

Wave Hydrodynamics across Steep Platform Reefs: A Laboratory Study

Dinh Quang Cuong ^{1*}, Thieu Quang Tuan ²

¹ *Ha Noi University of Civil Engineering, 55 Giai Phong Str, Ha Noi, Vietnam.*

² *Thuyloi University (formerly Water Resources University), 175 Tay Son Street, Hanoi, Vietnam.*

Received 28 May 2022; Revised 23 July 2022; Accepted 28 July 2022; Published 01 August 2022

Abstract

This paper presents a laboratory study on wave transmission across steep platform reefs, aiming at furthering knowledge of wave hydrodynamics and establishing empirical formulations of spectral wave parameters across the reef flat. The ultimate aim of this study is to determine the design wave load to design fixed offshore structures on coral reefs flat. The process of wave transmission across the underground coral strip with a large front slope has been studied on a physical model in the wave trough with nearly 300 experimental cases combined from 05 underground band models and many random wave scenarios and scenarios at different submerged depths. Experimental results show that the abrupt transition in depth from deep water ahead to relatively shallow water in the reef is responsible for the difference in the wave at the top of the strip compared to the wave on the normal beach, especially regarding the statistical distribution of the wave height. Breaking waves at the abrupt transition have deviated the wave height distribution curve from the deep-water (Rayleigh) theoretical distributions and even the existing shallow-water distributions, including the effect of breaking waves. Two sets of empirical formulations of the spectral wave parameters (H_{m0} and $T_{m-1,0}$) are eventually derived for the surf zone and the region behind the surf zone, respectively. These local wave parameters can be used as inputs to a wave height distribution model for determining other design characteristic wave heights on steep platform reefs.

Keywords: Wave Transmission; Platform Reefs; Reef Flat; Large Front Slope; Wave Breaking.

1. Introduction

The Vietnamese continental shelf is primarily made up of deteriorated coral reefs, resulting in an uneven seafloor with numerous coral reefs rising as lotus islands between valleys. On the Vietnamese continental shelf, atolls are usually very flat, with a width of hundreds to thousands of meters and a submerged depth of roughly 5 to 25 meters.

At the foot of atolls, the water depth is frequently over 100 meters. The foothill (slope 1/1 to 1/2) and the lighter slope (slope 1/5-1/15) are the transition slopes from the deep water at the foot of the island to the shallow water at the top of the island. The rapid change of the front slope from deep to shallow water produces unusual hydrodynamic waves on coral reefs that are unlike those found on gentle beaches with minor beach slopes. Breaking waves on reefs with steep foreshores are not the same as waves on sloping beaches with gradually shifting. According to research published in Nelson [1], the ratio of individual wave height to maximum water depth on a horizontal reef flat (beyond the surf zone at the reef edge) should not exceed 0.55, which is significantly lower than the commonly accepted estimate of 0.80. In a laboratory study on regular waves on a fringing reef, Gourlay [2] showed that wave-breaking conditions on the reef edge differ substantially from those on a plane beach. A non-linearity parameter indicating wave conditions at the reef edge is used to classify the wave transmission regime. The maximum wave height to depth ratio on the reef flat is shown

* Corresponding author: cuongdq@huce.edu.vn; cuongdq@nuce.edu.vn

 <http://dx.doi.org/10.28991/CEJ-2022-08-08-015>



© 2022 by the authors. Licensee C.E.J, Tehran, Iran. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC-BY) license (<http://creativecommons.org/licenses/by/4.0/>).

to depend on this non-linearity parameter and turns out to be consistent with the finding by Nelson [1] for a horizontal bed. Yao et al. [3] experimentally examined the characteristics of the breaking of monochromatic waves on fringing reefs with various fore-reef slopes. It follows that, as a result, most of the majority of the wave breaking features over the reef, such as breaker types and breaker indices, are mainly characterized by the relative reef-flat submergence (i.e., the ratio of the water depth over the reef flat to the offshore incident wave height), but not by the surf similarity commonly used for plane beaches [4].

Besides wave breaking, numerous field and laboratory studies exist in the literature on reef wave dynamics [5–10]. Collectively, these describe the two important hydrodynamic features on reefs that are low-frequency motions or infra-gravity waves (frequencies $f < 0.04\text{Hz}$ on field scales, henceforth designated as IG waves) and the super-elevated water level (wave setup). When compared to those on open, mild beaches, their magnitudes can potentially be increased in steep reef situations.

