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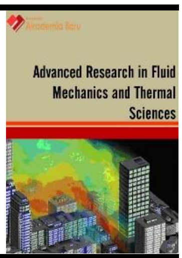

Meshless Fluid Structural Interaction (FSI) Simulation of Deformation of Flexible Structure due to Water Dam Break

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ABSTRACT

A new meshless-based solver has been used to study the deformation of flexible structure due to water dam break. This meshless Fluid Structural Interaction (FSI) solver couples the Smoothed Particle Hydrodynamics (SPH) and Lattice-Spring Model (LSM). SPH and LSM are used to model the motions of fluid and solid particles, respectively. As both are essentially particle-based methods, the force coupling at the interface is straightforward. The numerical results have been compared with the benchmark numerical solutions of dam break problem and good agreement has been found.

1. Introduction

The numerical method for simulating fluid flow can be broadly classified into two categories. The first category refers to those methods that require discretization of the entire flow domain using polygons (or meshes), or more-specifically known as the mesh-based methods. One of the common mesh-based methods is the Finite Volume Method [1-12], which is very popular amongst the CFD users. The second category does not require the use of polygons (mesh); however, computation is performed using zero-dimensional points (mesh-less method). Some examples are Moving Particle Semi-implicit (MPS) method [13-15], hybrid particle-mesh methods [16-19], Dissipative Particle Dynamics (DPD) [20, 21] and Smoothed Particle Hydrodynamics (SPH) [22-24], to name a few. SPH is one of the oldest meshless methods that has been gaining popularity in CFD nowadays.

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Likewise, the methods available in simulating solid mechanics can be broadly classified into mesh-based and mesh-less methods. Undoubtedly, Finite Element Method (FEM) can be regarded as the popular mesh-based method in studying solid deformation. Recently, the use of meshless method such as Lattice Spring Model (LSM) has been gaining popularity as well [25]. The accuracy of LSM has been proven to be at par with that of FEM [26,27].

In the current work, we intend to use the coupled SPH-LSM meshless method in simulating Fluid Structure Interaction (FSI) problem. Specifically, we intend to study the accuracy of SPH-LSM method in solving the dam-break flow involving a flexible gate.

2. Methodology

In the current work, the continuity and momentum equations are discretized using SPH:

$$\frac{d\rho_i}{dt} = \rho_i \sum_j V_j(\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla_i W_{ij} \tag{1}$$

$$m_i \frac{d\mathbf{v}}{dt} = -\sum_j (V_i^2 + V_j^2) \frac{P_i\rho_j + P_j\rho_i}{\rho_i + \rho_j} \nabla_i W_{ij} + \sum_j (V_i^2 + V_j^2) \frac{2\mu_i\mu_j}{\mu_i + \mu_j} \frac{\mathbf{v}_i - \mathbf{v}_j}{\|\mathbf{r}_{ij}\|} \nabla_i W_{ij} \cdot \frac{\mathbf{r}_{ij}}{\|\mathbf{r}_{ij}\|} + m_i \mathbf{g} \tag{2}$$

where V is the fluid volume, m is the fluid mass, $\mathbf{v}$ is the fluid velocity vector, ρ is the fluid density, P is the fluid pressure, $\boldsymbol{r}_{ij}$ denotes $\boldsymbol{r}_i$–$\boldsymbol{r}_j$, $\boldsymbol{g}$ is the gravitational vector and μ is the fluid viscosity. The quintic spline kernel function [28] was used to represent W.

In order to model the solid motion, each solid particle is connected with its neighbouring solid particles via springs as shown in Figure 1. Here, the spring stiffness for horizontal and vertical springs are denoted as k_L and the spring stiffness for diagonal spring is denoted as k_D. Following the LSM method [26] for 2D plane strain problem, the following spring stiffness values can be obtained:

$$k_L = \frac{2E}{1+\upsilon} \tag{3}$$

$$k_D = \frac{E}{1+\upsilon} \tag{4}$$

$$T = \frac{E(4\upsilon - 1)}{(1+\upsilon)(1-2\upsilon)(2+\sqrt{2})^2}. \tag{5}$$

