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Fundamental study for wash out simulation of bridge girders by using a particle method

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ABSTRACT

On March 11, 2011, the huge tsunami caused by the great east Japan earthquake devastated many infrastructures in pacific coast of north eastern Japan. Particularly, the damage of outflow of bridge girders caused a traffic disorder and these collapse behaviors led to delay of recovery after the disaster. In this study, the bridge wash away accident is selected as a target issue, and it is represented by a numerical simulation. For this purpose, Smoothed Particle Hydrodynamics (SPH) Method, which is one of the pure mesh free methods, is utilized for the free surface flow analysis and also for the rigid body motion simulation. .

The key features of our developed code are a stabilization technique for the Incompressible SPH (ISPH) and its high performance computation for the large scale models. In this study, rigid body motion is introduced for the fluid-structure interaction behavior during bridge wash away simulation. In the numerical analysis, fluid impact force acted on the upper bridge structure is measured for the fixed bridge model as a first step. And then the upper bridge structure, modeled as a rigid body, is washed away by receiving an impact fluid force. The wash away simulation of the bridge girder in its real scale showed good agreement with the real accident on the great east Japan earthquake tsunami.

1. INTRODUCTION

On March 11, 2011, the huge tsunami caused by the great east Japan earthquake devastated many infrastructures in pacific coast of north eastern Japan. Particularly, the damage of outflow of bridge girders caused a traffic disorder and these collapse behaviors led to delay of recovery after the disaster. After 2011 tsunami, disaster prevention and mitigation techniques are actively developing in coastal infrastructures and establishing prediction method for tsunami disaster is one of the severe issues toward the next millennium tsunami.

In this study, the bridge wash out accident is selected as a target issue, and we try

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to represent these accidents by using a numerical analysis. For this purpose, one of the mesh free methods; Smoothed Particle Hydrodynamics (SPH) Method is utilized for Tsunami flow. The SPH technique was originally proposed by Lucy (1977) and further developed by Gingold and Monaghan (1977) for treating astrophysical problems. Its main advantage is the absence of a computational grid or mesh since it is spatially discretized into Lagrangian moving particles. This allows the possibility of easily modeling flows with a complex geometry or flows where large deformations or the appearance of a free surface occurs. Recently, this method is widely used in field of fluid and solid dynamics.

A stabilized ISPH, which is one of the modified versions of the SPH and can evaluate much smoothed pressure distribution acted on the structure, has been developed by our research group. Then a fluid-solid interaction algorithm including rigid body motion is developed in this study. One of the segments of a bridge girder, which was washed away in the tsunami, is selected as a target structure. The wash out simulation of the bridge girder shows good agreements with our predictions.

2. IMPROVED ISPH

In this section, a stabilized ISPH as Asai et al. (2012), which includes a modified source term in the pressure Poisson equation, for incompressible flow, is summarized.

2.1 Governing equation

The governing equations are the continuum equation and the Navier-Stokes equation. These equations for the flow are represented as

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{u} + \frac{1}{\rho}\nabla \cdot \boldsymbol{\tau} + \mathbf{F} \tag{2}$$

where ρ and ν are density and kinematic viscosity of fluid, $\boldsymbol{u}$ and p are the velocity and pressure vectors of fluid respectively. $\boldsymbol{F}$ is external force, and t indicates time. The turbulence stress τ is necessary to represent the effects of turbulence with coarse spatial grids. In the most general incompressible flow approach, the density is assumed by a constant value with its initial value.

