Three-Dimensional Numerical Simulation of Tsunami Bore Inundation Flow Around Cylindrical Structure Surrounded by Weir

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ABSTRACT

The extension of tsunami’s destruction due to the damaged of hazardous material containers, such as oil storage tanks, in the Japan tsunami 2011 leads to the investigation of tsunami inundation flow around cylindrical structure surrounded by weir. The investigations are conducted by using three-dimension numerical simulation based on modified Navier-Stoke equations and VOF model. Tsunami wave bore is introduced by applying an analytical equation, which proposed by Fukui (1962). The results indicate that the existence of protective weir significantly reduce wave velocity inside the protective weir.

Key words: Tsunami bore; inundation flow; cylindrical structure; numerical simulation; protective weir

INTRODUCTION

In the past century, tsunami has been rated as fifth deadliest natural disaster in this world (Battencourt et al., 2006). The long wave and height velocities characteristics of tsunami cause impulsive and powerful impacts on large-scale areas at the adjacent period. Further, the fact showed that despite several structures were barely able to withstand the massive power of tsunami inundations, some structures failed due to the scouring or buckling problems. In case of tsunami, the mentioned problems are related with the inundation runup and drawdown flow around the structure (Yeh and Li, 2008).

And after the devastating disasters of Japan tsunami 2011, which showed the extension of destruction due to damaged of hazardous material storages and oil tank storages, the leading concern of mitigation strategies is laid on the protection of hazardous material container. The building code of oil tank storage require weir protection to prevent any disperse of leaked materials to the surrounding environment. The existence of protective weir may produce random and complex motion of inundation flow against the protected structure. However, the effects of such flow on structures with weirs have not been thoroughly investigated. Therefore this study investigates the effect of the regulated weir protection to the tsunami inundation flow around the cylindrical structure, supposed as oil tank storage.

In order to understand the interactions between tsunami waves and three-dimensional structures, a numerical simulation shows great performance since it gives principal physical quantities, such as a pressure, velocity and free surface elevation, at any points

Nowadays, three-dimensional numerical simulation has been vastly developed (Arikawa and Yamano, 2008; Goto et al., 2009; Tomita et al., 2006; Kawasaki et al., 2006). Among those simulations, the method based on volume of fluid (VOF; CADMAS-SURF) is considered one of the promising numerical techniques to simulate three-dimensional interactions between tsunami waves and structures. The investigations are conducted by simulating tsunami bore runup into a dike through three-dimension numerical simulations by applying the modified Navier-Stoke equations and VOF method, which are
employed in CADMAS-SURF 3D model. In this study, tsunami bore runup is introduced by applying an analytical equation, which was proposed by Fukui (1962). This study also investigates the applicability of the numerical tsunami bore with the experimental test.

METHODOLOGY

(1) Experimental Facilities and Procedures

Experiments were performed with using an open channel of 12m long, 0.4m wide and 0.4m deep as shown in Fig. 1. A bore with various different heights \( H_1 \) was generated by lifting division plate instantaneously, which initially separates the downstream quiescent water from the upstream deeper water. The downstream water depth \( h_2 \) was set in 0.045m. While the water level on upstream side of the division plate \( H_1 \) was changed in the range from 0.15-0.30m in order to obtain various bore heights.

The model scale was assumed 1/30 in this study. A dike with 0.11m in height was installed on the downstream side 5.8m distance from the division plate. At 0.3m from the dike’s corner, a cylindrical structure with different diameter, e.g. 0.04m, 0.08m and 0.11m, was set on the dike. The height of the cylinders was 0.15m. The cylinder was attached to the metal beam to measure the horizontal wave force on it.

Three wave gauges (W1, W2, W3) and one velocity meter (V1) were placed on the propagation area. While in the inundation area, one wave gauge (W4) and one velocity meter (V3) were placed beside the cylindrical structure. One velocity meter (V2) was placed 0.05m in front of cylinder to collect velocity data.

To obtain force data, four stress-strain gauges were attached to the beam as shown in Fig.1. A moment equilibrium equation in two points was used to estimate wave force from these gauges. Five pressure gauges were attached to the front face of the cylinder with 0.015m distance between two gauges.

