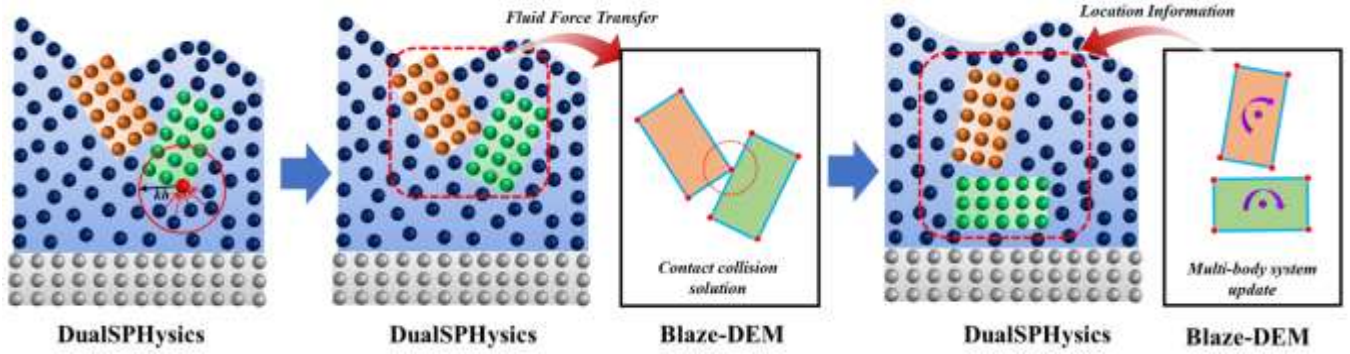
SPH-DEM coupled strategy



Coupling solver modeling:

