Smoothed Particle Hydrodynamics - Methodology and Applications

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@NTU

MES, Peking University—History

Peiyuan Zhou

- **1952—Established** by Peiyuan Zhou at Peking University, **1st** Dept. Mech. in PRC
- **1958—**China's **first** low-speed wind tunnel
- **2000—**State Key Laboratory for Turbulence and Complex Systems
- **2006—**Joined in COE
- **2012—** Ranked as **NO.1** in PRC
- **450** faculty, **3200** B.S., **820** M.S., **280** Ph.D.

The MES serves the world by providing a high-quality learning environment, outstanding research laboratories, and challenging experiences for our students in science, industry and technology.

60th Anniversary Celebration

MES, Peking University—Divisions

Fluid Mechanics

- Turbulence
- Computational fluid dynamics methods
- Aerodynamics
- Propulsion, heat transfer and advanced engines

Solid Mechanics

- Micro/nano-mechanics, mechanics and physics of complex materials
- Mechanics of smart materials and structures
- Elasticity and plasticity
- Experimental mechanics

Engineering Mechanics

- Computational mechanics,
- Fluid-structure interaction
- Mesh and meshfree methods
- Structural dynamics
- Mesh generation

Biomechanics and Medical Engineering

- Cell mechanics
- Bio-solid mechanics
- Bio-fluid mechanics
- Mechanobiology
- Bio-imaging and bio-instrumentation

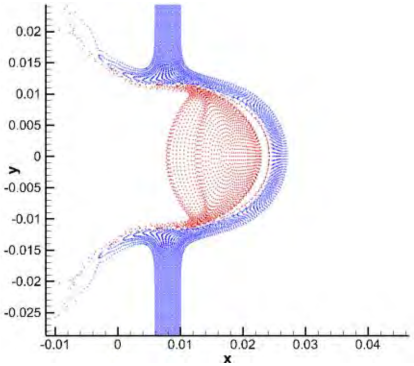
Dynamics and Control

- Cooperative control of multi-agent systems
- Robust tracking control
- Redundant control and dynamic control allocation
- Nonlinear dynamics and control
- Dynamics and control of systems with group symmetries

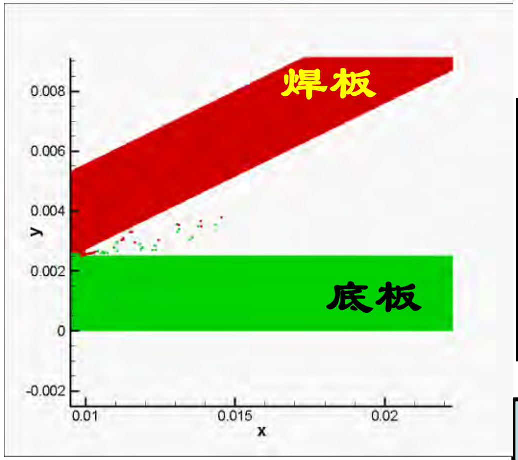
Research team – Computational FSI

Liquid sloshing

Impact and penetration



Explosive welding



Numerical methods

网格类，FVM…
粒子类，SPH…
耦合类，SPH/FEM

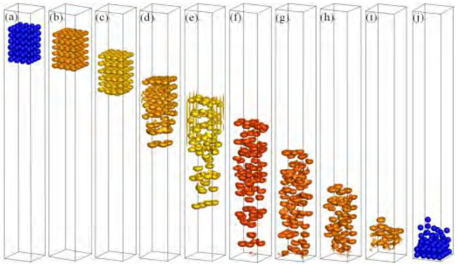
CPU,GPU,CPU+GPU

高性能计算技术

Key issues

液面变形、破碎
结构变形、破坏
强流固耦合作用

复杂载荷作用下的流体运动规律、流固耦合效应、结构失稳与破坏及防护



Powder Transport
Gas-particle two-phase flow

Computational Mechanics, FSI, Multi-scale modeling

Outline

1. Background

1.1 Continuum scale complex problems

- **Examples: tsunami, dam collapse, penetration…**
- **Difficulties:**

  Free surfaces, deformable boundaries, moving interfaces (for FDM)

  Large deformations (for FEM)

  Complex mesh generation and mesh adaptivity (for both FDM and FEM)

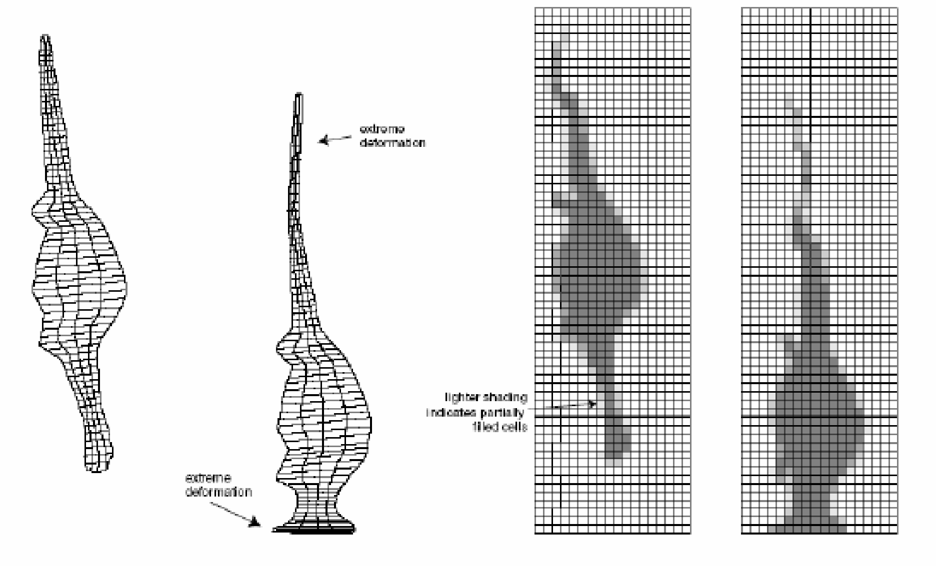
Tsunami with complex interface dynamics

Water discharge and dam collapse with free surface

Explosion and impact

1. Background

Difficulties for FDM/FEM



Lagrangian grid-based methods

- Grid moving with object
- Easy to get time history of movement and deformation
- Convenient to track moving features
- Difficult to treat large deformations

Eulerian grid-based method

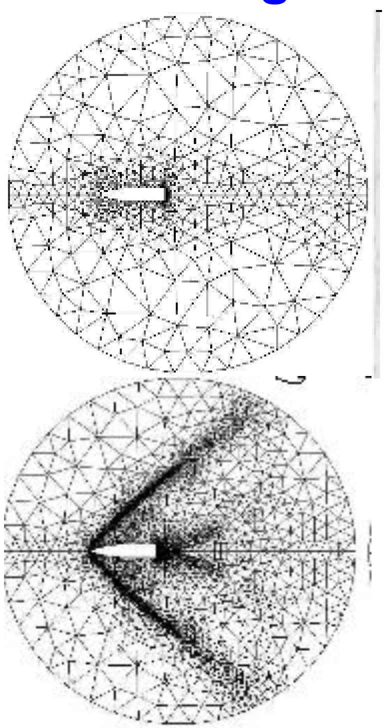
- Grid fixed on space
- Easy to treat large deformations
- Difficult to get time history
- Difficult to track moving features

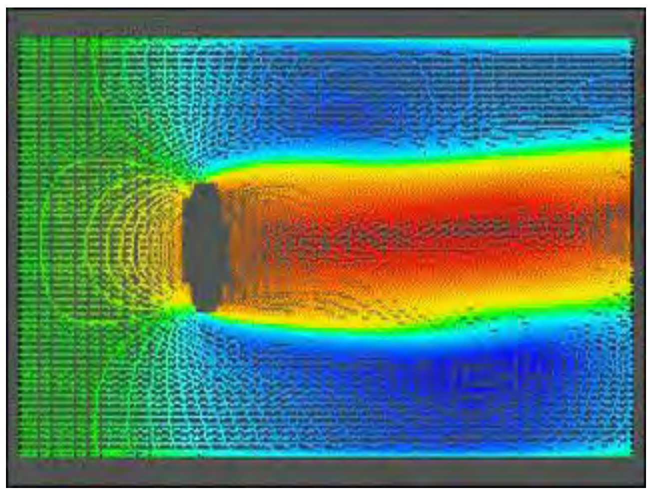
Particle methods such as SPH combine advantages of FDM & FEM

1. Background

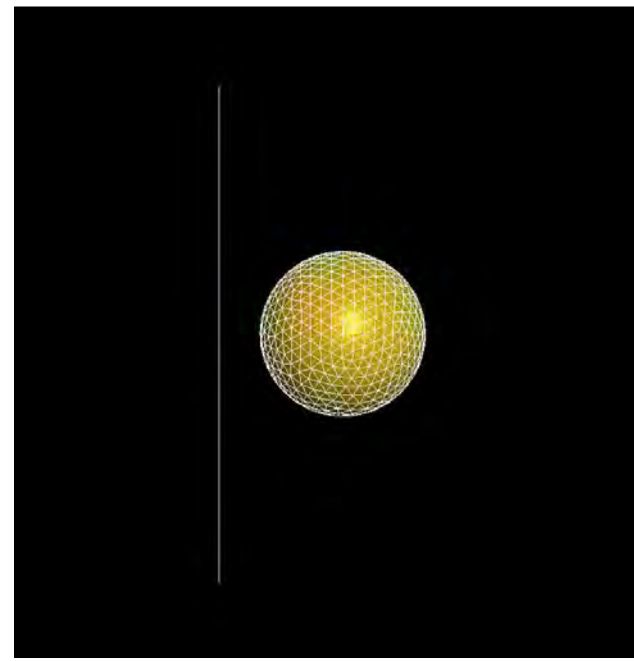
Meshing problems

It is a great challenge to generate or adapt mesh: structured/unstructured, body-fitting, mesh adaptivity, moving mesh, mesh rezoning…, Cost 2/3 work load





Moving mesh



Mesh rezoning

Mesh adaptivity

1. Background

Discontinuous problems

Granular flows in environmental, chemical, geophysical, bio-engineering…

Landslide and mud flow

- Transport, storage of *granular material* (corns, chemicals, iron debries etc.)

Figure 9 - View from top of players' tunnel - bidirectional crowd flow.

- Traffic, pedestrian flow (evacuation modelling in architectural design)

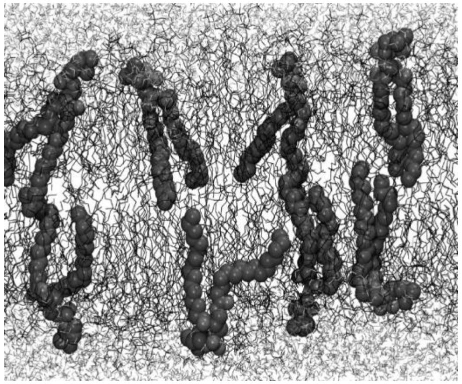
1. Background

1.2 Micro/Nano scale problems

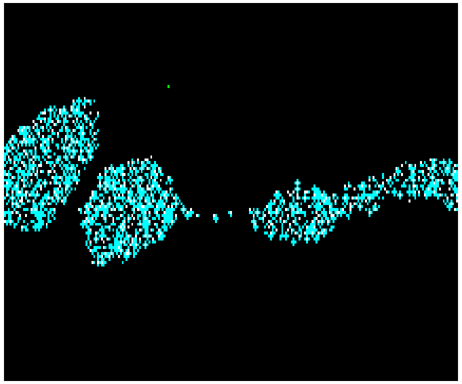
Traditional numerical methods based on continuum scale constitutive equations may not be valid, especially when the dimension diminishes…

1.3 Problems with multi-scale physics

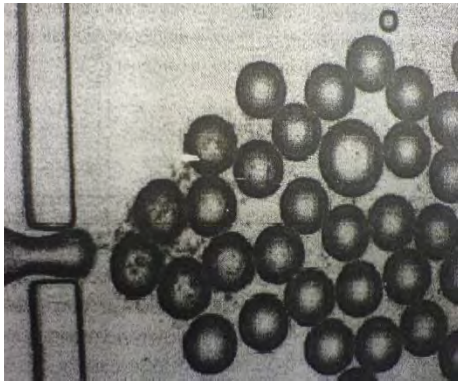
Coupling MD with FDM/FEM is complicated and not natural…



Cross section of a bilayer of lipid in water molecules



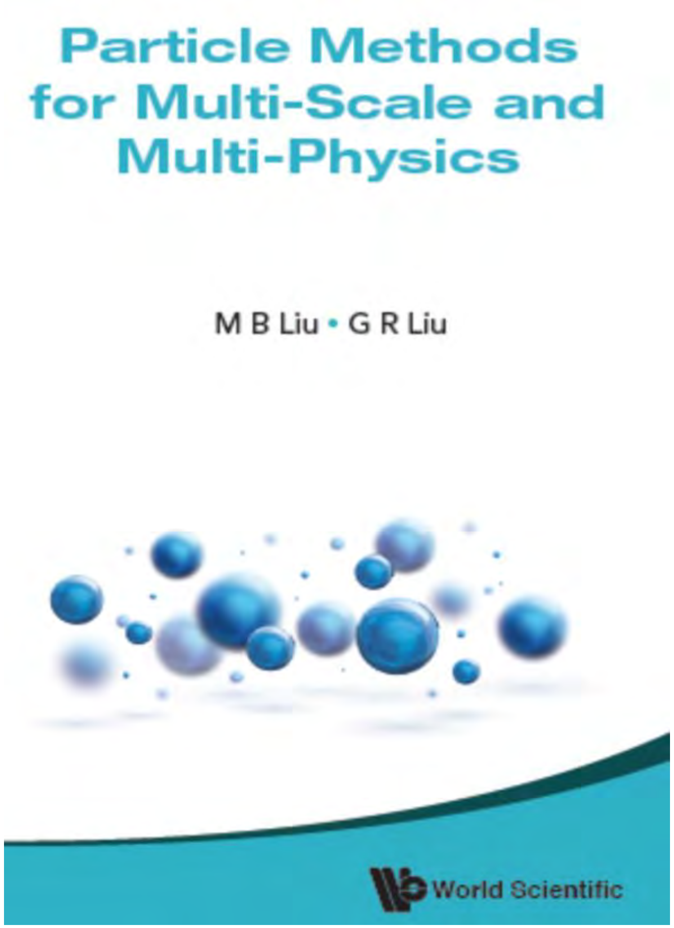
Evolution of a polymer drop break-up



Water droplets in oil

1. Background

http://www.worldscientific.com/worldscibooks/10.1142/5430



http://www.worldscientific.com/worldscibooks/10.1142/9017

2. SPH methodology – Basic concepts

2.1 History

- *Originally invented* for solving astrophysical problems in open space
- *Recently applied* to general fluid dynamic problems

2.2 Numerical approximation

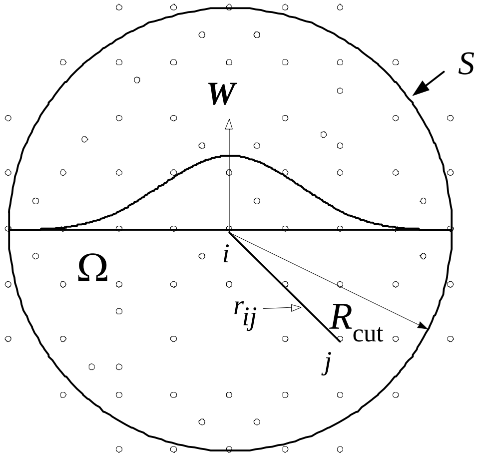
- *Weight function* (or *smoothing function*) , *W*, centered on particles and describe continuous or discrete field function,

Kernel approximation:

$$f_i \cong \int f(\mathbf{x}) W_i(\mathbf{x}) d\mathbf{x} \qquad f_{i,\alpha} \cong \int f(\mathbf{x}) W_{i,\alpha} d\mathbf{x}$$

Particle approximation:

$$f_i \cong \sum_{j=1}^{N} f_j W_{ij}\, m_j / \rho_j \qquad f_{i,\alpha} \cong \sum_{j=1}^{N} f_j W_{i,\alpha}\, m_j / \rho_j$$



SPH approximations in a two-dimensional space

2.3 SPH equations of motion

Density

$$\rho_i = \sum_{j=1}^{N} m_j W_{ij} \qquad \frac{D\rho_i}{Dt} = \sum_{j=1}^{N} m_j (\mathbf{v}_i^\beta - \mathbf{v}_j^\beta) \cdot \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\beta}$$

Momentum

$$\frac{D\mathbf{v}_i^\alpha}{Dt} = -\sum_{j=1}^{N} m_j \frac{p_i + p_j}{\rho_i \rho_j} \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\alpha} + \sum_{j=1}^{N} m_j \frac{\mu_i \varepsilon_i^{\alpha\beta} + \mu_j \varepsilon_j^{\alpha\beta}}{\rho_i \rho_j} \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\beta}$$

$$\frac{D\mathbf{v}_i^\alpha}{Dt} = -\sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2}\right) \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\alpha} + \sum_{j=1}^{N} m_j \left(\frac{\mu_i \varepsilon_i^{\alpha\beta}}{\rho_i^2} + \frac{\mu_j \varepsilon_j^{\alpha\beta}}{\rho_j^2}\right) \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\alpha}$$

Energy

$$\frac{De_i}{Dt} = \frac{1}{2} \sum_{j=1}^{N} m_j \frac{p_i + p_j}{\rho_i \rho_j} (\mathbf{v}_i^\beta - \mathbf{v}_j^\beta) \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\beta} + \frac{\mu_i}{2\rho_i} \varepsilon_i^{\alpha\beta} \varepsilon_i^{\alpha\beta}$$

$$\frac{De_i}{Dt} = \frac{1}{2} \sum_{j=1}^{N} m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2}\right) (\mathbf{v}_i^\beta - \mathbf{v}_j^\beta) \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\beta} + \frac{\mu_i}{2\rho_i} \varepsilon_i^{\alpha\beta} \varepsilon_i^{\alpha\beta}$$

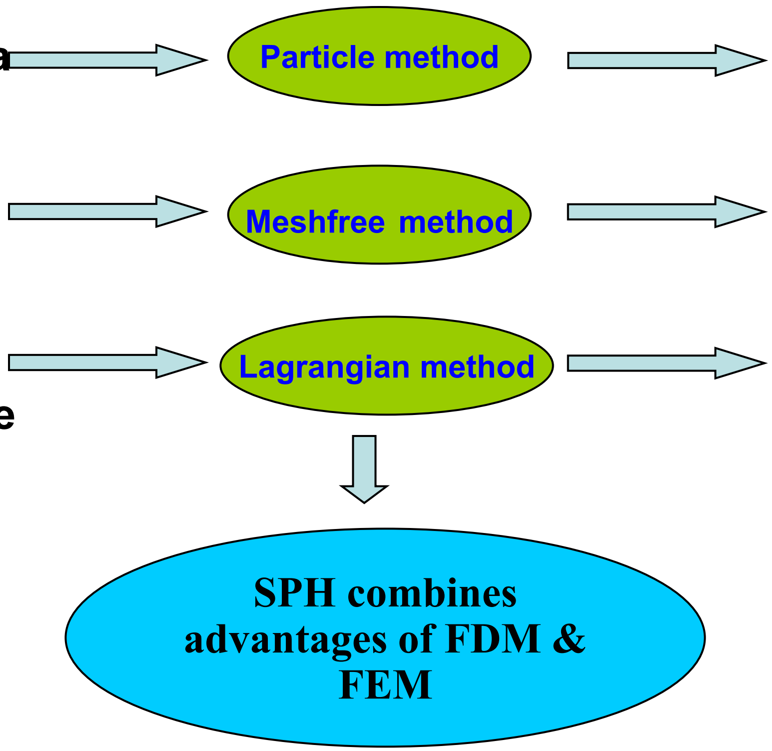
Strain rate

$$\varepsilon_i^{\alpha\beta} = \sum_{j=1}^{N} \frac{m_j}{\rho_j} \mathbf{v}_{ji}^\beta \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\alpha} + \sum_{j=1}^{N} \frac{m_j}{\rho_j} \mathbf{v}_{ji}^\alpha \frac{\partial W_{ij}}{\partial \mathbf{x}_i^\beta} - \left(\frac{2}{3} \sum_{j=1}^{N} \frac{m_j}{\rho_j} \mathbf{v}_{ji} \cdot \nabla_i W_{ij}\right) \delta^{\alpha\beta}$$

2.4 Features and advantages

Features

- Particles are used to represent the state of a system
- Governing equations are discretized and approximated on particles
- Particles move with the object



Merits/demerits

- Mass rigorously conserved, no loss/gain
- Easy to treat large deformations
- Easy to obtain time history of movement and deformations
- Method under development
- Heavier computational cost

2.5 Constructing smoothing function

- **Original SPH empirically specifies that the weight function W satisfies some special requirements like (a) normalization $\int_{\Omega} W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'=1$, (b) Delta function property $\lim_{h\to 0} W(\mathbf{x}-\mathbf{x}',h)=\delta(\mathbf{x}-\mathbf{x}')$, and (c) symmetric (even) property.**
- **Weight function constructing conditions**

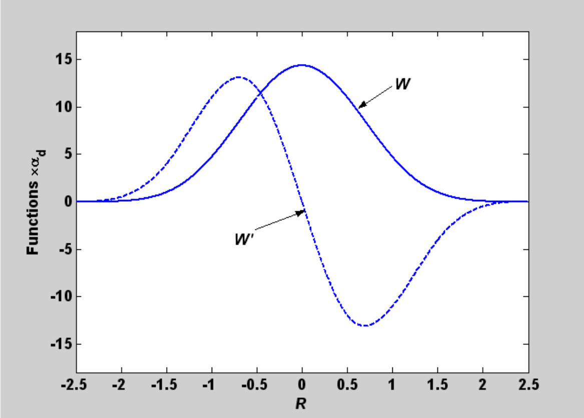
$$f(\mathbf{x})=\int_{\Omega} f(\mathbf{x}')W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'$$

Taylor series analysis

$$f(\mathbf{x}')=\sum_{j=0}^{n}\frac{(-1)^j f^{(j)}(\mathbf{x})}{j!}(\mathbf{x}-\mathbf{x}')^j+r_{n+1}(\mathbf{x}-\mathbf{x}')$$

$$f(\mathbf{x})=\sum_{j=0}^{n}\frac{f^{(j)}(\mathbf{x})}{j!}\int(\mathbf{x}-\mathbf{x}')^j W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'+r_{n+1}(\mathbf{x}-\mathbf{x}')$$

$$\left.\begin{aligned}
M_0&=\int W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'=1\\
M_1&=\int(\mathbf{x}-\mathbf{x}')W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'=0\\
M_2&=\int(\mathbf{x}-\mathbf{x}')^2W(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'=0\\
&\vdots\\
M_n&=\int(\mathbf{x}-\mathbf{x}')^nW(\mathbf{x}-\mathbf{x}',h)d\mathbf{x}'=0
\end{aligned}\right\}$$



Example: a quartic weight function

$$W(\mathbf{x}-\mathbf{x}',h)=a_0+a_1R+a_2R^2+\ldots+a_nR^n,\quad R=\frac{|\mathbf{x}-\mathbf{x}'|}{h}$$

Liu et al., *JCAM*, 2003

2.6 Improving accuracy - FPM

- **The original SPH method does not have C^0 consistency for particle approximation, so the numerical accuracy of the original SPH method is quite low especially for disordered particles or boundary particles.**

