Large-Scale Parallel Simulation of Coastal Structures Loaded by Tsunami Wave Using FEM and MPS Method

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Abstract. A 3-dimensional large-scale Fluid-Structure Interaction (FSI) framework is developed for the simulation of strength of the coastal structures to withstand tsunami. One-way coupling is used in this framework. Moving Particle Simulation (MPS) is adopted for fluid computations involving free surface flow and Finite Element Method (FEM) is adopted for structural computations. To achieve high parallel efficiency and reduce development costs, the open parallel source named ADVENTURE_Solid is used as the structural analysis solver and LexADV_EMPS is used as fluid analysis solver. Since our proposed framework combines two different numerical methods: FEM and MPS, and distribution of physical values in their methods are differently expressed; therefore interpolation related to fluid forces on fluid-structure interface is required. Accuracy of the interpolation directly affects reliability of result obtained by the FSI simulation. In this study we propose three interpolation methods and quantitatively evaluate their accuracies by solving a benchmark test case. In addition, using an interpolation method that achieves highest accuracy among the three methods, we perform a large-scale parallel FSI simulation of a nuclear power station subjected to a tsunami wave to demonstrate applicability of our proposed framework.

Keywords: Fluid-Structure Interaction, Moving Particle Simulation, Finite Element Method, Parallel Simulation

1. Introduction

Tsunami is one of the most serious natural disasters in coastal areas. Tsunami energy is spread in all directions from the source of earthquake. Buildings in the coastal area are
damaged by the impact of tsunami and this causes serious casualties and economic loss. One of our aims in this research is to evaluate the structural integrity of buildings located in coastal areas. A great deal of research on large-scale tsunami simulation has been conducted based on shallow water equations [1,2] and Navier-Stokes equations with free-surface boundaries [3]. These simulations play an important role to evaluate inundation area and load on buildings. However, for more sophisticated integrity evaluations, numerical simulation of Fluid-Structure Interaction (FSI) analysis of coastal buildings damaged by tsunami wave will be needed; but studies on the FSI analysis involving free-surface flow [4-6] are limited to development of numerical methods and not applicable to real problems.

From the numerical simulation point of view, FSI is a multi-physics phenomenon which occurs in a system involving fluid and structure problems. For the modeling of tsunamis, fluid flow involves free surfaces with complex geometry and moving boundary. Finite Element Method (FEM) is now widely used to numerically solve structural, fluid, and multiphysics problems. However, analyses of tidal waves by FEM have difficulties in dealing with moving boundaries including the free-surfaces [7]. Numerical techniques to the moving boundaries can be classified into two typical categories: interface tracking methods and interface capturing methods. The interface tracking methods including the arbitrary Lagrangian-Eulerian method [8] treats moving boundaries as boundaries of finite elements that move to track them. Though the interface tracking methods are known to provide high accuracy, their applicability is limited in the case of violent motions of boundaries because of remeshing (which is not easy to efficiently parallelize), which is needed to maintain good mesh quality. On the other hand, the interface capturing methods, as exemplified by the volume of fluid (VOF) method [9] and the level set method [10,11], use special functions such as the Heaviside function to describe the interfaces implicitly, and the scalar field of the functions moves by the advection equation. However, it is not easy to keep sharp interface using the interface capturing methods in long-term analyses since artificial diffusivity for stabilization of the advection term makes these functions smooth. On the other hand, mesh-free particle methods such as Moving Particle Simulation (MPS) [12,13] or Smoothed Particle Hydrodynamics (SPH) [14,15] have been used for simulation of free surface flow. MPS or SPH has advantages in dealing with the free surface and the moving boundaries. Currently these methods are also used for structure and FSI problems. However, compared to FEM, it is difficult to obtain local high precision using mesh-free particle methods, especially around surfaces of structure because mesh-free particle methods do not define surface of structure directly.

