Design wave crest height on submerged coral reefs

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Abstract. The topography of a submerged coral reef is divided into three parts, including a reef flat, a fore reef, and a deep fore reef. The water depth of the reef flat is a few to ten meters. When the wave propagates into the reef flat, most of them will be broken. This process often happens in a complicated way. The difference in wave transformation in this kind of reef is a sudden change in its topographic profile from hundreds of meters to a few meters in shallow water. In particular, there is the formation of infragravity waves (IG wave) which are generated by the interaction of wave groups and are mainly due to fluctuations in the breaking point on the reef. On the other hand, the wave crest height on the reef flat is very large compared to the wave height. Predicting wave propagation and wave crest height is crucial in analyzing and designing structures on the submerged coral reefs, such as determining the deck elevation, avoiding flooding, etc. This paper predicts the distribution of wave crest height on the submerged coral reef in shallow water based on a physical model.

Keywords: Submerged coral reefs, steep fore reef slop, shallow water, infragravity waves, wave crest height distribution.

1 Introduction

There are many coral reefs in the Vietnam Sea Zone, including fringing, barriers, and atolls. Most of them are submerged reefs. According to our survey, the cross-section of the submerged coral reefs is divided into 3 parts, moving inside from the deep water: the deep fore-reef as a vertical wall; a fore reef with a steep slope with the depth of the water being about 30.0 to 50.0 meters; and the top is a reef flat. The water depth of the reef flat is shallow and varies from 4.0 to 10.0 m. Fig.1. show the the cross-section of the submerged coral reefs.

When designing a harbor or jacket structure, one of the important issues is determining the deck elevation and the zone of wave action on the structures, for example Fig.2. Normally, the air gap of the jacket structures is determined based on the wave crest height above the still water level and the reserve space. In practice, the measurement to determine the wave peak height above SWL is very difficult, due to the limitations of the measuring equipment and the survey time at the site.

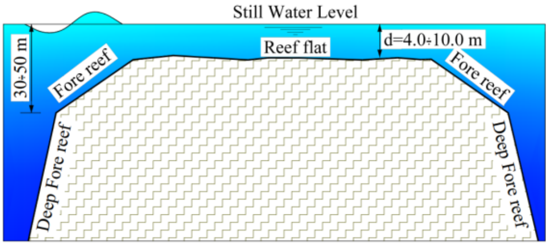

Fig. 1. A typical cross-section of the submerged coral reef

Wave crest height is usually determined according to different wave theories depending on wave characteristics such as Airy, Stock, and Cnoidal waves... The wave crest height above still water level (η_c) is determined by the Massel [1]:

$$\eta_c = \alpha\beta H_s \tag{1}$$

The coefficient α is in the order of 1 and describes the effect of turbulence of a breaking wave. β is the coefficient (0.5< β <1.0), and it is related to the steepness of a wave crest and trough. The coefficient α can only be found through experiments. In the design process, the highest wave crest has been determined by first of all estimating the maximum wave height. Thereafter, the corresponding crest height is obtained by introducing the wave height into the 5th Stoke or Cnoidal model.

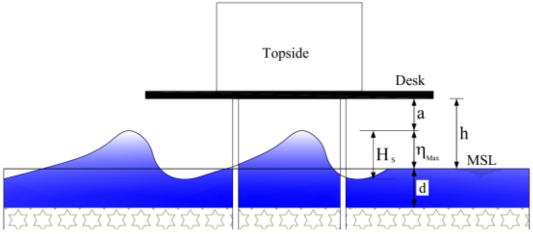

Fig. 2. The air gap of the jacket structures

As mentioned above, coral reefs have a very special topography, so when the waves propagate through the reef, the changes of wave parameters are very strong due to the step slope in front of the reef as well as the depth of water on the reef flat. In recent years, many authors have studied wave propagation on coral reefs, including fringes, barriers, and atolls. Many wave character studies on shallow coral reefs were conducted as early as the last century, such as Munk and Sargent 1948 [2]; Roberts et al., 1977 [3]; Lee and Black, 1978 [4]; Nelson, 1994 [5]; Gourlay, M.R., 1994 [6]; Massel, S.R., 1996 [7], they shown that wave energy is significal dissipated when waves come to the fore reef and the wave height distribution is changed due to breaking process in reef crest and flat, the wave heights distribution is not fit whit Rayleigh distribution as a offshore, the maximum wave height on the reef flat is as low as 0.55 of mean water depth on the reef flat.