Original SPH particle approximation ⟹

$$f_i \cong \sum_{j=1}^{N} f_j W_{ij} \, m_j / \rho_j \qquad f_{i,\alpha} \cong \sum_{j=1}^{N} f_j W_{i,\alpha} \, m_j / \rho_j$$

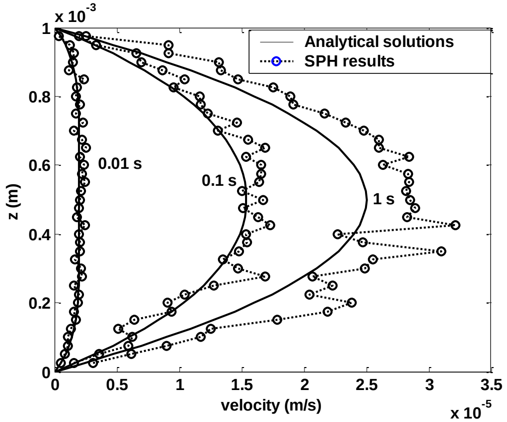
- ***Finite particle method (FPM)*, retaining the advantages of SPH with higher order accuracy .**

$$\begin{bmatrix} f_i \\ f_{i,\alpha} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{N} W_{ij} \, \Delta v_j & \sum_{j=1}^{N} (\boldsymbol{x}_j^{\alpha} - \boldsymbol{x}_i^{\alpha}) W_{ij} \, \Delta v_j \\ \sum_{j=1}^{N} W_{ij,\beta} \, \Delta v_j & \sum_{j=1}^{N} (\boldsymbol{x}_j^{\alpha} - \boldsymbol{x}_i^{\alpha}) W_{ij,\beta} \, \Delta v_j \end{bmatrix}^{-1} \begin{bmatrix} \sum_{j=1}^{N} f_j W_{ij} \, \Delta v_j \\ \sum_{j=1}^{N} f_j W_{ij,\beta} \, \Delta v_j \end{bmatrix}$$

Numerical scheme of FPM

- ✓**FPM has C^0 and C^1 consistency for particle approximation.**
- ✓**FPM is not influenced by disordered particle distribution and the selection of smoothing function.**
- ✓**FPM is more computational expensive than the original SPH.**

2.6 Improving accuracy - FPM

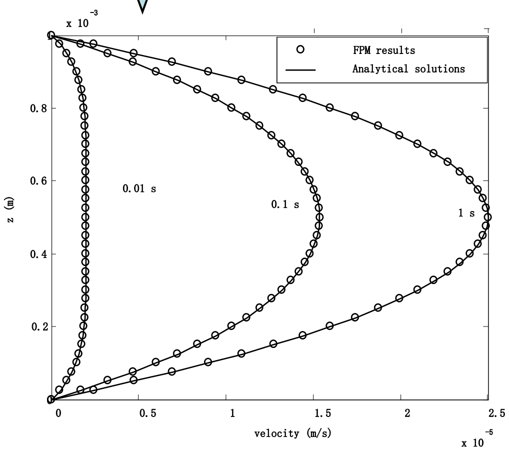


Conventional SPH

$$f_i \cong \sum_{j=1}^{N} f_j W_{ij} \, m_j / \rho_j$$

$$f_{i,\alpha} \cong \sum_{j=1}^{N} f_j W_{i,\alpha} \, m_j / \rho_j$$

numerical oscillation removed

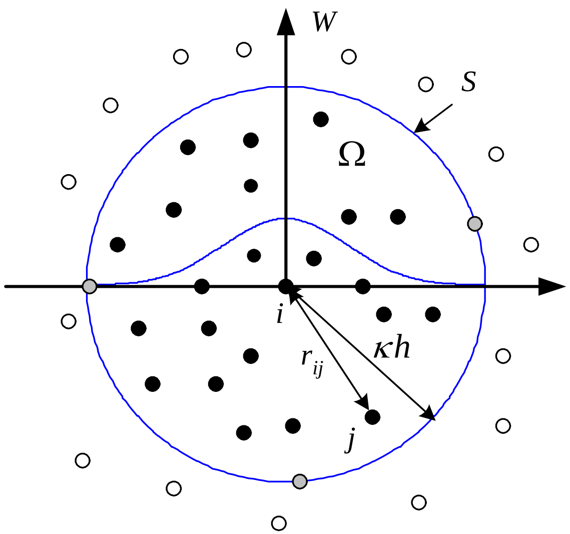


Improved scheme (FPM)

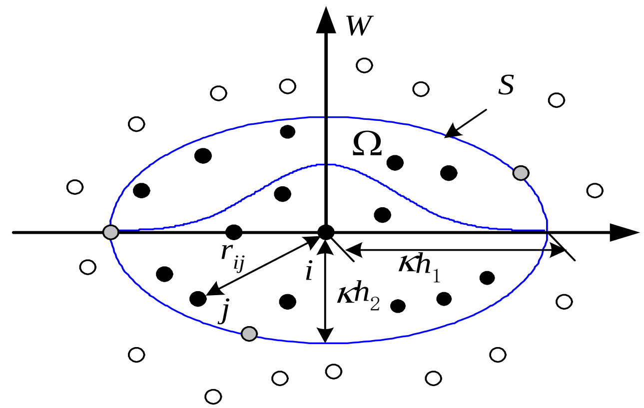
$$\begin{bmatrix} f_i \\ f_{i,\alpha} \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{N} W_{ij} \, \Delta v_j & \sum_{j=1}^{N} (\mathbf{x}_j^{\alpha} - \mathbf{x}_i^{\alpha}) W_{ij} \, \Delta v_j \\ \sum_{j=1}^{N} W_{ij,\beta} \, \Delta v_j & \sum_{j=1}^{N} (\mathbf{x}_j^{\alpha} - \mathbf{x}_i^{\alpha}) W_{ij,\beta} \, \Delta v_j \end{bmatrix}^{-1} \begin{bmatrix} \sum_{j=1}^{N} f_j W_{ij} \, \Delta v_j \\ \sum_{j=1}^{N} f_j W_{ij,\beta} \, \Delta v_j \end{bmatrix}$$

Accuracy and stability of SPH and FPM

2.7 Adapting SPH (ASPH)



SPH: isotropic weight function



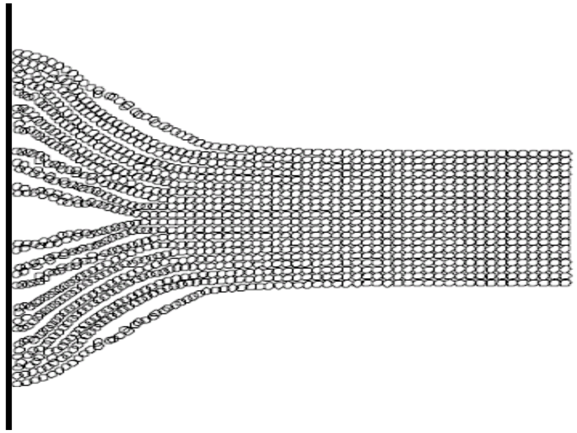
ASPH: anisotropic weight function

✓different axes to match the particle spacing as it varies in time, space and direction

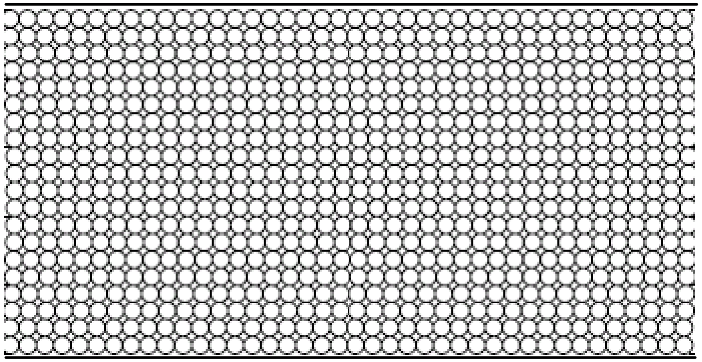
✓Capable of catching anisotropic deformation

✓suitable for problems with large dimension ratio

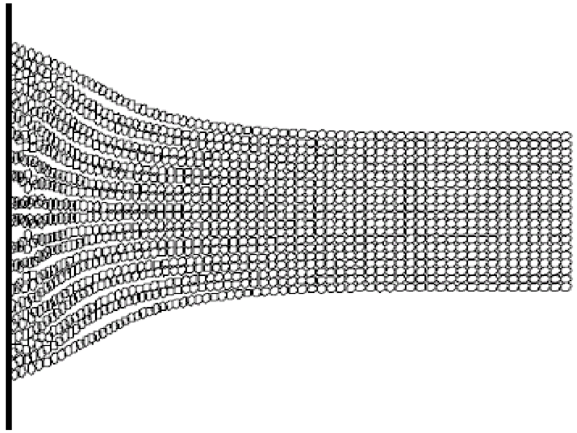
2.7 Adapting SPH (ASPH)



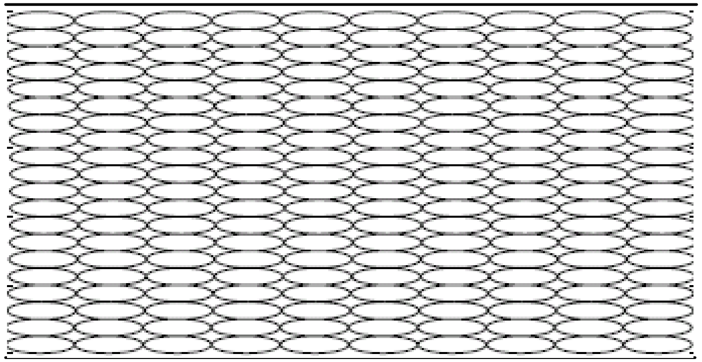
SPH: a metal bar impacting on a solid wall



SPH: flow in a micro channel with 800 particles



ASPH: a metal bar impacting on a solid wall



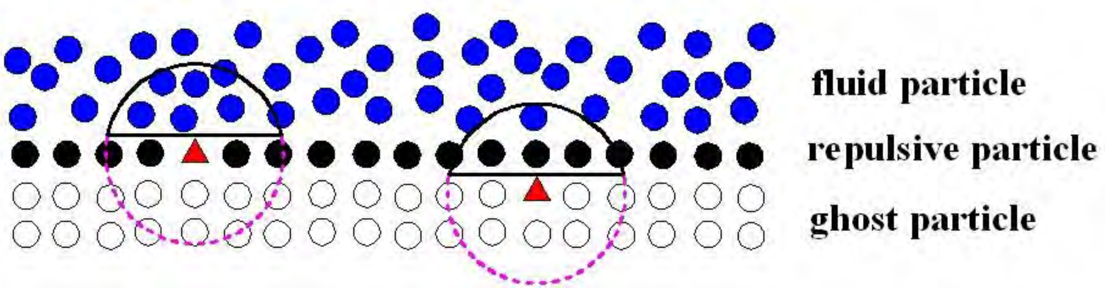
ASPH: flow in a micro channel with 200 particles

Liu et al., *JSW*, 2006

2.8 Solid boundary treatment (SBT)

- **As a meshfree, Lagrangian particle method, SPH is difficult in exactly implementing solid boundary conditions (SBC).**
- **Virtual particles are usually used to implicitly implement SBC, and the distribution of virtual particles and the calculation of their properties influence the accuracy of SPH simulation.**
- **A new SBT algorithm—coupled dynamic SBT：**

  1、Two types of virtual particles：Repulsive and ghost particles
- **2、New repulsive force and new approximation scheme**



$$F_{ij} = 0.01c^2 \bullet \chi \bullet f(\eta) \bullet \frac{\boldsymbol{x}_{ij}}{r_{ij}^{\ 2}}$$

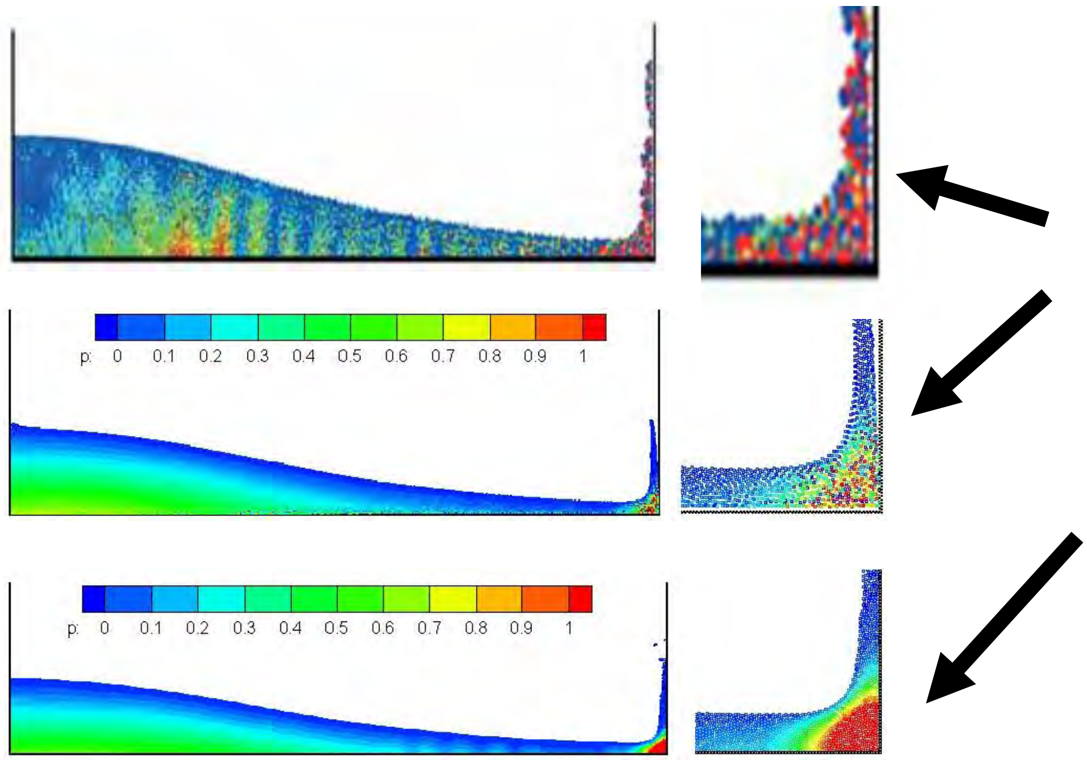
$$\chi = 1 - \frac{r_{ij}}{1.5\Delta d} \qquad 0 < r_{ij} < 1.5\Delta d$$

$$\eta = r_{ij} / (0.75 h_{ij})$$

$$f(\eta) = \begin{cases} 2/3 & 0 < \eta \le 2/3 \\ (2\eta - 1.5\eta^2) & 2/3 < \eta \le 1 \\ 0.5(2-\eta)^2 & 1 < \eta < 2 \\ 0 & otherwise \end{cases}$$

Liu et al., *JHD*, 2013

2.8 Solid boundary treatment (SBT)



Conventional SBT algorithms in SPH lead to pressure oscillation, and large errors in calculating pressure load on structures

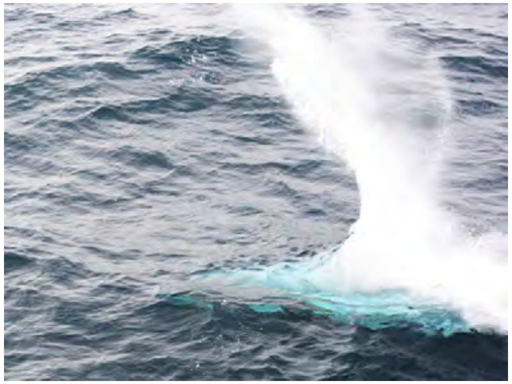
The new SBT algorithm produces smooth and accurate pressure field and is more attractive for FSI problems.

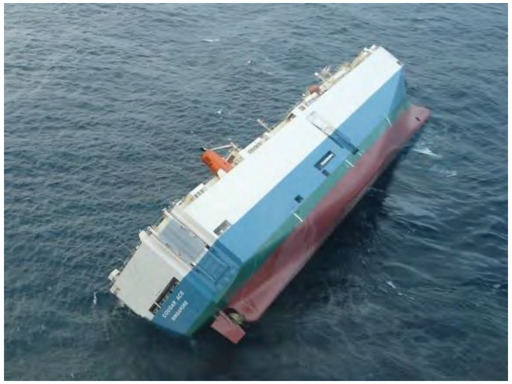
A typical example: dam collapse

3. SPH for hydrodynamics – Free surface flows

With fixed, moving or deformable boundaries

- **Dam collapse and water discharge**
- **Tsunami and flooding**
- **Wave dynamics**
- **Liquid drop dynamics**
- **…**

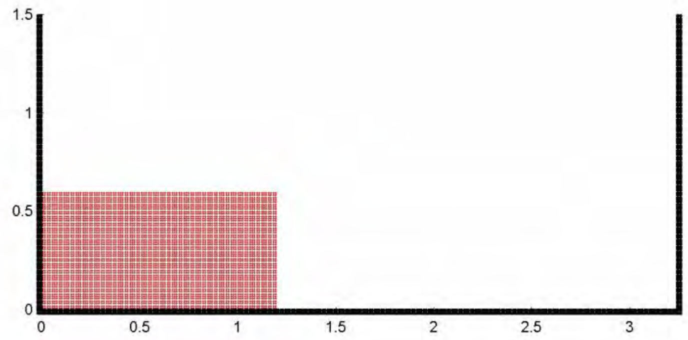




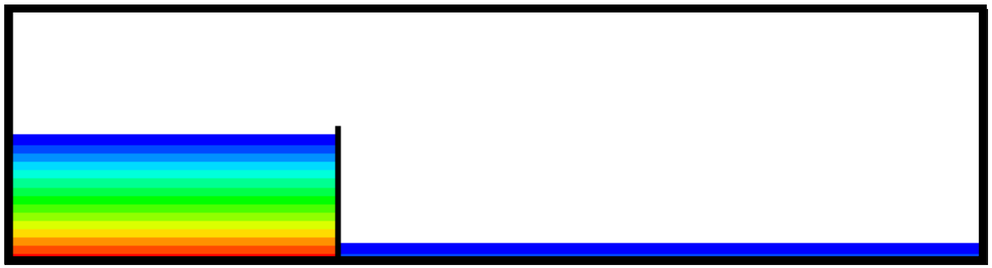
Liu M. B. et al., *ArCME*, 2010

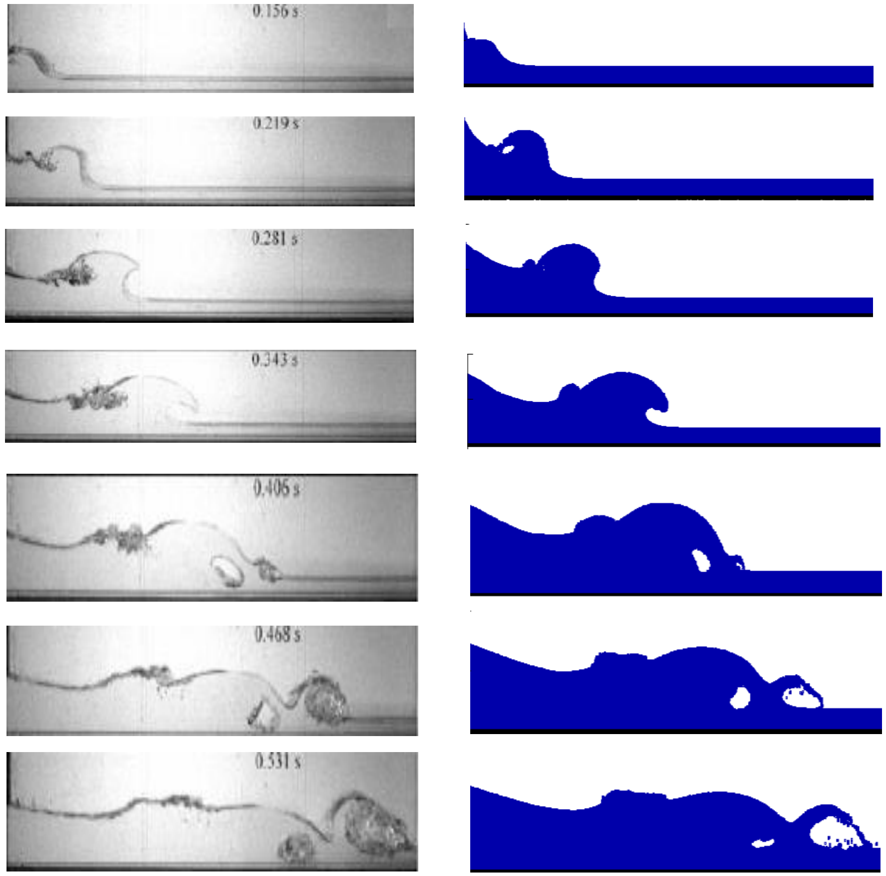
3. SPH for hydrodynamics – Free surface flows