As a way to take advantage of both the finite element and mesh-free particle methods, this study uses different discretization methods to solve FSI problems. MPS is adopted for fluid analysis and FEM is adopted for structure analysis. Though this strategy to solve FSI problem has advantages, as explained above, but interpolation related to fluid forces on
fluid-structure interface is required because distribution of physical values in their methods are differently expressed. Unlike in the case of using same method for fluid and structure, the way of interpolation is not obvious. In this paper we propose interpolation methods and evaluate their accuracy by solving a benchmark test case.

At the same time, computational resources and parallel computing technology are needed to simulate our target problems. This is because accurate evaluation of the structure interacting with tsunami requires high spatial resolution to handle the complex shape of structure and its interaction with waves. Therefore, one of the numerical challenges for large-scale FSI simulation is to deal with the high computational cost. Parallel technology is indispensable. In order to solve such large-scale problem with high parallel efficiency, this study adopts open parallel sources named ADVENTURE system [16] and LexADV library [17] for large scale FSI simulation. For structural analysis, ADVENTURE_Solid [18] is used, and for fluid analysis, the LexADV_EMPS [19] is used. ADVENUTER_Solid is a finite element analysis solver. The LexADV_EMPS is an explicit MPS solver with a library for dynamic domain decomposition and inter-domain communication. Both the solvers were developed as open source software by ADVENTURE system. The main features of ADVENUTRE_Solid and LexADV_EMPS are suitable for parallel and large scale analysis.

In this paper, we basically discuss interpolation methods between FEM and MPS method based on a one-way coupling situation from fluid to structure. The organization of this paper is as follows. In section 2, we will introduce the large-scale parallel solvers and the calculation for FSI problems. In section 3, three interpolation methods of equivalent nodal load on the fluid-structure interface are discussed. In section 4, we solve the benchmark problems for comparing the calculation accuracy of the three interpolation methods discussed in section 3. In section 5, as a practical problem, we apply our MPS-FEM coupling approach to the turbine building of Fukushima Dai-ichi Nuclear Power Station Unit 1. The stress of the turbine building from tsunami loading is estimated with our MPS-FEM coupling approach. These numerical experiments are done on Japan’s super computer, the K computer.

2. Large-scale parallel solvers and calculation for FSI problems

2.1 Parallel Solvers for MPS and FEM

By applying solution method with weak coupling, high parallel computing performance can be obtained more easily than strong coupling. Total performance can be evaluated by the coupled applications respectively. The MPS-FEM coupling simulation in this study consists of two different applications. As we described in Section 1, for fluid analysis, LexADV_EMPS is used and for structural analysis, ADVENTURE_Solid is used.

LexADV_EMPS is a large-scale parallel explicit MPS method solver framework. The main features of the LexADV_EMPS are two-level domain decomposition, halo exchange
pattern of communication, and dynamic load balancing on the distributed-memory parallel computers. LexADV_EMPS has strong scaling efficiency and has achieved about 90% of parallel efficiency both on the K computer and on the FX100 [20].

The ADVENTURE_Solid module is a finite element method analysis solver designed in the ADVENTURE_Project. The main features of the ADVENTURE_Solid are the Hierarchical Domain Decomposition Method (HDDM) and parallel data processing. High strong scaling efficiency and Good speed up ratio has been obtained on the K computer [21].

### 2.2 One-way coupling of FSI problems

It is assumed that the infinitesimal deformation of structures which means the motion of a fluid flow influences a solid structure, but the motion of structure does not affect the fluid flow field. Our fluid-structure interaction analysis becomes one-way coupling analysis from fluid to structure.

In Fig. 1, the solution procedure is shown for one-way coupling. Initially, the fluid flow calculation is performed by Explicit MPS method [22]. After the calculated pressures are converted into their equivalent nodal forces on the fluid-structure interface the structure problem is solved using ADVENTURE_Solid. After that, the fluid flow for the next time step is calculated. The solution is finished when the time step reaches the predefined maximum number of iteration.

\[
\rho \frac{Dv}{Dt} = \nabla \cdot \sigma + g.
\]  

(1)

In this research, we assume the infinitesimal deformation for structure, and then effects from structural deformation to fluid are negligible. Therefore, we set the FSI problems as the one-way coupling problem between incompressible fluid flow with free surface and structure. In three-dimensional space, the governing equation follows the Cauchy’s first law of motion and can be written in the form
Here \( D/Dt \) means the Lagrange differential, \( \rho \) is the density of continuum, \( \mathbf{v} \) is the velocity vector, \( \sigma \) is the stress tensor, and \( \mathbf{g} \) is the gravitational acceleration vector, respectively.

