Fully Nonlinear Numerical Simulation of Fluid-Structure Interaction based on Smoothed Particle Hydrodynamics and Structural Finite Element Method

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Research Background

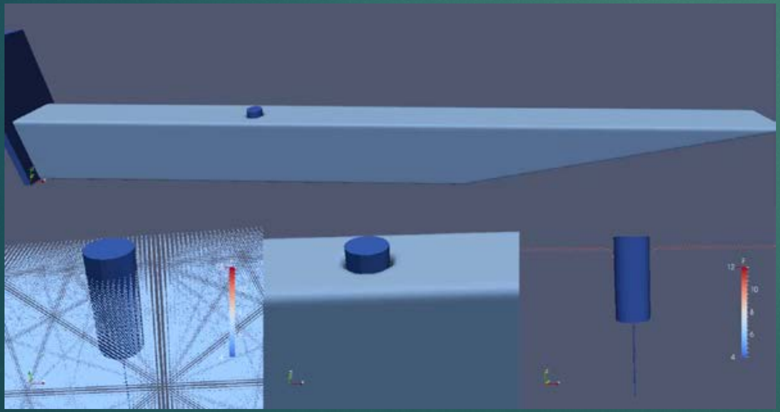
- With an increase of size of ships or floating offshore structures, it is highly necessary to evaluate the structural elastic-plastic response under severe hydrodynamic load.

- Even though lots of researches have been conducted to simulate the fluid-structure interaction (FSI) problem, less attention is paid on the plastic and post-ultimate structural behavior.

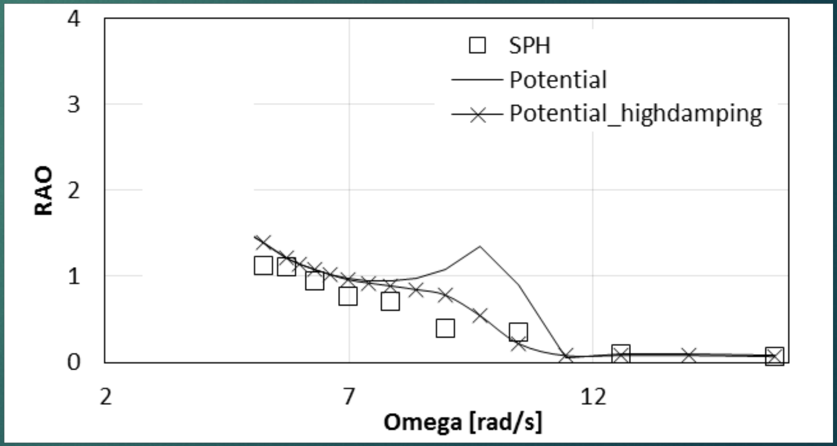
- FSI simulation usually involves time-consuming problem. It is necessary to establish a FSI model with high calculation efficiency.

Previous Research

- Based on Smoothed-Particle-Hydrodynamics (SPH, DualSPHysics) and structural beam element, the authors had proposed a numerical model to analyze the ringing behavior for riser of tethered buoy system. *(ViolentFlows2016)*
- The feasibility of SPH model is proved by comparing the numerical results based on wave panel method (potential theory).



FSI simulation of tethered buoy system



Comparison of RAO (surge) between the results based on SPH and potential theory

Research Objectives

- Establish a FSI numerical model which can not only deal with the fully nonlinear hydrodynamic problem but also takes account of the elastic, plastic and post-ultimate structural behavior.

- Solve the FSI problem with high calculation efficiency by utilizing the parallelization computation capability of CPU&GPU.

- Validate the proposed FSI numerical model by the model test results.

Numerical Model-

Smoothed-Particle-Hydrodynamics (SPH) model

Governing Equation in SPH:

$$\frac{d\mathbf{v}}{dt} = -\frac{1}{\rho}\nabla P + \mathbf{g}$$ momentum equation

$$\frac{d\rho}{dt} = -\rho\nabla\bullet\mathbf{v}$$ continuity equation

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}$$ trajectory equation

$$P = B[(\frac{\rho}{\rho_0})^{r} - 1]$$ relationship between pressure and density

- Dynamic Boundary Condition (DBC) is utilized to simulate the boundary particles in which, the boundary particles are calculated based on Governing Equation without updating the coordinates.
- DeltaSPH (Molteni, D. et al. 2009) formulation is applied to eliminate the influence of unphysical fluid pressure oscillations on the FSI coupling interface. $\frac{d\rho}{dt} = -\rho\nabla\cdot\boldsymbol{v} + 2\delta_{\varphi}hc_0\sum(\rho_b-\rho_a)\frac{\boldsymbol{r}_{ab}\cdot\nabla_a W_{ab}}{r_{ab}^2}\frac{m_b}{\rho_b}$
- Open source code, **DualSPHysics** is utilized to establish the SPH model.