3.1 Dam collapse and water discharge



Dam collapse

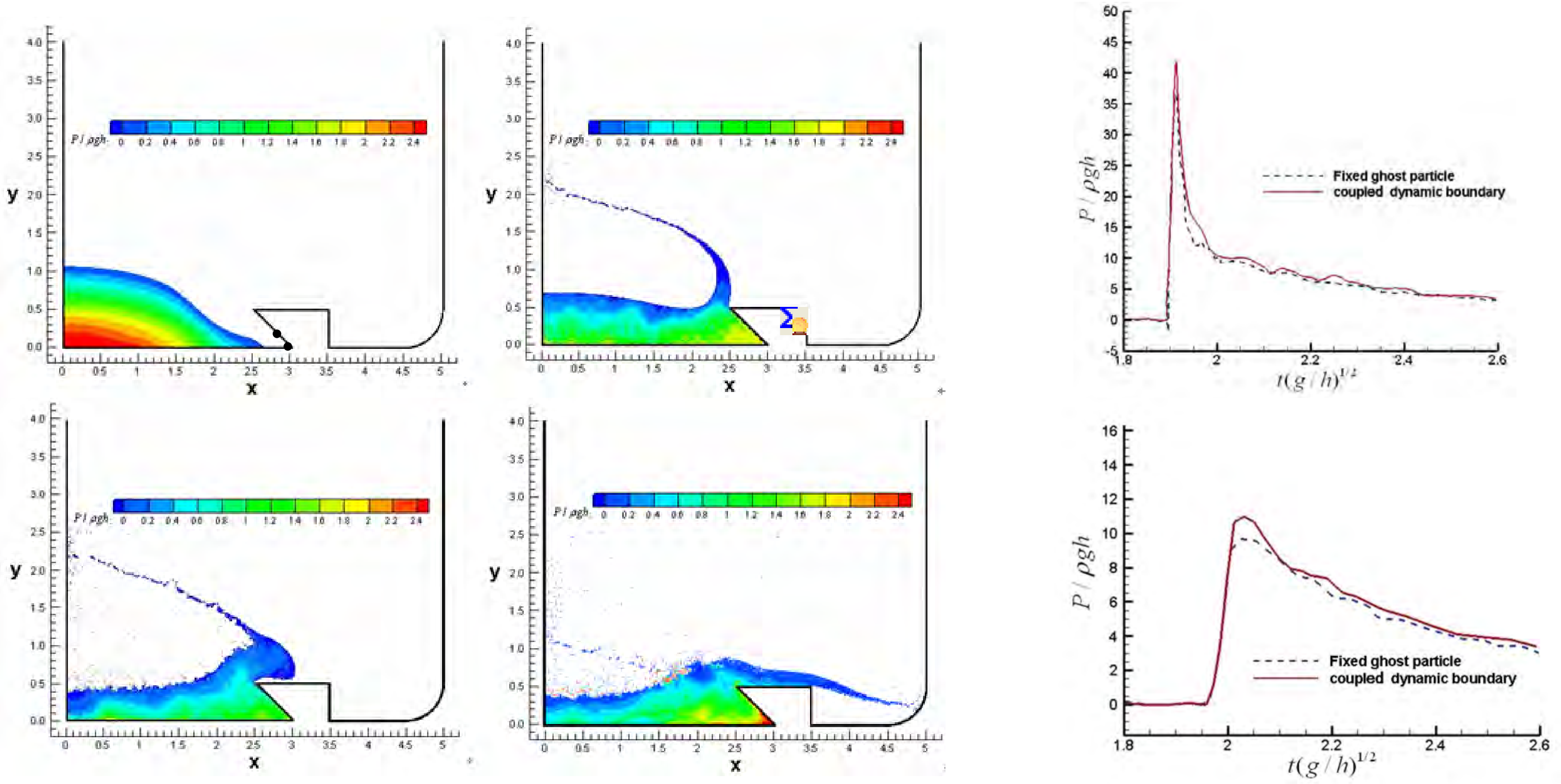




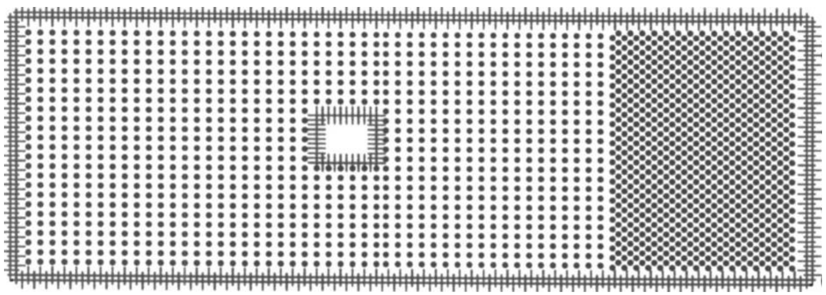
Water discharge

Shao, Liu et al., *IJCM*, 2010

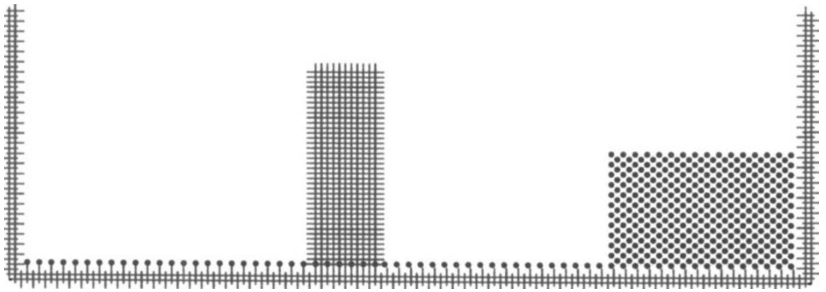
3.2 Water impact – dam break against an obstacle



3.2 Wave impact – water impact on building

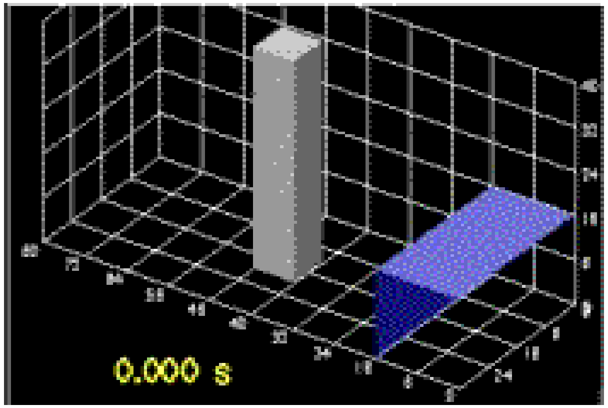


Top-bottom view

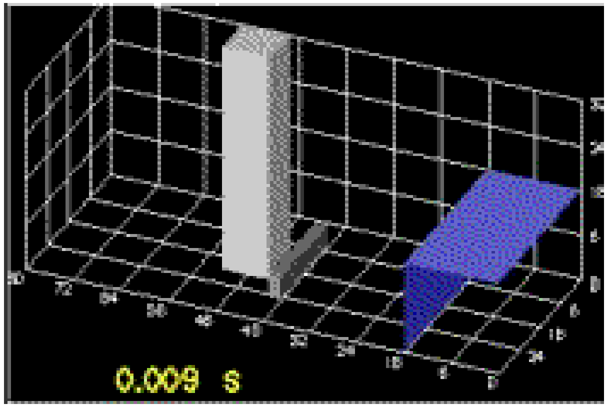


Front-back view

Initial particle distribution



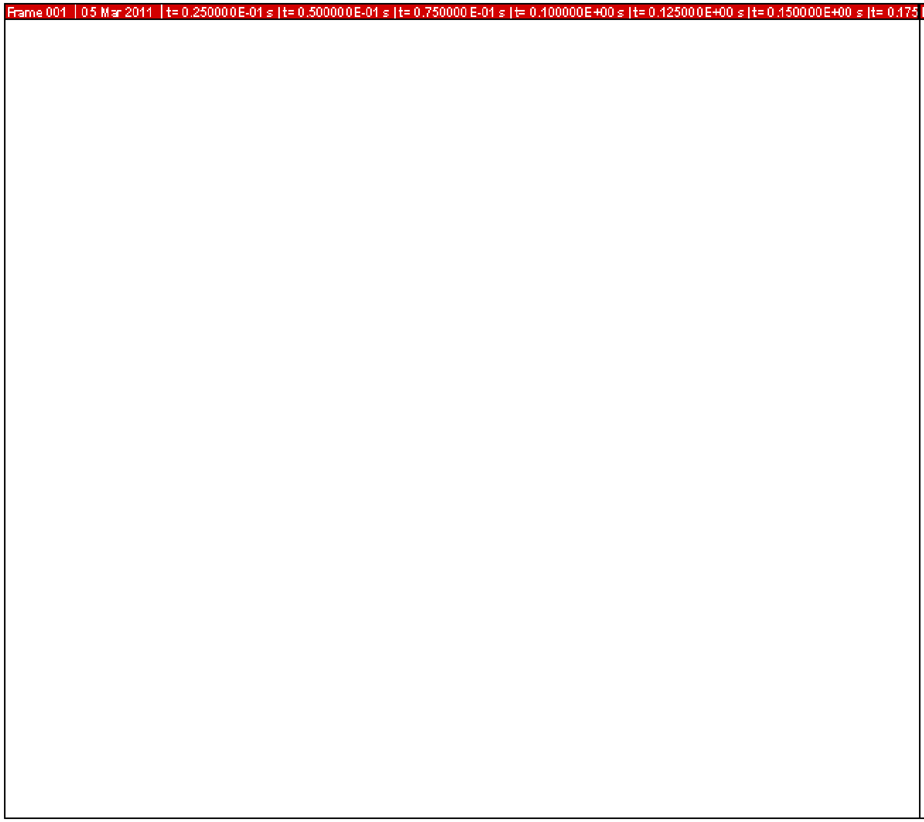
Without mitigation

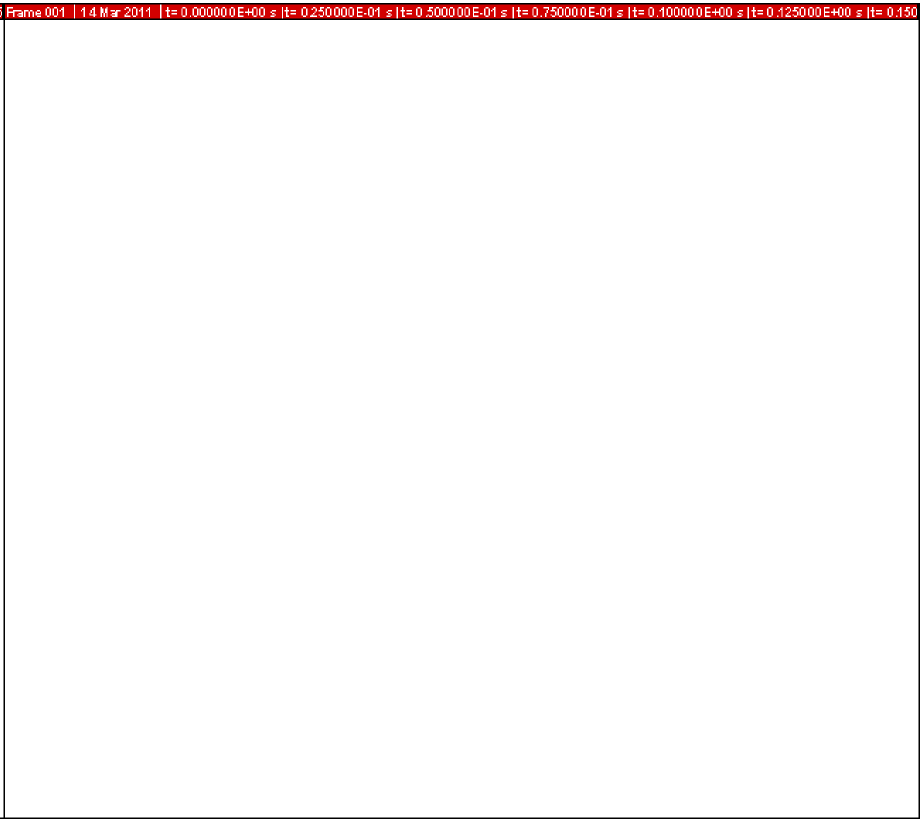


Mitigation with a dike

3. SPH for hydrodynamics – Free surface flows

3.3 Injection flow



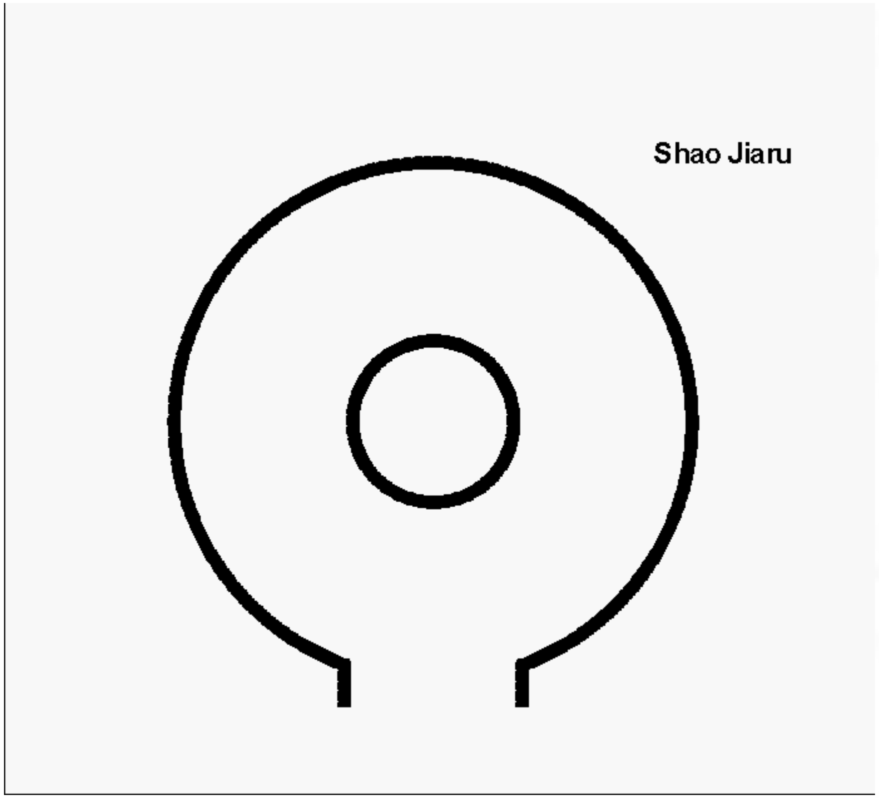


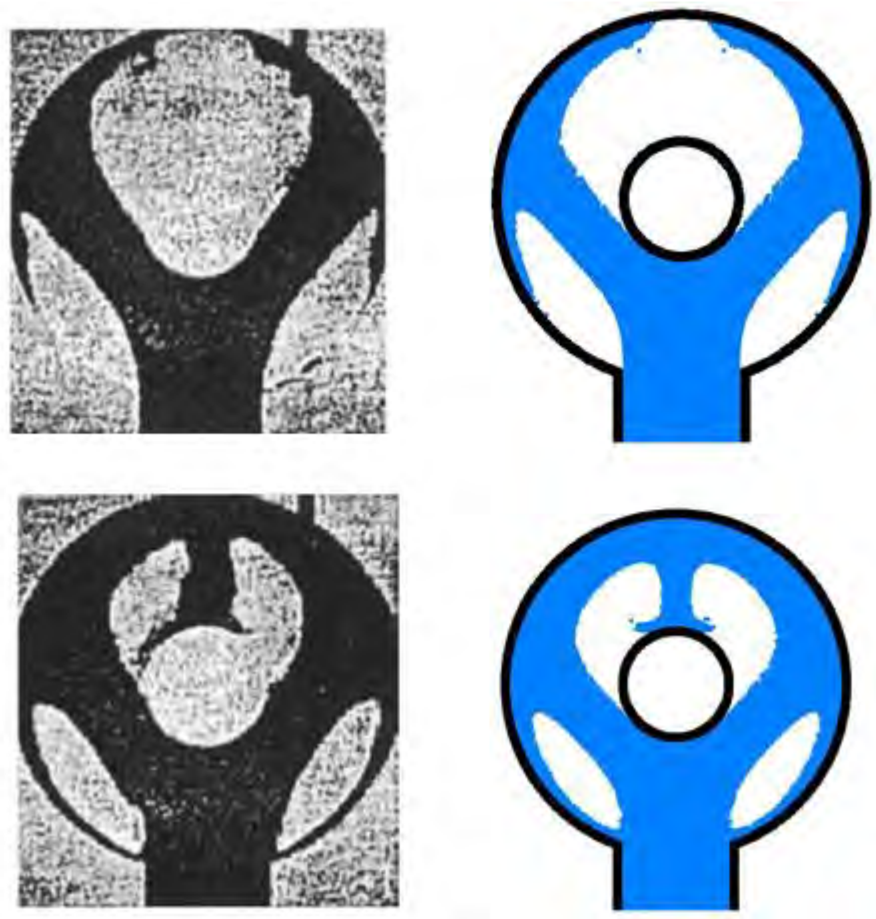
Water injection into an empty container

Water injection into a filled container

3. SPH for hydrodynamics – Free surface flows

3.3 Water injection



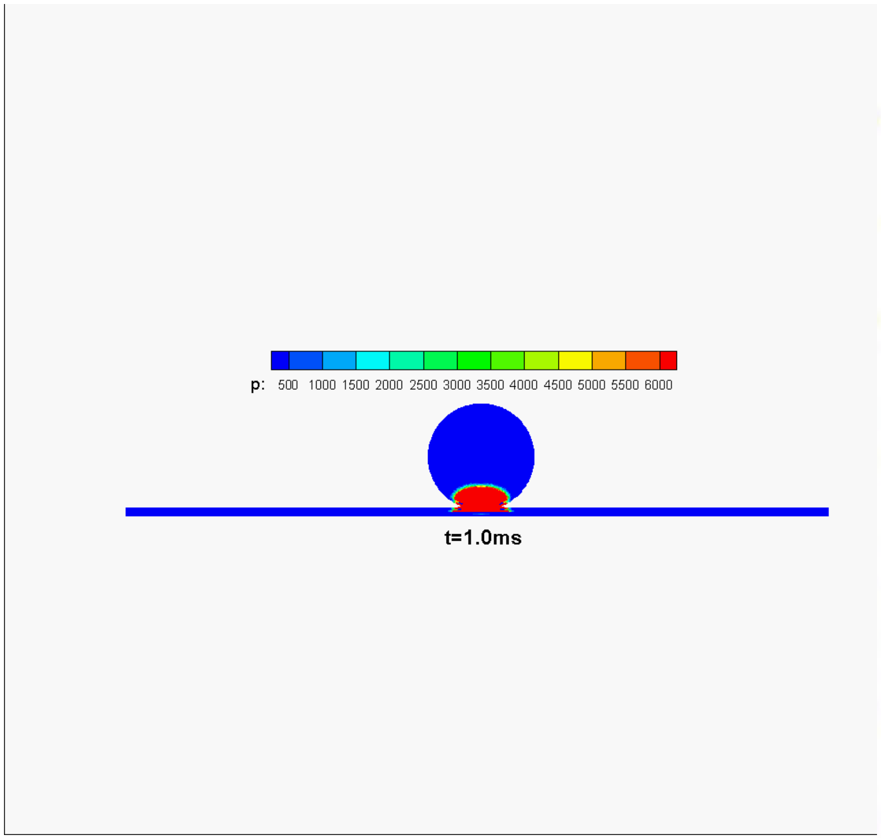


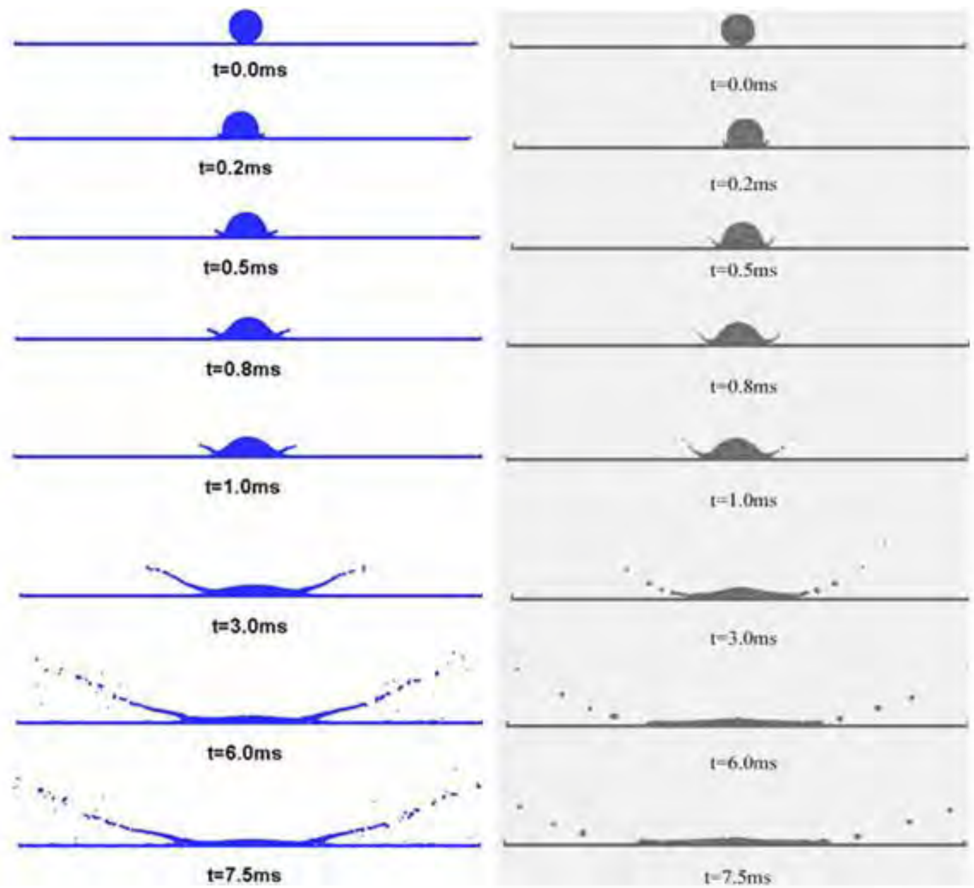
Experiment **SPH simulation**

Water injection

3. SPH for hydrodynamics – Free surface flows

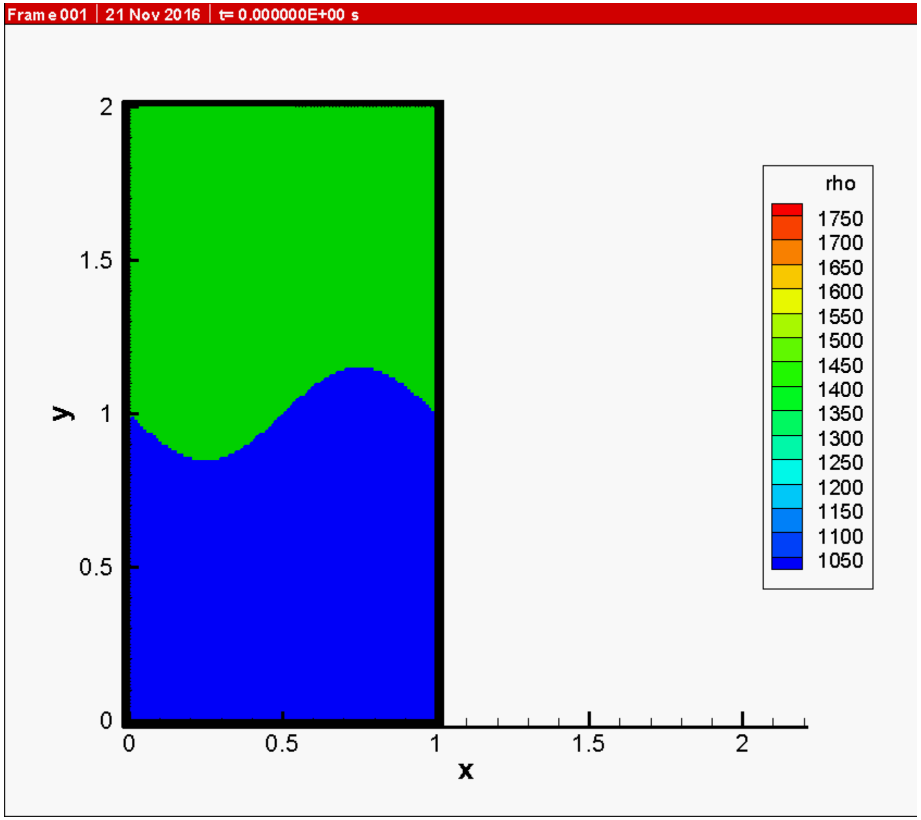
3.4 Multi-phase flows – liquid drop impact on thin liquid film