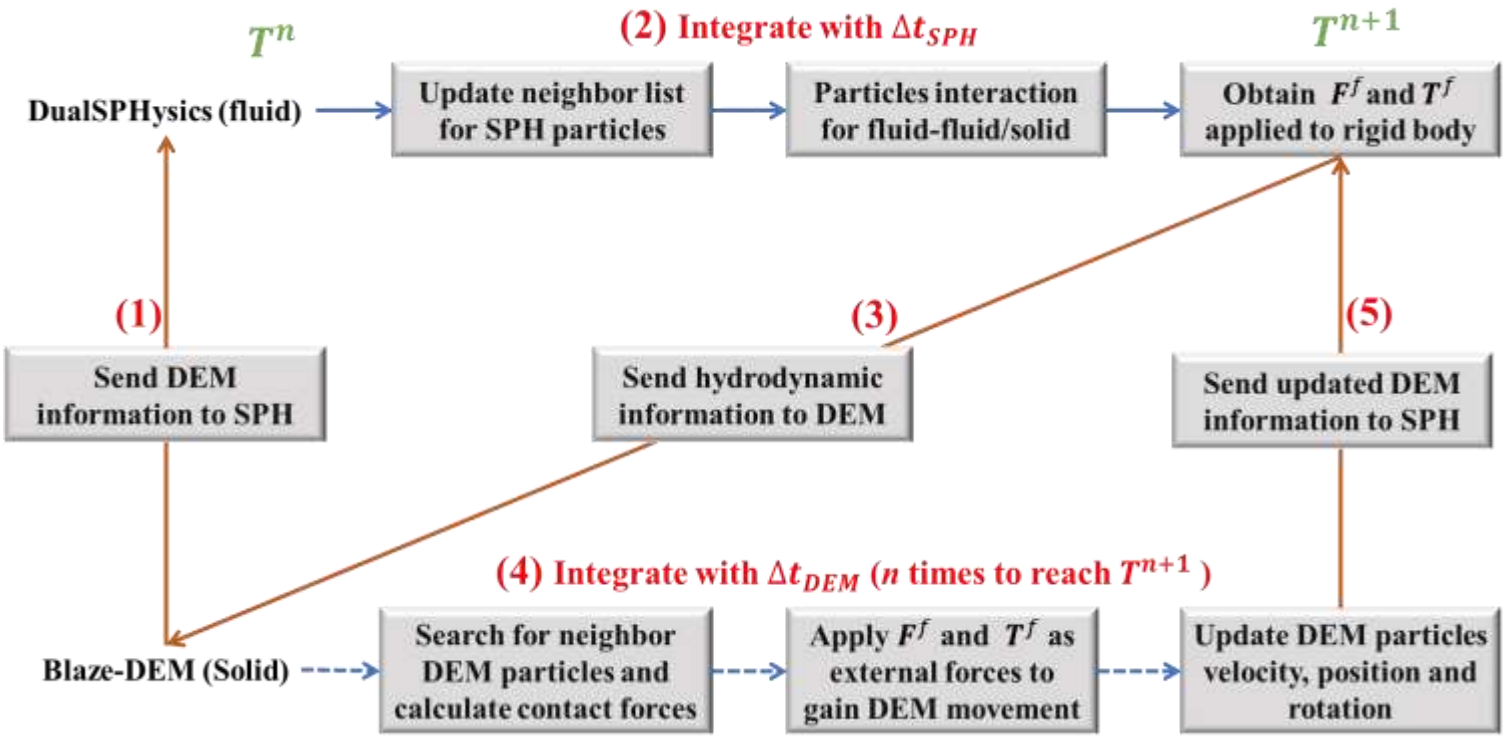
DSPH: Discrete into particles

Blaze: Objects with points, lines and faces



- Send hydrodynamic force generated by SPH particles to DEM solver by the coupling interface
- Blaze-DEM calculates force and solves the motion information of DEM objects
- Return position, velocity and force of DEM objects to DSPH to complete the two-way coupling

SPH-DEM coupled strategy