Numerical Model-

Structural Finite Element model

Commercial software, ABAQUS is utilized in this research.

- Robust structural simulation tool for analyzing elastic, plastic and post-ultimate behavior.
- Supply Force-Displacement transfer-interface by user-defined subroutine
- Dynamic explicit solver of ABAQUS is used in the proposed FSI model.

Numerical Model-

Fluid-Structure Coupling Scheme

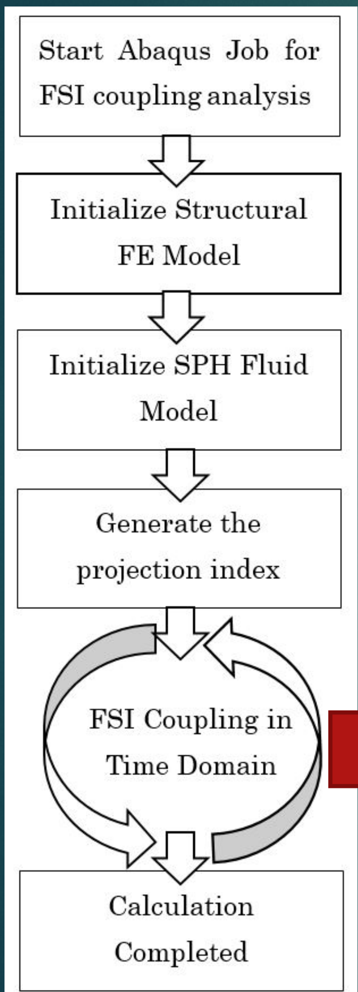
- The partitioned algorithm is used to weakly couple the fluid and structure models. Both fluid and structure model are built in SPH and ABAQUS relatively.

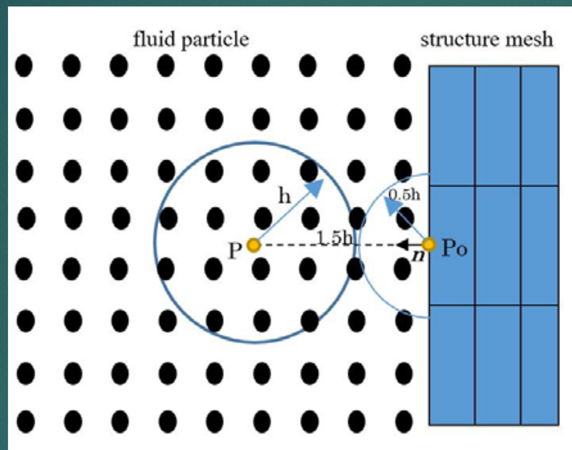
- By user-subroutine function, VDload, supplied by ABAQUS, the structure displacement/velocity and fluid pressure is transferred between the SPH and ABAQUS model.

- Open code DualSPHysics is reconstructed and compiled to Dynamic Link Library (DLL) which can be directly called from the subroutine VDload in each time step.