In recent years, studies on wave propagation on coral reefs have increased. Lowe et al., 2005 [8], [9] studied the effects of wave propagation on submerged reefs with canopies with a cylindrical texture under the influence of bottom friction. YAO. Y, 2012 [10] have carried out waves over fringing coral reefs on a wave flume with a water depth of the reef ranging from 0.03 m to 0.10 m, which means it is too shallow. Mark L. Buckley et al., 2016 [11] studied the wave setup over a fringing reef with large bottom roughness simulated by the 01 bottom roughness of the cubes (simulating a rough bottom) and very low water depth of the reef flat (less than 2 m). Maria Kazolea et al., 2017 [12] simulated wave propagation, breaking, and overtopping with a vertical wall on a reef flat. Wen et al., 2018 [13] studied wave breaking over a submerged step and the distribution of wave height with two water depths in the range of 0.02 and 0.10 m. Wave propagation, breaking, and setup on steep fringing reefs were simulated by Zhang et al., 2018 [14]. Also in 2018, and 2021, Yao et al., [15], [16] studied the waves propagating to the fringing reefs with a roughness of the reef crest only. Most of the above-mentioned studies are not suitable for our study area and also have not mentioned the wave crest height, a very important parameter when designing wharf or jacket structures on the submerged reefs. In Vietnam, Tuan et al,. 2019 [17], [18] have pointed out the difference in the distribution of wave heights when carrying out wave flume experiments to demonstrate the process of wave propagation across the steep-slope submerged reef for the smooth bottom of the reef. Tao et al., 2021 [19] shown that the wave crest height can reach up to 0.95 times the wave height. In 2023, Dinh QC et al., [20] carried out many research scenarios on wave propagation through coral reefs with low water levels to evaluate the attenuation of wave energy due to bottom roughness but have not shown the character of wave crest heights. Similar to the above authors, the wave crest height in the reef flat was not significantly studied.

Besides studying wave parameters such as wave height, wave period, wave spectrum energy, etc., there are also many studies on wave peak height through distribution functions of wave height or wave peak height such as: Battjes 1970 [21] ; Jahns, 1972 [22]; For-ristall, 1978 [23] and 2000 [24]; Tuan et al., 2019 [17], however, their predictions differ significantly, and most of the studies focus on deep water or shallow water with normal beaches (small slope), which means they are not close to submerged reef. Based on Forristall [24], the two-parameter Weibull distribution in the short-term model of the wave crest heights is calculated as Eq. (2):

$$p(\eta_c > h) = \mathrm{Exp}\,[-(\eta/(\alpha H_s)^{\beta}] \qquad (2)$$

in which, η_c is wave crest heights above still water level, h is the value of wave crest heights, H_s is the significant wave height, the parameters α and β are functions of water depth and wave characteristics, and they are determined according to Eq. (3):

$$\alpha=0.3536+0.2892S_1+0.1060U_r;\ \beta=2-2.1597\ S_1+0.0968(U_r)^2 \qquad (3)$$

S_1 is a measure of steepness, and the U_r is the Ursel number, which is a measure of the influence of water depth on the non-linearity of waves as following Eq. (4):

$$S_1=2\pi H_s/(gT_1^2);\ U_r=H_s/(k_1^2d^3) \qquad (4)$$

where T_1 is the mean wave period, which is calculated from the ratio of the first two moments of the wave spectrum, k_1 is the wave number for a frequency of $1/T_1$, H_s is the significant wave height.

It is clear that studying design wave crest height on submerged coral reefs with a steep slope is quite limited. This paper predicts the distribution of wave crest heights above static sea level when waves propagate from offshore into the submerged reef using a physical model. The wave crest height distribution that is obtained will be compared with the Forritall's distribution, and the research results will contribute to a reasonable choice of wave crest height in the design of structures on the reef.

2 Experiment

2.1 Physical model setup

Based on the field survey results and research objectives, we have selected some of the typically submerged coral reefs for research as follows: The water depth of the reef varies from 4.0 m to 8.0 m, the water depth of the incoming wave zone is more than 24 m, and the fore-reef slope is between 1/5 and 1/10. We have carried out the physical model experiments in the wave flume at the Thuyloi University (Hanoi, Vietnam). The wave flume's dimensions of length, width, and height are 45.0m, 1.0 m, and 1.2m, respectively. There is a piston-type wave maker with an Active Reflection Compensation (ARC-Deltares) in order to suppress the reflected wave. Wave gauges can record the water surface elevation with a 0.1 mm of range and a frequency range up to 100 Hz. The Vectrino-II 3-D flowmeter was setup at WG5 to synchronously measure a bottom flow velocity with the wave gauge, synchronous measurements of wave and velocity at WG5 were used for the analysis of wave reflection in accordance with the wave energy flux method by Sheremet et al. (2002) [25].
Based on the capacity of the wave generator and prototype characteristics, we have chosen an experimental scale of 1/40 and a period scale of 1/√40 (following the Froude's scale law).
According to previous studies Tuan et al., 2019 [16], the slope of the fore-reef slope, within the consideration range i = tanα = 1/5 - 1/10, has a negligible influence on the regime wave hydrodynamics on the submerged reef. Therefore, this study only considers a representative seaward slope i = 1/5. The width of reef flat B = 15.0 m (corresponding to 600 m in the prototype) and covered by a smooth concrete mortar. At the end of the flume, there is a passively absorbing boundary of reflected waves, which is composed of a tangled rock roof with a gentle slope of 1/6. An video camera is arranged perpendicular to the flume wall at the top of the outer shelf to record the entire image of waves in the reef-edge surf zone for all experimental cases. The experimental modeling is shown in Fig.3. Some experimental photos are illustrated in Fig.4.