2.2 Modification in the source term of pressure Poisson equation

The main concept in an incompressible SPH method is to solve a discretized pressure Poisson equation at every time step to get the pressure value. In a sense of physical observation, physical density should keep its initial value for incompressible flow. However, during numerical simulation, the 'particle' density may change slightly from the initial value because the particle density is strongly dependent on particle locations in the SPH method. If the particle distribution can keep almost uniformity, the difference between 'physical' and 'particle' density may be vanishingly small. In other words, accurate SPH results in incompressible flow need to keep the uniform particle distribution. For this purpose, the different source term in pressure Poisson equation can be derived using the ‘particle’ density. The SPH interpolations are introduced into the original mass conservation law before the perfect compressibility condition is applied.

$$< \nabla \cdot \boldsymbol{u}_i^{n+1} > \; = -\frac{1}{\rho^0} \frac{< \rho_i^{n+1} > - < \rho_i^{*} >}{\Delta t} \tag{3}$$

Then, the pressure Poisson equation reformulated as:

$$< \nabla^2 p_i^{n+1} > \; = \frac{\rho^0}{\Delta t} < \nabla \cdot \boldsymbol{u}_i^{*} > + \alpha \frac{\rho^0 - < \rho_i^{*} >}{\Delta t^2} \tag{4}$$

where α is relaxation coefficient, $\boldsymbol{u}_i^{*}$ is temporal velocity and triangle bracket < > means SPH approximation. Note that this relaxation coefficient is strongly dependent on the time increment and the particle resolution. Then, the reasonable value can be estimated by the simple hydrostatic pressure test using the same settings on its time increment and the resolution.

3. REAL SCALE SIMULATION

In the following section, the result of the real scale simulation by using a stabilized ISPH is introduced. Then, the mechanism of the bridge wash out accident is considered from the evaluation of fluid force.

3.1 Analysis model

The detail of girder model are shown in Fig.1. This three dimensions girder model is generated from CAD data of Utatsu Bridge which is in Minamisanriku-cho, Miyagi prefecture. This bridge is one of bridges received damage by east Japan earthquake disaster, and one of segments of a bridge 8th segment which was washed out is selected in this analysis. The wave is modeled for two cases: a surge stream and a gentle stream as shown in Fig.2. Initial water level is set to be 15 m. The initial velocity of the wave is set 10 m/s referring to shallow water long-wave equation. In addition, the initial wave velocity 10 m/s is continuously given at the position of 50m and 30m from the left corner of the water storage in case of a surge and gentle stream respectively. The depth of the girder model is 10.0 m. The bridge girder model is on a bridge pier model, and both are fixed. The particle distance d = 6cm, time increment t = 0.001s and the total number of particles is about 55 millions.

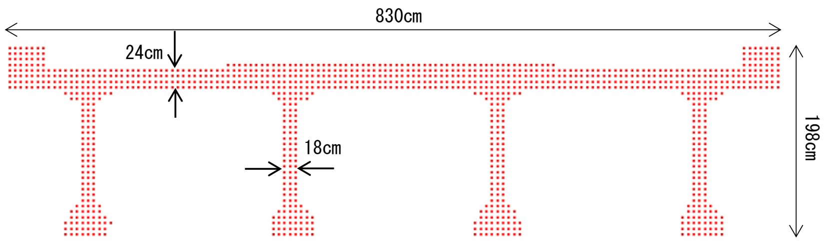
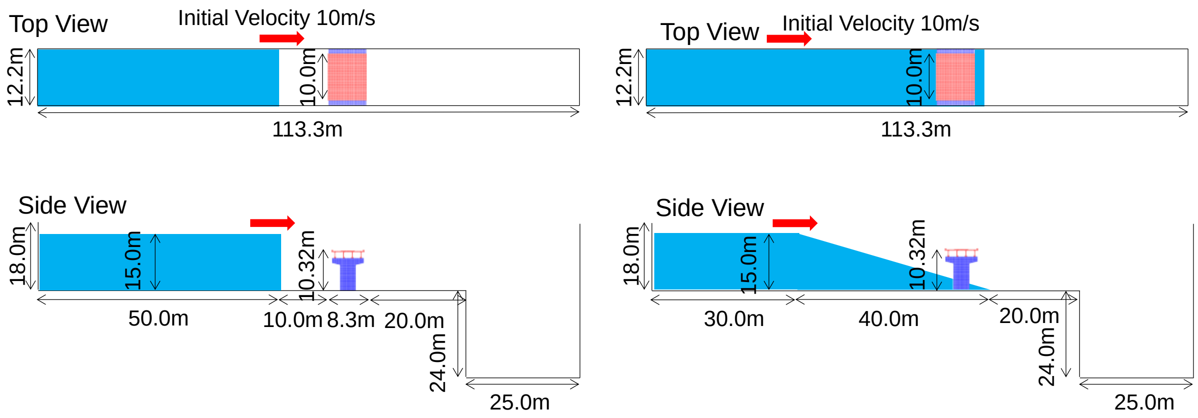