It is vital to precisely estimate the design wave heights (severe conditions) at various locations throughout the top of the coral reef flat when developing engineering structures on the flat crests of coral reefs. Currently, there is very little research on hydrodynamic waves in extreme (design) circumstances in the literature, with the focus being on environmental issues in comparatively flat waters [6]. Wave propagation through coral reefs with steep forecourts has received very little research. The findings of the research on the physical model in the wave trough are presented in this work, which assesses the wave propagation process through atolls with steep front shelves and establishes empirical formulas for the parameters. The wave spectrum on the reef flat is required as input for the Tuan and Cuong [11] wave height distribution model to determine the design characteristic wave heights on steep submerged reefs. The data from measured waves can also be used to verify the accuracy of numerical wave models.

2. Experiments with Physical Models in Wave Troughs

The hydraulic laboratory at Thuy Loi University conducted experiments on physical models to analyze wave hydrodynamics on steep platform reefs (Vietnam). These are the results of Tuan and Cuong's first experimental series, which focused on the distribution model of wave heights [11]. The main equipment system for the experiment is a wave trough with the following effective parameters: $45\text{ m} \times 1.0\text{ m} \times 1.2\text{ m}$. At heights of up to 0.25 meters and peak durations of 2.5 seconds, the automatic active reflection adjustment (ARC) system may generate both even and irregular waves. Figure 1 depicts the experimental setup. A smooth, impermeable replica reef stands 50cm above the flume's bottom. The model length scale chosen is 1/40, based on prototype and laboratory circumstances. The reef's flat top width must be broad enough to accommodate both the reef-edge breaking zone and the transmitted region (beyond the surf zone) for monitoring the full-wave transformation process throughout the reef on the needed model. The width B was set at 8 meters based on this criterion. The reef front shelf was simulated with two typical slopes, 1/5th and 1/10th, respectively, to examine the effect of the foreshore slope on wave propagation through the reef (see Figure1). A modest riprap slope at the other end of the flume absorbs any remaining wave energy.

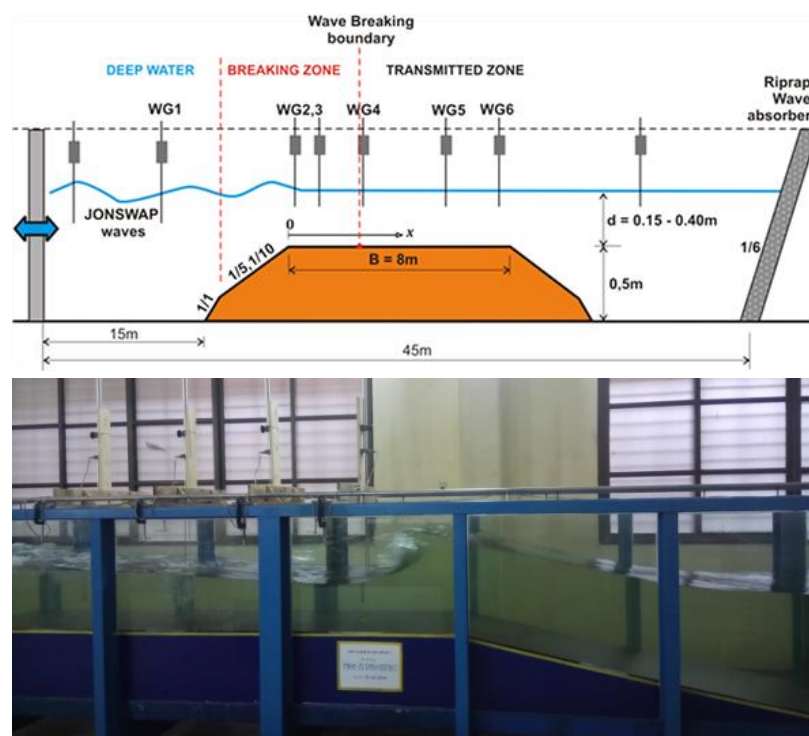


Figure 1. Experimental layout of wave transmission across the submerged reef

Capacitive wave meters are installed at three areas on the coral reef: deep water (offshore), surf zone at the reef's edge, and surf zone behind (transmission zone). Different wave conditions can be obtained by shifting the position of wave gauges on the reef according to the test situation. A video camera is mounted on the side of the wave trough (flume) to record photos of the water surface, particularly the areas with break waves, near the coral reef's edge.

