



Experimental Validation of Smoothed Particle Hydrodynamics for Nonlinear Free Surface Flows in Marine Engineering

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Doctoral Dissertation

**Experimental Validation of Smoothed Particle
Hydrodynamics for Nonlinear Free Surface Flows in
Marine Engineering**

(海洋工学における非線形自由表面流れのための SPH の実験
的検証)

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Abstract

In the marine engineering field, there are many problems related to free-surface flows such as water waves, sloshing, slamming, green water, and flooding. In the case of ship operations at sea, an incident wave is a dominant element affecting ship motion; thus, addressing water waves and their interactions with ship motion is a major problem. Another important issue is sloshing because it is a great threat to liquid carriers. Sloshing is the resonance of liquid inside a tank induced by external oscillation, and it is regarded as highly nonlinear free-surface flow. To address such nonlinear free-surface flows, advanced numerical simulation methods are urgently needed.

In this study, smoothed particle hydrodynamics (SPH), a truly mesh free and fully Lagrangian computational fluid dynamics method, is adopted to simulate nonlinear free-surface flows of water waves and sloshing. A dedicated experiment is performed to validate SPH simulations for each subject. SPH simulations are accelerated using a graphics processing unit to enable the use of a sufficiently large number of particles. Through systematic experimental validation, the capability of SPH for nonlinear free-surface flows, i.e., wave generation and propagation, and sloshing in a prismatic tank is demonstrated in this study together with a discussion on how to set numerical parameters depending on problems.

In Chapter 1, the background and motivation of the research are described and then the main subject and objectives of the study are explained.

In Chapter 2, a detailed literature review of SPH simulation of free-surface flows in marine and civil engineering is made to determine missing elements to be investigated in the present study.

In Chapter 3, details of the weakly compressible SPH used in this study are presented. Here, the SPH governing equation formulation, spatial interpolation, and pressure field are explained. In addition, numerical modeling of the two-phase SPH used for sloshing analysis is described.

In Chapter 4, the validation results and discussion regarding the first subject of wave generation and propagation of water waves are presented. Two-dimensional and single-phase SPH simulation is performed under the same condition as the experiment for the validation purpose. Here, the measured time history of the piston motion of the wavemaker was directly imposed in SPH simulation as the moving wall boundary. The SPH simulation agrees reasonably well with the experiment in terms of waves generated by the wavemaker and long-distance wave propagation along with the tank. The SPH result can provide better accuracy for the steady amplitude of waves compared to that of the well-known Biesel transfer function based on linear wave theory, as well as the variation in hydrodynamic pressure. In addition, large and sudden deformation of the free-surface resulting from the bank was also successfully captured by SPH. Finally, three-dimensional SPH simulation was also performed using over 20 million particles and a similar accuracy to that of the two-dimensional SPH was confirmed. Through these comparisons, it was well demonstrated that two- and three-dimensional SPH is capable of addressing nonlinear water waves.

In Chapter 5, the validation results and discussion regarding the second subject of sloshing in a prismatic tank are presented. Single-phase and three-dimensional SPH simulation for sloshing in external sway and roll oscillation is conducted using over 10 million particles for a

filling ratio of 25%. The SPH result showed qualitative agreement with the experiment in free-surface evolution, but the fluid run-up along the sidewall was not well captured. The prediction of hydrodynamic impact pressure was not satisfactory in terms of the pressure peak. Therefore, two-phase SPH simulation but in two dimensions was attempted to determine the importance of air phase for the sloshing simulation. The two-phase SPH agreed better with the experiment in terms of free-surface evolution, including run-up along the sidewall and the hydrodynamic impact pressure, particularly for a filling ratio of 50%. The existence of air significantly affects the run-up of fluid and the pressure prediction near corners, where the water impact is significant, which improves as a consequence.

In Chapter 6, properly and effectively setting numerical parameters for SPH simulation is discussed because several parameters need to be tuned to obtain proper accuracy. Particle spacing, coefficient of smoothing length, and coefficient of artificial viscosity are the dominant parameters for water waves. Particle spacing, coefficient of smoothing length, and speed of sound are influential in obtaining proper pressure variation in sloshing.

In Chapter 7, the study is summarized and conclusions are presented based on the results; future works are also mentioned.

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Chapter 1

Introduction

1.1 Background

In the era of trade globalization, the amount of trade increases yearly. Marine transportation plays a vital role in the world economy because it can deliver goods from one country to another country in a large quantity. Ships as means of transportation have an advantage in terms of weight, capacity, and costs compared to other means of transportation such as airplanes. Ship weight is proportional to ship mass as explained by Archimedes law. It states that increasing ship mass will increase ship capacity and weight. A vessel could carry tons of oil from one country to another country while an airplane could not carry nearly the same amount. The costs using marine transportation are cheaper as quantity is linear to shipping cost. A larger capacity leads to lower price paid for by the costumer as transportation frequency decreases compared to that using a smaller capacity vehicle such as an airplane. However, marine transportation has a significant threat from sea weather conditions because the seas are not always calm. Ships have to maintain operation during bad weather such as storms, severe wind, and large waves. Figure 1-1 shows a ship's incapability to maintain operation under bad weather conditions and eventually drifting in the sea. These conditions endanger ship operations during transportation in the sea. A water wave is one significant force affecting ships in the sea. Another important event in marine transportation is sloshing. Sloshing is defined as the resonance of fluid inside a tank via an external oscillation motion. In maritime transportation, a source of external oscillation is waves. Sloshing can endanger ship stability when there is energetic sloshing inside the tank. Waves and sloshing are examples of the main threats of marine transportation for liquid carrier at sea.

In marine transportation, there are many problems related to free-surface flows such as water waves, sloshing, green water, flooding, among others. A water wave is one of the classical problems that many studies have addressing using theoretical, experiment, and numerical methods. Nonlinear waves are a significant issue in the marine engineering and naval architecture fields because these phenomena are very complex and difficult to predict. Tsunamis and freak waves are an example of nonlinear phenomena that can lead to disasters.

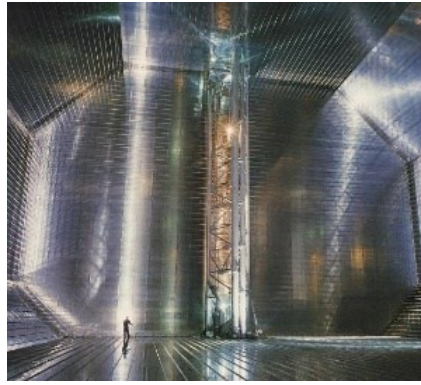
Naturally, sea waves are nonlinear with complex free-surface flow and it is difficult to solve such a problem using a theoretical solution.



<https://www.marineinsight.com/videos/watch-salvage-modern-express-smit-salvage>

Figure 1-1. Ship loss ability to maintain operation in bad weather condition.

As previously mentioned, another important phenomenon during ship travel in the sea is sloshing. Sloshing is a natural phenomenon when ships carry liquid cargo such as chemicals, oil, liquefied natural gas (LNG), among others. Sloshing means any motion of a free liquid inside a container or tank when the tank is partially filled. The fluid inside the tank can freely move. It could be a violent flow phenomenon in the marine engineering field that is highly challenging to predict because of the chaotic movement of fluid inside the tank. Figure 1-2 shows an LNG carrier with a membrane-type carrier. An oil or LNG carrier demands sloshing analysis because of the vulnerability of the ship during transport from the source to the customer that can be in a different continent or country. Therefore, impact pressure is a dangerous phenomenon when sloshing occurs in an LNG carrier because it can create an explosion caused by the impact between the LNG and the wall. When sloshing is very energetic, the excessive motion of fluid inside the tank can also influence ship stability, causing structural damage.



<https://www.businesswire.com/news/home/20081217005080/en/1735488/ExxonMobil-Technology-Yields-World%e2%80%99s-Largest-LNG-Carrier>

Figure 1-2. A LNG tank of membrane type carrier

From the aforementioned discussion, it can be concluded that water waves and sloshing are demanding problems in the marine engineering field. Because water waves and sloshing are nonlinear phenomena and free-surface flows, a numerical approach and experiments are appropriate methods to apply in these problems. The particle method is one of the numerical methods that has the merit of addressing free-surface and violent flows and large deformation and could be a promising method to apply to these studies. In this study, smoothed particle hydrodynamics (SPH) is used to address free-surface flows of water waves and sloshing. SPH has an advantage of no grid generation (meshless) and is a pure Lagrangian approach, which is suitable to address free-surface flows.

1.2 Objective of the Study

The main objective of this study is experimental validation of smoothed particle hydrodynamics for water wave and sloshing problems. The objectives of the study are to

1. Make a dedicated model experiment for water waves and sloshing.
2. Validate large-scale SPH simulation for generation and propagation of water waves.
3. Validate single- and two-phase SPH simulation for sloshing in a prismatic tank.
4. Derive appropriate set parameters for water waves and sloshing problems.

1.3 Outline of the Thesis

Chapter 1 introduces the study background, objective, and outline.

Chapter 2 presents a literature review of the applications of SPH on wave generation and propagation completed in past studies. A comparison of past studies to the present study is presented in this section. This section also includes a literature review of SPH used for sloshing.

Chapter 3 introduces the SPH methodology, basic SPH theory, kernel function, smoothing length, momentum equation, continuity equation, delta-SPH based on weakly compressible SPH (WCSPH). This chapter introduces also the SPH solver DualSPHysics with its features and an example in a sloshing test case.

Chapter 4 describes a validation case of SPH for wave generation and propagation using DualSPHysics ver. 4.0. The case is for long travel distance propagation with three water depths, two periods, and three wavemaker strokes. A dedicated experiment is conducted at the Kobe University wave basin with a length of 60.0 m, width of 6.0 m, and an adjustable water depth from 0 m to 1.5 m. Validations of water waves, including large deformation surface waves, using an obstacle box are completed. In addition, a pressure sensor is used to capture dynamics pressure during the experiment. Furthermore, three-dimensional SPH is executed with short-distance propagation for two water depths. Finally, validation studies are summarized with recommended parameters that are suitable for water wave propagation and generation using SPH.

Chapter 5 describes a validation case of SPH for sloshing in a prismatic tank. First, an experiment was conducted at the National Research Institute of Fisheries Engineering (NRIFE). The length of the prismatic tank is 0.36 m, the width is 0.30 m, and the height of the tank is 0.21 m. The experiment is completed in four degrees of freedom using a forced excitation machine. The motions are sway, roll, heave, and yaw motions. The motions include two frequencies of external excitation with several amplitude excitations. Three pressure sensors are used in the experiment to measure impact pressure on the wall of the tank. Validations of sloshing are conducted using large-scale particle simulation using over 10M particles in three dimensions using single-phase SPH. Moreover, two-phase SPH is executed and a comparison result to single-phase is completed via an experiment. It shows two-phase SPH has a significant effect on the SPH result regarding pressure prediction and free-surface evolution.

Chapter 6 discusses parameter tuning in the SPH method for water waves and sloshing. Particle spacing, smoothing length, coefficient of artificial viscosity, and speed of sound are tuning parameters in SPH simulation. The parameters are used for validation studies as discussed. Finally, recommended parameter setting is derived based on a current study of water waves and sloshing in a prismatic tank.

Chapter 7 provides a conclusion of experimental validation of SPH for water waves and sloshing in a prismatic tank. Future works are mentioned to fill the research gap based on the present study.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, a literature review is presented to explain past applications of the SPH method for free-surface flows. The merit of SPH for application to the marine engineering field, i.e. water wave propagation and sloshing in this study, is explained. Finally, recent developments of General Purpose of Computing on Graphics Processing Unit (GPGPU) technology in SPH are listed to show the applicability of the SPH method to realistic engineering problems. The literature review includes SPH applications in marine and civil engineering fields on complex free-surface flows and fluid–structure interaction.

2.2 Meshless Method and Lagrangian Approach

Computational fluid dynamics (CFD) as one popular branch of physics has been developed since Claude-Louis Navier and George Gabriel Stokes successfully derived the Navier–Stokes (N-S) equation to describe the motion of viscous fluid substances. There are many researchers using N-S equation to solve problems for fluid dynamics in physics. To derive the motion of fluid dynamics, a physics phenomenon must be transferred to a computational method. It needs a domain discretization. There are two methods of discretization, using a grid as in the well-known mesh method, and a non-grid method, as in the well-known meshless method. The mesh method has reached maturity because it has been developed for more than a century; however, the meshless method, such as the smoothed particle hydrodynamics (SPH) method, is not yet mature. It began when Lucy [1], Gingold and Monaghan [2] used smoothed particle hydrodynamics (SPH) for astrophysical problems. During the following years many meshless methods have been developed for fluid dynamics problems. Table 2-1 shows the meshless methods presented by Liu and Liu [3].

Table 2-1. Typical meshless methods presented by Liu and Liu [3]

Method	Method of Approximation	References
Smoothed particle hydrodynamics (SPH)	Integral representation	Lucy, 1977; Gingold and Monaghan, 1977
Finite point method (FPM)	Finite difference representation	Liszka and Orkisz, 1980; Onate et al, 1996
Diffuse element method (DEM)	Moving least square (MLS) approximation Galerkin method	Nayroles et al., 1992
Element free Galerkin (EFG) method	MLS approximation Galerkin method	Belytschko et al, 1994; 1996; 1998
Reproduced kernel particle method (RKPM)	Integral representation Galerkin method	Liu et al, 1995; 1996
HP-cloud method	MLS approximation, Partition of unity	Duarte and Oden, 1996
Free mesh method	Galerkin method	Yagawa and Yamada, 1996; 1998
Meshless Local Petrov-Galerkin (MLPG) method	MLS approximation Petrov-Galerkin method	Atluri and Zhu, 1998; 1999; Atluri and Shen, 2002
Point interpolation method (PIM)	Point interpolation(Radial and Polynomial basis), Galerkin method, Petrov-Galerkin method	Liu and Gu, 1999; 2001a-d; Gu and Liu, 2001 a,c; Liu, 2002; Wang and Liu, 2000;2001;2002
Meshfree weak-strong form(MWS)	MLS, PIM, radial PIM (RPIM), Collocation plus Petro-Galerkin	Liu and Gu, 2001; 2003c; 2003

The advantage of the meshless method compared to that of the mesh method is discussed by Violeau and Rogers [4]; it has an extraordinary capability to simulate a large variety of complex flows. The advantage of the meshless method is the ability to address the following:

- a. A distorted and rapidly moving free-surface without any restriction with respect to topologies.
- b. Highly nonlinear, inertia-dominated flows and the impact process.

- c. Multi-fluid flows and multi-physics.
- d. Fluid/structure interactions, including rigid body motion in a fluid and fluid/elasticity coupling.
- e. Ease of programming (at least for basic) either in two or three dimensions.

Because this method was developed about approximately two decades ago and is not yet mature compared to the mesh-based method, there are several drawbacks as follows:

- a. Long computational time, particularly in three-dimensional simulations.
- b. Difficulties in prescribing wall boundary conditions, and greater problems at open (inflow/outflow) boundaries.
- c. Inaccurate pressure prediction, at least for the original WCSPH variant.
- d. Difficulties in dealing with variable space resolution for (nearly) incompressible flows.

Recent SPH studies show that several issues have been resolved, such as open boundaries (inflow/outflow) by Tafuni et al. [5,6] and variable space resolution by Vacondio et al. [7]. To reduce computational runtime in a particle method (SPH), General Purpose computing on Graphics Processing Units (GPGPU) technology has been introduced. GPGPU is developed from the game technology. Harada et al. [8] runs his entire SPH computation in GPU. Herault et al. [9] used Compute Unified Device Architecture (CUDA) introduced by NVIDIA to run computation in GPU. To overcome pressure noise in WCSPH, researchers implemented delta-SPH (δ_ϕ -SPH) invented by Molteni and Colagrossi [10] to reduce of density fluctuation. It shows the particle method (SPH) has been significantly improved. SPH is a promising method for the next generation of Computational Fluid Dynamics (CFD). In this study, open-source SPH solver DualSPHysics is used to overcome complex free-surface flows in the marine engineering field.

2.3 Overview of Smoothed Particle Hydrodynamics (SPH)

SPH was developed by Lucy [1], Gingold and Monaghan [2] for astrophysics problems and later on Monaghan improved this method for a free-surface flow problem in water waves on a beach slope and for a dam break [11]. SPH shows advantages compared to the grid-based

method because it is easier to capture large deformation and the highly nonlinear phenomenon of fluid dynamics. Monaghan and Kos reported that SPH well captures a solitary wave and wave run-up during an experiment where splashes are also well captured by SPH [12]. SPH shows accuracy for the prediction of free-surface flows in a single-phase and later on it was developed into multiphase flows by Monaghan and Kocharyan [13]. The represented multiphase flows are used to solve dusty gas showing SPH can capture the phenomena of air and dust.

Because SPH was developed for astrophysics problems initially, as a consequence liquid is treated as weakly compressible in classical SPH and it is well-known as Weakly Compressible of Smoothed Particle Hydrodynamics (WCSPH). An issue for WCSPH because fluid is treated as weakly compressible is that it allows density to readily fluctuate with a small fluctuation (approximately 1%). Later, to resolve this problem, a truly Incompressible Smoothed Particle Hydrodynamic (ISPH) was developed with solving Poisson Pressure equation every time step [14,15]. There are many SPH-solvers available, for instance AQUAplus, DualSPHysics, GADGET, GPUSPH, IMPETUS, LS-DYNA, Neutrino, ndspmh, PASIMODO, SPH-flow, SPHERA, SPHysics, and SPLASH. In this study, DualSPHysics is employed to address applications of marine engineering problems. DualSPHysics is based on WCSPH and has been applied for GPGPUs by Crespo et al.[16] making it easier to introduce a large number of particles. DualSPHysics was developed based on the SPHysics code, but it has been optimized and parallelized using open MPI for CPUs or GPGPU for GPUs.

DualSPHysics version 4.0 and version 4.2 are used in this study to apply complex free-surface flows of water waves and sloshing. The fundamental difference in the two versions is multiphase flows are included in version 4.2. The important application of multiphase flows is realistic fluid flows can be simulated as in reality nearly fluid flows are two-phase flows. In addition, the effect of the air phase on free-surface flows could have significant effects such as impact pressure in the sloshing case. The air-entrapped effect on two-phase flows is not captured when a simulation is conducted in single-phase flows. Simulation of two-phase flows will provide more insight in understanding SPH applications in the marine engineering field.

2.4 Water Wave Propagation and Generation

Experimental studies had been completed over the years to study water wave propagation, but the limited facilities and expensive cost has made this option relatively little used by researchers. A numerical method has shown rapid development compared to that of experimental studies because it is linearly growing with the development of computer technology that supports numerical computation. Among the numerical methods, SPH is a meshless and Lagrangian approach. SPH has an advantage in large deformation problems and there is no need for special treatment in tracking free surfaces making it suitable for water wave generation and propagation. SPH is a promising method to apply in water waves because it is a pure Lagrangian and meshless approach so every particle can move freely based on their interested neighbor particle. Because there is no grid in the computational domain large deformations can be well captured using this method. The first attempt to apply this method for water waves was made by Monaghan and Kos [12] for a solitary wave on Cretan beach, and it showed SPH could very accurately reproduce the phenomena. Dalrymple and Rogers [17] applied SPH for numerical modeling of water waves to capture breaking waves on beaches in both two and three dimensions using a different time-stepping algorithm. The result shows SPH has an excellent capability to apply nonlinear phenomena such as breaking waves, solitary waves, or tsunamis.

Recently, several studies applied SPH for water wave propagation. Barreiro et al. [18] applied SPH for coastal engineering problems to predict the force exerted on an object of the coast such as urban furniture. Altomare et al. [19] reported SPH application for the interaction of waves with armour block sea breakwater for medium propagation waves. Water wave propagation at a medium distance was successfully conducted and validated using experimental data or the analytical solution of Stokes second-order wave theory by Altomare et al. [20,21]. The application of SPH to a solitary wave was reported by Cunningham et al. [22] for the prediction of tsunamis on onshore structures agreed well with the experimental data. Pringgana et al. [23] performed SPH to simulate tsunami-induced bore impact on a discrete onshore structure on a dry bed. Most SPH applications for water waves are for medium-distance propagation and there are still few studies applying SPH to long-distance propagation.

The present study attempted to apply SPH to long-distance propagation in a large numerical wave tank. The distance between the wave probe and wavemaker is 24.6 m. Twelve

wavelengths are needed to reach the wave probe from the wavemaker. In this study, three water depths, three piston wavemaker amplitudes, and two wavemaker periods were used. Using a wave basin at Kobe University, validation of water waves was carried out by using directly measured piston motion during the experiment. This study includes two-dimensional (2D) and three-dimensional (3D) simulations using directly imposed movement of the piston motion wavemaker based on experimental data.

2.5 LNG Tank Sloshing.

As mentioned in Chapter 1, a crucial phenomenon in marine engineering problems is ships in waves (seakeeping). A dangerous event is sloshing which occurs in liquid carriers such as oil, chemical, and LNG carriers. Sloshing is a natural phenomenon in a partially filled tank because of fluid movement inside a tank that can influence ship stability. Many studies of sloshing have been conducted over decades using mesh-based approaches with a different scheme such as the finite difference method [24,25], finite volume method [26,27], finite element method [28,29] and boundary element method [30,31]. However, because these methods are based on a grid some difficulties include large deformations, discontinuous fluid motions of violent flow, and tracking of a free-surface. Some improvement was made by Hirt and Nichols [32] using volume of fluid and level set method by Sussman et al. [33]; however, these methods still have difficulties capturing large deformations and violent free-surface flows. SPH is an emerging approach and is a suitable method to apply to a sloshing problem. Because of the nature of the meshless method it is easier to capture large deformation of boundaries and violent free-surface flows. As mentioned in the previous section, this study will carry out validation of SPH using a large number of particles in single-phase SPH in three dimensions and two-phase SPH simulation in two dimensions.

Application of SPH in the sloshing problem has showed promising results so far. Cao et al. [34] simulated sloshing in a rectangular shape that agreed well with the experimental data. Shao et al. [35] applied an improved SPH to obtain a smoother pressure field because WSPH has spurious pressure problems. Application of incompressible SPH (ISPH) was reported by Gotoh et al. [36] using Higher-order Laplacian (HL) to increase the performance of ISPH for violent sloshing flow. Delorme et al. [37] and Chen et al. [38] conducted validation of impact pressure using SPH with forced roll motion in 2D simulation. Kim [39] used SPH and FDM to

validate impact pressure using a rectangular tank. Using an improved SPH, Colagrossi et al. [40] corrected the pressure field as a remedy for pressure noise and Shao et al. [35] used kernel gradient correction as a new treatment of a solid boundary to obtain smoother distribution in the pressure field of a rectangular tank. Rafiee et al. [41] performed 2- and 3-D SPH simulation of a rectangular tank in sway motion using improved SPH. Bouscasse et al. [42] investigated shallow water sloshing using delta-SPH in sway motion from small amplitude to large amplitude excitation as did De Chowdhury and Sannasiraj [43]. Recently, long-duration simulation of sloshing in a small filling ratio was performed by Green and Peiro [44]. It showed SPH matched the experiment both for wave elevations and forces on the tank. These results clearly show that SPH is suitable for largely deformed free-surface flows such as sloshing. However, most of these previous studies used a simple rectangular tank with the single-phase SPH method and a relatively small number of particles. In the present study, sloshing in a prismatic tank subjected to sway and roll motions were investigated and experimental validation of single- and two-phase SPH methods was attempted. DualSPHysics version 4.2 was used to accommodate two-phase SPH developed by Mokos et al. [45].

In the present study, first, an experiment was conducted at the NRIFE using a prismatic tank with a forced oscillation machine. The machine can produce regular motions of sway, roll, heave, and yaw. Three pressure gauges were set up in the middle of tank with four video cameras. Two video cameras were set up near the prismatic tank and two outside of the forced oscillation machine. In this study, large-scale 3D particle simulation and 2D two-phase SPH simulation are conducted to address sloshing in the prismatic tank.

Chapter 3

Smoothed Particle Hydrodynamics

3.1 Introduction

This chapter presents basic theory of Smoothed Particle Hydrodynamics (SPH). Nature of SPH, governing equations in Lagrangian form, other basis of SPH such as smoothing length, delta-SPH, kernel function, and so on are explained. In addition, an open source SPH solver, DualSPHysics is presented with pre- and post-processing feature. Finally, an example of applications of SPH is presented for a typical benchmarking test.

3.2 Theory of Smoothed Particle Hydrodynamics

Particle method has developed and advanced two-decade and shown promising results to address free-surface flows. Smoothed Particles Hydrodynamics (SPH) is one of the earliest particle methods that developed to tackle astrophysical problems in 1977's by Lucy [1], Gingold and Monaghan[2]. Later on, SPH was extended for free-surface flow problems introduced by Monaghan[11]. Dam breaking result showed the capability of SPH to deal largely deformable free-surface flows. From the viewpoint of numerical modelling, SPH has an advantage for free-surface flow problems because it is truly meshless method and fully Lagrangian method. This method uses collective motions of a large number of particles to represent flows with a Lagrangian description of motion rather than Eulerian description.

SPH uses an interpolation method to approximate values and derivatives of continuous field quantities by using discrete sample points. The sample points are identified as particles that carry concrete entities e.g., masses, velocity, position, etc. The quantities are obtained as weighted averages from the adjacent particles. Since SPH does not require computational grids, there is an advantage to overcome free-surface flows such as water waves, sloshing, tsunamis, and wave breaking.

This chapter will describe the basis of SPH that used in this study. There are two variants in SPH, one is weakly compressible SPH (WCSPH) and the other is incompressible SPH (ISPH). DualSPHysics version 4.0 and version 4.2 implements WCSPH only and does not implemented ISPH yet, but an effort to improve DualSPHysics with ISPH implementation has started. WCSPH has shown acceptable pressure fields for engineering applications such as sloshing[46]. More details on the SPH basic equation are described below.

3.2.1 Smoothed Particle Hydrodynamics (SPH) Interpolant

In SPH any field function $A(\mathbf{r})$ in domain Ω can be approximated by integral interpolate as Equation (3-1) where W is kernel function and $\mathbf{r}$ vector of position, and h is smoothing length.

$$A(\mathbf{r}) = \int_{\Omega} A(\mathbf{r}') W(\mathbf{r} - \mathbf{r}', h) d\mathbf{r}' \quad (3-1)$$

In discrete notation Equations (3-1) leads to an approximation of the function at particle a (interpolant point) as below

$$A(\mathbf{r}_a) = \sum_b A_b V_b W(\mathbf{r}_a - \mathbf{r}_b, h) \quad (3-2)$$

If $V_b = m_b / \rho_b$ and $W_{ab} = W(\mathbf{r}_a - \mathbf{r}_b, h)$ is kernel function or weighting function the derivative of the interpolants can be obtained by using

$$\nabla A(\mathbf{r}_a) = \sum_b m_b \frac{A_b}{\rho_b} \nabla W_{ab} \quad (3-3)$$

Where ∇W_{ab} denotes the gradient of W_{ab} with respect to particle a . Equation (3-3) can be used to estimate the gradient of arbitrarily scattered data. Figure 3-1 show diagram of SPH with distance particle (r_{ab}) with smoothing kernel (W_{ab}) with a radius of influence ($2h$).

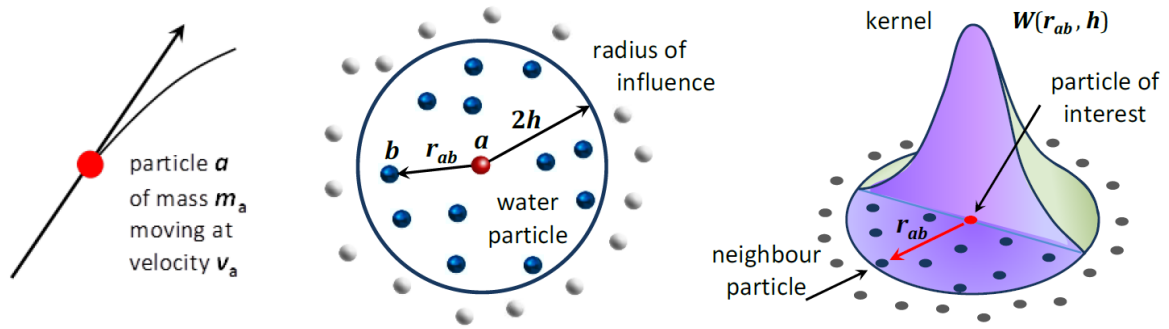


Figure 3-1. The diagram of SPH with smoothing kernel.[47]

3.2.2 Weighting Functions (Smoothing Kernel)

The capability of the SPH model depends on the choice of the smoothing kernel. Kernels are expressed as a function of the non-dimensional distance between particles (q), given by $q = r / h$ where r is the distance between any two given particles a and b . Smoothing length (h) controls the size area around particle a in which neighbouring particles are considered. Smoothing kernel must satisfy several conditions there are major properties or requirements summarized by Liu and Liu[48] described as

1. The smoothing function must be normalized over its support domain (*unity*).
2. The smoothing function should be compactly supported (*Compact support*).
3. $W(\mathbf{r} - \mathbf{r}') \geq 0$ for any point at $\mathbf{r}'$ within the support domain of the particle at any point $\mathbf{r}$ (*Positivity*).
4. The smoothing function values for a particle should be monotonically decreasing with the increase of the distance away from the particle (*Decay*).
5. The smoothing function should satisfy the Dirac delta function as the smoothing length approaches zero (*Delta function property*).
6. The smoothing function should be an even function (*Symmetric property*).
7. The smoothing function should be sufficiently smooth (*Smoothness*).

