environmental sciences
proceedings

Proceedings

Measurements of Wave Reduction Due to Artificial Reef With Varying Width on an Atoll

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† Presented at the 6th International Electronic Conference on Water Sciences (ECWS-6), Online, 15–30 November 2021.

Abstract: The Spratly Islands consist of many islands, banks and shoals and especially coral reefs. Since 1980s, manmade structures have been increasingly constructed, thus resulting in unexpected negative effects on these shoals and reefs. Reef balls would be a feasible measure to create a favorable environment for restoring corals and sea creatures and to reduce waves attacking any cay of the atoll platforms. Therefore, the article explores how a field of Reef Balls affect the propagation process of and reduce the height of wave on an atoll. Using a 2D physical wave flume, we conducted 75 test scenarios, which combine three crest freeboards, five widths of the Reef Ball field and five deep-water waves. The experimental results reveal that the width and freeboard mainly govern the wave reduction. The wave reduction efficiency tends to be dependent upon the relative field width. Furthermore, the Reef Balls field performs most effectively with a width ranging from 1/5 to 3/5 of the shallow water wavelength (on the atoll platform).

Keywords: atoll; artificial reef; wave reduction; reef width; wave reduction efficiency; reef freeboard; Reef Ball (RB)

Citation: Thuy, P.T.; Tung, T.T.; Le Hai, T. Measurements of Wave Reduction Due to Artificial Reef With Varying Width on an Atoll. *Environ. Sci. Proc.* **2021**.

Academic editor: Zhi-jun Dai

1. Introduction

Researchers divided coral reefs into 3 basic types: fringing reef, barrier reef and atoll (Figure 1) [1]. Atolls do not exist separately, they often gather in groups, for ex-ample: the Maldives Islands in the Indian Ocean, the Marshall Islands in the Western Pacific Ocean, the Seychelles Islands in the Indian Ocean, and the Spratly and Paracel Islands in the East Sea of Vietnam.

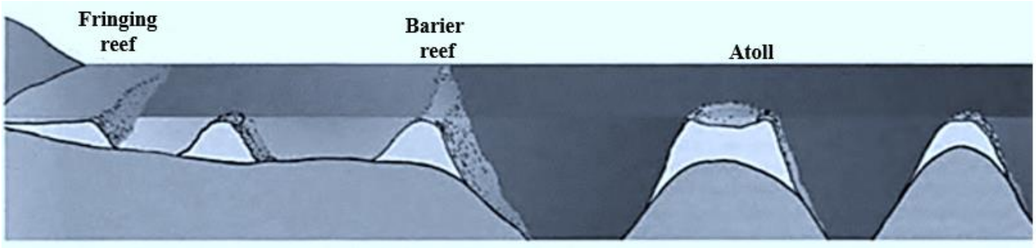

Figure 1. Coral reef types (Spalding, et al. 2001 [1].

Atolls are made of underground mountains at great bathymetry. The surface of these mountains have a part that always rises out of the above the sea water level even at highest tide, called core. The coral platforms around the core are expanded many times larger than the core. Beyond the coral platforms are high fore-reef slopes, con-tinuing into the deep sea (Figure 2).

Located in the middle of the ocean where the hydrodynamic regimes are really complicated, these atoll topographies are made up of coral rocks with different properties. In the center of these atolls, the corals have a high density and solidity, but on the surface and the platform, the large porosity of corals are easily damaged by incident waves.

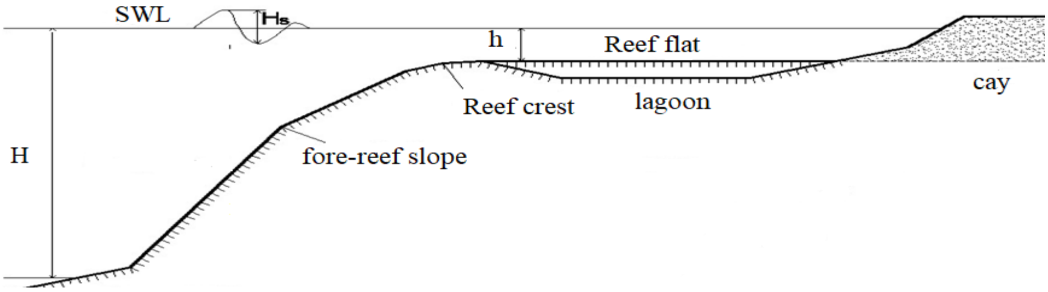

Figure 2. Topographical characteristics of the coral reef .

