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# Study on Wave Overtopping Discharge Affected by Guiding Wall Angle of Wave Dragon Device Using FLOW-3D Software

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**ABSTRACT**

The Wave Energy Converters (WECs) have become the main attraction in producing electricity by converting the wave's energy to electricity. The focus of the WECs is the overtopping of the wave. The higher of overtopping water collected in the basin, the higher the power produced. Producing the higher overtopping also requires higher wave flow rate entry. In the Wave Dragon system, the rate of wave flow entering the reservoir is influenced by the guiding wall (reflector) angles and wave height. Hence, most overtopping concepts have tried to increase the water addition into the pool studying their geometrical parameter, mainly on the guiding wall of Wave Dragon. The unknown effect of the guiding wall angles on the overtopping and effect of the wave characteristic remained. Thus, this study aims to investigate the appropriate guiding wall angle on the influence of different wave heights affecting the performance of the Wave Dragon unit. Then, using FLOW 3D software to apply different guiding wall angles and wave characteristics to the device parameters for investigation. The numerical result highlights that the higher overtopping discharge is obtained during the upper limit of wave height and guiding wall angle. Besides, percentage different between the simulations model and experimental observation, was found at 15%. The result of this study will be beneficial to the industry related to wave potential energy, especially Wave Dragon, and it will also help them improve their device performance.

## 1. Introduction

In this modern era, energy is essential for living, and various energy sources have begun to make way for adaptation in these people. Electrical energy is one of the essential elements of energy and has been commonly used for running devices such as technology-based machines [1-9]. Thus, the past few years the wave energy has gradationally been brought into a focus. The wave energy resources are very large and provide high potential for extraction, especially the Wave Energy Converters (WEC). This study will concentrate on a floating (WEC) that is deployed offshore. Wave

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Dragon is Wave Energy Converter (WECs) that capture the energy by overtopping type [9]. It extracting energy principally by means of overtopping of waves up to a ramp and into a reservoir [11-13]. The Wave Dragon consists of three main components which are two guiding walls (reflector) that direct the waves towards a ramp [13-15]. The main platform known as a floating reservoir consist of a double curved ramp that facing the incoming waves and hydro turbines [16]. A set of turbines that converts the potential energy gained when wave overtopping into the reservoir. The produced electricity is converted using alternates current and direct current (AC/DC) power electronic converters to the grid frequency [13]. The main function of wave dragon is to generate electricity generated through the conversion of the overtopping wave process [4-12,17-20]. But some of the energy produced is still lower and does not reach the desired target. A study on Wave Dragon has been implemented to solve this problem by improving the device and its performance. The study focusses on the problem that related to guiding wall angle that influenced the wave dragon performance in producing the wave energy. On the impact of various guiding wall angles to the overtopping wave, not much is currently known. Hence, the aim is to study the effect of guiding wall angles, including the effect of different wave heights to the overtopping wave discharge through simulation.

### *1.1 Experimental Work*

The significance of the project is to increase the performance of the Wave Dragon in producing electricity by converting the energy of the wave to electricity through the overtopping process [21]. The study according to different guiding walls (reflector) angle of Wave Dragon is required in order to obtain a best parameter for increasing overtopping volume [22]. Previous experimental work by [21,22] was used as a basis parameter to be simulated in this study. The same experimental model was simulated using a CFD of FLOW 3D software for aimed to getting the best overtopping wave in produce the energy [21,22].

This study is also simulating guiding wall effect under the different wave characteristics which is height and period of wave. The appropriate wave rate for this device is also important to produce high energy production [24]. At the end of this project, the proportional values obtained was analysed to determine the relationship of the guiding wall angles and wave characteristic. A moderate rise in wave height results in a substantial amount of wave overtops to the ramp since the overtopping volume in a wave is highly dependent on wave height [25]. Thus, the energy that generated also will increase.

### *1.2 Overtopping Device*

Devices that capable of generating electricity from the waves energy are commonly referred to as the Wave Energy Converter (WEC). The overtopping kind of WECs, or a converter that uses the potential energy gained when waves overtop into a reservoir at a higher level than MWL by directing the water back into the sea through a number of turbines [3-27].