In DualSPHysics code there are two smoothing functions provided by the developer that user can choose, the following kernels are;

- a. Cubic spline[49]

$$W(r, h) = \alpha_D \begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3 & 0 \leq q \leq 1 \\ \frac{1}{4} & 1 \leq q \leq 2 \\ 0 & q \geq 2 \end{cases} \quad (3-4)$$

Where α_D is equal to $10/7\pi h^2$ in two dimensional and $1/\pi h^3$ in three dimensional. The tensile correction method, proposed by Monaghan [50], is only actively used in the cases of a kernel whose first derivative goes to zero with the particle spacing q .

b. Quantic[51]

$$W(r, h) = \alpha_D \left(1 - \frac{q}{2}\right)^4 (2q + 1) \quad 0 \leq q \leq 2 \quad (3-5)$$

Where α_D is equal to $7/4\pi h^2$ in two dimensional and $21/16\pi h^3$ in three dimensional, with an influence domain of $2h$ ($q \leq 2$) are considered.

3.2.3 Momentum Equation

The momentum conservation equation in a Lagrangian form of WCSPH is

$$\frac{dv}{dt} = -\frac{1}{\rho} \nabla P + \mathbf{g} + \mathbf{\Gamma} \quad (3-6)$$

Where $\mathbf{\Gamma}$ refers to dissipative terms and $\mathbf{g}$ is gravitational acceleration. In DualSPHysics offer two different options for the effect of dissipation, there is Artificial Viscosity by Monaghan[52] and Laminar viscosity and Sub-particle Scale (SPS) Turbulence introduced by Gotoh et al.[53]. In this study, Artificial Viscosity is chosen for all simulation. Momentum Equation (3-6) becomes as following

$$\frac{dv_a}{dt} = \sum_b m_b \left(\frac{P_a + P_b}{\rho_a \rho_b} + \Pi_{ab} \right) \nabla_a W_{ab} + \mathbf{g} \quad (3-7)$$

$$\Pi_{ab} = \begin{cases} \frac{-\alpha \bar{c}_{ab} \mu_{ab}}{\rho_{ab}} & \mathbf{v}_{ab} \cdot \mathbf{r}_{ab} < 0 \\ 0 & \mathbf{v}_{ab} \cdot \mathbf{r}_{ab} > 0 \end{cases} \quad (3-7)$$

Where $\mathbf{r}_{ab} = \mathbf{r}_a - \mathbf{r}_b$ and $\mathbf{v}_{ab} = \mathbf{v}_a - \mathbf{v}_b$ with $\mathbf{r}$ and $\mathbf{v}$ being the particle position and velocities respectively with $\mu_{ab} = h \mathbf{v}_{ab} \cdot \mathbf{r}_{ab} / (\mathbf{r}_{ab}^2 + \eta^2)$, $\bar{c}_{ab} = 0.5(c_a + c_b)$ is the mean speed of sound, $\eta^2 = 0.01h^2$ and α is a coefficient that needs to be tuned in order to introduce the proper dissipation. In two-phase flows, because there is air phase, equation of momentum in air phase written as following

$$\frac{d\mathbf{v}_a}{dt} = -\sum_b m_b \left(\frac{P_a + P_b}{\rho_a \rho_b} + \Pi_{ab} \right) \nabla_a W_{ab} - 2a\rho_a^2 \sum_b \frac{m_b}{\rho_b} \nabla_a W_{ab} \quad (3-8)$$

$$a = 1.5g \left(\frac{\rho_{ow}}{\rho_{oa}^2} \right) L \quad (3-9)$$

Where ρ_{ow} and ρ_{oa} are the initial densities of the two-phase or water and air in this study. L is a characteristic length depending on particle spacing and the case being modeled. The two-phase flow that used in DualSPHysics is based on Colagrossi and Landrini model [54]. It was developed by Mokos et al.[45].

3.2.4 Continuity Equation

As mentioned that DualSPHysics is based on WSPH, the conservation of mass or continuity equation was solved in Lagrangian form as

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \mathbf{v} \quad (3-10)$$

$$\frac{d\rho_a}{dt} = \sum_b m_b (\mathbf{v}_a - \mathbf{v}_b) \nabla_a W_{ab} \quad (3-11)$$

Which is the movement of particles are described as

$$\frac{d\mathbf{r}}{dt} = \mathbf{v} \quad (3-12)$$

In WCSPH simulation the mass of each particle remains constant and only their associated density fluctuates. In two-phase flows, the continuity equation becomes as

$$\frac{d\rho_a}{dt} = -\rho_a \sum_b \left[(\mathbf{v}_a - \mathbf{v}_b) \cdot \nabla_a W_{ab} \frac{m_b}{\rho_b} \right] \quad (3-13)$$

3.2.5 Equation of State.

As the fluid in WCSPH is treated as weakly compressible and an equation of state is used to determine fluid pressure based on particle density this procedure introduced by Monaghan. Using Tait's equation of states that describes the relationship between pressure and density

$$P = b \left[\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right] \quad (3-14)$$

Where b is a constant related to the fluid compressibility and can be determined from $b = c_0^2 \rho_0 / \gamma$ with $\rho_0 = 1000 \text{ kg/m}^3$ is the reference density at the free-surface. c_0 is the speed of sound that is given by $c_0 = c(\rho_0) = \sqrt{(\partial P / \partial \rho)|_{\rho_0}}$ and γ is the polytropic constant ranging between 1 to 7, in DualSPHysics the polytropic constant is 7 for water and 1.18 for air. For two-phase flow equation of state, there is a new term called the constant background pressure (X) while $X=0$ is used for free-surface flow. Where a and L refer to Equation (3-9), equation of state in two-phase flow becomes.

$$P = b \left[\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right] + X - a\rho^2 \quad (3-15)$$

3.2.6 Time-Step Algorithms

DualSPHysics includes a choice of numerical integration schemes if momentum ($\mathbf{v}_a$), density (ρ_a), and position ($\mathbf{r}_a$) equations are first written in the form.

$$\frac{d\mathbf{v}_a}{dt} = \mathbf{F}_a \quad (3-16a)$$

$$\frac{d\rho_a}{dt} = D_a \quad (3-16b)$$

$$\frac{d\mathbf{r}_a}{dt} = \mathbf{v}_a \quad (3-16c)$$

These equations are integrated in time using a computationally simple Verlet based scheme or more numerically stable but computationally intensive two-stage Symplectic method.

3.2.6.1 Verlet Scheme

The algorithm was developed by Verlet[55] that is divided into two parts which is first part as follow ;

$$\mathbf{v}_a^{n+1} = \mathbf{v}_a^{n-1} + 2\Delta t \mathbf{F}_a^n \quad (3-17a)$$

$$\rho_a^{n+1} = \rho_a^{n-1} + 2\Delta t D_a^n \quad (3-17b)$$

$$\mathbf{r}_a^{n+1} = \mathbf{r}_a^n + \Delta t \mathbf{v}_a^n + 0.5\Delta t^2 \mathbf{F}_a^n \quad (3-17c)$$

Where the superscript n denotes the first time step, $\mathbf{F}_a^n$ and D_a^n are calculated using Equation (3-7) and every time steps N_s ($N_s \approx 50$ is suggested) variables are calculated according to

$$\mathbf{v}_a^{n+1} = \mathbf{v}_a^n + \Delta t \mathbf{F}_a^n \quad (3-18a)$$

$$\rho_a^{n+1} = \rho_a^n + \Delta t D_a^n \quad (3-18b)$$

$$\mathbf{r}_a^{n+1} = \mathbf{r}_a^n + \Delta t \mathbf{v}_a^n + 0.5\Delta t^2 \mathbf{F}_a^n \quad (3-18c)$$

On this study, this was not used preferred.

3.2.6.2 Symplectic Scheme

The Symplectic integration algorithm is time-reversible in the absence of friction or viscous effect, this method was developed by Leimkuhler et al.[56]. During the predictor stage, the values of acceleration and density are estimated at the middle of the time step according to

$$\rho_a^{n+\frac{1}{2}} = \rho_a^n + \frac{\Delta t}{2} D_a^n \quad (3-19a)$$

$$\mathbf{r}_a^{n+\frac{1}{2}} = \mathbf{r}_a^n + \frac{\Delta t}{2} \mathbf{v}_a^n \quad (3-19b)$$

During the corrector stage, $d\mathbf{v}_a^{n+1/2}/dt$ is used to calculate corrected velocity and therefore position, at the particles at the end of the time step according to

$$\mathbf{v}_a^{n+1} = \mathbf{v}_a^{n+\frac{1}{2}} + \frac{\Delta t}{2} \mathbf{F}_a^{n+1/2} \quad (3-20a)$$

$$\mathbf{r}_a^{n+\frac{1}{2}} = \mathbf{r}_a^{n+\frac{1}{2}} + \frac{\Delta t}{2} \mathbf{v}_a^{n+1} \quad (3-20b)$$

At the end of the time step, $d\rho_a^{n+1}/dt$ is determined using the updated values D_a^{n+1} and updated values of $\mathbf{r}_a^{n+1}$ and $\mathbf{v}_a^{n+1}$ [57].

3.2.7 Variable Time-step Algorithms

With explicit time integration schemes, the timestep is dependent on the Courant-Friedrichs-Lewy (CFL) condition. A variable time Δt is calculated according to Monaghan et al.[12]

$$\Delta t_f = CFL \cdot \min(\Delta t_f, \Delta t_{cv}) \quad (3-21a)$$

$$\Delta t_f = \min_a \left(\sqrt{\frac{h}{f_a}} \right) \quad (3-21b)$$

$$\Delta t_{cv} = \min_a \frac{h}{C_s + \max_b \left| \frac{h v_{ab} r_{ab}}{(r_{ab}^2 + \eta^2)} \right|} \quad (3-21c)$$

Where Δt_f is based on the force per unit mass ($|f_a|$) and Δt_{cv} combines the Courant and the viscous time step controls. Where CFL is a coefficient in the range of $0.1 \leq \text{CFL} \leq 0.3$.

3.2.8 Delta-SPH (δ_ϕ -SPH)

DualSPHysics has applied delta-SPH formulation that introduces a diffusive term to reduce density fluctuations. The state equation describes a very stiff density field, and together with the natural disordering of the Lagrangian particles, high-frequency, low amplitude oscillations are found to populate the density scalar field based on work of Molteni and Colagrossi [10]. The equation of continuity becomes

$$\frac{d\rho_a}{dt} = \sum_b m_b \cdot \mathbf{v}_{ab} \cdot \nabla_a W_{ab} + 2\delta_\phi h c_0 \sum_b (\rho_b - \rho_a) \frac{\mathbf{r}_{ab} \cdot \nabla_a W_{ab}}{r_{ab}^2} \frac{m_b}{\rho_b} \quad (3-22)$$

This modification can be explained as the addition of the Laplacian of the density field to the continuity equation. Antuono et al. [58] have presented a careful analysis of the influence of this term in the systems, by decomposing the Laplacian operator, observing the converge of the operators and performing linear stability analysis to inspect the influence of the diffusive coefficient. Due to truncation of the kernel (no particles are being sampled outside of an open boundary), the first-order contributions are null [59] resulting in a net force applied to the particles. This effect is not considered relevant for non-hydrostatic situations, where this force is many orders of magnitude inferior to any other force involved. Corrections to this effect were proposed by Antuono et al. [59]. A delta-SPH (δ_ϕ) coefficient of 0.1 is used for all simulations in this study.

3.2.9 Shifting Algorithm

Anisotropic particle spacing is an important stability issue in SPH as, especially in violent flows, particles cannot maintain uniform distribution. The result is the introduction of noise in the velocity and pressure field, as well as the creation of voids within the water flow for certain cases. The algorithm was first created for incompressible SPH but can be extended to weakly compressible SPH. In DualSPHysics the shifting algorithm was based on work of Vacondio et al. [60]. With the shifting algorithm, the particles are moved ('shifted') towards an area with fewer particles (lower particle concentration) allowing the domain to maintain a uniform particle distribution and eliminating any voids that may occur due to the noise.

3.2.10 Boundary Condition

DualSPHysics has implemented several boundaries conditions. The boundary is described by a set of particles that are considered as a separate set to the fluid particles. DualSPHysics provides functionality for solid impermeable and periodic open boundaries. The boundaries in DualSPHysics classified as follows

a. Dynamic boundary condition (DBC)

The Dynamic Boundary Condition (DBC) is the default method provided by DualSPHysics based on works of Crespo et al. [61]. This method sees boundary particles that satisfy the same equations as fluid particles. However, they do not move according to the forces exerted on them. Instead, they remain either fixed in position or move according to an imposed/assigned motion function (i.e., moving objects such as gates, wave-makers or floating objects)

b. The periodic open boundary condition

The periodic open boundary condition is the form of a periodic boundary condition which is achieved by allowing particles that near an open lateral boundary to interact with the fluid particle near the complimentary open lateral boundary another side of the domain.

c. Pre-imposed boundary motion

Pre-imposed boundary motion is particles behave as dynamic boundary condition however rather than being fixed, they move independently of the forces currently acting

upon them. This boundary condition was used to define complex simulation scenarios such as wave-making paddle in water waves.

d. Fluid-driven objects

It is also possible to derive the movement of the object based on interaction with fluid particles and using these forces to calculate its motion

3.3 DualSPHysics Code

DualSPHysics code is an open source SPH solver that was developed by University of Vigo (Spain), University of Manchester (U.K), University of Lisbon (Portugal), Flanders Hydraulics (Belgium), University of Parma (Italy). DualSPHysics was developed to apply SPH to real engineering problems, and hence it can be run on either CPUs or GPUs [62] and it can be downloaded freely at <http://dual.sphysics.org/index.php>. Figure 3-2 shows the logo of DualSPHysics code. DualSPHysics is a set of C++ and CUDA which was developed based on the SPHysics code.



Figure 3-2. Logo of DualSPHysics.

The Current version of DualSPHysics has implemented the two-phase SPH model for liquid-gas developed by Mokos et al.[45] for the application in violent hydrodynamics flows. Recently there are many researchers using DualSPHysics for solving fluid dynamics problems because the code has been optimized for parallel computing on GPU and CPU. Many advanced algorithms have been implemented, e.g. Active Wave Absorb System (AWAS), multiphase, automatic wavemaker, and many others will release in incoming years. In this study, DualSPHysics version 4.0 and version 4.2 were used.

3.3.1 Pre-processing

DualSPHysics version 4.0 and 4.2 used in the present study needs some steps to complete before running the code. The major difference between version 4.0 and 4.2 is two-phase SPH implementation that was used for a sloshing case. Following the guideline of DualSPHysics, step-by-step procedures to create a model and running a case are realized. The first stage can be divided into two main parts. The first part is several steps to define the initial geometry configuration, and the second part deals with parameter information that is needed for the execution process and is described in the XML file named `casedef` and `execution`.

`Casedef` is part of XML which are consist of three parts, i.e. `constantdef`, `geometry`, and `motion`. `Constantdef` is part of definition for several constants such as gravity acceleration, density, maximum water height, speed of sound, coefficient of smoothing length, and CFL number. Within `geometry`, there is an option to define fluid orientation both in two-dimension and three-dimension. Particle spacing is set with `pointmin` and `pointmax` to set minimum and maximum of the Cartesian coordinate of particles and a numerical domain will be created. `Motion` is part of definition of movement of boundary particles such as floating, prescribe motion of piston wavemaker and motion of tank for sloshing case.

The `execution` part defines parameters to run simulation such as kernel function, value of artificial viscosity (α), time step algorithm, delta-SPH (δ_ϕ -SPH), time simulation, minimum and maximum of density, etc.

3.3.2 Post-processing

Post-processing is one key issue to describe fluid dynamics phenomenon in computational fluid dynamics (CFD) because visualization of physical phenomena based on a numerical result is essential. Using tools provided by DualSPHysics, physical quantities can be obtained from SPH summations. These numerical quantities can be used to compare with experimental data like water elevation, pressure, and velocities. Moreover, wave profile can be visualized using Visualization Toolkit (VTK) Paraview. Using Paraview software, pressure contour, vector velocities of waves can be visualized for easy understanding of fluid dynamics phenomena.

DualSPHysics provides measurement tools, for instance, `measuretool`, `computeForce` and `isoSurface` for evaluation of numerical results. From the standpoint of open source SPH code, only DualSPHysics provides complete tools for pre-processing and post-processing. Moreover, the developer of DualSPHysics has developed the graphical user interface (GUI) called `DesignSPHysics` and the visualization code called `VisualSPHysics`.

3.4 Application of DualSPHysics: SPHERIC Benchmark Test 10

A case test of SPH for marine engineering application was included in DualSPHysics package i.e., sloshing in a rectangular tank. This case was based on experimental works of Souto-Iglesias et al.[63]. Sketch view of sloshing in a rectangular tank is shown in Figure 3-3. Pressure sensors were used to measure pressure in 6 different location. The width of the tank is 900 mm, the height of the tank is 508 mm, and the filling ratio is 18 %. The detailed information about the test can be seen at <http://spheric-sph.org/tests/test-10>. In this experiment, two liquids were used, which are water and oil, and the centre of rotation is at the bottom of the tank. For the validation test, the pressure sensor in the first location was used to validate impact pressure by DualSPHysics version 4.0. The parameters used in DualSPHysics are shown in Table 3-1. The simulation time is 8.35 s. Particle spacing is 2.0 mm and total number of particles in 2D is 22,064.

Table 3-1. Parameters setup in DualSPHysics

Parameters in DualSPHysics	
Kernel function	Wendland
Time step algorithm	Symplectic
Viscosity treatment	Artificial viscosity $\alpha = 0.05$
Coefsound	20.0
Initial particle size (mm)	2.0
Coefh	0.919
CFL number	0.20
Delta-SPH	0.10
Duration of simulation (s)	8.35

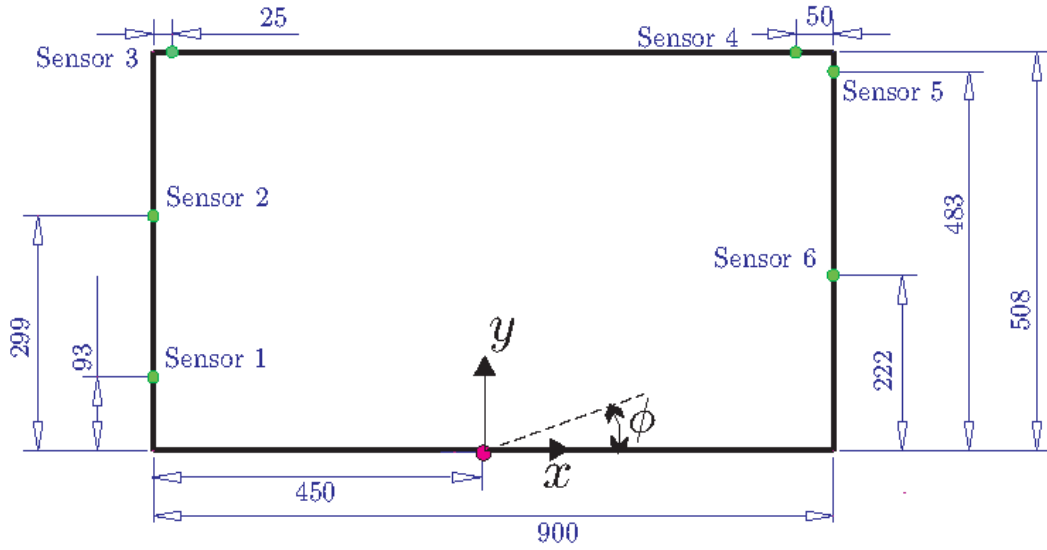


Figure 3-3. Schematic view of benchmarking test of SPHERIC test 10[62].

Figure 3-4 shows results of sloshing simulation using GPU Geforce GTX Titan. It took 0.45 hours to complete the computation. Figure 3-4 shows snapshots of sloshing simulation at $t = 0.0$ s, 0.9 s, 1.8 s, 2.4 s, 3.0 s, 3.3 s with contour of velocity magnitude. Large deformation of fluid is well captured by SPH. It shows the capability of SPH to overcome violent flows such as sloshing. Figure 3-5 shows comparison results between SPH and experiment for impact pressure at Sensor 1. SPH shows a good agreement with the experiment. Though the peak pressure is overestimated, the first time impact pressure is well captured by SPH. The results show the noise of pressure still exists although the code is based on delta-SPH. This is a classical problem when we use the weakly compressible SPH. In contrast, incompressible SPH (ISPH) gives smooth pressure results but it's more time-consuming. Because the pressure Poisson equation needs to be solved at every time step. Recently the effort to implement ISPH to DualSPHysics has been successfully carried out by Chow et al.[64], and it is scheduled to release oncoming years.

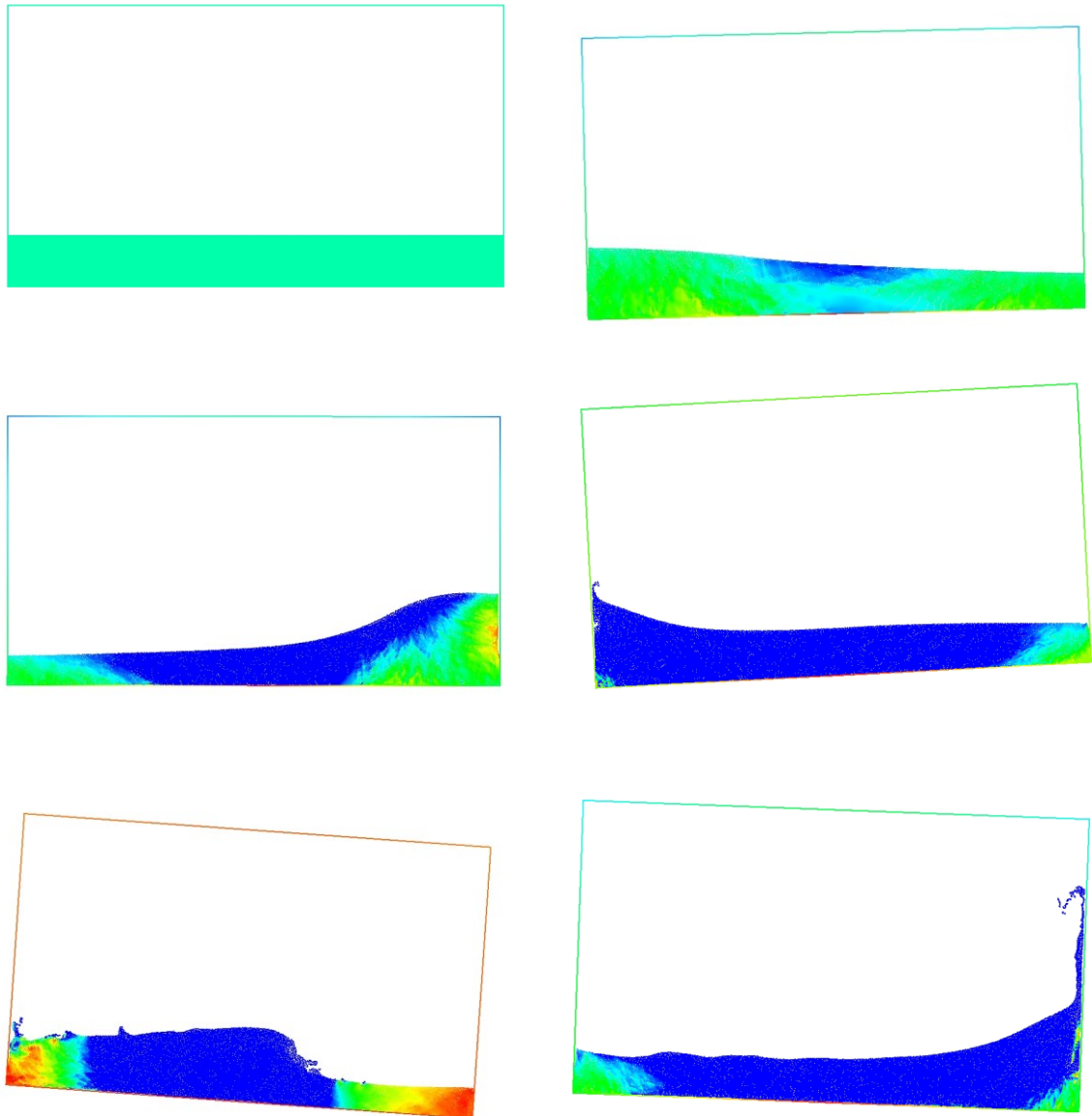


Figure 3-4. Snapshot of SPH simulation for a rolling tank in SPHERIC test 10 colour represent velocities with $t = 0.0$ s, 0.9 s, 1.8 s, 2.4 s, 3.0 s, 3.3 s.

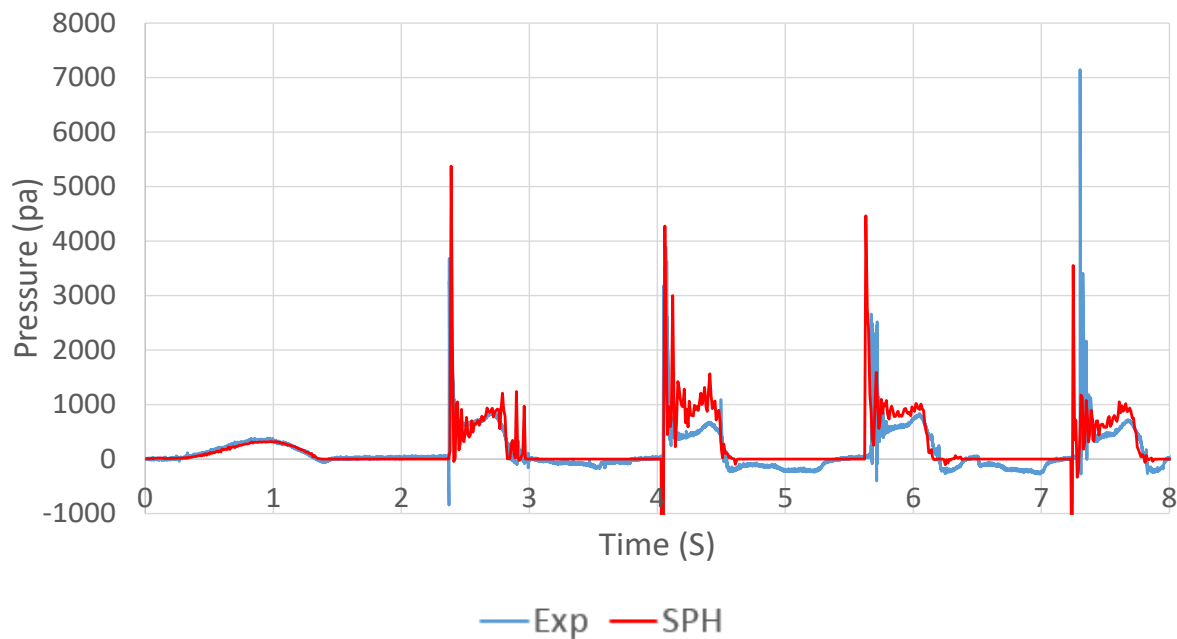


Figure 3-5. Comparison of impact pressure between SPH with experiment.

3.5 Concluding Remarks

SPH has been widely applied to solve problems related to fluid dynamics in marine engineering. The method has showed the capability for free-surface flows such as water wave propagation and sloshing. It shows SPH could reproduce nonlinear phenomenon such as a breaking wave that is difficult to address by mesh-based methods. DualSPHysics developed based on SPHysics project shows its potential to apply to real engineering problems because it's easier to handle a million particles using the latest GPGPU technology. GPGPU computation can accelerate computation remarkably compared to multi- CPU computation.

An example of SPH application to the marine engineering field is shown for a sloshing case that is included in a package of DualSPHysics code. It is one of SPHERIC benchmarking tests. DualSPHysics could predict the impact pressure in the tank compared to an experiment by Souto-Iglesias et al. [63]. In the following chapters, DualSPHysics will be applied to more realistic and important problems in the marine engineering field, i.e. water waves and sloshing problems. In this study, DualSPHysics version 4.0 and 4.2 are used to perform SPH simulations.

Chapter 4

Experimental Validation on Water Wave Generation and Propagation

4.1 Introduction

This chapter presents application of SPH to a water wave generation and propagation problem. Long-distance water wave propagation in 2D and medium-distance water wave propagation in 3D are validated. This chapter discusses the influence of parameters and necessity of parameter tuning to get proper accuracy. In addition, large deformation of wave surface is also validated for a shallow water wave deformation due to so-called bank effect.. Besides, hydrostatic and hydrodynamic pressure are also validated using experimental data. As the result, it was demonstrated that SPH can reproduce water wave generation and propagation both in two and three-dimensional analysis. Nonlinear water waves using an obstacle-box can be also well captured.

