Investigation on Reflected Wave by Different Geometrical Ramp Shape of Overtopping Break Water for Energy Conversions Using Experimental and Simulation

M F Roslan¹, M F Ahmad¹* and M A Musa¹

¹Programme of Maritime Technology, School of Ocean Engineering, Universiti Malaysia Terengganu, Malaysia 21030

*E-mail: fadhli@umt.edu.my

Abstract. Innovation trends on the development of breakwater have prolong its functionality from coastal protection to harness wave energy. One of the latest structural being study is the overtopping breakwater for the energy conversion which integrate breakwater with wave energy converter. An impact of linear ramps on reflection of the structural been studied in detail in some previous researches and create opportunity in exploring vast scope of study including the ramp shape. Therefore, intention of this study is to experimentally investigate the effectivenss of various geometrical ramp shapes of the structural toward the reflected wave. In addition, simulation was conducted and compare with the experimental result to ensure the agreement of the outcomes. This study used different wave parameters and effect of relative depth ($H_m/h$) to acquire data on the behaviour of the reflected wave that describe the effectivenss of the structure. The findings of this study in the experimental work indicates that the cubic ramp shape precedes the linear ramp with 21.5% more efficient under certain wave conditions. Besides, this study additionally reveals similarities in both methods and conclude that ramp shape has significant influence on the reflection of the wave from the structure and the highest percentage of discrepancy for the CFD is 22.3%. However, the contribution of the different ramp shape is absent at the maximum depth but significantly affect as well as the depth decrease.

1. Introduction

Coastal area and the ecosystem offer many services to human society; residential, food supplies, recreational enchantment and industrial activities [1]. Rapid development of the coastal area transforms the landscape and exposed the vicinity toward pollution, erosion and habitat loss. Consequently, most of the world’s shoreline are retreating in a landwards direction cause by erosion process [2] and the ecosystem experienced some of the most rapid environmental change but astonishingly the demographic tendencies increasing swiftly [3]. Hence, preservation and retaining the shoreline from nature characteristic of wave and current is essential.

Countermeasures that may be applied to the coastal area are beach nourishment, groins, sand bypass, detach breakwater and rubble mound breakwater [4]. For quite century, rubble mound breakwater is the most typically used to defend harbours and shore line [5]. It principally dissipated the incoming wave energy on the slope and porous structure, reflected partly to the ocean and partly transmitted into the harbour area because of penetration and overtopping [6]. Recently, the innovation of rubble mound breakwater have integrate the breakwater with wave energy convertor (WECs) recognized as overtopping breakwater for energy conversion (OBREC) [7]. The hybrid system harvest
the wave energy using concrete ramp to increase overtopping phenomenon and store within the reservoir as potential energy which then turns the low head hydraulic turbines to generate electric [8].

The performance of OBREC rely on the overtopping activity that strongly related with the reflected wave; high overtopping creates low reflection due to more dissipation [9]. By changing wave climate and intense sediment scour, reflected wave result in structure destabilization, erosion at nearby beach and unstable ocean state at the entrance of harbor [10-12] Since OBREC used the concept of overtopping to capture wave energy, enhancement on the performance of OBREC are terribly useful. One approach to improvise OBREC is by optimize its geometrical shape or configuration [13,14]. Additionally, overtopping significantly relate with wave run up over the ramp surface; roughness, slope angle, length, crest freeboard permeability and shapes [15]; roughness, slope angle, length, crest freeboard permeability and shapes [16]. Different ramp shapes accumulate different energy for wave run up and have an impact on the reflection of the incoming wave [15].

Hence, this study aims to analyze the reflected wave for various geometrical ramp shapes of OBREC that quantified the amount of energy and determined the efficiency of the structure [17,18]. Reflection coefficient can be obtained using variety of methods that have been proposed by researchers and one of them is using the resolution technique [19,20].To attained the aims, this study performed the experimental work and used the CFD approach by referring previous researchers [21, 22].

2. Method and Materials

The design of the OBREC being improves through the geometrical ramp shape. The ramp designs are based on the previous study which are linear, concave, convex and this study introduce new idea to have cubic ramp that are expected to have better performance.

2.1. Experimental setup

Experimental procedure has been carried out in Port and Harbour 3D wave basin at National Hydraulic Research Institute Malaysia, (NAHRIM). The basin is approximately 30m x 30m x 1.5m and is geared up with multi element wave maker with 30 paddles of the flat type to generate regular wave. and passive wave absorber to avoid reflection of wave. Couple of probes have been deployed in
order to record wave elevation and used to calculate the reflection coefficient. Different type of wave parameters and water depth used to study reflection behaviour creates by OBREC model.