Using superscripts of \( F \) and \( S \) for distinguishing, \( \sigma^F \) is the stress tensor in the fluid region and \( \sigma^S \) is the stress tensor in the solid region. Assume that the fluid is incompressible, the relationship of stress to strain rate can be described in (2) and (3). The stress tensor of incompressible flow \( \sigma^F \) is given by:

\[
\sigma^F = -p\mathbf{I} + 2\mu \mathbf{D},
\]

where \( p \) is the pressure, \( \mathbf{I} \) is the 2nd-order identity tensor, \( \mu \) is the viscosity coefficient.

The strain rate tensor \( \mathbf{D} \) is defined as follows:

\[
\mathbf{D} = \frac{1}{2} \left( \nabla \mathbf{v} + (\nabla \mathbf{v})^T \right),
\]

where the superscript “\( T \)” means “transpose”.

As we described in Section 2, we assume that deformation of the structures is infinitesimal, which means the motion of a fluid flow influences a solid structure, but the motion of structure does not affect the fluid flow field. Therefore the boundary condition on the fluid-structure interface is given by the following equation:

\[
\sigma^F \mathbf{n} - \sigma^S \mathbf{n} = 0,
\]

where \( \mathbf{n} \) is the outward unit normal vector of the fluid-structure interface. From (4), it can be seen that the forces on the fluid-structure interface satisfy the law of action and reaction. The surface force acting on the structure is expressed as follows:

\[
\mathbf{f} = -\sigma^S \mathbf{n} = -\sigma^F \mathbf{n}.
\]

By using (2), (4) can be equivalently transformed into

\[
\mathbf{f} = -(\mathbf{-pI + 2\mu D}) \mathbf{n}.
\]

In this study, the target structure is the buildings damaged by tsunami. For the target structure, shearing force due to viscosity has less influence than the vertical force due to pressure. Therefore, supposing here the term viscosity can be ignored, and then the second term on the right hand side of (6) is erased, then (7) can be obtained

\[
\mathbf{f} = p \mathbf{n}.
\]

3. Calculation of equivalent nodal forces

In this paper, for the structure analysis, we consider the three-dimensional space which is discretized by the second-order isoparametric tetrahedron element. Figure 2(a) shows the quadratic tetrahedral element which is on the fluid-structure boundary. One quadratic
tetrahedral element contains ten nodes. The area of triangle ABC is on the fluid-structure boundary. The point G is the centroid of the triangle ABC. \( \mathbf{n} \) is the outward unit normal vector to the triangle ABC. Three interpolation methods (Interpolation method A, B and C) are discussed for equivalent nodal force as follows. In the formula of interpolation method A, B and C, the fluid pressure at a particle can be obtained from the MPS fluid analysis. The other variables can be determined in one quadratic tetrahedral element of mesh. The distribution of fluid force on the fluid-structure interface is converted to the equivalent nodal forces of nodes in finite elements. Focusing on an element whose area is \( \Delta \), the equivalent nodal forces corresponding to node \( i \), \( \mathbf{F}_i \), is defined as follows:

\[
\mathbf{F}_i = \int_{\Delta} q N_i dS
\]  

where \( q \) is the distributed load and \( N_i \) is the shape function of node \( i \).

