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NUMERICAL MODELLING OF REGULAR WAVE PROPAGATION USING OpenFOAM

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Numerical Modelling of Regular Wave Propagation Using OpenFOAM

Dissertação apresentada para obtenção do grau Mestrado em Energia para a Sustentabilidade

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Resumo

Uma vez que o consumo de combustíveis fósseis provoca impactos ambientais críticos, o desenvolvimento das energias renováveis tem-se tornado uma prioridade em muitos países. Desta forma, as energias solar e do vento são comercializadas, enquanto a energia das ondas está ainda nos seus primeiros passos. A energia das ondas é uma ampla fonte de energia limpa, no entanto ainda muitas barreiras e obstáculos têm de ser ultrapassados para ser possível captar a potência real que se encontra armazenada nas ondas oceânicas. Nas décadas recentes, alguns protótipos de conversores de energia das ondas foram construídos e testados, todavia, quase todos foram destruídos passado algum tempo devido à sua incapacidade em resistir às condições adversas dos oceanos. Uma vez que os ensaios laboratoriais são bastante caros e morosos, actualmente é comum recorrer-se a simulações numéricas. Muitos investigadores desenvolveram o seu próprio tanque de ondas numérico com o intuito de avaliar o comportamento das ondas.

Esta dissertação de mestrado tem como objetivo desenvolver um tanque de ondas numérico para estimar a propagação de ondas regulares e o seu comportamento na interacção com o fundo do mar, usando a aplicação waves2Foam, desenvolvida no âmbito do software OpenFOAM. Para tal, três cenários e alguns sub-cenários são definidos com base nos diferentes tipos da teoria de Stokes aplicável a ondas. Os resultados mostram que o waves2Foam é capaz de simular relativamente bem todos os tipos de rebentamento de ondas, ainda que com algumas limitações. A reflexão das ondas na fronteira de saída foi relatada em muitos estudos, pelo que a aplicação waves2Foam possui um método de absorção chamado zona de relaxamento, que impede a reflexão das ondas a partir da fronteira de saída do tanque. Finalmente, os resultados do presente estudo demonstram que o waves2Foam é uma poderosa ferramentas para simulação numérica da propagação de ondas e sua absorção. Conclui-se ainda que o OpenFOAM tem algumas limitações, como por exemplo, é incapaz de simular ondas com declive superior a 0.05, casos em que foram observados alguns problemas tais como o amortecimento da onda.

Palavras-chave: quebra de onda, tanque de ondas numérico, OpenFOAM, ondas regulares, zona de relaxamento, teoria das ondas de Stokes, canal de ondas, waves2Foam

Abstract

As increase in consumption of fossil fuels causes crucial environmental impacts, renewable energy development has become the priority of many countries in the world. In this way, solar and wind energies are commercialized while ocean wave energy is still in its initial steps. Wave energy is a large source of clean energy but still many barriers and obstacles must be removed in order to capture the real power stored in the ocean waves. In previous decades, several prototypes of wave energy converters have been built and tested, but, almost all of them were destroyed after a while due to their incapability in coping with the harsh condition of the oceans. As laboratory experiments are very expensive and time consuming, today, numerical simulation is commonly used. Many researchers developed their numerical wave tank in order to evaluate behaviour of waves.

This master thesis aims to develop numerical wave tanks for assessing propagation of regular wave and its behaviour interacting with seabed using waves2Foam. To do so, three scenarios and some sub-scenarios are defined based on different types of Stokes wave theory. Reflection of the waves from outlet boundary was reported in many studies while waves2Foam is accompanied by an absorption method called relaxation zone which prevents reflection of the waves from outlet boundary of the numerical wave tank. Finally, the results of the present study demonstrate that waves2Foam is a powerful toolbox in numerical modelling of wave generation and absorption in numerical wave flumes and waves2Foam is capable to simulate all types of breaking waves as well. It is also concluded that, waves2Foam has some limitations, for instance, it is unable to simulate waves with steepness above 0.05 in which some problems such as damping of the wave have been observed.

Keywords: breaking waves, numerical wave tank, OpenFOAM, regular waves, relaxation zone, Stokes wave theory, wave flume, waves2Foam

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ρ – Density	[kg.m^{-3}]
U – Velocity Field	[m.s^{-1}]
u – Velocity component in x axis	[m.s^{-1}]
v – Velocity component in y axis	[m.s^{-1}]
w – Velocity component in z axis	[m.s^{-1}]
t – Time	[s]
p – Pressure	[Pa]
g – Acceleration gravity	[m.s^{-2}]
μ – Dynamic Viscosity	[Pa.s]
x – Longitudinal coordinate	[m]
y – Vertical coordinate	[m]
z – Transverse coordinate	[m]
α – Volume (phase) fraction	
ρ_w – Density of water	[kg.m^{-3}]
ρ_a – Density of air	[kg.m^{-3}]
L – Wavelength	[m]
H – Wave height	[m]
h - Water depth	[m]
φ – Velocity potential	
k – Wave number	Rad.m^{-1}
ω – Wave frequency	Rad.s^{-1}
η – Surface elevation	[m]
ξ – Surf similarity number	
ξ_0 – Surf similarity number for deep water region	
ξ_b – Surf similarity number at break point	
β – Beach slope angle	
L_0 – Deep water wavelength	[m]
T – Wave period	[s]
R – Wave run-up	[m]

$R_{2\%}$ - Wave Run-up happens 2% of the time [m]

C – Sea condition coefficient

p_0 – Total pressure [Pa]

List of Abbreviations

- OpenFOAM – Open Field Operation and Manipulation
- CFD – Computational Fluid Dynamics
- NWT – Numerical Wave Tank
- VOF – Volume of Fluid
- IB-VOF – Immersed Boundary-Volume of Fluid
- SWL – Still Water Level
- WECs – Wave Energy Converters
- NTS – Not to Scale

1 INTRODUCTION

Pollutant depletion and global warming caused by consumption of fossil energies have led researchers to find sustainable alternatives. Nowadays, renewable energy has become the top priority in most developed and some developing countries. There are various types of renewable energy with different capacity all over the world. In recent years, as wave energy has the highest potential in comparison with other renewables, it attracts more attention among the researchers and research institutes. However, there are still some technical issues and barriers which are required to be solved in order to get the real wave power. It is definitely crucial to design and construct sturdy wave energy converters which can cope with the harsh condition of the oceans (Du and Leung, 2011).

Since the 1970s, environmentalists tended to develop renewable energy with the aim of reducing environmental impact caused by fossil energy consumption, and also to decrease the dependency to oil. Large wind turbines appeared in that decade but solar systems was being used mainly for heating and cooling purposes for many years. Recently, renewable energy systems had started to be an alternative for fossil energy, and renewable energy has had a considerable sharing in energy production both the United States and Europe (Martinot and Sawin, 2009). Currently, wave energy attracts the attention of researchers due to its massive energy density which is the highest amount in comparison with other sources of renewables. Meanwhile, there are some technical issues which are required to be overcome to achieve the real amount of energy from waves (Du and Leung, 2011).

In the past, wave studies were based on experimental and physical models which were both time and cost consuming. Today, due to improvement and development of powerful computers and computational methods, numerical models are mostly used. Recently, many researchers have developed their numerical wave tanks to simulate ocean waves (Liu and Losada, 2002). Numerical models are still under development in order to become an appropriate alternative for laboratory experiments.

Numerical models are in fact mathematical models that use some sort of numerical time-stepping procedure (in transient studies) to obtain the models' behaviour over time. Numerical modelling is a powerful method of predicting and visualizing the dynamic behaviour of physical systems.

Computational fluid dynamics (CFD) software uses simplified equations but they will speed up the research as well as making it easier to study behaviour of wave and its behaviour when interacting with floating devices, sloped sea bed and also shore-based devices.

1.1 Goals and Objectives

This master thesis aims to present numerical modelling as a useful method to improve ocean wave technologies by developing numerical wave tanks to simulate how a regular wave will be propagated. It will help the ocean engineering science to see how waves will interact with wave energy converter devices as well as sea bed. To do so, computational fluid dynamics (CFD) software, known as OpenFOAM, is used to model the numerical wave tanks. The study can also demonstrate the capability of OpenFOAM, which is an open source software, in modelling regular waves.

Creating numerical wave tanks using OpenFOAM is not a new issue, as many researchers have already used it to simulate their numerical wave tanks such as Morgan et al. (2010); Afshar, (2010); Lambert (2012); Cao et al. (2011) and Higuera et al. (2013a). As aforementioned, this master thesis will show the capability of OpenFOAM to create numerical wave tanks in different scenarios and it will compare the obtained results with those from other studies. Actually in current study, the first three scenarios of Lambert (2012) will be modelled using a new toolbox (known also as “solver”) which was developed by OpenFOAM users, known as waves2Foam. The obtained results will be compared against the results of Lambert (2012) to see the differences of a pre-existing solver, called interFoam, and the newly developed solver.

1.2 Motivation

The worldwide energy demand scenario is rising continuously. As well known, resources of fossil energy are finite as well as they cause pollution and environmental impacts which has become a major public concern. These issues have encouraged the researchers and research institutes to develop sustainable energy technologies.

In this way, wind and solar technologies are now commercialized and distributed in the world. Other sources of renewable such as biomass, biofuels, geothermal, etc., have also some part of energy production sharing all over the world. Considering the huge amount of energy stored in ocean waves led me to conduct research in this area. According to the report by World Energy Council in 1999, the worldwide potential of wave energy is more or less 2 Terawatts (Thorpe, 1999).

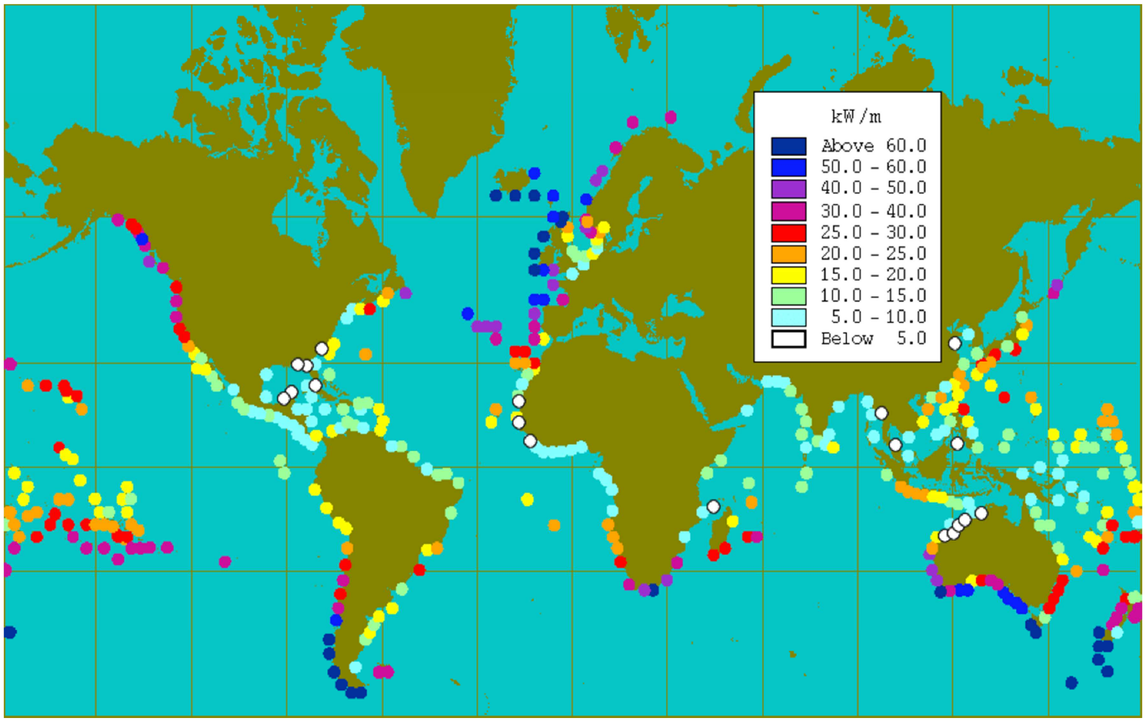

Figure 1 - Worldwide wave energy potential, (Source: Global Energy Network Institute, n.d.).

As it is shown in Figure 1, ocean waves have a huge potential of energy production all around the world. In some areas, the average amount of energy stored in wave exceeds 60 kW per meter; in winter, this amount may become more than two times and during storm it can be up to 1 MW per meter.

1.3 Thesis Structure

According to the goals and objectives, this master thesis is divided into six sections:

This first section introduces the dissertation topic as well as goals, objectives and motivation of the study and also the structure of the thesis.

The second section presents state of the art, including numerical wave tanks and OpenFOAM. Firstly, studies of experimental and numerical wave tanks are indicated and then more precisely, the references in which OpenFOAM is used as CFD software to develop numerical wave tanks are reviewed.

The third section presents the governing equations and wave theories used in this study such as Navier-Stokes equations that are used in OpenFOAM to model waves at the inlet of the numerical wave tank domain. Particle velocity equation, surface elevation equation, different breaking waves, surf similarity and wave run-up are discussed as well in this section.

The fourth section presents all the methodology used in this study to create the numerical wave tank. The geometries of different scenarios are defined and depicted. All input data such as wave characteristics and properties for all scenarios and physical properties of air and water are presented. In other words, all the pre-processing steps, such as mesh generation, definition of boundary conditions, definition of simulation control properties, as well as the post processing steps are presented in this section.

Section five shows, compares and discusses the results of the different scenarios defined in section four. The limitation and strength of the software, namely of the solver used in this study, are also presented.

As a conclusion, the last section presents a summary of the study and discusses if the goals and objectives of the study are met. This section also ends with some recommendation for further developing of the present study or suggestion for future one.

2 STATE OF THE ART

2.1 Numerical Wave Tanks

Wave tanks are types of laboratory sets which are used for creating experimental surface waves and studying waves' behaviour. They are usually rectangular shape box filled with water. An actuator is installed in the inlet to generate waves and at the outlet a wave absorbing system is installed to prevent wave reflection. Wave basin and wave flume are the two common types of wave tanks. Wave basin, which is both wide and long, is often used for testing ships; and wave flume, which is narrower and transparent, is often used for observing waves' behaviour (Wikipedia, 2013a). All scenarios of this master thesis are wave flumes that are numerically modelled. A lot of works have been carried out to study the ocean waves' behaviour while some of them are discussed in this section. For instance, Hsiao et al. (2008) presented a new laboratory experiment in which they made a super-tank for simulating breaking solitary waves on a low slope beach. They also studied the present methods to calculate breaking waves and their run-up.