On the fore-reef slopes and platform, seagrasses and seaweeds grow and develop. Currently, due to human activities and climate changes, this ecosystem has been destroyed in many places, and the recovery rate is quite slow. It needs a solution to both reduce waves, prevent erosion and help restore the ecological environment of these atolls. The suggested solution is to use artificial reefs. Amongst many others, Reef Balls™ would be a feasible measure to create a favorable environment for restoring corals and sea creatures and to reduce waves attacking any cay of the atoll platforms. Most previous research works have focused on the bio-environmental aspects such as fish populations in the vicinity of the reef, reef productivity, or comparison between artificial reefs and natural reefs[2]. However, these artificial reefs also change the hydrodynamic regime on the platform, especially wave characteristics transmitted through the reefs [2]. Therefore, the article explores how a field of Reef Balls affect the propagation process of and reduce the height of wave an atoll platform. To this end, experiments in a 2D wave flume were conducted with varying crest freeboards, field width and water depth.

2. Experiment design

The model experiments were carried out in Holland wave flume in Thuyloi University which is 45m long and 1.0m wide, from January to May, 2021. The piston-type wave generator is equipped with an active reflection compensation system and capable of making irregular wave height up to 0.30 m and 3.0s in peak period.

2.1. Prototype conditions

The geometry of an atoll is based on topographic profile of 01 cay in Spratly Islands: the core elevation is +4m and has a hard embankment surrounding the core; the average width of platform is about 300-600m, the fore-reef slope is 1/5, the shore of the island [4].

The water depth on the platform fluctuates according to the topography and the average water level is from 2m to 3,5m [4].

Deep water waves: the dominant wave direction are Northeast and North with the height and period of Hs = 2.0-2.5m and T_p=6.2s-7.0s respectively [4]. Extreme waves height can reach over 10m [4]. However, due to the limited water depth on the platform (average 2-3.5m), the wave height in shallow water is determined by the formula suggested by Miche (1944), Divoky el al (1970)), Chen and Wang (1983) is in the range of 2-2.5m

$$H_{max} = \frac{\gamma_1}{k} \tanh\left(\frac{\gamma_1}{\gamma_2} kd\right) \quad (1)$$

A field of Reef balls was used as an artificial reef, would be a feasible measure to create a favorable environment for restoring corals and sea creatures and to reduce waves attacking any cay of the atoll platforms. The Reef Ball size was selected based on the standard of Reef Ball [5] and the water depth on the reef flat (the surface porosity of RB is 33%)

2.2. Model set up

The location of artificial reefs is at a half of the reef flat length [6]. Based on the prototype conditions and capacity of wave flume, the model length scale of 1/15 was selected.

Capacitance wave probes are installed in three regions along the reef flat and in deep water. Of which, P1 measured deep-water waves, located at 15 m from the wave maker; four wave Probes P2, P3, P4, P5 are arranged in front of the reef to measure and detect reflected waves from beach or structure. P6 measured behind the reef. The sampling rate was set at 50 Hz for all wave gauges. The experimental setup is shown in Figure 3.

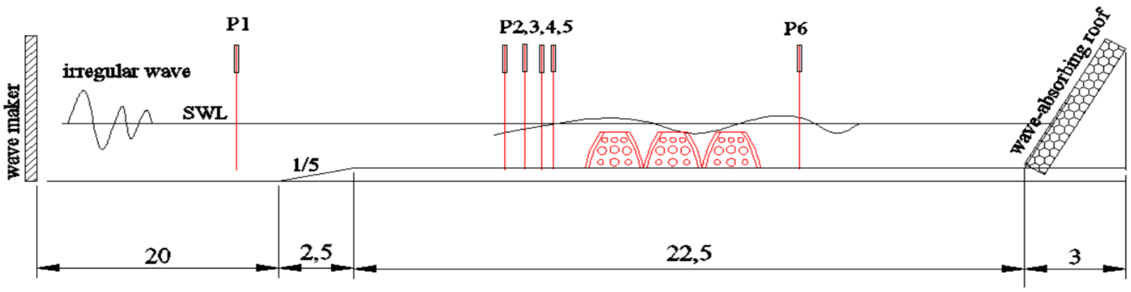

Figure 3. Experiment set up for wave reduction due to artificial reef on an.

The experimental program as outlined in matrices of Table 1 consists of 75 test scenarios, which combines three crest freeboards (0; 5cm and 10cm); five widths of the Reef Ball field (11, 9, 7, 5, 3 rows of Reef Ball) and five deep water waves.

The test waves were JONSWAP spectrum with peak enhancement factor $\gamma = 1.25$ is found the most suitable for the deep-sea region in the East Sea of Viet Nam. Each of experiments were carried out about 1000 waves to sufficiently cover the main frequency domain of desired wave spectra and allow for stable statistical properties of wave heights

Table 1. Test scenarios.