Numerical Model-

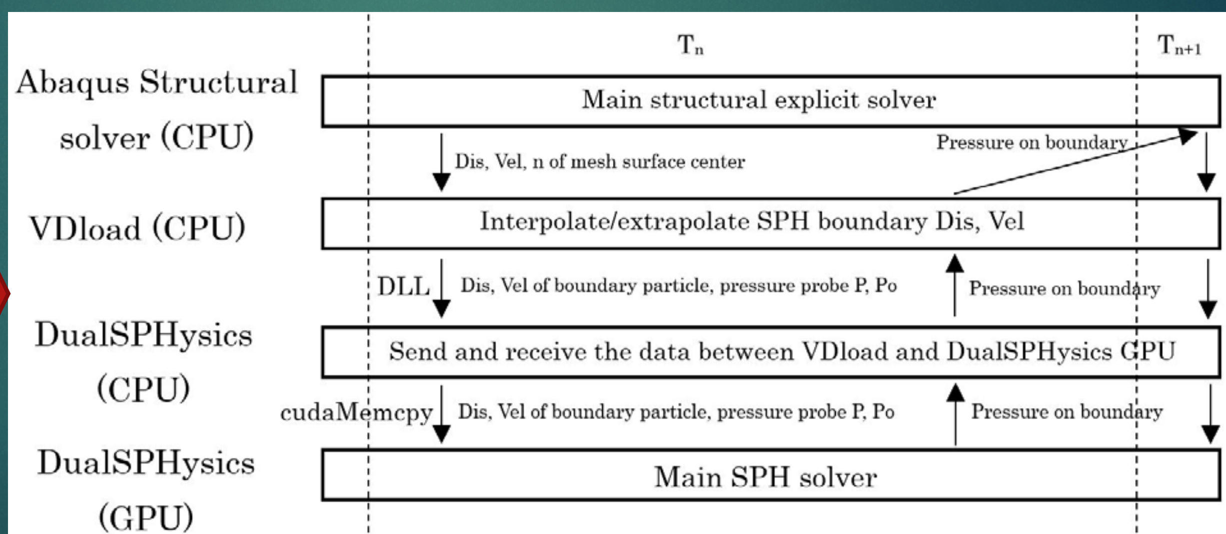
Fluid-Structure Coupling Scheme





Calculation of the fluid pressure on the boundary

$$P_P = \frac{\sum P_b W_{bp}}{\sum W_{bp}}$$



Flowchart of coupling process

National Maritime Research Institute, Japan

Numerical Model-

Calculation Equipment

The SPH calculation is accelerated by the GPU parallelization technique based on the open source code DualSPHyics. While, the ABAQUS structural analysis is conducted with normal CPU parallelization.

The detail information of the calculation equipment is:

GPU: GTX980Ti, 2816 cuda cores, 5734.4 GFLOPS

CPU: Intel i7-3930k, 6 cores, 137.57 GFLOPS

Memory: 32GB

Benchmark Study

A series of 2D primary benchmark tests are conducted to check the performance of the proposed FSI model.

- Elastic beam impact

Simulation results based on the proposed FSI model is compared with the analytical solution (Scolan 2004)

- Elastic gate

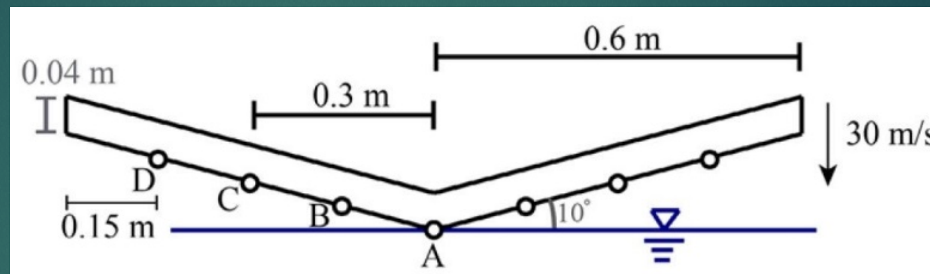
Simulation results based on the proposed FSI model is compared with the model test results (Antoci et al. 2007)

- Dam break with an elastic plate

Simulation results based on the proposed FSI model is compared with the model test results (Liao et al. 2014)