Overtopping devices are one of the many WECs, which collect incident waves water to drive low head turbines. There are many devices that use the overtopping process to capture the energy. For examples, WaveCAT, OBREC, Wave Catamaran, Sea Slot-cone Generator and Wave Dragon. The water is then returned to the sea via a low-head turbine coupled to a generator, converting the potential energy gained in the overtopping water into electrical energy. Since the effectiveness of these WEC technologies is dependent on wave propagation, very huge structures can be constructed.

Control and stabilisation of the floating structure are key concerns for floating overtopping WECs in order to maximise power output [15].

Modelling the overtopping flow time series strongly relies on empirical data [28]. In a reservoir above sea level, an overtopping system collects incident waves of seawater before releasing it back into the water through turbines. Oblique overtopping is a mechanism that describes how overtopping happens slowly when waves pass between the hulls and makes a relatively modest angle with the overtopped structure [29]. Based on the device's current wave condition (H_s, T_p) and freeboard crest Rc (ramp crest height above mean water level, MWL), water overtopping into the pool (Q_overtop).

The energy produced in pool is a result of the overtopping wave through freeboard crest on ramp. The research, however, concentrate on systems constructed to reduce the overtopping levels, contrary to the Wave Dragon's objectives [21-27]. Experiments in the lab with high overtopping rates on a wide range of ramp angles, profiles, and crest freeboard levels in a variety of sea states showed that a highly effective double curved ramp developed by the Wave Dragon to transform incident wave power actually works very well [15].

### *1.3 CFD Modelling*

The Navier-Stokes equation and the continuity equation are fundamental flow equations that are discretely resolved for each computational cell in computational fluid dynamics, a technique for simulating a flow cycle. In many ways, using the CFD application is like setting up an experiment. The results of an experiment that is not properly set up to imitate a real-life situation would not be reflective of that reality [30]. Modern CFD applications include various branches of physical science that can rely on CFD applications including heat transfer, radiation, nuclear reaction, electromagnetic field, oceanography, vascular medicine, and so on. The general CFD experiments were focused on the field of fluid mechanics and included nonlinear waves, viscous effects, overtopping wave, green water effects, slamming loads, wave breakage, etc [31]. Through the use of several CFD software programmes, researchers have recently been gradually exploring wave hydraulic behaviours and structural design performance, mainly in the area of wave overtopping discharges.

The reliability of FLOW-3D as a design tool was primarily studied by Dentale by looking at the overtopping of the Wave Dragon energy converter, and Eskilsson and Kofoed [28] had looked at the reliability of 3D numerical simulation over overtopping discharge. Nevertheless, only a small number of researchers utilised the use of FLOW-3D in their research on wave behaviours over a coastal and overtopping device structures [32-36]. The results from those mentioned researches proved that FLOW-3D is one of an innovative CFD software with ability to simulate real-life situation [37,38]. The FLOW-3D based on RANS, which was created for simulating turbulence and laminar flow [39], and Volume of Fluid (VOF), which was created for free-surface calculation techniques [40-44].

## **2. Methodology**

The aim of this study is to obtained wave energy generated through overtopping wave based on the appropriate device parameter. Some methods have been carried out to get the desire results to achieve the objective because certain conditions will affect the energy production. Validation is utilised in every CFD instance to evaluate how well the computational results match the experimental data. Because of this, all of these geometries were rebuilt utilising the same structural design parameters as the previous experiment during geometrical building using a CAD programme.

For begins with validation testing the significant wave height during overtopping wave of the Wave Dragon performance using simulation. In order to conduct the validation, some tests have been used by carried out at different significant wave heights and time periods. The test used a constant angle of guiding wall at 90 degrees. After the test completion, the results of the test were calculated using the MATLAB to get the average significant wave height data.

Then, proceeding to the first objective which is to quantify overtopping discharge due to difference wave heights using simulation. In this simulation is also used Flow-3D software to collect the result for different wave height influences and wave period to the overtopping process. The constant angle of the guiding wall remained at 90 degrees. The model of Wave Dragon designed using the AutoCAD software. The test identifies the wave condition that produce higher overtopping discharge value. Then, the wave condition that produces a higher overtopping was used to proceed for the objective 2.

