Numerical Experiments on Tsunami Wave Forces on Open Structures Using Dam-Break Method

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Abstract. Open wall structures, such as those found in mosques, sustained large forces generated by a tsunami as in the case of the 2004 Indian Ocean tsunami. Although the surrounding buildings were flattened, there were a number of mosques in the tsunami affected area could still stand in the middle of the area. These motivated this study to look into more details the hydrodynamic forces generated around the open structures. This research was aimed at investigating the tsunami wave forces on open structures and at knowing relation between the tsunami waves velocity and the pressures on the pillars of the open structures. DualSPHysics was used to simulate the tsunami wave forces on the structures. The DualSPHysics is a smoothed particle hydrodynamic model with mesh-less method. We simulated 12 numerical simulations by constructing a 130 m wave flume equipped with dam-break at one end to generate the tsunami-like flows. Four pillars were set to imitate a simplified model of open wall structure. Numerical observation points were placed at offshore part of the model, in front of the pillars (lee-side) and at the back of the pillars (wake-side). Simulations were performed for about 6 seconds started from releasing the dam gate and before the flow being reflected by the other end of the flume. This study proved that the impacts of the tsunami-like forces are more significant of the front row of the pillars. Meanwhile, tsunami wave forces at the back row of the pillars group are inconclusive to the wave velocity and wave heights.

1. Introduction

Open wall structures such as mosque’s walls were found to remain with minimum damages due to impacts of tsunami waves in several areas. The 2004 Indian Ocean tsunami case revealed many cases where mosques remained standing despite massive destructions of buildings around. This could provide opportunity to utilize the mosque as an alternative place to evacuate. However, there are limited number of studies have investigated the impacts of tsunami waves on mosques that have open wall structures.

In tsunami prone area, tsunami evacuation buildings are not sufficient to accommodate all evacuees in many areas. One of the examples could be found in Aceh. In Banda Aceh, the number of official assigned evacuation buildings are six buildings. In total, all the assigned evacuation buildings could facilitate about 4,500 people at one time. This is far from the number of human exposure should any tsunami hit the city in the future. About one third of the city population could become victims of the tsunami (or about 80,000 people). If only about 2% of the human exposure to be assigned to use the evacuation buildings, the present condition is far from sufficient. Therefore, other alternatives to
facilitate safe and sufficient evacuation sites should be considered. Another serious problem is caused by an extremely short time available to perform evacuation and difficulties to access public information/media during the emergency period [9]. The return migration process in Banda Aceh has increased number of coastal population in the city and it means the tsunami risk also has also increased in recent years [10].

One of the most potential alternatives is mosques. A number of mosques in Aceh could be used as tsunami shelters provided their structures being modified to suit the evacuation process and their capacities to sustain from earthquake and tsunami are properly checked. In order to provide a preliminary information on the open structure capacity to sustain tsunami wave forces, a set of numerical experiments were performed.

Thanks to the advances in numerical modelling using Smoothed Particle Hydrodynamic Method, details numerical studies involving complex forms of testing objects now become possible. The development of computer software and hardware in recent years has also facilitated numerous studies in computational fluid dynamics (CFD). This study is one of recent applied researches to support ideas on providing ample tsunami evacuation buildings by using existing public facilities, namely mosques that have open wall structures. This study was aimed at investigating tsunami wave forces on open structures where model of a mosque with open walls was used. We presented the results that show the influence of tsunami wave heights at the offshore, generated by dam-break method, on forces on pillars of open wall structures.

2. Methods

2.1 DualSPHysic

Smoothed Particle Hydrodynamic (SPH) is a relatively new method that enables scientists to precisely simulate wave breaking process and non-linear effects of waves [1]. SPH is a Lagrangian mesh-less method that uses particles movement and their interactions with structures. The Navier-Stokes equations were discretized and integrated to the coordinates of the particles. SPH simulations provide new opportunities to tsunami scientists to look into more detail of the tsunami wave forces on open structures. In recent years, the development of smoothed particle has reached new advancements by the use of GPU (Generic Processing Unit) in the simulation process. DualSPHysic that was developed in early 2010 has been widely acknowledged as one of breakthroughs in the numerical experiments [2]. The GPU system supported the simulations by accelerating the simulations significantly faster than conventional CPU. Mass conservation formulae of SPH was developed to consider the particle movement and acceleration as they were caused by the particle interaction with its neighbouring particle [3]. The momentum equation applied in SPH can be seen in Equation (1) as follows.

$$\frac{d\mathbf{v}_a}{dt} = -\frac{1}{\rho} \nabla P + \mathbf{g} + \Theta$$  \hspace{1cm} (1)

where $\mathbf{v}_a$ is vector velocity in x, y, z directions, $P$ is pressure, and $\rho$ is density of the fluid, $\mathbf{g}$ is gravitational acceleration in z direction only, and $\Theta$ is vector of dissipative terms. Meanwhile, $\nabla$ is a Laplace operator as follows.

$$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}.$$  \hspace{1cm} (2)

The validity of the DualSPHysic in tsunami-like simulations have been confirmed by Cunningham et al. using wave maker method [4]. In this case, we used a group of cylindrical columns that support a concrete plate to represent the open structure of a mosque. Particles in SPH are treated as circular in two dimensional model and spherical as in three dimensional model. In this study, we used three dimensional model. Furthermore, instead of wave-maker method, we deployed dam-break method to
generate long waves, as if in the case of tsunami waves. The GPU enables us to run for millions of particles as it also helps us to conduct a more detailed simulation [6].