Benchmark Study-

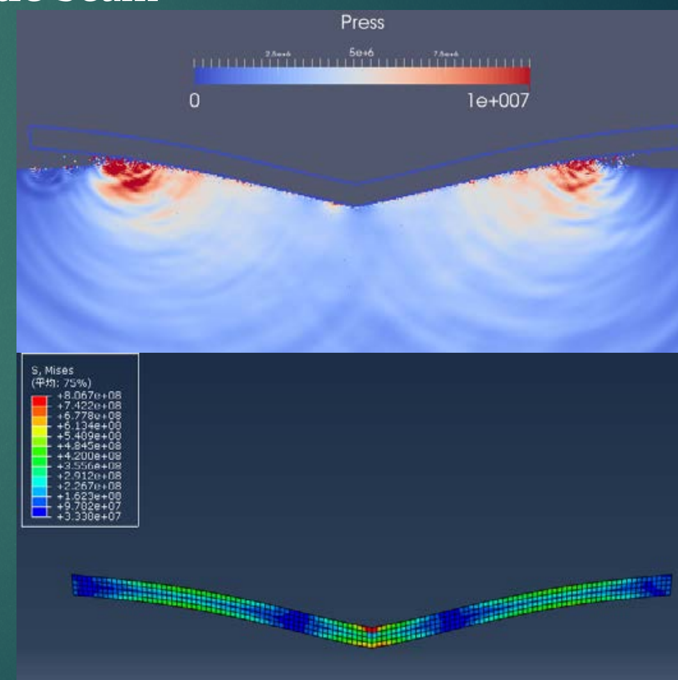
Elastic beam impact



Dimension of the elastic beam

The physical and numerical parameters for the elastic beam

Young's modulus	67.5 Gpa
Possion Coefficient	0.34
ρ_{beam}	2700 kg/m3
ρ_{water}	1000 kg/m3
Particle size	0.002 m
Mesh size	0.01 m
Particle number	759502
Mesh number	496

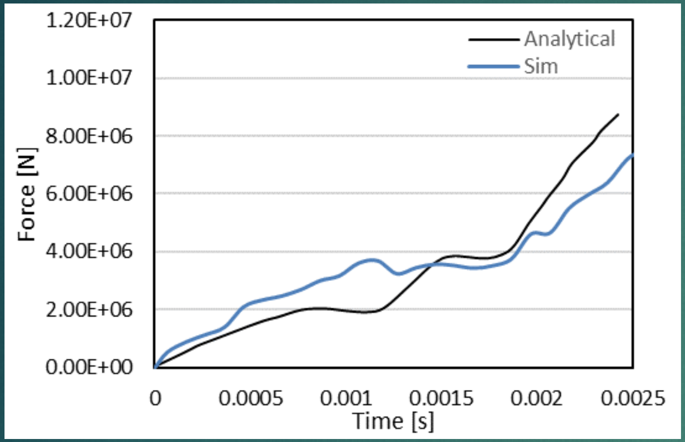


Distribution of fluid pressure and structural stress (t=0.0025s)

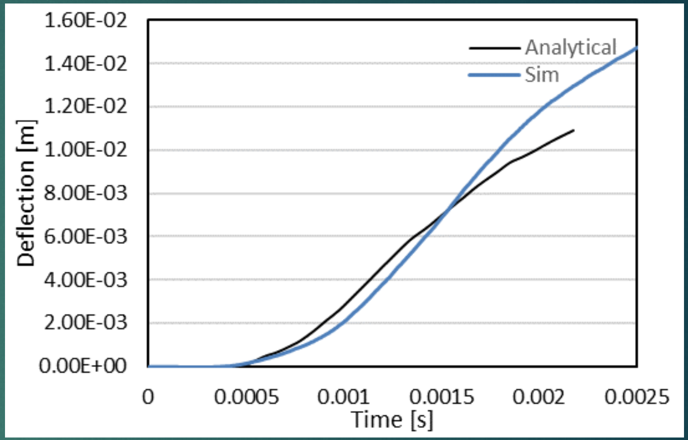
National Maritime Research Institute, Japan