Here, the stiffness T is introduced to simulate the elastic behaviour at arbitrary Poisson ratio. These stiffness values are dependent on Young's modulus E and Poisson ratio v. The elastic force acting on the solid particle I (see Figure 1) can then be computed as:

$$\mathbf{F}_{S,I} = \sum_J -\frac{\partial U_{cell}}{\partial \delta l_{IJ}} \hat{\mathbf{u}}_{IJ} \tag{6}$$

where $\hat{\mathbf{u}}_{IJ} = (\mathbf{r}_I - \mathbf{r}_J)/\|\mathbf{r}_I - \mathbf{r}_J\|$ is the displacement vector connecting solid particles I and J. The term $-\frac{\partial U_{cell}}{\partial \delta l_{IJ}}$ is defined in the following manner [26]:

$$-\frac{\partial U_{cell}}{\partial \delta l_{IJ}} = \begin{cases} -k_L \delta l_{IJ} - \frac{T}{2}\left(\sum_{J=1}^{8} \delta l_{IJ} + \sum_{M=1}^{8} \delta l_{JM}\right) & J \in 1,2,3,4 \\ -k_D \delta l_{IJ} - \frac{T}{2}\left(\sum_{J=1}^{8} \delta l_{IJ} + \sum_{M=1}^{8} \delta l_{JM}\right) & J \in 5,6,7,8 \end{cases}, \tag{7}$$

where δl_{IJ} is the change of length of the half spring. In order to couple the SPH and LSM methods, the solid particles in the vicinity of the solid-fluid interface are treated as dummy particles in the SPH solver. Depending on the wall boundary conditions, the velocities of these dummy particles can be calculated accordingly [29].

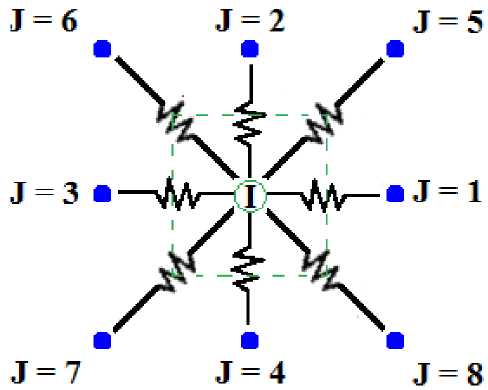


Fig. 1. Spring network in the solid body

3. Results and Discussion

The SPH-LSM solver has been developed and it was applied to solve the dam break flow involving a flexible structure. This test case is attractive as the experimental data of the gate displacement is available [30]. Also, previous researchers [31] have done validations on their SPH-FEM FSI solver using this test case as well. Figure 2 shows the size of the water column before collapsing, whereby its width (W) and height (H) were fixed at 0.1 m and 0.14 m, respectively. The following fluid properties were employed: μ = 0.001 Pa.s and ρ = 1000 kgm^{-3}. There is a hinge at the top of the flexible gate. In order to model the hinge, the top elastic gate particles were connected with the neighbouring stationary dummy particles as shown in Figure 2. The thickness and the height of the flexible gate were fixed at 0.005 m and 0.079 m, respectively. The material properties of the flexible gate were fixed as: E = 12 MPa, ν = 0.40 and ρ = 1100 kgm^{-3}. A uniform particle spacing of 1.0 mm was used. A monitor point was placed at the free end of the flexible gate. Its displacement with respect to time was then monitored as time progresses. The flow computation was executed until t = 0.4 s.

Figure 3 compares the simulated displacement values against those obtained from the SPH-FEM solution [31]. Overall, the agreement is very encouraging. While the agreement between SPH-LSM and experimental data is good at t < 0.08 s, our numerical results are somewhat lower than those measured at t > 0.08 s. This could be due to the 2D plane-strain assumption made in our current model. In addition, we anticipate that the model can be further improved if the flexible gate is modelled using the hyperelasticity model, as Yang and his co-workers [31] have shown that the hyperelasticity model could give better accuracy.