The test program is shown in Table 1. The substance of the experiment is a mix of wave parameters at various submerged depths. The JONSWAP spectral waveform was utilized as the test wave, with a peak enhancement factor of 1.25, which is believed to be the best for deep sea waters off the coast of Vietnam. Only at the wave board boundary are the wave characteristics in Table 1 nominal (steering). Peak wave periods calculated using s_0p values of 0.03 and 0.04, respectively, for two typical storm wave steepnesses. These test combinations were removed from occurrences with significant super-elevated water levels behind the reef or caused the highest wave heights exceeding the flume height. With 275 tests, each lasting roughly 1000 waves, the entire program of experiments was finished. Experiments like the ones described above are adequate to cover the major frequency domain of the desired wave spectrum while maintaining constant statistical properties of wave heights.

Table 1. Summary of the wave hydrodynamic test program on a steep platform reef

Steering waves	Reef flat depth d (m)	Fore-reef slope
$H_{m0} = 0.09\text{m}, T_p = 1.2\text{s}$		
$H_{m0} = 0.09\text{m}, T_p = 1.4\text{s}$		
$H_{m0} = 0.12\text{m}, T_p = 1.4\text{s}$	0.15	
$H_{m0} = 0.12\text{m}, T_p = 1.6\text{s}$	0.20	
$H_{m0} = 0.15\text{m}, T_p = 1.55\text{s}$	0.25	1/5
$H_{m0} = 0.15\text{m}, T_p = 1.8\text{s}$	0.30	1/10
$H_{m0} = 0.17\text{m}, T_p = 1.65\text{s}$	0.35	
$H_{m0} = 0.17\text{m}, T_p = 1.9\text{s}$	0.40	
$H_{m0} = 0.2\text{m}, T_p = 1.8\text{s}$		
$H_{m0} = 0.2\text{m}, T_p = 2.1\text{s}$		

3. Data analysis - General Characteristics

The influence of reef shape and hydraulic conditions on wave propagation behavior will be evaluated in this section, and the results will be used to deduce the empirical formulas in the next section. As a result, some wave propagation on reef parameters are determined as follows [11].

Wave transmission coefficient:

$$K_T = \frac{H_{m0,x}}{H_{m0,i}} \tag{1}$$

where K_T is wave transmission coefficient at an arbitrary location, H_{m0x} and H_{m0i} are spectral local (at distance x from the outer reef edge, see also Figure 1) and offshore incident wave heights, respectively.

Reef-flat shallowness:

$$\chi = \frac{\cos \alpha}{\sqrt{d / L_{0m}}} \tag{2}$$

in which, χ is a reef-flat shallowness factor (the shallower the reef flat the larger value of χ is and vice versa), α is fore-reef slope angle ($\alpha = 0$ for locations behind the surf zone), L_{0m} is deep-water wavelength based on local spectral period $T_{m-1,0}$.

Measured spectral transformation as typically shown in Figure 2 illustrates a general feature of wave transmission across the reef flat is that wave energy is largely dissipated within the reef-edge surf zone (Figures 2-a to 2-c). Despite the fact that it is largely unchanged after the surf zone (Figures 2-d to 2-e). This hints that wave transmission in these two regions should distinctly be considered.