![Figure 2. Illustration for experimental setup](image)

**Figure 2.** Illustration for experimental setup

| Type of Wave | Wave Period Tp (s) | Significant Wave Height Hs (m) | Depth(D) Min-Max (m) |
|--------------|--------------------|-------------------------------|---------------------|
| R1           | 1.43               | 0.0527                        |                     |
| R2           | 1.91               | 0.083                         |                     |
| R3           | 2.04               | 0.102                         |                     |
| R4           | 2.22               | 0.1173                        |                     |

Table 1. Wave parameter and depth

The OBREC model and ramp shapes are designed using AutoCAD software before being construct with the aid from CNC machine. Scale 1:15 (Froude scaling) was used based on previous model developed by Vicinanza [22]. The main structural of the experimental model is estimated to be 4m (wide) x 3.4m (length) x 0.7m (height).

![Figure 3. Design of OBREC and ramp shape using autoCAD](image)

**Figure 3.** Design of OBREC and ramp shape using AutoCAD

The ramp shapes are designed using polynomial equation with 1.8 m height of crest free board and Slope angle used is 19° for better performing of WECs [23].

![Figure 4. Ramp shape configuration: a) Linear b) Convex c) Concave d) Cubic](image)

**Figure 4.** Ramp shape configuration: a) Linear b) Convex c) Concave d) Cubic

Numerous studies have attempted to separate components of incoming and reflected wave which is beneficial in determine the performance of many coastal structures [19]. This study used method proposed by Goda and Suzuki [20] where two history probes have been used to be function as the
wave gauge by installing at least one \( \lambda \) from toe of the breakwater [24]. Fast Fourier Transform (FFT) being used to analyzed and estimate the amplitudes and by smoothing the estimated periodograms, wave spectra are presented to obtain the energies of resolve incident and reflected wave \( E_1 \) and \( E_2 \).

\[
K_r = \sqrt{\frac{E_1}{E_2}}
\]

2.2. Simulation setup

Computational fluid dynamic (CFD) of FLOW 3D provide advantages in time and cost consuming. In this study, FLOW 3D version 10.1 is used to simulate each of the conditions that run for the experiment. The result of both experiment and simulation then compare to validate the availability of the software for future work.

\[
\frac{V_f}{\rho} \frac{\partial \rho}{\partial t} + \frac{1}{\rho} \nabla \cdot (\rho u \mathbf{A}_f) = -\frac{\partial V_f}{\partial t}
\]

\[
\frac{\partial \bar{\mathbf{u}}}{\partial t} + \frac{1}{V_f} (\bar{\mathbf{u}} \mathbf{A}_f \cdot \nabla \bar{\mathbf{u}}) = -\frac{1}{\rho} \left[ \nabla \rho + \nabla \cdot (\tau \mathbf{A}_f) \right] + \bar{\mathbf{G}}
\]

\[
\frac{\partial \mathbf{F}}{\partial t} + \frac{1}{V_f} \nabla \cdot (\mathbf{F} \bar{\mathbf{u}} \mathbf{A}_f) = -\frac{\mathbf{F}}{V_f} \frac{\partial V_f}{\partial t}
\]

In the simulation the basin used to be the major component in the simulation with two subcomponents, breakwater and the ramp. The boundary for the basin was once setup (4m width x 30m size x 1m height) without wave generator. It was setup to create actual condition where at origin point of y-min direction, wave boundary was declared to have linear wave and at the end of y-max direction outflow boundary was used. At z-max, the boundary has been integrated with pressure boundary to determine the time history of hydrodynamics parameters, Z-min is assigned as wall and the rest of the boundary (x-min – x-max) were setup as symmetry.
Further, meshing block used to separate between the region where the fluid is flowing and location of reflected wave takes place using confirming mesh that fit to the geometry. To obtain best result for the simulation and minimize computational burden, ratio between fine and course mesh used is 1:2 as recommended by Flow 3D inventor [21].

Fluid region has been set up to define fluid initial condition of the overall numerical set-up, the water level in front of the structure has been fixed at 0.4 m, 0.35m and 0.45m. A RNG turbulence closure have been chosen. A time step of 0.01s has been employed and finish time has been made up to be 60s.