Fig.1 Detail of the bridge girder model

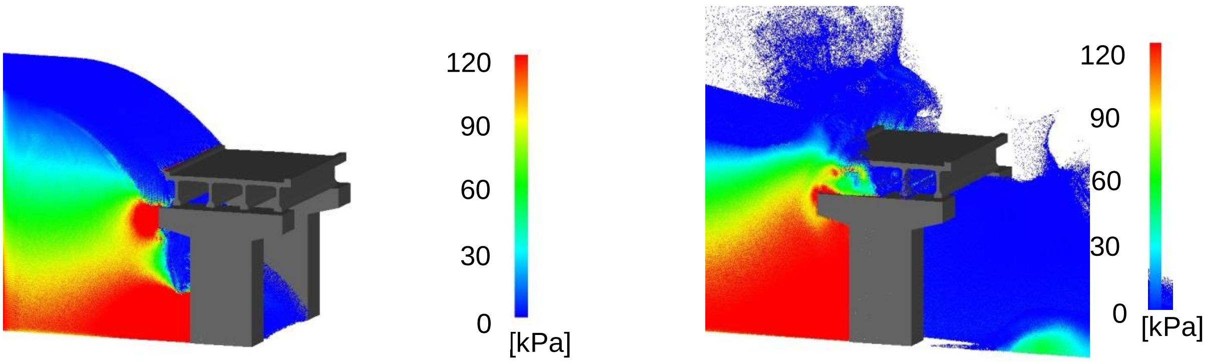


(i) Surge stream (ii)Gentle stream

Fig. 2 Analysis model

3.2 Result

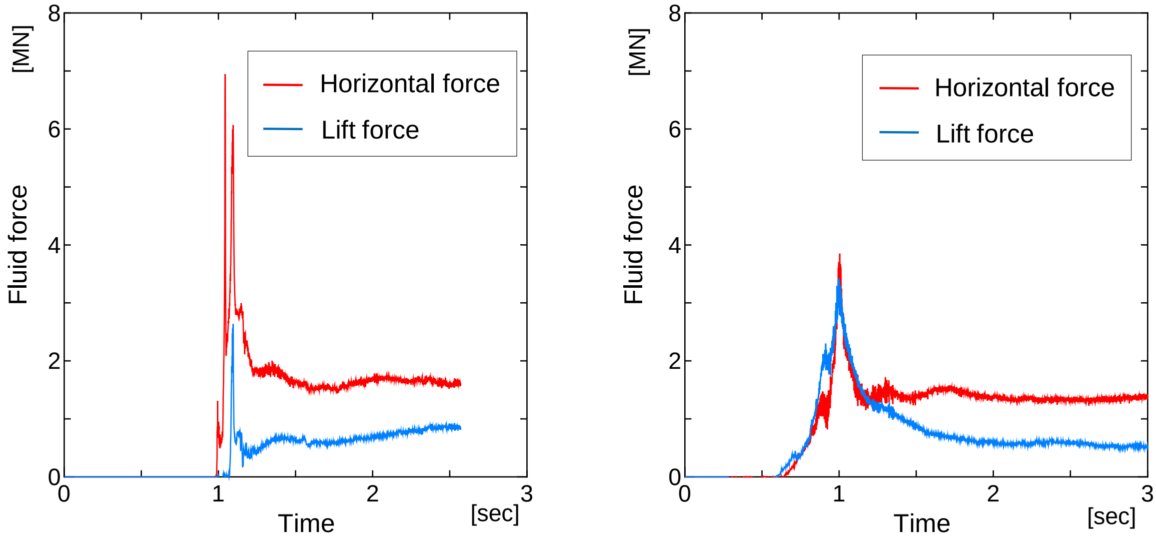
Fig.3 shows snapshots of the appearance of water near the bridge model in case of a surge stream and a gentle one. The contour of these picture shows pressure of water particles and the unit is [kPa]. Focus on the pressure, water pressure is in static pressure distribution before bumping against the bridge model, and water particle attacking bridge model show high pressure. These facts show that, the current analysis can calculate water action qualitatively. In this analysis, we can't validate the value of pressure, while the current ISPH algorithm was validated with a good accuracy for fluid force compared to experimental result in small model Asai et al. (2012).



