DEVELOPMENT OF AN EXPERIMENTAL TEST FOR EVALUATING RAMP SHAPES ON OVERTOPPING BREAKWATER FOR ENERGY CONVERSION

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Abstract:

The utilization of the existing breakwater constructions into wave energy conversion has been often adopted to rendering a revenue of the capital cost of investment. The paper has contributed to viable concept of a new integrated design through more effectively capturing wave-overtopping which finally converts into electrical energy. This design is hereafter called Overtopping Breakwater for Energy Conversion (OBREC). The development of an experimental test of the current OBREC has been conducted to obtain a proper ramp shape through evaluating the amounts of the wave-overtopping discharges into the reservoir incorporated with wave-reflection coefficients. To achieve the objective, ramps of several geometries such as linear, convex, concave and cubic shapes have been experimentally investigated at the National Research Institute Malaysia (NAHRIM) laboratory. The experimental study showed that the cubic-ramp shape has resulted in more significant amount of the wave-overtopping discharge into the reservoir associated with the low wave-reflection coefficient than the other ramp shapes. In general, it is merely concluded that this investigation provides very promising concept of the new proposed OBREC design to harness the larger wave energy.

Keywords: Ramp shapes, OBREC, wave energy converter (WEC); wave overtopping, wave reflection.

NOMENCLATURE

$q^*_{Reservoir}$	Non-dimensional average overtopping discharge	H_s	Significant wave height
$q_{Reservoir}$	Average overtopping	L	Wave length
R_r	Crest freeboard	$E1$	Incident wave
R_r^*	Non-dimensional crest freeboard	$E2$	Reflected wave
S_r	Wave Steepness	Tp	Wave Period
K_r	Reflection coefficient	g	gravity

1. Introduction

The dependence on fuel has led many researchers to find other alternative's source to meet energy demand. One of the energy sources that mostly explored is from the waves, which provide cleanest, safe, and inexhaustible energy (WB et al., 2009; Mustapa et al., 2017). There are more than a thousand patents that have been issued for capturing wave energy (Vicinanza et al., 2014). However, most of them are still under research and immature phase. The main obstacle is believed due to the cost and reliability of the structure to withstand various ocean wave conditions. In recent years, an innovative idea has been proposed to re into a current offshore or coastal structure. Several concepts of integration between WEC and marine structure have been introduced as discussed by Mustapa et al. (2017). One of the most successful integration concepts that have reached the prototype level is

a concept known as Overtopping Breakwater for Energy Conversion (OBREC) (Di Lauro et al., 2019) as shown in Fig. 1.
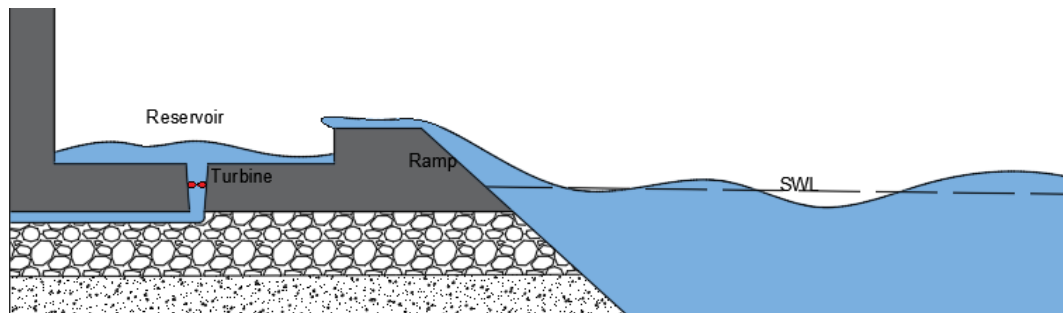