Model				Prototype			
B(m)	**Hs (cm)**	**Tp (s)**	**Rc (cm)**	**B(m)**	**Hs (cm)**	**Tp (s)**	**Rc (m)**
1.90	10	1.5	0	28.5	1.5	5.81	0
1.50	12	1.7	5	22.5	1.8	6.58	0.75
1.20	15	1.8	10	18.0	2.25	6.97	1.5
0.80	18	1.9		12.0	2.7	7.36	
0.45	20	2.1		6.8	3	8.13	

2.3. Measurement and calculation factors

The measured parameters are wave height and wave period in deep wate and reef flat. For the deep water, the wave height is determined as significant wave height (Hs) and spectra peak period (Tp). For shallow water, on the reef flat, the spectral wave heights H_{mo} and period of characteristic wave spectrum Tm-1, 0 is measured [7]:

$$\text{Hs} \approx \text{Hmo} = 4{,}004\sqrt{m_o} = 4{,}004\sqrt{\int_{f_{min}}^{f_{max}} S(f)df} \tag{2}$$

$$T_{m-1,0} = \frac{m_{-1}}{m_0} = \frac{\int_{fmin}^{fmax} f^{-1} S(f) df}{\int_{fmin}^{fmax} S(f) df} \tag{3}$$

where, S(f) is the variance spectral density, m is the n-th order spectral moment, f is the wave frequency; fmax, fmin are considered lower and upper frequencies, respectively.

Reflection coefficient Kr is measured and calculated using 4 wave probes in front of the reef, Kr is the ratio of the reflected to the incoming wave height:

$$K_r = \frac{H_r}{H_i} \tag{4}$$

Transmission coefficient Kt at the coastal structure is the ratio of transmitted wave height to the incoming wave height:

$$\text{Kt} = \frac{H_{mo,t}}{H_{mo,i}} \tag{5}$$

Wave reduction efficiency:

$$\varepsilon\% = 100\ x\ (1 - Kt) \tag{6}$$

3. Results and discussion

3.1. Wave spectrum variation across reef flat.

The variation of the wave spectrum at the reef flat is illustrated in Figure 4. In the deep water area, the wave spectrum has a pointed shape (at P1). When propagates into the platform, most of wave is broken at the reef crest. The secondary waves are formed and continue to transmit on the reef flat. The characteristics of these waves are on are low frequency and long period (called infra-gravity wave –IG), the wave spectrum tends to stretch out towards the low frequencies. Comparing two graphs (a) and (b), it is clear that: while the wave energy spectrum trend remains unchanged along the reef flat (P2, P3, P4, P5, P6) in case of absence of a structure, the wave energy spectrum trend changes markedly infront of and behind the structure. The wave spectrum shape is similar to those after undergoing repeated wave break, changing more obtuse. At the location in front of the Reef Ball (P2, P3, P4, P5), the energy density values of the spectral peaks not differ, but at behind, the wave spectrum tends to be more stretch, and the wave period is longer (P6).

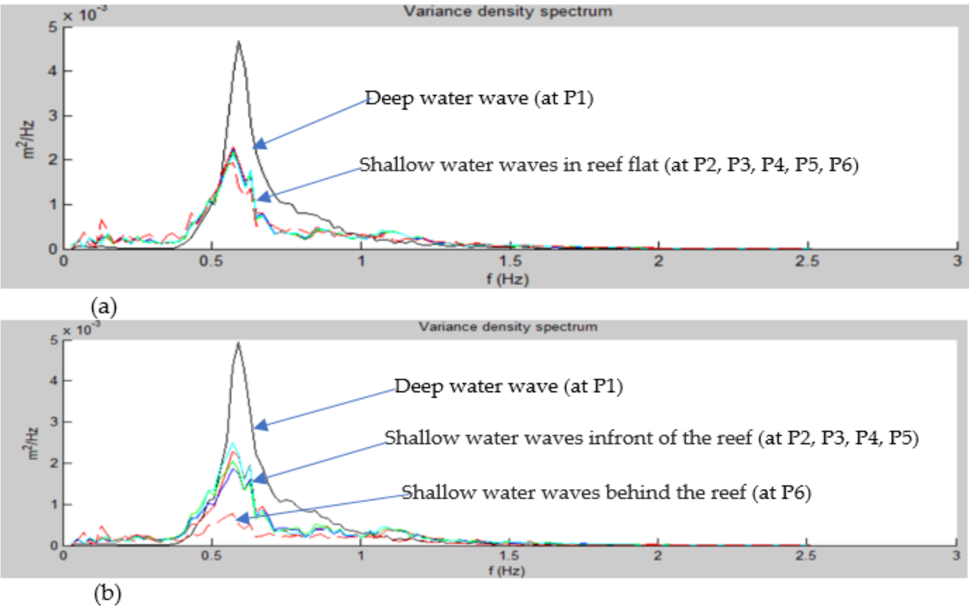

Figure 4. The results of the wave spectrum: scenario Rc =10cm; Hs= 12cm Tp= 1.9s. Incase of absence of a structure; (b) Incase of having a structure.

