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EXPERIMENTAL COMPARISON OF LINEAR AND CUBIC RAMPS FOR HYBRID OVERTOPPING BREAKWATER ENERGY CONVERSION

MOHD AZLAN MUSA, MUHAMMAD FARIS ROSLAN*, AHMAD FITRIADHY, ALIASHIM ALBANI, MOHD HAIRIL MOHD, MOHD ASAMUDDIN A. RAHMAN, MOHAMMAD FADHLI AHMAD AND MUHAMMAD NADZRIN NAZRI

Department of Maritime Technology, Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.

**Corresponding author: m.farisroslan@gmail.com*
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Abstract: Overtopping Breakwater for Energy Conversion (OBREC) is a new integration design concept with multifunctional abilities. The concept used structure sharing cost strategy between Wave Energy Converter (WEC) and traditional breakwater with the aims of energy capture and protection purposes. A prototype of the OBREC device was developed in Italy in 2017 and showed unsuitable output for mild wave conditions. Thus, several studies have been conducted to increase the hydraulic performance of OBREC, particularly by improving their geometries. The latest finding identified that the Cubic ramp geometry had given a promising result in increasing their effectiveness. Nevertheless, a comprehensive study of Cubic shapes on wave behaviour variations is still limited. Therefore, this study will comprehensively investigate the effect of environmental variation over the cubic and linear (as a basis) ramp shapes. Physical experimental methods were used in this study by comparing the hydraulic and power performances of both shapes to be implemented in Malaysia waters. The result indicates that cubic has higher performances than the linear shape for almost all environmental conditions. However, OBREC application in Malaysia requires support from other renewable energy sources, especially during non-monsoon season.

Keywords: Malaysia wave, OBREC, overtopping, ramp shape, wave energy device.

Introduction

Wave is an alternative source of energy that has been actively studied to generate electricity. It is anticipated that converting less than 0.1% of ocean energy into electricity will supply more than five times the world's energy requirement (Muzathik *et al.*, 2011). The use of wave energy to generate electricity has several advantages, such as high predictability and high density in many places, and therefore, has become a common research theme for further studies.

Thousands of concepts have been developed, with some fully implemented; however, the advancements show that wave energy devices (WEC) are still far from being used in wide practical engineering applications (Drew *et al.*, 2009). It is believed that the high construction and operation costs of WECs have led to the unconfident level of investors to participate in this field. According to Mustapa *et al.* (2017), maintenance and constructions cost has been the main obstacles that limit the development of WEC implementation. Thus, a structure-sharing strategy could be one of the solutions to reduce costs. A standalone device can be integrated with hybrid systems embedded within another existing coastal or offshore structure. The cost-sharing, space-sharing, and multi-functionality of hybrid structures can all be achieved through the integration strategy. As a result, the cost per structure may be efficiently decreased and wave energy device becomes more feasible (Zhao *et al.,* 2019).

Thus, this paper focuses on integrating a breakwater with an overtopping wave device, which was introduced by researchers from Italy in 2014 (Vicinanza *et al.,* 2014). This innovation, called "Overtopping Breakwater for Energy Conversion (OBREC)" aims to utilise traditional breakwater fully. Italian researchers have implemented it for a full-scale prototype test at Naples harbour, as shown in Figure 1. The concept is seen as very compatible and suitable to be adapted in existing Malaysia breakwaters, where some of their geometries are quite similar as demonstrated in Figure 2.