Fig.1: The OBREC Concept

The concept has been tested and formulated at Aalborg University, Denmark since 2012 for energetic wave climate (North Atlantic coastline). It is a combination of traditional ruble-mound breakwater and reservoir structures, which is functioning as erosion protection and energy storage respectively. The incoming waves pass through the breakwater ramp and reach crest freeboard before storing it in the reservoir. Then, the low head hydraulic turbine placed in the reservoir will be rotating for generating the electricity (Iuppa et al., 2016). OBREC's effectiveness in generating electricity has been reported from 2 to 8kW (Mustapa et al., 2017), which could be considered relatively low outcome compared to other WEC devices. This has led to more research exploration in improving OBREC efficiency. Thus, since OBREC used the overtopping concept for capturing the wave; it is essential to improve their waste overtopping water in the reservoir where the increasing of water waste in the reservoir will directly increase the electricity generated. Besides, the behaviors of other hydraulic properties such as wave transmission and reflection were also required to be noticed for the sustainability of the device.

Several attempts have been made to enhance overtopping wastewater as well as other hydrodynamic parameters on OBREC, particularly by improving their structural geometries. In 2014, Italian research group conducted an improvement of OBREC geometries with additional special nose placed on the top crown of the reservoir, and the result showed a significant improvement of average overtopping rate up to 60% and reduction of 22% of reflection compared to original OBREC structure (Vicinanza et al., 2014; Contestabile et al., 2015). However, nose recognition does not appear to be necessary for the location of moderate wave characters. This is because the nose was introduced to prevent overtopping beyond the crown of reservoir, which commonly happened during rough wave situation. In 2016, the same group of researchers had investigated the curve (convex) and flat ramp shape intending to improve the overall knowledge of OBREC behavior. They found that the curve (convex) shape has reduced a reflection and overtopping approximately by 20%. On the other hand, a numerical study using OpenFOAM software was conducted by Barbosa et al. (2019) and analyzed the ramp curvature effect on overtopping discharge of OBREC device. It was reported that convex shape gave the maximum water waste during lower ramp L:B (height / length) ratio but opposite for the highest L:B ratio, which tends to concave ramps bring more overtopping waves (Barbosa et al., 2019). It is believed that the more overtopping occurs due to the seaward face/ramp shape which respects the accumulation of water run-up (Pullen et al., 2007).

This indicates a need to understand more on the influence of OBREC ramp shape to the overtopping and reflection performance. Thus, this paper aims to extend the available knowledge on the effect of ramp shape over the overtopping and reflection coefficients of OBREC by introducing more shape parameters by using the experimental approach. It investigates existing shape (linear) and an additional three types of ramp shapes (convex, concave and cubic) for better understanding and further research.

2. Experiment Procedure and Setup

The experimental setup has been conducted using the National Hydraulic Research Institute Malaysia, (NAHRIM) wave basin facilities. It has 30 m length x 30 m wide x 1.5 m height in size and fitted with multi-element wavemaker with 30 flat-paddles for generating a normal wave and preventing with the wave absorber at the end of the basin. Water level sensors were used in the reservoir to measure the volume of water captured from the

overtopping activity and a couple of probes have been deployed (Fig. 2) in order to record wave elevation and used to calculate the reflection.
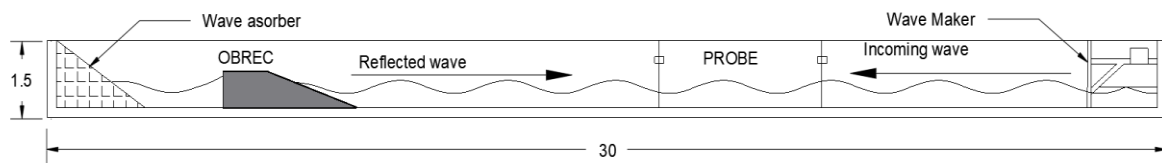

Fig. 2: Illustration for experimental setup

A scale of 1:15 (Froude scaling) of the OBREC model was designed and constructed based on the previous model developed by Vicinanza et al. (2014). The main structural dimensions of the experimental model were estimated to be 4m (wide) x 3.4m (length) x 0.7m (height). It consists of replacing some part of breakwater with a ramp and reservoir as shown in Fig. 3.
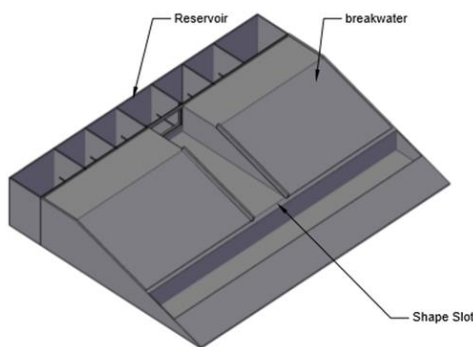
Fig. 3: Main OBREC model in CAD and experimental setup.