3.2. Reflection wave.

The determination of the reflected wave is essential in the calculation of the incident wave. When the incoming waves are transmitted to the front of the artificial reef, the wave interacts with the reef. A part of the waves is reflected back and others part pass through the reef. The measurement and detection of reflected waves is very important. The determination of the reflected wave coefficient allows to determine the wave energy dissipation capacity of the reef. The result is shown in Figure 5.

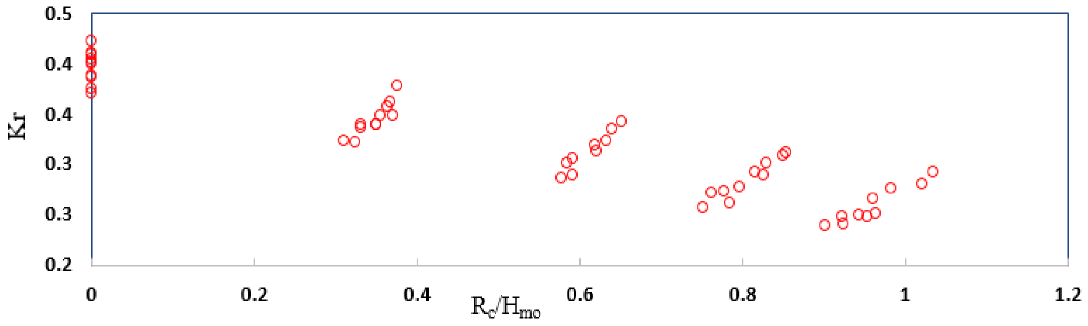

Figure 5. Relationship between Kr and Rc/Hmo when B=2m.

Figure 5 shows the variations of the wave reflection coefficient Kr with the relative freeboard Rc/Hmo. The results show that:

+ For reefs made from Reef ball, with boundary conditions in the experiment, the wave reflection coefficient measured and analyzed from 04 wave probes (P2, P3, P4 and P5) in the range of 0.25-0.42.

+ The wave reflection coefficient tends to be inverse with relative freeboard. Comparing the reflection coefficient at the same location before and after the construction shows that the reflectivity rise by about 10% on average. The wave reflection coefficient at conventional structures is presented in Table 2.

Table 2. Reflection coefficient of some types of structure [8].

Number	Structure types	Kr
1	Seawall forms with crest above the water surface	0.7~ 1.0
2	Seawall forms with crest under the water surface	0.5 ~ 0.7
3	Rubble-mound slope breakwater (slope 1:2 or 1:3)	0.3 ~ 0.6
4	Seawall relate to energy-absorbing beach-control	0.3 ~ 0.5
5	Natural sand beach	0.05 ~ 0,2
6	A field of Reef Ball	0.25~0,42

From above arguments, the Reef Ball blocks have a surface porosity of 33%, structure relate to energy-absorbing beach-control, perfectly suitable for artificial reefs.

3.3. Wave reduction due to artificial reef with varying width

There are 65 tests were chosen from the whole data experiment in the report which represent the variation in water depths, reef widths and incoming waves (Figure 6).