(2) Governing Equations

This study considers the incompressible viscous fluid. The numerical wave flume is developed by applying the governing equations for interaction between waves and porous structure. The governing equations for the body model are the continuity equation (Eq.1) and the modified Navier-Stoke equations (Eqs. 2-4) in three-dimension cross sections. This system of equations is proposed by Sakakiyama and Kajima (1992):

\[
\frac{\partial}{\partial x} \left( \chi_x u \right) + \frac{\partial}{\partial y} \left( \chi_y v \right) + \frac{\partial}{\partial z} \left( \chi_z w \right) = \gamma S \rho \tag{1}
\]

\[
\lambda \frac{\partial u}{\partial t} + \frac{\partial}{\partial x} \left( \nu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( \nu \frac{\partial u}{\partial z} \right) = -\frac{\rho}{\gamma} \frac{\partial \rho}{\partial x} + \frac{\partial}{\partial x} \left[ \chi_x \nu_e \left( \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[ \chi_y \nu_e \left( \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left[ \chi_z \nu_e \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right] - \gamma D u - R_t + \gamma S u \tag{2}
\]

\[
\lambda \frac{\partial v}{\partial t} + \frac{\partial}{\partial x} \left( \nu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( \nu \frac{\partial v}{\partial z} \right) = -\frac{\rho}{\gamma} \frac{\partial \rho}{\partial y} + \frac{\partial}{\partial x} \left[ \chi_x \nu_e \left( \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[ \chi_y \nu_e \left( \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left[ \chi_z \nu_e \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right] - \gamma D u - R_t + \gamma S y \tag{3}
\]

\[
\lambda \frac{\partial w}{\partial t} + \frac{\partial}{\partial x} \left( \nu \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z} \left( \nu \frac{\partial w}{\partial z} \right) = -\frac{\rho}{\gamma} \frac{\partial \rho}{\partial z} + \frac{\partial}{\partial x} \left[ \chi_x \nu_e \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[ \chi_y \nu_e \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left[ \chi_z \nu_e \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) \right] - \gamma D u - R_t + \gamma S z \tag{4}
\]

Where \( t \) is the time, \( x \) and \( y \) are the horizontal coordinates, \( z \) is the vertical coordinate, \( u, v, w \) are the velocity components in the \( x, y, z \) directions respectively. \( \rho^* \) is the density of the fluid, \( \rho^* \) is the relative density of the fluid, \( p \) is the pressure.
\( \nu_e \) is the kinematic viscosity (the sum of molecular kinematic viscosity and eddy kinematic viscosity), \( g \) is the gravitational acceleration, \( \gamma \) is the porosity, \( \gamma_x, \gamma_y, \gamma_z \) is the areal porosities in x, y and z projections, \( S \) is the source of mass for wave generation, \( S_x, S_y, S_z \) is the momentum source in x, y, z respectively, \( \lambda_x, \lambda_y, \lambda_z \) is defined from \( \gamma, \gamma_x, \gamma_y, \gamma_z \) using the following relationships in Eq.5:

\[
\lambda_v = \gamma_v + (1 - \gamma_v)C_M \\
\lambda_x = \gamma_x + (1 - \gamma_x)C_M \\
\lambda_y = \gamma_y + (1 - \gamma_y)C_M \\
\lambda_z = \gamma_z + (1 - \gamma_z)C_M
\] (5)

Where \( C_M \) is the inertia coefficient.

The resistance force components \( R_x, R_y, \) and \( R_z \) are described by Eqs. 6~8.

\[
R_x = \frac{1}{2} C_D (1 - \gamma_x) u \sqrt{u^2 + v^2 + w^2}
\] (6)

\[
R_y = \frac{1}{2} C_D (1 - \gamma_y) v \sqrt{u^2 + v^2 + w^2}
\] (7)

\[
R_z = \frac{1}{2} C_D (1 - \gamma_z) w \sqrt{u^2 + v^2 + w^2}
\] (8)

Where \( C_D \) is the drag coefficient; \( \Delta x, \Delta y \) are the horizontal mesh sizes and \( \Delta z \) is the vertical mesh sizes in porous media. The governing equations are discretized by using the finite difference method on a staggered mesh and solved using the simplified marker and cell (SMAC) method.

The Volume of Fluid (VOF) method, which was introduced by Hirt and Nichols in 1981, is used in this study to distinguish between the air and water zones. Youngs (1982) described an algorithm to track the interface between the air and water zones that consist of two steps: 1) the interface is approximated by a linear volume in each cell, therefore each of the cell has the value of fractional function between zero and unity, 2) track the interfaces by solving an advection equation, for the function, \( F \), in a time series. The three-dimensional advection equation for fractional function is given as Eq. 9:

\[
\gamma, \frac{\partial F}{\partial t} + \frac{\partial (\gamma u F)}{\partial x} + \frac{\partial (\gamma v F)}{\partial y} + \frac{\partial (\gamma w F)}{\partial z} = \gamma_S F
\] (9)

Where \( \gamma_S \) is the source of \( F \) due to the wave source method.