In order to investigate the effect of ramp shape over the overtopping and reflection coefficients, four different configurations of ramp shapes have been tested. These were designed using a polynomial equation with 1.8 m height of crest freeboard and slope angle 19° for better performing of overtopping wave converter as stated by Vicinanza et al. (2012). The design parameters like reservoir width and length, polynomial degree and crest level dimensions have to be opportunely modified for Malaysia coastline. Some of these parameters has been evaluated by Musa et al. (2020), Musa et al. (2016) and Roslan et al. (2019). In any case, a specific site study with laboratory tests has to be performed to properly define the OBREC geometrical parameters. Detailed ramp and OBREC parameters used in this research are given in Table 1.

The construction of ramps parameters was mainly used CNC machine with the precision level adjusted to up to ± 1mm. This was to ensure that ramp shape parameters obtained were accurate and according to the desired size. Fig 3 and Fig 4 gives an overall idea of ramps shape construction and setup for this research.

Fig. 4: Ramp shapes construction and assembly process

Table 1: OBREC Parameters and Ramp Shapes.

Type of shape	OBREC parameters (1:15)		2D illustration	Polynomial Degree
	Crest Level (Rr)	Reservoir Width (Br)		
Linear				$f(x) = -a_1 x + a_0$
Convex	0.12	0.415		$f(x) = -a_2 x^2 - a_1 x + a_0$
Concave				$f(x) = a_2 x^2 - a_1 x + a_0$
Cubic				$f(x) = a_3 x^3 - a_2 x^2 + a_1 x + a_0$

In the reservoir, the measurement of the overtopping volume is quantified by water discharge level (h) which recorded via an Arduino ultrasonic sensor (HC-SR04) and data logger (Fig. 5 (a) to (c)). The changes in water level could be detected with precision up to 1mm height and the data logger was set up to collect water level changes in 0.01 second. The reservoir compartment was divided into seven main partitions for measuring overtopping volume through fluid elevation. The separation was to ensure that small changes of volume could be detected with little fluctuation of water level.
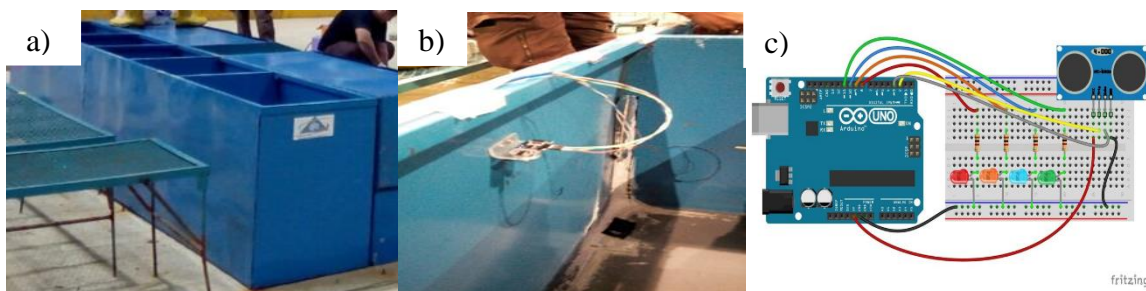

Fig. 5: a) Reservoir separated into 7 parts b) Placement of Ultrasonic Sensor c) Arduino Uno Data Logger setup

Different types of wave parameters and water depth are used in this study to see a wide range of ramp shape impact on OBREC performance. The present study uses the sampling data of time series wave height collected by Institute Oceanography and Sekitaran (INOS), University Malaysia Terengganu from April 2013 to Mach 2014. The data were collected by using Acoustic Wave and Current Profiler (AWAC) equipment laid on the seabed. The device positioned at 5°25'51.98N and 103° 7'9.92E, which was located around 3 nautical miles from shoreline. Four (4) types of waves with regular form are then were presented as average characters according to

the situations. The waves are namely as R1 which represent an average wave during southwest monsoon, R2 is an average wave in a year, R3 average wave during northeast monsoon season and R4 denote as an average maximum wave in a year (Table 2).