4.2 Experimental Setup

Firstly, a dedicated experiment conducted to make validations of numerical computation. The experiment was done at Kobe university wave basin with a length of the tank is 60 m, width 6.0 m, and maximum changeable water depth is 1.5 m see Figure 4-1. There are two experiments conducted in these studies, first using long-distance propagation whose wave gauge is located 24.6 m front wavemaker. Secondly, using medium-distance propagation whose wave gauge set in 6.0 m in front of wavemaker. Wave basin was equipped with a piston-type wavemaker and there is a window observer located in the middle of the tank. Wave gauge was set in 24.6 m in front of wavemaker to capture of wave elevation as well as pressure gauge was used in the same distance. The position of pressure gauge is at the bottom of the tank with a video camera was set in the same distance of wave gauge to capture wave profile in the experiment. In the present study, there are two periods of wavemaker used 1.95 s and 1.15 s. The amplitude of wavemaker was carefully repeated to get the same amplitude of piston wavemaker in three water depths. In this study, only regular wave is generated. Three amplitude of piston stroke wavemaker were used i.e., 16.5 mm, 33.0 mm and 50.5 mm for all

water depths. Because in the present study, we directly impose movement of piston wavemaker in the experiment, a laser sensor was used to capture the displacement of piston wavemaker (see Figure 4-2). Using measured piston, a numerical simulation is conducted with directly impose of this input in numerical wave tank (NWT).

(a)



(b)

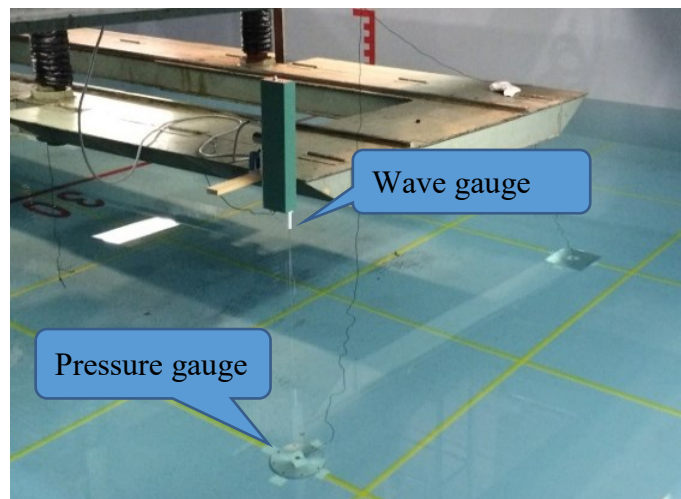


Figure 4-1. Wave basin at Kobe University (a) and position of wave probe and a pressure gauge (b).

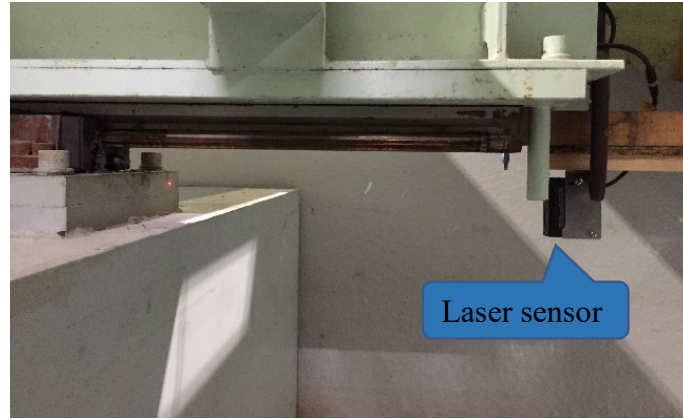


Figure 4-2. Laser sensor setup for the capture of the movement of piston wavemaker.

Figure 4-3 shows measured of piston wavemaker in the experiment for both periods 1.95 s and 1.15 s. The laser sensor is attached in front of a piston wavemaker to capture displacement of the piston wavemaker. Figure 4-3 shows laser sensor can capture the movement of piston wavemaker from transient mode to the steady condition. Figure 4-3 (a) is period 1.95 and Figure 4-3 (b) is 1.15 s. The blue colour is 16.5 mm amplitude of wavemaker, 33.0 mm is orange and green is 50.5 mm. Table 4-1 shows the ratio of water depths and wavelength(λ) for wave steepness. It shows wave generation includes of depth water and shallow water wave case. The condition using water depth 1.1 m and using period 1.15 s was represented for shallow water condition, and the others were shallow water cases. Wavelength (λ) was calculated using Equations (4-1) based on small wave amplitude theory. Table 4-2 presents of Froude number in three water depths. Froude number is calculated with Equation (4-2) where d is depth, U is celerity. It shows the period of 1.15 s is subcritical flows, on the other hand, the period of 1.95 s is a combination of supercritical and subcritical flow

$$\lambda = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{\lambda}\right) \quad (4-1)$$

$$Fn = \frac{U}{\sqrt{gd}} \quad (4-2)$$

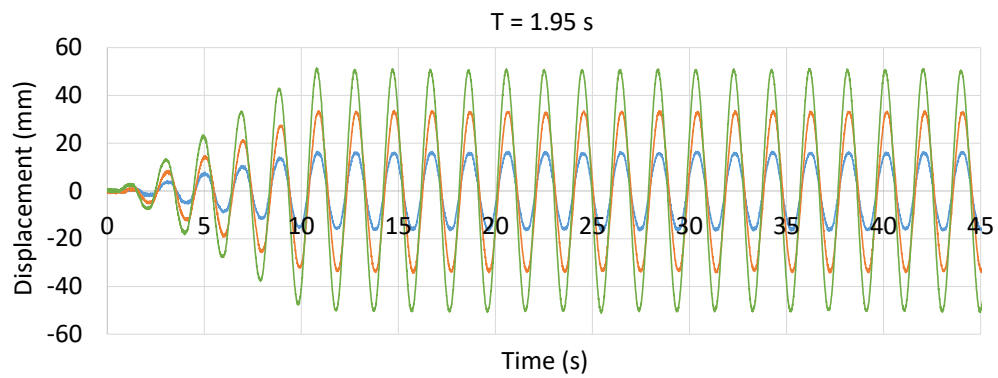
Table 4-1. Water depths, the ratio between depths and wavelength

Water depth(m)	$T=1.95(s)$	$T=1.15(s)$
	(h/λ)	
1.10	0.21	0.53
0.75	0.16	0.37
0.40	0.11	0.22

Table 4-2. Froude number in three water depths.

Water depth(m)	$T=1.95(s)$	$T=1.15(s)$
	(Fn)	
1.10	0.93	0.55
0.75	1.12	0.66
0.40	1.54	0.91

(a)



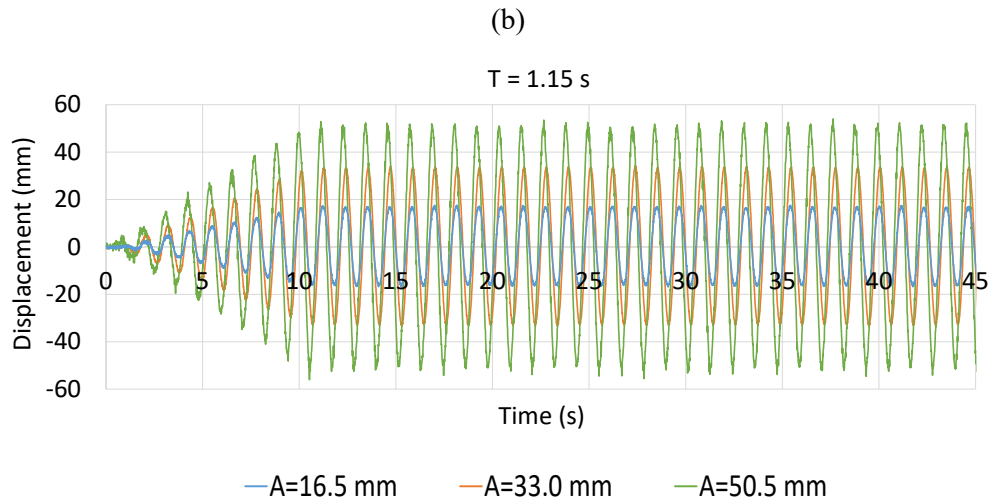


Figure 4-3. Measured time histories of displacement of piston wavemaker (a) 19.5 s and (b) 1.15 s.

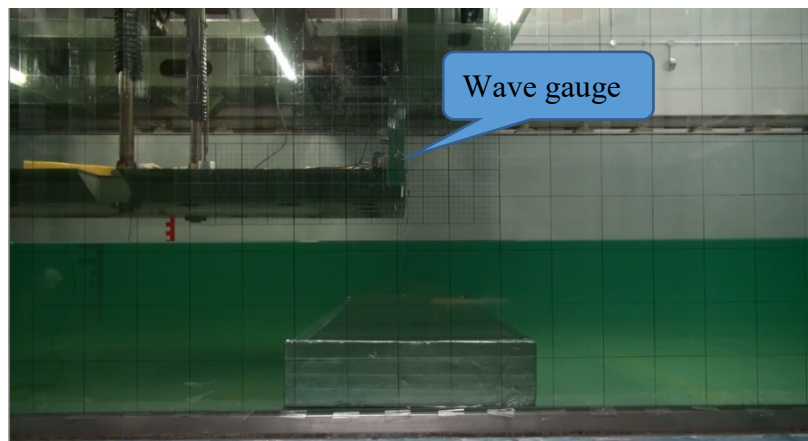


Figure 4-4. Experimental setup to capture large deformation of the surface wave.

Figure 4-4 shows the obstacle-box shape that is used to reproduce large deformation of wave surface/ ‘bank effects’ caused by a sudden change of water depth. In this case, water depth is 0.6 m with a height of the box is 0.4, width 5.25, and length is 0.5 m. Wave gauge was set in the middle of the box to capture wave elevation. The period of wavemaker is 1.15 s with the amplitude of piston motion is 50.5 mm. This is a challenging case because this case, nonlinear and large deformation waves are tried to reproduce using SPH in long-distance propagation.

4.3 Numerical Setup

Schematic view of numerical wave tank shows in Figure 4-5 the dimension of the numerical wave tank is the same as in the experiment. Figure 4-5 is showed waves propagated in the long-travel distance. It needs twelve wavelengths using a shorter wavelength. The distance is 24.6 m from wavemaker to wave gauge, this is the longest validation of water waves propagation that is made during that time. The position of wave gauge was set the same as in the experiment. In this simulation pressure gauge was set at near free-surface because there is a high fluctuation when point measurement becomes deeper. Because in the present study, only regular wave is generated, only two-dimensional analysis was conducted in SPH simulation.

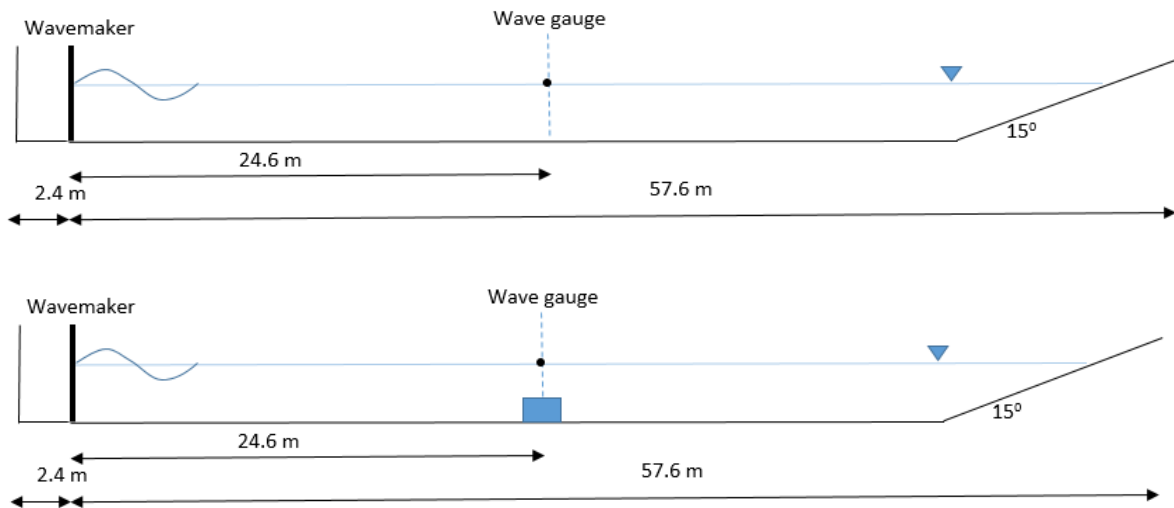


Figure 4-5. Numerical wave tank with and without box and position of wave gauge.

Figure 4-6 depicts a numerical wave tank using a shorter measurement of wave gauge for 3D water waves. The position of wave gauge is 6.0 m from wavemaker. The dimension of numerical wave tank is 15.0 m for the length and width of the tank is 0.3 m. Using a shorter numerical wave tank (NWT), the three-dimensional water wave is tried to reproduce for SPH simulation. In this case, only the period wavemaker 1.15 s is used with the amplitude of piston motion is 50.5 mm.

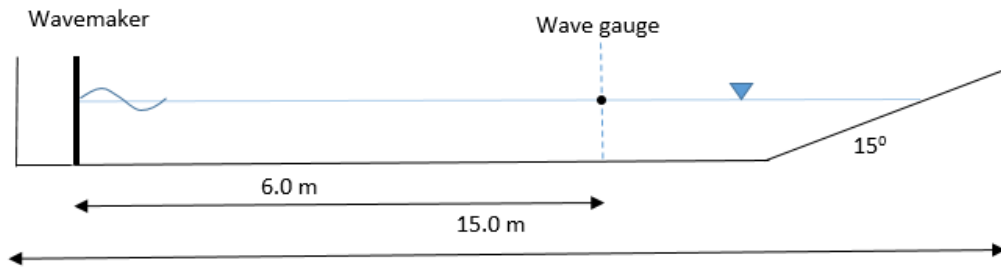


Figure 4-6. Schematic view of numerical wave tank in 3D.

Table 4-3 shows the parameters set up in numerical computation using DualSPHysics for the 2D case. All those parameters were firstly calibrated to get proper accuracy for all case in long-distance water wave propagation. In this case, Wendland kernel function is used with the effect of dissipation using artificial viscosity coefficient (α) 10^{-4} . To reduce of density fluctuation delta-SPH is used with value 0.1 for all case. Particle spacing is 3.0 mm for all simulation with a coefficient of smoothing length (coefh) is 2.0. Time simulation is 45 second with 5 seconds to settle down the fluid particle. Piston wavemaker is started move same with $t=0$ as in the experiment.

Table 4-3. Parameters setup in DualSPHysics for 2D simulation

Parameters in DualSPHysics	
Kernel function	Wendland
Time step algorithm	Symplectic
Viscosity treatment	Artificial viscosity $\alpha = 10^{-4}$
Coefsound	20.0
Initial particle size (mm)	3.0
Coefh	2.0
CFL number	0.30
Delta-SPH	0.10
Duration of simulation (s)	45.0

Table 4-4 shows the parameters set up for the three-dimensional problem for shorter water wave propagation. In this case, wave gauge is 6.0 m from wavemaker. Using recommendation parameters from DualSPHysics developer is sufficient to reproduce the water wave phenomenon. In this case, the coefficient of artificial viscosity (α) changes to 10^{-2} , coefh

1.2 is used. For reduce computation cost, particle spacing 4.5 mm is used. Moreover, to avoid reflection of waves, a time simulation is reduced to 30 seconds with 5 seconds to settle down the fluid particle.

Table 4-4. Parameters setup in DualSPHysics for 3D simulation

Parameters in DualSPHysics	
Kernel function	Wendland
Time step algorithm	Symplectic
Viscosity treatment	Artificial viscosity $\alpha = 10^{-2}$
Coefsound	20.0
Initial particle size (mm)	4.50
Coefh	1.20
CFL number	0.30
Delta-SPH	0.10
Duration of simulation (s)	30.0

4.4 Long-distance Water Wave Propagation using Two-dimensional SPH

Smoothed particle hydrodynamics (SPH) has been applied to water wave propagation by Monaghan [12], Dalrymple and Rogers[17]. It shows SPH applicability to water wave problem. In this study, water wave propagation is reproduced for long-distance propagation i.e., 24.6 m from wavemaker. Using two periods of wavemaker 1.95 s and 1.15 s it needs twelve of wavelength (λ) for periods of 1.15 s. It is a challenging case because there are still few studies using SPH for long-distance propagation[65].

All SPH simulation was done using GPU Titan X 12 GB GDDR5 using a computer at Maritime Safety System Laboratory, Graduate School of Maritime Science. Computation time for the deepest water depth is 65 hours for 50 seconds of simulation time. Grid study was conducted to see the effects of particle spacing on accuracy. Figure 4-7 shows the results of grid study using five particle spacing, i.e., 2.0 mm, 3.0 mm, 4.0 mm, 5.0 mm and 6.0 mm. It shows that the evolution of wave elevation is sensitivity to particle spacing (dp). Particle spacing 2.0 mm and 3.0 mm show similar results, but to get reasonable accuracy and

computation time, particle spacing 3.0 mm is more favourable to use compared to 2.0 mm. It shows increasing of particle resolution has a significant impact on the evolution of free-surface. It caused the number of particle in the vertical direction is increased by decreasing particle spacing, but it also will increase of computation runtime and the total number of particles. Table 4-5 shows the total number of particles in grid study using water depth 0.4 m with amplitude piston motions 16.5 mm. Table 4-6 shows the total number particle for all water depths using particle spacing 3.0 mm. The accuracy becomes worse when ratio H/dp is under 14. It shows on case water depth 0.4 m with period 1.95 s. To get proper accuracy, particle spacing needs increasing with the resolution of ratio H/dp more than 14.

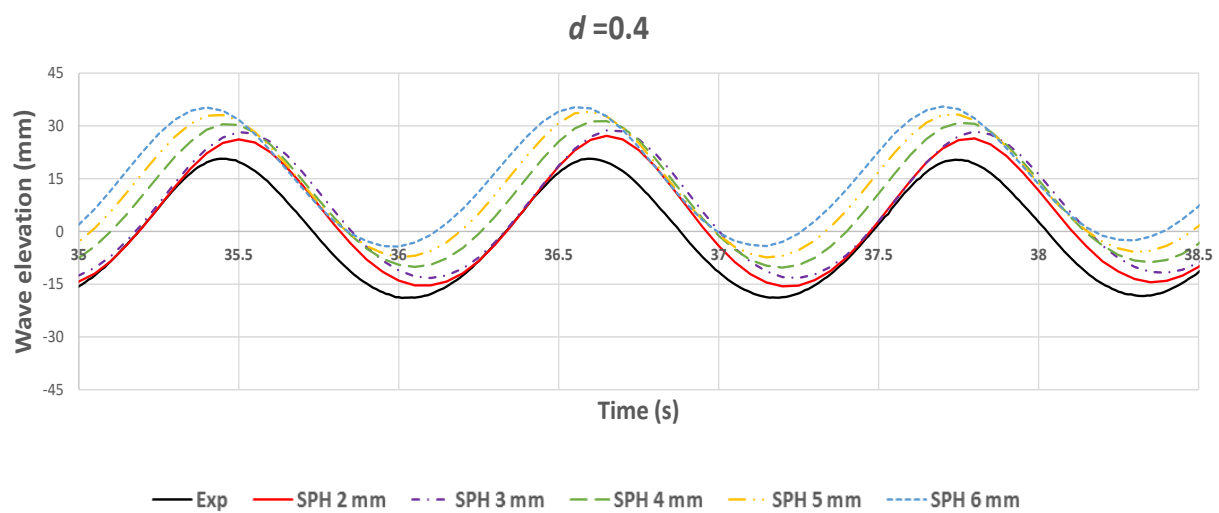


Figure 4-7. Grid study with $T = 1.15$ s, $A = 16.5$ mm and $d = 0.4$ m

Table 4-5. Particle spacing and total particles for grid study

Water depth (m)	Initial particle spacing (mm)	Total number of particles
0.4	2.0	5,370,127
	3.0	2,388,834
	4.0	1,351,731
	5.0	868,045
	6.0	607,864

Table 4-6. Initial particle spacing and total particles in three water depths

Initial particle spacing (mm)	Water depth(m)	Total number of particles
3.0	1.10	6,724,154
	0.75	4,521,922
	0.40	2,388,834

Figure 4-8 shows comparison results of wave elevation at 24.6 m distance from the wavemaker between the experiment and the SPH simulation for the amplitude of 50.5 mm and the period of 1.15 s of the piston motion. In all water depths, SPH shows a good agreement with the experiment in the wave amplitude from the transient state to the steady-state. A certain average shift of wave elevation can be found in the SPH results as the water depth decreases. The SPH seems in good accordance with the experiment. This means that the SPH simulation can reproduce the wave period and the phase velocity even in long propagation-distance. The wave surface profile is reproduced as shown in Figure 4-10, and it also indicates that SPH has good agreement with the experiment though wave profile is a non-sinusoidal shape. The quite similar result is confirmed for the cases of period 1.95 s (longer waves) as shown in Figure 4-9.

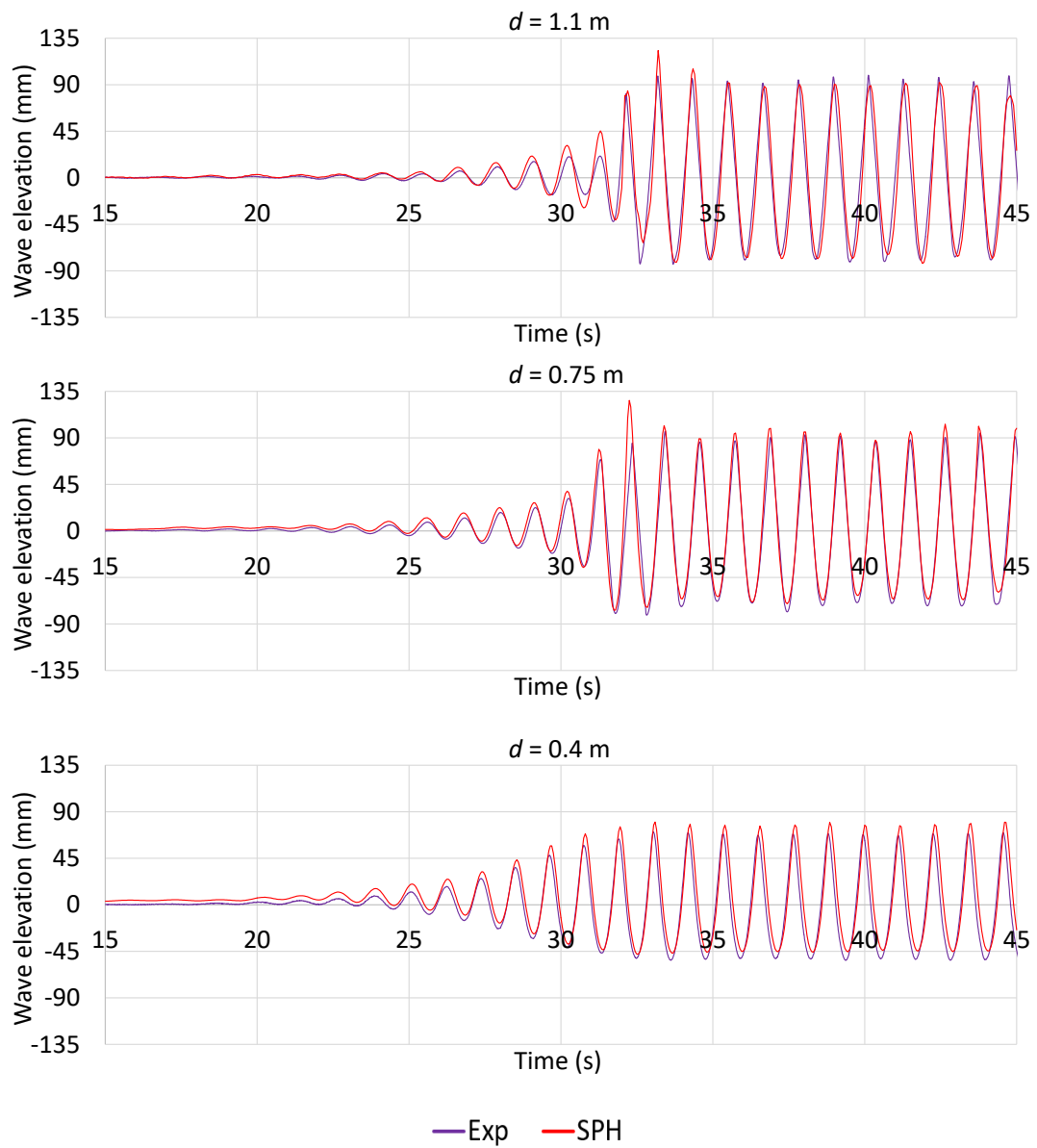
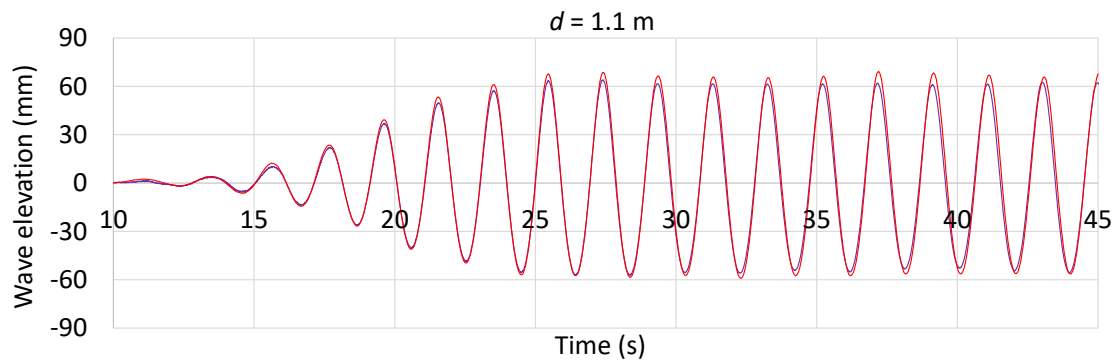


Figure 4-8. Comparison of wave elevation $A=50.5$ mm and $T=1.15$ s.



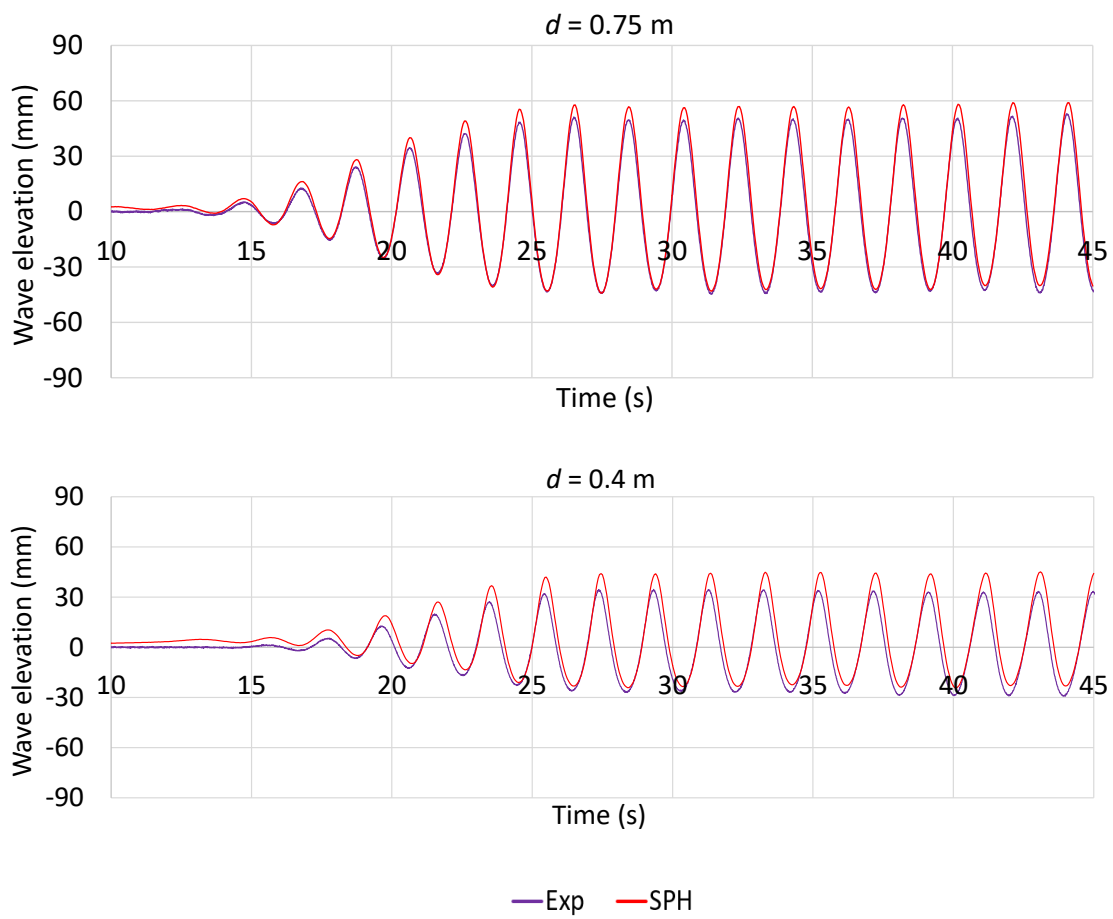


Figure 4-9. Comparison of wave elevation $A=50.5 \text{ mm}$ and $T=1.95 \text{ s}$.