Benchmark Study-

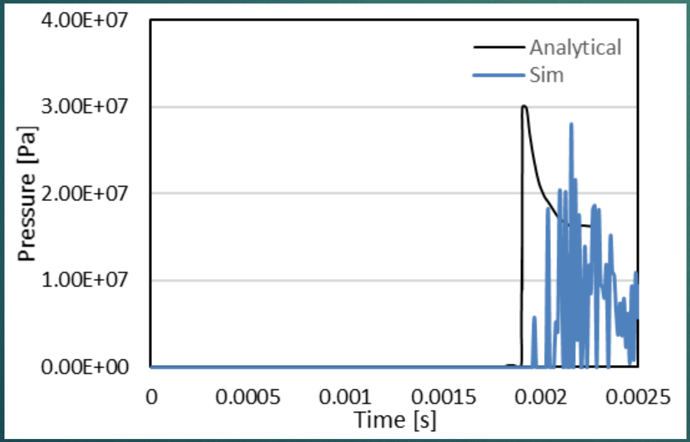
Elastic beam impact

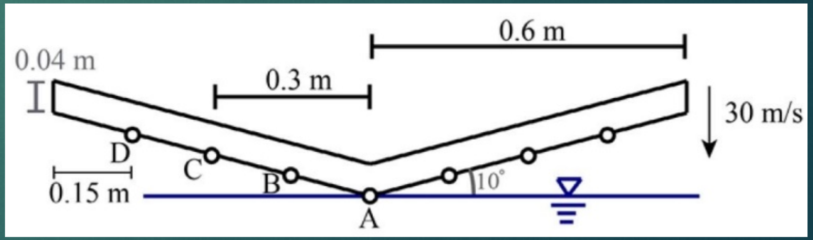


Comparison of integrated vertical force



Comparison of deflection at measuring point C

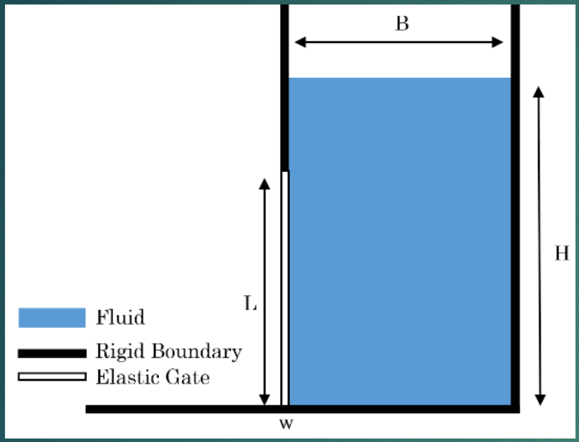




Comparison of impact pressure at measuring point D

Benchmark Study-

Elastic gate



Arrangement of Elastic gate

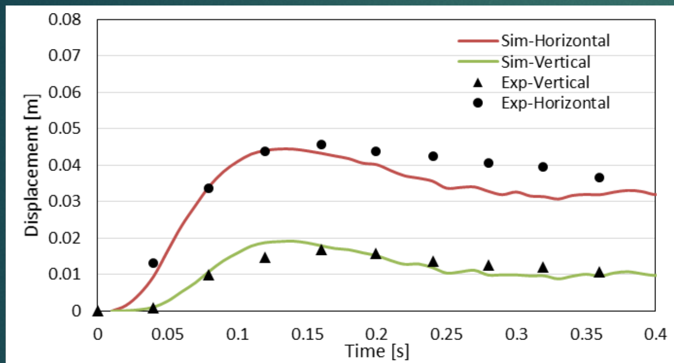
The model test was conducted by Antoci et al. 2007.
As only the top of the elastic gate is fixed on the rigid wall and the bottom of the gate (gate tip) is free for deflection, the fluid is initially released through the elastic gate to the left-hand side due to the gravity.

The physical and numerical parameters for the elastic gate

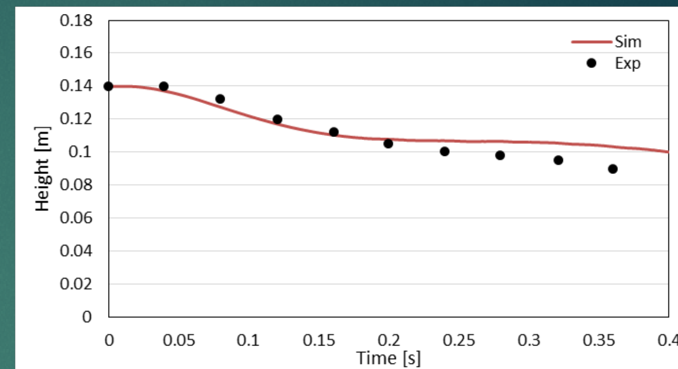
H	0.14 m
B	0.1 m
L	0.079 m
w	0.005 m
Young's modulus	12 Mpa
Possion Coefficient	0.5
P_{gate}	1100 kg/m3
ρ_{water}	1000 kg/m3
Particle size	0.0005 m
Mesh size	0.001 m
Particle number	68761
Mesh number	405