Recently, many researchers have numerically developed their wave tanks because it is easier, cheaper and quicker. Numerical models can be created either based on Stokes wave theory or Boussinesq equations for simulating ocean waves. Using Stokes theory different types of waves can be modelled both in shallow water area and deep water area, while Boussinesq equations are suitable for modelling waves in shallow water area (Lambert, 2012). Note that, in this master thesis, for the first two scenarios Stokes first order wave theory is used while Stokes second order wave theory is used for all cases of third scenario.

Recently, both Orszaghova et al. (2012) and Chazel et al. (2010) have carried out studies in wave modelling based on Boussinesq equation. Chazel et al. (2010) developed their one dimensional model to simulate nonlinear dispersive regular wave propagation. They verified the model against the laboratory experiment data of Dingemans (1994) and finally they test the propagation of non-breaking irregular waves over a submerged bar by simulating the laboratory experiment of Becq-Girard et al. (1999). It is mentioned in their study that Boussinesq models are not capable to precisely simulate high waves. Orszaghova et al. (2012) also developed a numerical wave flume, as aforementioned based on Boussinesq theory and nonlinear sallow water equation. As some difficulties were found in modelling of breaking waves, they tried to do some additional modification. They successfully modify the Boussinesq model by adding hybrid models and so they were capable to simulate breaking waves.

Moreover, Ohyama et al. (1995) made an investigation on wave propagation based on different wave theories. They used fully nonlinear Stokes second order as well as Boussinesq theories. They presented in the paper that, the fully nonlinear theory has the best solution. They also mentioned that, second order theory was precise enough to simulate low amplitude waves and Boussinesq had the best projection of waves over the bar. It was also pointed out that, there was some overestimation in using Boussinesq. The work of Ohyama et al. (1995) is being used as a reference of validating numerical tanks in many other studies such as Shen and Chan (2011) that studied the behaviour of wave over a submerged bar using the combined IB-VOF (Immersed Boundary-Volume Of Fluid) model. Shen and Chan (2011) also compared the simulation results against experimental data of other researchers and it was concluded that, the simulated model is precise enough to provide prediction of the wave profile not only in shallow water with strong nonlinear effect but also in transmitted wave region with strong dispersion.

Experiment of Dingemans (1994) compared the Boussinesq models and laboratory measurements and it was based on the experiment made by Beji and Battjes (1993). Beji and Battjes (1993) performed a laboratory experiment to show the behaviour of waves passing over a submerged bar. The models used by these two studies are quite similar. These two studies are quite popular for validating the numerical wave tanks. Present master thesis uses the wave parameters of Beji and Battjes (1993) to validate the numerical wave tank. To do so, the executable tutorial developed by Jacobsen (2012a) in waves2Foam is used.

Furthermore, Koo and Kim (2007) developed their fully nonlinear two-dimensional numerical wave tank to study wave-body interactions for stationary surface-piercing. Stokes second order theory was used in this study and the results was validated against the laboratory experiment performed by Nojiri and Murayama (1975). Moreover, Zhan et al. (2010) developed their numerical wave tank using Navier-Stokes equation. They validated their model against Ohyama et al. (1995) by simulation of wave propagation over a submerged bar, wave run-up, wave refraction and diffraction. Senturk (2011) also used Stokes second order theory to study free surface waves. In his study, he made a comparison between analytical results and linear and nonlinear Stokes waves. Both Koo and Kim (2007) and Senturk (2011) also discussed about how to prevent reflection of waves from outlet boundary.

2.2 OpenFOAM

Open Field Operation And Manipulation, known as OpenFOAM, is an open source computational fluid dynamics package of C++ libraries and codes that are created to conduct numerical modelling of solid and fluid mechanics problems and it was first released in 2004 (OpenFOAM, 2013).

OpenFOAM is first and foremost a C++ library that is used to create applications. Applications are either solvers or utilities. Solvers that are each designed to solve a specific problem in computational continuum mechanics and utilities that perform simple pre-and post-processing tasks, mainly involving data manipulation and algebraic calculations (OpenFOAM, 2013). OpenFOAM is distributed with a large number of solvers and utilities to cover a wide range of problems. However, it is possible for users to write their own codes and solvers for their specific problems or to modify the existing solvers due to the open source nature of OpenFOAM. To do so, some pre-requisite knowledge of the underlying methods, physics and programming techniques is needed. It is also accompanied by some third party packages that provide valuable supports. Among them, a post-processing software, ParaView can be mentioned which is used for visualizing the field. Although for this master thesis ParaView is used for visualizing the results, OpenFOAM results can also be observed by other visualization software such as Tecplot. For this master thesis OpenFOAM released version 2.2.0 installed in Ubuntu 12.04 LTS operating system was used.

Nowadays, there are various articles in which OpenFOAM has been used to study behaviour of ocean waves. Afshar (2010) used OpenFOAM to develop his numerical wave tank to study fifth order waves. He simulated his model based on interFoam which is a solver for incompressible multiphase flows. He implemented relaxation method for both inlet and outlet boundary of the domain. By defining relaxation zones, it was presented that waves in the outlet of the domain are absorbed efficiently. Afshar (2010) validated his numerical wave tank against Whalin (1971), but the validating process was not complete because of some shortages and limitations of interFoam in version 1.6 of OpenFOAM which is solved in newer versions.

Morgan et al., (2010) used rasInterFoam solver to develop their numerical wave tank (numerical flume). The results were validated and compared against the experimental data of Dingemans (1994) . They presented that, rasInterFoam is capable to simulate Dingemans (1994)'s experimental model with a rational exactness. It was illustrated that the model works better in front face of the submerged breakwater rather than back face. Morgan et al. (2010) also studied different ways to prevent reflection from outlet boundary.

A two dimensional numerical wave tank has been developed based on Stokes second order theory by Li and Lin (2010). They also use OpenFOAM for modelling of a floating object within the numerical wave tank to study behaviour of waves interacting with the floating object. Li and Lin (2010) validated their results against Nojiri and Murayama (1975) and it was presented that, the results of the study was reasonably good comparing with the experimental results.

Cao et al. (2011) created their numerical wave tank based on Navier-Stokes theory and using OpenFOAM to study the wave run-up around a fixed vertical cylinder. They measured the maximum wave run-up and compared the result with a published experimental data. Their result can be useful for designing coastal structures and platforms. Higuera et al. (2013a) also conducted a research to study wave generation and absorption for Navier-Stokes wave theory.

Lambert (2012) developed a numerical wave tank based on Stokes second order theory using OpenFOAM. Different scenarios have been defined in her study to assess different types of waves as well as different types of breaking waves. Lambert (2012) verified the results of her study against Dingemans (1994). This master thesis will compare the present results of the third scenario against Lambert (2012)'s because the geometry of the third scenario in both studies are the same but different solver are used to simulate the models.

Higuera et al. (2013a) introduced OpenFOAM utilities and analysed the solvers relevant to free surface flow. They also discussed how to create a boundary condition for wave generation and absorption. They have validated their results against a laboratory experimental data in another study by the same authors. Higuera et al. (2013b) found that there is a good agreement between the simulation results and experimental results with regard to breaking of waves and its run-up. Higuera et al. (2013b) used the experimental result presented in Lara et al. (2012) to validate the numerical results obtained by Higuera et al. (2013a).

2.2.1 *waves2Foam*

waves2Foam is a toolbox recently developed by OpenFOAM users to simulate free surface wave generation and absorption (Jacobsen et al., 2012). A relaxation zone technique known as active sponge layer has been applied to the library as well as a large range of different wave theories. The base of this toolbox is interFoam while an active sponge layer zone defined as relaxation zone method has been added to the solver (OpenFOAMWiki, 2013a). Different types of waves such as current-type waves, regular waves, solitary waves, and irregular waves as well as a combined wave, a combination of the any other types, are defined in this library. Regular waves consist of Stokes first order wave theory (Airy wave), Stokes first order standing wave theory, Stokes second order wave theory, modulated Stokes second order wave theory, Stokes fifth order wave theory, First order cnoidal theory and Stream function wave theory (OpenFOAMWiki, 2013b). In this master thesis, Stokes first order wave theory is used for the first two scenarios and Stokes second order wave theory is used for the third scenario to make it comparable against the results obtained by Lambert (2012). waves2Foam also comes with some tutorials such as 3Dwaves, bejiBattjes, periodicSolitary, squarePile, standingWave and waveFlume. This powerful toolbox which is regularly updating, is available online on OpenFOAMWiki (2013a).

Although waves2Foam is newly introduced, many scientists developed their studies using this toolbox. Jacobsen et al. (2012), who are the developers of the toolbox, have implemented a C++ toolbox that has the ability to generate waves (not only wave propagation but also wave breaking) as well as the ability to absorb waves by applying a relaxation zone. In Jacobsen et al. (2012), rectangular and circular ring shape relaxation zones are defined and in is recommended that other shapes of relaxation zone can be easily modelled by modifying the code and programming. The result of the study is validated against the laboratory experiment carried out by Chapalain et al. (1992). Moreover, Ransley et al. (n.d.) published a poster in which they studied the development of open-source CFD software in modelling the interaction of waves and wave energy converters (WECs). They showed that waves2Foam is capable to simulate behaviour of waves interacting with WECs in addition to generate and absorb waves.

Seiffert and Ertekin (2012) developed their two dimensional numerical wave tank based on Navie-Stokes equation to simulate propagating of solitary and cnoidal waves over submerged bar. The result of their study was compared with a numerical model which was simulated based on a nonlinear wave theory for shallow water, known as Green-Naghdi theory. Both scenarios modelled within OpenFOAM but with different solvers and comparing results presented a good agreement between them. Moreover, another study carried out by Jensen et al. (2014), in which they conducted a numerical study using waves2Foam to investigate the porous media equations mentioned in different literature references. Finally it was concluded that, OpenFOAM is capable to predict the interaction between waves and structures. Due to the result of their study, they have recently added a new tutorial into their toolbox.

In current study, waves2Foam is used to simulate the models while Lambert (2012) used interFoam, so finally, a comparison will be made between the results of present study and those from Lambert (2012). As the capability of OpenFOAM to simulate wave behaviour and its interaction with WECs has been already proved, this master thesis aims to simulate waves using wave2Foam toolbox and check the result against those presented by Lambert (2012). In section five, some new sub-scenarios are defined as well, in order to demonstrate the capability of waves2Foam. The version OpenFOAM release 2.2.0 and waves2Foam r2025 are used in the context of this present master thesis.

3 GOVERNING EQUATIONS AND WAVE THEORIES

Fenton (1990) introduced and explained different types of wave theories and made a comparison between them. There are various types of wave theories but Navier-Stokes equations are basically used by OpenFOAM which are described as below:

$$\rho\left(\frac{\partial u}{\partial t}+u\,\frac{\partial u}{\partial x}+v\,\frac{\partial u}{\partial y}+w\,\frac{\partial u}{\partial z}\right)= -\frac{\partial p}{\partial x}+\,\mu\,\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\,\rho g_x \quad (1)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\,\frac{\partial v}{\partial x}+v\,\frac{\partial v}{\partial y}+w\,\frac{\partial v}{\partial z}\right)= -\frac{\partial p}{\partial y}+\,\mu\,\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\,\rho g_y \quad (2)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\,\frac{\partial w}{\partial x}+v\,\frac{\partial w}{\partial y}+w\,\frac{\partial w}{\partial z}\right)= -\frac{\partial w}{\partial z}+\,\mu\,\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\,\rho g_z \quad (3)$$

Where ρ represents density in [kg.m^{-3}], t represents time in [s], p represents pressure in [Pa], g represents acceleration gravity in [m.s^{-2}], μ represents dynamic viscosity in [Pa.s] and u, v and w represent velocity components in x, y and z directions, respectively in [m.s^{-1}].

As the flow in considered incompressible, ρ is constant so the continuity equation that must be satisfied is as below:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Volume of fluid (VOF) is a numerical method for tracking and locating free surface which is the interface of air and water in the present study (Wikipedia, 2013b). This method is used by OpenFOAM to specify the fraction of each fluid (air and water) in each cell. The volume (phase) fraction equation is presented below in which α represents the volume (phase) fraction, t represents time and U refers to velocity. α is always between 0 and 1. $\alpha=0$ means the cell is fully filled by air and $\alpha=1$ means the cell is only filled by water.

$$\frac{\partial \alpha}{\partial t}+\nabla.(\alpha U)=0 \quad (5)$$

The density of each cell can be calculated by the following equation, where ρ_w is the water density and ρ_a is the air density:

$$\rho = \alpha\rho_w + (1 - \alpha)\rho_a \tag{6}$$

Note that this density is the density of the mixture of air and water inside each cell.

3.1 Stokes First Order Wave Theory

Stokes first order wave or airy wave theory refers to a linear wave theory which is used for modelling of gravity waves on the surface of a fluid. Stokes first order wave theory is used in coastal and ocean engineering for simulating waves' behaviour. This theory is also used for simulating tsunami waves before reaching the coastal area. Airy wave theory has usually been used for estimation of wave characteristics. The results of this linear theory would be accurate not only for shallow water region with a small fraction of wave height and water depth but also for deep water area with a small fraction of wave height and wavelength. This theory is applied on the first two scenarios.

3.2 Stokes Second Order Wave Theory

There are various types of wave equations and theories used in development of numerical wave tank which are already mentioned in state of the art (see section 2). Among all the theories, Stokes wave theory has been often applied to the studies which investigating behaviour of waves. Stokes second order wave theory refers to a non-linear theory which is used for modelling of periodic regular free surface waves. Stokes second order wave theory is generally used for simulation of the interaction between waves and structures (both shore-based and off-shore). They are applied on the studies in order to specify wave behaviours such as free surface elevation and flow particle velocity. As Stokes theory does not work well for shallow water, it is mostly used for deep water and medium depth areas while for shallow water cnoidal theory provides more accurate estimation.