2.2 Numerical Experiments
We developed a hypothetical wave flume with its dimensions are 130 m in length, 12 m in width and 8 m in height (see Figure. 1). Dam-break gate was imitated at the upstream part of the flume and one frame of open structures that mimic the mosques open wall were made at the downstream part of the flume. The dam-break gate retained water column with varied heights. There were two types of objects to be tested, i.e. one was an open-structure wall to imitate a mosque wall and the other one was close-structure wall for comparison. A slope media was made to imitate the coastal slope of 1:50. It was expected the slope to reconstruct non-linear effects of coasts.

![Figure 1. The Wave Flume Dimension for Numerical Simulations.](image)

We employed Wendland Kernell function in the simulation, with particle size of 0.01 m. The simulations were performed using double precision mode in particle interaction, and step algorithm of Verlet was used. Documentation of Verlet scheme can be found at [5]. The simulations were run for 20 seconds with water mass density of 1000 kg/m$^3$. We set up lattice bound and fluid bound in the simulations. Furthermore, Courant-Friedrich-Levy (CFL) coefficient was 0.2 and $\gamma$ was 7. Delta-SPH coefficient that controls large wave number was disabled (set to zero). Smoothing particle length was calculated as $\sqrt{3d_p^2}$ since this is a 3 dimensional model, where $d_p$ is particle size.

The following table shows the scenarios of the numerical experiment in this study.

| Water depth Behind the Dam Gate (m) | The height of the opening gate (m) | Simulation Number |
|-----------------------------------|-----------------------------------|------------------|
| 1.4                               | 1.0                               | #111             |
|                                   | 0.8                               | #112             |
|                                   | 0.6                               | #113             |
|                                   | 0.4                               | #114             |
| 1.2                               | 1.0                               | #211             |
|                                   | 0.8                               | #212             |
|                                   | 0.6                               | #213             |
|                                   | 0.4                               | #214             |
| 1.0                               | 1.0                               | #311             |
|                                   | 0.8                               | #312             |
|                                   | 0.6                               | #313             |
|                                   | 0.4                               | #314             |
At the lee-wake sides of the pillars, a series of numerical observation points were placed at every 0.1 m interval of the points in z-direction. Depth average velocities ($\overline{U}$) were calculated as in Equation (3).

$$\overline{U}^t = \frac{1}{h} \int_0^h U(z)^t \, dz,$$  \hspace{1cm} (3)

Here, $z$ is distance from the bed level to the observe points and $t$ is time of the simulation in second, and $h$ is total depth of the water at time $t$. The $\overline{U}^t$ was calculated started when the wave hit the pillars after 0.1 second to allow the wave depths at significant levels (deeper than 0.25 m). Maximum values of the $\overline{U}^t$ were plotted in graphs to see the tsunami wave velocities influence on forces at the lee-wake sides of the pillars.

3. Results

Based on numerical observation points placed at offshore area and in front of pillars, we observed the influences of tsunami waves generated on lee-side of the pillars. Figure 2 shows the influence of wave heights measured at the onshore part of the flume on forces on pillars. The onshore wave height observation points were placed about 1 cm in front of the pillars. Here, there is no significant different between front row pillars and back-row pillars. The influence of the increasing tsunami wave heights on forces on pillars is linear. The similarity between the front row and back row pillar is most likely due to combination between wave heights and velocities on pillars.

![Figure 2](image_url)  \hspace{1cm} Figure 2. Influence of off-shore tsunami wave heights on forces working on pillars of an open structure.

Figure 3 shows the influence off-shore wave heights (upstream wave height) on forces working on pillars. Here, the front pillars have a steeper increase of forces due to the increase of the generated wave heights released from the gate.
Figure 3. Influence of Off-shore wave heights on forces working on pillars of an open structure.

Figure 4 shows the comparison of the influence of the depth averaged velocity at the lee-side of the both rows of the pillars on maximum forces induced by the tsunami waves. The back row pillars group received smaller forces than the front row pillars. This is due to the eddies generated at the wake side of the front row pillars reduce the forces of the waves at the lee-side of the back-row pillars group. This study used a group of pillars where Morison formulae was not applied to convert the force on cylindrical types pillars. This could underestimate forces generated by long waves, as in the case of tsunami waves [7]. Converting pressures resulted by the DualSPHysic sensors to forces could give smaller values than if the Morison formulate applied [8]. Notwithstanding the use of the Morison formulae, this study could provide important information on pressures exerted by tsunami-like waves.

Figure 4. Influence of depth average velocity

4. Conclusions

This study attempted to investigate forces generated by tsunami waves on open wall structures by means of numerical experiments. DualSPHysic was utilized to simulate simplified structure of the open wall that have two rows of pillars, i.e. front-row pillars and back-row pillars. The shape of the pillars is cylindrical. This study concludes that influence of the tsunami wave heights on forces at the front-row pillars is linear with a steeper increase than the back-row pillars. The depth averaged velocity at the front-row pillars generated larger forces at the lee-side of the pillars compared to the back-row pillars group. Further investigations are needed to see the forces generated by tsunami waves with a complete structure of an open wall, as in the case of a mosque.
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