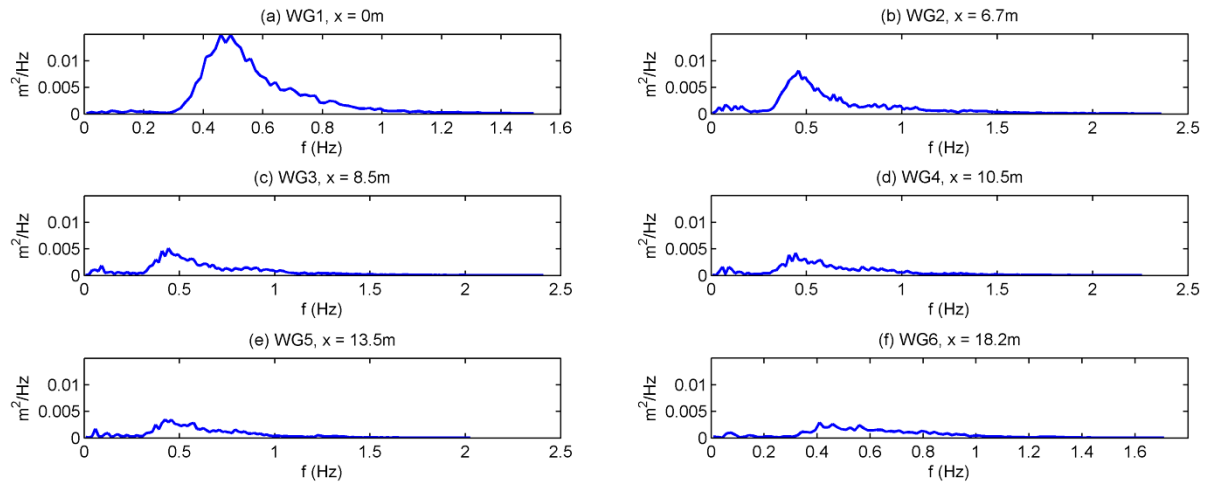


Figure 2. The coral reef's spectral transformation: (a) offshore boundary $x = 0$ m (b) and (c) reef-edge surf zone $x \leq 8.50$ m (d) - (f) $x > 8.5$ m behind surf zone (transmitted zone)

Figure 3 shows the K_t transmission coefficients at various points on the reef plane as a function of relative inundation depth d/H_{m0} . Wave transmission on the reef is proportional to the relative submerged depth, similar to other frequent submerged coastal structures [12], but it behaves differently inside and behind the surf zone (namely the transmitted zone). The increase in K_T with d/H_{m0} is rather steep for relatively modest inundation (i.e. until $d/H_{m0} 1.50$) in the surf zone ($\times 1.8 - 2.4m$), but then slows down or stays the same as d/H_{m0} increases. In the transmitted zone, this rise is usually significantly slower.

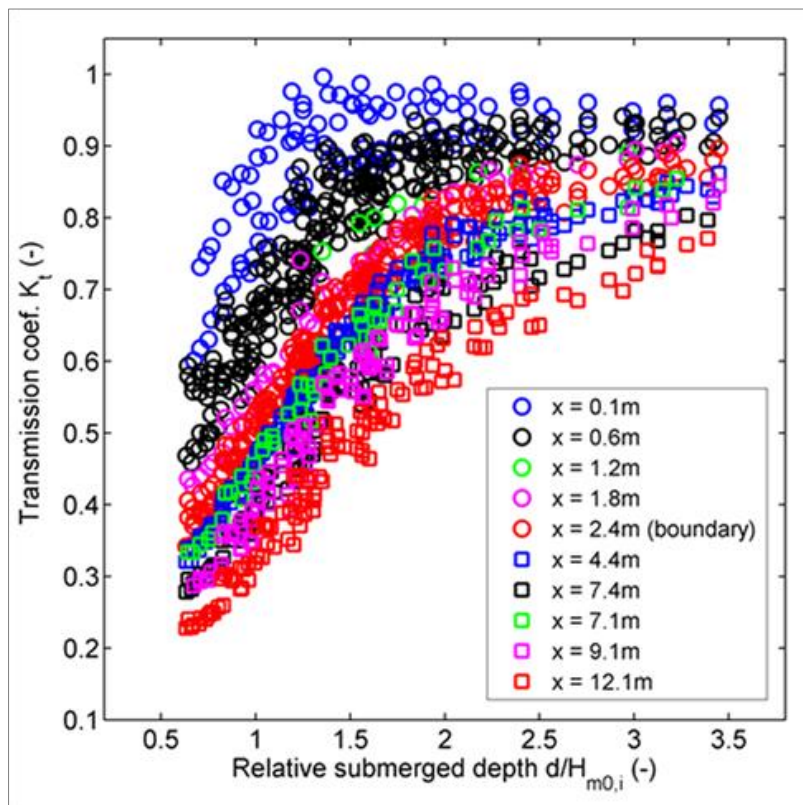


Figure 3. Effects of the relative submerged depth d/H_{m0}

Regarding characteristics of the local maximum wave height H_{max} on the reef flat, ratios H_{max}/H_{m0} and H_{max}/d in variation with the reef-flat shallowness factor are shown in Figures 4 and 5, respectively. Generally speaking, these are seen to vary in wide ranges with extreme boundary values deviating far from those ordinarily derived for locations on shallow beaches. The ratio H_{max}/H_{m0} varies in the range of 1.2 to 2.0 and quickly decreases with the increase relatively deep water ($\chi \leq 3.0$) and remains relatively unchanged in shallower water ($\chi > 3.0$). Its values are also higher behind the surf zone ($x > 1.2m$) compared to those within the surf zone.