![Diagram showing finite elements and fluid particles in the MPS-FEM method](image)

Figure 2: Finite elements and fluid particles in the MPS-FEM method

3.1. Interpolation method A

The pressure function \( p(x) \) on the fluid-structure boundary can be calculated as follows:

\[
p(x) = \frac{\sum_{i} \omega(x)^{(i)} p^{(i)}}{\omega(x)^{(i)}} ,
\]

where \( \omega(x)^{(i)} \) is the weight function of MPS, \( p^{(i)} \) is the fluid pressure at a particle \( i \). In this interpolation method A, we assume pressure distribution is constant in the surface element, and the pressure value \( p_{ABC} \) is calculated as a pressure at the centroid \( x_g \) as follows:

\[
p_{ABC} = p_{g} = p(x_g).
\]

Next, the effect of the pressure \( p_{ABC} \) is applied to the structure through nodal forces on the nodes. The number of the nodes is shown in Fig. 2(b). The shape functions \((N_1-N_6)\) can be physically presented by volumetric coordinates \(L_1,L_2,L_3\), to each node are written as follows:
Here, \( L_i = S_i/S \) where \( S \) is the area of the triangular ABC and \( S = S_1 + S_2 + S_3 \) as shown in Fig. 2.

When the uniform distribution \( p_{ABC} \) is loaded to the surface ABC, the nodal force on the primary nodes \( (F_2 \) and \( F_3 \) are as same as \( F_1 \)) and secondary nodes \( (F_5 \) and \( F_6 \) are as same as \( F_4 \)) can be computed as follows:

\[
F_1 = n p_{ABC} \int_\Delta L_2 (2L_1 - 1) |J| dS \\
= n p_{ABC} 2S \left( \int_\Delta (2L_1^2 - L_1) dL_1 dL_2 \right) \\
= 0,
\]

\[
F_4 = n p_{ABC} \int_\Delta 4L_1 L_2 |J| dS \\
= n \frac{p_{ABC} S}{3}.
\]

where \( \Delta \) is the domain of the triangle ABC, \( J \) is the Jacobian matrix which is converted from the element coordinates to the area coordinates and \( |J| = 2S \).

### 3.2. Interpolation method B

In the interpolation method A, the pressure \( p_{ABC} \) is calculated from the pressure, which is loaded on the fluid-structure boundary, the centroid (G point) of the triangle ABC. In this interpolation method B, the pressure \( p_{ABC} \) is the average value of the pressure which is loaded on the centroid (G point) and all of the 6 nodes:

\[
p_{ABC} = \frac{p_g + \sum_{j=1}^{6} p_j}{1 + N},
\]

where \( N \) is the total number of nodes, here \( N = 6 \). \( p_g \) is the value of pressure which is loaded on the centroid, \( p_j \) is the pressure loaded on the each node, respectively. According
to (9), \( p_g \) and \( p_j \) are also given by:
\[
p_g = p(x_g),
\]
\[
p_j = p(x_j)(j = 1, 2, \ldots, 6).
\]
Then the equivalent nodal force is calculated as same as (12) and (13):
\[
F_1 = F_2 = F_3 = 0,
\]
\[
F_4 = F_5 = F_6 = n\frac{P_{ABC}S}{3}.
\]

### 3.3. Interpolation method C

In the interpolation method C, the equivalent nodal force \( f_k^s \) means the \( k \)th local nodes of the \( s \)th triangle ABC element. According to (7), \( f_k^s \) is defined as follows:
\[
f_k^s = \int_{\Gamma_s} p(x)nN_k \, d\Gamma,
\]
where \( \Gamma_s \) is the surface region ABC of the quadratic tetrahedral element which is on the fluid-structure boundary, \( p(x) \) is the pressure distribution on the region ABC, \( N_k \) is the shape function of the \( k \)th local node which is based in 2nd-order Lagrange polynomial, respectively.