The second objective determines the effect angle parameter of a guiding wall (reflector) on overtopping discharge using simulation. Some tests have been carried out using a different angle of guiding wall. The model of Wave Dragon designed using the AutoCAD software. Subjecting the model to similar wave condition as in objective 1, the Flow-3D software estimates the best angle of the guiding wall. The overall methodology summary is shown Figure 1.

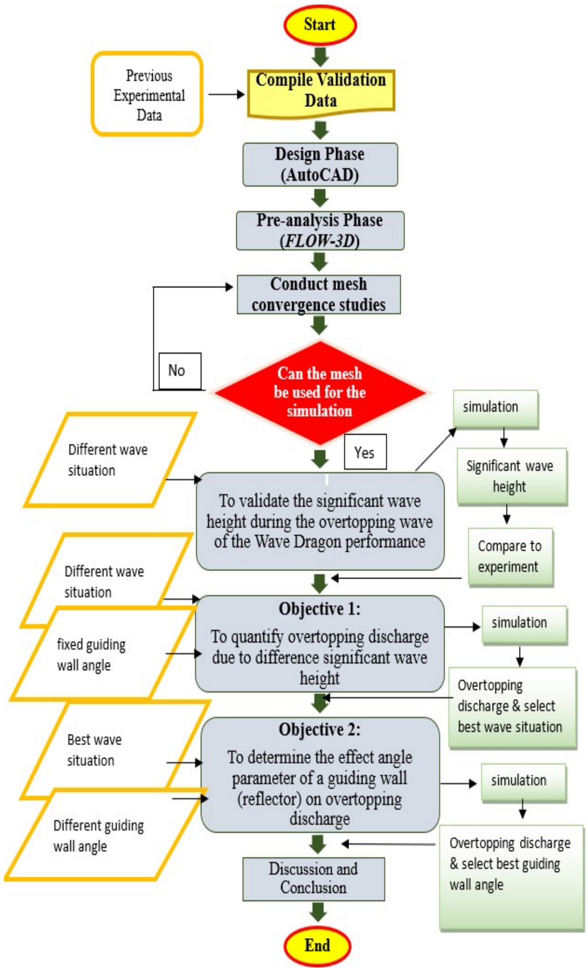


**Fig. 1.** Workflow diagram of the studies

The test is run in the numerical simulation for this study with a scale of 1:45. The dimension of the model are as following Table 1.

**Table 1**
Principle dimension of Wave Dragon

| Measurement | Detail |
|---|---|
| Width, *(m)* | 188 |
| Height, *(m)* | 15.10 |
| Weight, *(tons)* | 10,000 |
| length, *(m)* | 109 |
| Length Of guiding wall, *(m)* | 81 |
| Total length of reservoir + ramp, *(m)* | 45.11 |
| Width of reservoir, *(m)* | 75 |

The first phase designed the model of the Wave Dragon device with fixed angle of guiding wall at 90º used in the simulation. The Wave Dragon device designed using AutoCAD 2016. Figures 2 and 3 showed the Wave dragon plan view.

