NUMERICAL SIMULATION OF TSUNAMI FORCE ACTING ON A FLOATING/SUBMERGED TSUNAMI SHELTER

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Abstract. After the Tohoku earthquake tsunami in Japan, many evacuating options from huge tsunami, e.g. tsunami tower, large building, moving onto hill, super-sized breakwater, underground shelter and small lifeboat, have been proposed in recent years. This disaster is one of the strongly nonlinear coupled interactions problem between wave and structures. We have proposed and developed one kind of a large-sized tsunami shelter with mooring that is capable of accommodating at least one hundred people or more to evacuate from run-up tsunami. Using the particle method, SPH, to evaluate the optimized configuration for reducing tsunami force and its motions due to tsunami attacking with breaking, the present work has proposed and developed one of tsunami shelter, “Ellipsoid type” including electric device and storage system. The size of “Ellipsoid type” is 75m length, 20m width, 9m height in practical use. The wall at the front and back face can be constructed by pre-stressed concrete to protect from several kinds of debris such as floating car, wood and ship. The “Ellipsoid type” of tsunami shelter can vary smoothly tsunami flow going through downstream and then it could be one of useful options evacuating from tsunami disaster. The result was validated with experimental results in tsunami attacking on the shelter near coastal region.

1 INTRODUCTION

In March 2011, the huge tsunami hitting on the Tohoku region, northern part of Japan, caused the great damage in not only many infrastructures but also many people, about 16,000 for died, 2,500 for missing and 6,000 for injured. Another huge earthquake and tsunami categorized in mega class will take place in NANKAI trough of the Pacific Ocean near Japan coast. Therefore many evacuating options for tsunami disaster have been proposed and developed in practical use since 2011. There are so many tsunami options such as tsunami tower, super-sized breakwater, moving to hill, underground shelter and coastal tsunami shelter on the ground, see in [1-3]. We have to consider some needs in hazard region and autonomous characteristics. It is important to select options based on them as rationalized measures against huge tsunami. For instance, it is necessary to protect a public safety with understanding information such as composition of population, locations of the main hospital and their capacity, support service especially for the aged and small children and industrial structure including fishery.
Many types of tsunami shelter have been proposed for few people and hundreds people in order to be available to evacuate them from tsunami in recent year. Some of them are floating or drifting type storing oxygen cylinder and some foods for surviving. However we should not ignore not only safety driving of those kinds of shelters but also influence on floating/drifting motions to other infrastructures because the shelters can be pushed away and freely drifting with no-control. Therefore the shelter with mooring have been also proposed to keep the position itself. It is difficult for the mooring system to design its length and strength which is dependent of tsunami water level and velocity on the ground.

Based on these background as the mentioned above, in the previous research [4,5], a new type of tsunami shelter whose capacity is hundreds people, has been proposed and developed to be able to evacuate from huge tsunami with easy access and safety. The proposed shelter can keep its position with mooring and it can also control floating/submerging to avoid more than 10m higher tsunami water level and strongly velocity due to run-up tsunami. Based on numerical simulation using SPH [6] and experiment, the purpose of this study is to compute fluid structure interaction between run-up tsunami and tsunami shelter and to optimize design of the shelter in order to reduce its motions and tsunami force.

2 FLOATING/SUBMERGED TSUNAMI SHELTER

A new type of tsunami shelter, floating/submerged type, has been proposed in our previous works [4, 5] as shown in Fig.1. The floating/submerged tsunami shelter has an important concept that is not only to protect tsunami attacking with highly water level and strongly velocity but also to avoid from them. This study focuses on a large sized shelter on the land near coastal area because the capacity is enough for large population and many equipment for surviving. Using mooring and ballast water, the shelter can be floated on tsunami water surface when tsunami water level is low less than 3-5m and it can be submerged under tsunami wave when the water level is more than 5 to 10m in huge tsunami condition. After tsunami hitting, the floating/submerged tsunami shelter can be used as temporary accommodation and emergency medical center. Under normal condition, this shelter can be usually utilized as communication space for living people and storage space for fish and marine products.