Table 2: Wave parameter in scale 1:15

Wave Condition	Wave Period Tp (s)	Significant Wave Height Hs (m)	Wave Length L (m)	Depth (D) Min-Max (m)
Southwest monsoon (R1)	1.43	0.0527	0.213	
Average per year (R2)	1.91	0.083	0.38	
Northeast monsoon (R3)	2.04	0.102	0.433	0.35-0.45
Max wave (R4)	2.22	0.1173	0.513	

The wave was input into wavemaker software to generate the wave and calibrated with probe install in front of paddle. In addition, in order calculate reflection coefficient two gauges were installed near the toe of the breakwater. Then, the incident and reflected spectra were determined using the technique suggested by Nallayarasu et al. (1995).

3. Governing Equations

The overtopping volume inside the reservoir was estimated using multiplication between reservoir areas to water discharge (h) level. Once the volume inside the reservoir is known, it is possible to estimate the flow rate ($q_{reservoir}$) by divided to the time domain. Then the general acceptance model of overtopping research was evaluated by comprehended the potential of non-dimensional overtopping wave plotted against the relative crest freeboard and wave steepness as shown in Equations (1), (2) and (3).

$$q^*_{reservoir} = \frac{q_{reservoir}}{\sqrt{gH_s^3}} \tag{1}$$

where $q^*_{reservoir}$ is a non-dimensional average overtopping discharge in the reservoir and R_r^* is the relative crest freeboard.

$$R_r^* = \frac{R_r}{H_s} \tag{2}$$

where Rr is crest freeboard of the front reservoir (m) and Hs is significant wave height (m).

$$Sr^* = Rr^* \frac{Rr}{L} \tag{3}$$

Where $Sr*$ is a non-dimensional wave steepness and L is the wavelength (m).

Furthermore, to evaluate the effect of the ramp shapes into reflection wave, there are few analysis models has been reviewed. Most of the studies have tried to distinguish inbound and reflected wave elements, mainly for determining the coastal structures' efficiencies (Varghese et al., 2016). This research uses the technique suggested by Nallayarasu et al. (1995) who used two historical probes to operate as the wave gauge by installing at least one wavelength (λ) from the breakwater's toes (Allsop & Hettiarachchi, 1989). In this technique, Fast Fourier Transform (FFT) was used by analyzing and predicting wave amplitudes using smoothing estimated periodograms for presenting spectra. The coefficient (K_R) of the reflected wave is obtained by dividing the square root of resolve incident (E1) and reflected wave (E2) spectra energies as shown in Equation 4.