Shallow water waves are defined as waves with $\mathrm{h/L} < 1/20$ and deep water waves are defined as waves with $\mathrm{h/L} \geq 1/2$. The Ursell number which is derived from Stokes wave expansion indicates the nonlinearity of long surface gravity waves on a fluid layer. This parameter which has been developed by Ursell (1953) can be used for checking the applicability of using Stokes second order wave theory. As it is important to check the applicability of second order wave theory, present master thesis checked the eligibility of using Stokes second order against the following equation and it was satisfied by all cases of third scenario and sub-scenarios in which Stokes second order theory is used.

$$\frac{L^2 H}{h^3} < \frac{8\pi^3}{3} \tag{7}$$

There are also different orders of Stokes theory such as fifth order. As pointed out in previous section, Stokes second order theory is commonly used in the literature due to complexities of fifth order as well as its well approximation and accuracy in the results. Stokes second order theory is used in different forms by many studies such as Ohyama et al. (1995); Koo and Kim (2007); Zhan et al. (2010); Li and Lin (2010); Senturk (2011) and Lambert (2012). This master thesis follows the form used by Lambert (2012).

3.2.1 Particle Velocity Equation

Particle velocity is the velocity of a particle which is transferred by a wave. The particle velocity according the Stokes second order theory is given as below:

$$\begin{aligned} u = -\frac{\partial\varphi}{\partial x} = \frac{H}{2}\frac{gk}{\omega}\frac{\cosh k(h+y)}{\cosh kh}\cos(kx-\omega t) \\ + \frac{3}{16}\frac{H^2\omega k \cosh 2k(h+y)}{\sinh^4 kh}\cos 2(kx-\omega t) \end{aligned} \tag{8}$$

$$\begin{aligned} v = -\frac{\partial\varphi}{\partial y} = \frac{H}{2}\frac{gk}{\omega}\frac{\sinh k(h+y)}{\cosh kh}\sin(kx-\omega t) \\ + \frac{3}{16}\frac{H^2\omega k \sinh 2k(h+y)}{\sinh^4 kh}\sin 2(kx-\omega t) \end{aligned} \tag{9}$$

u is the horizontal component of particle velocity and v is the vertical component. Both u and v are partial derivatives of velocity potential φ. H represents the wave height from peak to trough in [m], g represents acceleration due togravity in [m.s^{-2}], h represents water depth in [m] while y is the vertical coordinate to describe wave motion (the points in which $y = 0$ makes a line known as still water level). t represents time in [s], x represents the distance along longitudinal direction in [m], ω represents the frequency of the wave in [Rad.s^{-1}] and k represents the wave number in [Rad.m^{-1}]. ω and k are defined in following equations in which L is the wavelength in [m].

$$\omega = (gk\, tanh\, kh)^{1/2} \tag{10}$$

$$k = \frac{2\pi}{L} \tag{11}$$

3.2.2 Surface Elevation Equation

In waves based on Stokes second order theory, the following equation, known as surface elevation equation, shows the displacement of water surface from still water level (SWL). The result of the numerical model developed in present study is validated against the analytical result of surface elevation equation.

$$\eta = \frac{H}{2}\, cos(kx - \omega t) + \frac{H^2 k}{16}\, \frac{cosh\, kh}{sinh^3\, kh}\, (2 + cosh\, 2kh\,)cos\, 2(kx - \omega t) \tag{12}$$

3.3 Breaking Waves and Surf Zone

A breaking wave is a water surface wave that its amplitude reaches a critical point which causes the crest of wave breaks and comes down (Wikipedia, 2013c). Waves will break both in shallow and deep water but the reason of breaking of wave in shallow water and deep water is completely different. In shallow water breaking of the waves is due to reaching shallower area (the beach) and also because wave heights are greater than before in this region while in deep water, breaking of waves is because of hydrodynamic instability (Lambert, 2012).

The region near the beach where wave breaks is called surf zone. The study will show that OpenFOAM has the ability to model the waves in surf zone considering a parameter called surf similarity, which can specify the type of breaking waves as well as wave run-up. As pointed out in Sarpkaya and Isaacson (1981), there are four types of breaking waves. All types of breaking waves are listed and briefly explained in following.

3.3.1 Spilling Waves

When the sea bed has a soft slope approaching the beach, the wave breaking type would be spilling. Spilling waves breaking time is quite longer than other breaking types. Figure 2 shows propagation of the spilling wave.

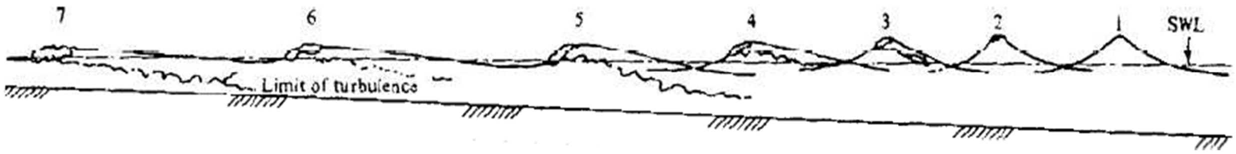

Figure 2 - Spilling wave breaking (numbers present the steps of breaking), (Source: Richardson, 1996).

3.3.2 Plunging Waves

When the sea bed has steeper slope or a sudden depth changes approaching the beach, the crest of waves curls and breaks down. This type of breaking is called plunging. Plunging waves generally break with more energy comparing with spilling waves. Figure 3 shows propagation of the plunging wave.

Figure 3 - Plunging wave breaking (numbers present the steps of breaking), (Source: Richardson, 1996).

3.3.3 Surging Waves

When the sea bed has a very steep slope approaching the beach the crest of the wave keep going without breaking and finally a small breaking will happen with a little foams and bubbles. This type of breaking usually occurs in areas with a narrow surf zone. Figure 4 shows propagation of the surging wave.

Figure 4 - Surging wave breaking (numbers present the steps of breaking), (Source: Richardson, 1996).

3.3.4 Collapsing Waves

"Collapsing waves are a cross between plunging and surging, in which the crest never fully breaks, yet the bottom face of the wave gets steeper and collapses, resulting in foam" (Wikipedia, 2013c). Figure 5 shows propagation of the collapsing wave.

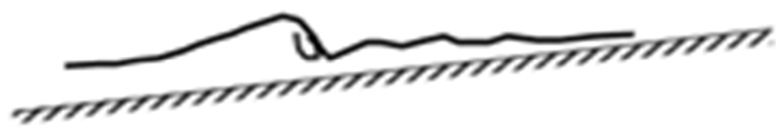

Figure 5 - Collapsing wave breaking, (Source: Wikimedia, 2011).

3.4 Surf Similarity

The Iribarren number or the surf similarity number is a dimensionless number for specifying the type of gravity wave breaking approaching to surf zone and sloping beach (Iribarren and Nogales, 1949). This parameter was first introduced by those authors and the number is defined as the following equation:

$$\xi = \frac{tan\,\beta}{\sqrt{\frac{H}{L_0}}} \tag{13}$$

Also L_0 , deep water wave length, can be defined as below:

$$L_0 = \frac{g}{2\pi}T^2 \tag{14}$$

By integrating equation 14 and equation 15, the surf similarity number can be defined as followings:

$$\xi_0 = \frac{tan\,\beta}{\sqrt{\frac{2\pi H_0}{gT^2}}} \qquad or \qquad \xi_b = \frac{tan\,\beta}{\sqrt{\frac{2\pi H_b}{gT^2}}} \tag{15}$$

where ξ_0 represents surf similarity number for deep water region while ξ_b represents surf similarity number at break point, β represents the bed slope angle in [degree], H_0 represents the deep water wave height while H_b represents the wave height at break point both in [m], L_0

represents the deep water wave length in [m], T represents period in [s] and g is gravity acceleration in [m.s^{-2}].

Table 1 shows different types of breaking waves using surf similarity number which were presented by Battjes (1974).

Table 1 – Surf similarity approximation for distinguishing breaking type (Battjes, 1974).

Breaking Type	$\boldsymbol{\xi_0}$	$\boldsymbol{\xi_b}$
Surging or Collapsing	$\xi_0 > 3.3$	$\xi_b > 2$
Plunging	$0.5 < \xi_0 < 3.3$	$0.4 < \xi_b < 2$
Spilling	$\xi_0 < 0.5$	$\xi_b < 0.4$

3.5 Wave Run-up

Wave run-up is the vertical distance between the point a broken wave reaches and still water level (SWL) as shown in Figure 6. By calculating wave run-up (R), it would be easier to predict floods and erosions.

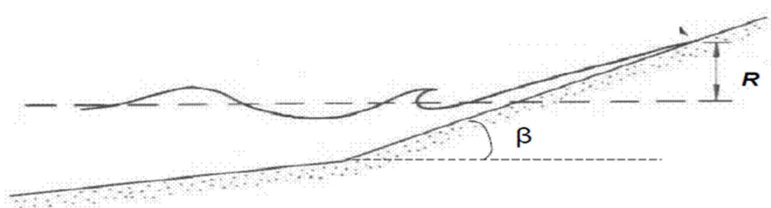

Figure 6 – Wave run-up (Source: Heimerl and Wisniewski, 2008).

Two percent wave run-up ($R_{2\%}$) is the wave run-up that only will occur in two percent of observed run-ups. The first equation for calculating of wave run-up was presented by Hunt (1959) and then it was reformed as below by Battjes (1974).

$$R_{2\%} = HC\xi_0 \tag{16}$$

in which C is a coefficient related to the sea condition, it was mentioned in Van der Meer and Stam (1992) that, the coefficient varies between 1.49 (developed sea) and 1.87 (young sea). Van der Meer and Stam (1992) also pointed out that the $R_{2\%}$ equation is only valid for plunging wave breaking.

4 METHODOLOGY

As aforementioned, this master thesis pursue the works done by Lambert (2012) in order to present the differences between doing the same model simulation with two different solvers. Lambert (2012) has used interFoam which is a pre-existing solver in OpenFOAM while present study uses waves2Foam, which is a toolbox developed by OpenFOAM users mostly by modifying interFoam.

4.1 Definition of Scenarios

This master thesis aims to model the first three scenarios modelled by Lambert (2012) and make a comparison between results. It should be indicated that, OpenFOAM works with three dimensional coordinate while this study uses two dimensional. Note that all domains simulated in scenarios have a thickness of 0.01 meter in z direction (this size is irrelevant to simulation as it is considered to be two dimensional). The scenarios modelled in this study are listed as below:

1. Basic flat-bottom numerical wave tank;
2. Validation tank against the laboratory experiments carried out by Beji and Battjes (1993);
3. Sloped numerical wave tank.

4.1.1 Basic Flat-bottom Numerical Wave Tank

Figure 7 shows a schematic view of the first scenario geometry.

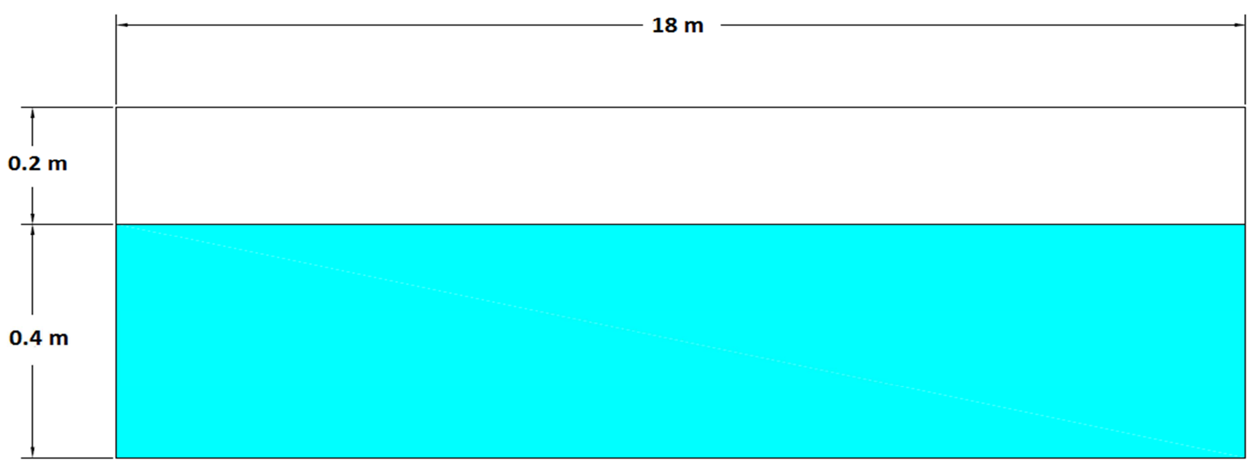

Figure 7 – Geometry of scenario 1 (not to scale (NTS)).

4.1.2 Validation Wave Tank

Figure 8 shows a schematic view of second scenario which is the validation tank based on Beji and Battjes (1993)'s experimental model developed by Jacobsen (2012a). The gauges which are used to report surface elevation are also depicted. Moreover, the accurate position of each gauge is presented in table 2.

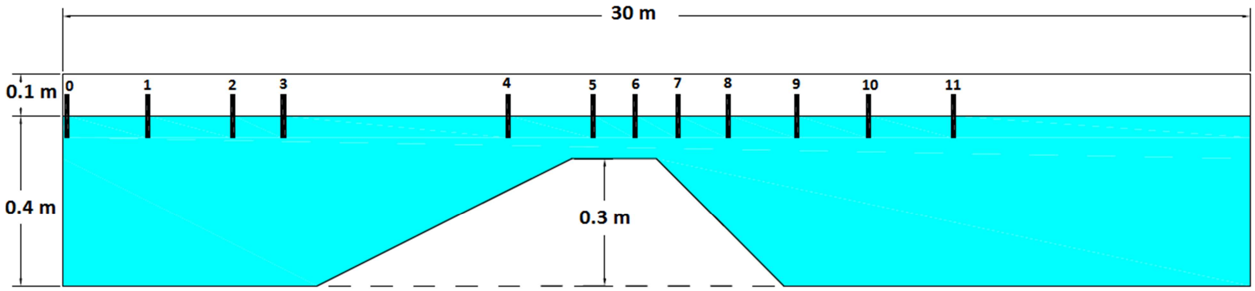

Figure 8 – Geometry of scenario 2 (NTS).