However, the main challenge of OBREC is to operate in poor (<4 kW) and mild wave (4-10 kW) climates as stated by (Contestabile *et al.,* 2020). To resolve those issues, researchers started to improve their hydraulic efficiency towards economic viability. In 2014, the OBREC was added with a nose or "parapet" on top of its structure to reduce the overtopping discharge at the rear side and collect more water in the reservoir. In their findings, the device has increased up to 50-60% overtopping volume to the reservoir (Vicinanza *et al.,* 2013; Contestabile *et al.,* 2015; Malik *et al.,* 2017). Since that, parapet has been chosen as criteria for OBREC design (Contestabile *et al.,* 2017). A similar geometrical modification study (Luppa *et al.,* 2016) by accessing curve ramp shapes aims to increase OBREC performance. However, the assessment reported that the curve shape had reduced performance by approximately 20% compared to a linear ramp. It is believed ramp shape parameters have contributed to the overtopping discharge due to the accumulation of wave run-up energy as stated by (Van der Meer *et al.,* 2018). Further study on ramp parameters has been conducted by (Barbosa *et al.,* 2019) which determines that concave and convex shapes are potential parameters for replacing linear shapes. Furthermore, the latest study by (Musa *et al.,* 2018; 2020; 2021) found that the cubic ramp shape is the best parameter for allowing more overtopping waves to enter the reservoir. In that study, seven polynomial shapes were tested using experimental and simulation approaches under mild wave conditions. However, it did not emphasise the variation of wave and environmental characteristics, especially for poor wave conditions.

Thus, this paper aims to comprehensively study cubic ramp shapes on the variation of environmental conditions (from low to high), particularly for Malaysian applications. The physical experimental model approach was applied to determine the actual performances of OBREC in the selected location. The study will highlight the comparison effects between

Figure 1: OBREC prototype implemented at Naples harbour, Italy (Pasquale *et al*., 2016)

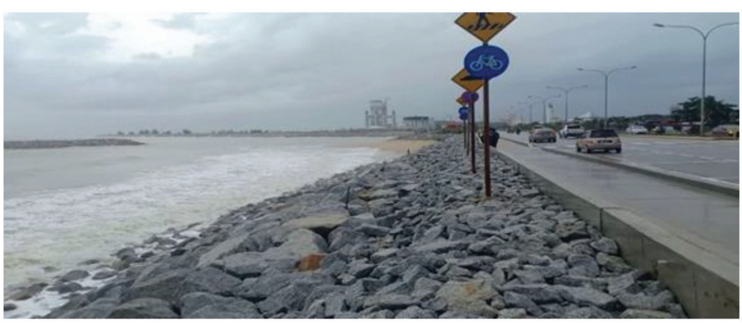


Figure 2: Breakwater design at Kuala Terengganu, Malaysia

cubic and liner shapes (as a basic parameter) to determine the real contribution of cubic shape in improving OBREC performance.

Materials and Methods

In order to investigate the effect of local wave characteristics on OBREC cubic shape, a specific location was selected. It is planned to be adopted at the Kuala Terengganu shoreline, which is currently experiencing erosion problems and is in the process of breakwater construction. A 10 m OBREC has been proposed to be built for pilot purposes. It enables output comparison based on prototypes from Italy researchers in 2016 (Pasquale *et al.,* 2016). For this study, an experimental scale of 1:15 was developed to investigate the overall effects of site environmental conditions on the OBREC modification. Sampling data of time series wave height is collected at the selected location by the Institute of Oceanography and Environment, Universiti Malaysia Terengganu, every year. The data were collected using Acoustic Wave and Current Profiler (AWAC) equipment laid on the seabed. It was specifically positioned at 5°25'51.98N and 103°7'9.92E, located around 300 m from the planning site. A simple analysis of energy flux in monthly and wave-scatted distribution is computed and shown in Figures 3 and 4. An estimated average wave power flux of 7.8 kW/m during monsoon and 0.5 kW/m non-monsoon were obtained, respectively. The data obtained clearly show that the potential wave power in Malaysia is slightly in the low and medium categories, as predicted by most of the previous researchers (Yaakob *et al.,* 2016).

In order to test all wave conditions from low to high potential, four main scenarios representing variations in wave period, wave height, draft, and months were tested under cubic and linear ramp configurations as shown in Table 1. Condition 1 represents the average wave height per year at various periods, condition 2 is the average wave period from minimum to maximum wave height, and condition 3 denotes the average wave height and period at the different draft lines. Lastly, condition 4 represents monthly average wave characters (Table 2).