Figure 2 shows one example of some arrangements of equipment and seats in the shelter. The front and back face are protected by double hull structure which is normally applied for ship building. There are many prepared facilities consists of emergency medical system, oxygen cylinder, life support system, food storage area, power generation and its battery, communication network system and so on for surviving during a few weeks or more. The windows and doors are stronger for high pressure and watertight. The evacuated people should be supported by seatbelt during tsunami forcing. In normal condition, the seats are put back under the floor and wider open-space can be kept to be community zone.
3 PARTICLE BASED METHOD

3.1 Governing Equations and computational method

To compute tsunami force and impact pressure, numerical work was conducted using particle based method, Smoothed Particle Hydrodynamics, SPH [6] which can track breaking wave and splashing after colliding on tsunami shelter. The governing equations for all phases can be discretized based on SPH method.

In this study, the governing equations for fluid phase consist of the mass conservation equation, the incompressible Navier-Stokes equation and the equation of continuity. The equations are expressed as follow:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]

\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\mu}{\rho} \frac{\partial^2 u_i}{\partial x_j \partial x_j} + g_i + F_{si}
\]

Figure 1: Concept of the floating/submerged tsunami shelter

Figure 2: Arrangement of equipment and seats in tsunami shelter
where \( \rho \) is the density, \( u_i \) is the velocity, \( P \) is the pressure, \( g_i \) is the gravity acceleration, \( F_{fsi} \) is the fluid structure interaction term.

The governing equations are solved using the splitting method as well-known conventional multiphase technique. The pressure including jump conditions caused by density between different phases can be solved by the Poisson equation given by

\[
\nabla \cdot \left( \frac{\nabla P^{n+1}}{\rho^*} \right) = \frac{\nabla \cdot u^*}{\Delta t}
\]

where \( * \) denotes the physical value after the advection step. The pressure of solid-phase can be obtained by this equation and it can be also applied for solving solid deformation if necessary.

The governing equations for solid phase are the continuity equation and momentum equation as follows:

\[
\frac{D\rho}{Dt} + \rho \frac{\partial u_i}{\partial x_i} = 0
\]

\[
\rho \frac{Du_i}{Dt} = \frac{\partial \sigma^{ij}}{\partial x_j} + g^i - F_{fsi}
\]

where \( \rho \) is the density, \( u^i \) is the velocity, \( \sigma^{ij} \) is the stress tensor for solid phase, and \( F_{fsi} \) is the fluid structure interaction term as the same in eq.(2) for fluid phase. The stress tensor in eq.(5) is given by

\[
\sigma^{ij}_s = -P \delta^{ij} + S^{ij}
\]

where \( S^{ij} \) is the deviatoric stress tensor and \( P \) is the pressure solved by eq.(3).

The model can consider large deformation of elastoplastic body if necessary. The solid body changes at every calculation step by using the following equation:

\[
\{dS^{ij}\} = [D^{op}] \{de^{ij}\}
\]

where \( D^{op} \) is the elastoplastic matrix, \( de^{ij} \) is the strain increment for a time, and \( dS^{ij} \) is the deviatoric stress increment for the time.

To compute rotations of solid phase during motions, the Jaumann derivative is employed to ensure material frame indifference with respect to rotation as follow:

\[
\frac{dS^{ij}}{dt} = 2\mu \left( \dot{\varepsilon}^{ij} - \frac{1}{3} \delta^{ij} \dot{\varepsilon} \right) + \Sigma^{ijk} \dot{\Omega}^{jk} + \Omega^{ijk} S^{kj}
\]

where \( \varepsilon \) is the strain rate tensor and \( \Omega \) is the spin tensor.
The fluid structure interaction $F_{fsi}$ is computed by acceleration obtained from pressure on particles. In the model, the fluid structure interaction $F_{fsi}$ in Eqs.(2) and (5) can be given by the following equation:

$$F_{fsi}(r_a) = -\frac{1}{\rho(r_a)} \sum_b m_b \frac{P(r_b)}{\rho(r_b)} \nabla_a W(r_a - r_b, h)$$

(9)

where $W$ is the kernel function, $m$ is the mass, $P$ is the pressure, $\rho$ is the density and $h$ is the referenced area where interaction between particles can be considered.