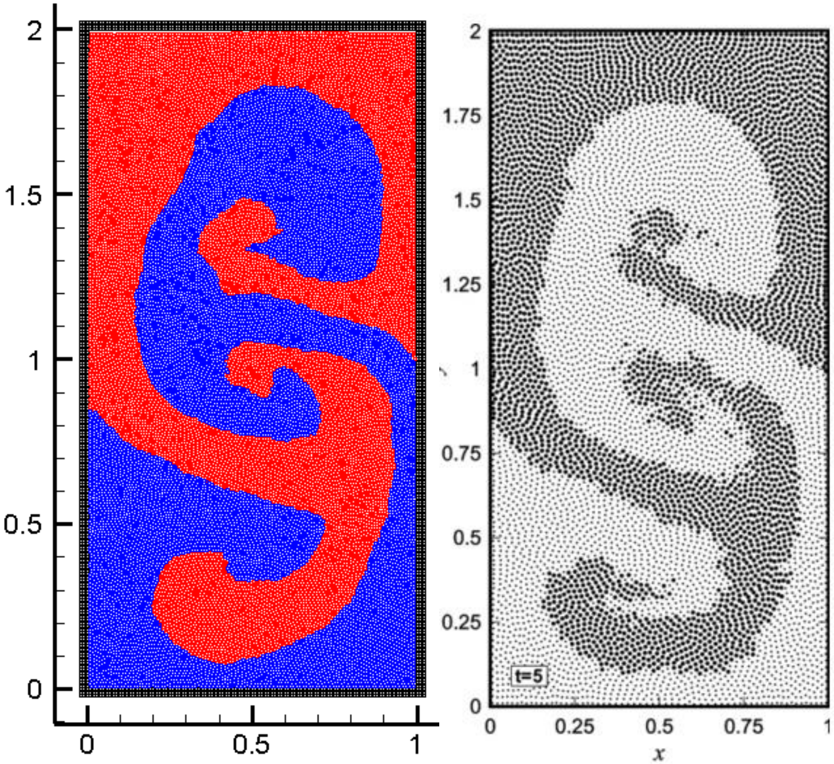




Ma, Liu et al., *APS*, 2012

3.4 Multi-phase flows – Rayleigh-Taylor instability





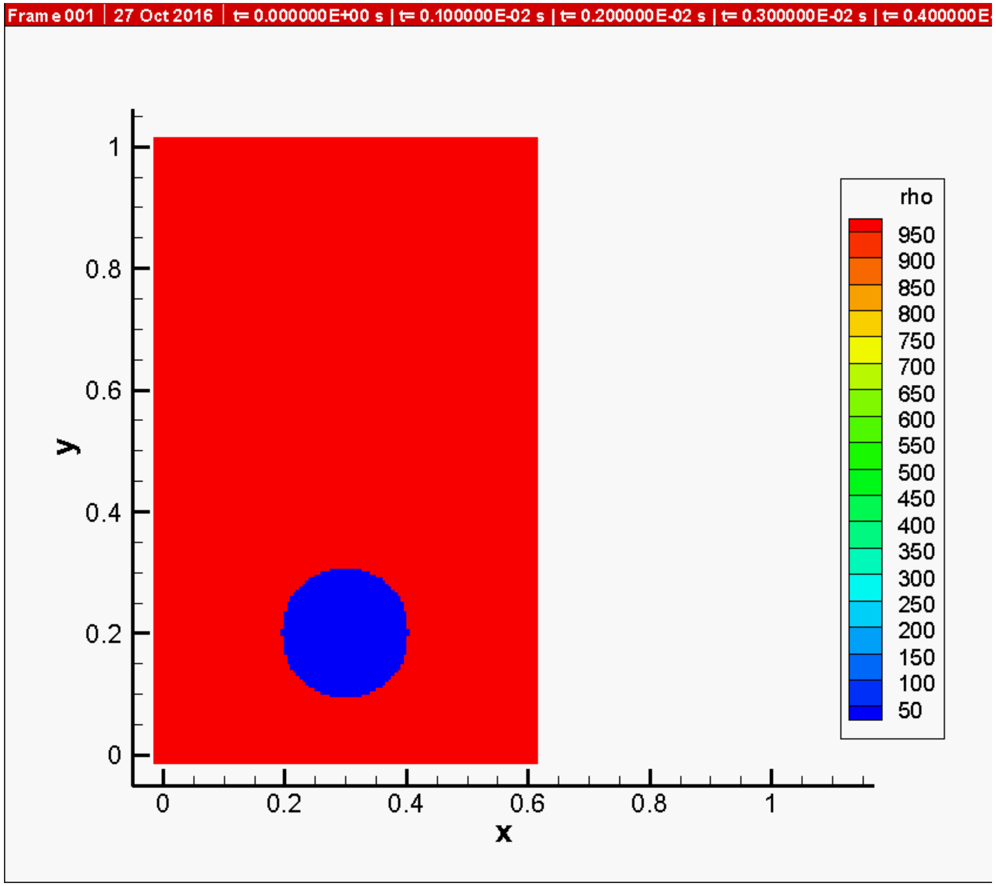
Present HU et al. 2007

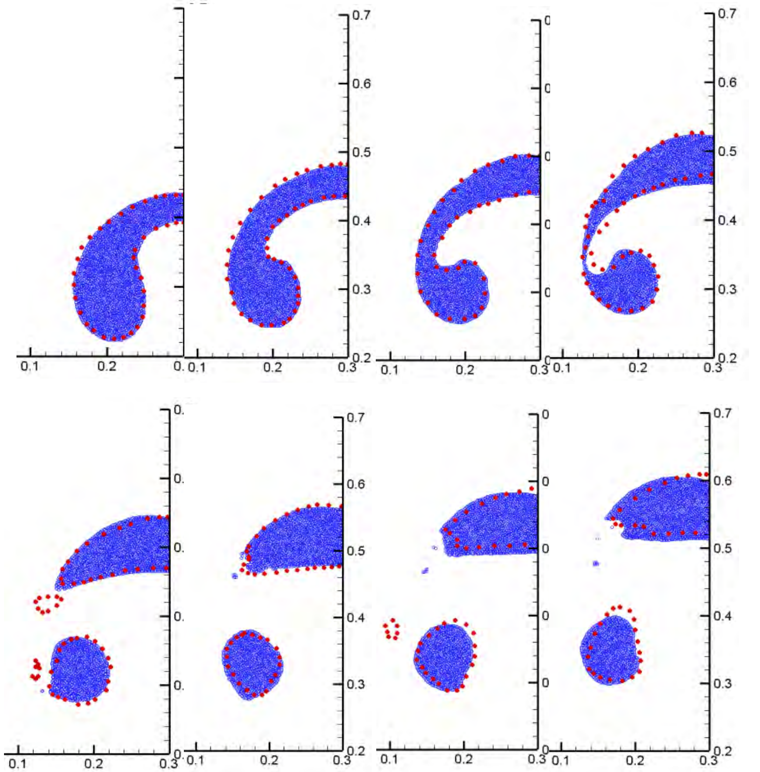
Heavier fluid: 1800 kg/m^3

Lighter fluid: 1000 kg/m^3

Chen, Liu* et al., *JCP*, 2013

3.4 Multi-phase flows – Air bubble rising





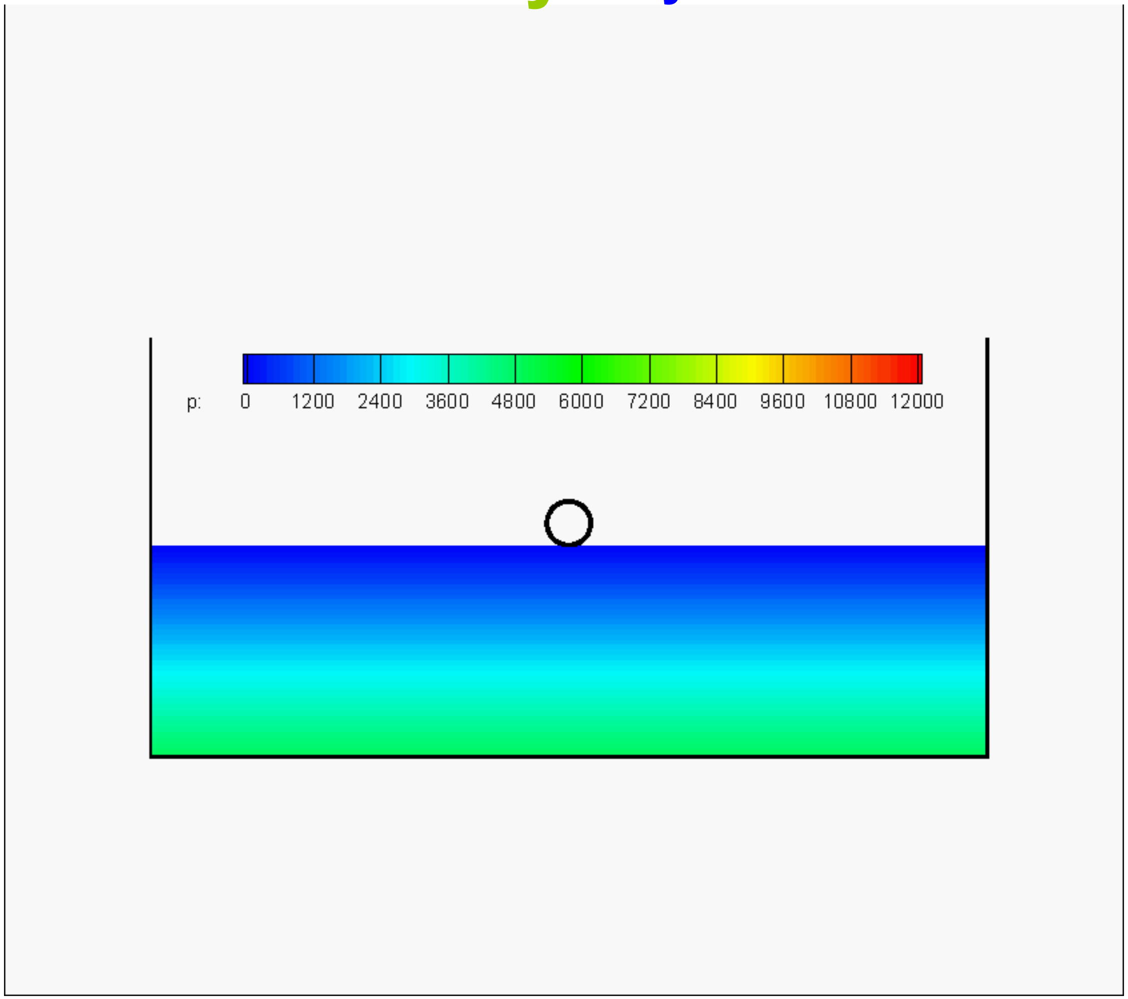
$t\sqrt{g/h}$=2.8, 3.6, 4.0, 4.4, 4.8, 5.2, 5.6, 6.0. The red dots are the Level-Set solution

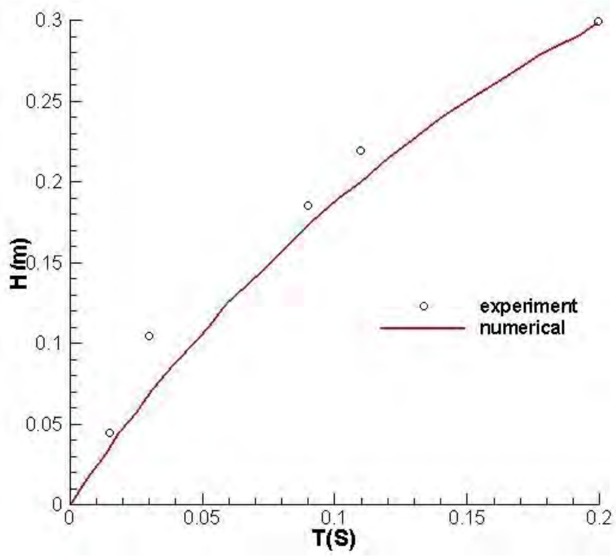
$$\rho_{air}/\rho_{water} = 0.001 \quad \mu_{air}/\mu_{water} = 0.05$$

Chen, Liu* et al., *JCP*, 2013

3. SPH for hydrodynamics – FSI problems

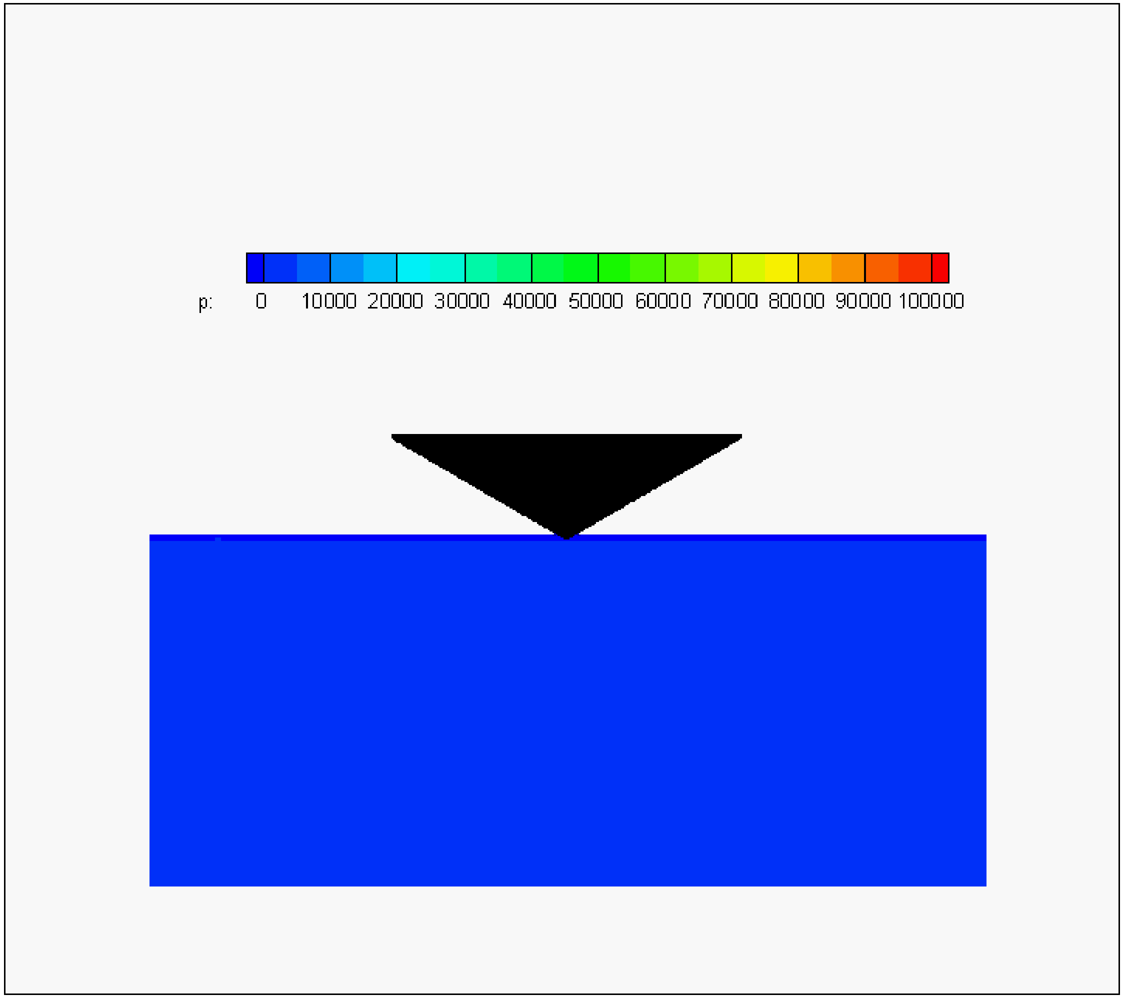
3.5 Water entry – cylinder

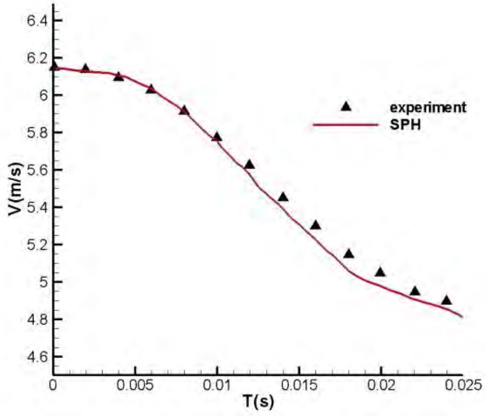




Penetration depth

3.5 Water entry – wedge



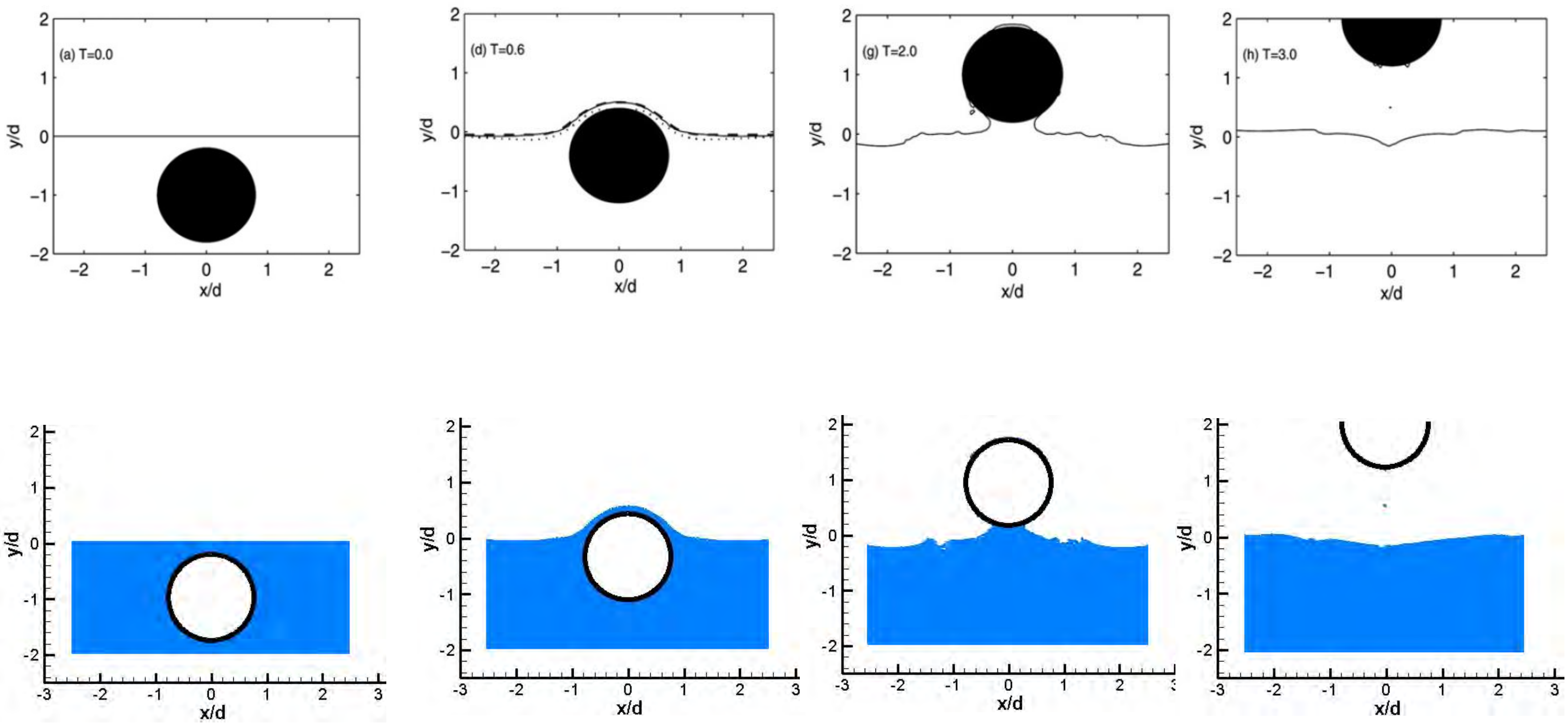


Falling velocity

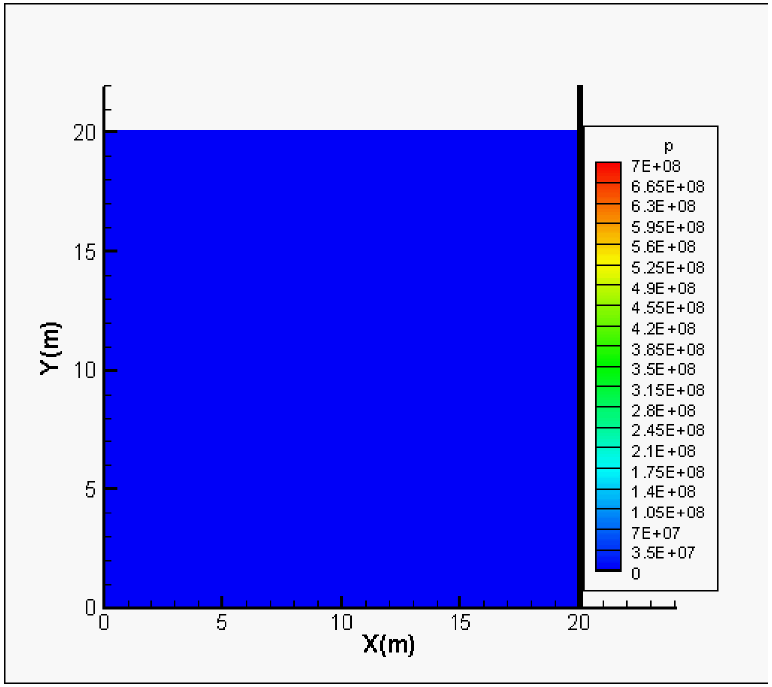
Liu et al., *IJNMF*, 2014

3. SPH for hydrodynamics – FSI problems

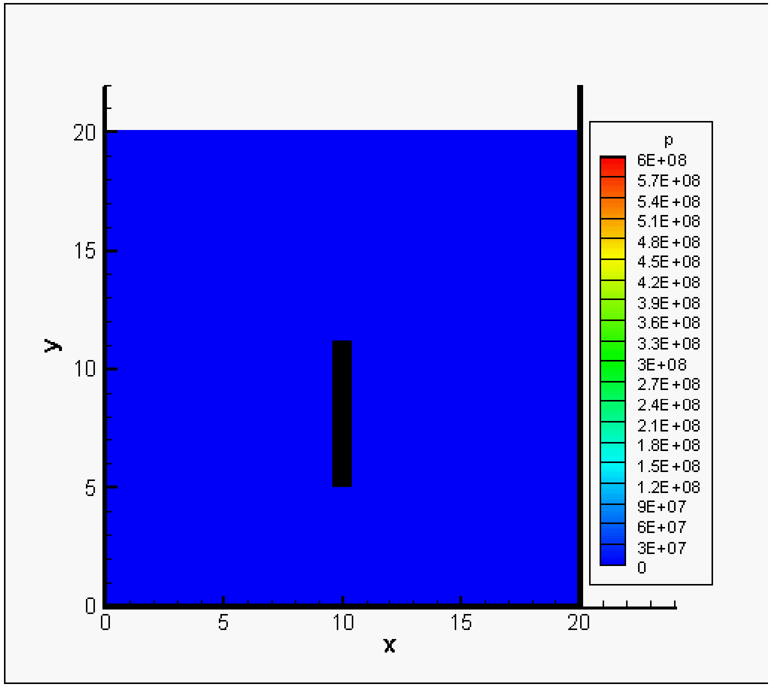
3.6 Water exit – cylinder



3.6 Water exit – Projectile launch

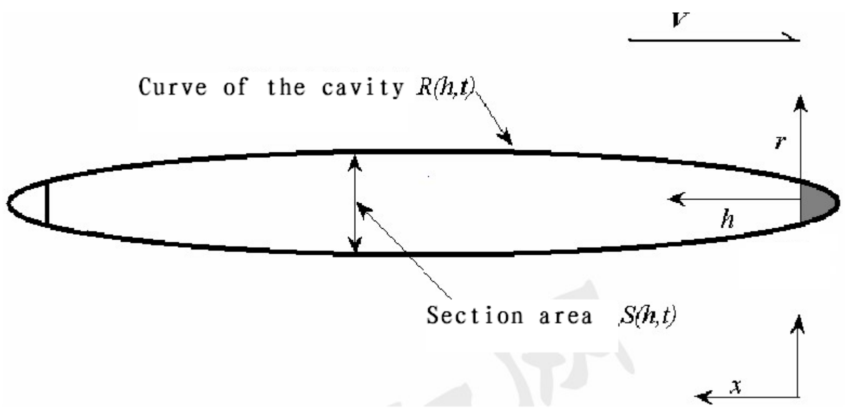


Projectile launch directly from water

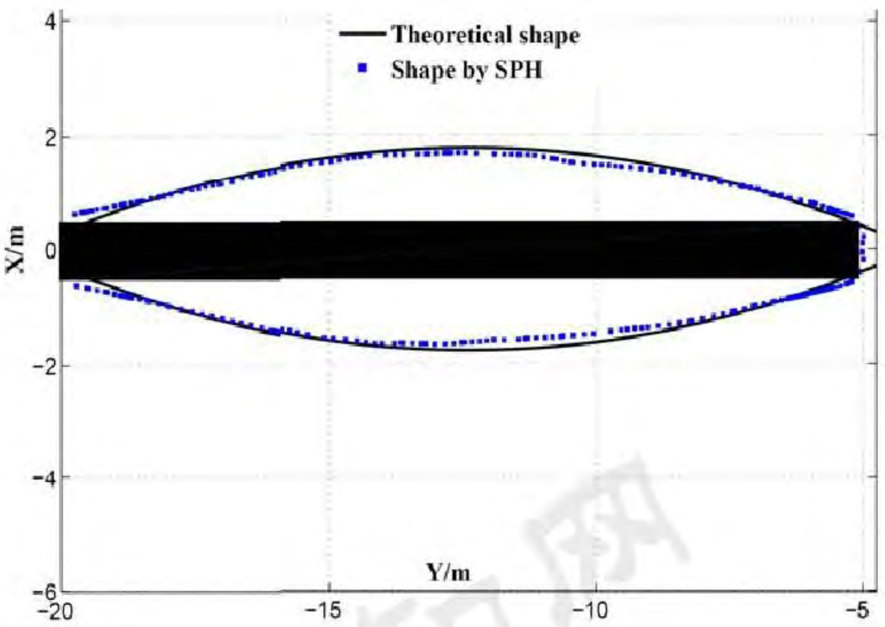


Projectile launch from a canister

3.6 Water exit – Projectile launch

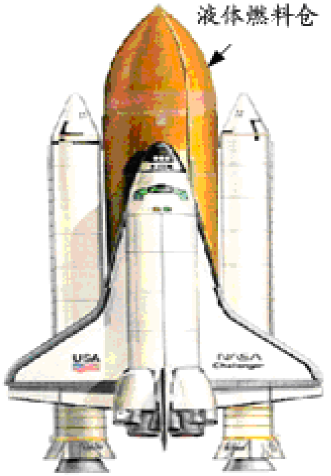


$$S_\tau^s = -4(S_\tau^c - S_0)\left(\frac{h^2}{L_0^2} - \frac{h}{L_0} - \frac{1}{4}\frac{S_0}{(S_\tau^c - S_0)}\right)$$