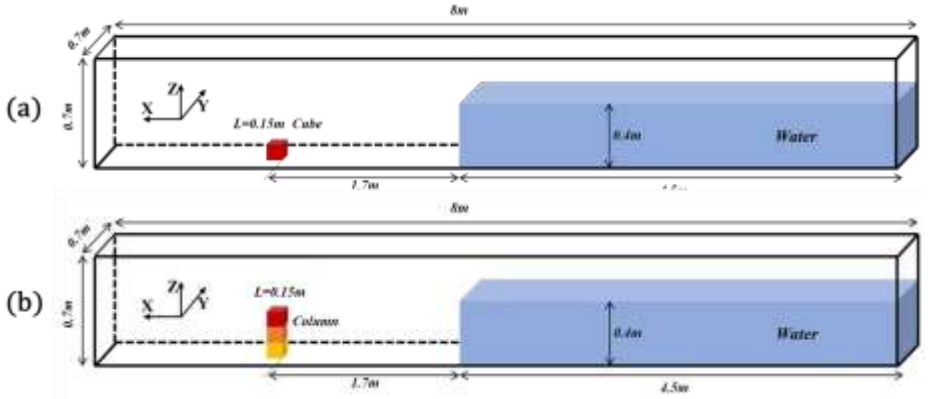


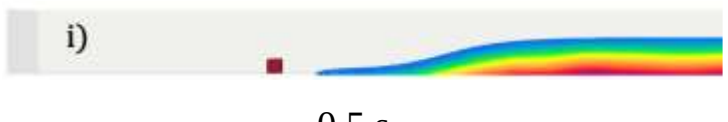
$$\Delta t_{SPH} = \mathrm{N} * \Delta t_{DEM}$$

- In one SPH time step Δt_{SPH}, obtain the hydrodynamic force on DEM objects;
- Solve all resultant forces of DEM objects combined with hydrodynamic forces and updates the position information F^f, T^f;
- SPH updates the position and velocity information of DEM objects. Then time comes to T^{n+1}