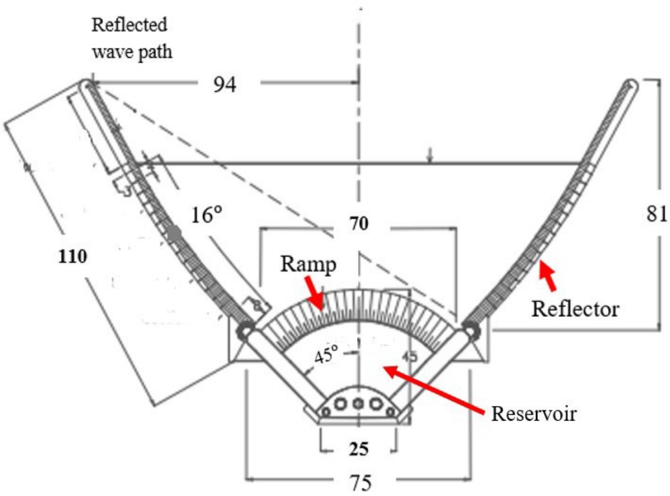


**Fig. 2.** Wave Dragon from the plan. Measures in m [36]

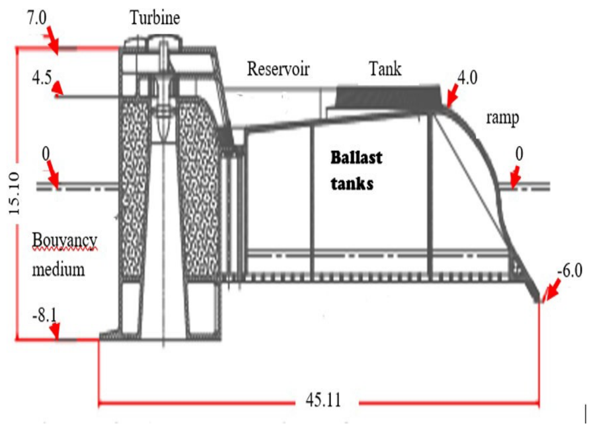


**Fig. 3.** A cross-section of Wave Dragon's ramp and basin components. Measures in meters

The wave settings and simulation have been built up similarly to experimental investigations. In the Danish portion of the North Sea, the offshore floating platform was typically located at a depth of 20 to 50 metres, or 25 to 100 kilometres from the coast [44]. The sketch of the Wave Dragon cross-section, as well as, the dimension used in this model is presented in Figure 4.

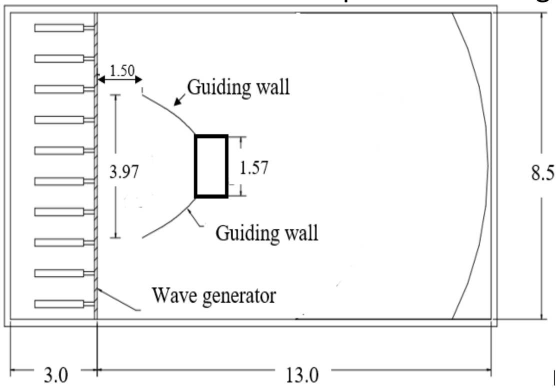


**Fig. 4.** Cross section of 2-D model set-up of Wave Dragon

Figure 5 shows the design of Wave Dragon device. The device designed using AutoCAD 2016 software. The guiding wall angle of first design is 90 degrees.

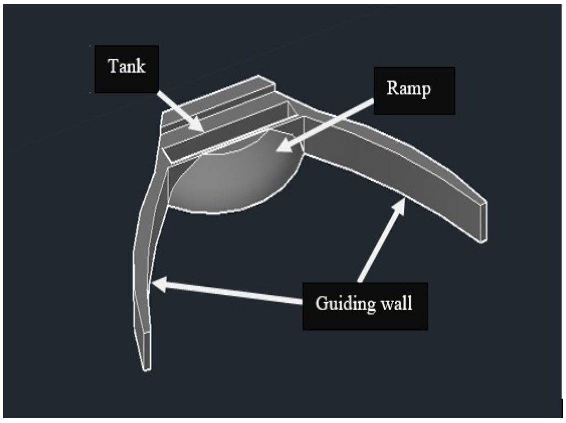


**Fig. 5.** Wave Dragon Model

Other studies involved design the Wave Dragon model at a fixed size but different angles of guiding wall. The different range angles of guiding wall tested include 50°, 60°, 70°, 80° and 90°. The test finds the suitable angle parameter of guiding walls during overtopping discharge. Figure 6 shows the wave Dragon with different guiding wall angles.