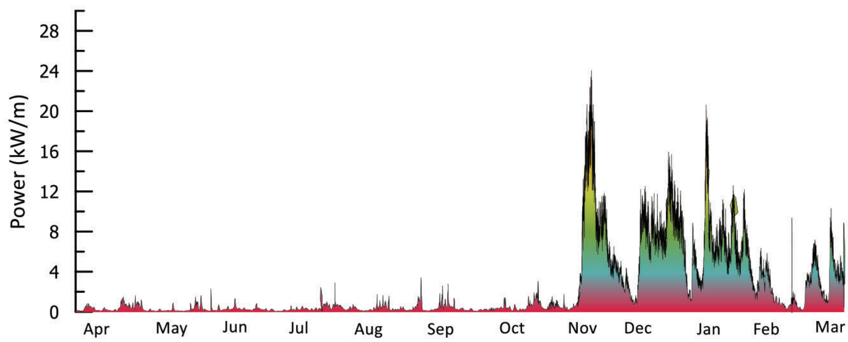


Figure 3: Wave energy flux in Kuala Terengganu area

Hs(m)	>10	9-10	8-9	7-8	6-7	5-6	4-5	3-4	2-3	1-2	0-1	Total
	238	239	1533	2255	1871	3202	4339	3493	2004	390	1	
>3	1	3	78	56	2							140
2.5-3.0		30	209	168	33	6						446
2.0-2.5	3	52	512	553	152	40	2					1314
1.5-2.0		49	420	803	571	96	42	4				1985
1.0-1.5	2	10	93	283	582	189	382	120	3			1664
0.5-1.0	78	35	112	243	327	1357	1671	1231	583	6		5643
0-0.5	154	60	109	149	204	1514	2242	2138	1418	384	1	8373

Peak Period (s)

Figure 4: Scatter table in Kuala Terengganu area

Table 1: Test parameters for conditions 1 to 3 (scale 1:15)

Test Conditions	Significant Wave Height Hs (m)	Period Tp (s)	Draft d (m)
Condition 1	0.083	1.03-2.32	0.4
Condition 2	0.02-0.16	1.91	0.4
Condition 3	0.083	1.91	0.3-0.5

Table 2: Test parameters for condition 4 (scale 1:15)

Month	Significant Wave Height Hs (m)	Period Tp (s)	Draft d (m)
January	0.128	0.086	
February	0.110	0.054	
March	0.107	0.056	
April	0.104	0.032	0.4
May	0.082	0.02	
June	0.075	0.034	
July	0.074	0.034	
August	0.085	0.034	
September	0.079	0.028	
October	0.109	0.076	
November	0.181	0.148	
December	0.208	0.096	

Experimental Model

Two ramps (cubic and linear) were developed based on Malaysia's breakwater and current OBREC geometries. The ramp was developed to have a crest height of up to 1.2 m as recommended by an early study conducted in 2017 (Musa *et al.,* 2016). The physical art of the ramp is illustrated in Figure 5 (a), while Figure 5 (b) shows sketching in 2D and 3D. The ramp structure is placed on the main body (representing breakwater) and the volumes of overtopping discharge output were measured in the reservoir attached at the back of the main device structures.

The experimental model was divided into three main components: (Main body) breakwater, (shape slot) containing various ramp shape parameters, and (reservoir) for overtopping measurement. The material used for constructing the model was 90% iron and 10% stones. There is a difference between this and the real application in which concrete is used. The roughness effect of both materials is assumed to be constant and does not have many

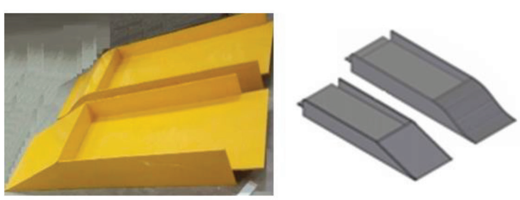


Figure 5 (a): Physical ramp model in the experiment influences on the overtopping discharge. The model applied a 1:15 scale and cut using a CNC machine with the precision level adjusted to up to ± 1 mm. The main body of the model was estimated to be 4 m (wide) x 3.4 m (length) x 0.7 m (height). The complete processes of model development and construction are shown in the following Table 3.