Table 2 – Position of validation tank gauges.

Gauge Number	Position [m]
0	0.1
1	2
2	4
3	5.2
4	10.5
5	12.5
6	13.5
7	14.5
8	15.7
9	17.3
10	19
11	21

Table 3 – Complementary coordinates of scenario 2.

$\boldsymbol{x}\ [\boldsymbol{m}]$	$\boldsymbol{y}\ [\boldsymbol{m}]$
0	-0.4
6	-0.4
12	-0.1
14	-0.1
17	-0.4
30	-0.4

4.1.3 Sloped Numerical Wave Tank

This scenario is implemented for simulation of breaking waves. To do so, this scenario is divided to three different models where each one simulates one type of wave breaking. Note that this scenario models exactly the same cases previously modelled by Lambert (2012) by using interFoam to compare the results of wave breaking. However, in the present study, waves2foam is used for the simulations. Scenario 3A intends to simulate a spilling wave breaking, scenario 3B simulates a plunging wave breaking and in scenario 3C a surging wave breaking is simulated. As discussed before, the breaking type depends on the slope of sea bed, so different slopes are considered for scenarios 3A, 3B and 3C which are indicated by β_1, β_2 and β_3 respectively. Scenarios 3A, 3B and 3C are shown in Figures 9, 10 and 11, sequentially.

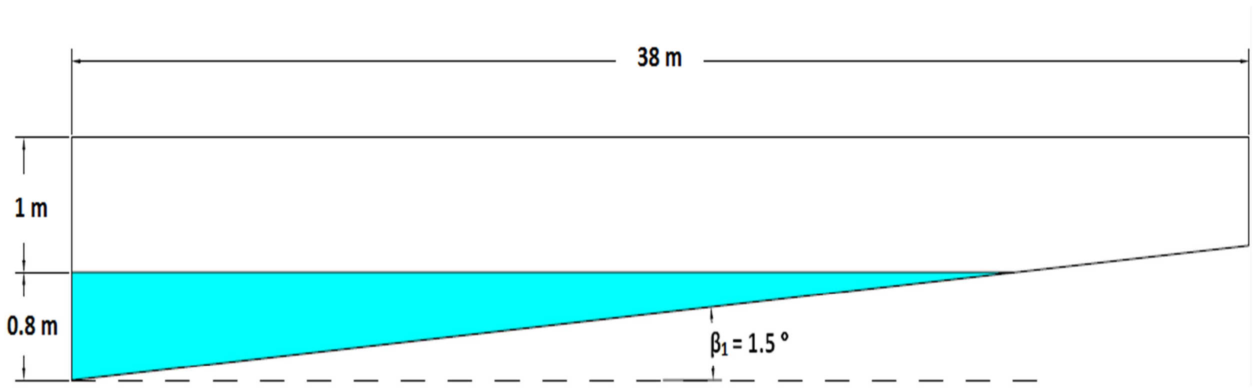

Figure 9 – Geometry of scenario 3A, $\boldsymbol{\beta_1 = 1.5}$° (NTS).

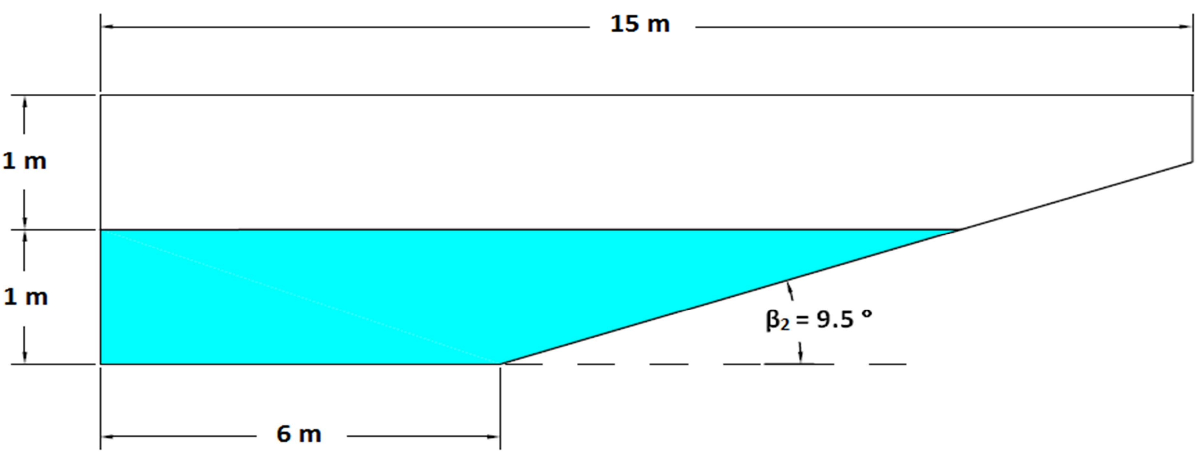

Figure 10 - Geometry of scenario 3B, $\boldsymbol{\beta_2 = 9.5}$° (NTS).

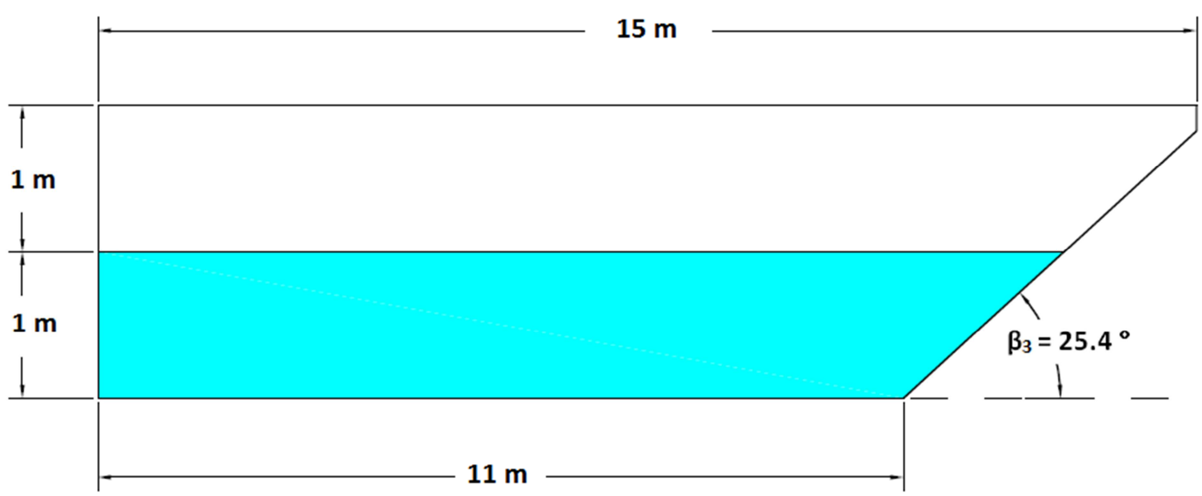

Figure 11 - Geometry of scenario 3C, $\boldsymbol{\beta_3 = 25.4}$° (NTS).

4.2 Mesh Generation

OpenFOAM comes with two utilities for generating of mesh. The blockMesh utility is used for generating of simple hexahedral mesh while snappyHexMesh is used for complex hexahedral meshes as well as split- hexahedral meshes. OpenFOAM has also the capability to convert meshes which have been already created in other software (third-parties) to a readable format (OpenFOAM, 2013).

For this master thesis, the BlockMesh utility is used for generating meshes for scenarios 1 and 3 while snappyHexMesh is used for validation tank by Jacobsen (2012a). In blochMeshDict file of all scenarios, the uniform grading is considered. The following table shows the mesh size of each scenario.

Table 4 - Mesh size for each scenario.

Scenario	Cell size in x direction [m]	Cell size in y direction [m]
1	0.05	0.01
2	0.01	0.01
3A	0.04	0.01
3B	0.04	0.02
3C	0.04	0.02

Note that, in all scenarios, each cell has a thickness of 0.01 in z direction.

4.3 Input Data

This section presents all data used as inputs for the simulation processes.

4.3.1 Wave Characteristics

The characteristics of waves used in scenarios are presented in table 4.

Table 5 – Wave Parameters for each scenario.

Scenario	Wave Length (L) [m]	Wave Height (H) [m]	Steepness (H/L)	Period (T) [s]	Water Depth (h) [m]
1	3.695	0.1	0.027	2	0.4
2	3.737	0.02	0.00535	2.02	0.4
3A	5	0.2	0.04	2.05	0.8
3B	5	0.2	0.04	1.94	1
3C	5	0.1	0.02	1.94	1

4.3.2 *Physical Properties*

The physical properties that are used in this study are presented in table 5.

Table 6 – Physical properties.

Property		Value
Acceleration gravity (g) [m.s^{-2}]		9.81
Density (ρ) [kg.m^{-3}]	Water	1000
	Air	1.2
Kinematic Viscosity (μ) [m^2.s^{-1}]	Water	10^{-6}
	Air	1.48×10^{-5}
Surface Tension (σ) [N.m^{-1}]		0.07

4.4 Boundary Condition

In numerical modelling, in order to simulate the behaviour of wave in a numerical wave tank, appropriate boundary condition must be applied. A numerical wave tank has five boundaries which are inlet, outlet, bottom, atmosphere and frontAndBack (Lambert, 2012). As it was already mentioned, in this study, all the cases are assumed as two dimensional. To do so, both front and back are considered “empty”. Note that, in scenario 2 and 3 the sloped parts of geometry are included in bottom boundary. The boundary conditions used in this master thesis is briefly described below according to the definition in OpenFOAM (2013):

- fixedValue means the value of the parameter is specified;
- zeroGradient means the normal gradient of the parameter is zero;
- totalPressure means the amount of total pressure (p_0) is fixed, so due to the total pressure equation ($p_0 = p + \frac{1}{2}\rho|U|^2$), by changing the amount of U, p will change accordingly;
- inletOutlet switches U and p between fixedValue and zeroGradient according to the direction of U;
- pressureInletVelocity uses when p is specified at inlet and U will be calculated from the flux normal to the patch;
- pressureInletOutletVelocity is the combination of last two boundary conditions.

4.4.1 inlet Boundary

The inlet boundary of the wave tank is the boundary in which wave should be created. There are two methods for generating waves in OpenFOAM. One is using piston-type wave maker as used in experimental wave tanks and the other one is implementation of moving boundary (Lambert, 2012). OpenFOAM consist of various pre—existing boundary condition such as fixedValue and zeroGradient but they are not appropriate ones to be used in this case. Also OpenFoam users developed a boundary condition, known as groovyBC, to be used for generating a wave in the inlet of numerical wave tanks. This boundary condition let the users to write the equations. For instance, Lambert (2012) used groovyBC boundary condition for velocity to implement the particle velocity equation and also for volume fraction to implement the surface elevation equation at the inlet. However, waves2Foam comes with moving boundary conditions for velocity field and volume fraction field such as waveVelocity in which particle velocity and waveAlpha in which surface elevation equation have been already implemented based on chosen wave theory. These boundary conditions are considered for velocity field and volume fraction respectively. Also a zeroGradient boundary condition is considered for pressure field.

4.4.2 outlet Boundary

The outlet is the boundary that wave passes and exits the domain. The problem that many studies faced with is the reflection of waves from outside in the outlet boundary. As indicated in state of the art (see section 2), studies such as Koo and Kim (2007); Morgan et al. (2010); Afshar (2010); Senturk (2011) and Lambert (2012) discussed this problem in their studies. Some methods proposed by them are listed and briefly explained as follow:

- Numerical damping, which is modification of momentum equation of the solver by adding a coefficient;
- A beach, which is a secondary structure installed at the end of the wave tank to absorb the energy of the waves;
- A sponge layer, which is a porous material installed at the end of the tank to absorb the energy of the waves;
- Increasing mesh size at the end of the tank, which will cause waves dissipation.

Morgan et al. (2010) tried the aforementioned methods and they all showed a longer runtime. Finally they prevent reflection by extending the length of the numerical models to double size. Also Lambert (2012) have used the same methodology to prevent reflection. In present study the relaxation zone method is used to prevent reflection of waves from outlet boundary for scenario 1 and scenario 2; also in scenario 2 the length of the tank is extended as well in order to prevent reflection. Note that, for the volume fraction and the pressure field zeroGradient boundary condition is considered while for the velocity field fixedValue boundary condition is considered.

4.4.3 bottom Boundary

The bottom is the boundary located at the bottom part of the wave tanks. For the velocity field fixedValue boundary condition is considered while for the volume fraction and the pressure field zeroGradient boundary condition is considered. Note that, for the scenario 2 and scenario 3 the sloped parts of the numerical wave tanks are also a part of bottom boundary.

4.4.4 atmosphere Boundary

The atmosphere boundary condition is the boundary of numerical wave tank which has interface with the air. For the velocity field pressureInletOutletVelocity boundary condition is considered, for the volume fraction inletOutlet boundary condition is considered and for the pressure fields totalPressure boundary condition is considered.

Table 6 summarize the boundary conditions applied to each boundary in all fields.

Table 7 – Summary of boundary conditions.

Boundary	**alpha1**	**P-rgh**	**U**
inlet	waveAlpha	zeroGradient	waveVelocity
outlet	zeroGradient	zeroGradient	fixedValue
bottom	zeroGradient	zeroGradient	fixedValue
atmosphere	inletOutlet	totalPressure	pressureInletOutletVelocity
frontAndBack	empty	empty	empty

4.5 Post-processing of the results

As mentioned before, OpenFOAM is accompanied by some third party packages that provide valuable supports. For post-processing, the software called ParaView comes with the OpenFOAM for visualization of the results in graphic and animation formats. Also the results can be exported to the other visualization software such as Tecplot. In this master thesis, ParaView is used in order to post-processing of all the results.

5 RESULT AND DISCUSSION

5.1 Scenario 1: Basic Flat-bottom Numerical Wave Tank

As mentioned in section 4, for this scenario the waveFlume tutorial made by Jacobsen (2012b) is used to show the capability of waves2Foam in simulating of the basic numerical wave tank within the OpenFOAM. The results of simulation were already verified against the theoretical results. Figure 12 and Figure 13 illustrate a section view of the wave propagation inside the wave flume modelled in waves2Foam toolbox. Note that waveAlpha boundary condition is used in the inlet to produce waves.