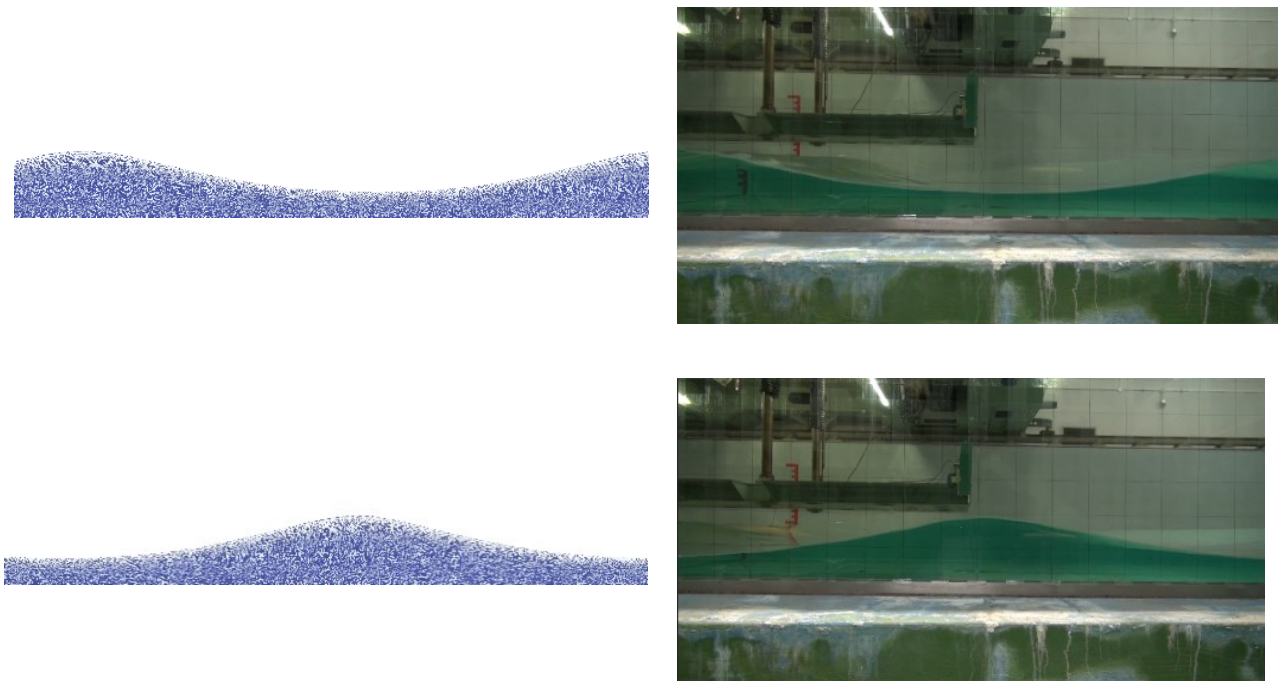


Figure 4-10. Comparison of wave profile between numerical and experiment.

4.4.1 Large Deformation of Wave Surface.

SPH model was applied to a problem of large deformation of wave-surface. Here the wave-surface deformation was occurred due to the sudden change of water depth by putting a box-shape obstacle as same as the experiment. The amplitude and the period of wavemaker are 50.5 mm and 1.15 s. Figure 4-11 shows the comparison of wave elevation at the middle position of the box-shape obstacle. Due to the so-called bank effect, wave crest was stretched in the experiment, and the SPH simulation provides a somewhat similar result. In the visual comparisons of a snapshot of wave-surface deformation shown in Figure 4-12, the simulated wave-surface indicated by red dashed line looks quite similar with the measured wave-surface indicated by solid purple line even with the large deformation involving wave-breaking.

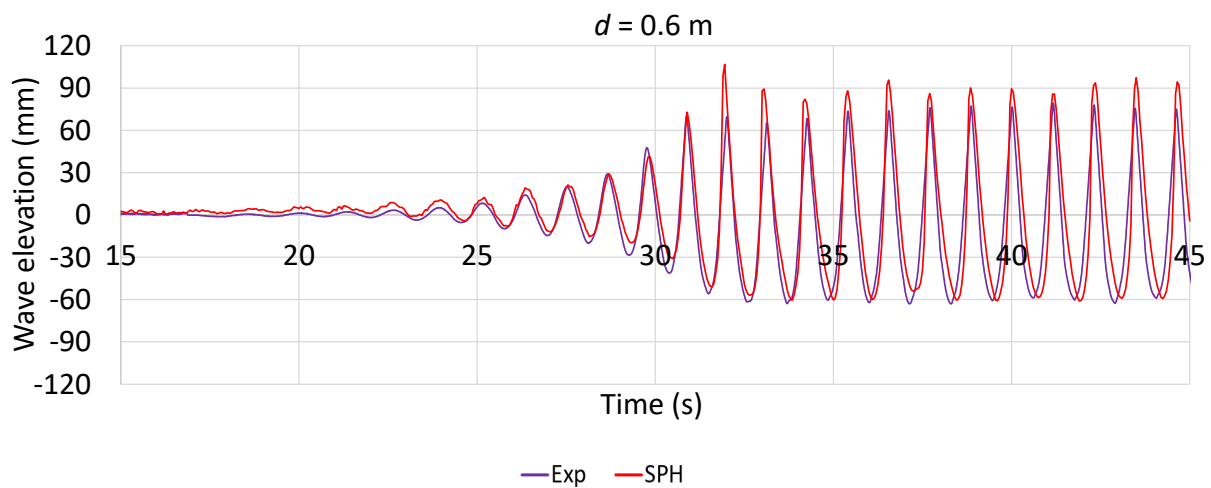
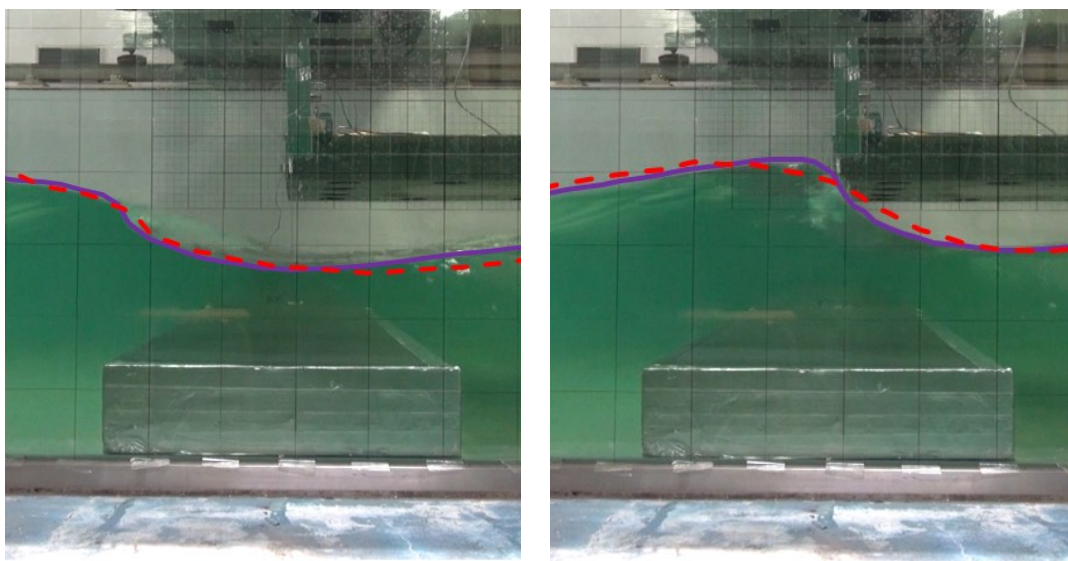


Figure 4-11. Comparison wave elevation between SPH and experiment with obstacle box.



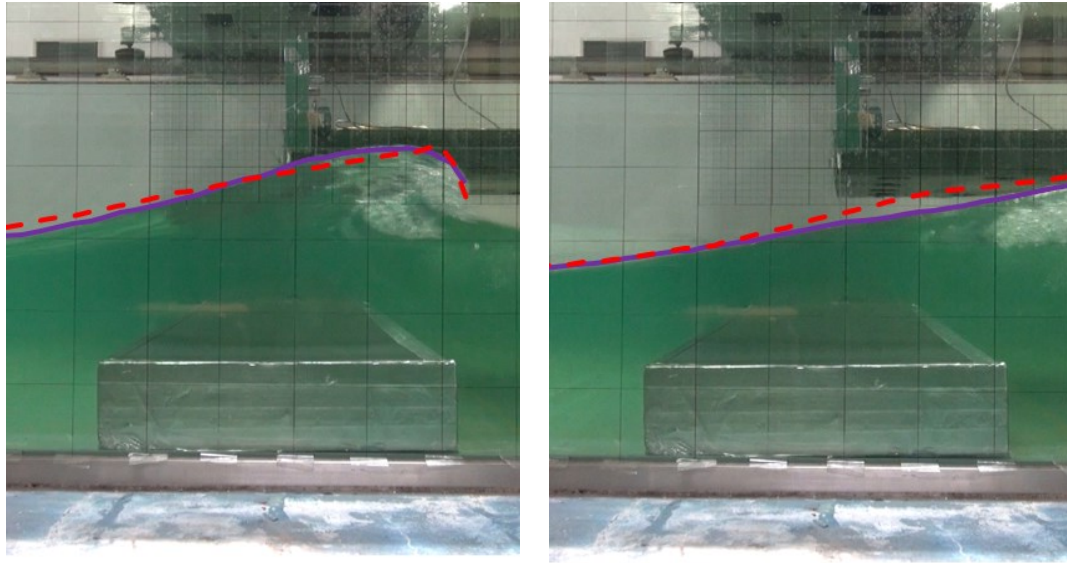
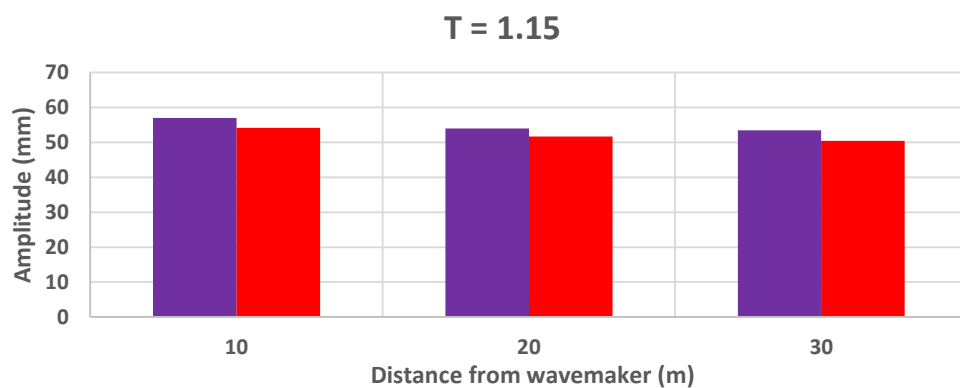


Figure 4-12. Visual comparison of wave-surface deformation at $t = 35.0$ s, 35.2 s, 35.4 s, 35.6 s.

4.4.2 Energy Dissipation and Comparison with Biesel Transfer Function

SPH showed the good agreement of wave elevation, but it was confirmed only for one position i.e., 24.6 m from the wavemaker. Therefore the measurement of wave elevation was carried at three different distance, those are 10.0 m, 20.0 m and 30.0 m from the wavemaker. The comparisons of steady amplitude at three different positions are shown in Figure 4-13. The SPH results show good agreement not only in the wave amplitude but also in the damping rate of wave amplitude along the propagation-distance. This result suggests both energy conservation and energy consumption are well achieved by SPH.



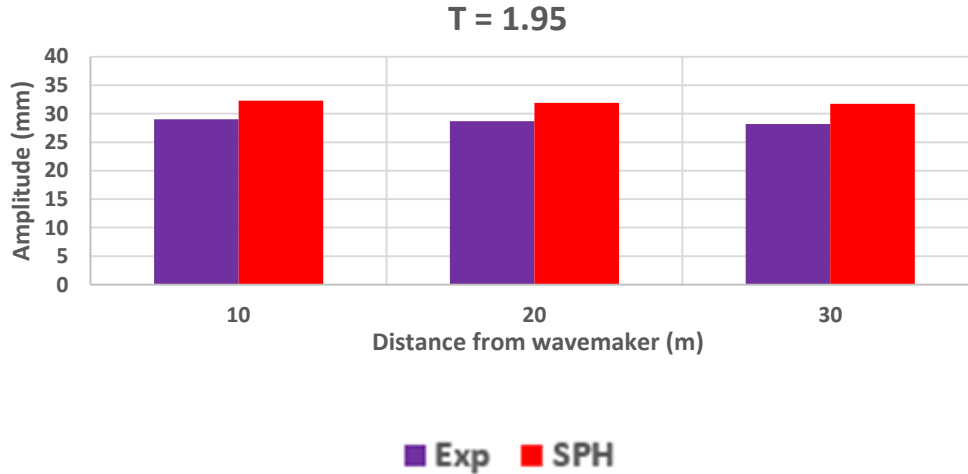


Figure 4-13. Decay rate study with $A = 33.0$ mm and $d = 0.75$ m.

For further discussion on the prediction accuracy of steady wave amplitude, the SPH result is compared with the well-known Biesel transfer function proposed by Biésel and Suquet [66] as well as the experiment. The steady wave amplitude can be estimated by Equation 4-3 as a solution of linear theory. Where H is the height of the wave and A is an amplitude of the wave. Table 4-7 shows comparison results and SPH shows a smaller error than the Biesel transfer function in most conditions. The maximum error and the averaged error of the Biesel transfer function are 18.1% and 7.4% for $T = 1.15$ s, and 32% and 16% for $T = 1.95$ s. The Biesel transfer function becomes worse for smaller water depth in case of the shorter waves and becomes worse for larger amplitude in case of the longer waves. It's because of Biesel theory can't account for non-linear aspects that become more influential as the relative depth decrease. On the contrary, the maximum error and the averaged error of the SPH are 8.5% and 4.6% for $T = 1.15$ s, and 9.9% and 7.5% for $T = 1.95$ s this confirm that SPH can reproduce non-linear aspect caused by reduction of water depth. This result clearly demonstrates the capability of SPH for water wave problems in wide ranges of wavelength and water depth. It should be noted that the SPH simulations here are using constant parameters for all conditions.

Looking at the SPH results in detail, the maximum and the second maximum errors are 9.8% found in the shallowest water depth. The experimental result shows that the wave amplitude decreases with the decrease of water depth and the increase of wave period. For example, the wave amplitude for water depth 0.4 m is about half the amplitude of water depth 1.1 m. Consequently, to this fact, the number of fluid particles in a wave height becomes smaller according to the decrease of water depth and the increase of wave period if a constant

particle spacing is used. In the case of the maximum error, the number of particles in wave height is 14. So it could be recommended to adopt at least 14 particles in a wave height to get appropriate accuracy.

$$\frac{H}{2} = \frac{2\sinh^2\left(\frac{2\pi h}{\lambda}\right)}{\frac{2\pi h}{\lambda} + \sinh\left(\frac{2\pi h}{\lambda}\right)\cosh\left(\frac{2\pi h}{\lambda}\right)} A \quad (4-3)$$

Table 4-7. Comparison of steady amplitude with a different method.

<i>T</i> (s)	<i>A</i> (mm)	<i>d</i> (m)	Exp. (mm)	SPH (mm)	SPH Error (%)	Biesel T.F. (mm)	Biesel Error (%)
1.15	16.5	1.10	32.9	30.1	8.5	32.4	1.5
		0.75	26.8	28.7	-7.1	29.5	-10.1
		0.40	20.4	19.1	6.4	19.4	4.9
	33.0	1.10	62.3	58	6.9	64.8	-4.0
		0.75	53.2	55.5	-4.3	59.0	-10.9
		0.40	40.6	39.6	2.5	38.7	4.7
	50.5	1.10	83.9	86.8	-3.5	99.1	-18.1
		0.75	81.7	81.0	0.9	90.4	-10.6
		0.40	60.6	60.0	1.0	59.3	2.1
1.95	16.5	1.10	18.2	19.6	-7.7	18.6	-2.20
		0.75	14.9	15.7	-5.4	13.0	12.8
		0.40	10.3	11.1	-7.8	7.0	32.0
	33.0	1.10	38.5	41.4	-7.5	37.3	3.10
		0.75	30.8	32.9	-6.8	26.0	15.6
		0.40	20.5	22.5	-9.8	14.0	31.7
	50.5	1.10	57.9	61.7	-6.6	57.0	1.60
		0.75	46.8	49.7	-6.2	39.8	15.0
		0.40	30.7	33.7	-9.8	21.4	30.3

4.4.3 Hydrodynamic Wave Pressure.

The validation of SPH on the dynamic wave pressure is attempted. Before that, the hydrostatic pressure at rest condition is calculated by SPH (see Figure 4-14) and is compared with the analytical solution. The analytical solution of hydrostatic pressure at the bottom of the tank is 7.30 kPa, and that of SPH is 7.28 kPa, so the error of SPH is only 0.9%. Figure 4-15 shows the pressure variation overtime calculated at several depths. Here the depth of 1.1 m means that pressure sensor is at the bottom of the tank, and the depth equal to 0 m means that the corresponding pressure sensor is at the original calm-water surface. Significant high-

frequency pressure fluctuations appear at a pressure sensor located at the bottom of the tank, but these high-frequency fluctuations decrease as the detection position moves to near the free-surface. Because pressure noise is very strong in the bottom of the tank, it was more favorable using pressure sensor at the original calm-water surface. Therefore the experimental result of wave pressure was converted from the bottom to the calm-water surface by multiplying $\cosh(2\pi d/\lambda)$ with the measured pressure, based on the linear wave theory. Figure 4-16 and 4-17 show the comparison results of dynamic wave pressure in the case of the maximum amplitude of piston motion. Note that the hydrostatic pressure is already subtracted from the measurement data, and the SPH result can be obtained only when the evaluation point is under the wave-surface. For all the investigated combinations of wave period and water depth, dynamic wave pressure predicted by SPH at free-surface is acceptable as well as the wave elevation discussed before. Because the pressure sensor is located at free-surface, the negative pressure cannot capture by SPH. Further investigation of dynamic pressure at the bottom of the tank is needed and will be carried out in future works. However, this study is mainly focused on the propagation of water waves for long-distance, which is an essential element to be used in ocean engineering research. In case of floating bodies in a wave, for example, the contribution to the hydrodynamic force acting on the floating bodies is limited to around the free-surface, and the accuracy of SPH simulation was confirmed at least near the free-surface by this study.

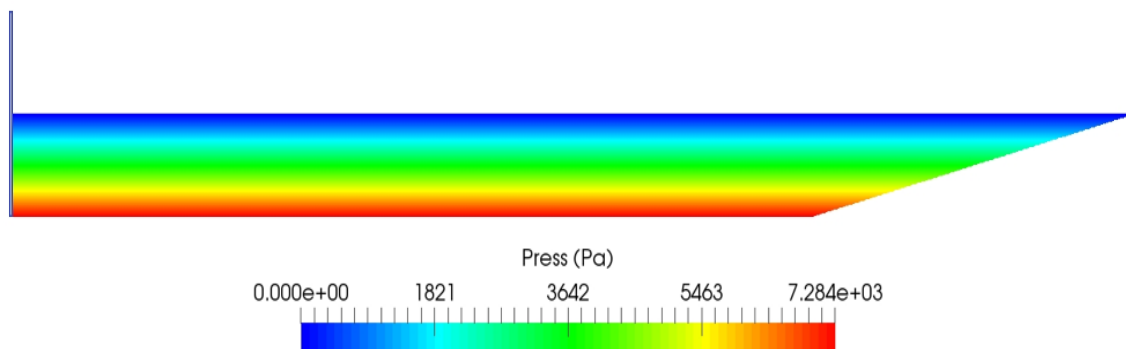


Figure 4-14. SPH results of hydrostatic pressure for $d=0.75$ m.

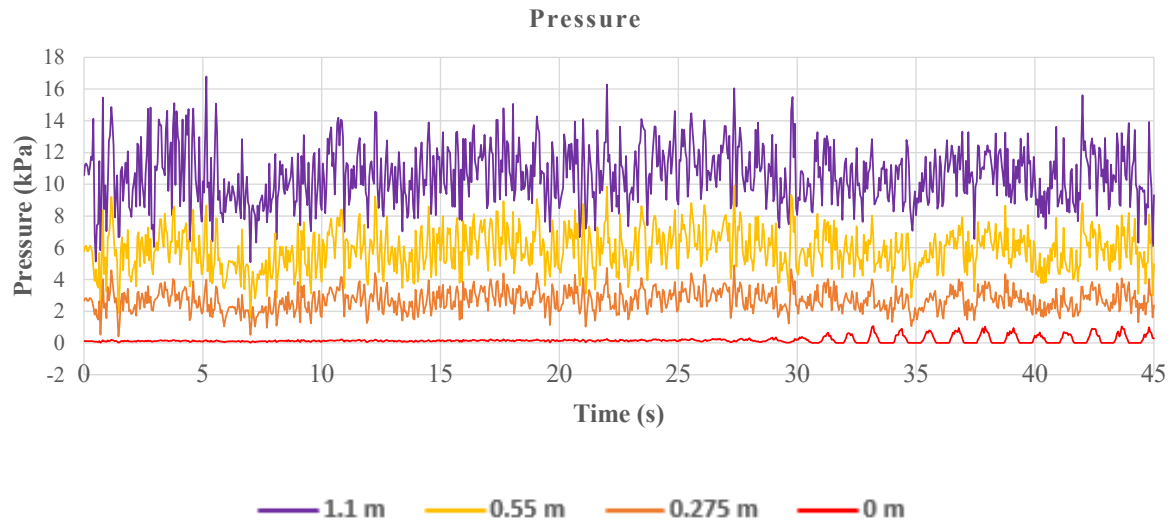
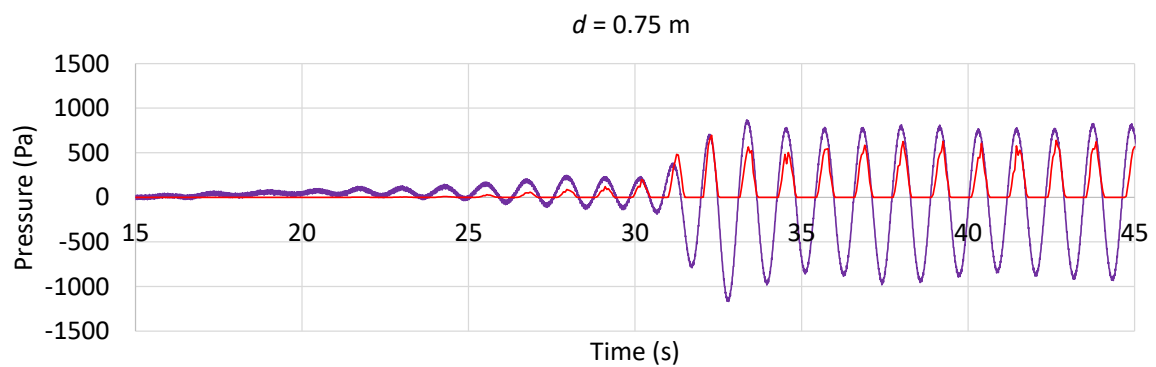
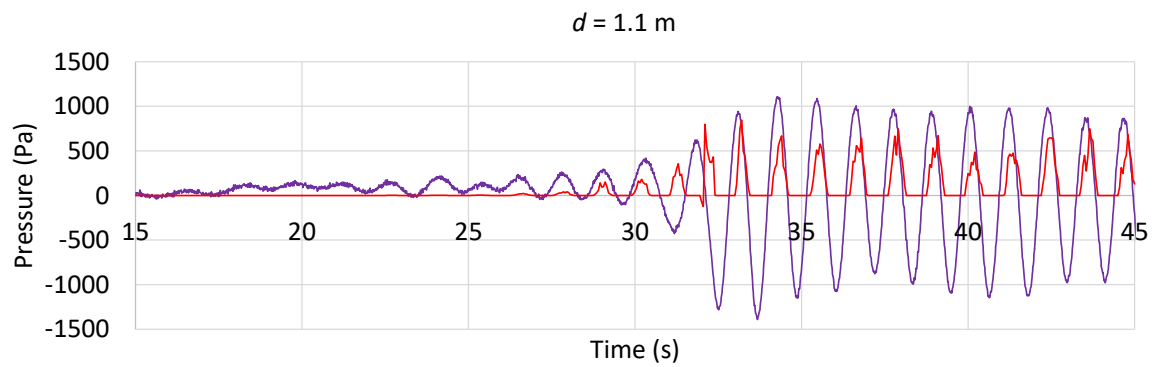


Figure 4-15. Pressure variation of SPH at different depths with $d=1.1$ and $A=50.5$ mm.



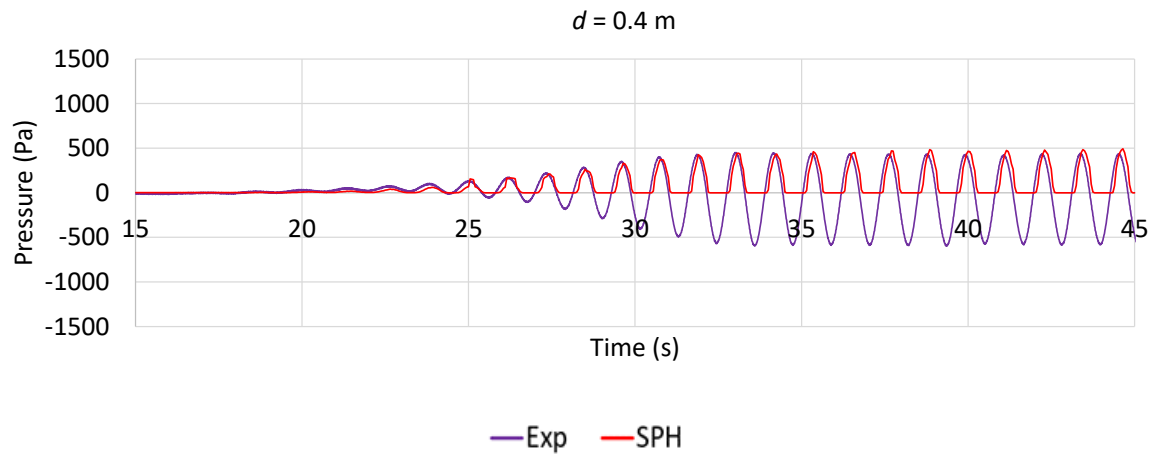
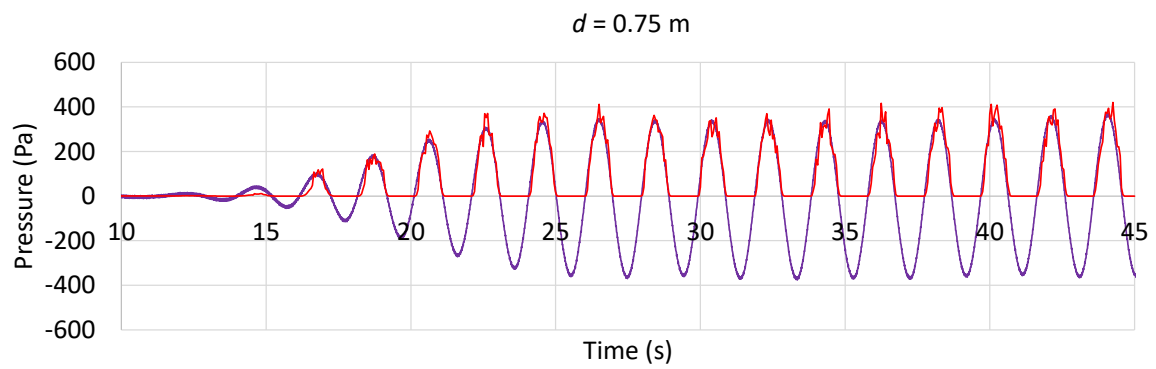
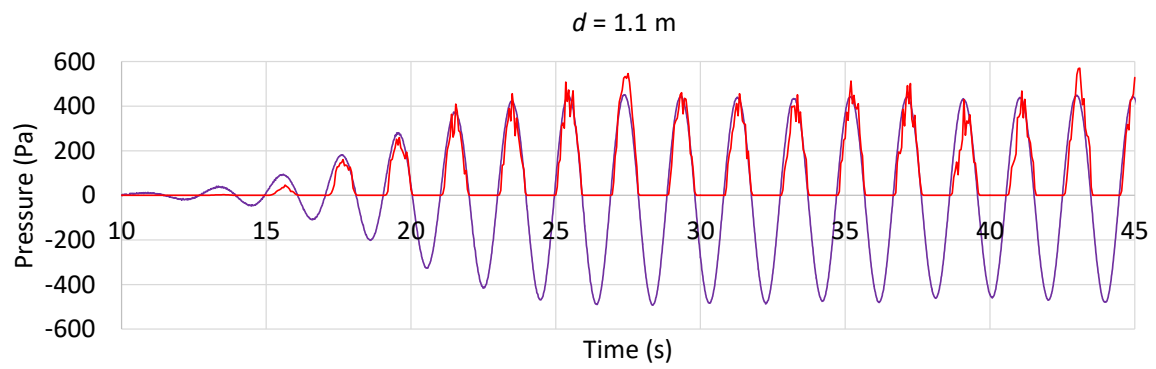


Figure 4-16. Dynamic wave pressure for $A = 50.5 \text{ mm}$ and $T = 1.15 \text{ s}$.