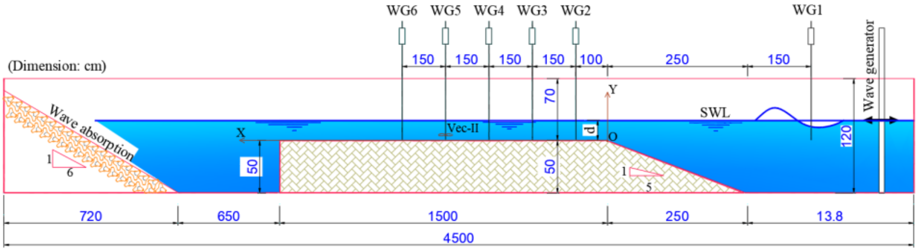

Fig. 3. Side view of the experimental modeling and setting up wave gauges

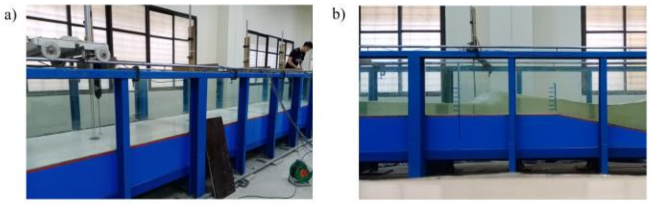

Fig. 4. a) Wave gauge and flowmeter installation, b) Breaking wave on the reef flat

3 Test program

Based on the statistical analysis of storm waves at the site, the storm waves in the deepwater boundary of the study area had a significant wave height, Hm0, ranging from 5.0 m to 8.0 m, and a peak wave period, T_p, ranging from 8 s to 12 s, which corresponded to a return period of one year to 100 years. Therefore, the tested significant wave height H_{m0} of 0.08 m to 0.18 m and the peak wave period T_p of 1.1 s to 2.0 s were used in the experiment. There are 12 random waves with an underlying JONSWAP spectrum (g = 1.25) that were tested, including two typical wave steepness values of 0.03 and 0.04. The experiment was carried out with three water levels and 12 coming waves, a total of 36 cases were carried out (see Table 1).

Table 1: The matrix of experimental program

Water depth in reef flat (d)				Model		Prototype		
Model (cm)	Prototype (m)	Note		H_{m0} (cm)	T_p (s)	H_{m0} (m)	T_p (s)	Note
				8.0	1.10	3.20	7.00	1
				8.0	1.30	3.20	8.20	2
				10.0	1.30	4.00	8.20	3
				10.0	1.50	4.00	9.50	4
10	4.00	a		12.0	1.40	4.80	8.90	5
15	6.00	b	×	12.0	1.60	4.80	10.10	6
0.20	8.00	c		14.0	1.50	5.60	9.50	7
				14.0	1.70	5.60	10.80	8
				16.0	1.60	6.40	10.10	9
				16.0	1.80	6.40	11.40	10
				18.0	1.70	7.20	10.80	11
				18.0	2.00	7.20	12.60	12

The measured data include individual wave heights, statistical and spectral wave parameters (e.g. $H_{1/3}$, $H_{1\%}$, T_p, $T_{m-1.0}$) at all wave gauges. Typical spectral and statistical wave parameters are defined according to:

$$H_{m0} = 4{,}004\ \sqrt{m_0} = 4{,}004\ \sqrt{\int_{f_L}^{f_U} S(f)df} \qquad (5)$$

$$T_{m-1,0} = \frac{m_{-1}}{m_0} = \frac{\int_{f_L}^{f_U} f^{-1} S(f)df}{\int_{f_L}^{f_U} S(f)df} \tag{6}$$

$$H_{1/3} = \frac{1}{(1/3)N} \sum_{1}^{(1/3)\mathrm{N}} H_i \tag{7}$$

in which, H_{m0} is the (spectral) significant wave height, m_n is the n-th order spectral moment, S(f) is the variance spectral density, f is the wave frequency, $T_{m-1,0}$ is the characteristic spectral period, $H_{1/3}$ is the (statistical) significant wave height, N is the number of waves in a record, H_i represents the individual wave heights sorted in descending order.