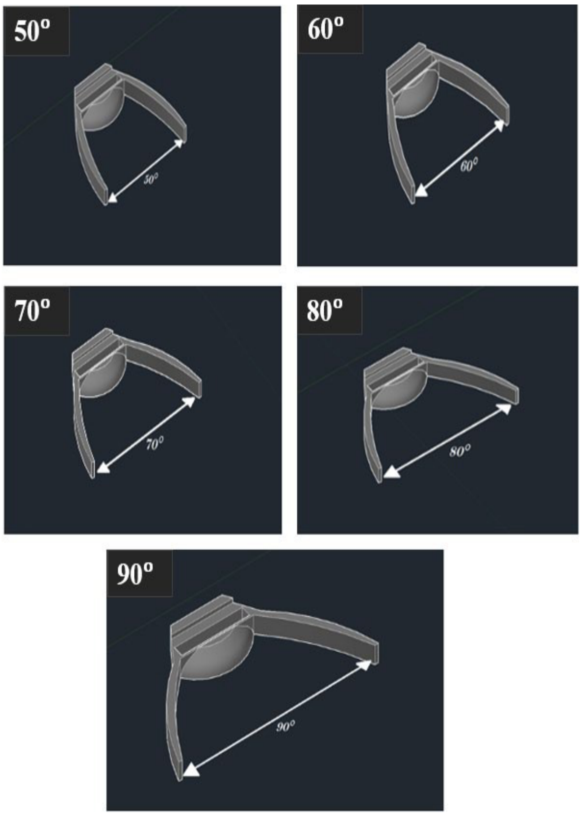


**Fig. 6.** Different angle designs

For meshing and geometry set up the mesh with nested block. Nested mesh block allows user to increase their meshing, but if no precaution, there will be some error occur during computation that might be terminated the simulation. In nested mesh block, the gridlines of both mesh block need to align. In order to do the numerical simulation based on common experimental arrangements, a numerical wave flume that has lengths of 8.5 metres in the X-direction, 16 metres in the Y-direction, and 7.8 metres in the Z-direction was built up. There are two sub-domains inside the computational domain (Figure 7).

While the mesh block 1 domain indicates the area where the structural geometry will be located, the mesh block 2 domain depicts the region where the fluid is flowing. The inventor of FLOW-3D recommended a 1:2 ratio between fine and coarse mesh. For this study, the mesh size for the mesh block 2 (coarse domain) was chosen to be made up of 0.2 size of cell, 8.5 x 16 x 12 meter and while the mesh block 1 (fine domain) mesh was 0.1 size of cell, 5 x 8 x 3 meter. Figure 7 shows the computational boundary meshing for numerical wave flume.

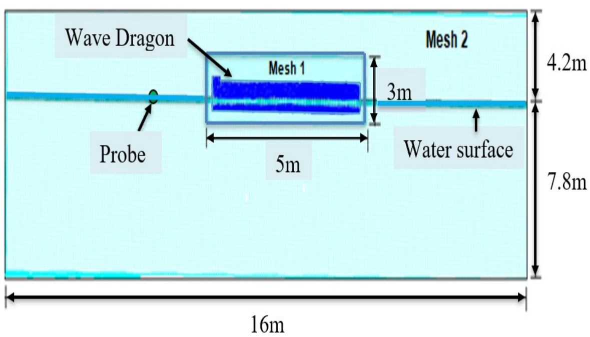


**Fig. 7.** Computational boundary meshing for a numerical wave flume

### *2.1 The Governing Equations for Data Analysis*

Using Non-Dimensional units to define the variables is highly helpful when comparing findings between different model scales. Results from the model scale can easily be applied to devices of any size. The overtopping formulas suggested for the Wave Dragon system are provided below [28,44] and are derived from the overtopping equation for dikes by [43]:

$$q = \frac{v}{t} \tag{1}$$

$$Q^* = \frac{q}{\sqrt{gH_s^3}} \tag{2}$$

For the Wave Dragon device, this formula has been improved by adding more parameters.

Where:
Q* is the non-dimensional overtopping discharge
q is the dimensional overtopping discharge ($m^2/m/s$) v is the volume of fluid ($m^3$)
t is the times (s)
$H_s$ is the significant wave height (m) g is the acceleration of gravity ($m/s^2$)

## 3. Results

The result and discussion focus on the effect of the wave height on the overtopping discharge. The simulation compared to the physical experiment. The study allows the estimation of non-dimensional average overtopping discharge over different wave situation and different angle of guiding wall. Hence, it allows the determination of optimum or best wave height that led to the highest overtopping discharge. The optimum wave height simulated with different angles of guiding wall allow the estimation of the higher overtopping discharge between them.

### *3.1 To Validate the Significant Wave Height During the Overtopping Wave of the Wave Dragon Performance – Validation*

The average of significant wave height during overtopping obtains through the simulation by using five different wave conditions and a fixed guiding wall angle. The average of significant wave height different from each wave condition was calculated. Table 2 shows the wave condition used in the simulation test for validation.