The Principle of Independence of the Cavity Sections Expansion

3.7 Liquid sloshing

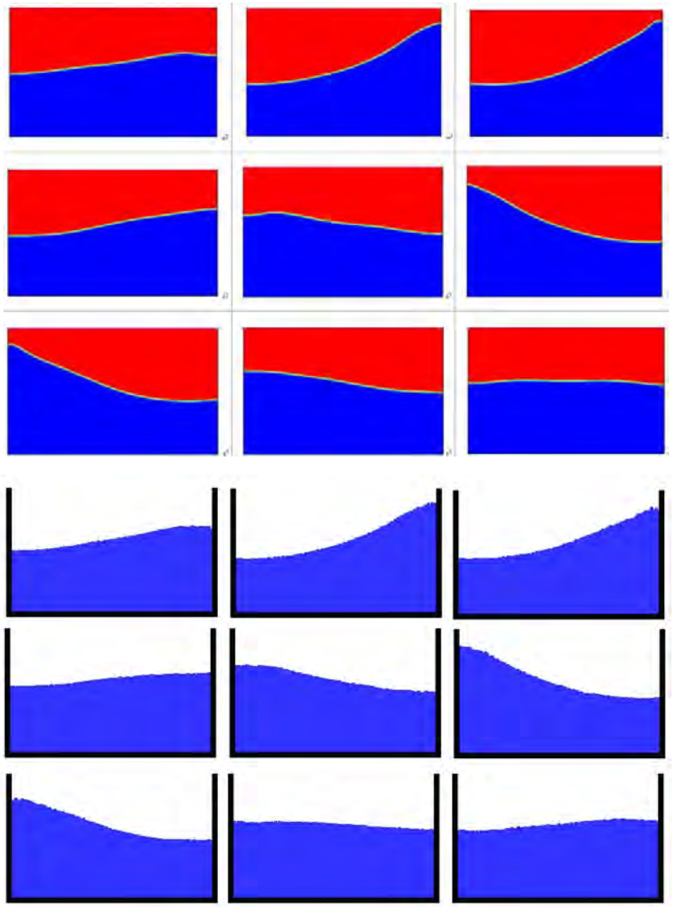


Liquid fuel sloshing in aerospace and aeronautical vehicles。

Water sloshing in a reservoir

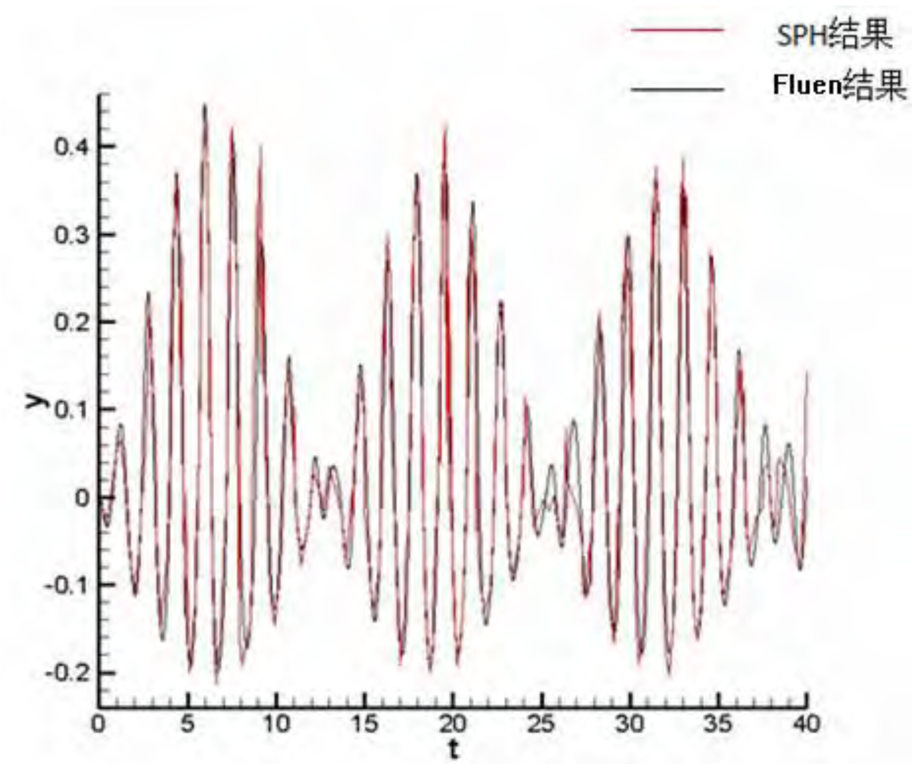
LNG sloshing in a LNG ship

3.7 Liquid sloshing – in a rectangular container



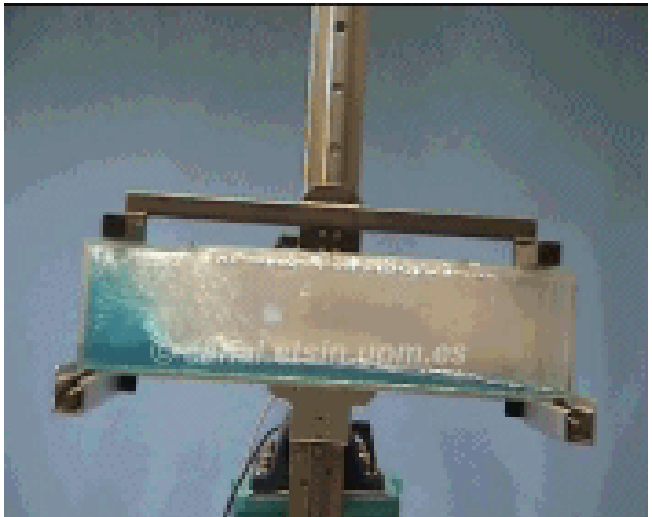
Fluent (up) vs SPH （bottom）

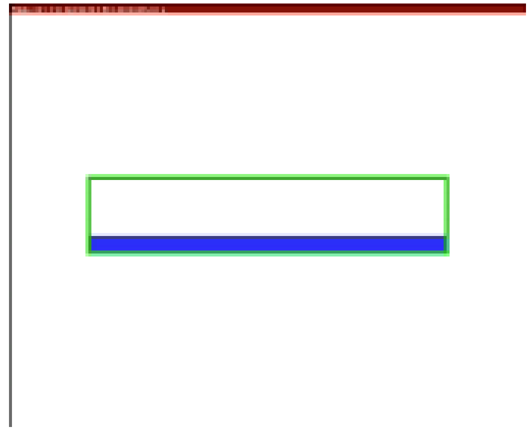
$$S = A\cos(2\pi t / T)$$



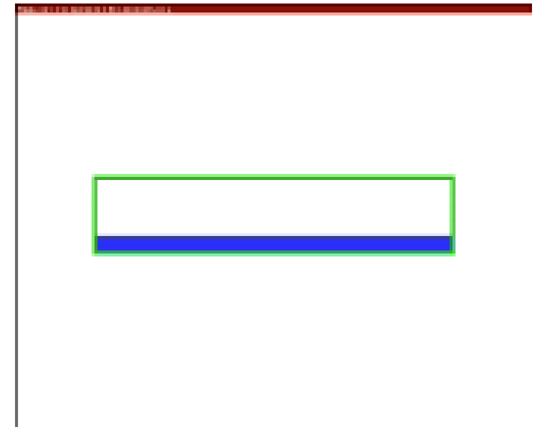
Water level at an observation point

3.7 Liquid sloshing – in a rotating rectangular container

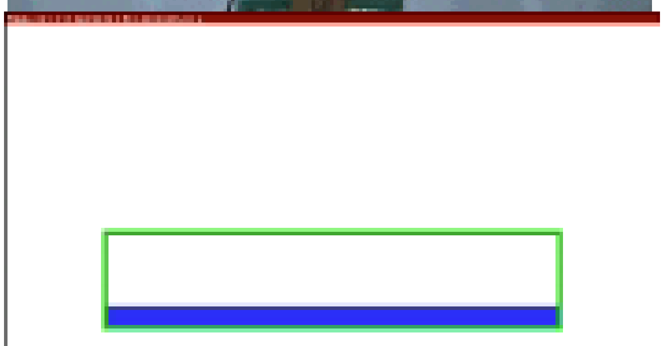




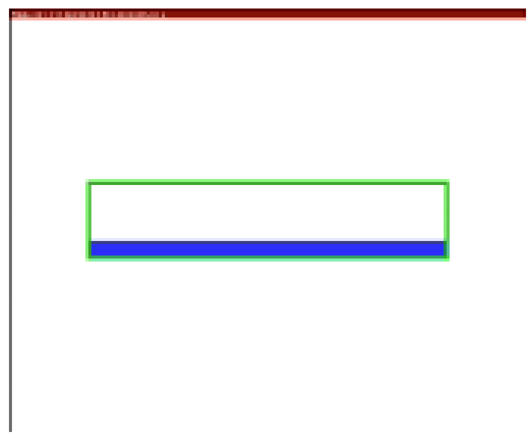
$\omega = 1.0\, rad/s$



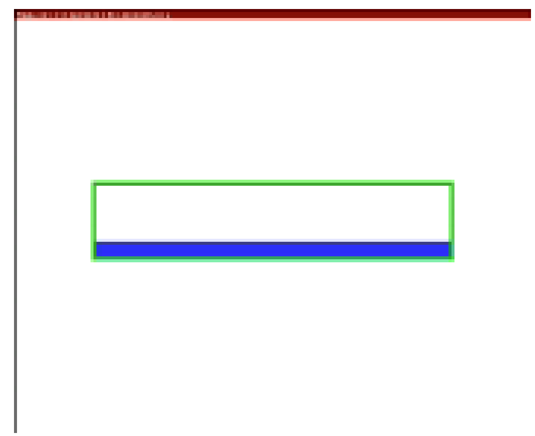
$\omega = 2.0\, rad/s$



$\omega = 4.1 rad/s$

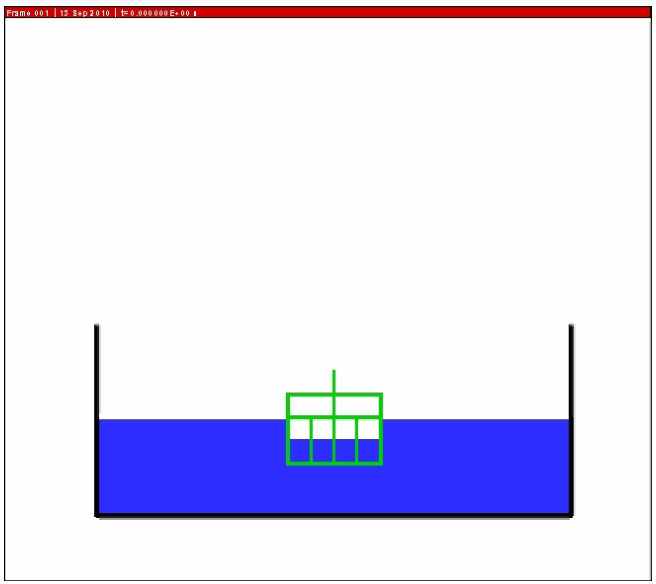


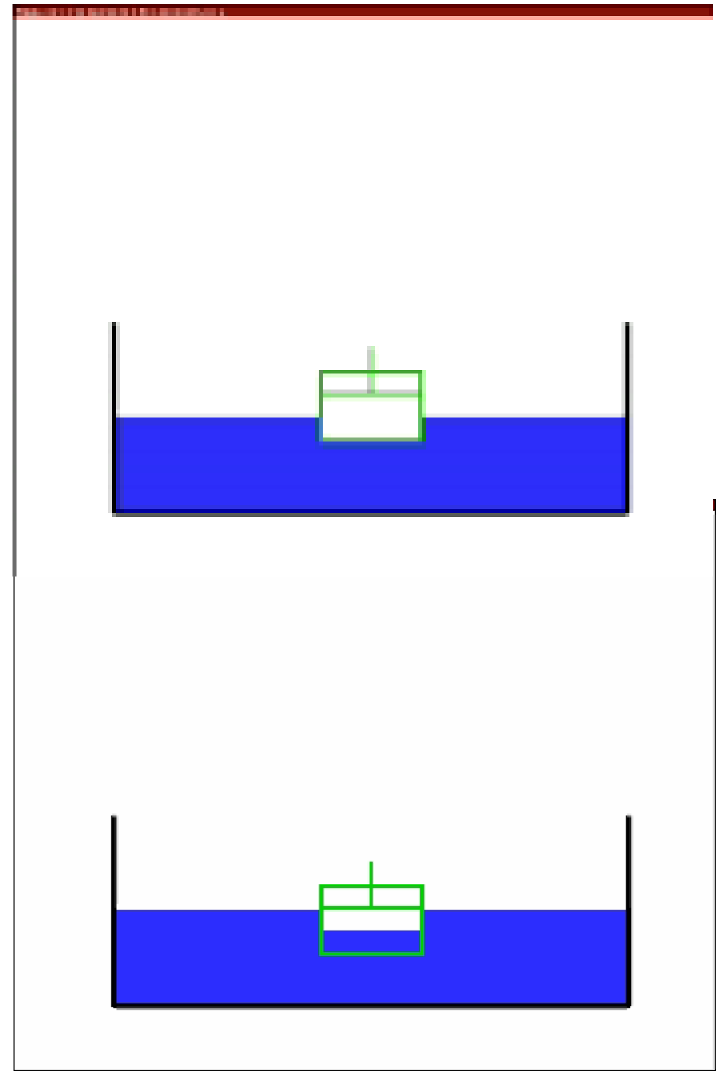
$\omega = 4.1 rad/s$



$\omega = 8.2\, rad/s$

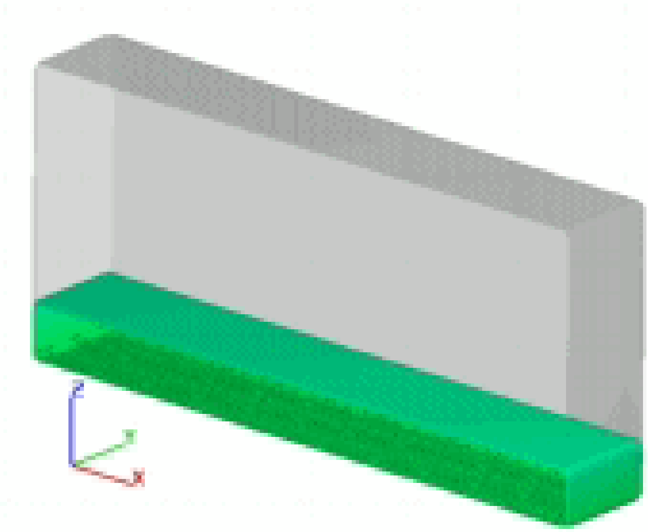
3.7 Liquid sloshing – Ballast water

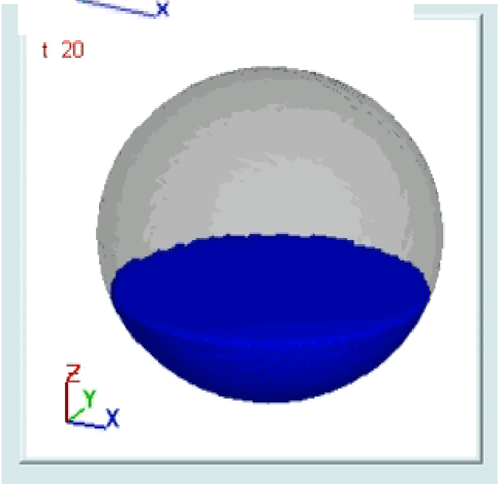


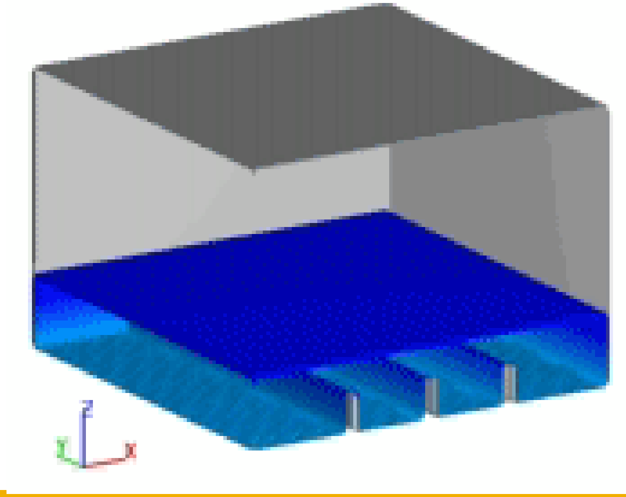


Yang, Peng and Liu, *IJCM 2011*

3.7 Liquid sloshing – in other shapes of containers

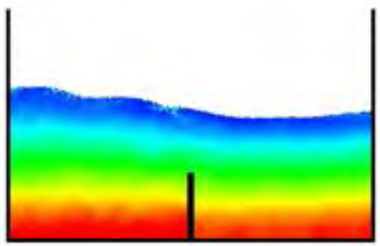


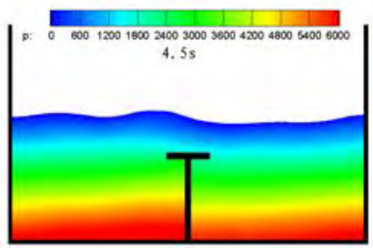




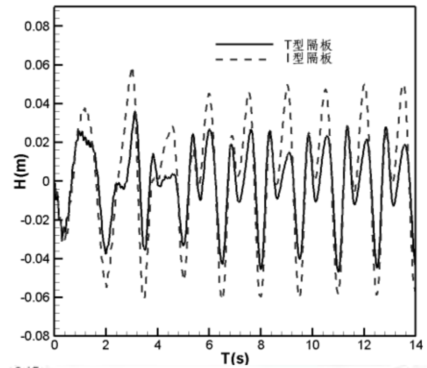
Yang, Peng and Liu, *IJCM 2011*

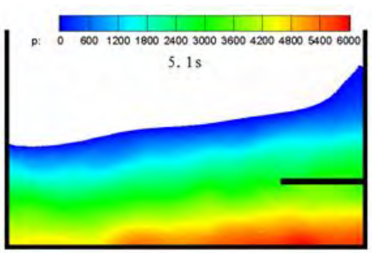
3.7 Liquid sloshing – sloshing mitigation