$$K_R = \sqrt{E_1/E_2} \tag{4}$$

4. Result and Discussion

Fig. 6 shows the time series of overtopping discharge for the different ramp shapes in wave condition R2. The overtopping starts to enter the reservoir at t 12s, and the water level then increased gradually in the reservoir. It also indicates that the cubic ramp shape has the highest overtopping discharge compared to other shapes. Total overtopping discharge volume reaches up to $0.05m^3$ for the 60s running time for cubic ramp shape followed by convex, linear and concave. The result shows significant relationships between geometrical polynomial orders of ramp shape and overtopping discharge. It is believed that the higher overtopping on a cubic shape occurred due to the higher accumulation of wave run-up energy or mass intensity (Fig. 7 and Table 3) on the cubic shape which is supported by Pullen et al. (2007) opinion. However, concave shape indicates a lower overtopping rate compared to other shapes, and it is contrary to the statement by Pullen et al. (2007) who predicted the concave shape attracting more wave run-up. This supposed due to the reflection of wave run-up at the top angle of curvature shape which directed the water to the sea as shown in Table 3. Table 3 gives more explanations regarding top angle curvature for each shape. The finding from this research has shown that there is a significant contribution of ramp shape or geometrical parameters to the overtopping discharge as well as to other hydrodynamic characteristics. It is consistent with the previous discussion which presenting different of hydraulic outcomes for various geometries (Pullen et al., 2007; Vicinanza et al., 2014; Contestabile et al., 2015; Iuppa et al., 2016; Barbosa et al., 2019). It is also similar with the mostly breakwater acceptances which conclude that the types of coastal breakwater structure geometries (sea wall, dike, rubble mound, etc.) play an important factor in affecting hydraulic performance (Calabrese & Vicinanza, 1999, Stagonas et al., 2010).
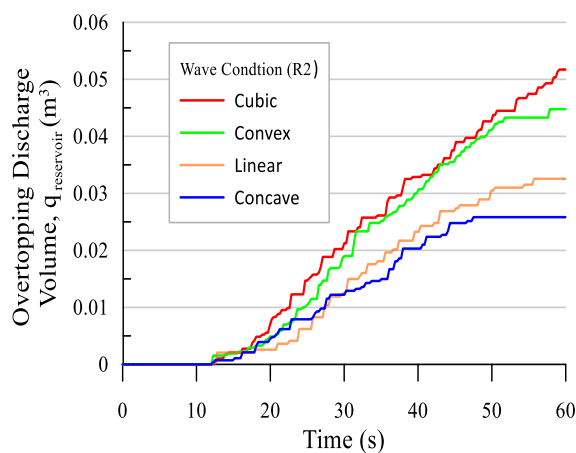

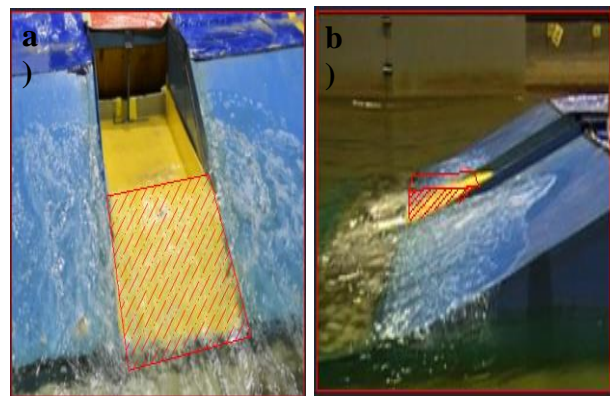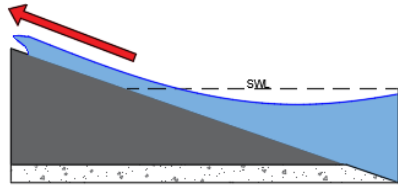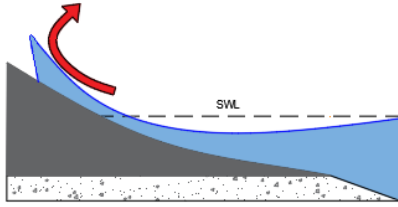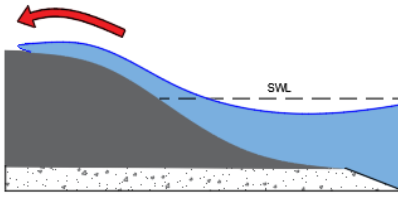Fig. 6: Total cumulative of overtopping discharge volume in time series
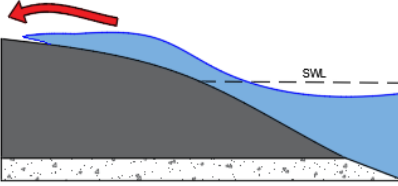
Fig.7: Cumulative wave run-up over the ramp shape

The relationship of overtopping discharge volume (q reservoir) and the wave condition is shown in Fig. 8. The result presents that, overtopping was increase gradually with the increase of wave height (R1-R3) but not for wave condition R4 even though it has the highest wave height. It is happened caused by wave condition R4 has the longest wave period among other conditions that extend the wavelength and reduce the number of the wave creates within the 60s of running time which indirectly reduces overtopping wave. This finding indicates a strong relationship between wave height and period for the overtopping wave which is parallel with the theories of wave energy flux. Whereas it is known that wave height and period are the main functions for wave energy and the increase of both parameters increases the power. It then was led to more run-up and overtopping waves passing through the structure. This finding is consistent with the findings of the past studies by Nam et al. (2008) and Stagonas et al. (2010) who investigate parametric study on overtopping wave converters, and they are reported the wave period and height were increased overtopping performance on their devices.