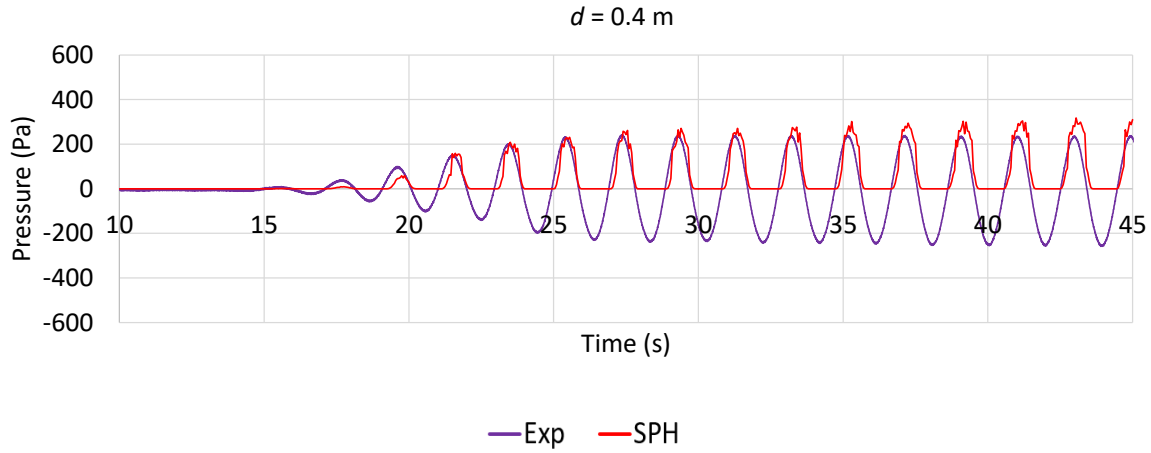


Figure 4-17. Dynamic wave pressure for $A = 50.5$ mm and $T = 1.95$ s.

4.5 Water Wave Propagation using Three-dimensional SPH.

All the discussions until here were based on the comparison results between the two-dimensional (2D) SPH and the experiment. Since three-dimensional (3D) simulation is sometimes required depending on problems, experimental validation of 3D SPH is also attempted. However, it is difficult to use the same experimental data used in the 2D SPH validation because the tremendous number of particles is required for realizing the same size of 3D NWT. Therefore a new experiment was conducted that is suitable for the 3D SPH validation on water waves. The experiment was held at the same wave basin of Kobe University and the location of the wave probe and pressure sensor was 6.0 m from the wave-maker. Regular wave trains were generated with $A = 50.5$ mm and $T = 1.15$ s for water depths of 0.40 m and 0.75 m.

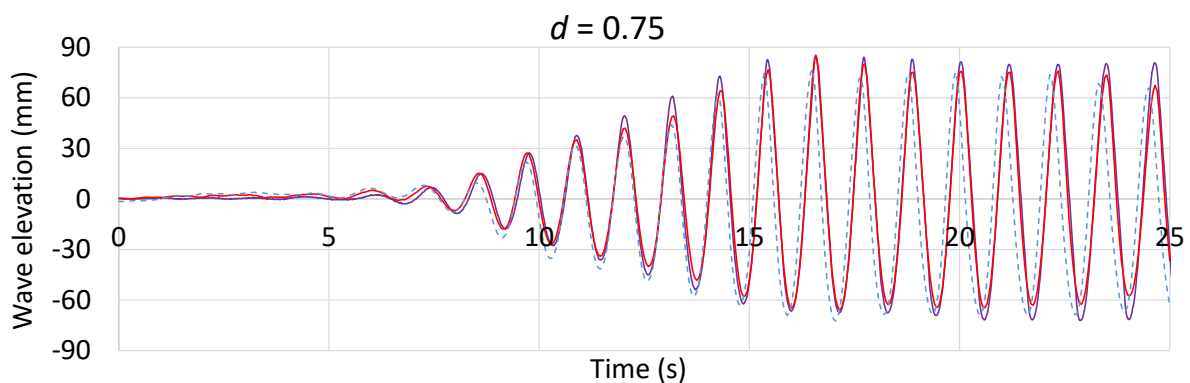
The particle spacing of 3.0 mm was used in 2D validation, so the same particle spacing is preferable to use in 3D. However, there is a limit of an available number of particles using single GPU because of DualSPHysics ver. 4.0 has not yet implemented the parallelization using multi GPUs. For this reason, particle spacing of 4.5 mm, 1.5 times as large the 2D case, was used for 3D SPH simulation. In this case, the number of particles in wave height is 28, for the water depth of 0.4 m. The dimension of NWT is shown in Figure 4-6. In this subsection, the 2D NWT and the 3D NWT have the same dimension and the width of 3D NWT is 0.3 m. The numerical parameters for 3D SPH are shown in Table 4-4. As the length of 3D NWT is much shorter than that of 2D NWT, a smaller value of coefh , compared to the 2D SPH in Table 4-3, was used to avoid excessive computational load. The coefficient artificial viscosity, α , is also

different from the 2D SPH because its optimal value depends on other parameters, like coefh. The total number of particles for the 3D NWT is more than 35 million for the deepest water depth, so the shallow and medium water depths, 0.4 m and 0.75 m, are only used (see Table 4-8). The computation time to complete 30 seconds simulation is about 2.5 weeks for the water depth of 0.75 m.

Table 4-8. Initial particle spacing and total particles in 3D

Initial particle spacing (mm)	Water depth (m)	Total number of particles
4.5	0.75	22,713,258
	0.40	12,171,792

The wave elevation of water waves 3D SPH was compared with the experiment as well as the 2D simulation for water depths of 0.4 m and 0.75 m, as shown in Figure 4-18. Here the 2D simulation was performed using the same parameter set for the 3D SPH, presented in Table 4-4, while the same particle spacing of 4.5 mm was used. The accuracies of wave elevation by 2D and 3D seem to be practically acceptable in term of wave elevation, but the accuracy of phase celerity by 3D SPH becomes slightly worse 4% for the case of medium water depth with error is 6.8% for steady amplitude. This could be related to the smaller smoothing length was used for the 3D simulation to reduce the computation time and the number of particles in the vertical direction is also needed to increase to get appropriate accuracy. The velocity field and velocity vector are shown in Figure 4-19. Using a passive wave absorber i.e., sloped beach, reflected waves are well eliminated, so the wave elevation by the simulation can be directly compared with the experiment.



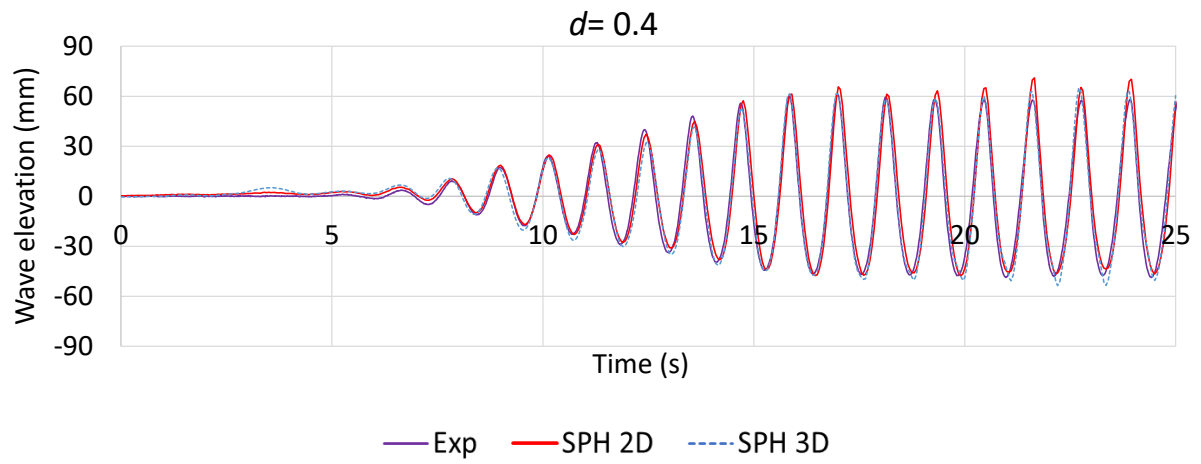


Figure 4-18. Comparison of wave elevation of the experiment, 2D and 3D SPH for $A = 50.5$ mm and $T = 1.15$ s.

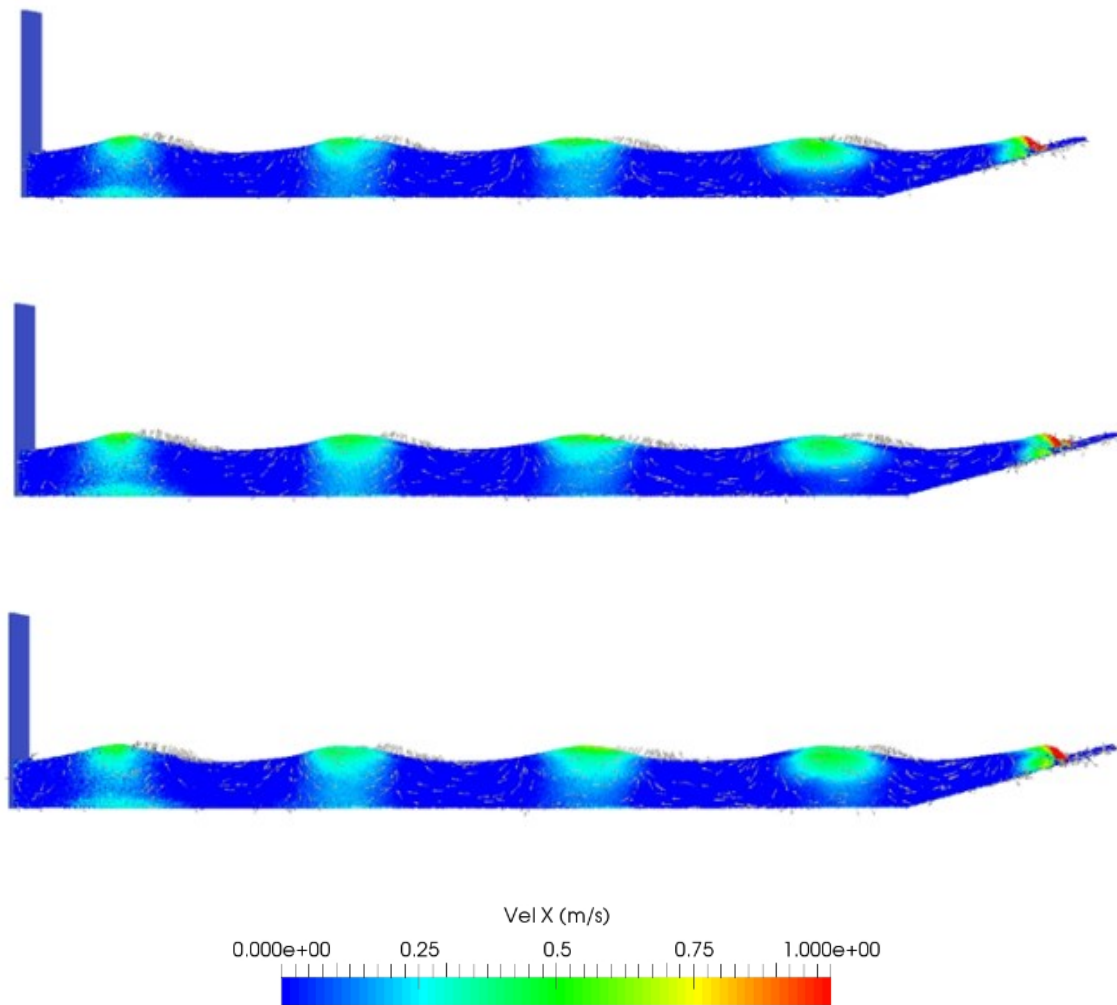


Figure 4-19. Velocity field and velocity vector of 3D SPH at $t=17.25$ s, 19.55 s and 21.85 s.

The hydrostatic pressure by 3D SPH for water depth 0.75 m is shown in Figure 4-20. As same as the 2D case, the smoothed pressure graduation can be confirmed. The static pressure at the bottom of the tank is 7.17 kPa, and the analytic solution is 7.30 kPa its difference 2.3%. Comparison results of dynamic wave pressure of the experiment and the 2D SPH and the 3D SPH are shown in Figure 4-21. The good agreement of 3D SPH and the experiment can be found for the shallow condition. The decline inaccuracy is found for the middle water depth as same as the wave elevation.

Since 2D SPH was well-validated for 2D water waves in the previous sections and the 3D SPH showed comparable accuracy with 2D SPH for the smaller NWT, it can be concluded the SPH can partly reproduce the physical character and behaviour of water waves with suitable accuracy from the engineering point of view. Correct assessment of the accuracy of pressure fields requires further investigation to compare measured and calculated values at the same depth.

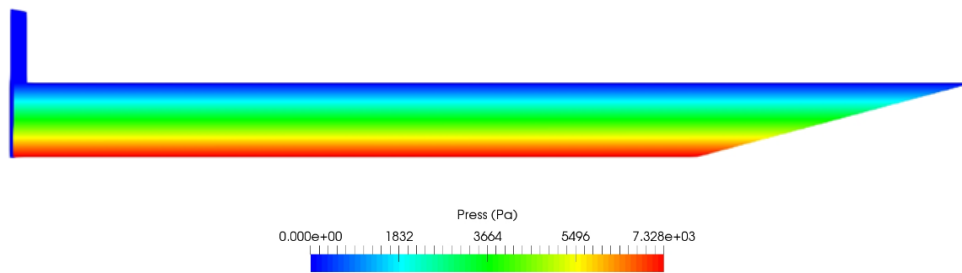
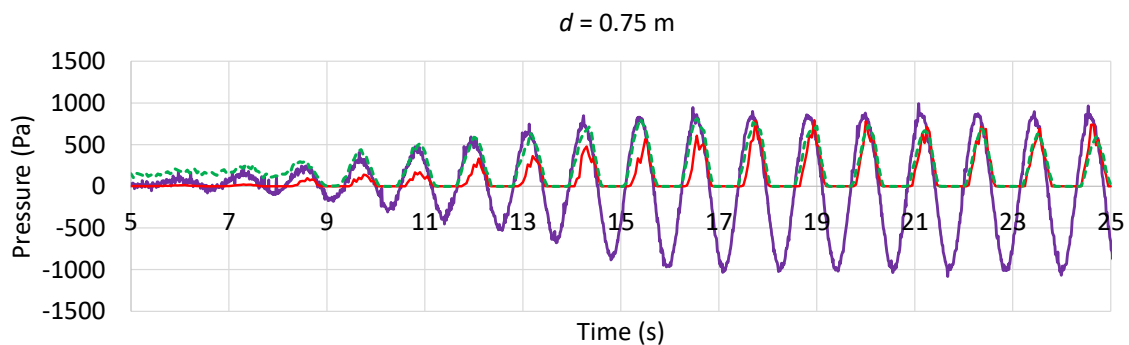


Figure 4-20. 3D SPH result of hydrostatic pressure for $d = 0.75$ m.



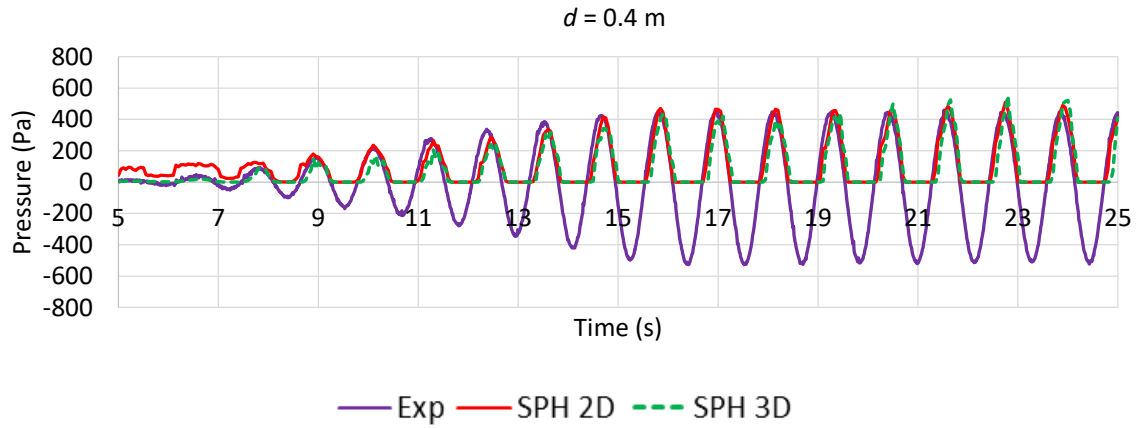


Figure 4-21. Comparison of wave dynamic pressure of experiment and 2D and 3D SPH for $A = 50.5$ mm and $T = 1.15$ s.

4.6 Concluding Remarks.

A dedicated experiment was done at Kobe University wave basin to make validation studies of water waves. A validation study was done using directly impose measured piston motions of piston-type wavemaker. It can be concluded using directly measured piston motions of wavemaker, SPH succeeds to reproduce wave propagation regarding the steady wave amplitude in all water depths. The validations studies are conducted with variations of water depths, amplitude piston motion, and periods of wavemaker. Wave surface profile shows good agreement with experiment results through the wave profile is apart from the sinusoidal waves.

Although wave gauge location is far from wavemaker, SPH is also well predicted first-time waves come and there is no phase velocity happened in all cases. The decay rate was conducted to measure wave propagation with three different distances. It was confirmed the decay rate has good agreement with experiment. It shows energy dissipation as in steady amplitude is well reproduced by SPH. In addition, large deformation of wave surface was reproduced using obstacle-box shape is well captured by SPH. Three-dimensional analysis of water wave is done using shorter distance. Wave elevation shows similar results with two-dimensional results. Hydrostatic pressure and dynamic wave pressure are well reproduced, it shows the applicability of SPH for wave generation and propagation both for long-distance or medium propagation is confirmed. These result has published to Journal of Marine Science and Engineering in special issue Computational Fluid Dynamics for Ocean Surface Waves [67].

Chapter 5

Experimental Validation on Sloshing in Prismatic Tank

5.1 Introduction

This chapter is carried out an application of SPH for sloshing flows of Liquefied Natural Gas (LNG) in the prismatic tank. Recently, the demand for sloshing analysis is increased caused by the increasing demand for LNG carrier. The study of sloshing was conducted using single-phase flow using a large-scale number of particles with one GPU later on two-phase flows is carried out to verify and validate the result. The results of two-phase SPH has good accuracy in predicting of impact pressure with the experiment result. Free-surface evolution in two-phase flows gives better accuracy than single-phase.

5.2 Experimental Setup

An experiment dedicated to the sloshing problem was recently conducted at the NRIFE using a prismatic tank. Figure 5-1 (a) presents an overview of a sloshing test using a four-degree-of-freedom forced oscillation machine. Four video cameras were used in the sloshing test. Two were GoPro Hero cameras that were placed near the tank to record the water behaviour inside the tank and the other two cameras were used to record the external motion of tank. Figure 5-1 (b) presents the prismatic tank, which resembles a membrane-type LNG tank. The tank is scaled to 1:125 and the length is 0.36 m, the width is 0.30 m, and the height is 0.21 m. In the experiment, the tank was subjected to external sway, heave, roll, and yaw oscillations (see Table 5-1). Several amplitudes and frequencies were used for the forced oscillation test. The impact pressure caused by sloshing is an important factor because it can lead to structural damage. To measure the hydrodynamic pressure on the tank wall at different locations, pressure gauges were positioned at three locations (P1, P2, and P3), as shown in Figure 5-1 (b). P1 is near the bottom of the sidewall, and P2 and P3 are on the upper chamfer. All gauges were positioned near corners to capture the impact pressure. Sloshing tests were conducted at filling ratios of 25% and 50%. The water height was 5.25 cm for the filling ratio of 25% and P1 was near the calm-water free-surface. The water height was 10.5 cm for the

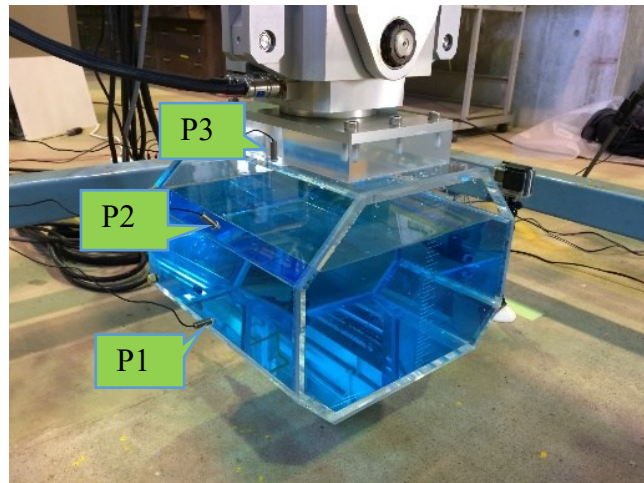
filling ratio of 50%. A schematic view of the prismatic tank is presented in Figure 5-2. Table 5-2 lists the dimensions of the tank.

Table 5-1. Experimental condition

Motion	frequency (Hz)	Amplitude (mm/deg)
Roll	1.04	1.09, 2.17, 4.33, 8.66
	1.34	
Sway	1.08	0.82, 1.63, 3.26, 6.52
	1.34	
Heave	1.04	2.85, 5.7
	1.34	
Yaw	1.08	3.0
	1.34	



(a)



(b)

Figure 5-1. Overview of forced oscillation machine for sloshing tests (a) and geometry of the prismatic tank (b).

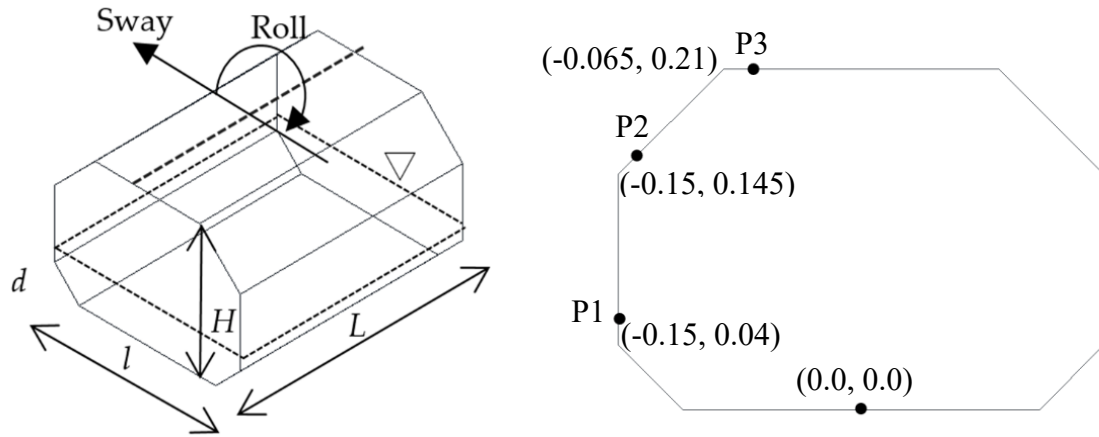
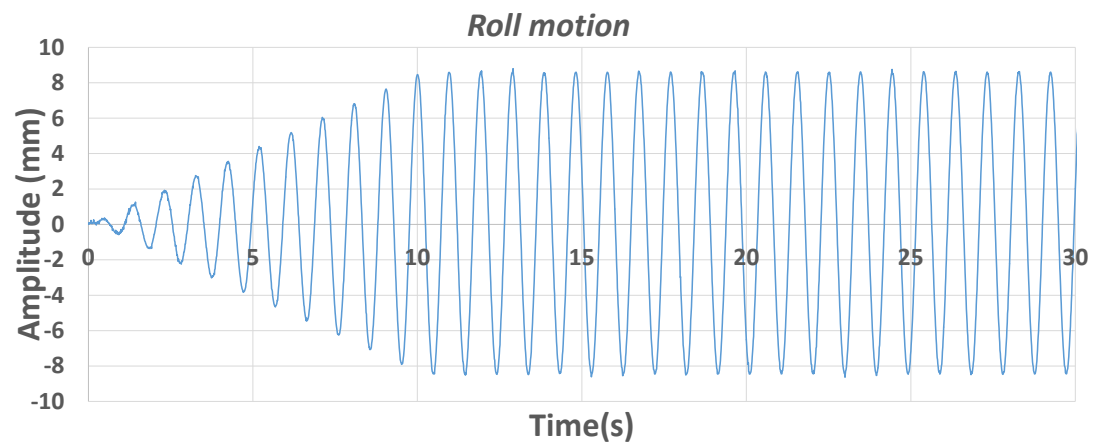
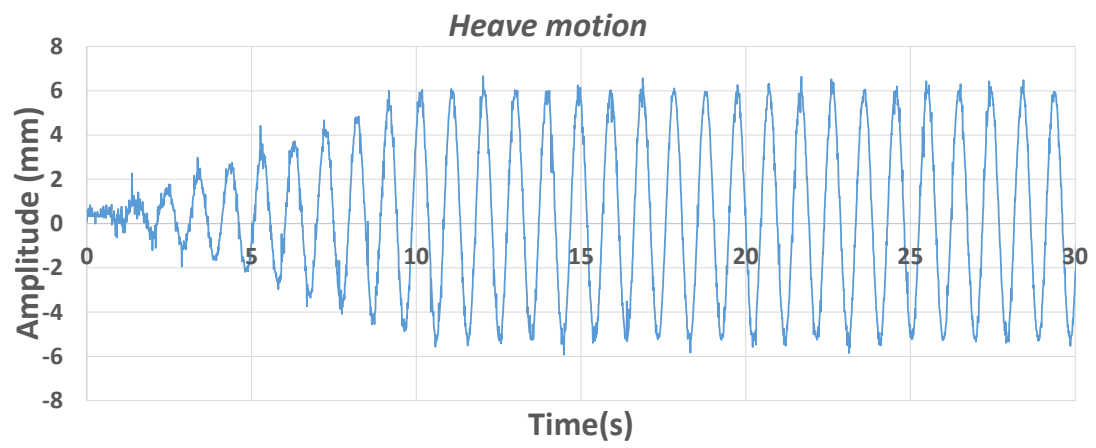
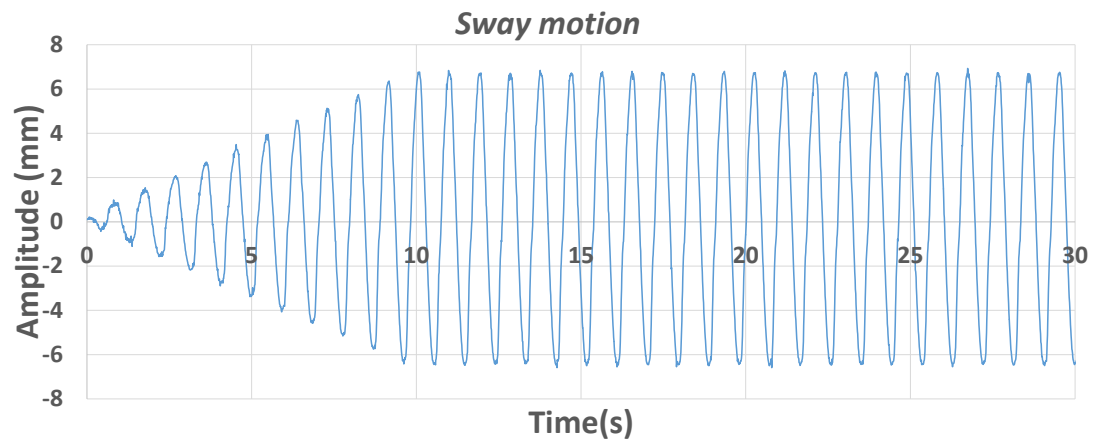


Figure 5-2. Geometry of LNG tank and definition of external oscillation (units in meter).

Table 5-2. Dimension of LNG tank (units in meter)

Height (H)	0.21
Width (l)	0.30
Length (L)	0.38
Water height (d)	0.0525 (25%)
	0.1050 (50%)

Figure 5-3 presents time histories of external oscillations with the maximum displacement imposed on the tank in each mode during the experiment. For all conditions, a simple linear ramping motion was applied for the first 10 s to avoid huge inertial forces. By directly imposing the measured displacements of the tank during SPH simulation, the SPH method can be validated in terms of fluid behaviour, including complex free-surface evolution and the time history of local pressure (e.g., impact at the corners of the tank). In this study, only the sway and roll motions are presented because sloshing cannot be observed when the tank is subjected to heave and yaw motions. Figure 5-4 presents the measured pressure at P1 with a filling ratio of 25%. It should be noted that in this paper, pressure refers to hydrodynamic pressure, which can be obtained by subtracting the analytical hydrostatic pressure under calm conditions from the measurement data. The sloshing caused by the roll motion is more violent compared to that caused by the sway motion because the centre of rotation is higher than the top of tank for the roll motion.



