EVALUATION FOR THE SAFETY OF TSUNAMI REFUGE BUILDING BY FLUID- RIGID COUPLED ANALYSIS BASED ON THE PARTICLE METHOD

Kyushu University Student Member ○Yi Li
Kyushu University Regular Member Mitsuteru Asai

1. OBJECTIVE

After the Great East Japan Earthquake in 2011, it is necessary to improve the coastal area's disaster prevention and mitigation technology. Recently, tsunami refuge buildings are constructed all around Japan and to select a good design for these structures is important. It is known that the piloti in the lower floor of a building can reduce the damage from tsunami. However, this design has the possibility to pull floating objects in and cause more serious damage to the building. In this paper, a fluid-rigid body interaction simulator based on the stabilized incompressible smoothed particle hydrodynamics method is utilized to evaluate the safety of tsunami refuge building during tsunami.

2. METHODOLOGY

2.1 SPH method

In this research, to do simulation with large deformation in 3-D dimension, SPH method (Smoothed Particle Hydrodynamics, a kind of particle method) is applied. In SPH method, a target continuum is discretized into a number of particles. The physical quantity of a target particle is approximated by summing relevant properties of all the particles within its range of the kernel as shown in Fig-1. The physical quantity of a target particle located at $\boldsymbol{x}$ is approximated by Eq.(1)

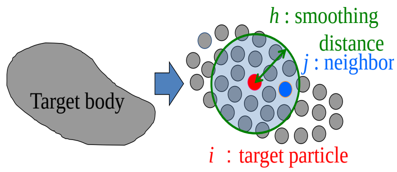

Fig-1 Concept of SPH method

$$f(\boldsymbol{x}) = \sum_{j=1}^{N} \frac{m_j}{\rho_j} f(\boldsymbol{x}_j) W(\boldsymbol{x} - \boldsymbol{x}_j, h), \tag{1}$$

where m_j, ρ_j, $\boldsymbol{x}_j$ and W represent mass, density, position of particle j and weight function respectively. The governing equations Naiver-Stokes equation and Continuity equation are resolved. Pressure value is calculated implicitly and velocity is updated explicitly, and to keep the density of fluid invariant, Stabilized incompressible SPH method is applied.

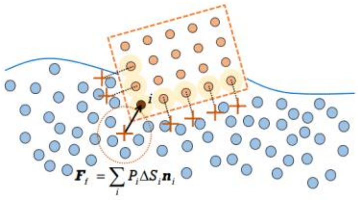

Fig-2 calculation for hydrodynamic force

2.2 Fluid-Rigid interaction analysis

In this research, the motion of rigid body is influenced by its gravity, hydrodynamic force and boundary force from the wall or other rigid bodies. Except gravity, both the hydrodynamic force and boundary force act on the rigid surface, so the rigid body can be considered as a moving boundary surface.

(1)Hydrodynamic force and momentum

Without the penetration of water particles, the hydrodynamic force $\boldsymbol{F}_f$ and momentum $\boldsymbol{M}_f$ acting on the rigid particle i can be calculated as,

$$\boldsymbol{F}_f = \sum_i P_i \Delta S_i \boldsymbol{n}_i, \tag{2}$$

$$\boldsymbol{M}_f = \sum_i \boldsymbol{r}_i \times P_i \Delta S_i \boldsymbol{n}_i, \tag{3}$$

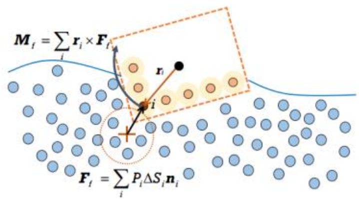

Fig-3 calculation for hydrodynamic moment

where P_i, ΔS_i, $\boldsymbol{n}_i$ and $\boldsymbol{r}_i$ mean hydrodynamic pressure, the area influence by the pressure, normal of the rigid particle i and distance from rigid body's center of gravity to particle i, as shown in Fig-2 and Fig-3.

(2)Contact force between rigid particles

The contact force $\boldsymbol{Fc}$ implemented on the rigid body can be decomposed into normal component $\boldsymbol{Fn}$ and shear component $\boldsymbol{Fs}$. The normal force $\boldsymbol{Fn}$ is modeled by using penalty-based linear damped-spring system based on the classical Hertzs theory as shown in Fig-4. And it can be decomposed into a repulsive force $\boldsymbol{F}_n^r$ and a damping force $\boldsymbol{F}_n^d$ as Eq.(4)

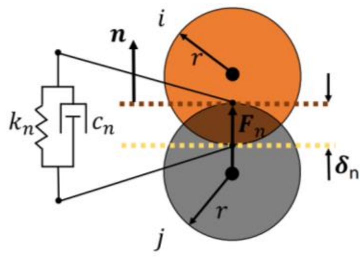

Fig-4 Diagram for normal contact force

$$\boldsymbol{F}_n = \boldsymbol{F}_n^r + \boldsymbol{F}_n^d = k_n \boldsymbol{\delta}_n + c_n \dot{\boldsymbol{\delta}}_n, \tag{4}$$

where the stiffness constant k_n and the damping constant c_n are given by,

Keyword Stabilized ISPH method, Fluid-Rigid Interaction, Evaluation for refuge building's safety
Address 744 Motooka Nishi-ku Fukuoka, Japan 8190395

$$k_n = \frac{4\sqrt{r}}{3}\frac{E_iE_j}{\left(1-\nu_i^2\right)E_j + \left(1-\nu_j^2\right)E_i}\sqrt{|\delta_n|}, \quad (5)$$

$$c_n = -2\frac{\ln(\epsilon)}{\sqrt{\pi^2 + \ln(\epsilon)^2}}\sqrt{Mk_n}. \quad (6)$$