Coupling solver verifications

➢ Dam break with cubes



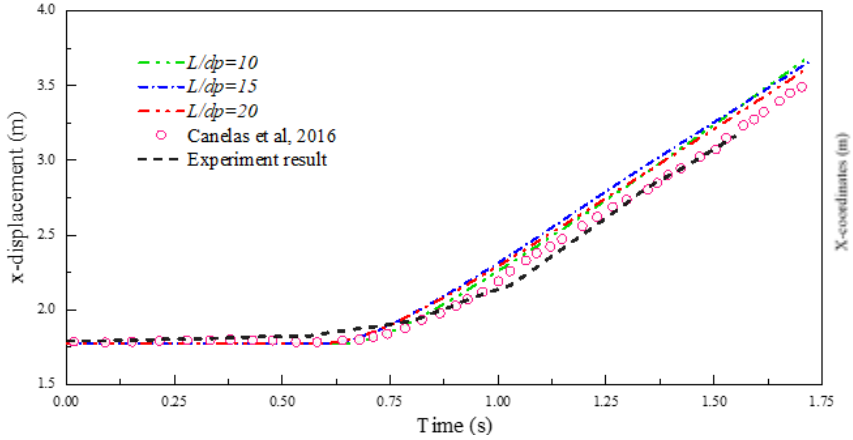


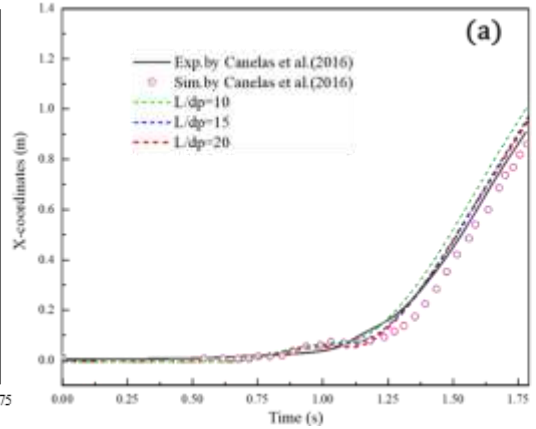
0.5 s

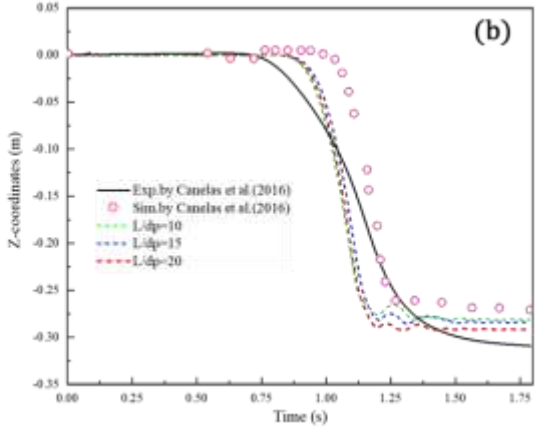
0.8 s

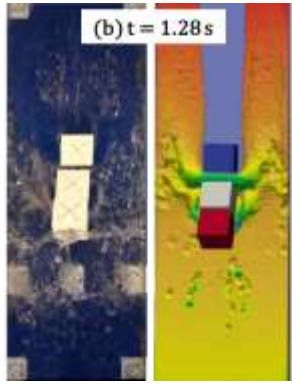
1.3 s

1.6 s





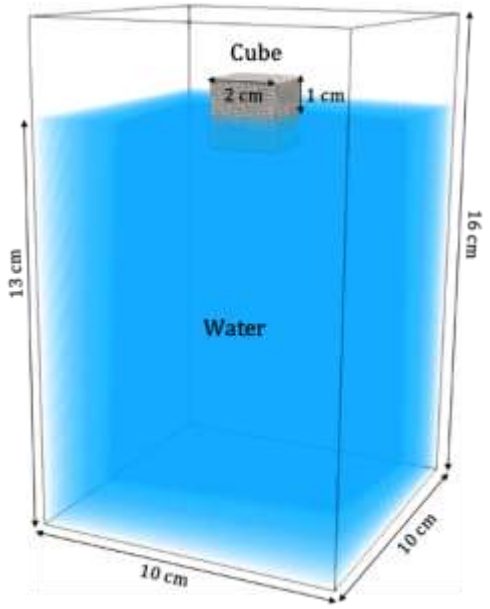


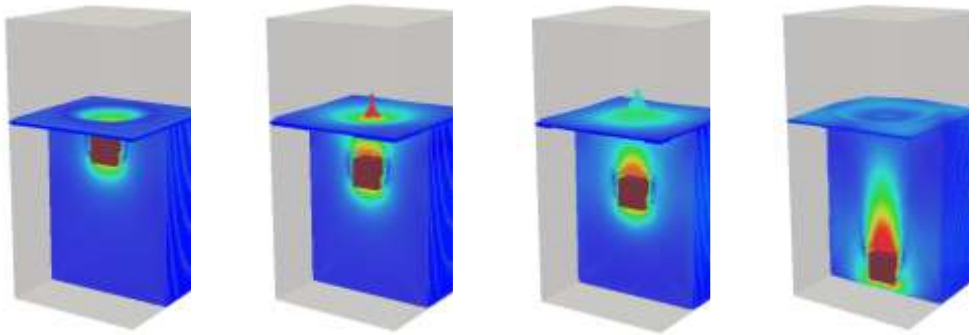


We verify the model's ability to handle fluid-structure coupling and multi-particle collisions