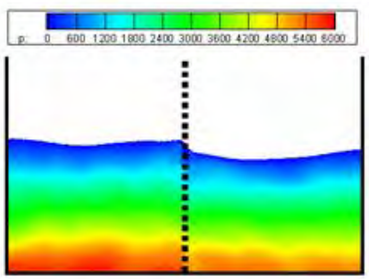


Vertical baffle

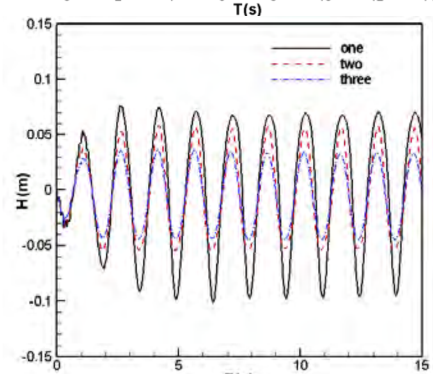


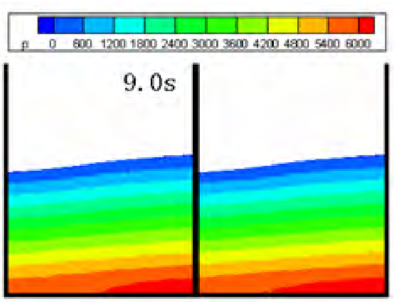


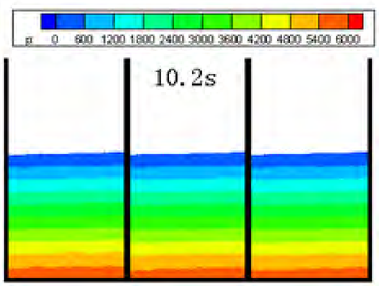
Horizontal …



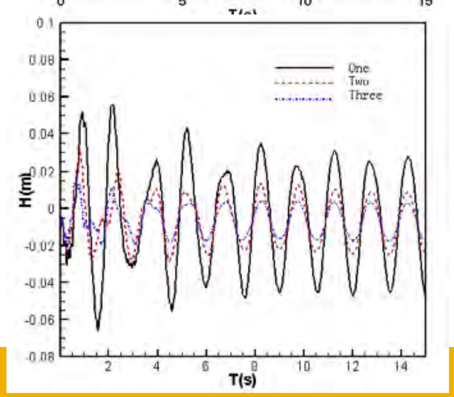
Porous …







Multiple compartments

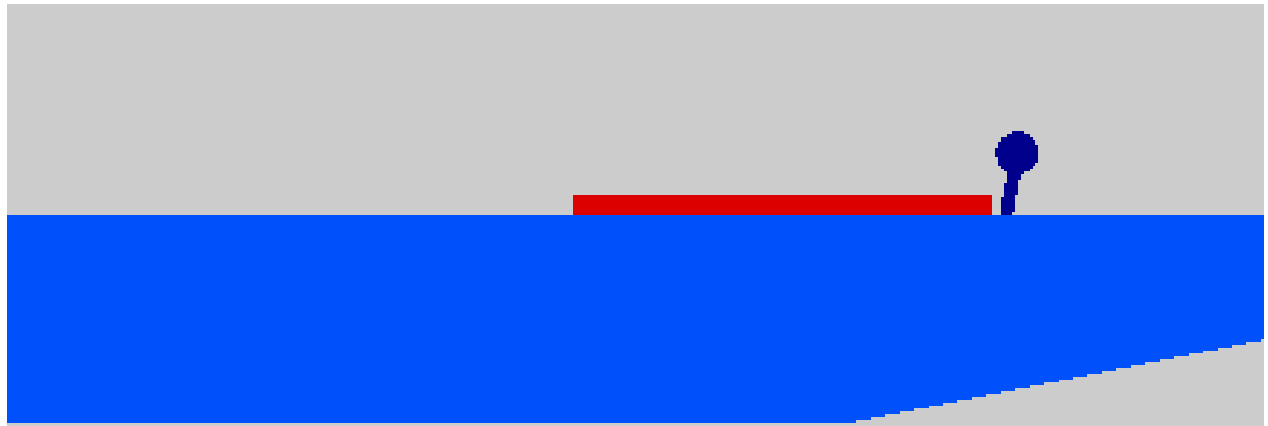


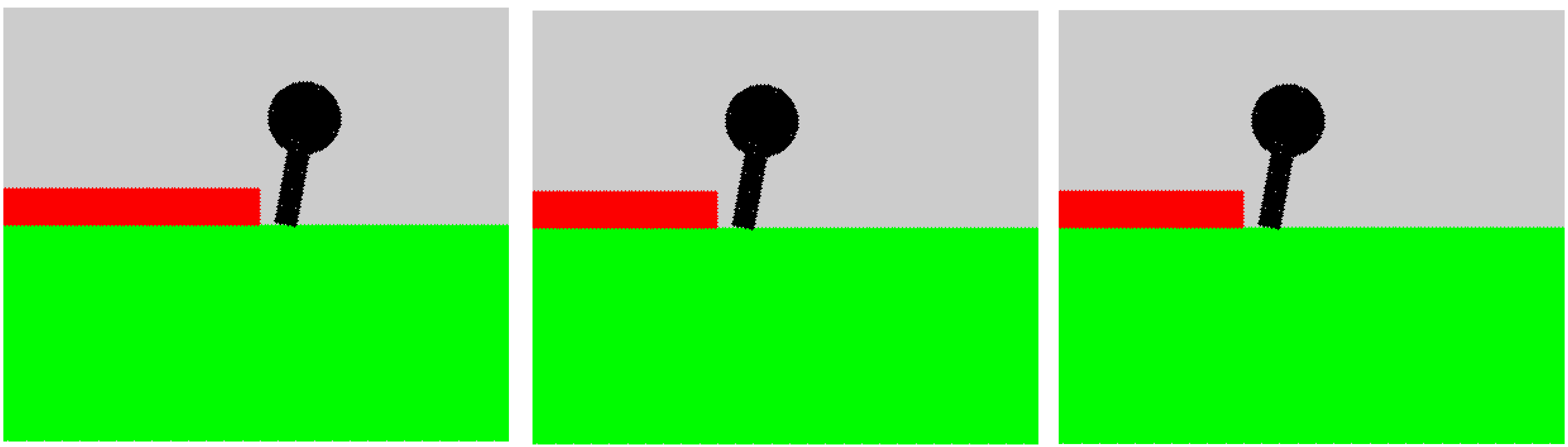
- M>T>I>-

Shao, Liu et al., *EC*, 2015.

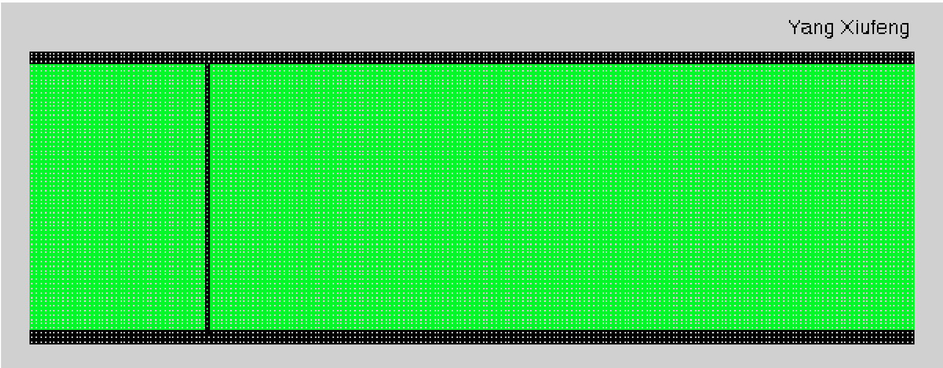
3.8 Boom and oil spill — Rigid boom

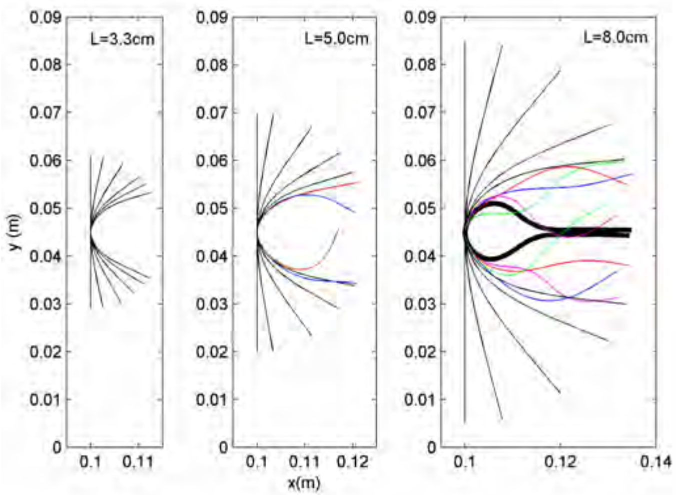
- Free surfaces
- Multiphase
- Fluid-solid interaction
- Wave-current





3.8 Boom and oil spill — Flexible boom (SPH+EBG)





Evolution of flow pattern

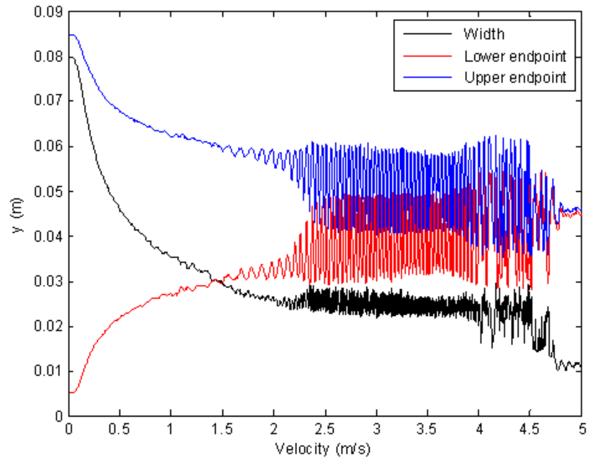
- Drag force
- Flow pattern
- Criterion for stability

$$D/U^2 \propto U^V$$

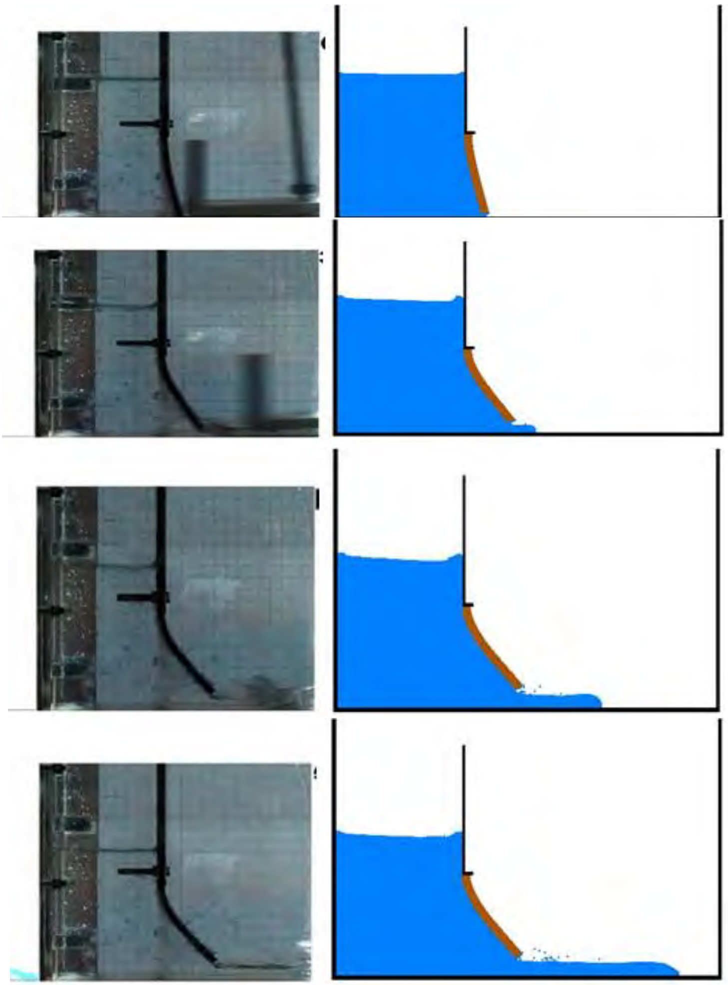
rigid：$V = 0$

flexible：$V = -2/3$

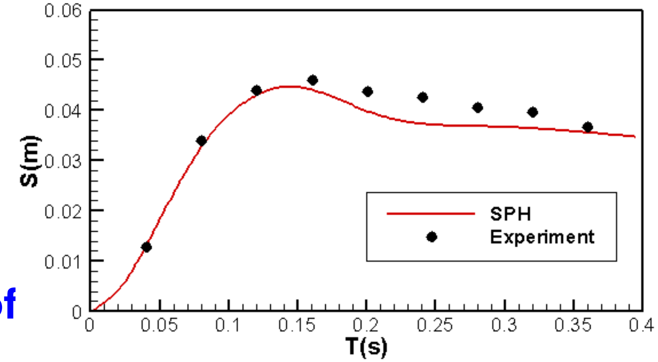
$$\begin{cases} \dfrac{L_x}{L} \approx 0.41 \\ \dfrac{L_x}{L}(u) = C\arctan(\alpha u^{\beta}) \end{cases}$$

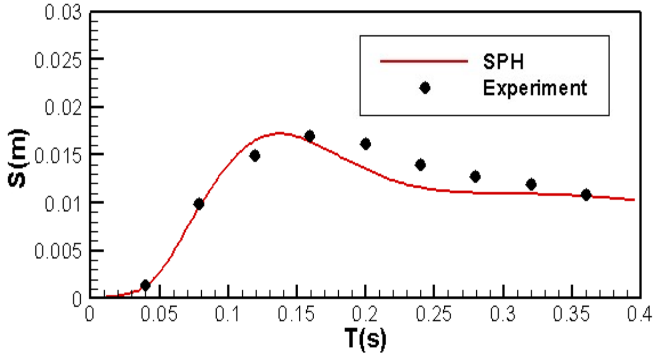


3.9 Hydro-elasticity – dam collapse with elastic plate

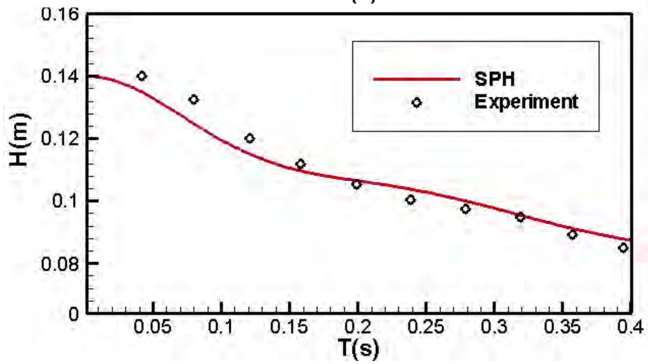


Displacement of plate free end





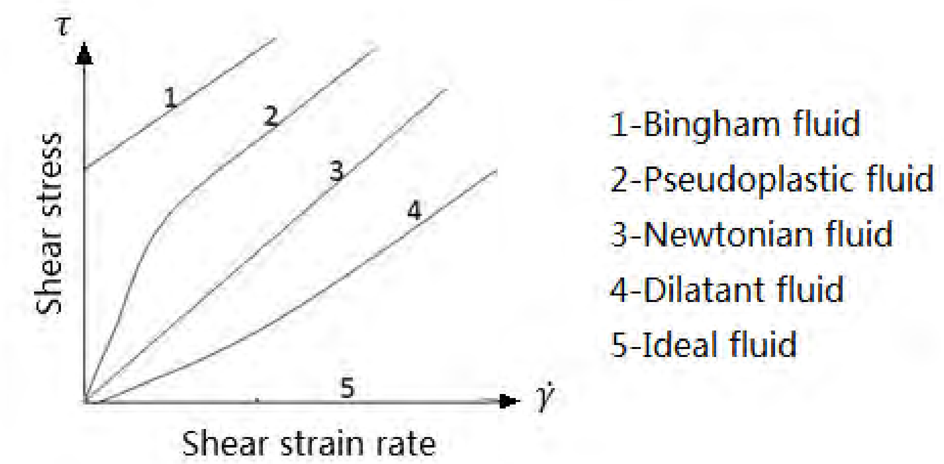
Water level

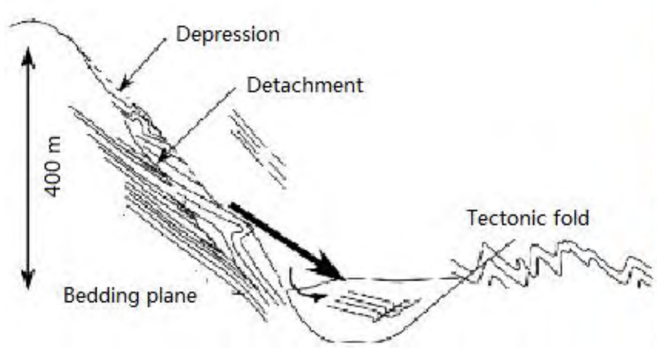


4. SPH for environmental flows

4.2 Landslide

- **Fast landslide – flow like**
- **Fluid model – non-Newtonian**
- **Surface topography – GIS data**



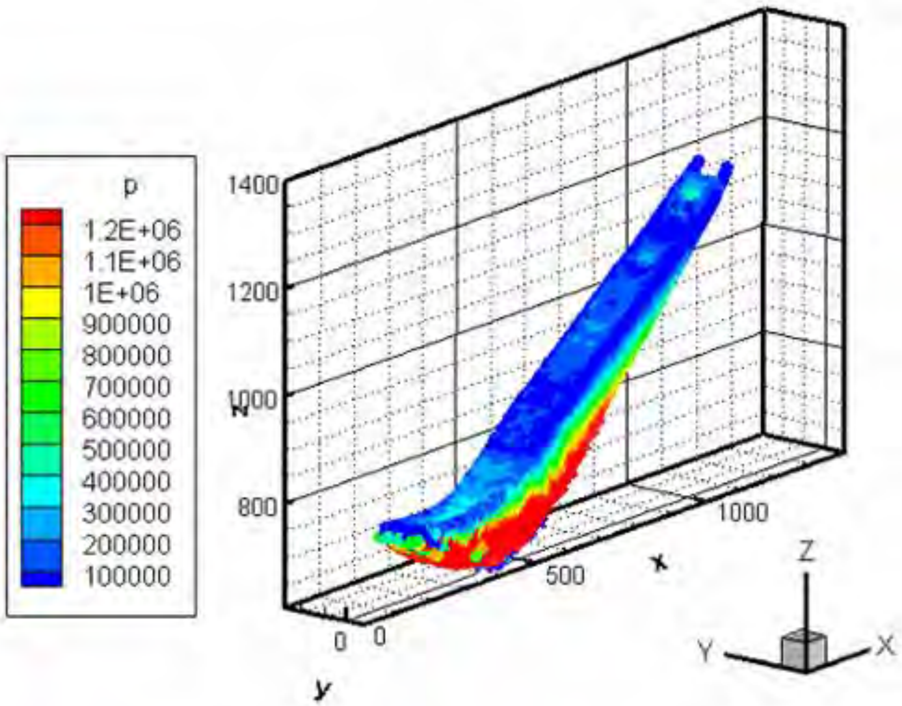


Tangjiashan Landslide: Pre- and post-earthquake topographies.

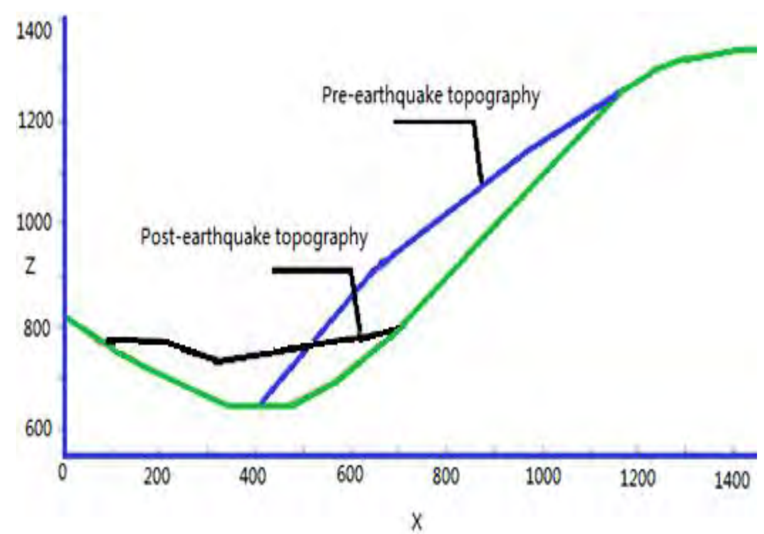
Hu, Liu et al., *Environmental Earth Sciences*, 2015.

4. SPH for environmental flows

4.2 Landslide



3D profile SPH model of Tangjiashan landslide

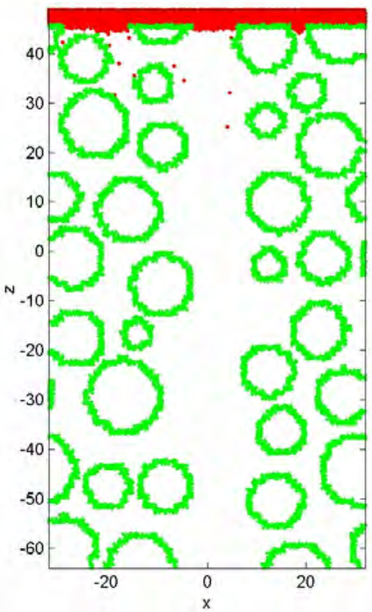


Pre- and post-earthquake topographies

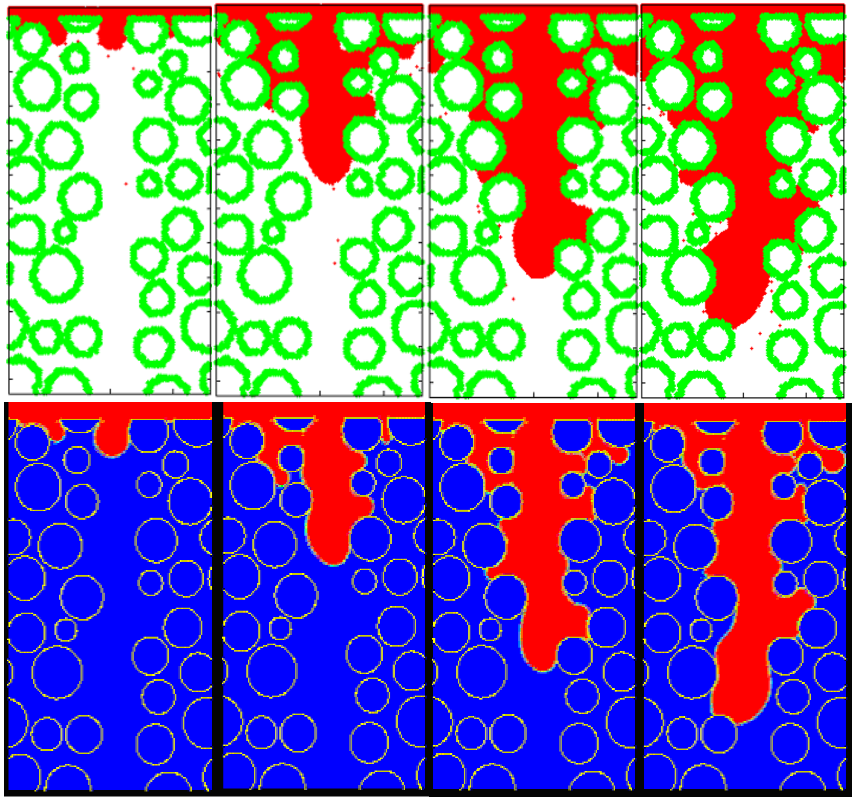
Hu, Liu et al., *Environmental Earth Sciences*, 2015.

4. SPH for environmental flows

4.4 Subsurface flows – porous media



SPH simulation

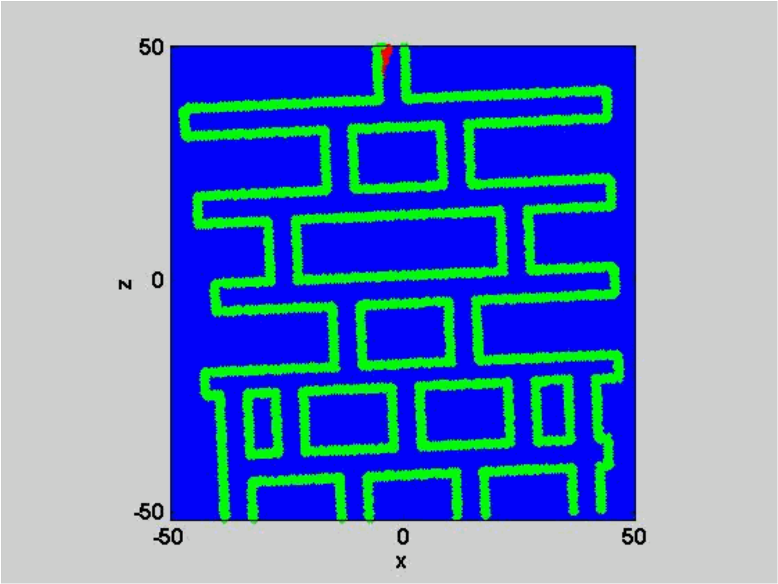


Comparison: SPH (top) and VOF (bottom)

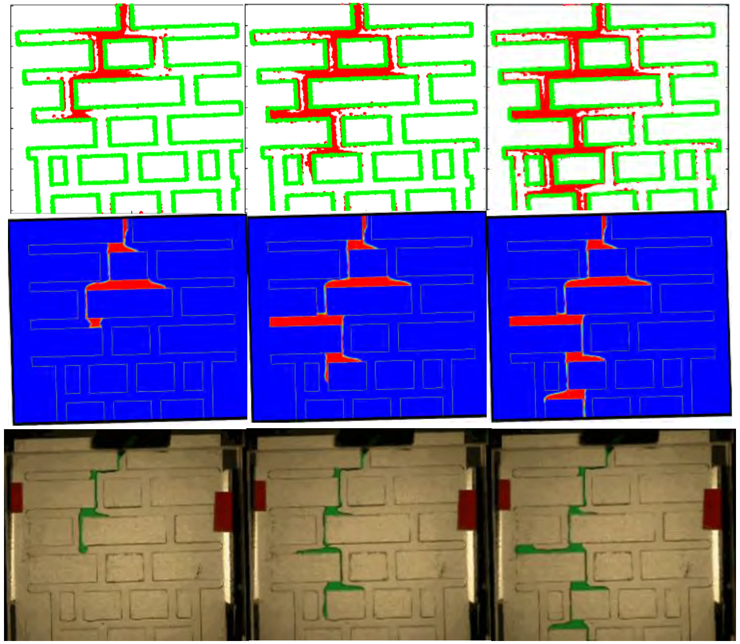
Multiphase flow in a fractured porous media

Liu et al., *Water Resources Research*, 2007.