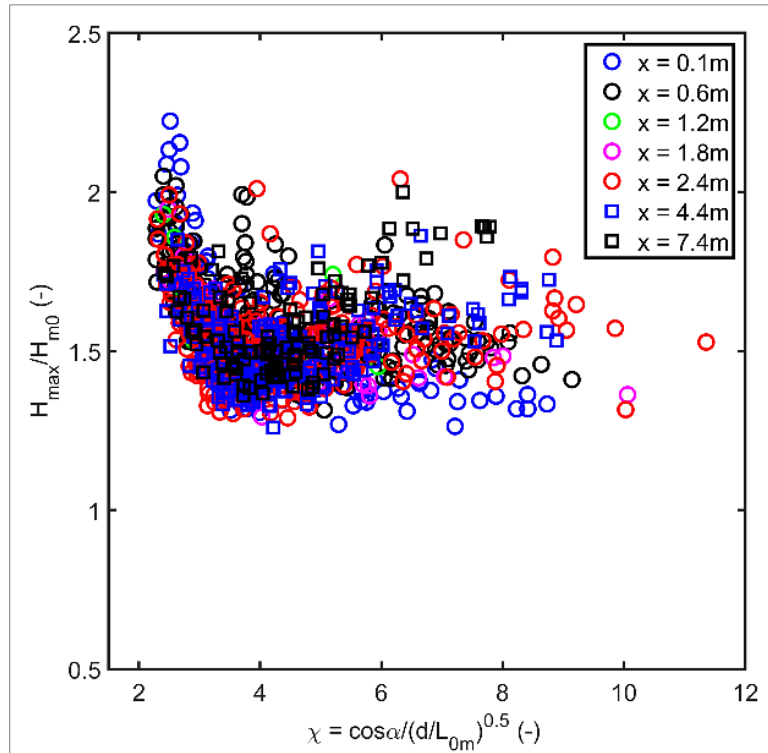


Figure 4. H_{max}/H_{m0} variation as a function of coral reef-flat shallowness

The ratio H_{max}/d also varies in a wide range between 0.4 and 1.3 and is proportional to χ (see Figure 5). It is shown to peak within the surf zone ($x \leq 1.2$ m) and quickly decline behind the surf zone. Particularly, within the surf zone, the maximum possible wave height H_{max} expressed in terms of the local water depth d is $H_{max}=(1.0 - 1.3)d$, much higher than the well-known theoretical limit $H_{max}=0.78d$ for waves on a shallow beach [13].

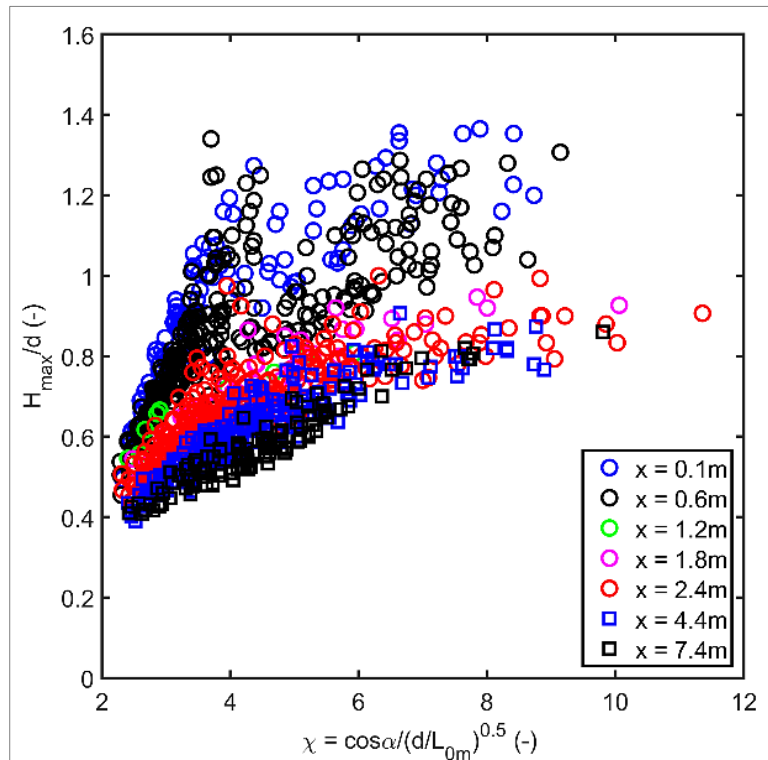


Figure 5. Variation of H_{max}/d with reef-flat shallowness χ

The wave transmission data showing the effects of the fore-reef slope are presented in Figure 6 for one location inside the surf zone ($x = 0.6$ m) and one in the transmitted zone ($x = 2.4$ m), respectively. For each of the locations, the data corresponding to two fore-reef slopes are shown (plus signs “+” for the slope of 1/5 and open circles “O” for the

slope of 1/10). In general, the influence of the fore-reef slope is determined to be secondary only when compared to the relative submerged depth. The effect appears to be considerably considered in the surf zone, but not in the transmitted zone. A steeper slope generally results in a larger wave height in the surf zone.