In the above equations, r means the particle radius, ϵ is the coefficient of restitution, ν and E represent the Poisson's ratio and the Young's modulus of the particles i and j which contact with each other.
The tangential contact force is modelled by the linear damped-spring model, coupled with a sliding friction element as shown in Fig-5, which can be written as,

$$\boldsymbol{F}_s = \min\left(\mu\|\boldsymbol{F}_n\|, \boldsymbol{F}_s^r + \boldsymbol{F}_s^d\right)\boldsymbol{s}, \quad (7)$$

where μ is the sliding friction coefficient at the contact surface. k_s and c_s is defined as,

$$k_s = 8\sqrt{r}\frac{E_iE_j}{2(2-\nu_i)(1+\nu_i)E_j + 2(2-\nu_j)(1+\nu_j)E_i}, \quad (8)$$

$$c_s = c_n. \quad (9)$$

(3)Quaternion and Rotation
In this research, unit quaternion is applied to represent the rotation of the rigid body. A rotation of θ radians about a unit axis $\boldsymbol{l}$ is represented by the unit quaternion $\boldsymbol{q}$ as,

$$\boldsymbol{q} = \left[\cos\left(\frac{\theta}{2}\right), l_x\sin\left(\frac{\theta}{2}\right)\boldsymbol{i}, l_y\sin\left(\frac{\theta}{2}\right)\boldsymbol{j}, l_z\sin\left(\frac{\theta}{2}\right)\boldsymbol{k}\right], \quad (10)$$

where $\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$ represent the unit vector directed along x, y, z axis.
To rotate a vector $\boldsymbol{v}^n$ by unit quaternion, the quaternion product can be calculated as,

$$\boldsymbol{v}^{n+1} = \boldsymbol{q} \wedge \boldsymbol{v}^n \wedge \boldsymbol{q}^{-1}, \quad (11)$$

where $\boldsymbol{v}^{n+1}$ represents the vector after rotation and $\boldsymbol{q}^{-1}$ is equal to the conjugate of quaternion $\boldsymbol{q}^*$.

3. ANALYSIS MODEL AND RESULTS

By using the method mentioned above, the motion caused by the fluid influence is discussed. The analysis model is shown in Fig-6. The floating object and structure in the model are a boat and a building. There are 2 kinds of structure model, a building with piloti and a building without piloti as shown in Fig-7. In the simulation, with 0.20m particle diameter the number of particles is about 15million. With 0.001s time increment, result of 40 seconds in the physical time is completed by supercomputer-K.
The comparison of the results is shown in Fig-8. In the 9.5s's result of the building model without piloti(right side), the water particles jump up much higher than the result in the left hand side. And from 10.5s to 12.0s, different from the result of the building with piloti where the floating object crashed into the structure, in the result of the building without piloti, the floating object doesn't impact the structure.

4. CONCLUSION

In this research, by using Stabilized ISPH method, the safety of the tsunami refuge building is evaluated. The building with piloti can reduce the hydrodynamic pressure from the tsunami because the water go through the piloti. While the floating object will be pulled into the building due to the inundation in the lower floor and cause collision with the structure. The collision occurs directly in the front of the structure.
In the future, other inflow conditions including several number of floating objects will be taken into account, and a stochastic evaluation of the safety should be discussed.

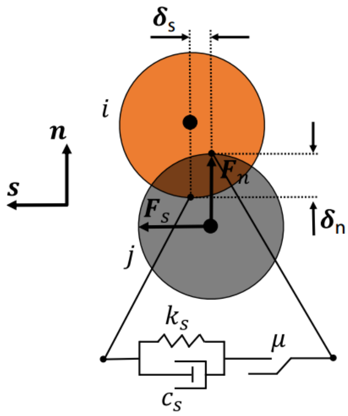

Fig-5 Diagram for tangential contact force

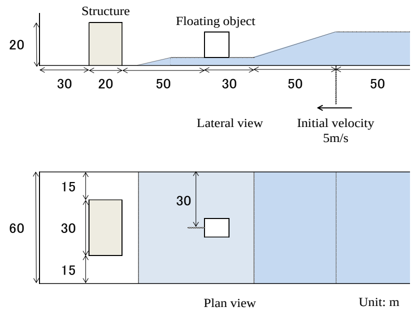

Fig-6 Concept for the analysis model

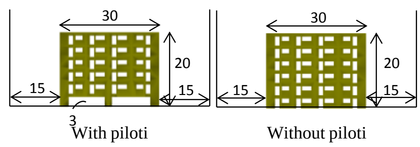

Fig-7 Diagram for the building model

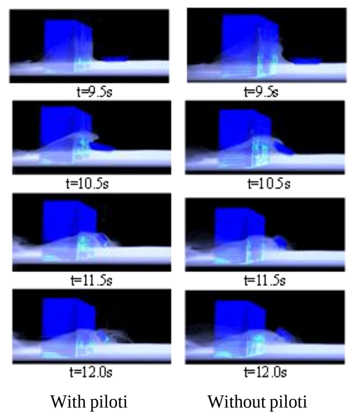

Fig-8 Comparison of the results with different building model