In the model, the shelter model consists of SPH particles to compute motions in 3D. Therefore, the 3D motions of the shelter is represented by describing translation and rotation of the center of gravity of the shelter using the following equations:

$$\frac{\partial^2 x_{s,k}}{\partial t^2} = \frac{F_{s,k}}{m_i} - F_{fsi}$$

(10)

$$I \frac{\partial \omega_i}{\partial t} = T_i$$

(11)

$$\frac{\partial \theta_i}{\partial t} = \omega_i$$

(12)

where $\theta_i$ is the rotational angle, $\omega$ is the angular velocity, $T_i$ is the torque, $I$ is the inertia moment, and $F$ is the fluid structure interaction. In addition, the center of gravity of the shelter can be obtained by solving the inertia moment of particles, and this is calculated by using Baraff theory[7]. Based on this theory in the model, equations for 3D motion are given by

$$r_g = \frac{1}{N} \sum_{i=1}^{n} r_i$$

(13)

$$I = \sum_{i=1}^{N} m_i |r_i - r_g|^2$$

(14)

where $N$ is the number of particles for shelter, $r_g$ is the position of the gravity center, $I$ is the inertia moment, $r_i$ is the position of the $i$th particle and $m$ is the mass of the particle. The inertia moment can be set at initial condition. Therefore, the coordinates of velocity of each particle in every time step can be tracked by using rotation matrix and the amount of angle rotation of the center of gravity to avoid the Gimbal lock phenomenon, and the quaternion is used instead of the rotation matrix. The numerical model can be enhanced for applying to shelter motions, overturning and sinking caused by nonlinear wave with breaking.

To keep computational efficiency and stability, the time increment for solid phase is approximately 1/10 to 1/50 of that for fluid phase. In this research, tsunami shelter can be supported by pole to simulate the experimental work. The tsunami shelter can be assumed as solid model in this work. In future work, motions of the tsunami shelter and its elastic deformation would be considered for practical design. Other details can be referred in Mutsuda et al. [8].
3.3 Shelter model

Tsunami force would be increasing with attacking angle to tsunami shelter when separation flow with vortex around tsunami shelter could occur in larger deadrise angle. To reduce tsunami force on tsunami shelter, based on the previous work [4, 5], the ellipsoidal tsunami shelter is focused in this study. Iida et al. [9] has verified that super-express in Japan, it called SHINKANSEN, has been optimized to investigate aerodynamics. Based on the results, especially the aspect ratio was set to be from 3 to 5, in front face and back one to reduce pressure resistance caused by tsunami attacking. Moreover the side face of the tsunami shelter is formed by the curved surface with streamline to control separation flow behind the tsunami shelter. Figure 3 shows tsunami shelters with different aspect ratio to compare tsunami force acting on them. The Ellipsoid3 (E3) and Ellipsoid3s (E3s) have aspect ratio 1/3 at the front face and back one. In Ellipsoid35 (E35) and Ellipsoid35s (E35s), the aspect ratios 1/3 and 1/5 are combined. The side face in E3s and E35s is also formed by streamline. The Box type, which is a typical building, is employed to compare pressure resistance with them.

3.4 Computational conditions

The computational domain is shown in Figure 4. To reduce computational time and cost, the tsunami conditions before breaking and run-up, such as surface profile, internal velocity and pressure, can be computed by Boundary Element Method [10] using exact solitary wave condition. These numerical results are set as the initial conditions in SPH.