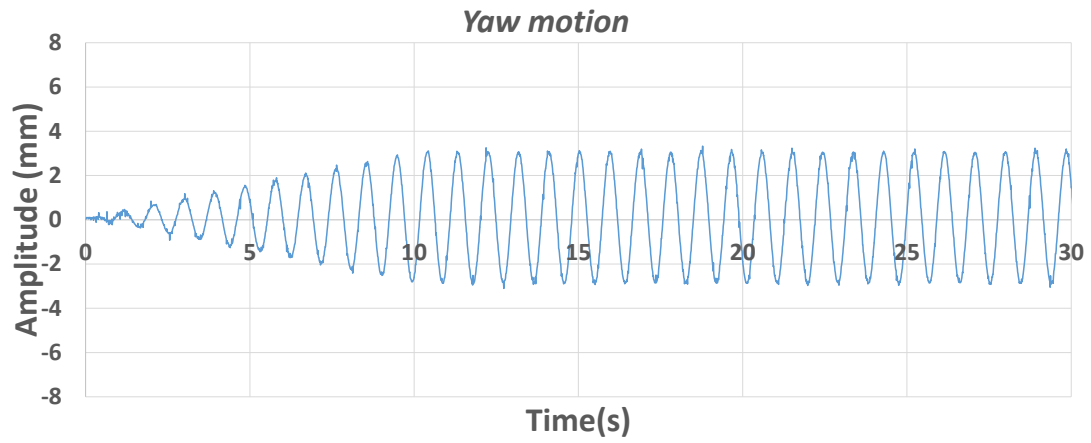
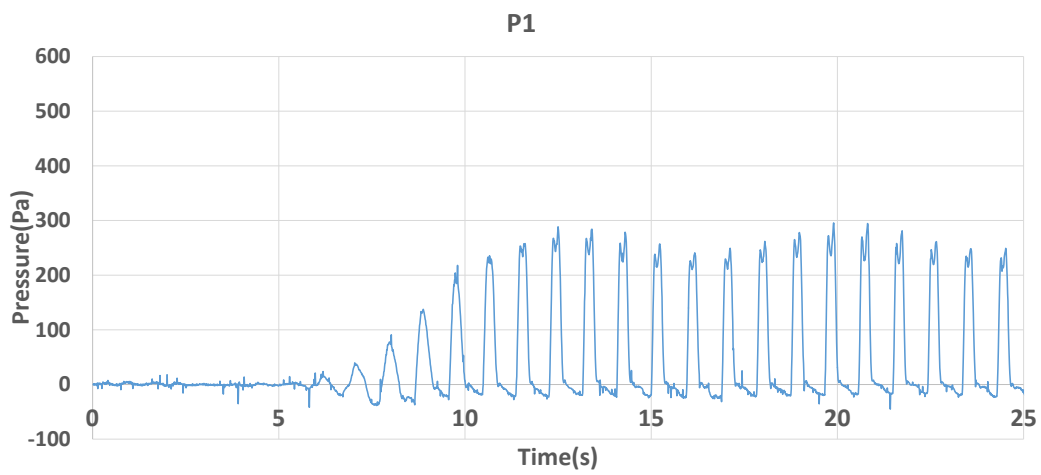


Figure 5-3. Time histories of forced oscillation motions with their maximum amplitude.

(a)



(b)

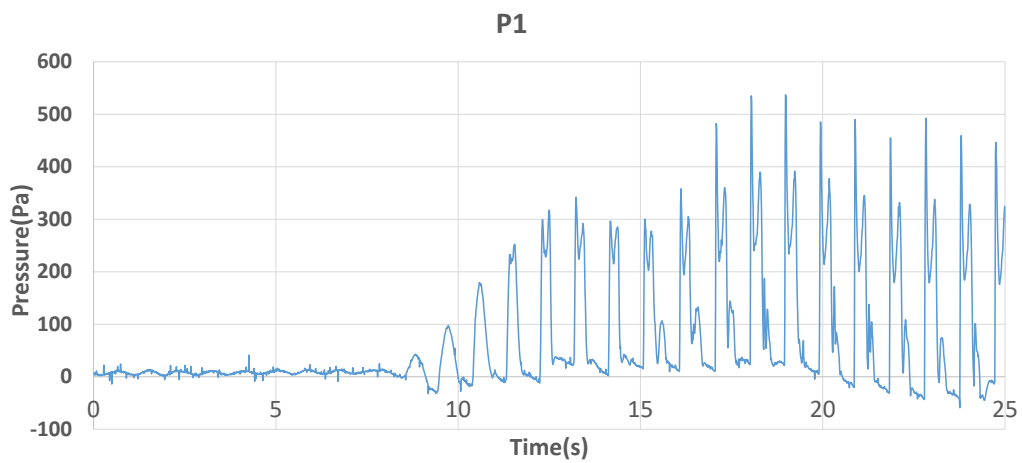


Figure 5-4. Measured pressure at P1 with filling ratio of 25 % in external oscillation of sway (a) and roll (b).

The natural period of the prismatic tank was estimated using Equation (5-1) and Equation (5-2), which derived by Faltinsen and Timokha[68]. Where ω_n is the natural frequency of the i -mode for a rectangular tank, d represents the water height, and l represents the length of the free-surface in the direction of tank movement. For a prismatic tank with a chamfered bottom, a correction factor was introduced in Equation (5-2), where δ_l and δ_2 are the horizontal and vertical dimensions of the chamfer, respectively.

$$\omega_n = \sqrt{\frac{i\pi g \tanh\left(\frac{i\pi d}{l}\right)}{l}} \quad (5-1)$$

$$\frac{\omega_n^2}{\omega_n^2} = 1 - \frac{\delta_1 \delta_2^{-1} \sinh^2\left(\frac{\pi i \delta_2}{l}\right) - \delta_1 \delta_2^{-1} \sin^2\left(\frac{\pi i \delta_1}{l}\right)}{\pi i \sinh\left(\frac{2\pi i d}{l}\right)} \quad (5-2)$$

5.3 Numerical Setup.

A tank with the same dimensions as that used in the experiment was used for SPH simulation to reproduce the sloshing phenomena observed in the experiment. A filling ratio of 25% was selected and the pressure gauge at P1 was located near the water surface. External oscillation was imposed based on a prescribed motion derived from the measured time histories of displacement during the experiment. In the simulation, an extra 5 s of simulation without external motion was included before oscillation began to settle the fluid particles. Table 5-3 lists the numerical parameters/conditions used in the SPH simulation. The Wendland kernel function was selected for the simulation. Here, “coefh” is defined as $h/dp\sqrt{3}$, where dp is the particle spacing, for three dimensions and $h/dp\sqrt{2}$ for two dimensions. The artificial viscosity coefficient α needs to be tuned to achieve proper dissipation. In this study, a value of 0.07 was used for all simulations based on trial-and-error testing. The parameter “coefsound” is defined as $Cs/\sqrt{gd_{swl}}$, where Cs and d_{swl} are the speed of sound and the height of water under calm conditions, respectively. Because the speed of sound has a significant influence on pressure fields based on the state equation, a coefsound value of 60 was derived through numerical trials mentioned later. The CFL number is a coefficient for calculating the optimal time step to satisfy the Courant-Friedrichs-Lewy condition. A delta-SPH coefficient of 0.1 was used to reduce

density fluctuation, as recommended by Molteni and Colagrossi [10]. Table 5-4 lists the numbers of particles used for a convergence study based on particle spacing. These particles were analyzed in a 3D simulation for a 25% filling ratio with external sway. The ratios of the width of the tank (l) to the particle spacing (dp), the inter-particle distance, were 75, 93.75, 125, 187.5, and 375 for the particle spacing values listed in Table 5-4. Using a finer particle spacing for simulation increases spatial resolution. It also reduces the gap between boundary particles and fluid particles, thereby enhancing the prediction accuracy of impact pressure when using DBPs. When using DBPs in SPH simulation, it creates gap between fluid particles and boundary particles cause by force exerted to boundary particles. It makes point measurement (pressure probe) cannot put on the exact position on the wall, so the gap between boundary particles and fluid particles needs to consider for the pressure probe. The gap of $1.5h$ was used for this study as recommended by the DualSPHysics. Figure 5-5 presents the results of the convergence study in terms of dynamic pressure under sway oscillations with $A = 6.52$ mm and $f = 1.04$ Hz. The SPH results using particle spacing values of 4.0, 3.2, and 2.4 mm cannot be used to evaluate shape of pressure variation in each swing, while those using particle spacing values of 1.6 and 0.8 mm can. When comparing two results, the results for a spacing value of 1.6 mm exhibit a prominent spike of negative pressure that was not observed in the experiment. Additionally, the root mean square errors for particle spacing values of 1.6 mm and 0.8 mm are 119.33 and 56.83, respectively, indicating that better agreement with the experimental results was achieved with a particle spacing value of 0.8 mm. Although even finer particle spacing could provide slightly better results, computation time would increase significantly. Therefore, a particle spacing of 0.8 mm will be assumed for the SPH simulations described hereafter.

Table 5-3. Computational setting in DualSPHysics

Parameters in DualSPHysics	
Kernel function	Wendland
Time step algorithm	Symplectic
Viscosity treatment	Artificial viscosity $\alpha = 0.07$
Coefsound	60.0
Initial particle size (mm)	0.8

Coefh	1.20
CFL number	0.275
Delta-SPH	0.10
Duration of simulation (s)	30.0

Table 5-4. Particle spacing and total number of particles for convergence study

External motion	Particle spacing (mm)	Total number of particles
Sway	4.0	98,766
	3.2	179,271
	2.4	420,414
	1.6	1,376,755
	0.8	10,501,723

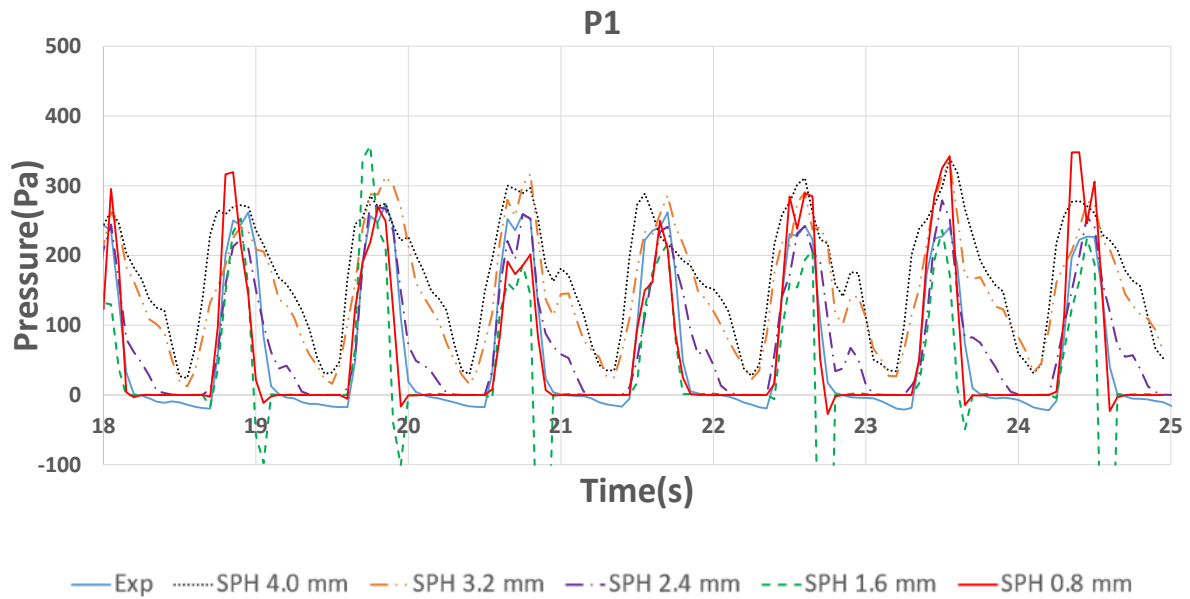


Figure 5-5. Convergence of pressure with particle spacing in external sway motion with $f=1.08$ Hz and $A=6.52$ mm.

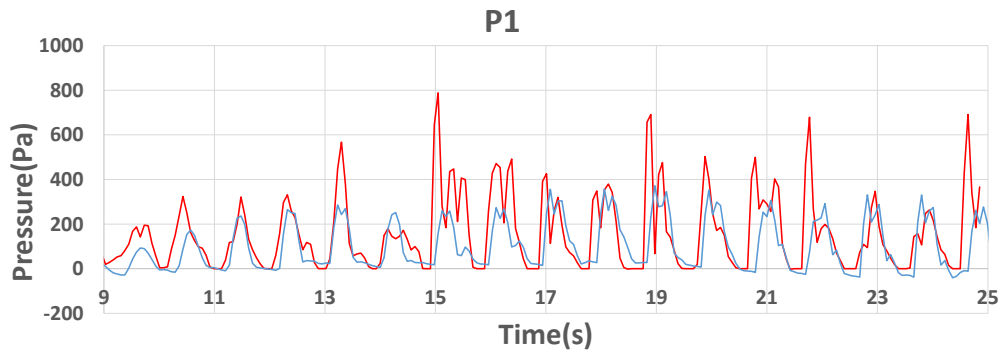
5.4 Sloshing Simulation by Three-dimensional Single-phase SPH

The speed of sound plays an important role in WCSPH. However, an artificially reduced value is commonly used to avoid excessive computational cost because an increase in speed requires a shorter time step, which increases total computation time. Using a reduced value for

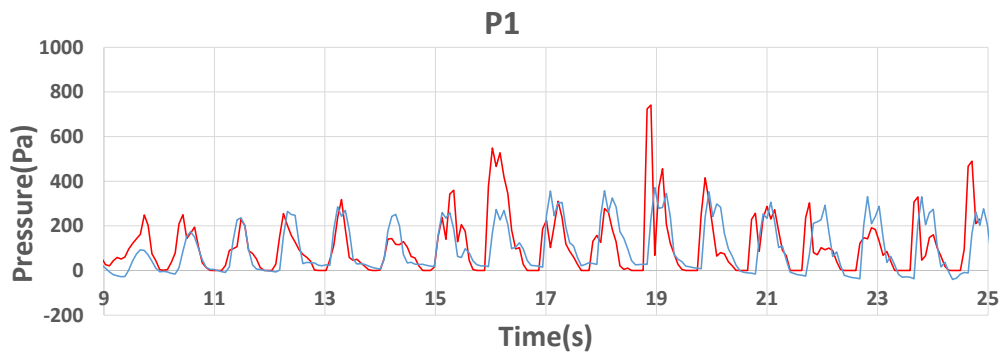
the speed of sound could result in less accurate results for impact pressure problems. Therefore, in this study, 3D single-phase SPH simulations using different values for the speed of sound were executed to determine the minimum adequate value. Figure 5-6 (a) presents a pressure comparison for P1 under roll oscillations. The selected coefsound values were 20, 40, 60 and 80. Coefsound of 80 provides the best results, but increases computation time by four times compared to a coefsound of 20. To balance accuracy and computation time, a coefsound of 60 was selected in this study.

The natural frequencies of the prismatic tank with different filling ratios were calculated using Equations (5-1) and (5-2) (see Table 5-5). To validate SPH for violent sloshing, the frequency of external oscillation should be close to the natural frequency of the tank. Therefore, values of $f = 1.08$ Hz and 1.04 Hz were selected for sway and roll oscillations, respectively, at a filling ratio of 25%. Additionally, the maximum amplitude was selected for the validation of each external motion.

(a)



(b)



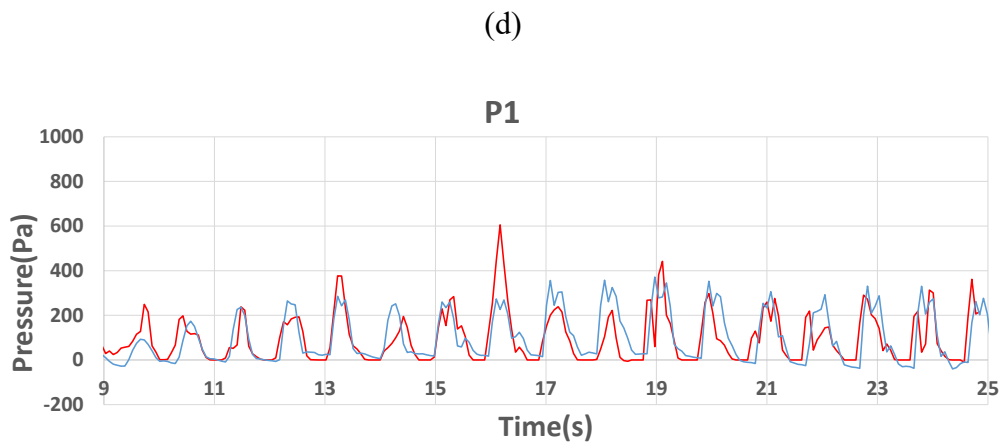
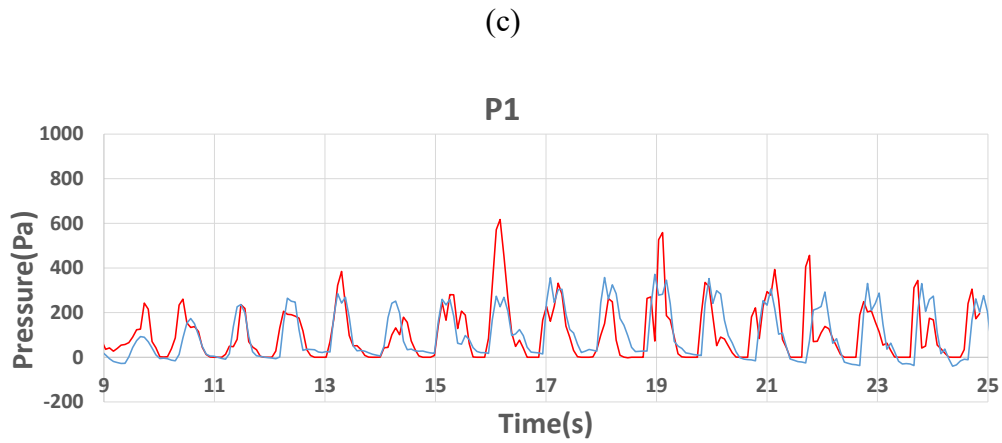


Figure 5-6. Influence of the speed of sound on hydrodynamic pressure with coefsound of 20 (a), 40 (b), 60 (c) and 80 (d).

Table 5-5. Natural frequency of prismatic tank in different filling ratio

Filling ratio	The natural frequency of prismatic tank (Hz)
25%	1.10
50%	1.43

Figure 5-7 presents a comparison of free-surface evolutions under sway oscillations. In this moderate sloshing situation, single-phase SPH can accurately reproduce the resonance of the fluid and free-surface deformation. Figure 5-8 presents a comparison of free-surface evolutions under roll oscillations. With this type of oscillation, the fluid motion in the tank becomes more violent, as shown in Figure 5-8, and the water front touches the top of the tank. The SPH simulation accurately reproduces the run-up, breaking, and splashing phenomena during sloshing, but the water does not reach the top of the tank. This could be because the

smoothing scheme and artificial viscosity used in SPH led to slightly greater dissipation compared to the real physics. Figures 5-9 and 5-10 present comparisons of pressure variation over time at P1 between the SPH and experimental results. In these graphs, the arithmetic means of pressure and peak pressure are drawn together. The dashed line represents the arithmetic mean of pressure and the dotted line represents the mean of peak pressure under each oscillation type over nine cycles. The results reveal that the mean pressure and mean of peak pressure are overestimated by SPH for both sway and roll oscillations, even though over 10 million particles were used. Additionally, one can see that the fluctuation in peak pressure in the SPH results is more prominent than that in the experimental results.

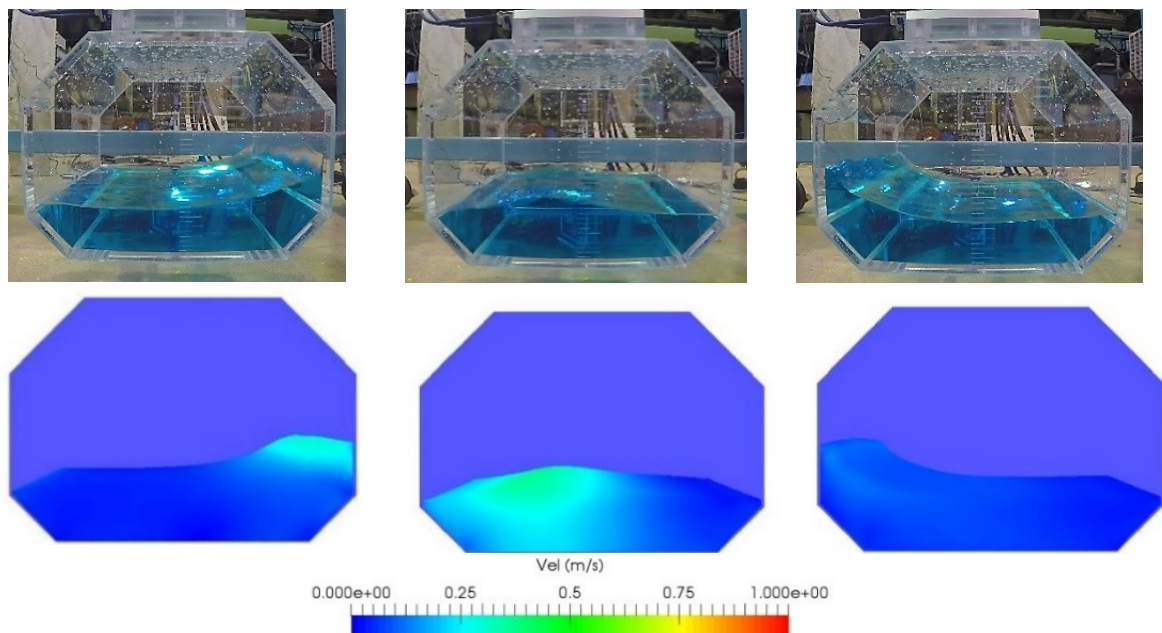
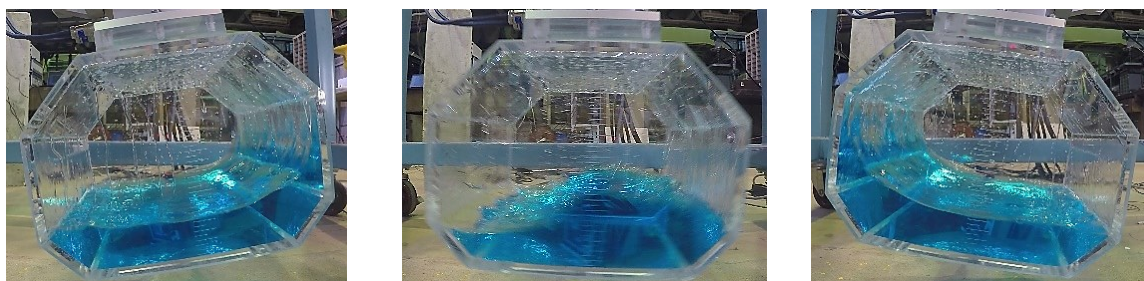


Figure 5-7. Free-surface evolution during sway oscillation at $t = 9.8$ s, 10.0 s, and 10.2 s.



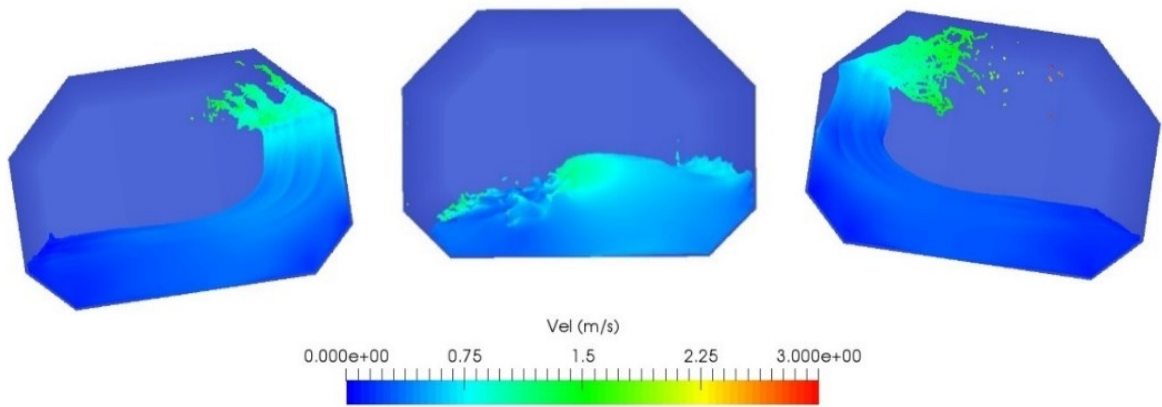


Figure 5-8. Free-surface evolution during roll oscillation at $t = 11.0$ s, 11.2 s, and 11.4 s.

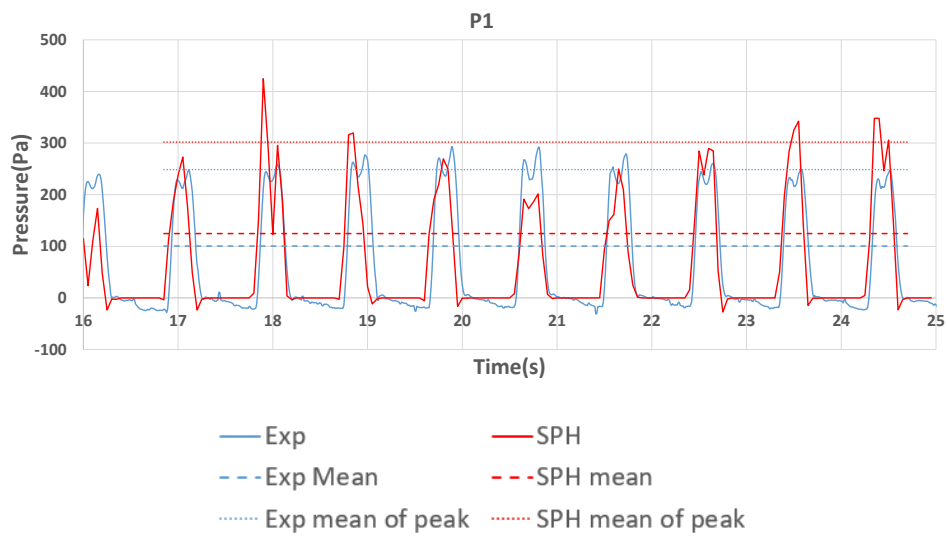


Figure 5-9. Impact pressure in sway excitation with particle spacing 0.8 mm.

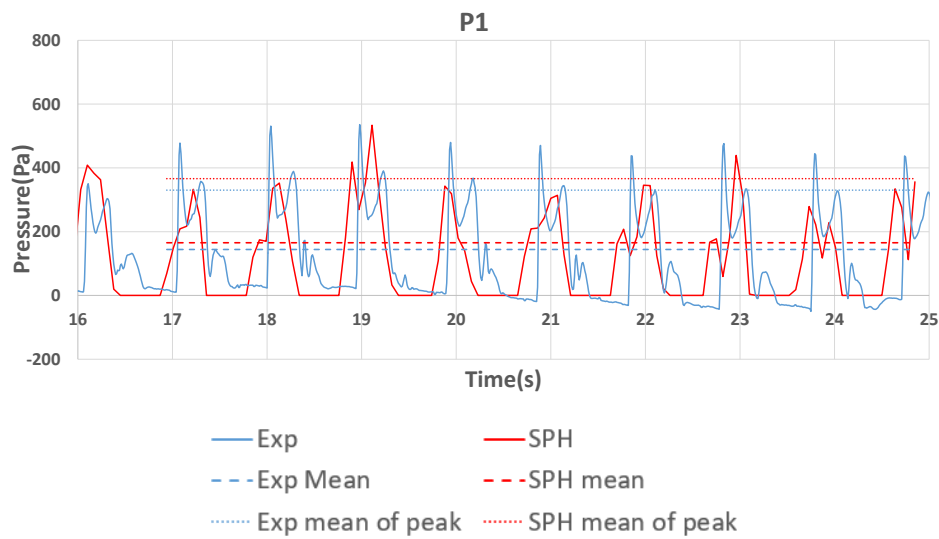


Figure 5-10. Impact pressure in roll excitation with particle spacing 0.8 mm.