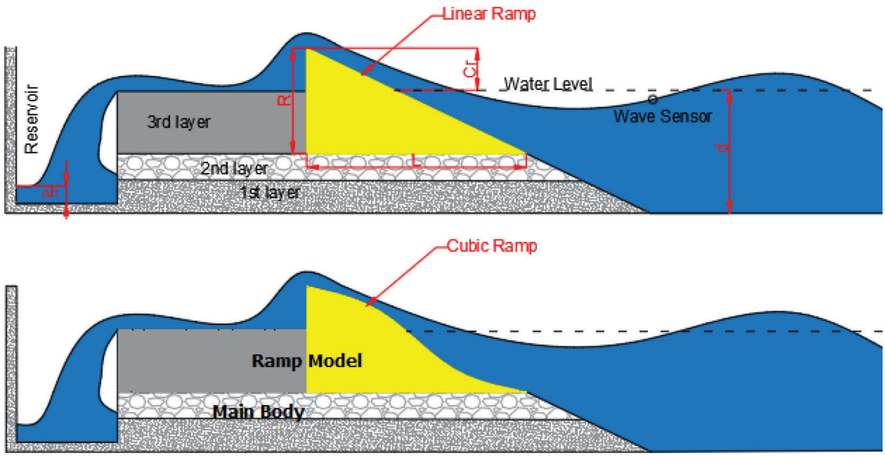
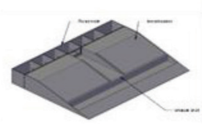


Figure 5 (b): Sketch drawing in 2D representing the ramp and breakwater model in the experiment

Table 3: Illustration of model construction

Illustration	Description
 	Design and G code processing for CNC machine.
 	Cutting and assembly of the ramp shape parameters. The geometries have been measured for precision up to ± 1 mm.
 	Basement/reservoir development. It has been constructed using steel with three layers of spaces filled with sand and two types of stone size.
 	The model is finished with paint and transferred into the basin for installation.
 	The model is arranged in the basin and ready for the calibration process.

Experimental Procedure

The installation and experimental activities were carried out in the Port and Harbour 3D wave basin at the National Hydraulic Research Institute Malaysia (NAHRIM). The basin was roughly 30 m x 30 m x 1.5 m in size and had a multi-element wave maker with 30 flat paddles. It was utilised with a passive wave absorber for preventing reflection waves. Model test configuration is shown in Figure 6.

Two measurement systems were deployed to estimate the performance of the OBREC device: Wave elevation sensor and water level sensor for measuring overtopping volume. Wave elevation sensor was placed at the toe of the breakwater structure for input wave measuring. The recorded time and frequency domain were then analysed using software embedded in wave maker machine provided by HR Wallingford Company. The software directly calculated significant wave height (*Hs*) and wave period (*Tp*) using the statistical distribution of zero cross-analysis method. The calibration was conducted to ensure that accurate input data were located for further testing. Overtopping discharge was measured using the volume flow rate inside the reservoir. The reservoir should be able to quantify the amount of collected water accurately. The reservoir was divided into five sections to ensure that it could be measured in small and large-scale volumes. The size of each partition in the reservoir was as follows: Tank 1 = 0.65 x 0.531 x *h*, tank 2, 4 = 0.7 x 0.531 x *h*, and tank 3, 5 = 0.975 x 0.531 x *h*. Each tank is installed with a water level sensor to monitor the water level variation, which can reflect the dynamic change in the overtopping discharges. The sensor works on the principle that the water level (h) changes directly proportional to the volume of overtopping discharge. The sensor measuring accuracy is 1 mm. The total volume at time series data can be calculated by adding all tank volumes.