Table 3: Effect of top angle curvature to the overtopping discharge

| Type of shape	Illustrations in front angle	2D Illustrations	Result and Descriptions
Linear			Medium overtopping discharge. Normal overtopping happens, where the incoming wave run-up over the ramp, passing the crest and enter to the reservoir.
Convex			Medium overtopping discharge. Convex shape provides low cumulative volume intensity for the run-up. However, the top angle of convex shape which directed to the reservoir offers more water for overtopping.
Concave			Low overtopping discharge. The concave shape brings a high cumulative of volume intensity for the run-up. However, the top angles of concave shape direct the water to the sea makes it un-useful for overtopping.
Cubic			High overtopping discharge. The cubic shape offers both high cumulative of volume intensity and top angle of the shape directed to the reservoir.
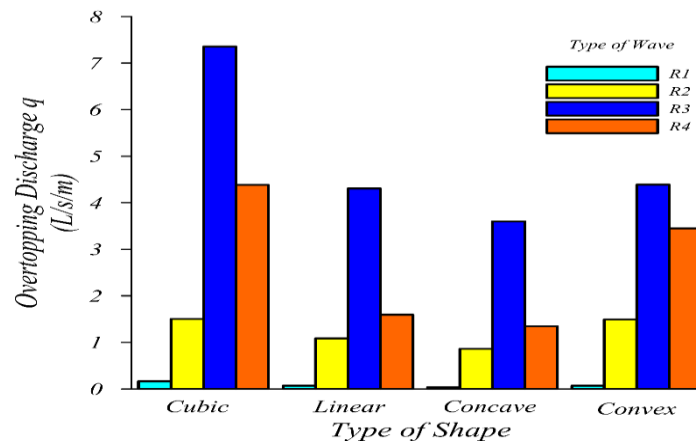
Fig. 8: Total overtopping discharge volume in different wave conditions and ramp shapes

Figs. 9 and 10 show non-dimensional overtopping discharge against crest board and wave steepness, respectively. Both graphs are plotted to compare the effectiveness of shapes based on an exponential trend line which mostly presented by coastal breakwater researchers (Maliki et al., 2017). Interestingly, both figures (Figs. 9 and 10) show that cubic shape has provided a precede trend line of overtopping discharge compared to other shapes in all crest and steepness level. Meanwhile, the convex shape has only the ability to capture overtopping

wave at lower crest and wave steepness. At high levels, their capabilities are quite similar with the linear and concave shapes. This is because the changes in crest and steepness level cause the changes in water intensity as shown in Fig. 11.

Fig. 12 indicates there are significant differences in the reflection coefficient (Ks) among the type of ramps for the wave parameter R1. Most of the ramp types show increases for reflected wave coefficient until wave parameter R2 but decreases for wave parameter R3 and R4. The lowest coefficient of the reflected wave is cubic type followed by convex, linear and concave. The results show the reflection coefficient (Ks) difference between cubic ramp shape and linear ramp shape on the wave parameter R1 where the cubic precedes the linear ramp shape by 21.5%, Convex also precedes linear ramp by 10% better but linear lead concave shape by 13%. This result indicates the ability of each ramp shapes to catch the overtopping wave and directly reduce the reflection create by OBREC. According to Eurotop, the curve shape has higher capabilities for overtopping compare to linear, though this study has further enhanced OBREC's ability by introducing a new cubic ramp shape to increase overtopping and reduce the reflection coefficient (Pullen et al., 2007) reflection and the overtopping performance of OBREC are strongly related (Battjes, 1975; Tofany et al., 2016); the higher the run-up and overtopping, the lower the reflection (Zanuttigh et al., 2009).
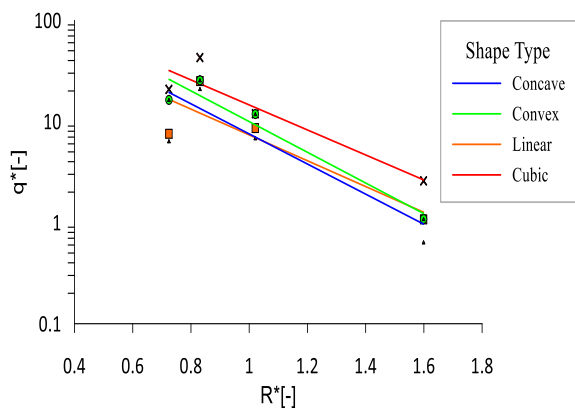