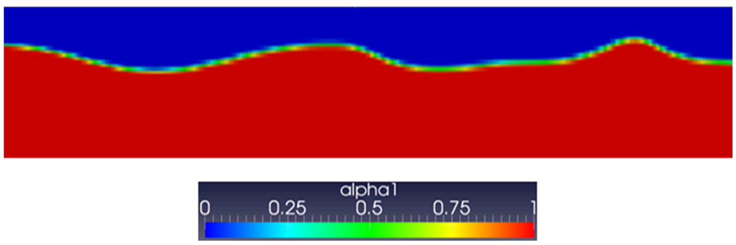

Figure 12 – Wave flume based on Stokes first order wave theory, Volume Fraction (alpha1) field at $\mathbf{t = 16s}$ (propagation direction is from left to right).

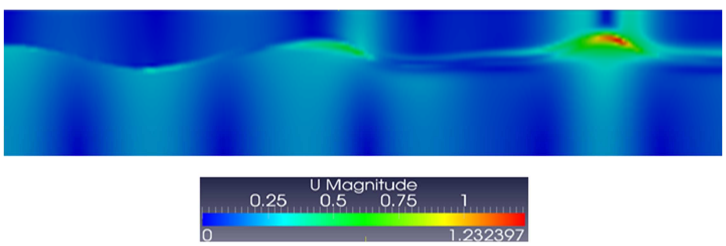

Figure 13 – Wave flume based on Stokes first order wave theory, Velocity (U) field at $\mathbf{t = 16s}$ (propagation direction is from left to right).

The visualization of the results specifies that waves2Foam present the result well. Comparing them with the result obtained by Lambert (2012) shows that waves2Foam simulate the wave propagation quite the same as interFoam. It should be mentioned that Lambert (2012) used GroovyBC boundary condition in which, she wrote the particle velocity and surface elevation equation while waves2Foam uses pre-defined boundary condition in which, these equations are already programmed.

In this scenario Stokes first order wave theory is used to simulate the wave behaviour in the wave flume. In order to compare the result of this scenario by changing the wave theory, two sub-scenarios are defined to simulate the same geometry and wave parameters using Stokes second order wave theory and Stokes fifth order wave theory. Figure 14 and Figure 15 show the volume fraction field and velocity field of the wave flume simulated based on Stokes second order wave theory.

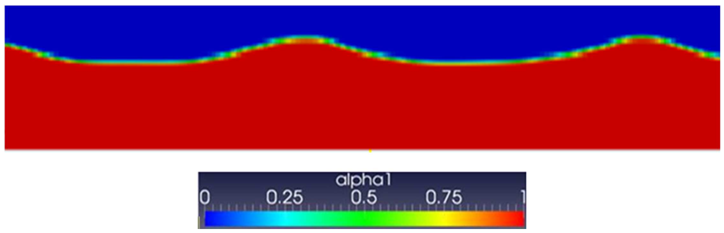

Figure 14 - Wave flume based on Stokes second order wave theory, Volume Fraction (alpha1) field at $\mathbf{t = 16s}$ (propagation direction is from left to right (sub-scenario 1.1)).

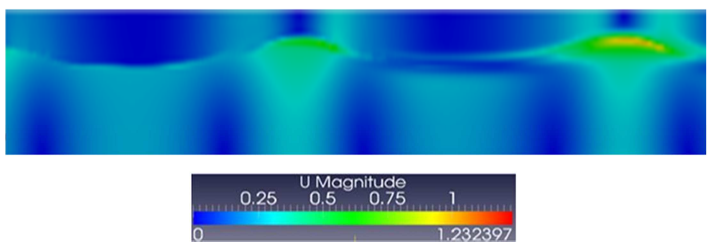

Figure 15– Wave flume based on Stokes second order wave theory, Velocity (U) field at $\mathbf{t = 16s}$ (propagation direction is from left to right (sub-scenario 1.1)).

Figure 16 and Figure 17 show the volume fraction field and velocity fields of the wave flume simulated according to Stokes fifth order wave theory. These two sub-scenarios are defined in order to indicate that waves2Foam has the capability of simulating waves based on complex wave theories such as Stokes fifth order.

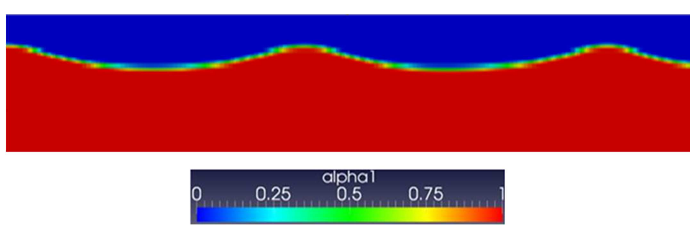

Figure 16– Wave flume based on Stokes fifth order wave theory, Volume fraction (alpha1) field at $\mathbf{t = 16s}$ (propagation direction is from left to right (sub-scenario 1.2)).

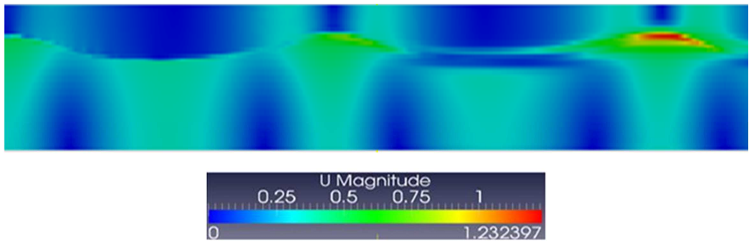

Figure 17– Wave flume based on Stokes fifth order wave theory, Velocity (U) field at $\mathbf{t = 16s}$ (propagation direction is from left to right (sub-scenario 1.2)).

Note that these two sub-scenarios have the same geometry and wave properties of the scenario one (except the wave theory) and all the figures only show a section view of the wave flumes at $t = 16s$.

Furthermore, another sub-scenario (sub-scenario 1.3) is defined in order to show the importance of implementing relaxation method that actually works like an active sponge layer to prevent wave reflection at the outlet boundary. To do so, in this sub-scenario the relaxation zone is removed from the scenario one. The results depicted in Figure 18 shows the comparison between the wave flume with implemented relaxation zone and the sub-scenario in which the relaxation zone is removed.

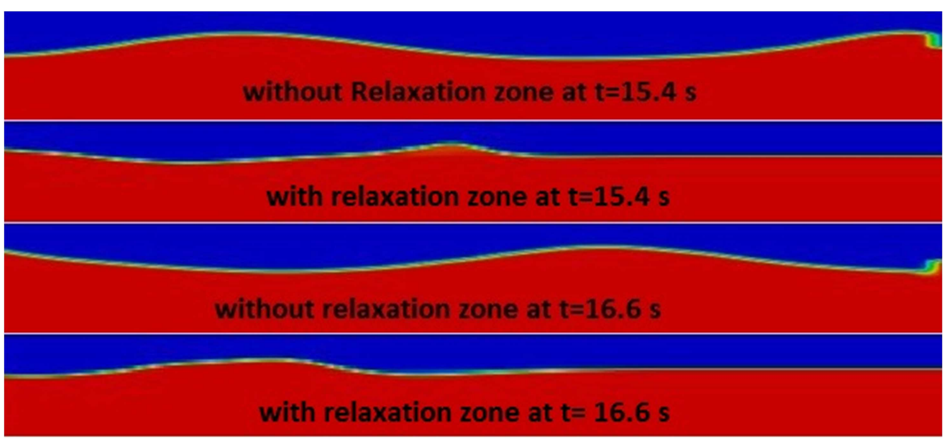

Figure 18 – Influence of implementing relaxation zone at the outlet boundary of wave flume (propagation direction is from left to right) (sub-scenario 1.3).

Figure 18 shows only a focused part of the end of the wave flume in which the influence of relaxation zone is depicted. As shown, the relaxation zone causes absorption of the waves at the outlet boundary and prevents reflection of the wave while the sub-scenario in which relaxation zone is removed apparently shows the reflection. This reflection influences the study and causes lots of mistakes in simulation. Therefore, it can be concluded that, relaxation zone method makes numerical simulation of waves more precise by preventing reflection of the waves from outlet boundary.

Some references such as Lambert (2012); Morgan et al. (2010) and Afshar (2010) have already discussed some limitation of OpenFOAM in simulating of waves. For instance, Lambert (2012) reported some limitation of OpenFOAM in simulating of wave with steepness more than 0.05 which are listed below:

- Simulation surface elevation does not match the ideal surface elevation curve.
- Damping of the waves
- Breaking of the waves (in steepness less than critical steepness)

The expression developed by Fenton (1990) shows the upper limit of wave steepness in which a wave breaks in deep water area.

$$\left(\frac{H}{L}\right)_{max} = \frac{0.141063 + 0.0095721\left(\frac{L}{h}\right) + 0.0077829\left(\frac{L}{h}\right)^2}{1 + 0.0788340\left(\frac{L}{h}\right) + 0.0317567\left(\frac{L}{h}\right)^2 + 0.0093407\left(\frac{L}{h}\right)^3} \tag{17}$$

In order to check the capability of waves2Foam two more sub-scenarios are defined to simulate waves within the wave flume based on the wave parameters indicated in table 8:

Table 8 – Wave parameters for sub-scenarios 1.4 and 1.5.

Sub-scenario	**Wave Length (L) [m]**	**Wave Height (H) [m]**	**Steepness (H/L)**	**Period (T) [s]**	**Water Depth (h) [m]**
1.4	2	0.2	0.1	2	1
1.5	2	0.3	0.15	2	1

Sub-scenario 1.4 is defined with the aim of assessing the capability of waves2Foam in correctly simulating of waves with steepness of 0.1. Figure 19 shows damping of the wave after one wavelength which is due to the incapability of waves2Foam in simulation of waves with steepness above 0.05.

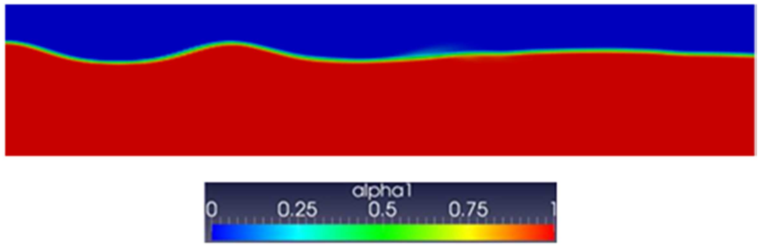

Figure 19 – Damping of wave with steepness of (H/L = 0.1) at $\mathbf{t = 20s}$ (sub-scenario 1.4).

Lambert (2012) also reported breaking of the wave with steepness of 0.1, i.e., smaller than critical breaking steepness (equal to 0.14) while in sub-scenario 1.4 only damping of the wave was witnessed. According the expression developed by Fenton (1990) (see equation 17), this wave must only break with steepness above 0.14, as indicated before. Moreover, in order to show if the wave breaks with steepness above the critical steepness, sub-scenario 1.5 is defined. The only difference of these last two sub-scenarios is the wave height, which is modified to obtain a steepness of 0.15 (see table 8). Figure 20 reveals again the limitation of waves2Foam in properly simulating sub-scenario 1.5.

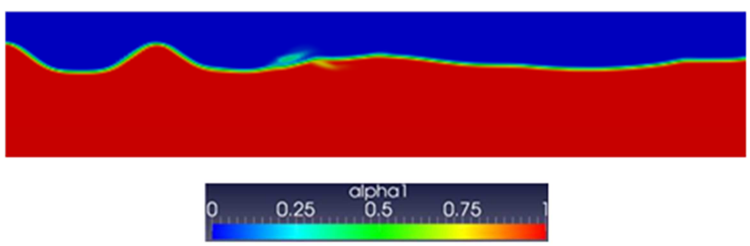

Figure 20 - Damping of wave with steepness of (H/L = 0.15) at $\mathbf{t = 20s}$ (sub-scenario 1.5).

Damping of the wave is observable, while it is accompanied with small breaking. The breaking can be seen during damping of the wave which is acceptable (see Figure 21). Nevertheless, it can be mentioned that, although waves2Foam works better than interFoam, there are still some limitations in waves2Foam in simulating of waves, especially waves with steepness above 0.05.

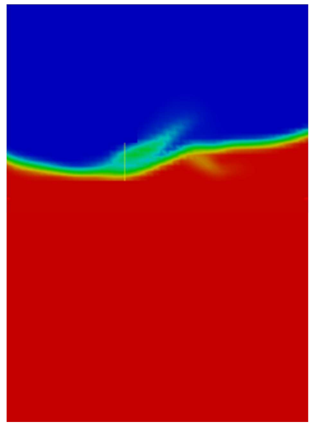

Figure 21 – Small breaking of wave with steepness of (H/L = 0.15) during wave damping (sub-scenario 1.5).

5.2 Scenario 2: Validation Wave Tank

In order to validate the capability of waves2Foam in proper simulation of numerical wave tank the experimental wave tank of Beji and Battjes (1993) was used by Jacobsen (2012a). For validating the results, as shown in Figure 8, 12 gauges (gauge 0 to gauge 11) were installed in the tank to report the surface elevation of the waves. The gauges 1 to 11 located exactly in same place as Dingemans (1994) while the gauge 0 is located in the beginning of the wave tank in order to evaluate if wave is generated properly in the inlet. Also the wave tank is extended 6 meters more in x direction after the submerged bar in order to prevent reflection of waves from outlet boundary by implementing a relaxation zone from 24 to 30 meters and to have more precise results. The simulation results have been validated against the experimental data by comparing the surface elevation results of simulation and experiment. Figure 22 shows the agreement between the results of simulation and experiment until the gauge 6 while the disagreements started from the gauges 7 and 8 (see Figure 23) and it increases from gauge 9 to gauge11 (see Figure 24). Note that, figure 22-24 were obtained using the tutorial developed by Jacobsen (2012a).