Governing Equations and Data Analysis

Linear and Cubic ramp shape performance were estimated based on hydraulic efficiency structure. It can be defined as the power stored in the reservoirs ($P_{reservoir}$) divided into the power of the incoming wave (P_{wave}) as shown in Equation 1.

$$\eta_{Hdr} = \frac{P_{Reservoir}}{P_{Wave}} \quad (1)$$

$P_{Reservoir}$ is defined as the potential power available from an overtopping wave. It can be determined by using Equation 2. While P_{wave} can be estimated using Equation 3.

$$P_{Reservoir} = \rho g H q \quad (2)$$

$$P_{Wave} = \left(\frac{\rho g^2}{64\pi}\right).0.9T_p.H_s^2 \quad (3)$$

where ρ is sea water density, g stands for gravity, Tp is wave period, Hs denote significant wave height, H represents the head of water discharge above the turbine, and the most important parameter is q which represents as overtopping rate. It is usually given as the average discharge per meter of wave crest (m3/s per m). This was estimated by dividing the selected volume by the time domain and per meter length of a model, as shown in Figure 8 and Equation 4.

$$q = \frac{\left(\frac{\Delta V}{\Delta t}\right)}{m} \quad (4)$$

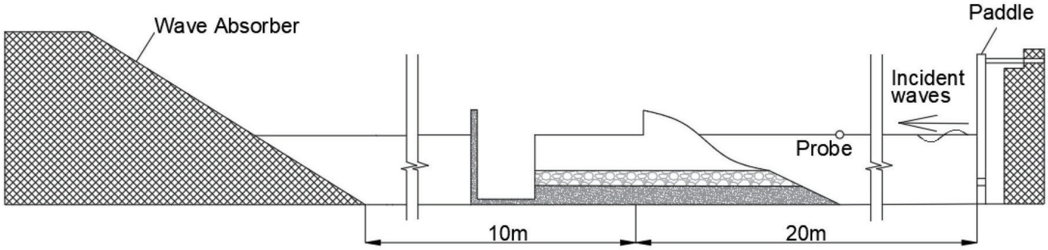


Figure 6: Model test configuration

Results and Discussion

Typical wave overtopping behaviour in the experimental model for cubic and the linear ramp is illustrated in Figure 7. An incoming generator wave approaches the device structure, as shown in Figure 7 (a). The next Figure 7 (b) shows the wave starting to pile up and breaking on at the toe of the structure. The water then runs up over the ramps as presented in Figure 7 (c). Finally, overtopping occurs when the waters pass over the crest freeboard and fill the reservoir as shown in Figure 7 (d).

Figure 8 shows the cumulative volume outputs of cubic and linear ramp models versus time series. It utilised a wave height of 0.08 m and a period of T=1.24 s. The water began to enter the reservoir in both configurations at t equal to 11 s, which indicates that the waves had started to stabilise and interact with the structure. As the wave passes over the crest, it will increase the water level in the reservoir. It also shows that unstable cumulation water patent is illustrated by the blue and purple colour's graph, which should be in more stable steps for linear wave input. However, the trend is consistent with the discoveries by (Kofoed, 2002; Nam *et al.,* 2008) who give the reasons that happened due to the presence of destructive and constructive waves, reflection process and loss of energy. This output also indicates that a stable condition of volume rate is between 30th to 50th s. Thus,