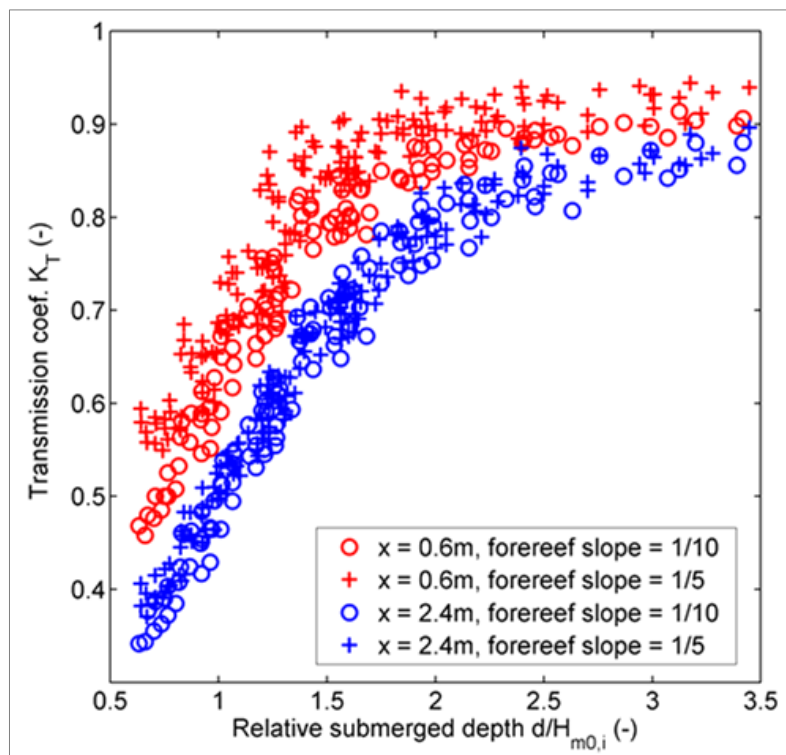


Figure 6. Effects of the fore-reef slope: inside surfzone (x = 0.60m) and transmitted zone (x = 2.4m)

The above analysis indicates that, for the description of wave transmission across the reef, the reef flat must be split into two regions in terms of the major energy dissipation mechanism (see Figure 1): the reef-edge surf zone where wave energy is mainly dissipated by wave breaking due to the sudden depth reduction, and the transmitted zone where wave energy dissipation is mainly by bed friction.

4. Formulations

The placement of structures in the surf zone is extremely unfavourable since the wave loading on the structures is extremely high in this area. The engineering design must clearly define the boundary between the surf zone and the wave-breaking zone in order to choose a safe location for the structure behind the surf zone or to design the structure to resist extreme conditions in the surf zone. The wave-breaking boundary will be determined in the next sections, which is the first time the boundary has been statistically estimated using visual observation data of tests on physical models. Characteristics of wave transmission behind the surf zone are also addressed.

4.1. Wave Breaking Boundary and Wave Breaking Point

Images indexed from the video record of wave trains along the reef edge are analyzed for each experiment to determine the number of breaking waves and their corresponding positions x_b measured from the breaking point to the reef flat's outer edge. As the breaking of irregular waves is a random process, the position or distance of a breaking wave is treated as a stochastic variable.

In general, the location of the breaking point in the surf zone is proportional to the maximum individual wave heights. Assume that in the $H_{m0,b}$ surf region, there is a link between x_b and the peak spectral wave height (see Section 4.2 for details). The following is the definition of the relative wave breaking location x_b^* :

$$x_b^* = \frac{x_b}{d \tanh \left(\frac{2\pi}{L_{op}} d \xi_{op}^{-0.12} \right)} \tag{2}$$

$$\xi_{op} = \frac{\tan \alpha}{\sqrt{H_{m0,i} / L_{0p}}}$$

where $\tan\alpha$ is the fore-reef slope, L_{op} and ξ_{op} are the incident deep-water wavelength and the Iribarren number based on the peak spectral period T_p , respectively.