In order to propagate a tsunami bore wave, the time history of water surface elevation and fluid velocity are set as the initial flow parameters in the ghost cells, which are set outside of the most upstream cells. These values will be calculated by using the governing equation for the rest of the domain. Fukui et al. (1962) had investigated the relations between fluid mean velocity and water surface...
displacement in the propagation of tsunami bore wave. Through analytical investigation and a series of hydraulic experiments, they derived the equation as shown in Eq. 10.

\[ U = C_\zeta \frac{gH_1(h_2 + \zeta)}{H_1} \sqrt{\frac{gH_1(h_2 + \zeta)}{2H_1(h_2 + \eta_\zeta)}} \]  

(10)

Where \( U \) is the mean velocity, \( g \) the acceleration of gravity, \( H_1 = h_2 + \zeta \) is the total depth from the datum (Refer to Fig. 2), \( \zeta \) is the temporal bore height. \( \eta \) is the velocity coefficients, which was obtained from the ratio of water level to wave height.

In addition, the weir dimensions, i.e. diameter and height, should be carefully estimated in order to restrain leaks from the any face of the storage container, even from its top section. Considering this, this study established various weir diameters (\( D' \)) and height (\( h' \)) to satisfy the building code as described at Table 1.

**Table 1. Numerical cases**

<table>
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<tr>
<th>Numerical cases</th>
<th>Cylindrical structures</th>
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<tr>
<td>D1</td>
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<tr>
<td>h1</td>
<td>h2</td>
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<td>Cylindrical weir</td>
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Note: O=conducted case

The computation domain at the initial time is set with some assumptions, e.g. still water condition with zero velocity, the initial pressure is given by hydrostatic pressure, water density is given by 998.2 kg/m³ and air density is 1.225 kg/m³. In this study, a no-slip condition is applied in the interface between fluid and solid body. Over 5 million grid squares were established with grid size of 0.01m on the x and y-axis, 0.005m on the z-axis. The estimated fluid velocity from Eq. 10 and water surface elevation data were used as input data at propagation boundary. The time interval was set from 0.00001second to 0.01second to obtain highly detailed outputs and minimize the instability risk.

**RESULTS AND DISCUSSIONS**

*(1) Verifications*  
This study conducted verification on the applicability of analytical tsunami bore through comparisons with experimental ones over wave principal physical

Fig. 2 Bore profile illustration (retrieved from Fukui, 1962)
quantities, such as water surface elevation, fluid velocity profile and wave force profile.

**Water Surface Elevation**

Fig. 3 shows the comparison of water surface profiles at propagation area (W2) in case of 0.11m diameter cylindrical structure, where the solid lines mean the measured data in experiment and dot lines mean simulated ones.

In measured data of every impoundment height, bore front face can be identified from the quick raise pattern in the beginning of measurement. And then bore propagated without significant water height changes. At the end, the wave reflection from the dike caused the fluctuations of wave height for case with $h_1=0.2m$ and $h_1=0.25m$. Those dynamic changes in experimental data were simulated fairly good in numerical simulation in every impoundment height.

Fig. 4 shows the water surface profile at 0.05m beside the cylindrical structure (W4) on the dike. In every case, measured bore height quickly increased at the moment of passing the wave gauges. The water depth reached the maximum after a few second, and then it showed decreasing tendency. The water surface profiles obtained from numerical simulation show similar profiles to the experimental results. Though the numerical simulation results were slightly overestimate the maximum water depth that occurs after the bore front passes the wave gauges.

**Fluid Velocity Profile**

As seen in Fig. 5, despite the differences at impoundment height, the velocity after the bore front show similar value as the wave completely adjust its flow after hitting the dike wall. Even under these complicated flow conditions, the numerical results show good agreement with experimental ones.
Fig. 6 shows the fluid velocities at 0.05m beside of the cylinder (V3). In all impoundment cases, the measured velocities quickly increased and took the maximum values in the same manner with velocities at the station 2, which can be seen in Fig. 5. And then, velocities started to show the gradual decreasing tendency.

The comparisons between experimental results and numerical ones also show good agreement in each case, though the simulated velocities slightly underestimate the inundated velocities.

Wave Force Profile

Fig. 7 shows the comparison of wave forces acting on the 0.11m diameter of cylindrical structure with 0.25m impoundment height. In experimental results, wave profiles oscillated a little after the bore hit the cylinder. These fluctuations in experiments came from the natural oscillation of measurement system.

As seen in Fig. 7, sharply increased initial force can be observed both in experimental data and numerical one when the wave hit the cylindrical structure at the initial contact. While the sustain wave force occurred a couple seconds later when the water surface elevation reached its maximum height on structure’s surface. Both of these forces were well observed in the experimental results and numerical ones. These force profiles correspond well with other studies (Haritos et al., 2005; Lukkunaprasit et al.; 2009)

Fig. 8(a) shows the comparison of simulated initial force with measures one, and Fig. 8(b) also shows the comparison of sustains force. Good agreement can be seen both in initial force and sustain one in the wide range of bore height. In the agreement on initial force, a correlation is slightly lower than that in sustain force, because the peak values of impact force usually depend on the sampling frequency of data in experiment and computational time interval in numerical simulation.