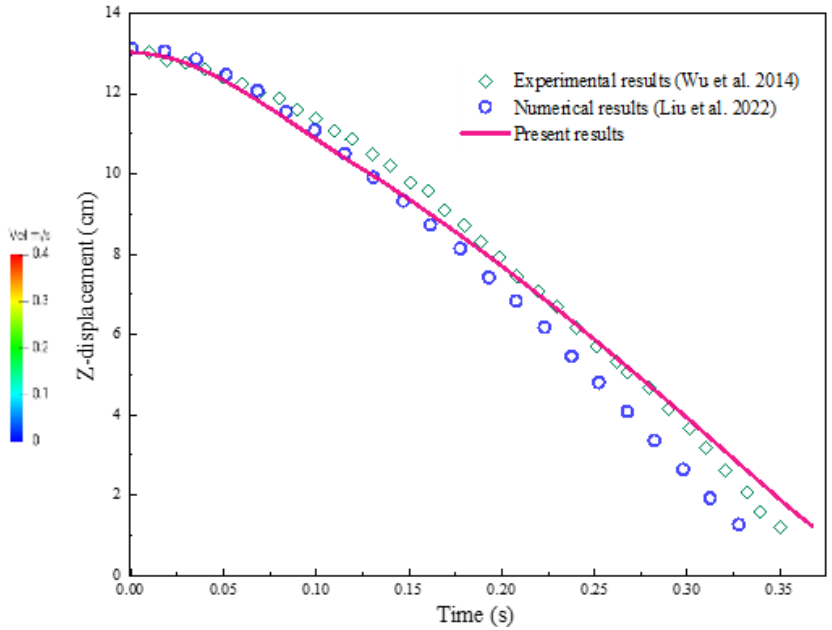
Coupling solver verifications

➢ Cube settlement



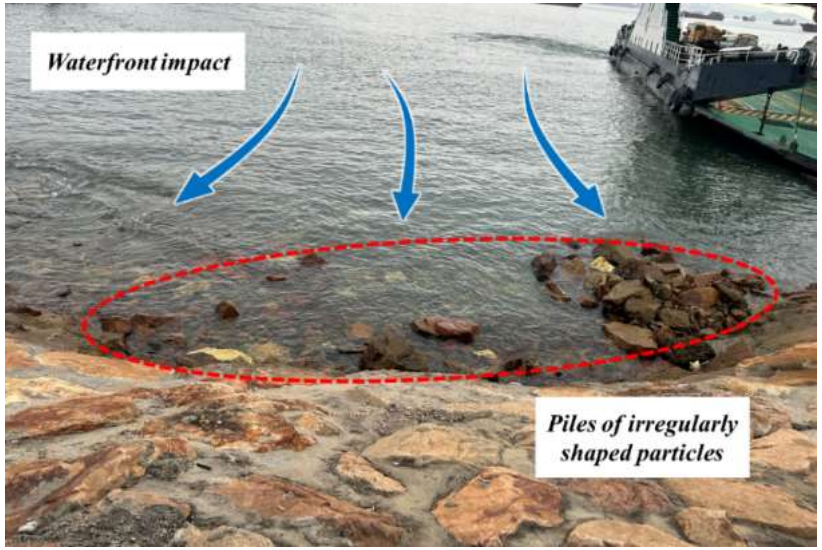


0.10 s 0.16 s 0.25 s 0.35 s

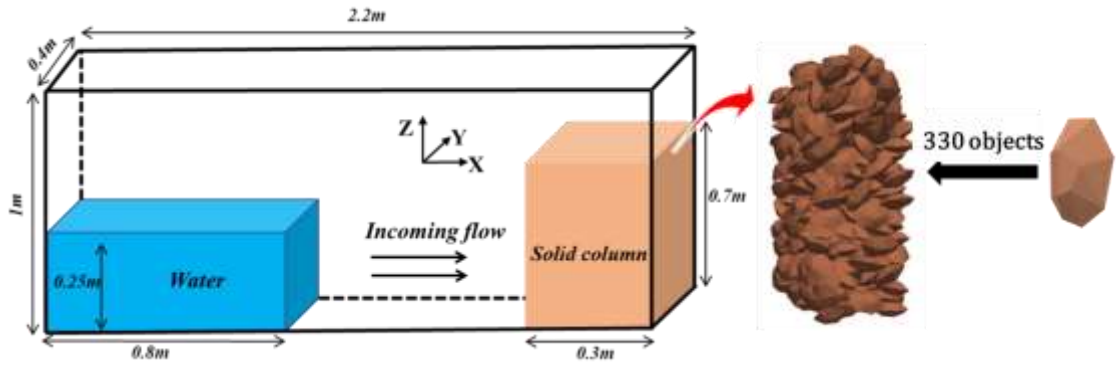


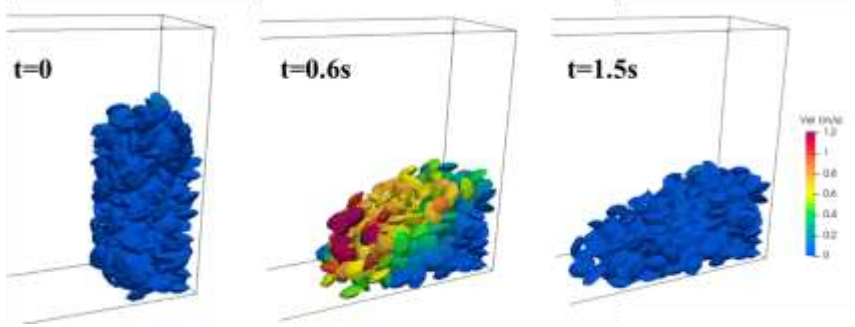
We verify the model's ability to handle fluid- solid coupling and multi-particle collisions