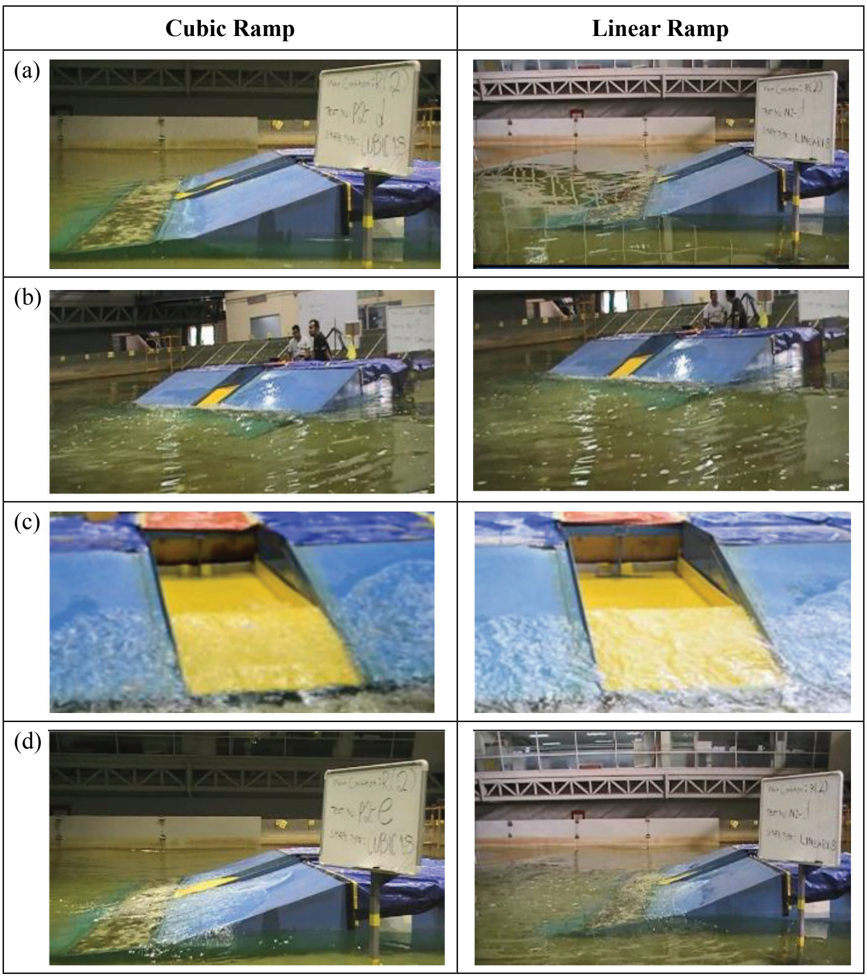


Figure 7: Overtopping wave occur during experimental test

future analyses of the overtopping rate are using this period by dividing volume by 20 seconds, as shown by Equation 4.

While in Figure 9 presents the overtopping rate between cubic and linear shapes in terms of wave height variability. Both shapes show that wave heights are proportioned to the overtopping rate. The increase in wave height will increase overtopping performances. At the highest wave height, the relative crest freeboard will be less, thus giving an advantage to the wave to overtop. The results agreed with the latest finding by (Palma *et al.,* 2020; Shankar *et al.,* 2002), who also indicate the same output pattern. Figure 9 also demonstrates polynomials trend line is developed for both shapes. The aim is to investigate the relationship between overtopping rate and wave height. According to the coefficient of determination, R^2, in statistical modelling, the experimental result of Cubic shape shows that about 89% of the variation in overtopping rate in the reservoir is associated with variation in wave height. In contrast, the experimental result of the Linear ramp shows that about 90% of the variance is associated with regression line. It means that the experimental data fits both the Cubic and Linear ramp regression trend lines.

A comparison among the wave periods at constant wave height (Hs=0.083 m) is shown in Figure 10. The result demonstrates that the wave periods contributed much to the influence of overtopping wave discharge for both shapes. The increasing wave period will increase overtopping performance, consistent with the finding by (Nam *et al.,* 2008; Mozahedy, 2010) who conclude that wave flux (proportioned to period) is the contributory factor for such a situation. Figure 10 also denotes that the overtopping rate for cubic shape is better than linear at the short period. However, both shapes have no significantly different output at higher period conditions. At a short-wave period, the cubic shape has allowed the constructive wave to happen closer to the structure and indirectly allows more water to surpass the structures.