Fig. 7 tsunami force of 250 mm impoundment height acting on the cylindrical structure

Fig. 8 Validation of wave forces: (a) Initial wave forces, and (b) Sustain wave forces validation.
From above investigations, it can be concluded that the numerical simulation based on VOF method expanded into three-dimensional problem provide fairly good results even in the complicated inundation process of bore.

(2) Tsunami Bore Inundation Flow round Cylindrical Weir

The results of effected inundation flow due to the weir existence can be described in term of wave surface elevation characteristics and wave velocity characteristics with its distribution on vertical and horizontal.

Wave surface elevation characteristics

As seen in Fig. 9, the cylindrical weir delayed the arrival of tsunami flow inside the weir area for momentarily. The initial water depth \((t=4.5 \sim 5 \text{ second})\) was significantly reduce, however after the depth of the inundation wave exceeded the weir height, the water surface level increased higher in case of the weir existence compare to without one. This was due to the weir acting as water container, tending to keep water inside itself while the sustained waves were continuously flowing above it.

The existence of weir tended to slightly increase the water surface elevation, not only inside the weir area but also outside of it as well. Fig. 10 shows the increasing water depth for various bore heights.

Wave velocity characteristics

Figs. 11a, 11b and 11c show the comparison of wave velocity profile at several locations in front of cylindrical structure between the case with protective weir and without ones. Maximum velocities occurred in the front section of the tsunami bore wave and then it decrease gradually along the time. Similar trend can be found in the case of weir existence, though some fluctuations occurred as an indication of formed turbulences. Heavy fluctuations can be observed in the middle area between weir and structure, as the overtopped wave hit the dike at this area. The existence of weir protection significantly reduces the wave velocity and also delays the arrival of tsunami wave inside of the cylindrical weir.
The vertical distribution of maximum wave velocity at several locations in front of the structure, as seen in Fig. 12, clearly indicates that wave velocity increase from the bottom to top. The positive and negative value indicates the direction of wave velocity in regard with x-axis. As can be seen in this figure, the highest positive wave velocity occurred at x=+0.22 m, just past where the overtopped wave hit the dike. While the negative ones, which indicate the opposite direction occurred at the bottom section due to the reflected wave flow from the structure.

The horizontal distribution of maximum wave velocity at the bottom, middle and top section of structure can be seen in Fig. 13. The zero degree indicates the direct impact location, which is perpendicular to inundation flow direction. The existence of weir tended to significantly increase the velocity at the front face of top section, however this effect decreases along the circumferential direction. Meanwhile there were no significant differences between with and without weir at the middle section. The weir was observed to cause the reduction of velocity at the side face of the structure at the bottom section.

In order to investigate the effect of weir height on the inundation flow, Fig. 14 shows the wave velocity profile with various weir heights with 0.26 m of weir diameter. The higher weir, which is type A3 was observed to significantly reduce the wave velocity at the bottom section, however the higher weir caused heavy fluctuation as an indication of complex and random motion of wave flow. In addition, the higher weir produced longer delays in the tsunami arrival time on the measured location.

The effect of weir diameter can be seen in Fig. 15, which shows the wave velocity profile with various weir diameters and 0.06 m of weir height. The smaller weir diameter, which means the smaller space between weir and structure, produce slower velocities at the bottom section, as the wave did not have significant space to accelerate its actions.
CONCLUSIONS

The interactions between a single bore and cylindrical structure are investigated through experimental and numerical study. In the numerical simulation of bore type tsunami, the analytical equation derived by Fukui et al., 1962 can be used to obtain the input fluid velocity profile from water surface elevation. The comparison between experimental results and numerical ones showed good agreements in term fluid velocities and water surface elevation on both propagation area and inundation area. Furthermore, good agreements were also confirmed in initial wave forces and sustain ones acting on the cylindrical structure.

This study clears the effect of protective weir existence on the wave velocity at the surrounding protected structure. Weir tended to cause the delay of tsunami arrival time and also reduce velocities at the top section of structure. The higher weir tended to have significant reduction of velocity with increasing turbulence magnitude. The wider diameter tended to reduce the wave velocity, as there is not enough space for wave to accelerate. The reduction of wave velocity may also means as the reduction of scour risk, as fluid velocity play an important role on the scour problems.

ACKNOWLEDGEMENTS

This study was facilitated by Hydraulic Laboratory of University of Miyazaki. All contributions are acknowledged.

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