Benchmark Study-

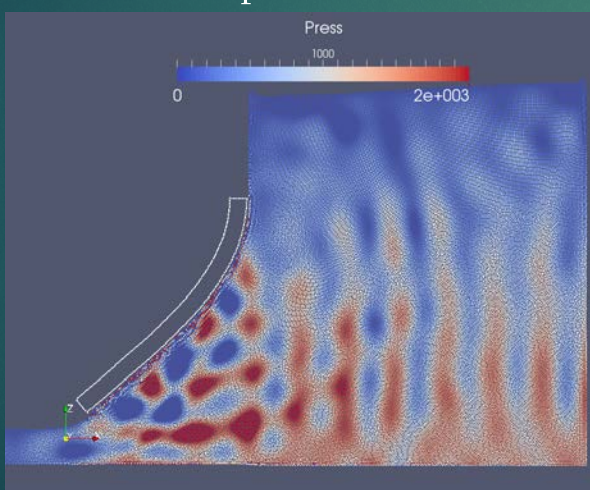
Elastic gate



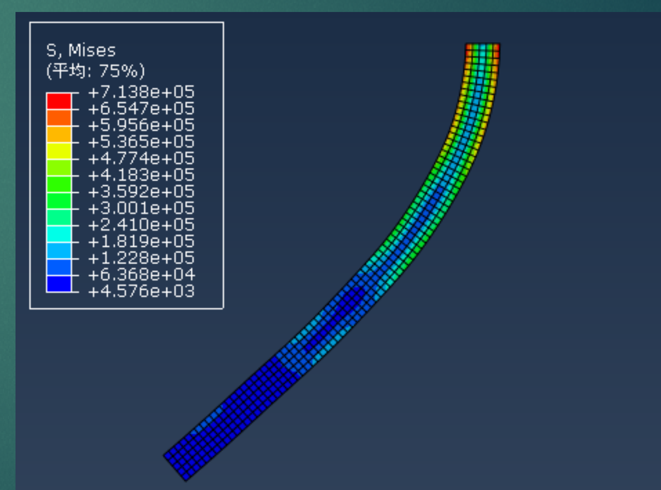
Comparison of gate tip horizontal and vertical displacement



Comparison of the height of fluid free-surface



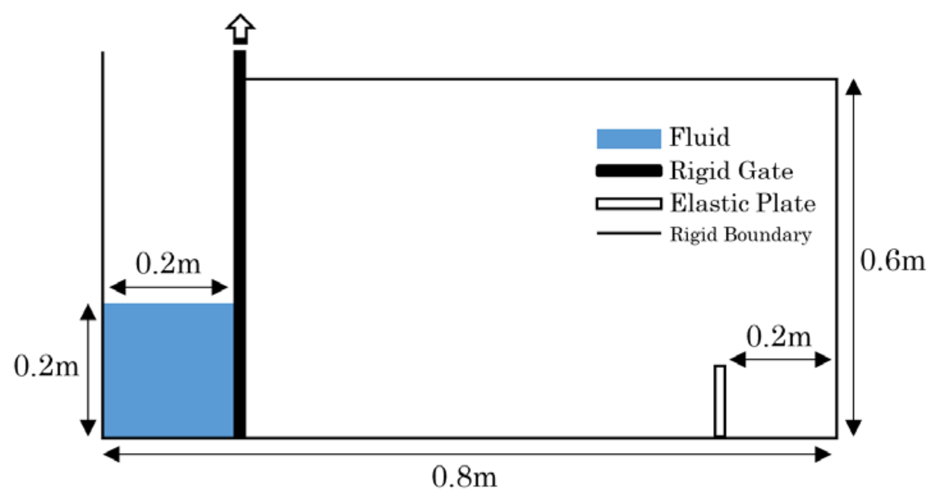
Distribution of fluid pressure (t=0.13s)



Distribution of structural stress (t=0.13s)

Benchmark Study-

Dam break with an elastic plate



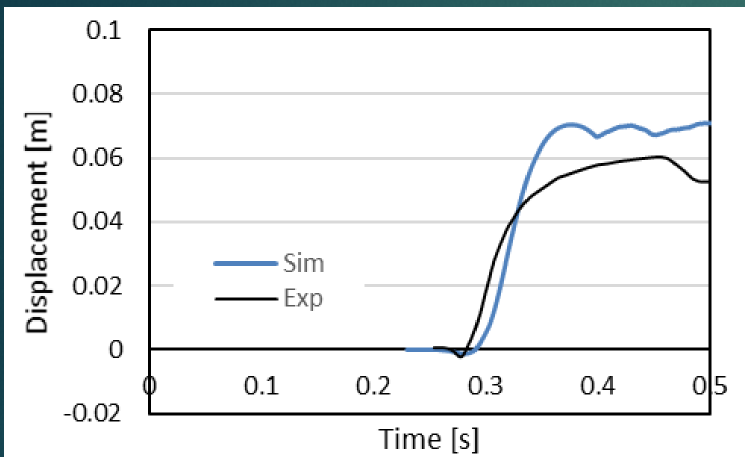
Arrangement of dam break with an elastic plate