**Table 2**
Wave situation input

| Wave situation | Wave height, $H_s$ (m) | Time period, $T_p$ (s) |
|---|---|---|
| 1 | 0.2 | 2.0 |
| 2 | 0.4 | 2.5 |
| 3 | 0.8 | 3.0 |
| 4 | 1.2 | 3.5 |
| 5 | 1.5 | 4.0 |

Table 3 displays the percentage error for each important wave height point in relation to various wave situations.

**Table 3**
The percentage error between numerical and experimental results

| Significant wave height (m) | | | |
|---|---|---|---|
| Wave situation | Experimental [36] | Simulation | Percentage error (%) |
| 1 | 0.342 m | 0.40 m | 14.5 |
| 2 | 0.624 m | 0.567 m | 10.0 |
| 3 | 1.136 m | 1.046 m | 8.6 |
| 4 | 1.668 m | 1.53 m | 9.0 |
| 5 | 1.995 m | 1.942 m | 2.7 |

As shown in the table, the percentage error according to comparison between simulation against experiment decreases which is close to 2% error. The value for both simulated and experimental result also does not differ too much.

From this result, the difference between both methods can be discussed as the differences in model configuration and parametric variable that are used for this study.

The graph presented in Figure 8 has shown a positive correlation associated with simulated results between the significant wave height of simulation and experiment. It is obvious as the wave height increases, the significant wave height also increases. As a result, the results showed good agreement between the simulated and experimental data.

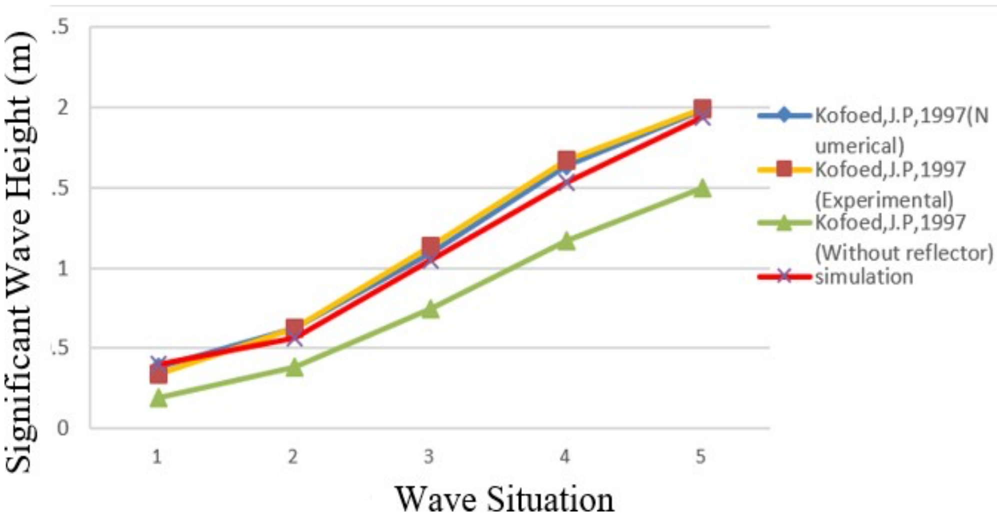

**Fig. 8.** Comparison between physical experiment and numerical simulation result

The likelihood of having trouble identifying the true scenario during numerical simulation configuration is the primary reason for the results between the simulated and experimental outcomes differing. The simulation model results were approximating the real behaviour of the WEC. Also, the simulation model used to investigate the theoretical model. There are several possible explanations to the discrepancy and one of which is the number of waves employed during simulations. It is impossible to employ a large number of waves through numerical simulation because the time consumed for simulation work is computationally demanding. Based on the graph data that corresponded to Figure 8, simulated result has shown about only 20% of the deviation from previous studies. Hence, the simulation model was able to recreate a close representation of the experimental condition.

### *3.2 To Quantify Overtopping Discharge Due to Difference Significant Wave Height– Objective 1*

The total of overtopping discharge is obtained through the simulation using five different wave conditions and fixed guiding wall angle. The overtopping discharge was found to strongly affected by the wave height and time period. Table 2 shows the wave condition used in the simulation test.

As the wave height increases, the overtopping discharge also increases. Table 4 shows the total of overtopping discharge at different wave conditions.