Fig. 9: Non-dimensionless Overtopping Discharge against relative crest board
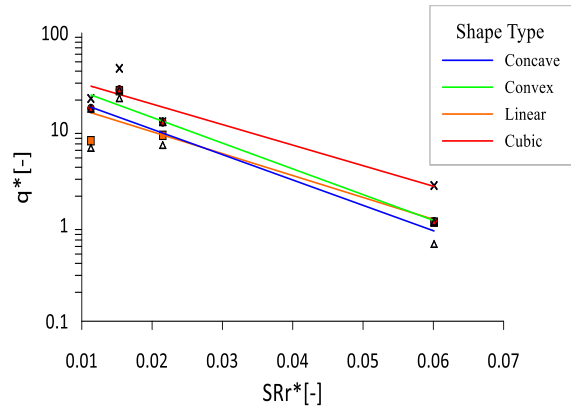
Fig. 10: Non-dimensionless Overtopping Discharge against wave steepness

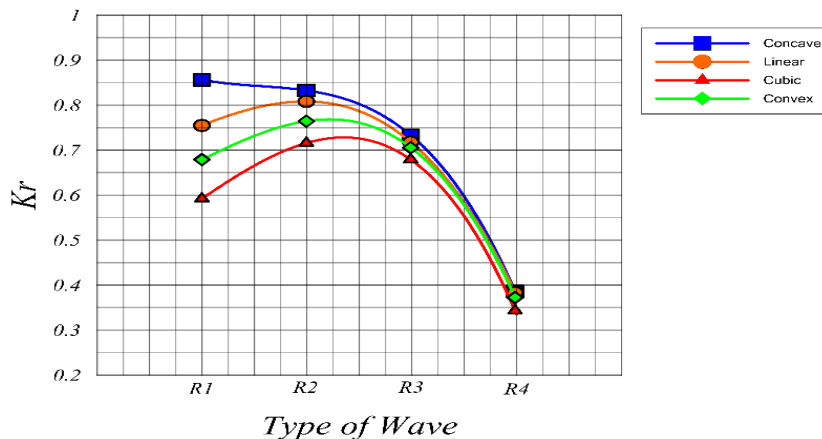Fig. 11: Crest level of water over the ramp

Fig. 12: Experimental result for Kr against different types of wave

5. Conclusions

Geometrical ramp shapes play a significant role in the hydraulic performance of OBREC. In this study, cubic ramp shape has been revealed to has better overtopping performance and absorbing wave (less reflected wave) compare to linear, concave and convex. It is indicated that few factors contribute to the overtopping and reflection; the top angle of the ramp shape and mass intensity or wave run-up energy. The cubic shape has provided both higher mass intensity attraction and good top angle for capturing more overtopping wastewater to the OBREC reservoir. This also could be one of the significant findings in this research that breakdown the normal application of linear ramp on overtopping device and coastal structures.

Moreover, the analysis of different ramp shapes under various wave parameters shows that the increase of wave height and period will increase the overtopping rate in all shapes. It is consistently parallel with wave energy flux theory which identified as a function of wave parameters. Thus, it indirectly shows that the changes of wave parameters should not be a constraint for future ramps shapes innovation.

Overall, the findings from this research could be used for further development and investigation. The project will also provide valuable knowledge of cubic ramp shape parameters as better shape configuration to hardness power in general and particularly for local users.

Acknowledgements

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