Figure 3: Configuration of tsunami shelter with different aspect ratio (unit:mm)
The tsunami shelters can be assumed as solid phase without deformation in this study. The time increment is 0.001s and the particle diameter is set to be 1 cm. The attack angles are set to be 0, 15, 30, 45, 90 deg. to tsunami wave direction. The tsunami height condition corresponds to a fully developed bore propagating on the ground.

4 NUMERICAL RESULTS

4.1 Tsunami wave motion and validation

Figure 5 shows one example of snapshots tsunami phenomena acting on the box shelter with experimental result. It can be found that the strongly splashing occurs on the front face of the box shelter and it causes highly tsunami force and impact pressure.

Figure 6 and 7 show tsunami wave propagation with the attack angles 0 and 45 deg. in Box and E35s. Figure 8 shows comparison of time history of tsunami force acting on Box type for the attack angle 0 deg. with experimental result. The numerical result is in good agreement with the experimental one and it is reasonable for evaluating fluid force on tsunami shelter.

4.2 Reduction of tsunami force and influence on tsunami attacking angle

Maximum pressure and averaged tsunami force are examined and their characteristics are clarified in this section. The force can be calculated by summation of tsunami pressure acting on shelter in wave direction.

Figure 9 shows time histories of tsunami force in the attack angle 0, 45 and 90 deg. to compare with the normal type, Box. Figure 10 and 11 shows relationships between maximum tsunami force, averaged tsunami force and attack angle, $H$ is the tsunami water level on the
ground, $\rho$ is the water density and $g$ is the gravity acceleration.

In the Box shelter, the tsunami force is largest in the attack angle 0 deg. and then it is decreasing until the attack angle is close to 30 deg. The tendency is also increasing over the angle 45 deg. This is because the incoming tsunami flow into the corner of the shelter can be separated along the side face of the shelter when the angle is larger. Then the resultant tsunami force is decreasing. In over the attack angle 45 deg. the tsunami force is stronger at the side face as the projected area increasing. On the other hand the averaged tsunami force is decreasing in E3s and E35s having the curved surface on the side face. The curved surface can avoid from strongly tsunami force because the separated flow on the front face can be controlled.

Figure 6: Box type (Left: 0 deg. Right: 45deg.)

Figure 7: Ellipsoid35s type (Left: 0 deg. Right: 45deg.)

Figure 8: Comparison of time history of pressure between computational result and experimental one in Box type
To evaluate and examine effect on reduction of tsunami force, comparison of maximum tsunami force and averaged tsunami force are compared as shown in Fig. 12 and 13. These data are obtained by averaging tsunami force at each attack angle. The most useful for reducing tsunami force in the maximum and averaged tsunami forces, is E35s with the largest aspect ratio on the front face and streamline on the side face among the shelters.

Figure 9: Time histories of tsunami force acting on tsunami shelter

Figure 10: Relationship between maximum tsunami force and attack angle of incident tsunami wave

Figure 11: Relationship between averaged tsunami force and attack angle of incident tsunami

Figure 12: Comparison of maximum tsunami force

Figure 13: Comparison of averaged tsunami force
5 EXPERIMENTS

In the previous chapter, the shelter, E35s, with large aspect ratio on the front face and streamline on the side wall, is available for reducing tsunami force. The motions of the shelter, E35s with mooring are examined in experiment.

5.1 Experimental setup and conditions

Figure 14 shows overview of experimental tank (40m length × 1.2m width × 2.5m depth) and some equipments to measure tsunami force. The valuable angle 1/3 to 1/100 of the sea bottom can be set up to generate several kinds of tsunami conditions. The flat bottom as the ground was located to be available for propagating run-up tsunami. The shelter supported by four wires and pulley was located on the turn table at the bottom. The turn table can be rotated to exchange the attack angle from 0 to 45 deg. as shown in Fig.15. The tsunami force can be measured by dynamometer and tension meter connected with the wires. To reduce snap-force due to impulsive pressure, spring with constant coefficient 210N/m was employed in this mooring system. The wireless motion sensor inside the shelter can obtain accelerations of the shelter in 6 degree of freedom. The incident tsunami wave height can be measured at WG1 and the run-up wave height is also captured at WG2 located on the strandline. The incident wave period in regular wave is 2s to avoid from water disturbance caused by previous tsunami wave.