Considering a quadratic tetrahedral element which is on the fluid-structure interface, the triangular element in the \((x, y)\)-plane can be mapped to a triangle in the \((\xi, \eta)\)-plane as shown in Fig.3. Then (19) can be transformed in the form:
\[
f_k^s = \int_{\Gamma_s} p(x(\xi))N_k(\xi)n|\gamma| \, d\Gamma,
\]
where \( J \) is the Jacobian matrix which is converted from the element coordinates to the area coordinates, defined as follows:
\[
dx = Jd\xi,
\]
\[
J = \frac{\partial x}{\partial \xi}.
\]

In the Fig. 3 the integration points \( \xi_{1}^{ip}, \xi_{2}^{ip}, \xi_{3}^{ip} \) determined based on the Gaussian quadrature are shown by the red cross. Using the Gauss numerical integration formula, (20) can be written by
\[
f_k^s = \sum_{i=1}^{3} |\gamma|p(x(\xi_i^{ip}))N_k(\xi_i^{ip})n\omega_i^{ip} = 2S_3n \sum_{i=1}^{3} p(x(\xi_i^{ip}))N_k(\xi_i^{ip})\omega_i^{ip},
\]
where \( \omega_i^{ip} \) is the weight of the Gauss quadrature corresponding to \( i \)-th integration point.
4. Numerical example for verification (model of 3-D hydrostatic pressure problem)

We consider the hydrostatic pressure problem for the benchmark to demonstrate the accuracy of the interpolation method A, B and C which is described in section 3: a container is filled with water and the dimensions are shown in Fig. 4.

The FSI analysis is performed as follows: for the fluid analysis, hydrostatic pressure is calculated by LexADV_E_MPS. On the fluid-structure interface, the nodal forces on the right side wall are converted by the computed pressure using the interpolation method A, B, and C, respectively. The structure analysis of the right side wall is calculated by ADVENTURE_Solid.

4.1. Analysis conditions of the fluid analysis

Here the zero point is defined on the bottom of the container, and the height of the fluid is 0.7 m. The hydrostatic pressure can be computed as follows:

\[ p = \rho |g|(0.7 - h), \]

where \( p \) is the hydrostatic pressure, \( \rho \) is the density of the liquid, \( g \) is the acceleration due to gravity, \( h \) is the height from the surface or the depth, respectively.

For the calculation A, B and C, the calculation conditions used in the fluid analysis are listed in Table 1. In the Explicit MPS method, weak compressibility caused vertical vibrations of the fluid surface. We choose a relatively high value for the kinematic viscosity to reach the static state as quickly as possible [23]. The value of five seconds (10,000th step) is regarded as the steady-state value. Four processors are used for the parallel computing.
4.2. Analysis conditions of the structure analysis

The analysis conditions of the structure analysis are shown in Table 2. Two processors are used for the parallel computing. The mesh of the analysis model is first subdivided into two parts. Then, each part is further subdivided into ten subdomains. The number of subdomains is determined by an existing study on convergence property of HDDM [24].

Table 2: Analysis conditions of the solid problem

|                        |         |
|------------------------|---------|
| Number of quadratic tetrahedral elements | 384     |
| Number of nodes         | 7433    |
| Young’s modulus [kg/s²/m] | $2.0 \times 10^{11}$ |
| Poisson’s ratio         | 0.3     |
| Structure density [kg/m³] | $7.0 \times 10^{3}$ |
| Number of parts         | 2       |
| Number of subdomains    | 10      |
4.3. Verification test

In order to compare the calculation accuracy of interpolation method A, B and C, the calculated results of displacement in the x-direction of the right side wall are compared to reference solutions.

As reference solutions, a structure analysis is considered as shown in Fig. 5. Here the dimensions of the wall shown in Fig. 5 are as same as Fig. 4. For the boundary conditions, the bottom of the wall is fixed and the theoretical hydrostatic pressure calculated by the Equation (22) is applied to the structure through nodal forces. The displacement in the x-direction of the wall is calculated by structure analysis as the reference solution.

The relative errors between the calculated solutions and the reference solutions are shown in Fig.6. While relative errors given by all the three interpolation methods are less than 4.0%, the interpolation method C achieves a better agreement compared with the interpolation method A and B. This is because the three integration points reproduce higher-order distribution of pressure on the fluid-structure interface. In addition, the interpolation method C can be generalized to the cases with more integration points based on the Gaussian quadrature. The advantage in accuracy compared with other methods would become significant in such the cases.