4 Resunts and discussions

The objective of this section is to understand the measured wave crest height distributions and evaluate the difference from the Forristall's distribution [24]. The differences will depend on the incoming wave and the water depth on the reef flat, which is essentially the dissipating effects of breaking waves on the reef crest, the establishment of IG waves, and the energy conversion quantity between SS waves and IG waves along the reef flat. To measure wave crest height distributions, we inspect the measured data of individual wave crest heights from all of the test series. The water surface elevation results at wave gauges are analyzed according to the statistical method, the wave crest height above the still water level is separated according to zero-crossing. Following from wave reflection analyses show that the bulk reflection coefficient at WG5 was insignificant (less than 10%), therefore ignoring wave reflections in the determination of the incident wave height along the reef flat. Simultaneous Forristall's distribution is shown to compare with experimental results.

Fig.5 to Fig.7 7 show the results of wave crest height distribution in the reef flat at WG3 and WG6, with the minimum and maximum incoming wave heights at positions near and far from the crest of the submerged reef.

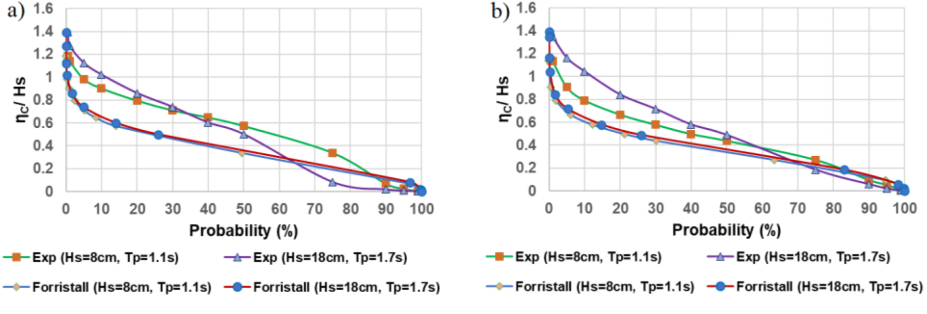

Fig. 5. Wave crest height distribution at WG3 (a) and WG6 (b) with d = 10 cm

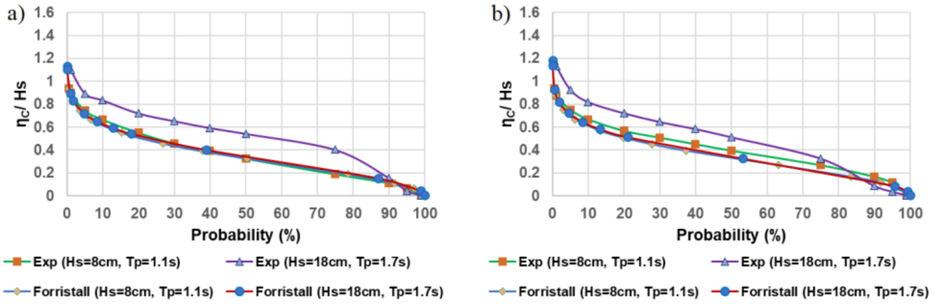

Fig. 6. Wave crest height distribution at WG3 (a) and WG6 (b) with d = 20 cm

Fig.5 to Fig.6 show that, if the incoming wave height is small (about 1/2 the water depth), the distribution of wave crest height is quite close to the Forristall's distribution, when the incoming wave height increases, the wave crest distribution is significantly different from Forristall. The wave crest height is significantly larger compared to H_S, it can reach up to 1.4 H_S.

The Fig.7 to Fig.9 illustrate the distribution results of all experimental cases and the lower and upper bounds of the Forristall's distribution (the blue lines are the upper and lower limits of Forristall's distribution).