4.4 Subsurface flows – fracture network



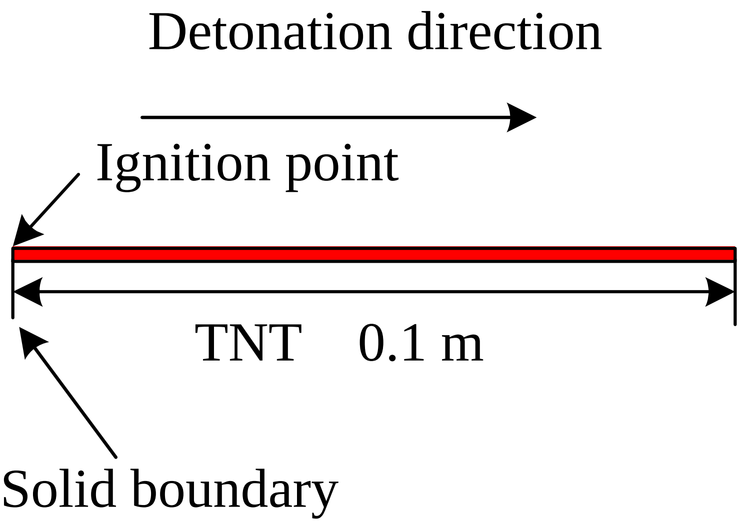
SPH VS VOF、Experiment



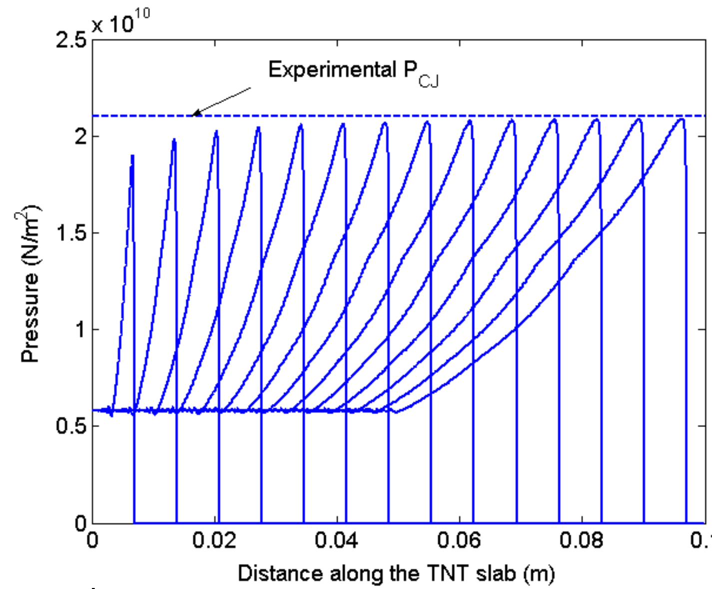
Multiphase flow in a fracture network

5. SPH for explosion and impact

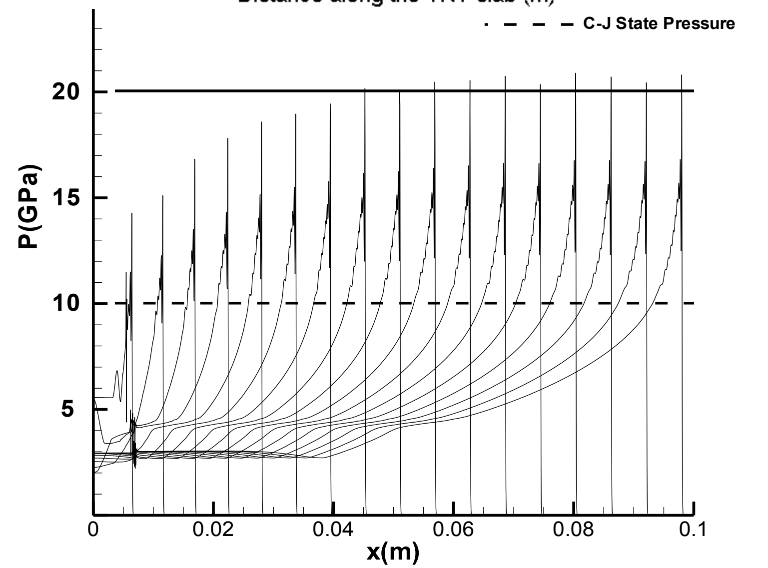
5.1 1D TNT slab detonation



Ideal explosive



Non-ideal explosive



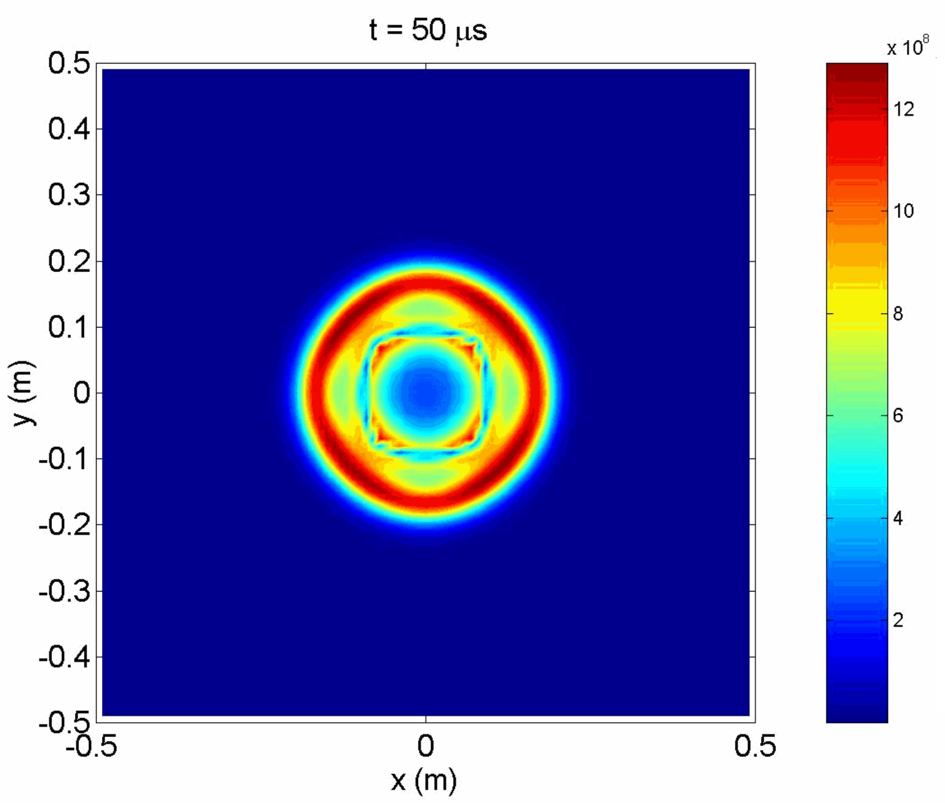
TNT slab detonation

Liu et al., *Shock Waves*, 2003

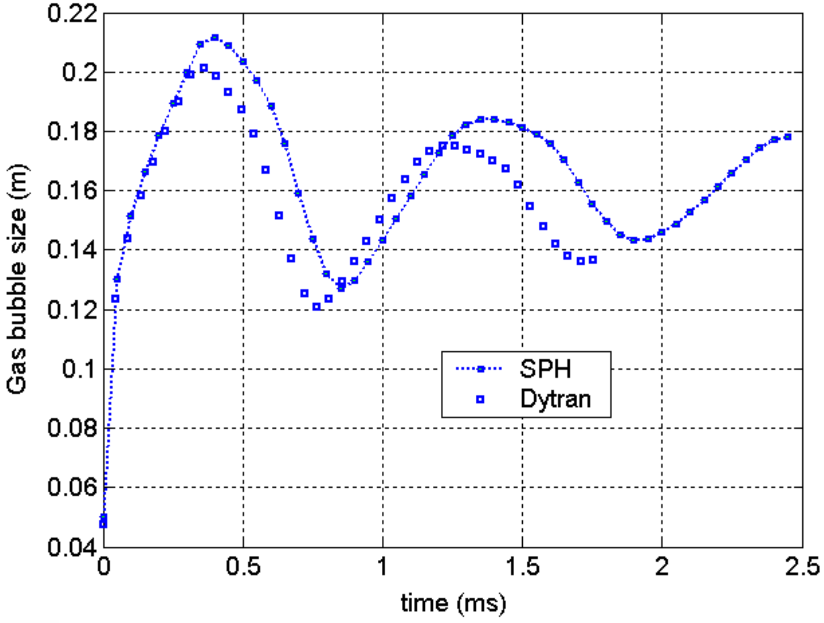
Liu et al., *Shock Waves*, 2013

5. SPH for explosion and impact

5.2 2D confined UNDEX



Pressure field

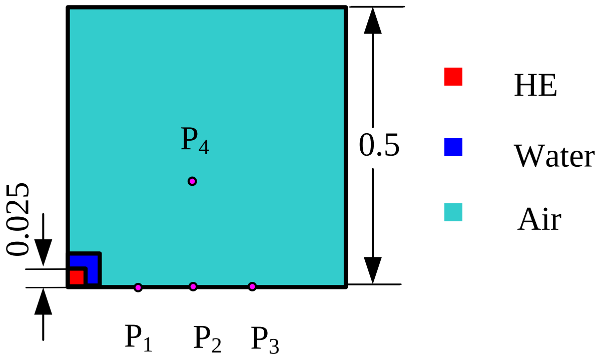


Bubble evolution

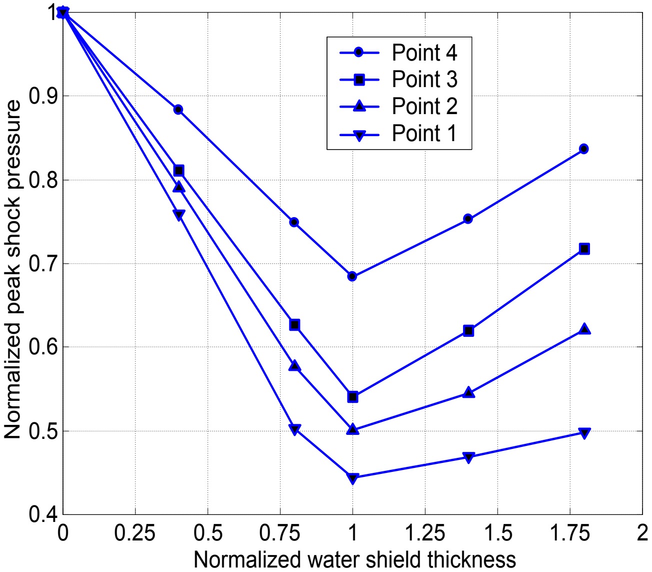
Liu et al., *C&F*, 2003

5.3 Water mitigation (WM)

Water held in plastic bags as a bomb shelter to mitigate blast effects



Contact WM

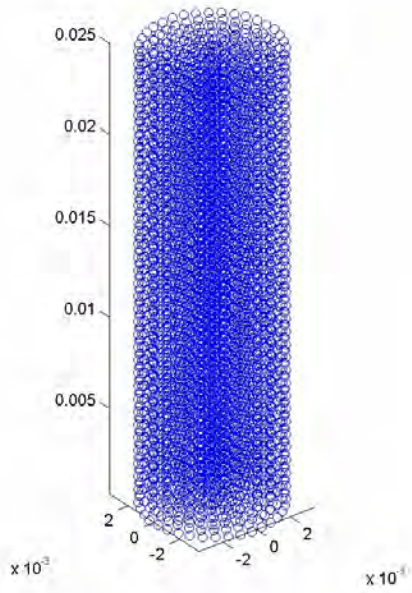


Peak shock pressure

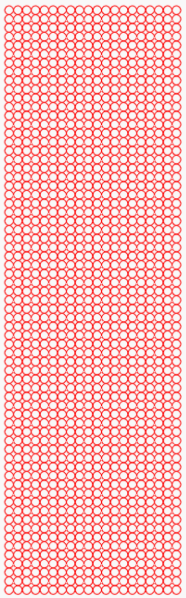
Liu et al., *Shock Waves*, 2002

5. SPH for explosion and impact

5.4 Middle & high velocity impact

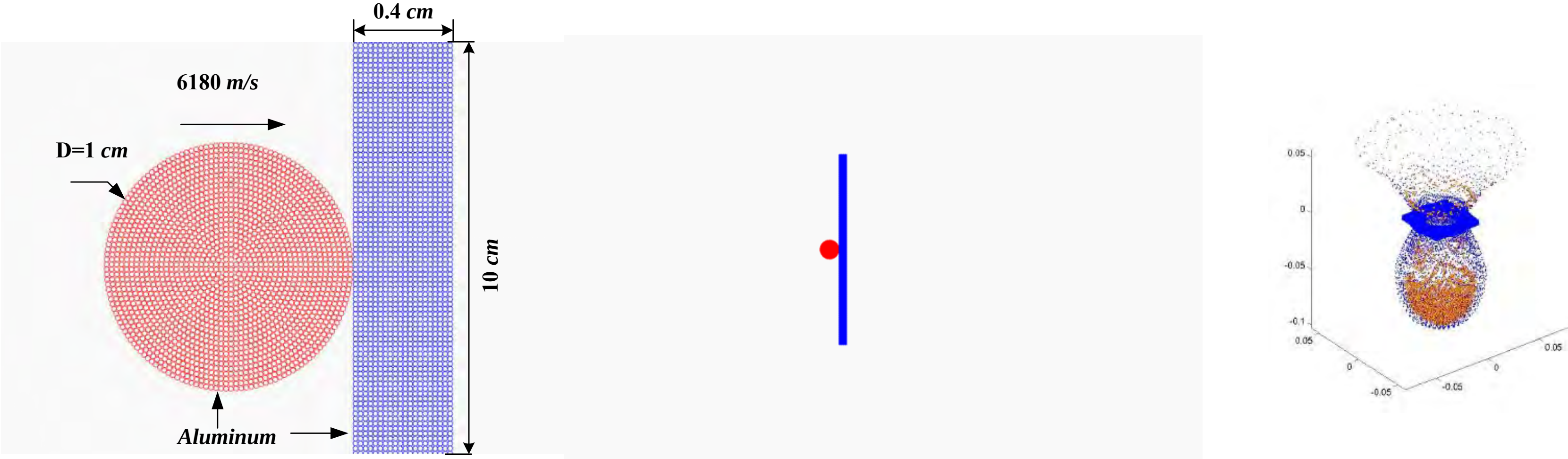


3D Taylor bar impact with SPH

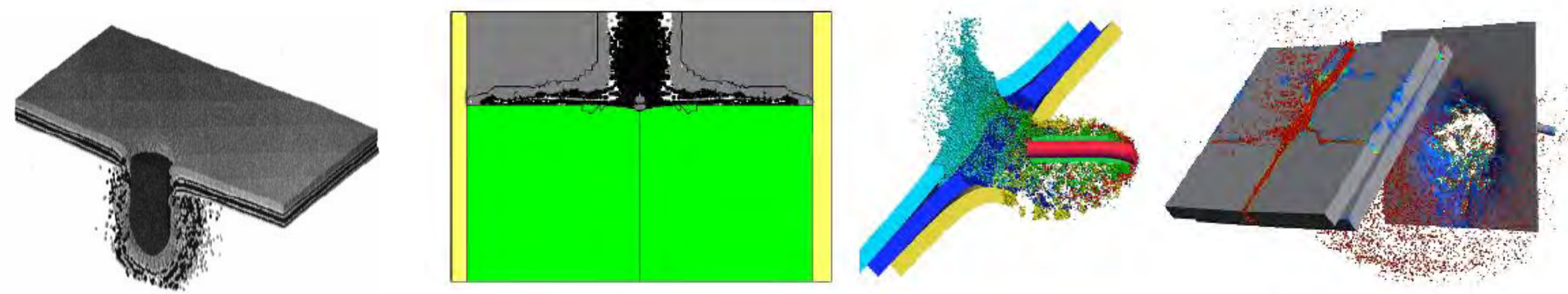


2D Taylor bar impact with adaptive SPH

5.5 Penetration

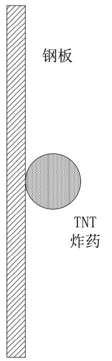


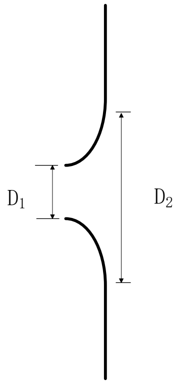
Al disk impacting/penetrating al plate at 6180 m/s

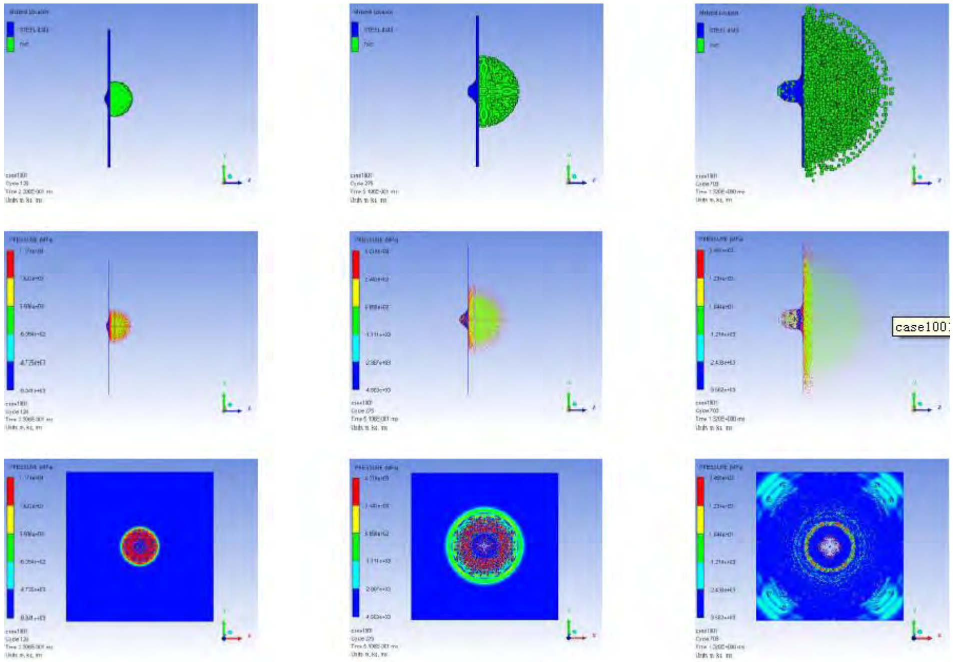


Other examples

5.6 Contact explosion





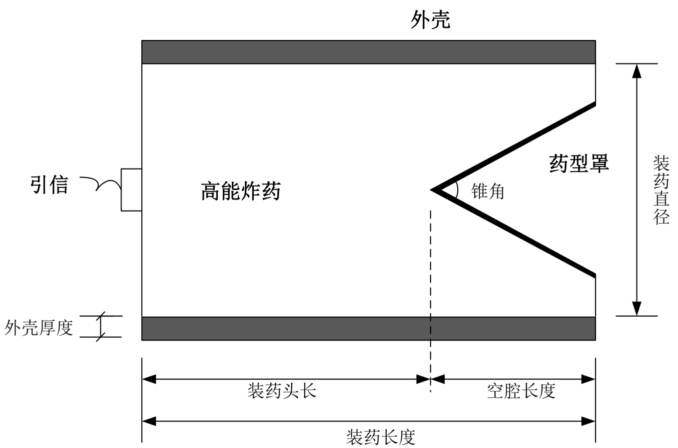


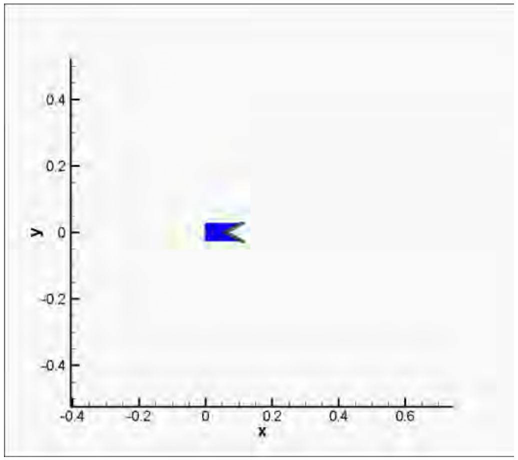
T = 0.23 ms　　T = 0.51 ms　　T = 1.32 ms

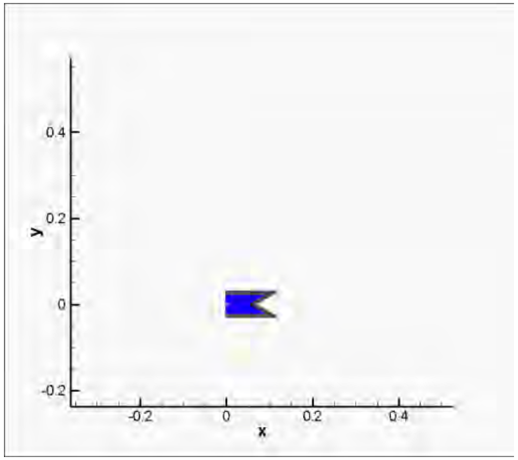
The shape of the crate is closely related to type, size and shape of the explosive charge