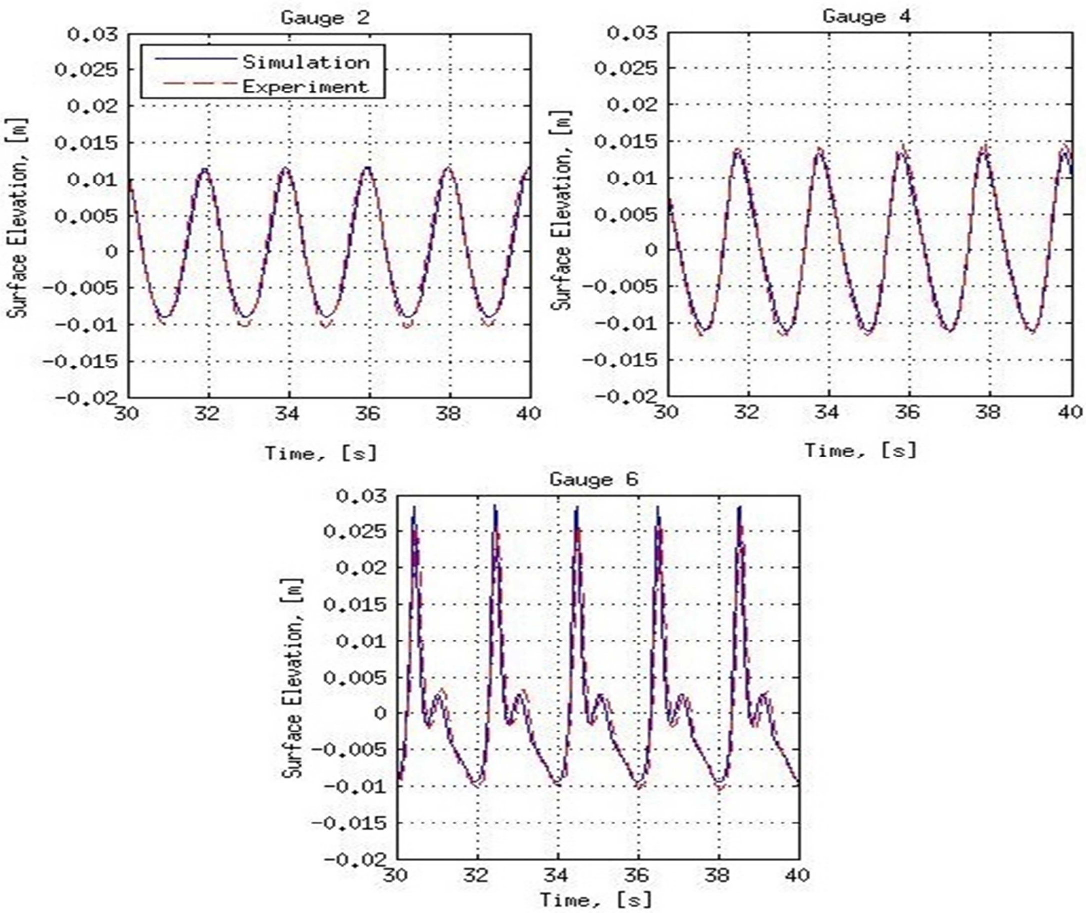

Figure 22 – Free surface elevation comparison of simulation and experiment result reported by gauges 2, 4 and 6 (before and on the submerged bar) of scenario 2, (Source: Jacobsen, 2012a).

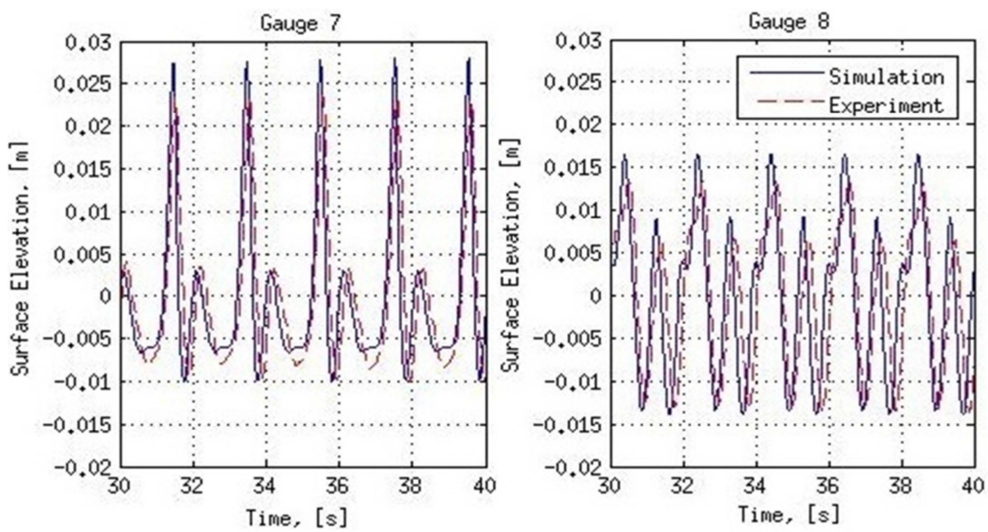

Figure 23 – Free surface elevation comparison of simulation and experiment result reported by gauges 7 and 8 (on the slope after submerged bar) of scenario 2, (Source: Jacobsen, 2012a).

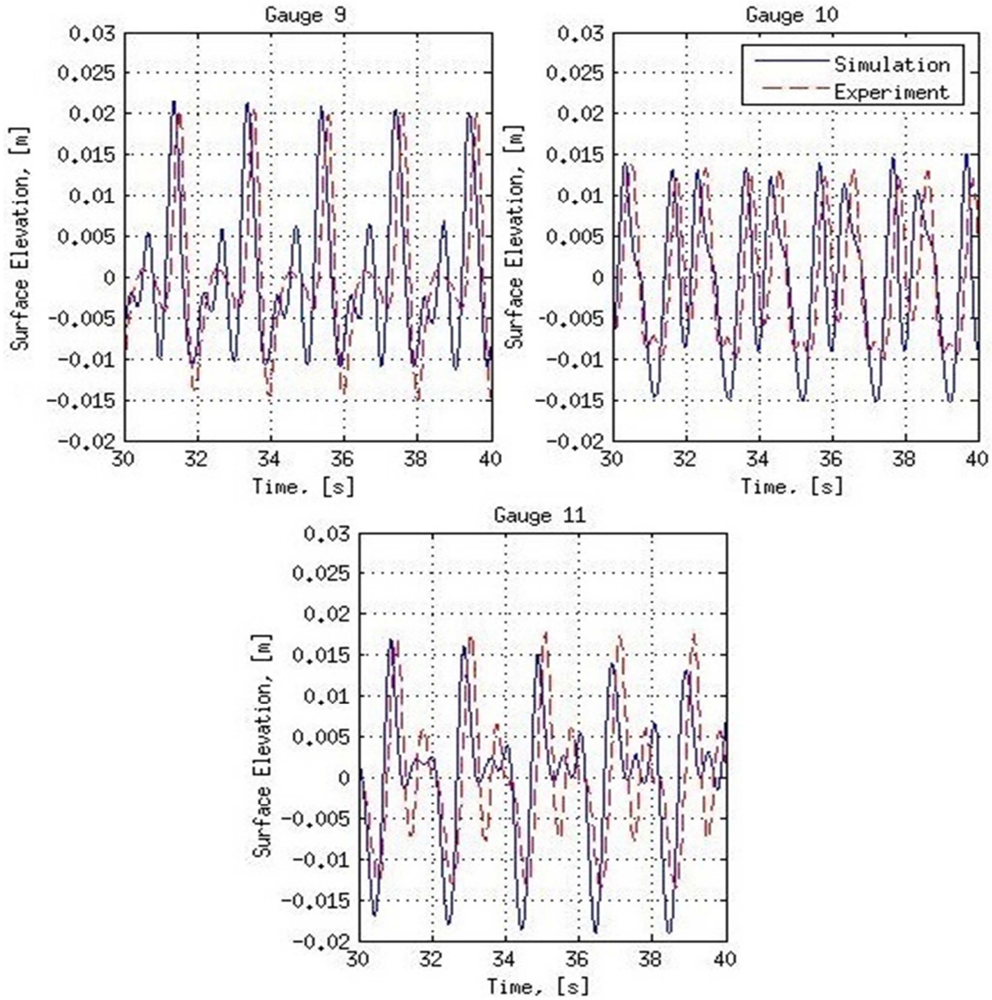

Figure 24 – Free surface elevation comparison of simulation and experiment result reported by gauges 9, 10 and 11 (after submerged bar) of scenario 2, (Source: Jacobsen, 2012a).

As reported by many studies such as Chazel et al. (2010); Morgan et al. (2010); Shen and Chan (2011) and also Lambert (2012) the simulation results started to show non-conformity from the experimental result from gauge 7 and 8 which are right after the submerged bar. Chazel et al. (2010) used Dingemans (1994) experiment as a validation case and reported that non-linearity and dispersion are the two main reasons of the differences observed between simulation and experiment results. They have mentioned that, nonlinearity causes development of higher harmonics which is released after the submerged bar. Finally, they indicated gauges 8 to 11 as the most difficult probes to be modelled numerically (see Figure 25). Morgan et al. (2010) also reported a good agreement in gauges 1 to 7 and again the disagreements of the results began to show up from gauge 8 and due to higher-order harmonics (see Figure 26).

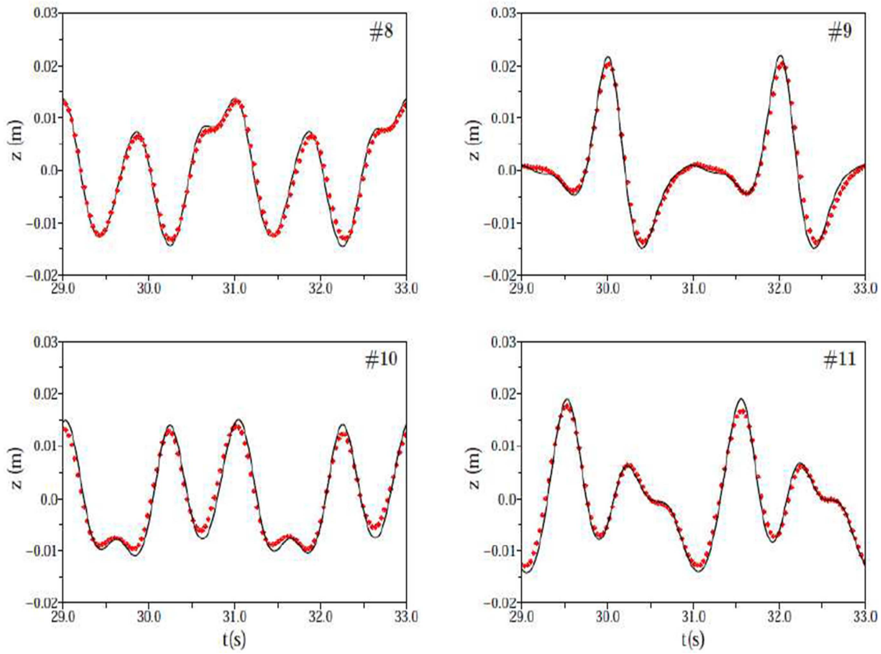

Figure 25 - Free surface elevation after the bar (gauges 8 to 11) Black line: results of the numerical model; red dots: measurements in the wave flume (Source: Chazel et al., 2010).

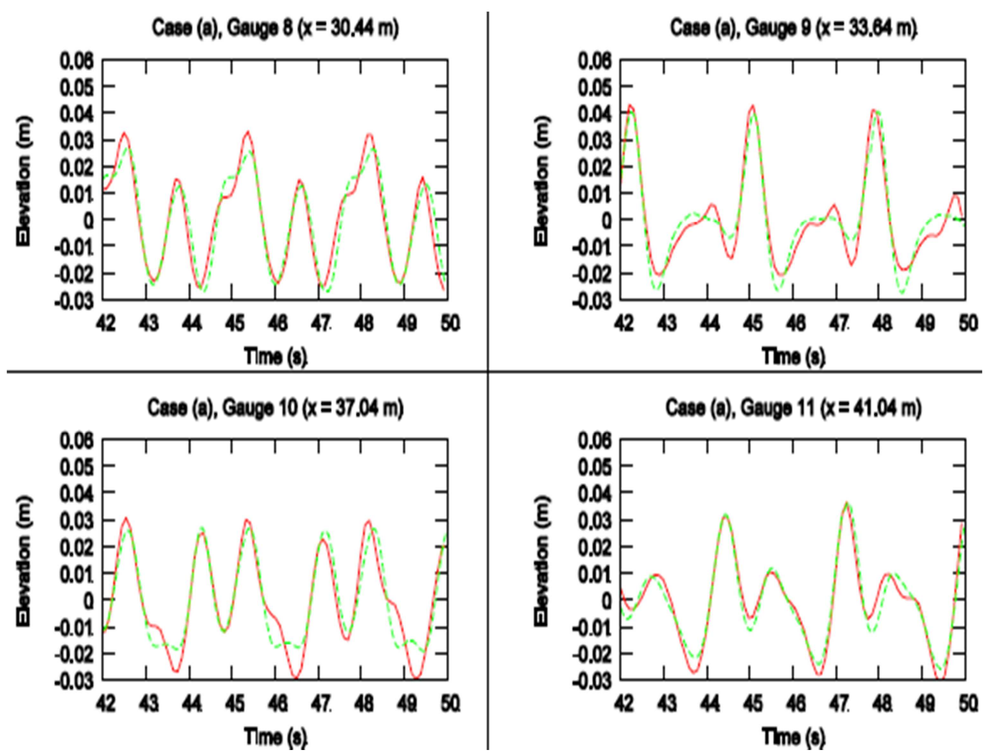

Figure 26 - Free surface elevation after the bar (gauges 8 to 11) red-solid line: results of the numerical model; green-dashed line: measurements in the wave flume (Source: Morgan et al., 2010).

In order to see the influence of extending the validation tank, this master thesis has modified the geometry of the “bejiBattjes” tutorial developed by Jacobsen (2012a). This modification is only applied on the length of the validation tank, where it is reduced from 30 to 24 meters. Note that the relaxation zone is also applied to this sub-scenario from 22 to 24 meters. This reduction of length to 24 meters was due to simulation of the same geometry as experimental model. Figure 27 shows the comparative result of this sub-scenario and experimental data in which the disagreements after the submerged bar is quite higher due to the reflection of waves. This reflection affects the surface elevation amount recorded by the gauges. It should be noticed that, the relaxation zone in the last 2 meters of the domain diminished the high amount of reflection; otherwise, the discrepancy of the experimental and simulation results would be higher.