5.5 Sloshing Simulation by Two-dimensional Two-phase SPH.

As described in the previous subsection, a 3D single-phase SPH method was applied to the prediction of sloshing in a prismatic tank. As a result, the violent resonance of fluid with complex free-surface excitation caused by external sway and roll was qualitatively reproduced with accurate impact pressure near the tank corners. However the simulated results did diverge from the experimental results, especially the pressure peak values, although using over 10M particles. To identify possible elements for reducing these discrepancies, two-phase SPH simulation was performed under the same conditions to analyse the influence of air phase on sloshing in a prismatic tank. The application of two-phase SPH was reported by Mokos et al. [45,46] and a ratio of the speeds of sound in liquid and gas phases of 7.5 resulted in good agreement with experimental results [46]. In this study, the speed of sound of water was determined to maintain a ratio above 7.0 when considering the real speed of sound in air (i.e., 343 m/s). For the sake of fair comparison and a clear discussion of the effects of air phase, a 2D simulation using a single-phase SPH method with the same particle spacing as the previous simulation was performed. The computation time for two-phase SPH simulation is much greater than that for single-phase SPH simulation because air particles must be calculated in addition to water particles. Additionally, the minimum time step satisfying the Mach number becomes smaller based on the greater speed of sound. As a result, it is infeasible to run 3D two-phase SPH for sloshing simulations with a large number of particles. However, it is not suitable to use a different particle spacing value and parameters for two-phase SPH when comparing the results to those of single-phase SPH. Therefore, we decided to run 2D sloshing simulations based on two-phase SPH using a consistent particle spacing of 0.8 mm. This is a reasonable choice because pure sway and pure roll motions were introduced in the experiment, meaning the flows in the tank can be regarded as 2D, rather than 3D. These assumptions led to a reduction in the total number of particles to 90,057 for 2D two-phase SPH simulation. Table 5-6 lists the parameters used for two-phase SPH simulation. As mentioned previously, the speed of sound has a significant influence on impact pressure and the ratio of the speeds of sound between air and water is important from the perspective of numerical stability.

Table 5-6. Computational setting in DualSPHysics.

Parameters in DualSPHysics	
Kernel function	Wendland
Time step algorithm	Symplectic
Viscosity treatment	Artificial viscosity $\alpha = 0.07$
Speed of sound for water & air (m/s)	46.5 & 343.0
Initial particle size (mm)	0.8
Coefh	0.95
CFL number	0.20
Delta-SPH	0.10
Duration of simulation (s)	30.0

5.5.1 Sloshing at Filling Ratio of 25%.

Figure 5-11 presents comparisons of the free-surface evolutions between single- and two-phase SPH, as well as the experimental results. In the result for two-phase simulation, the red-colored region is air phase and the blue-colored region is water phase. Two-phase SPH exhibits a smoother free-surface shape compared to single-phase SPH. This could be because the number of neighboring particles near the free-surface is increased with the inclusion of air particles. The two-phase simulation shows better agreement with the experimental results, especially in terms of the run-up along the side wall. The single-phase simulation tends to exhibit less run-up and the fluid easily detaches from the side wall based on the exclusion of an air phase. Figure 5-12 presents the pressure contours under static and dynamic conditions for a filling ratio of 25% under roll oscillation. One can see that both SPH simulations yield smooth hydrostatic pressure contours, but the two-phase SPH exhibits a smoother pressure distribution under dynamic conditions. In SPH, flow is simulated by solving partial differential equations locally with a compact support. However, the pressure field can be naturally smoothed over the entire liquid domain. Figure 5-13 presents a comparison of local pressure at P1 for sway and roll oscillations. The peak values tend to be overestimated by both single- and two-phase SPH. The mean value is also overestimated for sway, but good agreement can be observed for roll. In general, the mean peak pressure is slightly more accurate for two-phase SPH. It is known that pressure fields generally exhibit oscillation based on the effects of density

fluctuation in WCSPH, but pressure fluctuation is also suppressed by taking the air phase into account. The shape of the pressure curve, especially the tail of the pressure curve after the peak, shows better agreement with the experiment results for roll for two-phase SPH. It should be noted that the single-phase 2D SPH results show better agreement with the experimental results compared to the single-phase 3D SPH results in Figure 5-9, and Figure 5-10, even though the same particle spacing is used. This implies that the accuracy of 3D simulation tends to be worse than that of 2D simulation. The SPH method adopts a Lagrangian formulation, so a uniform distribution over time is an important element for the accurate analysis of flows. This uniform distribution might be more difficult to maintain in 3D simulations compared to 2D simulations.

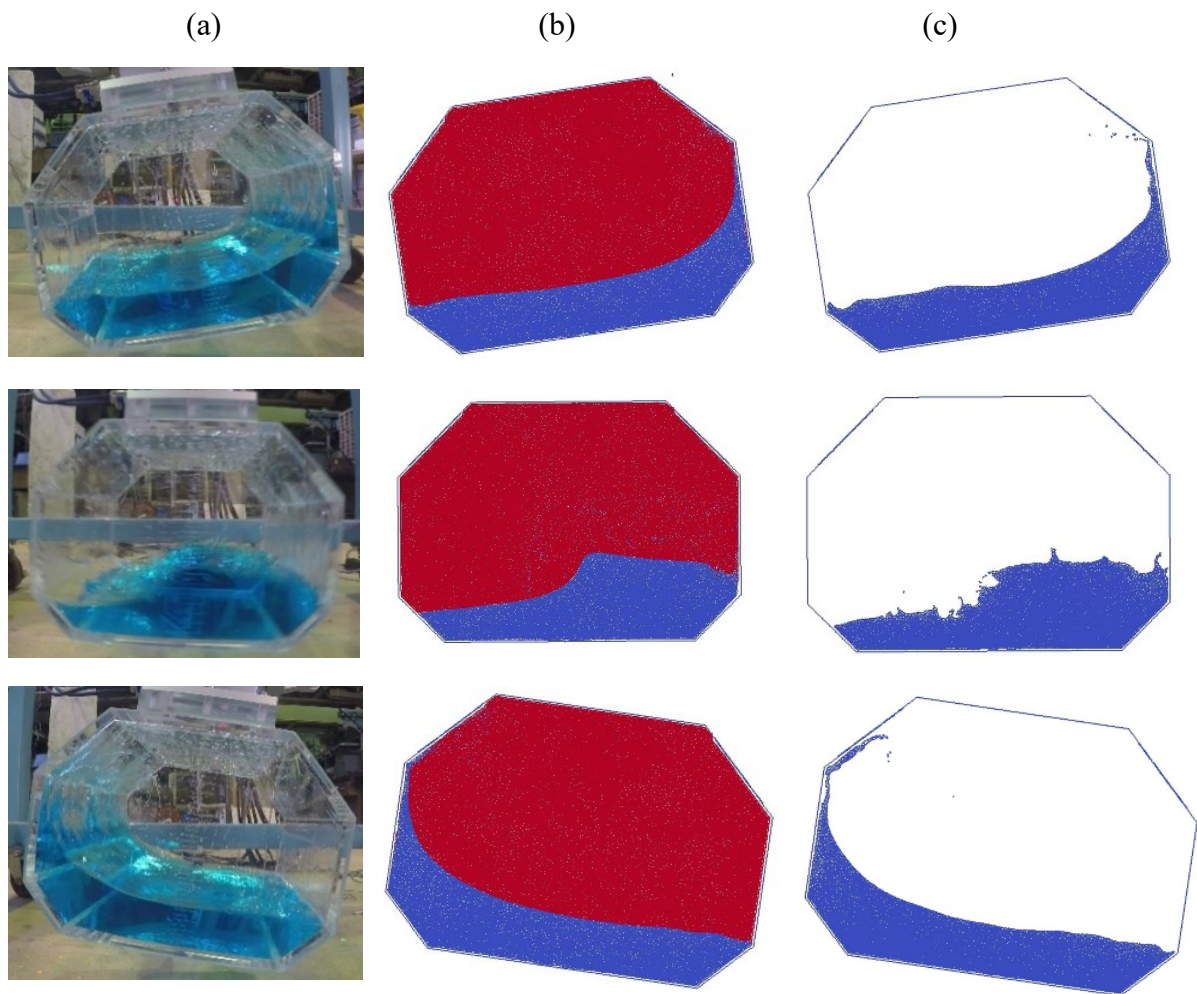


Figure 5-11. Free-surface evolution during roll oscillation in experiment (a), two-phase SPH (b) and single-phase SPH (c) with of filling ratio 25 % at $t = 11.0$ s, 11.2 s, and 11.4 s.

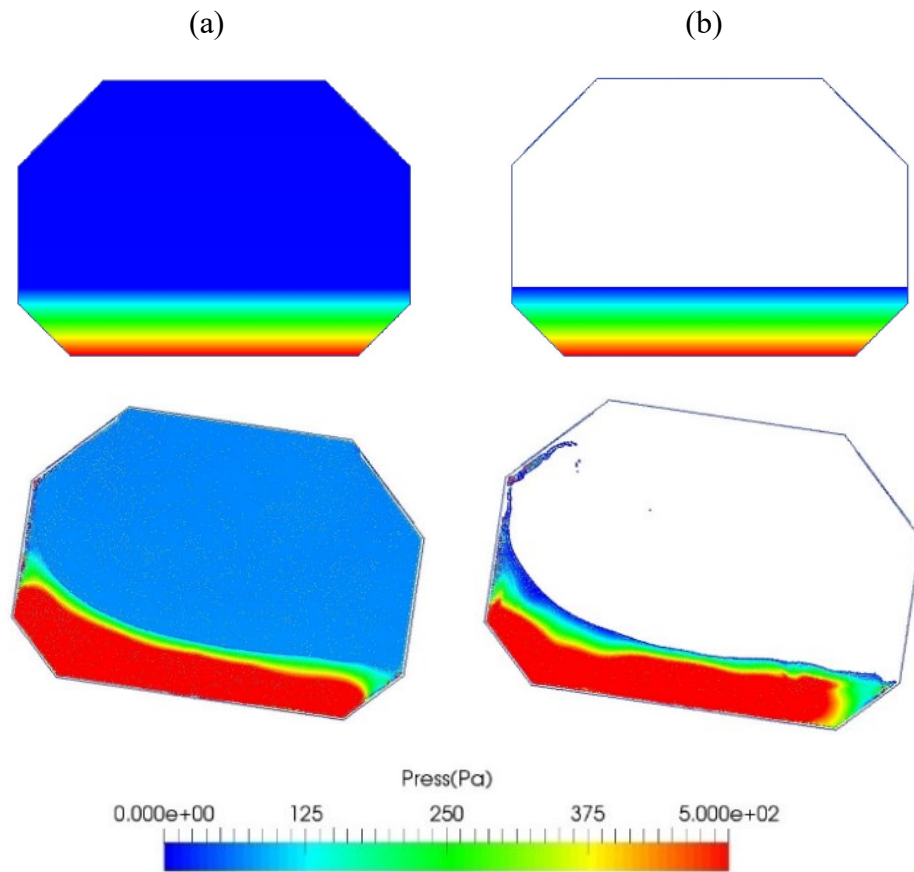
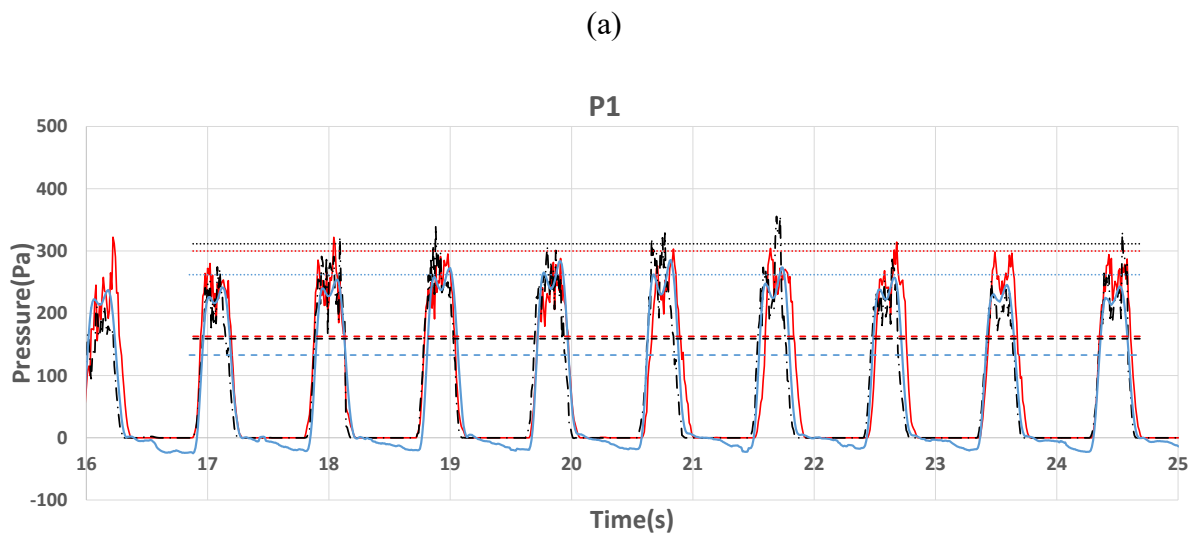


Figure 5-12. Pressure Contour during roll oscillation in two-phase SPH (a) and single-phase SPH (b) at $t = 0.0$ s and 11.4 s



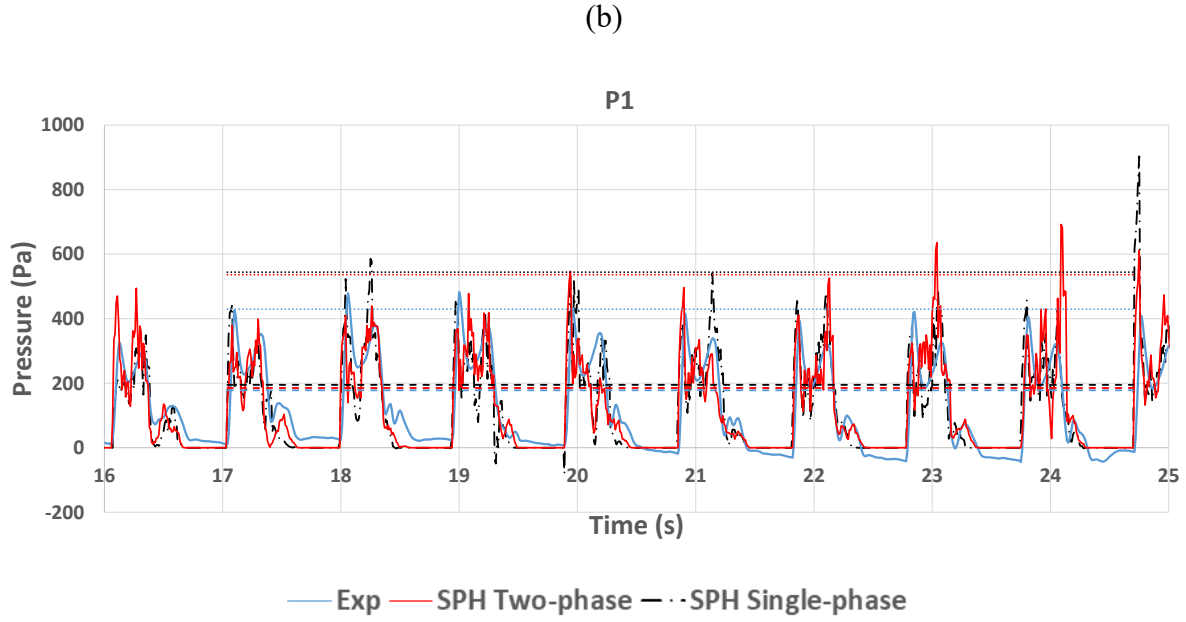


Figure 5-13. Comparison of pressure at P1 for sway (a) and roll (b) with filling ratio of 25 %.

5.5.2 Sloshing at Filling Ratio of 50%.

Figure 5-14 presents images of free-surface evolution under roll oscillation with $f=1.30$ Hz and $A = 8.66^\circ$ for a filling ratio of 50%. For two-phase SPH, the front shape of the run-up can be maintained along the side wall and touches the top wall, which is similar to the experimental observations. In contrast, for single-phase SPH, the fluid easily detaches from the side wall, similar to the filling ratio of 25%. Figure 5-15 presents the pressure contours under static and dynamic conditions. A smoother pressure distribution can again be observed in the liquid phase for two-phase SPH and one can see that the presence of air clearly affects the behavior of liquids, especially in terms of run-up and spraying. Figure 5-16 presents a comparison of the local pressures at P1 and P2 under sway oscillation with $f= 1.34$ Hz and $A = 6.52$ mm at a filling ratio of 50%. In the two-phase SPH results, the arithmetic mean of pressure shows reasonable agreement with the experimental results and the mean of peak pressure also shows reasonable agreement at P1, whereas single-phase SPH failed to predict these values accurately. The prediction accuracy of pressure at P2 is poor because the pressure at this point is relatively spikey compared to that at P1. However the two-phase SPH results show much better agreement with the experimental results than the single-phase SPH results at P2. A similar trend of improvement in terms of pressure accuracy can be observed for the roll oscillation shown in Figure 5-17. The accuracy of peak pressure at P2 is worse than that in

the sway case because the flow inside the tank is more violent and the impact pressure is much greater than that in the sway case. However the importance of the air phase is clearly demonstrated here because single-phase SPH cannot capture the impact pressure at all.

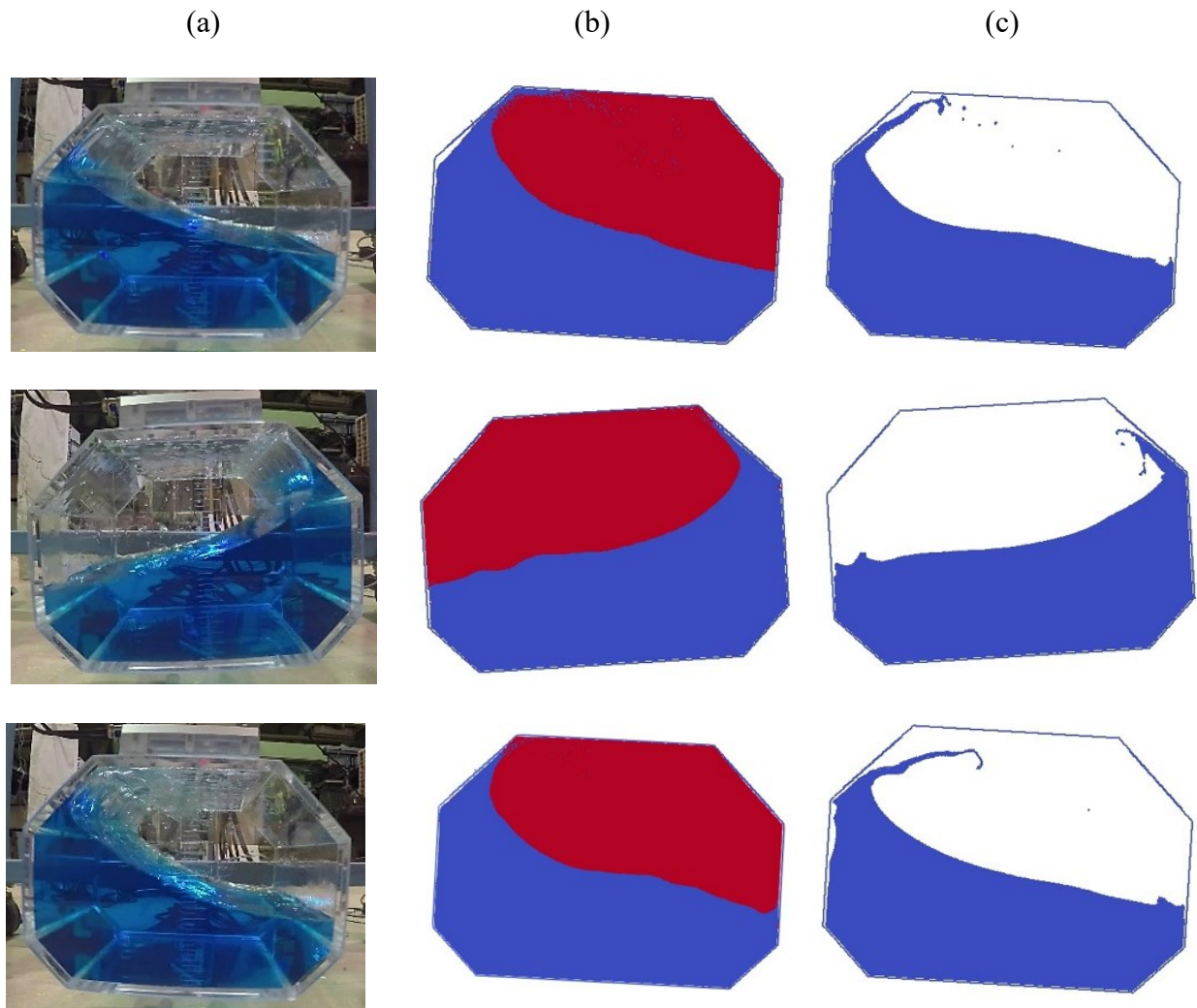
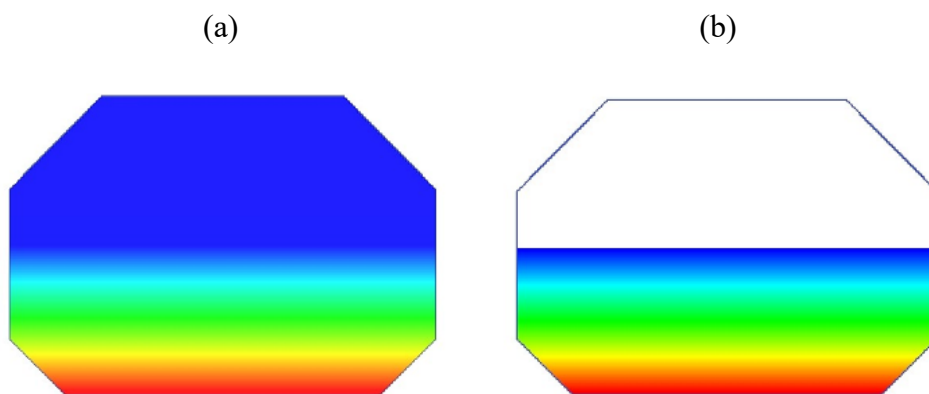


Figure 5-14. Free-surface evolution of roll excitation in experiment (a), two-phase (b) and single-phase (c) with $t = 3.6$ s, 3.9 s and 4.4 s.



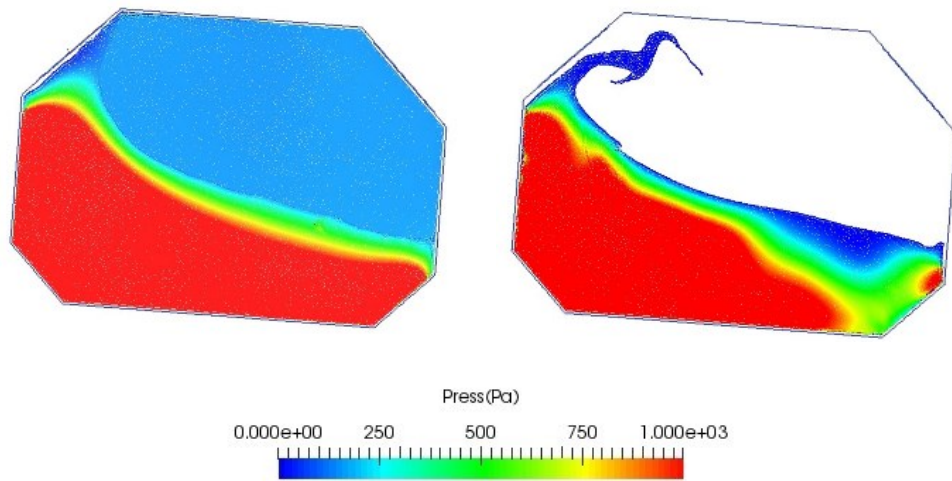


Figure 5-15. Pressure Contour of filling ratio 50 % of two-phase (a) and single-phase (b) with $t = 0.0$ s and 12.15 s.

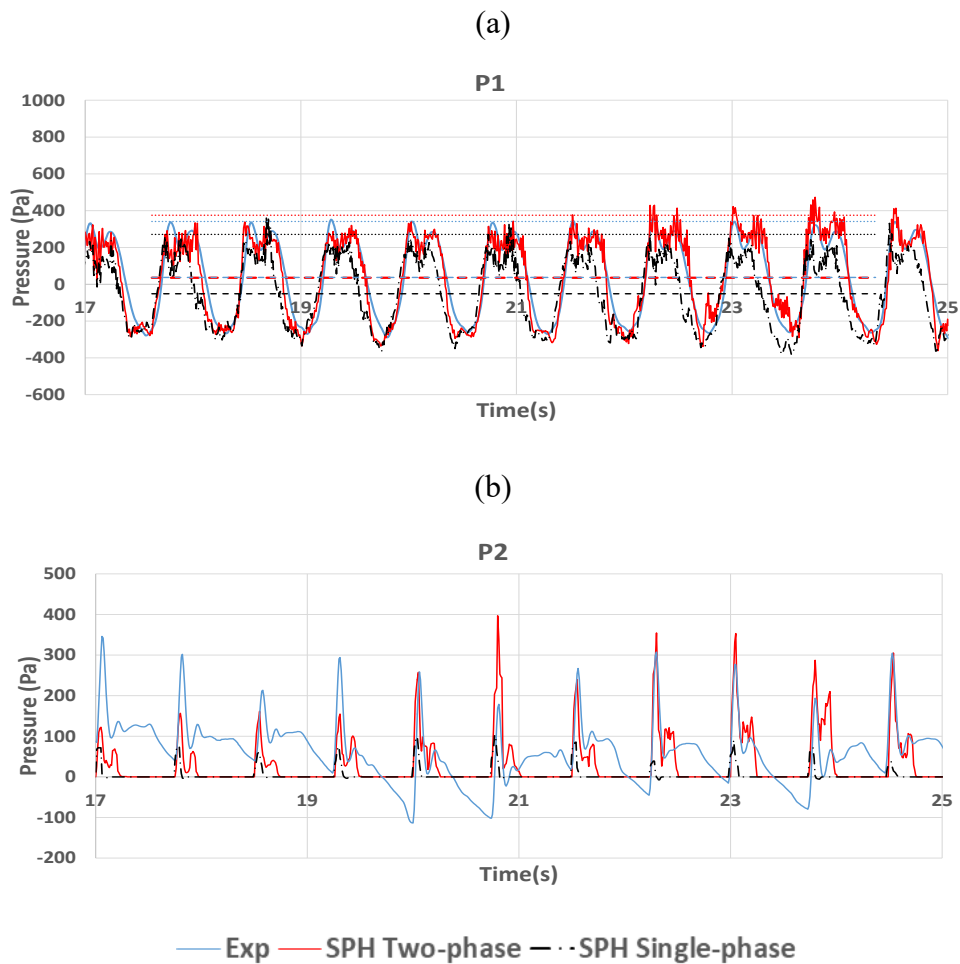


Figure 5-16. Comparison of pressure at P1 (a) and P2 (b) for sway oscillation with filling ratio of 50 %.