![Figure 14: Experimental setup](image1)

![Figure 15: Mooring setup of tsunami shelter (Top view)](image2)

5.2 Shelter motions

Figure 16 and 17 show comparison of surge motion $A x/g$ (positive: downstream side) and pitch motion (positive: uplift of the front face) in the case of the attack angle 0 deg. The
wave height $H$ is normalized by the shelter width $d$. The surge motion in E3s and E35s is lower than that in Box type. All of the values are less than 0.5g in the wave conditions, which means safety level for evacuating people. On the other hand the pitch motion is the same tendency in all wave conditions. The averaged pitch angle is approximately 3 to 4 deg. The ellipsoid type has no advantage in pitch motion comparing with Box type. Therefore it should be necessary in practical use to reduce the pitch motion after modifying the shelter. Figure 18 shows comparison of yaw motion in the case of the attack angle 45 deg. The yaw motion in the ellipsoid type, E3s and E35s, is lower than that in Box type. This tendency is remarkable as the wave height is larger. It can be seen that the ellipsoid type can reduce not only tsunami force but also shelter motions caused by tsunami attacking.

6  FURTHER RESEARCHES

One of further researches is to develop a tsunami tower building to avoid from tsunami attacking. The concept can be applied with only minor change for the existing building to reduce construction cost comparing with that for tsunami shelter. This could be a practical
measure as one tsunami option near coastal area where there are many existing building and the people living there.

This study have proposed two modified buildings with opening parts optimized in arrangement and their ratio to the projected area and no-wall at the first floor like a piloti as shown in Fig. 19 and their numerical results are shown in Fig. 20. Figure 21 shows comparison of averaged tsunami force acting on the tsunami tower building. It can be seen that the opening parts and piloti are one useful minor change for the existing building. Their reduction rates are around 30% or more.

Figure 22 shows one more application for arrangement of building including tsunami tower or shelter to reduce tsunami force. Unpredictable tsunami force caused by the surrounding buildings and accommodations can be occured in populated zone. The snapshots are one example arrangement in coastal area. Some of the small buildings behind the larger building can escape from directly tsunami attacking. This result means that it should be considered to make appropriate arrangement of building and accommodation in populated zone near coastal line in order to reduce tsunami forcing and impulsive pressure.

![Figure 19: Tsunami tower building](image)

(a) Normal (Type A)  (b) Opening parts (Type B)  (c) Piloti (Type G)

![Figure 20: Tsunami tower building](image)

(a) Normal (Type A)  (b) Opening parts (Type B)  (c) Piloti (Type G)

![Figure 21: Comparison of averaged tsunami force acting on tsunami tower building](chart)

- Averaged tsunami force \( [10^2, \text{ Pa}] \)
6 CONCLUSIONS

This study has proposed and developed the floating/submerged tsunami shelter to evacuate huge tsunami attacking and then has also investigated tsunami force acting on the shelter and its motions caused by tsunami impact force in particle based method and experimental work. The main results can be summarized as follows.

The ellipsoidal tsunami shelter (E35s type) can drastically reduce tsunami force and impact pressure. Moreover the surge and yaw motions in E35s with mooring system type can be also reduced comparing with Box type. In further research, the tsunami tower building with opening parts and piloti is also useful as one of tsunami evacuating options. The tsunami shelter and tower building should be arranged to reduce unpredictable tsunami force caused by a surrounding building and accommodation.

In future effort, mooring system including elastic wire will be optimized and effects on drift of floater such as wood, broken house ship and car, will be also investigated.

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REFERENCES