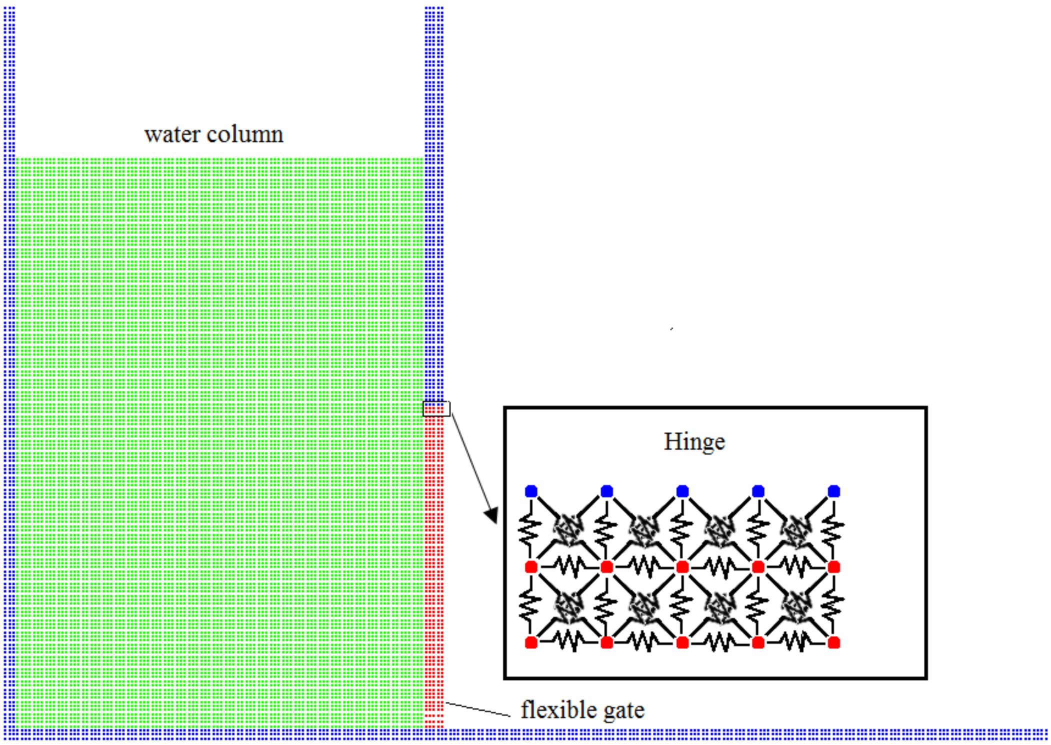
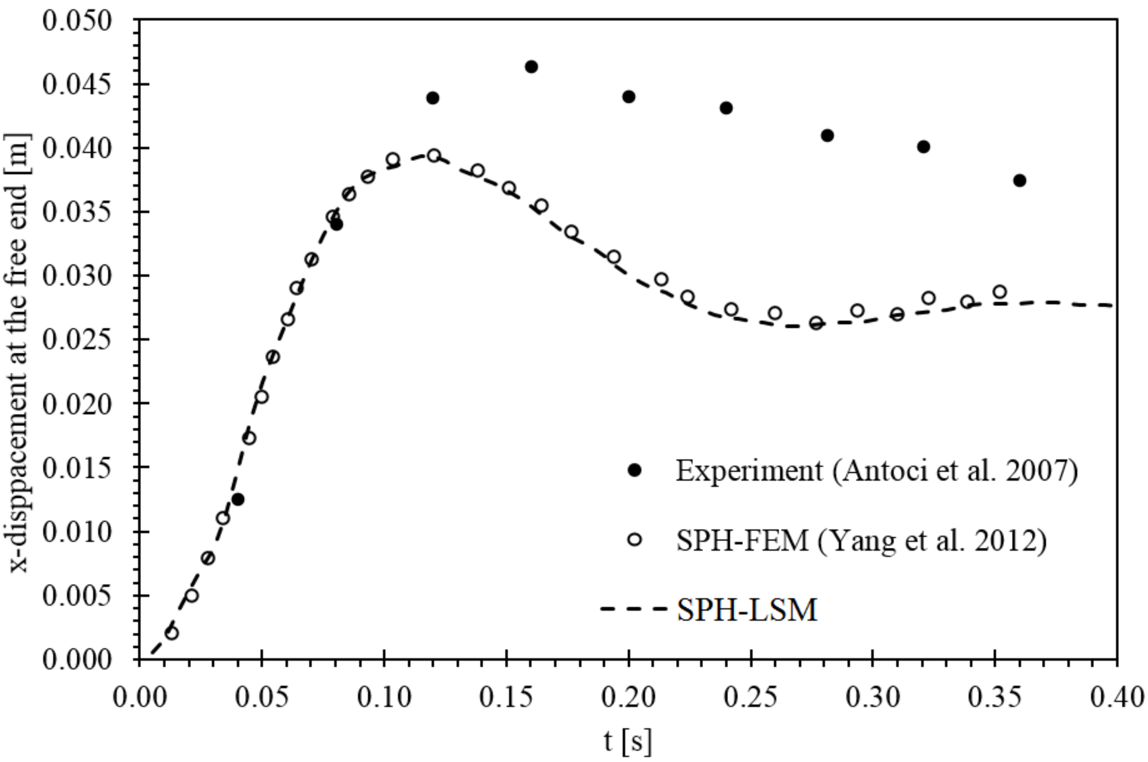
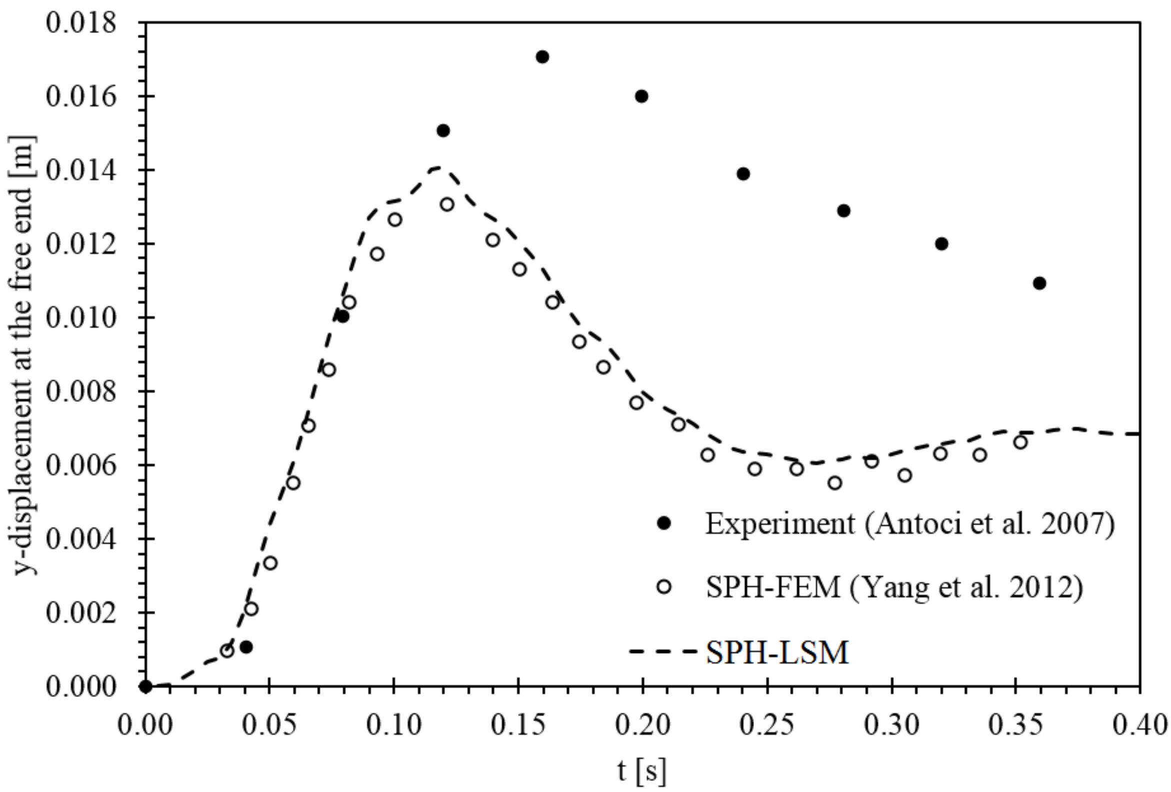


Fig. 2. Initial positions of particles (red: flexible gate; blue: fixed wall; green: water)



(a)



(b)

Fig. 3. x- (a) and y- (b) displacements at the free end of the flexible gate

4. Conclusions

The Smoothed Particle Hydrodynamics (SPH) method has been coupled with the Lattice Spring Model (LSM) method to model Fluid Structural Interaction (FSI) problem. The coupled method has been used to simulate dam break flow through a flexible gate. The numerical results have been compared against those obtained from the SPH-Finite Element Method (SPH-FEM) and good agreement has been found.

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