3. Result and Discussion

The discussion of the result begins with the comparison of experimental results for different ramp shape to the different wave parameter tested. Previous studies reveal that OBREC is able to reduce up to 22% reflection against traditional breakwater by using a linear ramp shape [22]. The most striking result to emerge from this study is that cubic ramp shape shows better performance in each test compared to linear, concave and convex. As Figure 7 shows, there is a significant difference between cubic ramp shape and linear ramp shape on the wave parameter $R_1$ where the cubic precedes the linear ramp shape by 21.5%. Concave also precedes linear ramp by 10% better but linear lead convex shape by 13%. This result is due to the ability of each ramp shape to trap wave energy via overtopping. According to Eurotop, the concave shape has higher capabilities for overtopping compare to linear and convex, though this study has further enhanced OBREC's ability by introducing a new cubic ramp shape to increase overtopping and reduce reflection on coastal defense [13].

![Figure 6. Boundary condition setup](image)

![Table 2. Boundary setup details](table)

| Boundary | Type of boundary condition |
|----------|----------------------------|
| $X_{\text{min}}$ | Symmetry |
| $X_{\text{max}}$ | Symmetry |
| $Y_{\text{min}}$ | wave |
| $Y_{\text{max}}$ | Outflow |
| $Z_{\text{min}}$ | Wall |
| $Z_{\text{max}}$ | Specified pressure |

![Figure 7. Mesh block setup](image)
The result of comparison between experimental work and simulation presented in Figure 8 is interesting because both methods show the same trend for all tests.

**Figure 8.** Experimental result for Kr against different wave

**Figure 9.** Comparison of experimental and simulation
Details for the results of the experimental work and simulation including the discrepancy percentage presented in Table 3. Obviously, the difference is not significant for R1, R2 and R3 wave parameter which is below 10% but the discrepancy percentage for R4 is 22%. This may be due to the splashing factor on the OBREC ramp or interpolation data error within the mashing block causing a certain volume of water miscalculated in the accumulation of energy wave run up and affect the reflection coefficient [25].

Table 3. Details on the result and discrepancy percentage of all tests

| Type of Wave | Linear Ramp Shape | Cubic Ramp Shape | Convex Ramp Shape | Concave Ramp Shape |
|--------------|-------------------|-----------------|-------------------|-------------------|
|              | Experiment | Simulation | Discrepancy (%) | Experiment | Simulation | Discrepancy (%) | Experiment | Simulation | Discrepancy (%) | Experiment | Simulation | Discrepancy (%) |
| R1           | 0.7550     | 0.7236     | 4.1588            | 0.5921     | 0.5796     | 2.1129            | 0.8564     | 0.8345     | 2.5642            | 0.6788     | 0.6484     | 4.4782            |
| R2           | 0.8083     | 0.7778     | 3.7705            | 0.7161     | 0.6818     | 4.7870            | 0.8325     | 0.8048     | 3.3289            | 0.7646     | 0.7327     | 4.1680            |
| R3           | 0.7159     | 0.7403     | 3.4045            | 0.6772     | 0.6420     | 5.2060            | 0.7311     | 0.7754     | 6.0502            | 0.7039     | 0.6809     | 3.2604            |
| R4           | 0.3759     | 0.4588     | 22.0464           | 0.3349     | 0.3845     | 14.826            | 0.3779     | 0.4621     | 22.2929           | 0.3647     | 0.4450     | 22.0230           |

The correlation between reflected wave and relative depth (H_m0/h) presented in Figure 9. For cubic and concave ramp shapes, the reflection coefficient decrease with the depth, however linear and convex ramp shapes show differ trends. Among the plausible explanations for these findings is that when the water level decreases, the wave momentum flux decreases by decreasing its weight of water in the swash zone. Cubic and concave ramp shape indicates its ability when the curve angle affects greatly to reduce the reflection; Reflection coefficient tends to increase with the slope [8]. This study also indicates that at maximum depth, the difference for the reflection coefficients of each different shape is not significant because the area for wave run up has decreased. The ramp shape do not plays it roles to reduce the reflection at this situation although overtopping is expected to be higher; increase of the submerge ramp length causes an increase of reflection [8].
4. Conclusions

In the present paper, different geometrical ramp shapes of overtopping breakwater for energy conversion being tested under circumstances of wave parameter and different depth using experimental work and CFD approach. Flow3D were properly carried out and compare with experimental result to ensure the agreement of the result and confirm the availability of the CFD. It can be conclude that geometrical ramp shape significantly influence the reflection coefficient where in this study reveal that cubic ramp shape has better performance compare to linear, concave and convex. Capability of the CFD in stimulating the experiment and study the behavior of the reflected wave are compatible and the ramp shape do not influence in reducing the reflected wave at maximum depth as the immerse ramp shape reduce the wave run up.

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