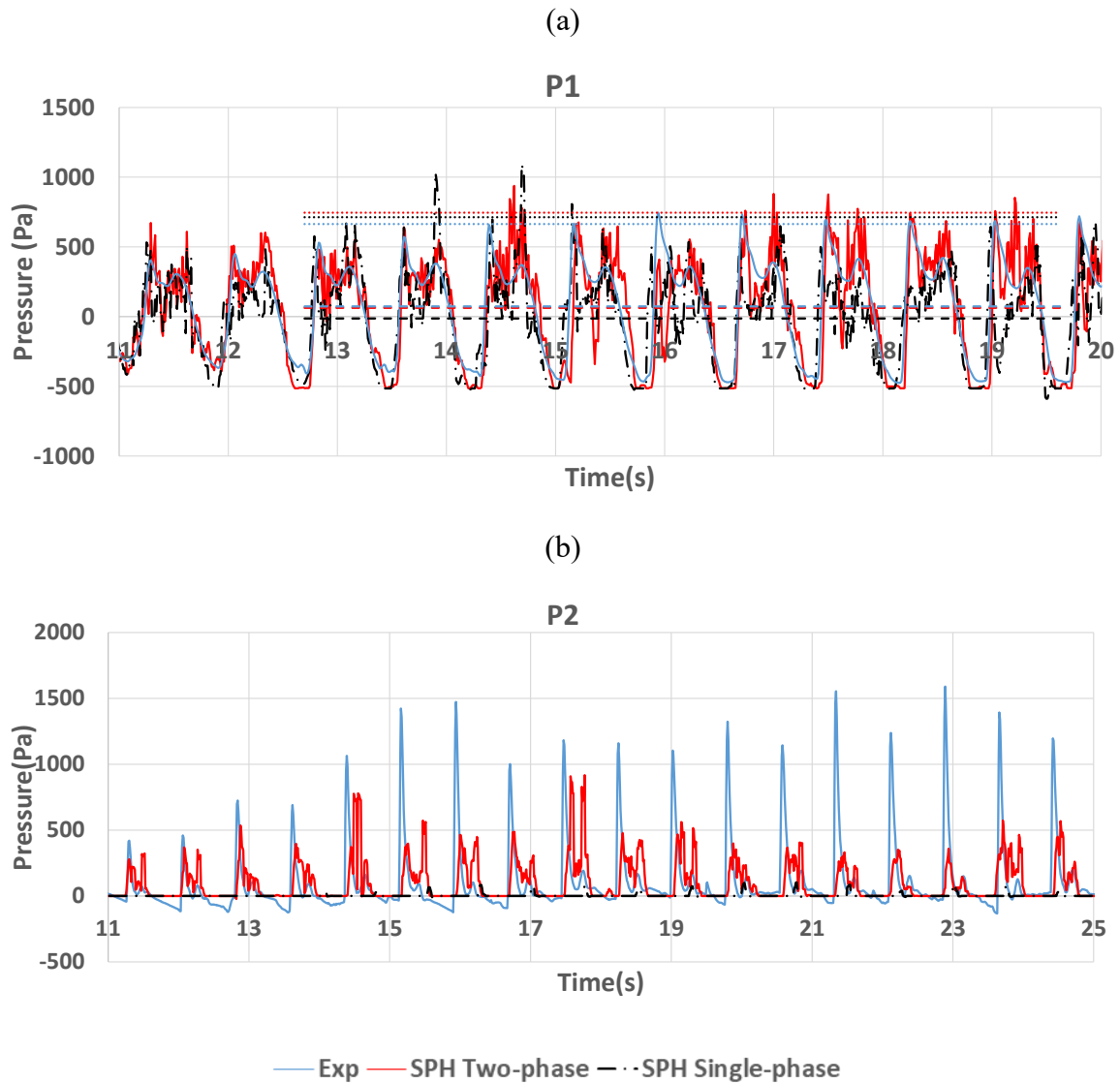
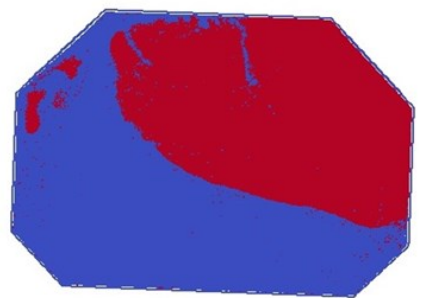
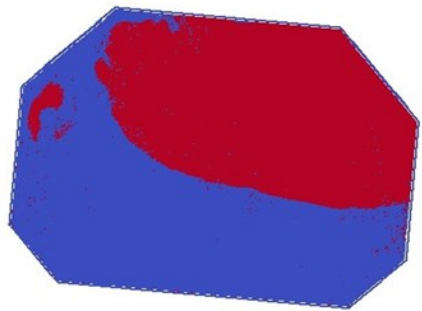
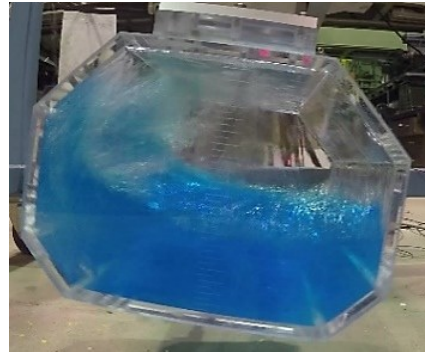
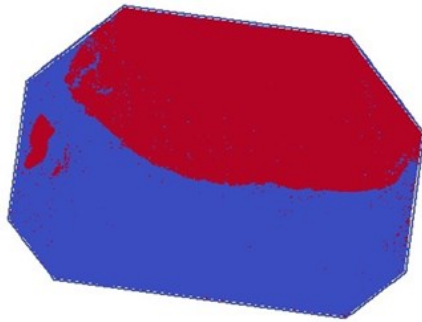


Figure 5-17. Comparison of pressure at P1 (a) and P2 (b) for roll oscillation with filling ratio of 50%.

5.5.3 Air and Water Mixture.

Figure 5-18 presents comparisons between the two-phase SPH results and experimental results under roll oscillation. The intension for this comparison is to highlight the air and water mixing that occurs during violent sloshing. In the two-phase SPH simulation, the existence of air pockets and an air-water mixture is captured, which matches the experiment. This is one of the major advantages of two-phase flow simulations in terms of deep discussion of the sloshing phenomenon itself. Mokos et al.[46] discussed the issue of air mixture creation and void creation in a two-phase flow. It is clear that much finer particle spacing is required to capture the creation process of air-water mixtures quantitatively. Further studies for the detailed

analysis of air effects using a large number of particles are expected. In addition, for the engineering standpoints, it is expected to couple two-phase SPH with a mathematical model for ship motion to carry out fully coupled ship-tank simulations, similar to those discussed in [69–71].



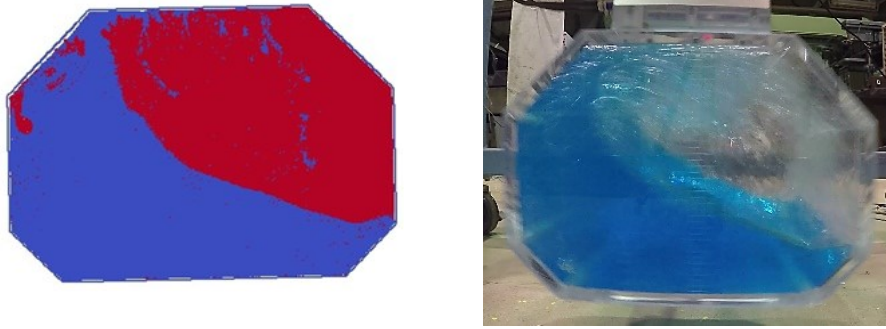


Figure 5-18. Snapshot of air mixture in roll excitation with filling ratio 50% at $t=16.15$ s, 16.20 s, 16.25 s, 16.30 s.

5.6 Concluding Remarks.

Single- and two-phase SPH simulations accelerated by a GPU were performed to analyse sloshing in a tank. For quantitative validation, a dedicated sloshing experiment was conducted using a realistically shaped prismatic tank that was subjected to external sway and roll oscillations. The experiment was successful, and fluid behaviour and impact pressure at three different locations were measured. Next, single-phase 3D SPH simulations were performed with several particle distances. It was confirmed that 0.8 mm of particle spacing is necessary to capture the shape of pressure variation. It was also confirmed that the speed of sound has a significant influence on impact pressure and pressure oscillation. By comparing the simulation results to the experimental results, it was demonstrated that large-scale single-phase SPH, using over 10 million particles, fails to represent free-surface evolution and impact pressure accurately. Next, a 2D two-phase simulation was performed and is validated by comparing its results to the experimental results, as well as those of the two-dimensional single-phase SPH simulation. Based on comparisons under different conditions, the importance of an air phase in sloshing phenomena was clarified and improvement of impact pressure simulation accuracy near the tank corners in terms of mean and peak pressures was confirmed.

Chapter 6

Parameter Setting Recommendation

6.1 General Discussion

This study has presented an experimental validation of SPH for free-surface flows in marine engineering field, water wave propagation and sloshing as examples. Simulation of SPH was conducted using a GPU to accelerate the simulation both in 2D and 3D simulations. The merit of using SPH to simulate free-surface flows is that it is easier to capture large deformation free-surface flows. Because SPH is a meshless method, this made it easier and shortened the time during the pre-processing process without the need to generate a grid which is time-consuming. The major drawback of the SPH method is the massive computational resources and time required for complex simulations, especially in 3D SPH simulations. This is associated with the number of neighbours per particle and the number of particles, which must be increased for the application for real engineering problems and complex flows, particularly in 3D SPH simulations. Application of a multi-GPU is demanded to overcome this problem. A multi-GPU accelerates the computation reducing the computational time.

In this study, the GPU Titan X 12 GB DDR 5 is used for 2D and 3D SPH simulation. Twenty-two million particles are successfully addressed using a single GPU for the water wave problem and 10 million for the sloshing case. The capability of SPH using GPGPU technology made it possible to run a SPH simulation of over million particles. The major drawback is the computational time remains high in the 3D SPH simulation though millions particles can now be addressed using a GPU. A multi-GPU code has been implemented in SPH as reported by Dominquez et al. [72], but it has not yet been released as an open-source code; thus, computational time remains problematic in 3D SPH simulation.

SPH is a numerical approach developed two decades ago and some problems remain as mentioned in SPHERIC grand challenge such as boundary condition, coupling to other models and applicability to the industry. In this study, only the dynamic boundary particle (DBP) is used [60]. This boundary condition itself has a drawback that a gap created between the boundary and fluid particles is caused by the artificial force exerted on the boundary. Using DBP makes point measurements cannot precisely in-wall and a gap exists between the

boundary and fluid particles. Another drawback is that pressure fields have spurious oscillation making it difficult to obtain a real pressure result from SPH simulation. The advantage of using this method is that it is easy to implement in SPH as there is no complicated procedure such as ghost particles.

SPH simulation relies on a kernel function; several parameters in SPH are tuning parameters used to obtain proper accuracy. Because the kernel function is one of the essential parameters, particle spacing is an important parameter in SPH. It will influence the particle neighbor in compact support. Using a finer particle spacing also reduces the gap between the boundary and fluid particle. Coefficient of smoothing length (coefh) is a tuning parameter in SPH. In SPH simulation, there is a need to optimize the smoothing length to define each case because this will influence how many particles exist in smoothing length. A small number of particles will lead to less information and a higher number of particles will lead to smoothing out that also decreases the accuracy. Each case in SPH will have a particular characteristic of smoothing length. Coefficient of artificial viscosity (α) needs to be tuned to obtain proper dissipation as a result of the particle spacing that is used in the simulation. When addressing pressure prediction in SPH, the speed of sound (coefsound) is a tuning parameter to obtain appropriate accuracy in pressure prediction. Unfortunately, the speed of sound is directly connected to the time step as a higher speed of sound will decrease the time step; as a consequence, computational time will increase. Using a higher speed of sound also reduces the pressure oscillation in SPH as shown in the sloshing case.

Water wave problems as a validation study were well captured by SPH. The reproduction terms are wave elevation, hydrostatic pressure, and dynamics pressure both in 2D (long-distance propagation) and 3D simulations (medium-distance propagation). In long-distance propagation, a larger smoothing length needs to use because wave is easy to decay, as shown in Figure 6-1. Because particle spacing is constant, another parameter that needs to be tuned is the coefficient of artificial viscosity. Figure 6-2 shows numerical results using two different α with two different coefh for a large numerical wave tank (NWT) in a shallow water depth. It shows coefh has significant influence on wave elevation. Coefh 2.0 shows better accuracy compared to coefh 1.8. After coefh value has been determined, α needs to be tuned. Figure 6-3 and 6-4 show numerical results for the same coefh with different α . In this case, the comparison was made using $\alpha = 0.01$ and $\alpha = 0.0001$. $\alpha = 0.0001$ showed better accuracy compared to $\alpha = 0.01$. It was also found decreasing α could increase the wave elevation though

it did not drastically increase the accuracy as did the smoothing length. Using a combination of both parameters, a long-distance propagation was successfully reproduced. For a shorter NWT, a validation study was conducted using a smaller smoothing length and higher α value. As the developer of DualSPHysics has mentioned that the parameters are valid only for three wavelengths of NWT, as a result of a shorter NWT the recommended parameters from the developer can be.

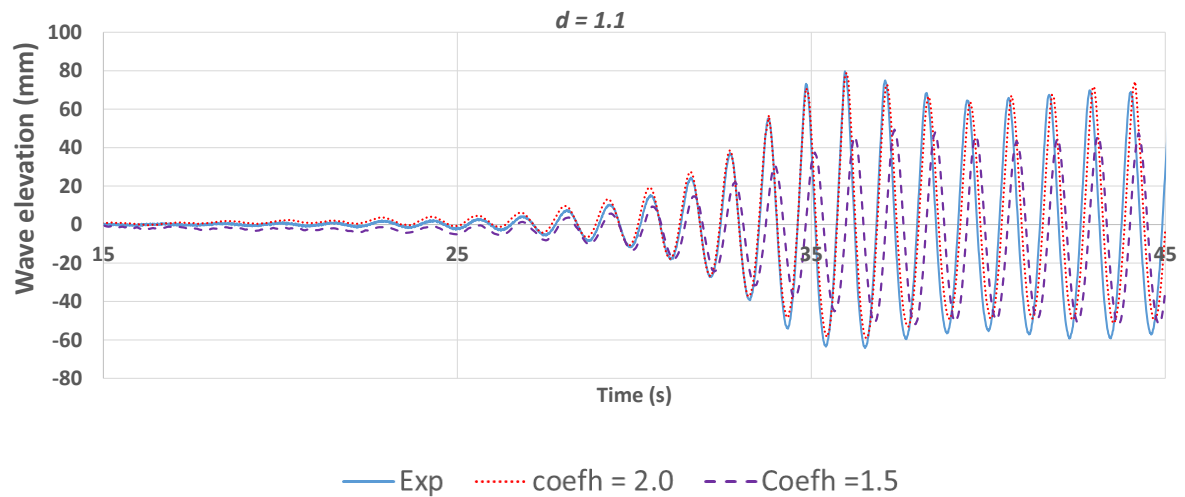


Figure 6-1. Comparison wave elevation with different coefh for $d=1.10$ m with $A=33.0$ mm.

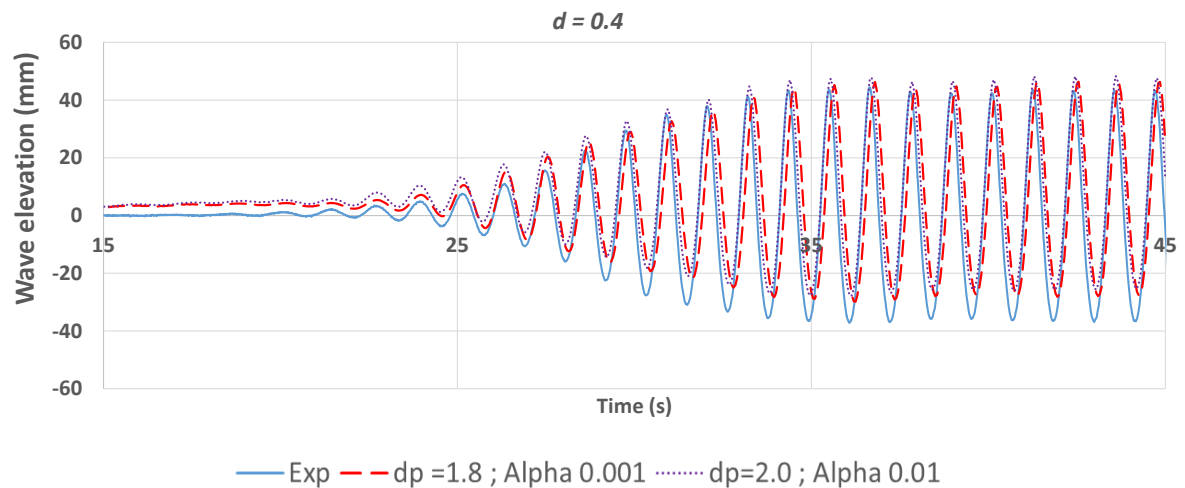


Figure 6-2. Comparison wave elevation with different coefh for $d=0.4$ m with $A=33.0$ mm.

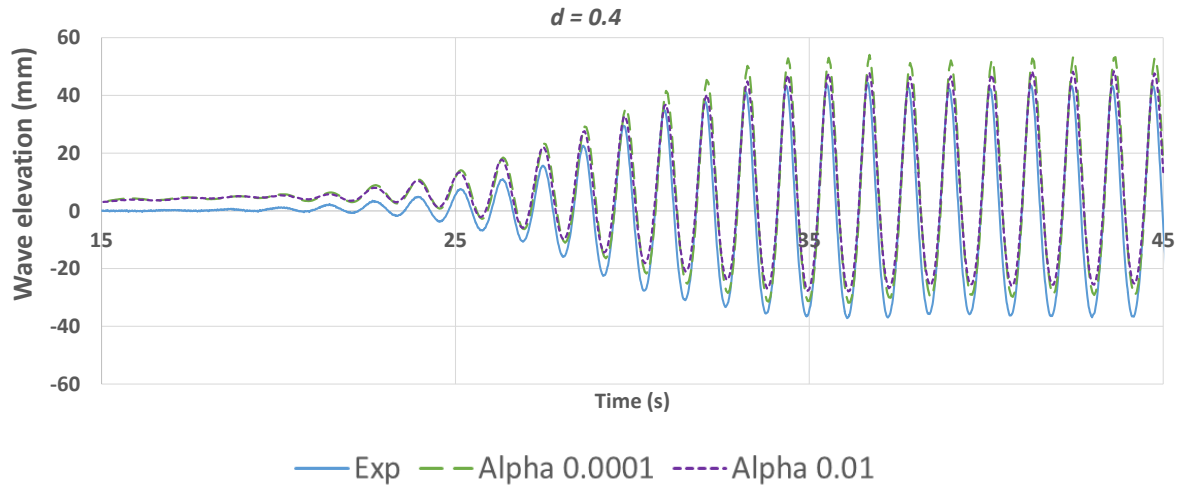


Figure 6-3. Comparison wave elevation with different coefficient of artificial viscosity for $d=0.4$ m with $A=33.0$ mm.

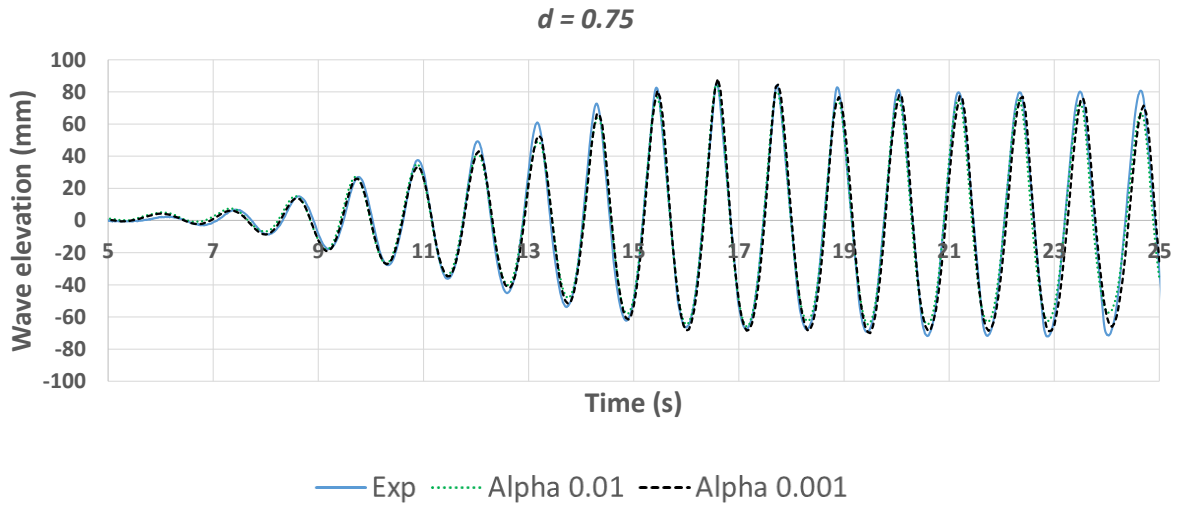


Figure 6-4. Comparison of wave elevation with different coefficient artificial viscosity with $d=0.75$ m with $A = 55.0$ mm in small NWT.

The validation study of the SPH method for the sloshing problem was slightly harder compared to that of the water wave problem. A difficulty is capturing the impact pressure in the sidewall tank because DualSPHysics is based on WCSPH that has a well-known spurious pressure field. From the three-point measurement of impact pressure, only one point of measurement is well validated using the SPH method. Particle spacing is an essential parameter; as mentioned in chapter 5, appropriate particle spacing will lead to proper accuracy. Because by default DBP is used as a result a gap occurs between the boundary and fluid particles. Pressure measurement cannot be precisely obtained on the wall. Figure 6-5 presents the different pressure measurement distances in two-phase SPH for sway motion with $f=1.08$

Hz and $A=6.52$ mm. $0.0h$ means the pressure measurement is exactly on the wall, where h is the smoothing length. The pressure shows zero or SPH cannot capture the pressure because pressure measurement is exactly on the wall, while $1.5h$ means the pressure measurement distance is $1.5h$ from the wall and a result exists for impact pressure.

Because in the sloshing case the domain is closed and external energy is put periodically, a shorter smoothing length was used. Speed of sound is an important parameter in the sloshing case as increasing the speed of sound lead to an increasing pressure that has a direct influence on the equation of state in SPH. Another effect is the pressure oscillation in the pressure field decreasing, but the higher speed of sound also increases the computational time as it directly affects the time step. Using over million particles in 3D SPH is infeasible as the computational time would be days even for a small domain. Application of a multi-GPU is demanded in SPH simulation to overcome the computational time in 3D SPH simulation and for the application of SPH for real engineering problems. The two-phase simulation shows better agreement than single-phase simulation; the free-surface evolution has a better agreement than that of the single-phase. Two-phase SPH conducted in 2D has overall good accuracy comparing two-phase SPH to single-phase SPH. But, two-phase SPH also needs a longer computational time than that of single-phase. The results show two-phase SPH is a recommended approach at this moment to apply in the sloshing problem. Coupled motions in the sloshing case have not yet been conducted because of the limitation in motions that can be used in DualSPHysics. More effort is needed to develop an application for sloshing flows in future works.

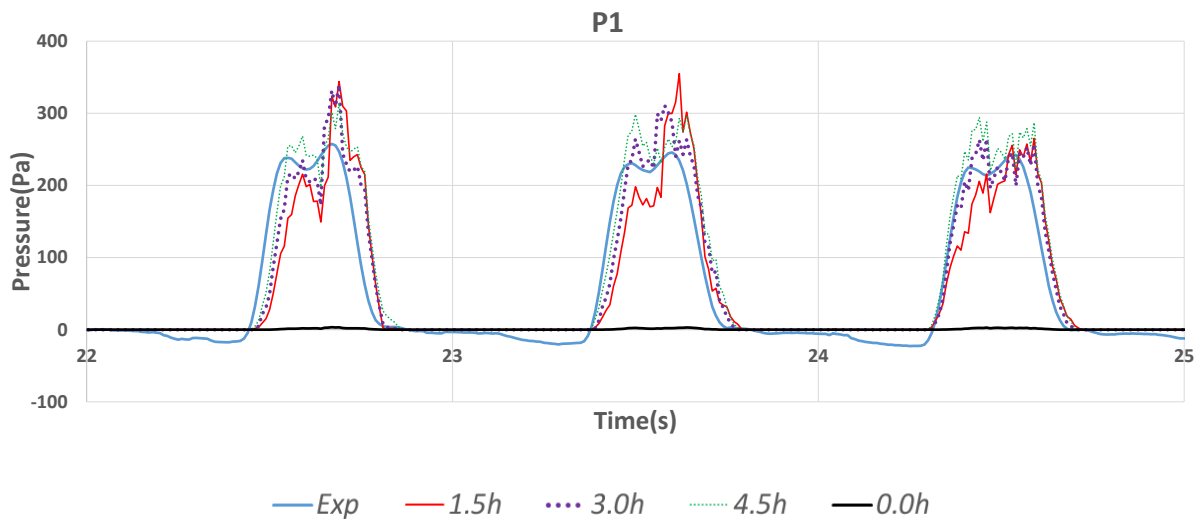


Figure 6-5. Effect of distance in pressure measurement resulting from DBP for two-phase SPH with $f=1.08$ Hz and $A=6.52$ mm.

6.2 Recommended Parameters for Water Wave Propagation

Experimental validation of the SPH Method for the water wave problem describes the capability of the meshless method to reproduce the water wave problem. Few researchers have used long-distance propagation that requires greater than twelve wavelengths for an NWT. A validation was completed not only for 2D simulation but also 3D simulation using a shorter NWT.

Some parameters need to be tuned to obtain appropriate accuracy using SPH such as smoothing length which needs to be a higher value than the recommendation of the developer. Another parameter is particle spacing, which needs to be less than $H/14$ to obtain appropriate accuracy in long-distance propagation problems, where H is wave height and L is the distance of wave probe to wavemaker. Sensitive analysis of particle spacing needs to be conducted to obtain optimal particle spacing and proper accuracy. The last parameter to tune is the coefficient of artificial viscosity to obtain a proper dissipation effect in water wave propagation. The parameters suitable for short-distance propagation do not automatically suit other cases such as long-distance propagation. The 3D water wave propagation shows the recommended settings from the developer are sufficient to reproduce in medium propagation. It can be concluded that parameters from the developer are valid only for three wavelength times in an NWT. When addressing long-distance propagation, parameters derived from the present study are recommended for use. The summarized parameters in Table 6-1 are important parameters to obtain appropriate accuracy in water wave problems.

Table 6-1. Parameters in SPH simulations for water wave propagation

Parameters	2D simulation $L > 10\lambda$	3D simulation $L < 3\lambda$
Coefh	2.0	1.2-1.5
Coefficient of artificial viscosity (α)	0.0001	0.01
Particle spacing (dp)	$dp \leq H/14$	

6.3 Recommended Parameters for Sloshing in Prismatic tank

Experimental validation of the 3D single phase SPH method for the sloshing problem shows a comparable result to that of the experiment, but pressure prediction shows a discrepancy, particularly in roll excitation motion. This can be caused by the large time step used in SPH simulation and the coefficient of artificial viscosity needs to be tuned to obtain proper dissipation. Although it was successful for conducting SPH simulation with a large amount of particle over 10M, the accuracy of SPH was not satisfied in the 3D case. However, using two-phase SPH simulation, better results are obtained. Speed of sound is a parameter that needs to be tuned properly in the sloshing problem. An appropriate speed of sound will lead to accurate pressure prediction, though it also has a significant effect on computational time.

Two-phase SPH was conducted in 2D simulation with less particles than in the 3D SPH, and it showed the air phase has a significant effect on pressure prediction and free-surface evolution. The air phase in two-phase SPH provides a better pressure prediction than the single-phase particularly at the upper-pressure gauge. A comparison between single- and two-phase SPH simulations with the same parameters of the 2D simulation was conducted. It showed the air phase needs to be included in the sloshing simulation to obtain a proper free-surface evolution and pressure prediction. The ratio of the speed of sound between the water and air phase is required to be above 7.0 to obtain adequate accuracy. The summarized parameters in Table 6-2 are essential parameters to obtain appropriate accuracy in terms of impact pressure in tank sloshing.

Table 6-2. Parameters in SPH simulations for sloshing

Parameters	2D simulation	3D simulation
Coefh	0.95	1.2-1.5
Coefsound	65	60
Coefficient of artificial viscosity (α)	0.01-0.07	0.01-0.07

Chapter 7

Conclusions and Future Works

7.1 Conclusions

An experimental validation study of SPH for free-surface flows was conducted for water wave generation and propagation, and sloshing in a prismatic tank. First, a dedicated experiment was conducted at Kobe University for water wave problems. The experiment was successfully conducted using a three-amplitude piston wavemaker, three water depths, and two wavemaker periods. An experimental validation study of SPH for water waves was completed using a GPU-accelerated solver. Tuning parameters in the SPH simulation were necessary to reproduce water wave propagation both in 2D and 3D domains. Particle spacing, smoothing length, and coefficient of artificial viscosity are tuning parameters used to obtain proper accuracy in a water wave propagation case. It can be concluded that parameters suitable for a small NWT are not automatically appropriate for a long NWT and vice versa. Large deformation of surface waves or ‘bank effects’ are well reproduced by SPH; thus, it is a promising method for water wave problems. The drawback is 3D SPH simulation is still limited using a single GPU, making it difficult to conduct 3D water wave simulations using a large domain.

A sloshing experiment was conducted at the NRIFE to conduct a validation study on sloshing in tanks. The experiment was conducted using a four degrees of freedom forced oscillation machine for a prismatic tank. Four motions were produced by the forced oscillation machine, i.e. sway, roll, heave, and yaw motions. The hydrodynamic pressure at different points were measured. For the sloshing case, the particle spacing, speed of sound, and coefficient of artificial viscosity are tuning parameters to obtain appropriate accuracy in the pressure field. Large-scale particle simulation was successfully conducted using a GPU-accelerated solver, but the result for impact pressure remained unsatisfactory. Therefore, two-phase SPH simulation was conducted to include an air phase in the sloshing simulation, showing that the air phase is an essential element in sloshing flow. The free-surface evolution showed better agreement with the experiment compared to that of the single-phase SPH. The pressure prediction was more accurate in the two-phase SPH. Air mixture phenomena were also reproduced using two-phase SPH.

GPU-accelerated SPH simulation was applied to nonlinear free surface flows in marine engineering field, i.e. long-distance propagation of water waves and violent sloshing in a prismatic tank. SPH simulations were well validated through systematic comparisons with dedicated experiments for each problem. It was well demonstrated SPH has sufficient accuracy and is capable for practical uses in marine engineering field.

7.2 Future Works

Experimental validation of SPH for nonlinear free-surface flows in marine engineering was conducted for water waves and sloshing. Water wave is a promising problem for the SPH application but the method needs some improvement to apply in real engineering problems. A combined wavemaker and prescribed motion of the ship cannot be executed using the latest code of DualSPHysics. DualSPHysics can only be applied to external motion on one object; there is need to modify the code to apply to fluid–structure interaction problems, like a ship in waves.

Experimental validation of SPH for sloshing in the present study was limited to a single motion excitation, but in reality, at sea, there are combined motions such as sway and roll. Modification of the code is needed to address this phenomenon as well as ships in waves. A sensitive analysis is required, particularly for parameters in 3D and 2D sloshing. Coupling of the two-phase SPH sloshing and a mathematical model for ship motion should be completed for fully coupled ship–tank motions in the future.

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