(i)Surge stream (time=1.2sec) (ii)Gentle stream (time=1.1sec)

Fig .3 Snapshots for the water flow near the bridge model

Fig.4 shows fluid force affecting to the bridge model in two cases. In case of a surge stream, horizontal force is much higher than lift force, so we can predict that the bridge girder model is washed out as pushed out by horizontal force and rotate a little by lift force. On the other hand, lift force is as large as horizontal force in case of a gentle force. So there is an assumption that the girder model is detach from the pier model by lift force, then it is washed out by horizontal force.



(i)Surge stream (ii)Gentle stream

Fig. 4 Comparison of fluid force

4. WASH OUT SIMULATION OF BRIDGE GIRDER

Finally, fluid-rigid coupling analysis is conducted by introducing rigid motion algorithm.

4.1 Fluid-rigid coupling algorithm

Koshizuka et al. (1998) proposed a passively-moving solid model to describe the motion of a rigid body in a fluid. According to this study, the treatment of the moving rigid body in the fluid can be divided into two steps. First, both the fluid and solid particles are solved via the same calculation procedures. Secondly, an additional procedure is applied to solid particles.

Considering *n* solid particles with location, $\boldsymbol{r}_k$, the center of the solid object, $\boldsymbol{r}_c$, and the relative coordinate of a solid particle to the center, $\boldsymbol{q}_k$, the moment of inertia, $\boldsymbol{I}$, of the solid object can be calculated.

$$\boldsymbol{r}_c = \frac{1}{n}\sum_{k=1}^{n}\boldsymbol{r}_k, \tag{5}$$

$$\boldsymbol{q}_k = \boldsymbol{r}_k - \boldsymbol{r}_c, \tag{6}$$

$$\boldsymbol{I} = \sum_{k=1}^{n}\left|\boldsymbol{q}_k\right|^2, \tag{7}$$

The translational velocity, $\boldsymbol{T}$, and rotational velocity, $\boldsymbol{R}$, of a solid object are calculated as:

$$\boldsymbol{T} = \frac{1}{n}\sum_{k=1}^{n}\boldsymbol{u}_k, \tag{8}$$

$$\boldsymbol{R} = \frac{1}{\boldsymbol{I}}\sum_{k=1}^{n}\boldsymbol{u}_k \times \boldsymbol{q}_k, \tag{9}$$

Finally, the velocity of each particle in the solid body can be expressed as

$$\boldsymbol{u}_k = \boldsymbol{T} + \boldsymbol{r}_k \times \boldsymbol{R}, \tag{10}$$

With the above rigid body correction, the motion of a free-moving object can be computed. Gotoh and Sakai (2006) and Shao (2009) showed that the above treatment can be applied to a free-falling wedge in water, and it works well in a stable computation where the Courant condition is satisfied. Fig. 5 shows the algorithm for the fluid-rigid coupling using stabilized ISPH method. A part of the results for wash out simulation of bridge girders is introduced.