![Figure 5: boundary conditions of the solid model](image1)

![Figure 6: Relative error of displacement in x-direction](image2)

5. Large-scale MPS-FEM coupling simulation

A practical large-scale MPS-FEM coupling simulation is executed on the K computer. The simulation target is the turbine building of Fukushima Daiichi Nuclear Power Station Unit 1. We will never forget the day and the powerful earthquake, Great East Japan Earthquake (magnitude 9.0), which struck Japan in 2011. The earthquake caused the large tsunami, which
severely damaged the Tohoku area. According to investigation, height of the tsunami running-up to the land reached 40.0m and was recorded as the highest in Japan [25]. The Fukushima nuclear power plant was affected by the flood, causing a major nuclear disaster. In this research, we apply our MPS-FEM coupling approach to the turbine building of Fukushima Daiichi Nuclear Power Station Unit 1. Figure 7 shows the location of the earthquake’s epicenter and the Fukushima Daiichi Nuclear Power Station. The distance from the epicenter to Fukushima Daiichi Nuclear Power Station is about 75km.

Figure 7: The location of the earthquake’s epicenter and the Fukushima Daiichi Nuclear Power Station (The images are from the Google Map [26])

The stress on the turbine building due to tsunami loading is estimated with our MPS-FEM coupling approach. According to the results of verification test in section 3, interpolation method C is adopted for this practical simulation. The FSI simulation has been done in three stages. First, the tsunami propagation analysis from epicenter to coastal area has been done by the two-dimensional shallow-water analysis. Using the analysis result obtained in the first analysis stage, the inflow and outflow boundary conditions are generated for the second analysis stage. Second, the tsunami inundation analysis of turbine building of Fukushima Daiichi Nuclear Power Station Unit 1 has been done by LexADV_EMPS [27]. In the second analysis stage, the entire analysis region is set as shown in Fig. 8. The turbine building is marked with red circle. Figure 9 shows the model of the turbine building. Finally, using the results of MPS, the stress of the turbine building from fluid pressure is calculated before the tsunami flowed into the turbine building. In this research, the second stage is carried out again on K computer with larger number of particles.

In the fluid computation, the total number of particles for the fluid computation is about 1.3 billion particles and the initial particle distance is 0.1m until the tsunami inundated into the turbine building. In the structure computation, the stress of turbine building is analyzed by
ADVENTURE_Solid. In the structure computation, the mesh of turbine building consists of 2,800,861 nodes and 1,694,962 quadratic tetrahedral elements. 4,800 processors are used for parallel computing. The result of the MPS-FEM simulation is shown in Fig.10. In Fig. 10, the stress concentration occurs around the place of the large object carrying-in entrance. The result is in line with the report of Nuclear Regulation Authority [28] in which the tsunami invasion was from this entrance after the destruction of the door.

Figure 8: Coastal model of Fukushima Daiichi Nuclear Power Station

Figure 9: The model of the turbine building

Figure 10: The result of the MPS-FEM simulation

6. Conclusions

In this study, we developed an MPS-FEM coupled system for 3-D large scale FSI simulation. The parallel software of LexADV_EMPS and ADVENTURE_Solid was used for fluid analysis and structure analysis respectively. The proposed MPS-FEM coupled system was tested with the help of hydrostatic pressure problem. From the simulation results, it is verified that the proposed interpolation method can achieve more accuracy and the computation cost
is not so high. Furthermore, the practical application of the developed system was shown by actual tsunami impact on the turbine building of Fukushima Dai-ichi Nuclear Power Station Unit 1. In future, we plan to check the verification and validation of this Fukushima Dai-ichi model. In this study, the infinitesimal deformation of structures is assumed and one-way coupling calculations are considered. However, in some situations two-way coupling calculations must be considered such as the fluid flow is also affected by structural deformation. Future work is needed to extend our developed system to two-way coupling calculations.

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