The model test was conducted by Liao et al. 2014.
The gate is removed suddenly along arrow's direction to generate the dam-break flow. The deflection of the elastic plate under the impact of the dam-break flow is measured

The physical and numerical parameters for the dam break with an elastic plate

Plate thickness	0.004 m
Plate height	0.1 m
Young's modulus	3.5 Mpa
P_{plate}	1161.54 kg/m3
P_{fluid}	997 kg/m3
Particle size	0.001 m
Mesh size	0.002 m
Particle number	45268
Mesh number	100

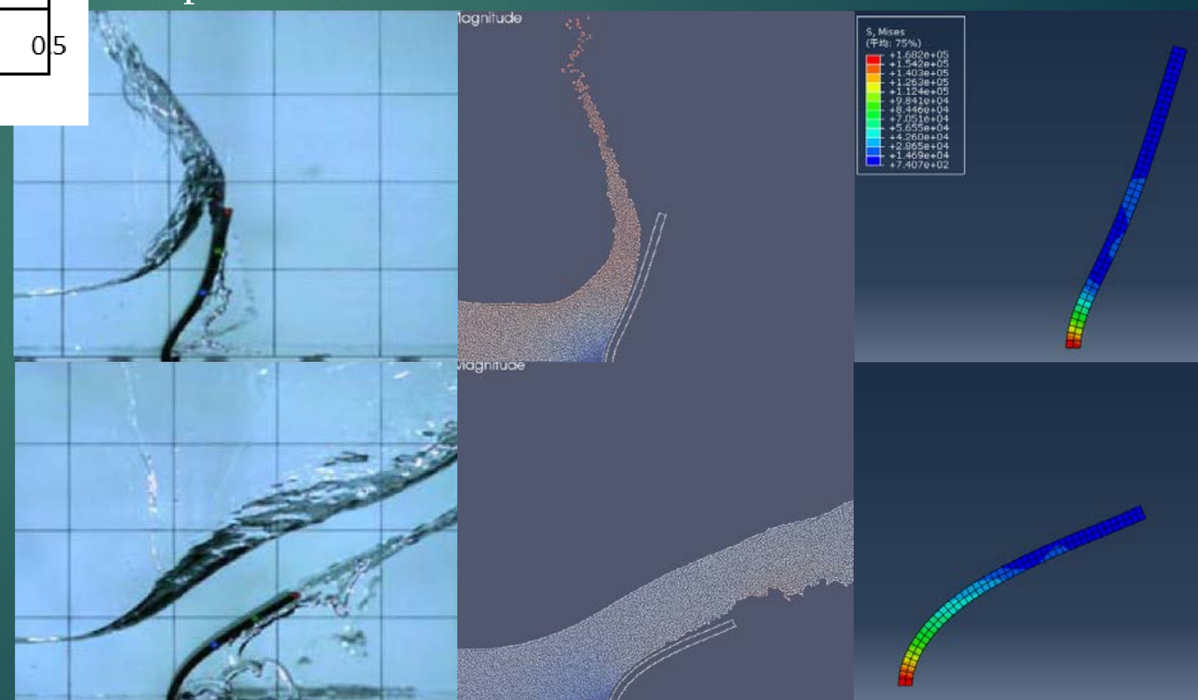
Benchmark Study-
Dam break with an elastic plate



Comparison of plate tip horizontal displacement

Flow profile and corresponding structure stress distribution

Experiment Fluid Model Structure Model



T=0.32s

T=0.47s

Conclusions

- A new FSI numerical model is established by which both nonlinear hydrodynamic force (SPH) and nonlinear structural behavior (ABAQUS) can be taken account into.
- Both GPU acceleration and CPU parallel calculation technique are utilized in the proposed FSI model.
- Three benchmark tests, elastic beam impact, elastic gate and dam break with an elastic plate, are carried out to validate the feasibility of the proposed FSI model qualitatively and quantitatively.

Future Work:

- Improve the SPH model to considering the air influence and surface tension effect
- Validate proposed FSI model by the experiments which involves the plastic/post-ultimate structural behavior.

Thank you for your kind attention.