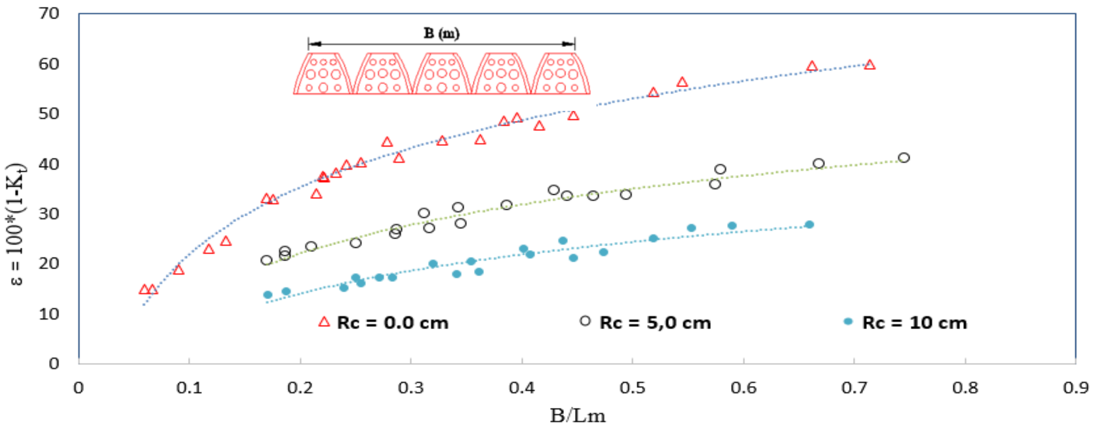

Figure 6. Relationship between relative reef width (B/Lm) and ε% when Rc=0.

In general, all the mentioned breakwater parameters show considerable effects on the wave reduction capacity are the widths (B), height, (h) freeboard (Rc) and volumetric porosity (r%). It is said that to reduce waves, it needs to increase the width and height or to decrease the porosity of structure. Herein, conventional structures are placed on normal beaches, where water depths are high. In that case, many previous studies have shown that, with the same porosity, the structural freeboard factor clearly presents its dominant effects is noticeably larger than that with relative width. However, on the atoll, due to limited water depth on the reef flat, in order to increase the effectiveness of wave reduction, it is considered to increase the width rather than increase the height or reduce the freeboard of structure.

Figure 6 shows the wave reduction efficiency in the relationship with the (B/L_m). Of which L_m is shallow water wavelength, written as follows:

$$L_m = \frac{g}{2\pi} T_m^2 \tanh\left(\frac{2\pi}{L_m} d\right) \qquad (7)$$

where, T_m is period of characteristic wave spectrum; d is water depth. In this experimental program the relative reef widths (B/L_m) are in the range of 0.06-0.75

As can be seen in the Figure 6, the wave reduction efficiency and relative freeboard tend to be inverse. The wave reduction efficiency is the greatest when Rc is the smallest.

The wave reduction efficiency tends to be dependent upon the relative width and covariate and non-linear relations dependent upon the relative width (B/L_m). Under the same conditions (freeboard and height of incoming wave), the wider the reef crest, the higher the wave reduction efficiency of the reef.

When $B/L_m < 0.2$ (artificial reef made up of less than 03 rows of Reef Ball), the wave reduction effect is almost weak. According to the scenarios that Rc =0; ε% is in the range of 15%~ 25% and it will get smaller as Rc increases. Therefore, with this type of submerged breakwater, it is recommended that the width of the breakwater is not less than $0.2L_m$.

The width of the reef crest rise, the wave reduction efficiency saw an increase dramatically when B/L_m is from 0.2 to 0.6, before rise slightly if he relative reef width (B/L_m) approaches to over 0.6, then the trend of the graph tends to stretch horizontally.

Overall, according to the experimental results, it is recommended that the effective range of B should be in the range of 0.2Lm to 0.6Lm. In other words $1/5L_m \leq B \leq 03/5L_m$.

4. Conclusion

The paper has presented and analyzed a series of experiments in a 2D wave flume to investigate how a Reef Balls field would affect the wave characteristics on an atoll platform. When propagating from deep water into the platform, most of waves brake. Waves enormously attenuate, the secondary waves are formed and continue to transmit on the reef flat. Moving on the reef flat of shallow water, the wave spectrum tends to stretch out towards the low frequencies. After passing through the field of Reef Balls, the wave spectrum becomes broader and lower.

Measurements derived reflection coefficient Kr varying between 0.25 and 0.42. Compared with other types of breakwaters, Reef Balls have a considerable ability to absorb incoming waves. Due to the low water depth on the reef flat, wave reduction is governed more considerably by the field width rather than the freeboard of the Reef Balls. Experimental results indicate that the effective width of the Reef Balls field should be in order of 1/5 to 3/5 of the shallow water wave length. To conclude, the obtained observations and measurements optimize the design of a Reef Balls field regarding wave reduction effect

Author Contributions: Conceptualization P.T.T. and L.H.T.; methodology, P.T.T., L.H.T and T.T.T; experiments, P.T.T; data analysis, P.T.T; writing, P.T.T, L.H.T and T.T.T. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The National independent research ĐLCN.19/15 "Research on solutions prevent erosion of a cay in Spratly Islands, Ha Noi, 2015-2019 funded by the Vietnamese Ministry of Science and Technology is acknowledged for providing materials and sample Reef Ball blocks used for experiments; The Thuy loi University' hydraulic laboratory for using wave flume.

Conflicts of Interest: The authors declare no conflict of interest.

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