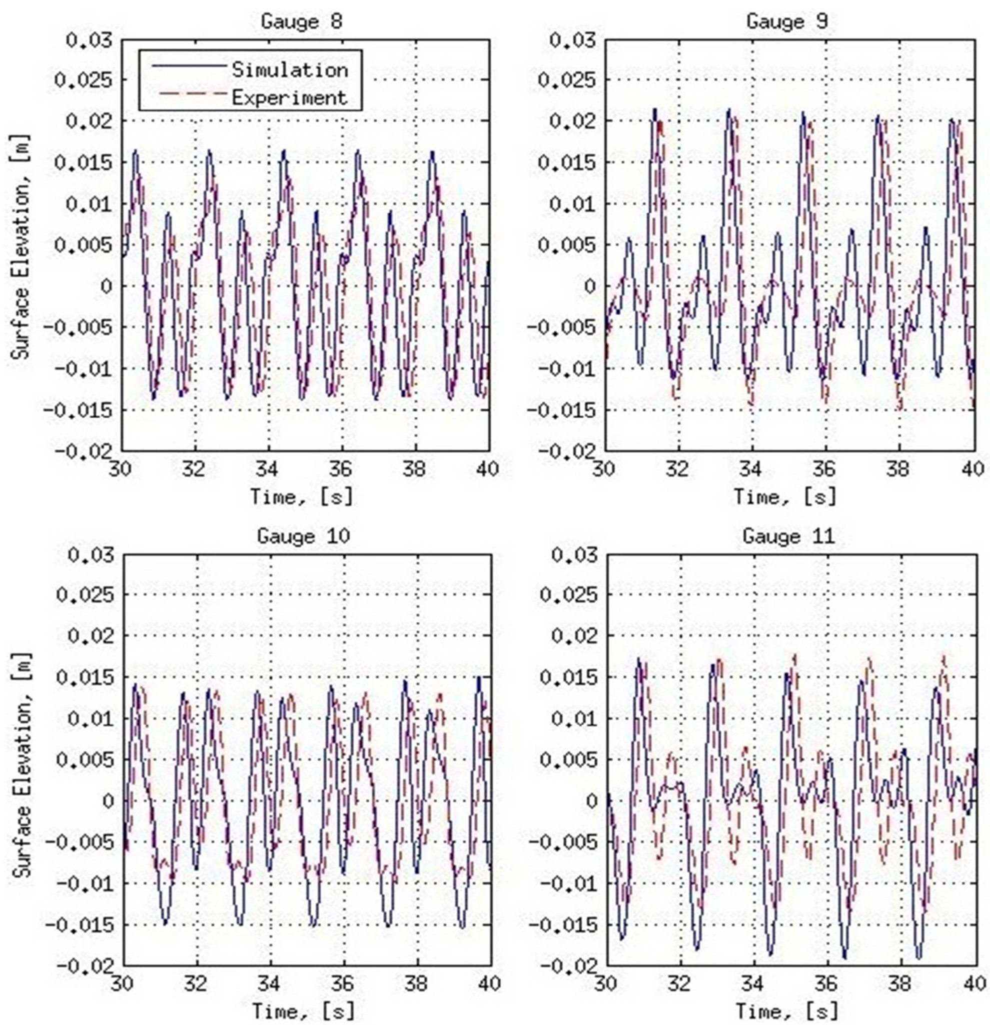

Figure 27 – Free surface elevation comparison of simulation and experiment result reported by gauges 8, 9, 10 and 11 (after submerged bar) of sub-scenario 2.1.

The capability of waves2Foam in simulation of numerical wave tank is approved in this scenario. As mentioned, the simulation results had good agreement with experiment results before the submerged bar while after the bar the disagreement appeared due to the higher harmonics. Also, influence of relaxation zone and extension of the length of tank in preventing reflection were proved.

5.3 Scenario 3: Sloped Numerical Wave Tank

This scenario is developed in order to present the capability of waves2Foam in simulating different wave breaking types. As mentioned in section 4.1.3, three different cases are defined in order to simulate different types of breaking waves. All the cases simulated in this scenario have satisfied the surf similarity limits presented in table 1(see section 3.4). According to the wave properties shown in table 5 (see section 4.3.1) the similarity number associated to each case and calculated by equation 15 (see section 4.3) are presented in table 9.

Table 9 – Surf similarity numbers associated to each case and their breaking type.

Scenario	Case	Surf Similarity Number	Breaking Type
	A	0.15	Spilling
3	B	0.91	Plunging
	C	3.64	Surging

5.3.1 Scenario 3A

Spilling wave breaking is properly simulated in this case. Figure 28 shows the breaking steps from creation of the wave to the break of it. Comparing the snapshot depicted in Figure 28 with the spilling wave breaking shown in Figure 2 (section 3.3.1), specifies that waves2Foam is able to correctly simulate spilling wave breaking. Note that the numbers indicate the steps of breaking the wave.

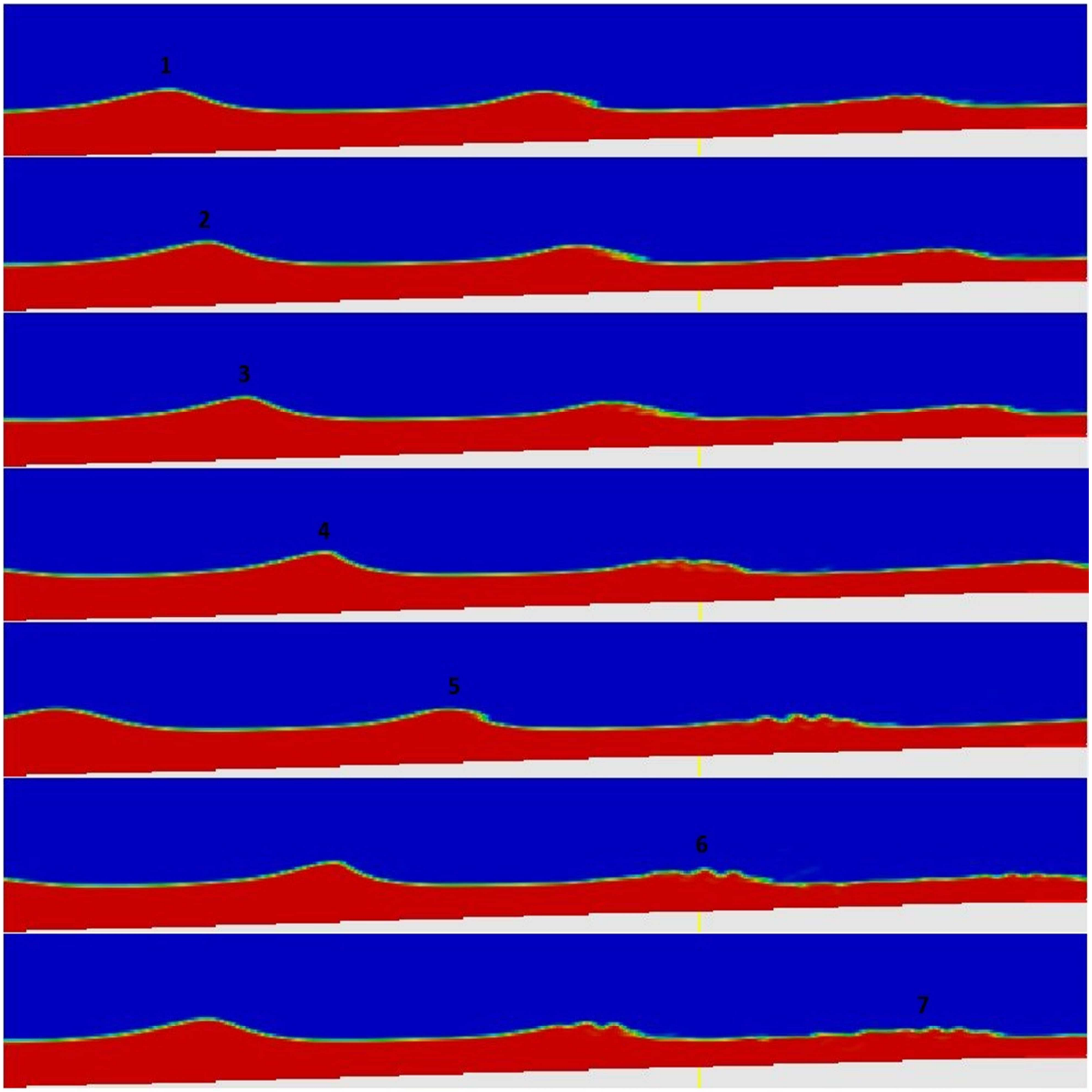

Figure 28 – Spilling wave breaking simulation (scenario 3A).

5.3.2 Scenario 3B

Plunging wave breaking is properly simulated in this case. Figure 29 shows the breaking steps from creation of the wave to the break of it. Comparing the snapshot depicted in Figure 29 with the plunging wave breaking shown in Figure 3 (section 3.3.2), indicates that waves2Foam is able to correctly simulate plunging wave breaking. Note that the numbers indicate the steps of breaking the wave.

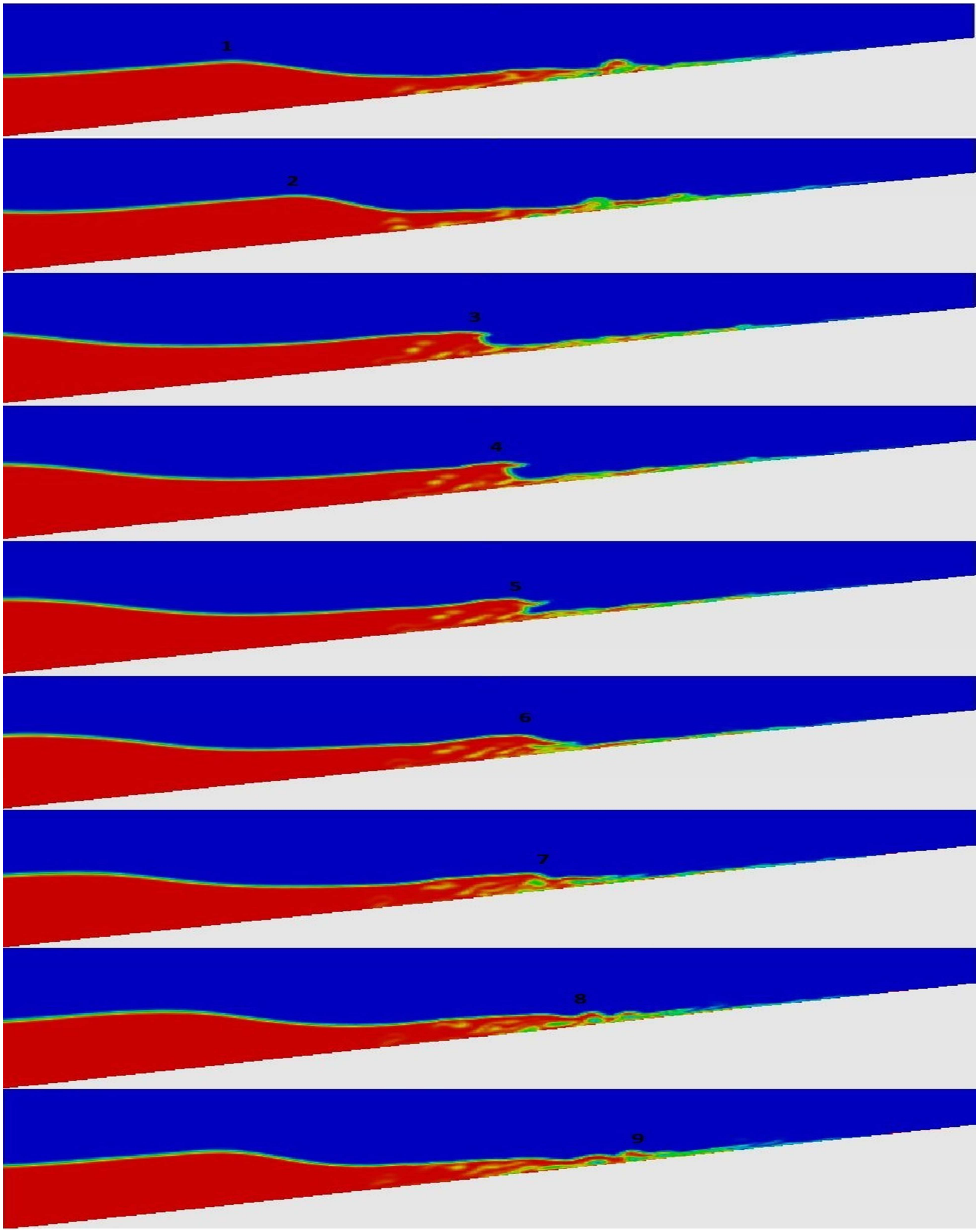

Figure 29 - Plunging wave breaking simulation (scenario 3B).

5.3.3 *Scenario 3C*

Surging wave breaking is properly simulated in this case. Figure 30 demonstrates the breaking steps from creation of the wave to the break of it. Comparing the snapshot depicted in Figure 30 with the surging wave breaking shown in Figure 4 (section 3.3.3), shows that waves2Foam is able to correctly simulate surging wave breaking. Note that the numbers indicate the steps of breaking the wave.