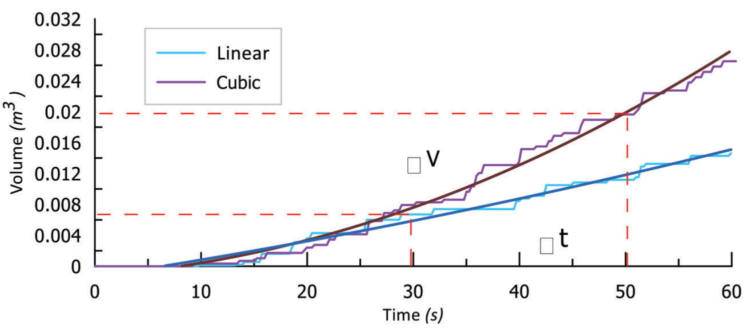


Figure 8: Comparison of cumulative volume between linear and cubic in time series

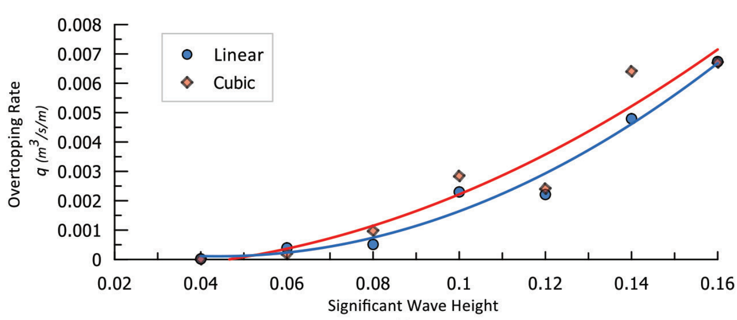


Figure 9: Overtopping rate for various wave heights in Malaysia

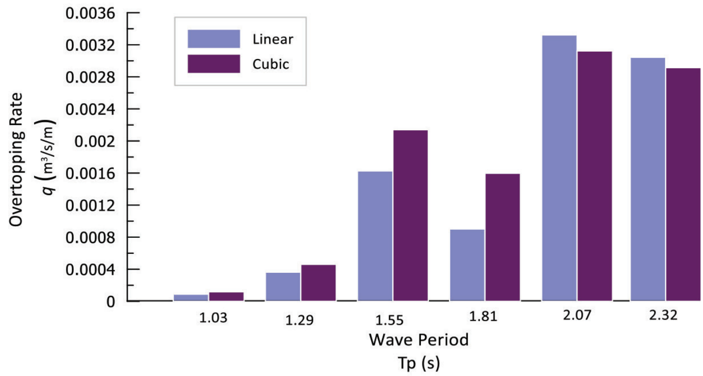


Figure 10: Overtopping at different wave periods in Malaysia environment

Figure 11 shows the same pattern of the overtopping wave of the cubic and linear ramps over the different drafts at Hs=0.083 m and Tp=1.91 s. The increase in the draft will indirectly increase overtopping performance, which is similar to the finding by (Nam *et al.,* 2008; Cavallaro *et al.,* 2020). The cubic ramp has dominated the overtopping amount at all draft levels. At the higher draft level, the cubic and linear performances were almost similar since the accumulations of wave run-up energy for both shapes were quite similar.

In order to determine the annual performance of OBREC in Malaysia water, an application of the annual performance of 10 m length energy breakwater was calculated based on output scaling using the Froude similarity method. The finding is presented in Figure 12, which shows the estimation of power generated in particular months. It can be seen that the highest overtopping power occurs from November to January, which relates to the North East monsoon (rough wave character). It achieves up to 45 kW for cubic shape and 40 kW for linear shape, respectively. However, from March to July, related to South West monsoon (calm wave character), the overtopping power rate reduced drastically and required more improvement. The overall average performance of OBREC was about 6.62 kW for cubic shape and 4.81 kW for linear shape. On the other hand, the result presented in this section is quite similar to the finding calculated by (Kralli *et al.,* 2019; Palma *et al.,* 2020) who estimated OBREC power contribution in deference places and situations.