Dam-break impacting a collapsed rock pile

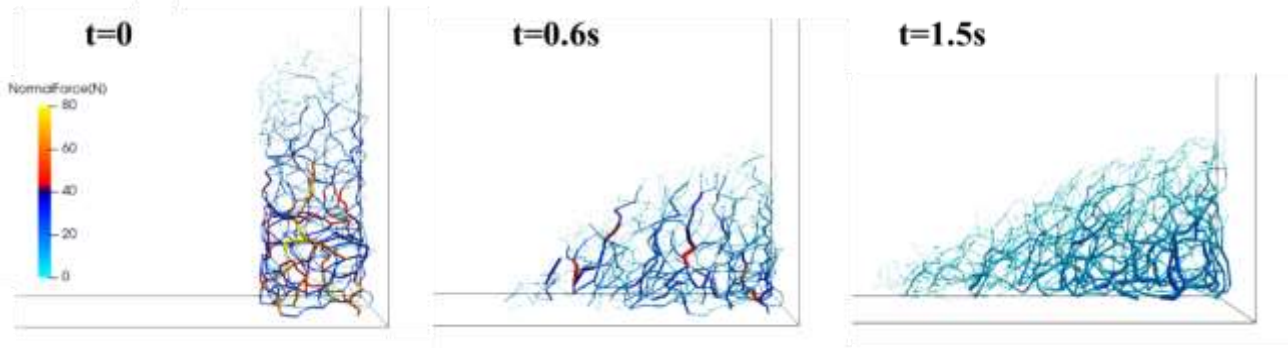


Coastal breakwater structure



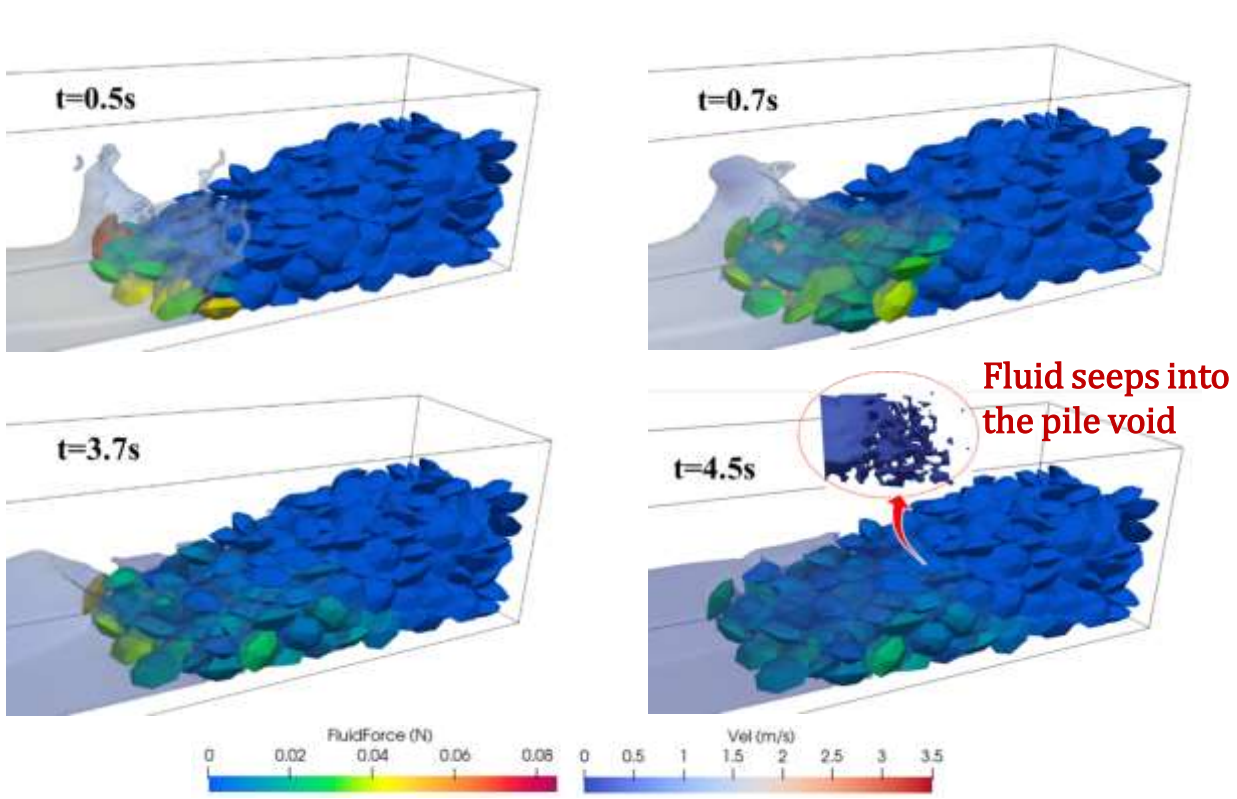


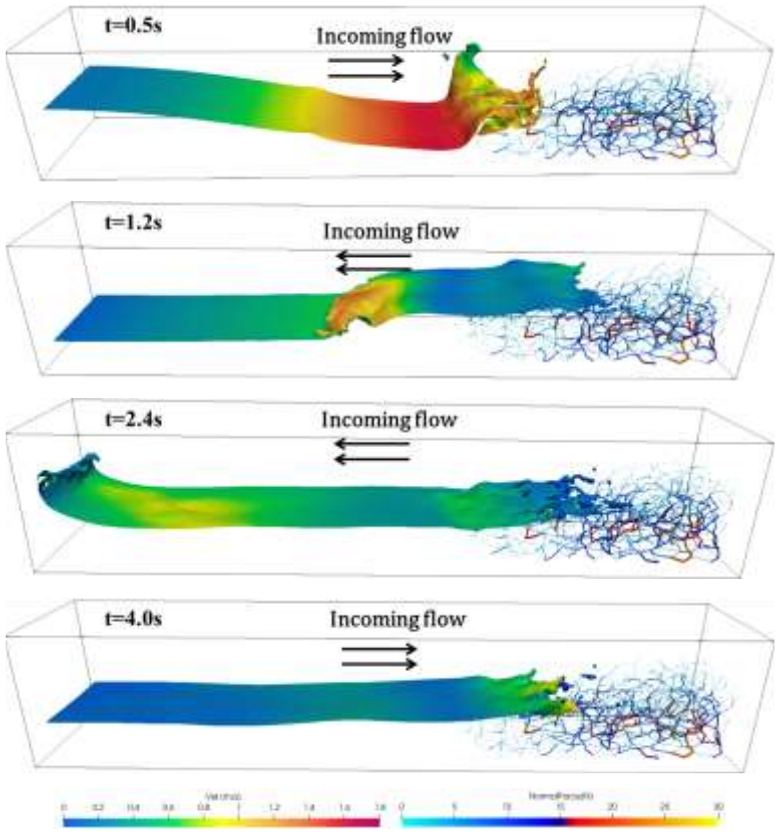
collapse



	Young modulus E ($N\ m^{-2}$)	Poisson coefficient v_p	Friction coefficient v_f	Restitution coefficient e
Flume	2.1×10^{11}	0.33	0.35	0.8
Rock	3×10^{9}	0.3	0.3	0.6

Dam-break impacting a collapsed rock pile





- Provide extensive information: such as velocity, fluid force and force chain distribution.
- Show significant potential for analyzing the dynamic response of free surface flow on the multi-block structures.

Conclusions

This study:

- A new SPH-DEM coupling is developed for interaction between polyhedral granular materials and fluid via coupling DualSPHysics and Blaze-DEM.
- On the basis of the three-dimensional fluid-solid coupling model, the interaction between free surface and rock pile is simulated, and the practical application potential of the model is further verified.

Model advantages:

- ✓ The resolved coupling method can **fully consider** the particle shape factor and solve the flow field information around the DEM objects;
- ✓ Good at **handling polyhedral granular materials**, including particle modeling and contact detection algorithms;
- ✓ Open source platforms are based **on GPU**, providing the ability of large-scale simulations under 3D conditions;
- ✓ The solver based on open source **is easy to update and modify** to better adapt to new simulation requirements.

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