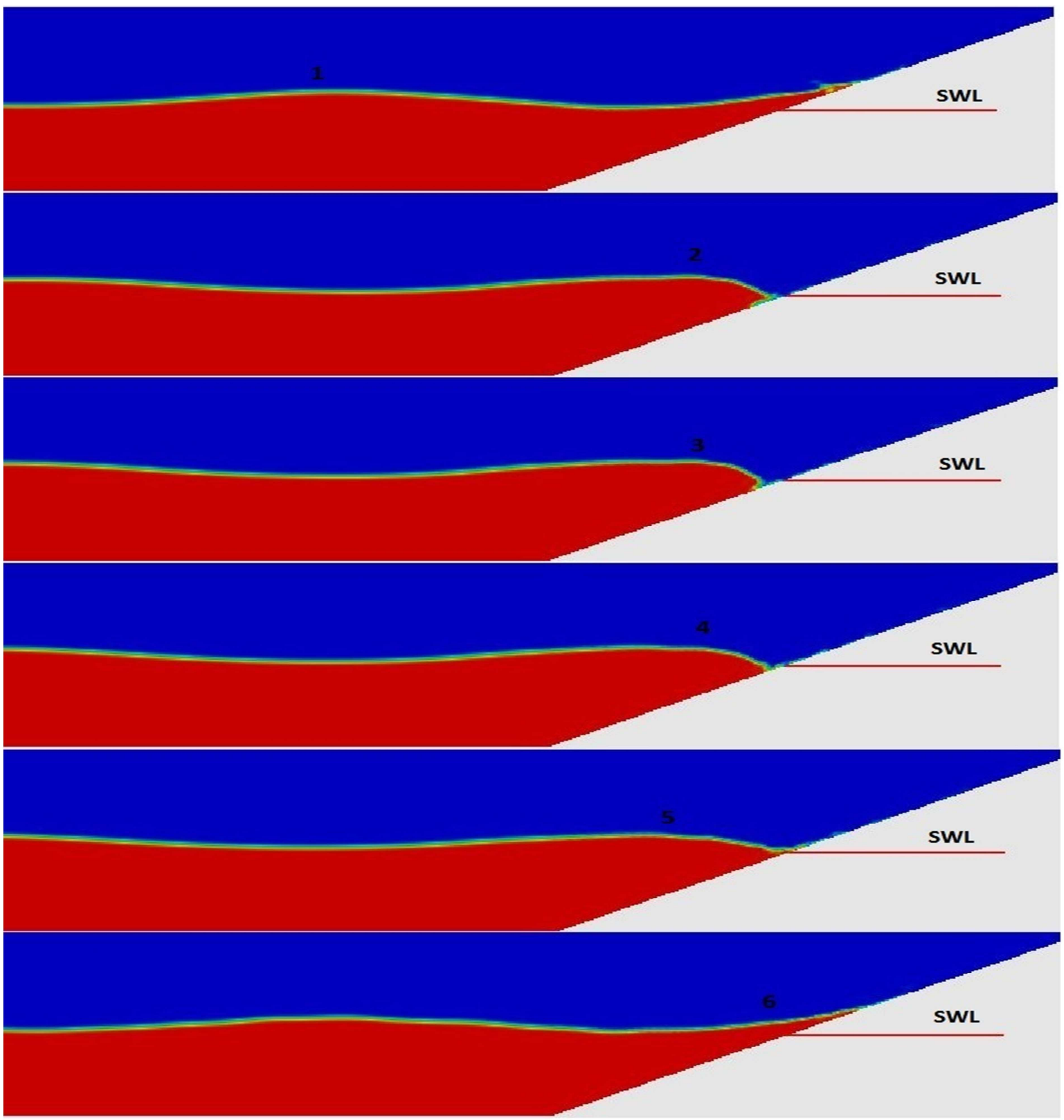

Figure 30 - Surging wave breaking simulation (scenario 3C); (SWL: Still Water Level).

Comparing the results of this scenario with those from Lambert (2012), shows that both interFoam and waves2Foam have almost the same performance in simulation of breaking waves. It should be pointed out that, as waves2Foam comes with wave generator boundary condition and different wave theories, it is easier and quicker to simulate breaking waves with waves2Foam. To see if waves2Foam is able to simulate collapsing wave breaking, an additional case is defined.

5.3.4 Scenario 3D

In order to simulate a collapsing wave breaking, an additional case is added to this scenario called scenario 3D, with the geometry shown in Figure 31. Surf similarity number of 3.3 (which is the limit between plunging and surging wave breaking) is considered for this case. Figure 32 depicts the steps of a collapsing wave breaking and the visual results have a good agreement with Figure 5 (section 3.3.4). As shown in Figure 32, the wave crest never fully breaks while the lower face of the wave falls and breaks that is in accordance with the reality.

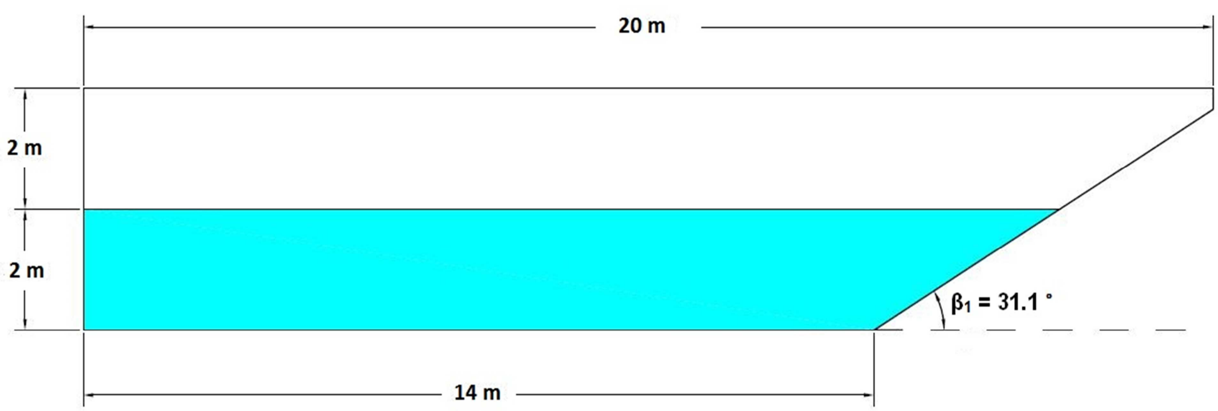

Figure 31 - Geometry of scenario 3D, $\boldsymbol{\beta_1 = 31.1}°$ (NTS).

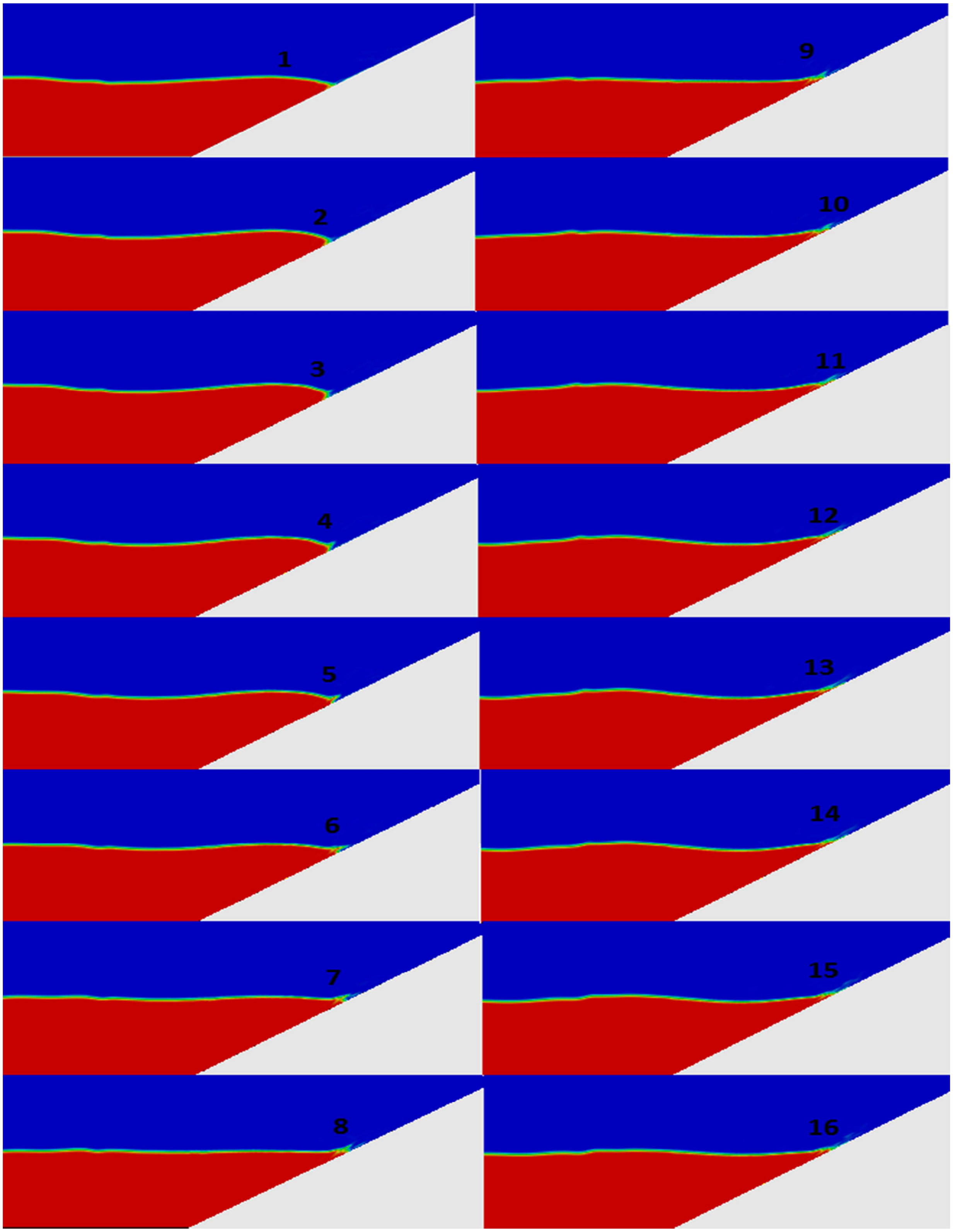

Figure 32 - Collapsing wave breaking simulation (scenario 3D).

6 CONCLUSION

In order to decrease dependency to fossil fuels which causes crucial environmental burdens, development of renewable energy as a sustainable alternative has become the priority of many countries in the world. This task have started since 1970's after the oil crises, so large wind turbines appeared in this decade while solar systems was being used mainly for heating purpose for many years. Nowadays, solar and wind energy systems are fully commercialized but ocean wave energy which has the highest amount of energy among renewables is still on beginning steps. Owing to development of ocean wave energy technology, some prototypes are designed, built and tested. Most of them are destroyed after couple of months because of some technical issues. For instance, heavy storms and severe condition of oceans were not tolerable for the prototypes.

Today, numerical modelling is developing due to improvements in both hardware and software technologies. Therefore, numerical models which are more effective in terms of both time and cost are still under development and test in order to become an alternative or complement for the laboratory experiments. Many researchers developed their numerical wave tanks to investigate behaviour of the ocean waves.

The present work also tested numerical wave tank to assess propagation of waves as well as their behaviour interacting with sea bed. In order to achieve the goals and objectives of the present study, three scenarios were defined. Each scenario also comes with some sub-scenarios to compare the results with those from different studies.

In the first scenario, a basic flat-bottom wave tank was simulated to assess the capability of waves2Foam in generating and absorbing the wave. As the first scenario was modelled based on Stokes first order wave theory, within two sub-scenarios, it was demonstrated that this toolbox is capable to simulate waves based on Stokes second and fifth order wave theories as well. Moreover, another sub-scenario was defined to investigate the influences of the relaxation zone, which was implemented in the outlet boundary. To do so, two cases with the same geometry were defined and the relaxation zone was removed in one of the cases. The results showed reflection of the wave from outlet boundary in the case without relaxation zone while it was not seen in the other case. Finally it was concluded that, simulation of waves in numerical flumes are more accurate using relaxation method because it prevents reflection of the waves from outlet boundary.

Furthermore, two more sub-scenarios were modelled to assess if waves2Foam is able to correctly model waves with steepness above 0.05 (this limitation of interFoam was already reported by Lambert (2012); Morgan et al. (2010) and Afshar (2010)). The results show damping of the waves with steepness of 0.1 while for waves with steepness of the 0.15 show both damping and small breaking (which was predictable as the steepness was above critical steepness) of wave are seen. Therefore, waves2Foam performed better than interFoam.

Second scenario which is the validation case simulates the laboratory experiment conducted by Beji and Battjes (1993). The numerical model (bejiBattjes tutorial) was originally performed by toolbox developer Jacobsen (2012a), who validates the simulation result against experimental data. As reported by many studies such as Chazel et al. (2010); Morgan et al. (2010) and Lambert (2012), validation results of present study also show agreement between simulation and experiment results in the gauges before the submerged bar while the disagreements start from gauges 7 and 8 and increase in gauges 9 to 11. These disagreements are mainly due to development of higher harmonics that occurs after the submerged bar. In this scenario, Jacobsen (2012a) extended the numerical wave tank in x direction in order to implement relaxation zone in the last 6 meters of the tank for preventing reflection. To show the influence of relaxation zone in the results, a sub-scenario was defined by reducing the wave tank length to 24 meters and put the relaxation zone only in the last 2 meters of the tank. The result showed higher disagreements in comparison with the main scenario.

The third scenario aimed to model different types of wave breaking. To do so, three cases were defined in order to check the capability of waves2Foam in simulating of breaking waves. Spilling, plunging and surging wave breaking are simulated in cases 3A, 3B and 3C respectively and the results of each case shows that waves2Foam is able to properly model breaking waves. In continue, an additional case called scenario 3D is defined to see if the solver is capable to simulate collapsing wave. In this case, the surf similarity parameter is considered the limit between plunging and surging breaking waves. The results of simulation proved also the capability of waves2Foam to model collapsing wave.

To sum up, this master thesis presents OpenFOAM as powerful software which can be used in ocean engineering science. Especially, due to its open source nature, OpenFOAM needs to be further developed by modifying the pre-existed solvers and codes. Moreover, present work shows that waves2Foam has the capability of correctly modelling of regular wave propagation both in generation and absorption of the waves as well as simulating the wave behaviour interacting with seabed and its breaking steps.

Finally, based on limitation of the software and toolbox discussed in this work, some recommendations for future developments are presented below:

- Reasons which cause higher harmonics after the submerged bar such as non-linearity and dispersion should be investigated to find a proper way, preventing higher harmonics after the bar in order to improve the agreement between results of simulations and laboratory experiments;
- The ability of the software and toolbox in terms of simulating waves with steepness above 0.05 should be assessed and increased;
- As an extension of the present work, also the ability of waves2Foam in simulating floating object within the numerical wave tank should be checked.

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