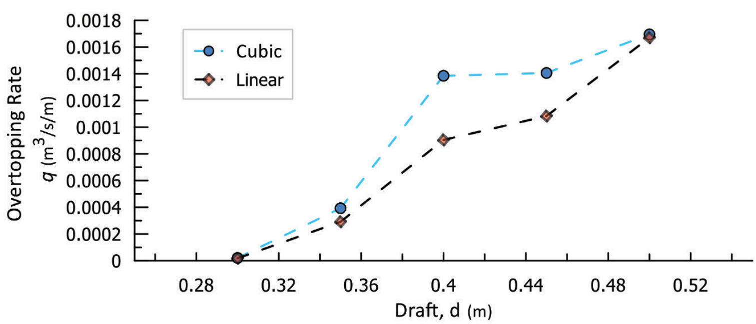


Figure 11: Overtopping wave for various drafts in the Malaysia environment

The percentage of wave energy captured by the device could be defined as hydraulic efficiency, shown in Table 4. The result indicates that the average hydraulic efficiency of Cubic shape is 9.14% and linear is 6.64%, respectively. The wave height is proportional to hydraulic efficiency due to more flux energy.

Conclusion

OBREC device has been designed with multiple functions to overcome erosion and wave energy demands. It has been developed up to full-scale implementation in the European region. Nevertheless, it has low energy efficiency, especially in poor and medium wave conditions like Malaysia. Several studies on the OBREC ramp shape geometries have discovered that the cubic ramp types can increase efficiency. However, the past study has not conducted a deep study on the variation of environmental conditions using cubic shape. This study extends past finding by comparing the environmental effect on cubic and linear ramp shapes. This research shows that cubic has advantages for all environmental conditions (wave height, period and draft). An average performance of OBREC applied in Malaysia waters was calculated at

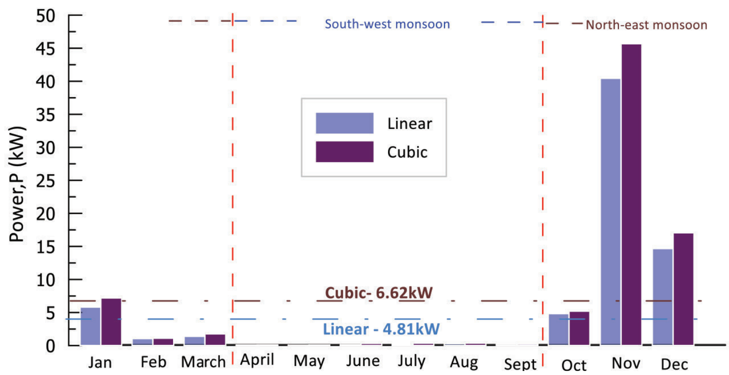


Figure 12: Overtopping power at various months

Table 4: Hydraulic efficiency of OBREC device applied in Malaysia

Tp	Hs	Wave Energy Flux (W/m)	Hydraulic Efficiency Cubic Shape (%)	Hydraulic Efficiency Linear Shape (%)
7.43	1.29	5463.16	13.17	10.64
6.36	0.81	1843.19	5.96	4.05
6.24	0.84	1944.85	9.06	6.61
6.05	0.48	616.14	1.57	1.32
4.74	0.3	188.66	4.23	2.48
4.37	0.51	502.55	6.35	2.8
4.27	0.51	490.54	7.23	3.74
4.93	0.51	566.15	6.40	4.39
4.58	0.42	357.11	6.01	5.78
6.34	1.14	3639.88	14.27	10.51
10.48	2.22	22820.14	20.01	13.33
12.05	1.44	11037.43	15.46	13.28
Average Hydraulic Efficiency			**9.14**	**6.64**

about 6.62 kW for cubic shape and 4.81 kW for linear shape, respectively. It also found that cubic shape has improved from 6.64% to 9.14% average hydraulic efficiency compared to the linear ramp, which equally with enhancement up to 37% power generated. An overall finding has guided the upcoming prototype model to consider cubic shapes in their projects. It can also open up further fundamental studies by deeply investigating cubic ramp geometries, especially with their inflection point locations.

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