The non-exceedance probability that a wave breaks within the reef-edge surf zone, $(x_b \leq x_b^*)$, can be calculated from the measured data. Figure 7 presents the measured data of the probability distribution $p(x_b \leq x_b^*)$ with the breaking position x_b^* .

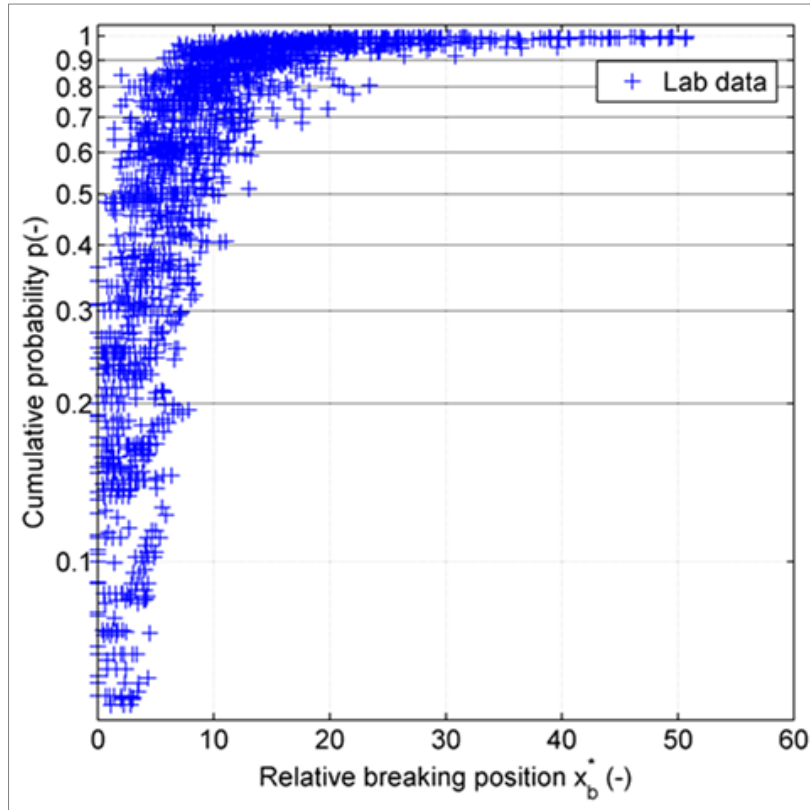


Figure 7. Probability distribution of relative wave breaking position

Although there exists no empirical probability distribution yet the surf zone position can be estimated from Figure 7 according to a selected significant level of non-exceedance probability.

Average wave breaking position, $p = 50\%$:

$$x_{b,50\%}^* = 10$$

$$x_{b,50\%} = 10d \tanh\left(\frac{2\pi}{L_{op}} d \xi_{op}^{-0.12}\right) \tag{3}$$

Wave breaking position with $p = 90\%$:

$$x_{b,90\%}^* = 20$$

$$x_{b,90\%} = 20d \tanh\left(\frac{2\pi}{L_{op}} d \xi_{op}^{-0.12}\right) \tag{4}$$

where $x_{b,p\%}$ is a wave breaking position that $p\%$ of the total breaking waves that stay within $x \leq x_{b,p\%}$.

4.2. Maximum Spectral Wave Height within the Surf zone

In contrast to the situation on a calm beach, wave breaking on the coral reef is focused in a limited coral reef-edge surf zone. For design purposes, it is therefore not desirable to determine the spectral wave height H_{m0} across the surf zone. Rather, the maximum spectral wave height within the surf zone is needed. For this, the maximal wave height H_{m0} out of all measuring stations within the surf zone is determined for each of the test cases. It appears that in most cases the maximal wave height occurs around the outer reef edge. Figure 8 shows the data of the maximal wave height plotted against the relative submerged depth d/H_{m0} .