**Table 4**
Total overtopping discharge at different wave conditions

| Wave height, $HH_{SS}$ (m) | Time period, $TT_{pp}(s)$ | Overtopping Discharge | |
|---|---|---|---|
| | | q (m$^3$/s) | Q* |
| 0.2 | 2.0 | 1.0 x $10^{-2}$ | 2.0 x $10^{-2}$ |
| 0.4 | 2.5 | 3.0 x $10^{-2}$ | 3.0 x $10^{-2}$ |
| 0.8 | 3.0 | 10 x $10^{-2}$ | 5.0 x $10^{-2}$ |
| 1.2 | 3.5 | 41 x $10^{-2}$ | 10.0 x $10^{-2}$ |
| 1.5 | 4.0 | 63 x $10^{-2}$ | 11.0 x $10^{-2}$ |

The non-dimensional wave overtopping rate in the reservoir of the simulated result is shown in Figure 9. The distribution of the simulated data plotted in the graph was calculated using Eq. (1) and Eq. (2). According to the graph result above, the wave height 1.5m is produced higher value of overtopping discharge compared to other wave heights. The increase of wave height, the increase the overtopping discharge. Once a large wave has entered the reservoir, so will overtop a larger volume and produced higher overtopping discharge. Hence, the wave condition 5 is considered as a suitable or best wave condition for overtopping.

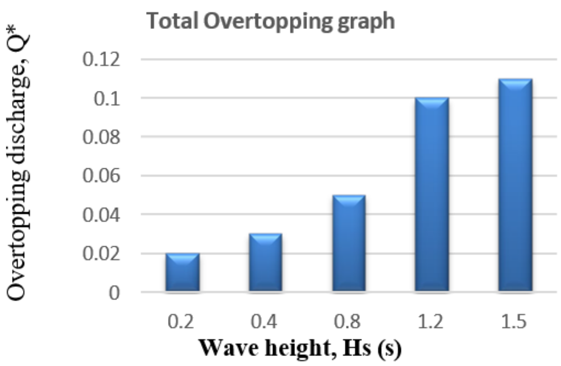


**Fig. 9.** Non-dimensional average overtopping discharge against wave height

The numerical simulation's analysed results centre on the wave overtopping discharge in the Wave Dragon device's front reservoir through investigations of wave overtop and wave loading up to the ramp on the structures. The outcome for the reservoir's non-dimensional average overtopping discharge result revealed that the methods given here had been effective in analysing the phenomenon of the interaction between wave overtopping and the Wave Dragon.

### *3.3 To Determine the Effect Angle Parameter of a Guiding Wall (Reflector) on Overtopping Discharge – Objective 2*

In this case, the total of overtopping discharge was obtained through the simulation using the best wave situations resulting from objective 1 and using different of guiding wall angles. The overtopping discharge has strongly influenced by the guiding wall angle. Figure 10 shows the comparison of waves overtopping discharge according to different guiding wall angles in numerical 3D.