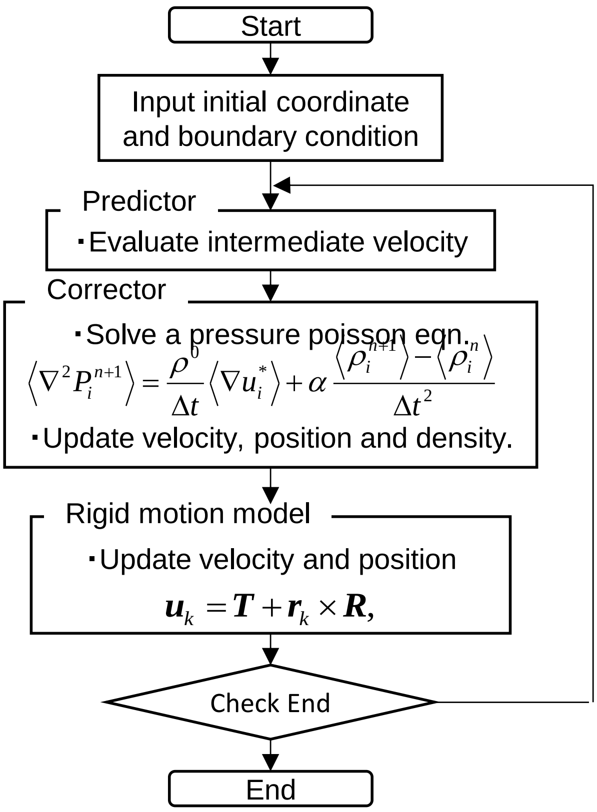


Fig. 5 Fluid-rigid coupling algorithm

4.2 Analysis model

The shape of this analysis model is same as one of the real scale simulation. The girder model of this simulation isn't fixed and move by above equation. The density of particles of the girder model is 24.5 kg/m^3 referring to the density of reinforced concrete.

4.3 Result

Fig. 6 shows the snapshot of wash out simulation in case of gentle stream. At the present stage, this analysis proceed until 1.6 second in real time, but this algorithm can represent that the bridge girder model rotate and is pushed out. In the future work, the accuracy and efficiency of this algorithm will be validated by comparison between a numerical solution and experimental results.

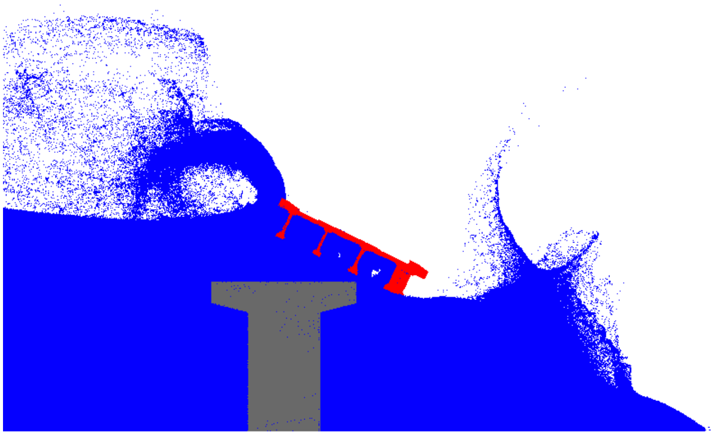


Fig. 6 Snapshot of moving girder model (time=1.55sec)

5. CONCLUSION

In the real scale simulations, the fluid impact force acted on the fixed bridge girder model is measured by using a stabilized ISPH. The fluid impact force in the cases of a surge stream and a gentle one are compared. In wash out simulation, stabilized ISPH with fluid-rigid coupling algorithm can represent the motion of bridge girder, and it shows good agreements with the accident report on March 11, 2011. The verification and validation of this simulation technique are unavoidable as our future work, before the simulation may apply to the design of bridge for huge Tsunami.

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