5. SPH for explosion and impact

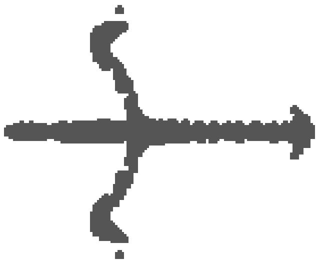
5.7 Shape charge with jet formation



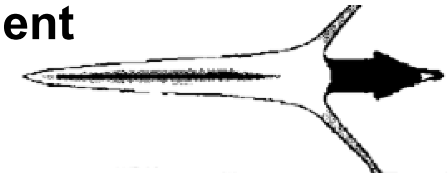




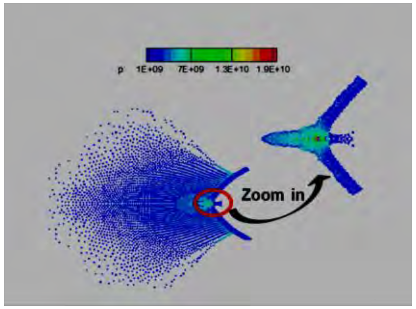
Simulation

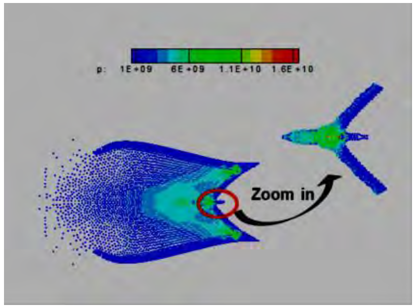


Experiment



Metal jets

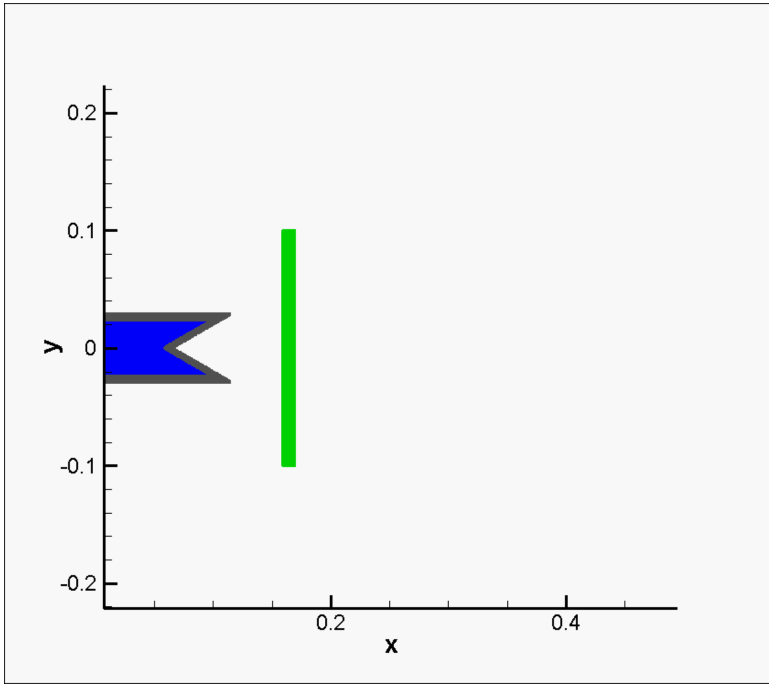


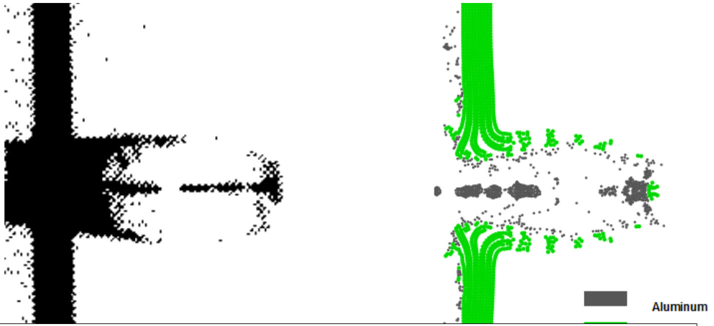


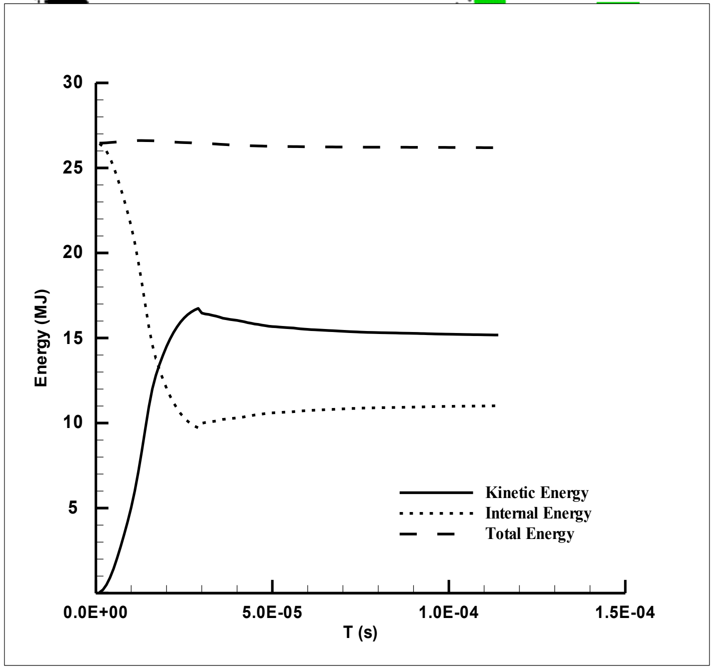
Metal jets without & with metal case

5. SPH for explosion and impact

5.7 Shape charge with jet formation & penetration

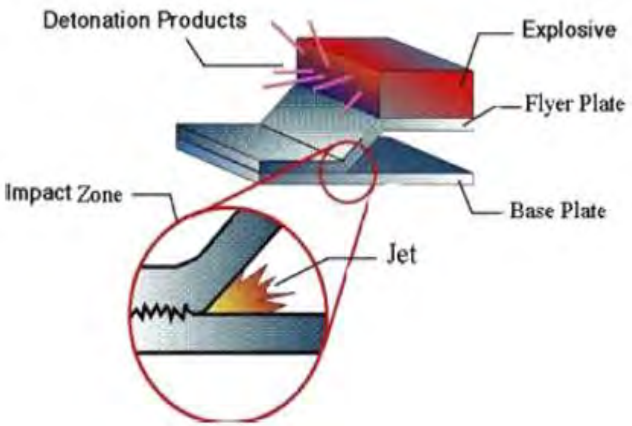


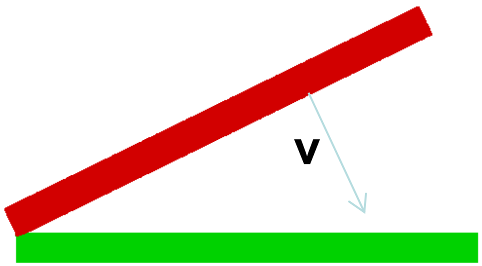


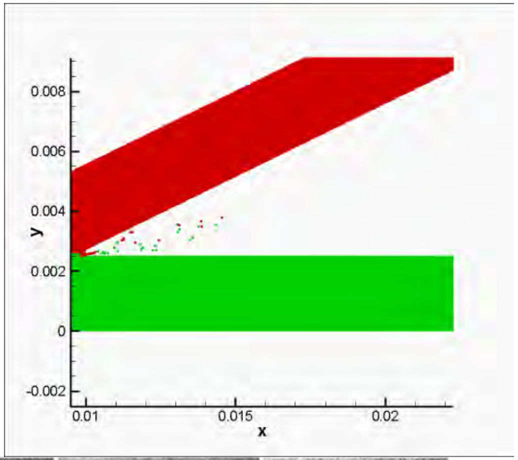


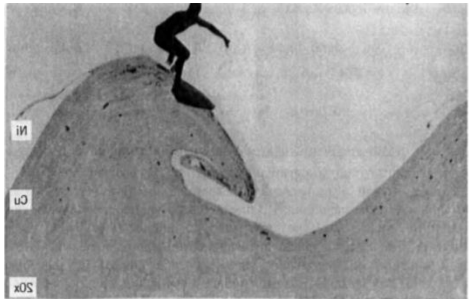
5. SPH for explosion and impact

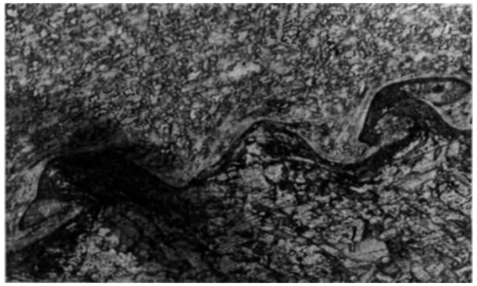
5.8 Explosive-driven welding

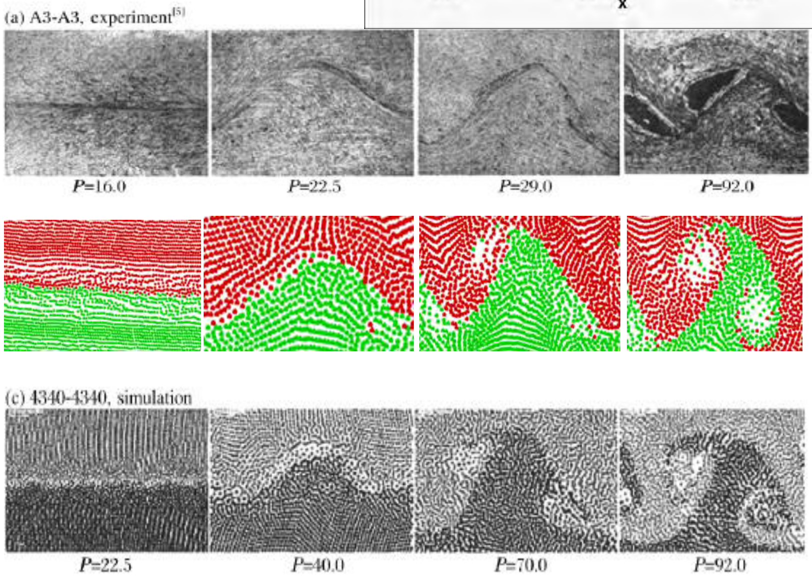










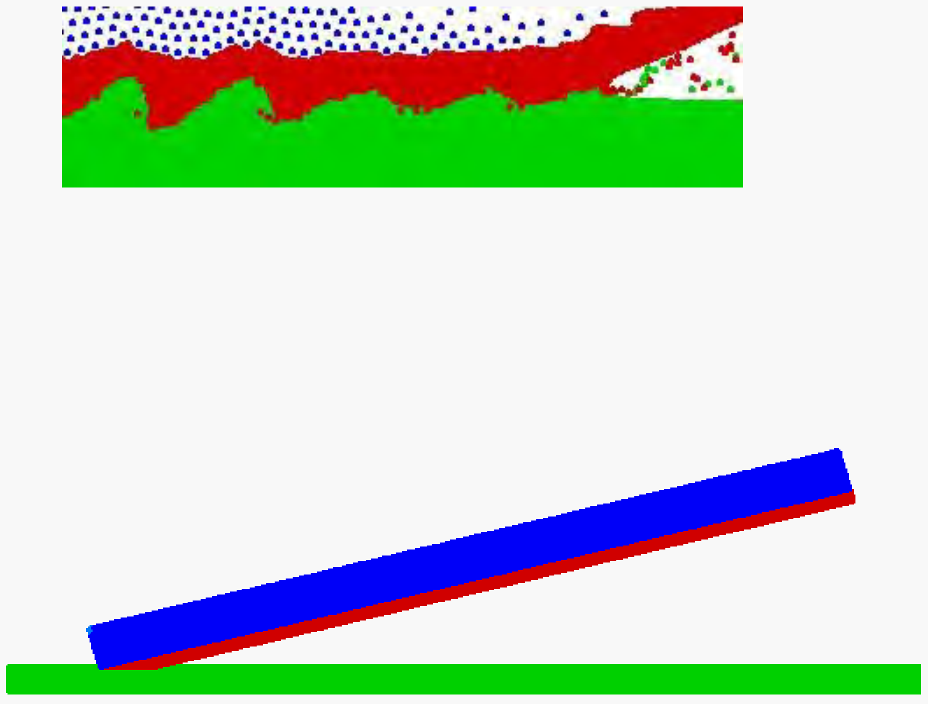


Welding from direct impact

Deribas (1967), Hydrodynamic model

5. SPH for explosion and impact

5.8 Explosive-driven welding



Explosive-driven welding

6. Prospects and future directions

❖ Better theories

- ✓ Relationship between particle-particle interactions,
- ✓ Theoretical foundation for multi-scale modeling,
- ✓ Fluid-solid interaction model.

❖ Applications:

- ✓ Protective technology,
- ✓ Coastal engineering and ocean hydrodynamics,
- ✓ Civil and environmental engineering,
- ✓ Bio/nano engineering,
- ✓ Movie and animation making…

6. Prospects and future directions

Code

- **Released the first SPH open source code;**
- **Developing a 3D SPH code for hydrodynamics and environmental flows**

1 Features

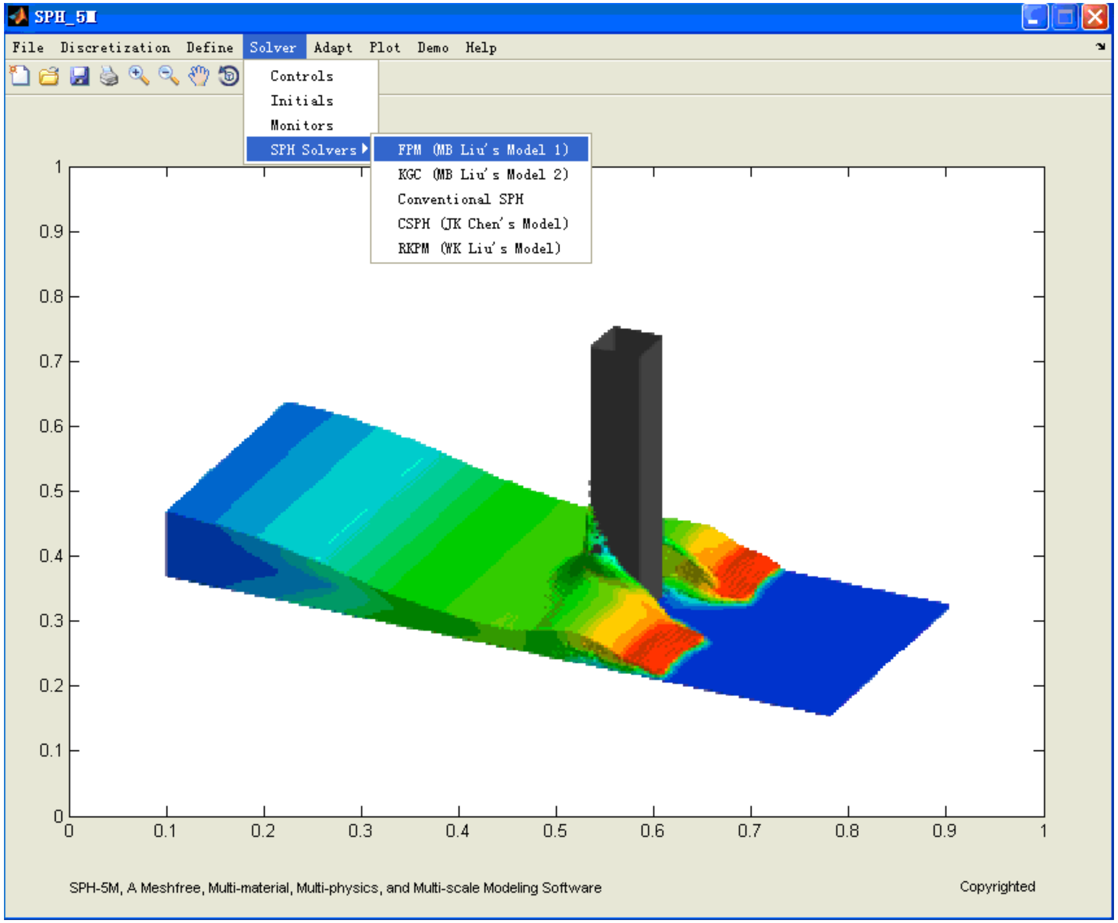
- 2 and 3D
- Lagrangian, particle method
- Nonlinear
- Explicit algorithm
- Multi-materials, Multi-scales, Multi-physics

2 Typical applications

- Free surface flows (breaking waves、dam collapse, flood...)
- FSI (slamming、sloshing、water-on-deck、 high speed water entry/exit)
- Extreme load (explosion, impact, penetreation)

2 Advantages

- Meshfree: easy in treating large deformation
- Lagrangian particle: easy in treating free surfaces and moving interfaces.
- FSI: simutaneously coupling



Target: 3D SPH code for FSI with wave and currents

5. Prospects and future directions

❖ Coupling approaches:

1. Coupling SPH/DEM for problems with solid particles (landslide, e.g.),

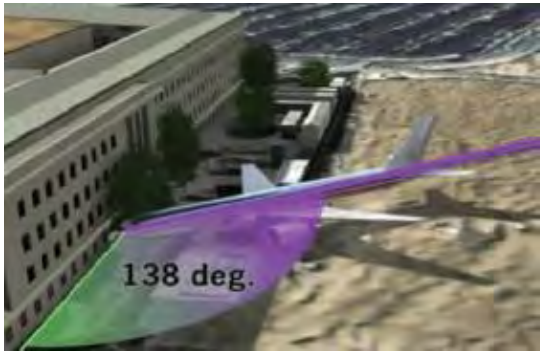
landslide

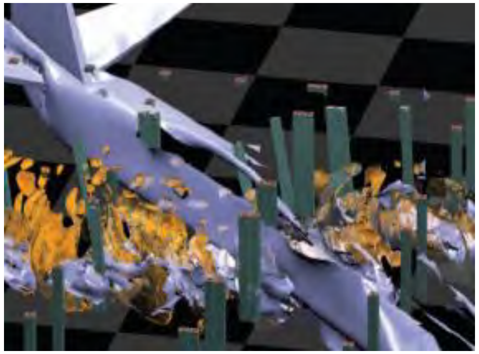
mud flow

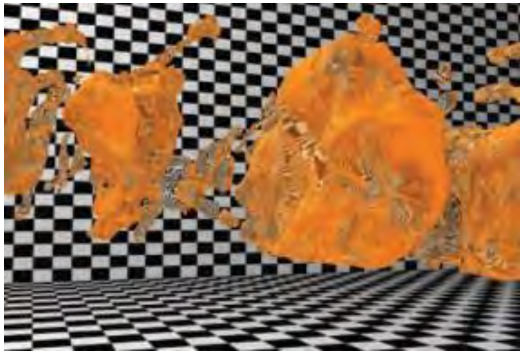
5. Prospects and future directions

❖ **Coupling approaches:**

2. **Coupling particle methods with FEM/FDM for boundary enhancement and fluid-solid interaction,**





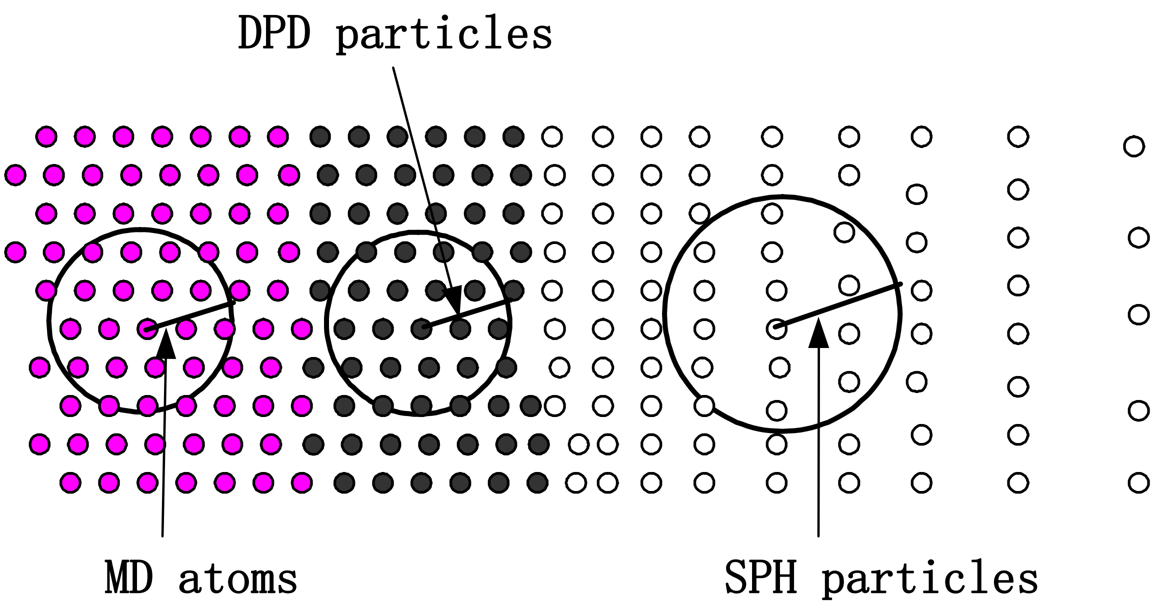


SPH+FEM modeling 911

5. Prospects and future directions

❖ Coupling approaches:

3. Coupling MD/DPD/SPH for multi-scale simulation,

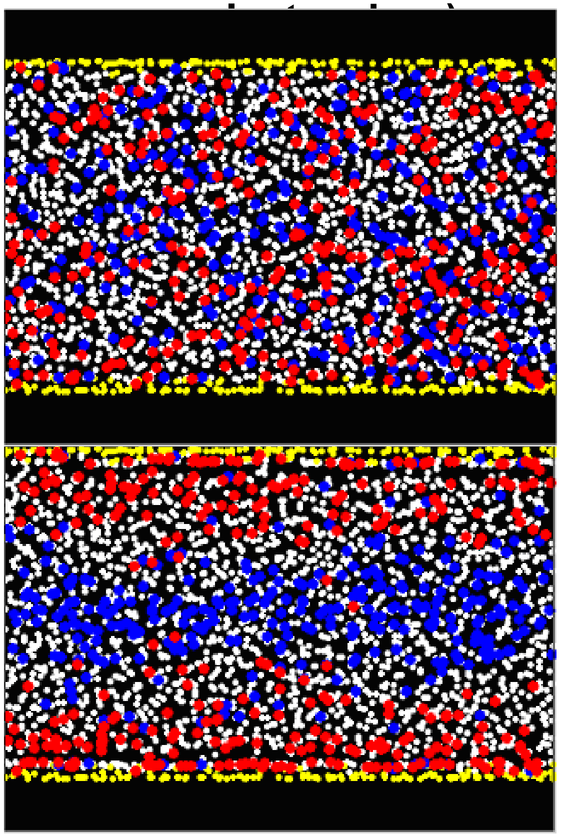


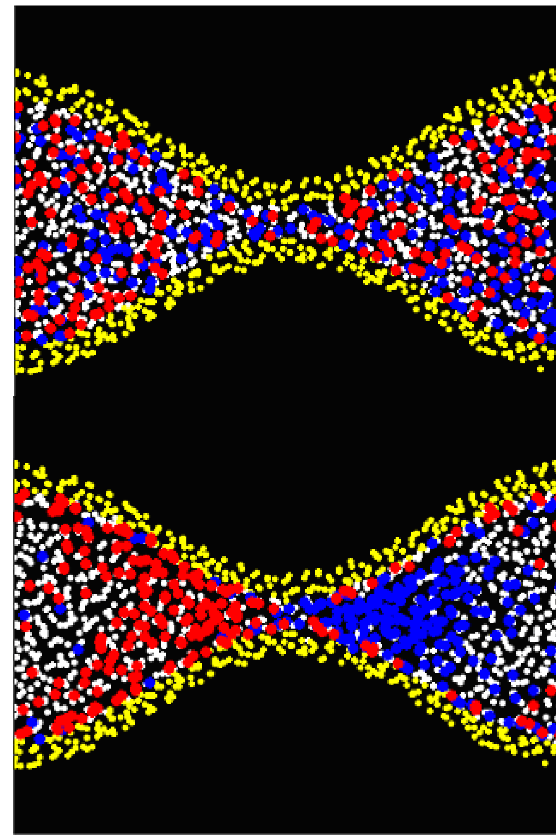
Multi-scale modeling: from nano to micro and to macro scale

5. Prospects and future directions

❖ Coupling approaches:

4. Coupling multiple physics (viscous, elastic, heat, chemical,





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Thank You!