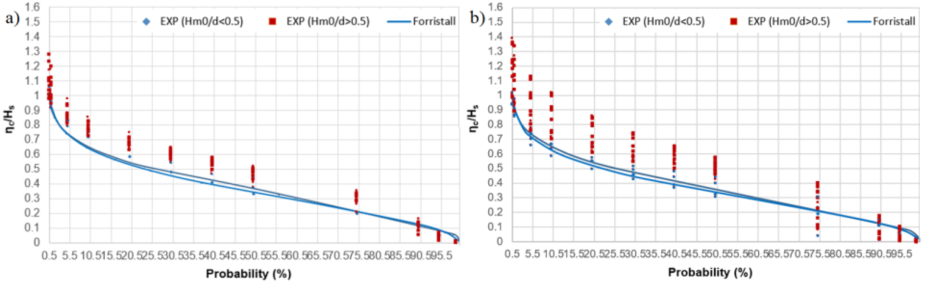

Fig. 7. Combine the wave crest height distribution at WG2 (a) and WG3 (b) for all of the tests

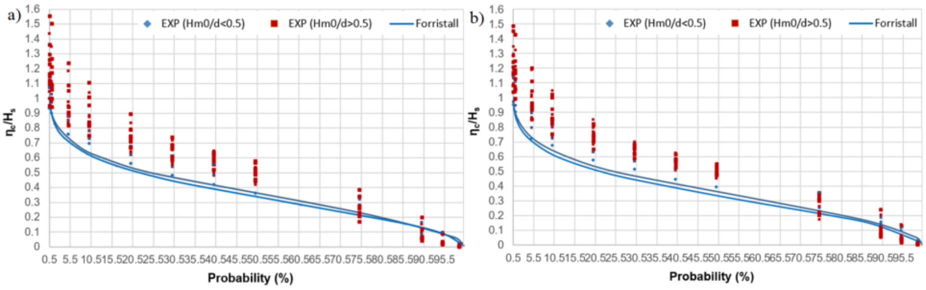

Fig. 8. Combine the wave crest height distribution at WG4 (a) and WG5 (b) for all of the tests

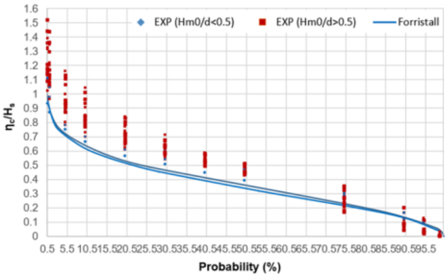

Fig. 9. Combine the wave crest height distribution at WG6 for all of the tests

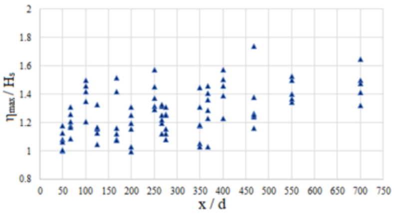

Fig. 10. The relationship between η_{max} and Hs along reef flat

The Fig. 7 to Fig. 9 show that, there is a large difference between the Forital distribution and the test results. At rare frequencies (0.5% or 1%), wave crest height is higher than Forritsall's model by 10% to 20%. Normally, in designing the maximum wave height (1%) at a shallow water region, H_{max} is usually calculated at 1.5 H_s. If the 5th order stock is used to model, the maximum wave crest height can be achieved at approximately 1.05 H_s [26], which is very small in comparison with the experiment results (ranging from 0.9 to 1.56 H_s).

Fig 10 shows that the ratio of the largest wave crest height to significant wave height reaches up to 1.8 times, the further away from the crest of the reef, the more this ratio may increase. This happens because, in the process of wave propagation on the reef, the energy of the SS wave is partly transferred to the IG wave, leading to the further away from the reef crest the number of short waves decreases and the long wave dominates.

5 Conclusion

The present study has considered the wave crest height distributions arising in the flat of the submerged reef, sea states return period of one year to 100 years in shallow and intermediate water depths. The results of a new experimental study have been presented.

A thorough analysis of all the data has been completed, including comparisons between data generated in different positions on the reef flat and, perhaps most importantly, a comparison between laboratory observations and Forristall. When taken as a whole, the experiment result data identify systematic departures from the commonly applied second-order model of Forristall or an approximate forecast according to [26]. These are dependent upon the characteristics of the incoming wave, the water depth on the reef flat, and the distance to the reef crest.

This study has shown the interesting results presented above for a submerged reef. In addition, the experiment data should be used to build, calibrate, and verify numerical models of wave propagation across a submerged reef.

New experiments were performed with incident waves collected in Vietnam according to the JONSWAP spectrum (g = 1.25) and wave steepness values of 0.03 and 0.04, so it is necessary to perform more experiments with different wave to get a better overall view.

When designing a harbor or jacket structure in the submerged reef, it is necessary to determine the appropriate wave crest height to avoid flooding or errors in wave load calculations. Therefore, the target for future work is to create a simple distribution model of wave crest height to use that is based upon the commonly recorded metocean parameters such as H_s, T_p, d, and that can fit scientific and engineering applications.

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