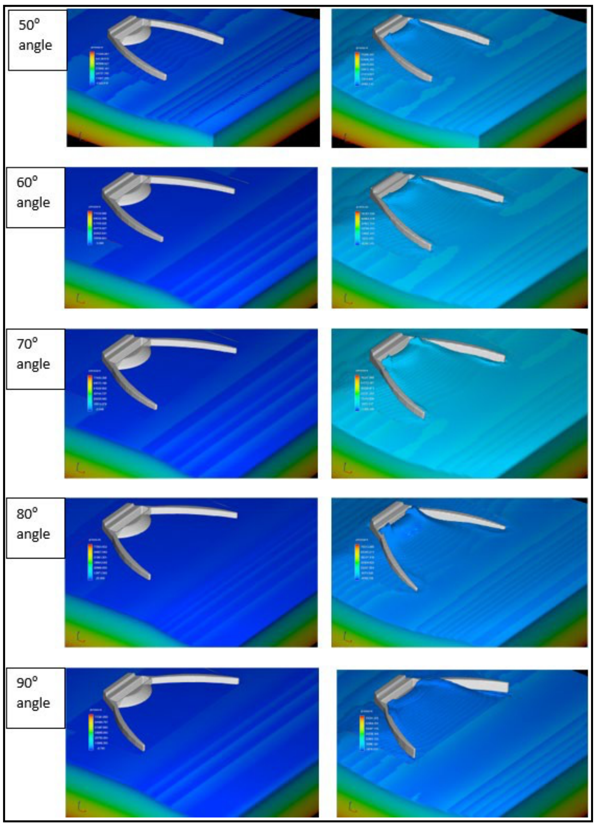


**Fig. 10.** Comparison of waves overtopping discharge according to different guiding wall angles in numerical 3D

The pattern of the graph shows that the angle of guiding wall was affecting the overtopping process. Figure 11 shows the total of overtopping discharge for different angles of guiding wall.

The Figure 11 shows the increasing amount of average overtopping discharge in the reservoir. Best results were obtained with the intermediate value of the guiding wall angles, 80° and 90°. In these simulations the wave condition used were H_s=1.5 m, T_p=4.0 s and the optimum value of the guiding wall angle obtained is 80°. Also, the angle 50°, 60° and 70° lead to substantially lower performances.

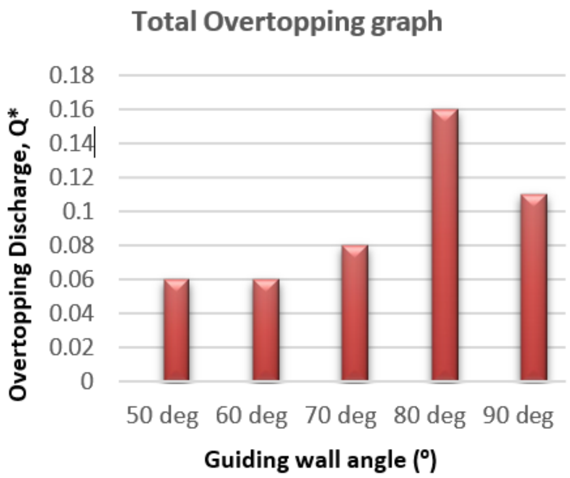


**Fig. 11.** Non-dimensional average overtopping discharge against different guiding wall angles

## 4. Conclusions

The study investigates the overtopping performance of the Wave Dragon device under different wave situations and different angles of guiding wall using Computational Fluid Dynamics (CFD). Based on the results several conclusions can be done to achieve the aim and objective of this study.

From the beginning of this simulation, the first step is to validate the significant wave height during the overtopping wave of the Wave Dragon performance. The study found the significant wave height generated in the numerical simulation increases with the wave height. The results showed a positive correlation of the simulated results between the significant wave height of simulation and experiment.

The first objective quantifies the overtopping discharge due to a difference in significant wave height. The study found the wave height increases with the overtopping discharge. Once a large wave has entered the reservoir, so will overtop a larger volume and produced higher overtopping discharge. The overtopping volume in a wave highly dependent on the height of the wave, so it can overtop the ramp by having only a moderate increase in height. Thus, the overtopping phenomenon affects the height of wave overtop and wave loading up to the ramp of the upcoming wave.

The second objective determines the effect angle parameter of a guiding wall (reflector) on overtopping discharge, the 80° angle of guiding wall produces the best performance and the highest overtopping discharge compared to other angles. Thus, 80° angle of guiding wall is considered as optimal energy discharge gained due to the higher velocity of the wave. A rotation of even a few degrees will have a very adverse effect on the reflection performance of the guiding wall, for instance, 50°, 60°, and 70° produce a lower value of overtopping discharge because the device is less stable. The open guiding wall like 80° and 90° can stabilize the motions of the model. But 90° angle is too wide cause the velocity of the wave to lower and cannot provide higher overtopping discharge.

For further research, several recommendations should be done to improve the output of the result. Firstly, both sides of the boundary should be in asymmetry condition to provide a real situation of the overtopping phenomenon in the wave flume. Another improvement in this study may be taken into consideration, which related to the number of the waves employed, porosity upon the existence of the wave condition, and surface roughness. On the other hand, the previous study used a specific meshing to generate a random wave from the computer program which differs from the numerical configuration in FLOW-3D that had a limitation in producing the specific wave for the simulation. Thus, the input data on a wider spectrum should be used to overcome this limitation.

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