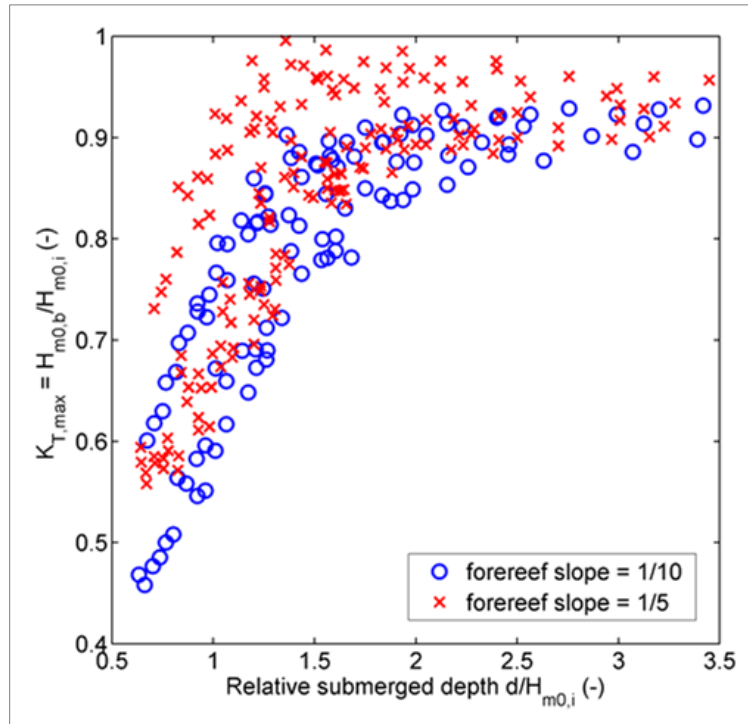


Figure 8. Data of maximal wave heights in surf zone

Regression analysis of the data yields the following equations of the maximum spectral wave height in the surf zone (see also Figure 9):

$$\frac{H_{m0,b}}{d} = 1.0 - 0.80 \tanh\left(1.25 \frac{2\pi}{L_{om}} d \xi_{om}^{-0.11}\right) \tag{6-a}$$

$$\frac{H_{m0,b}}{d} = 1.0 - 0.76 \tanh\left(1.55 \frac{2\pi}{L_{op}} d \xi_{op}^{-0.12}\right) \tag{6-b}$$

In which, $H_{m0,b}$ is the maximum spectral wave height within the surf zone, L_{om} and ξ_{om} are the incident deep-water wavelength and the Iribarren number based on the spectral period $T_{m-1,0}$, respectively.

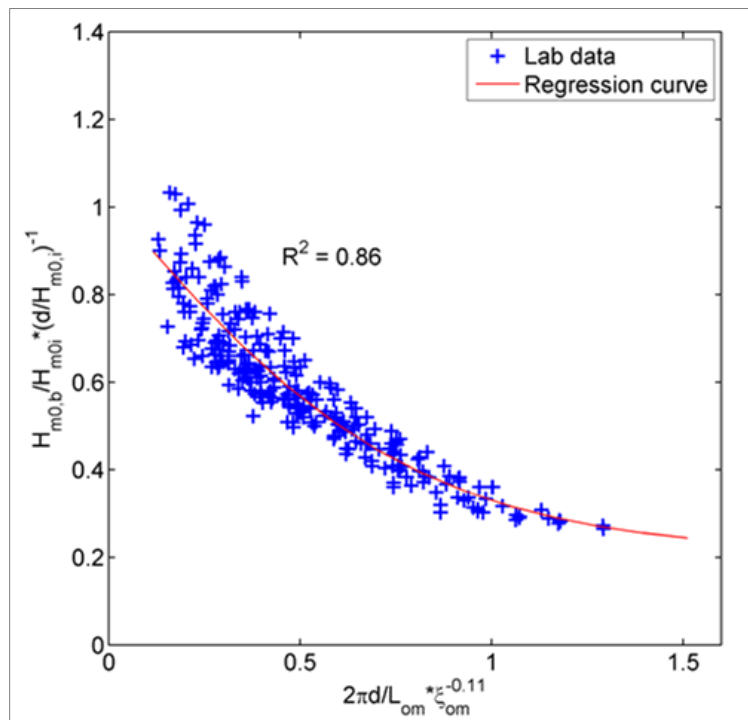


Figure 9. Regression data of $H_{m0,b}$ (based on $T_{m-1,0}$)

Note that the use of either Equations 6-a or 6-b solely depends on the availability of the spectral period (in fact the use of $T_{m-1,0}$ always gives a better data agreement). It follows from these equations and also noticed in the measured data that the maximum $H_{m0,b}$ within the surf zone never exceeds the water depth over the reef flat.

4.3. Maximum Characteristic Period $T_{m-1,0}$ in the Surf zone

The wave spectrum in the surf zone stretches towards the low frequency bands or has several peaks due to the intense wave breaking (see also Figure 1). The peak period T_p is no longer applicable in this circumstance. In many offshore structure design analyses, the use of the typical spectral period $T_{m1,0}$ is shown to be more appropriate [14]. Figure 10 shows the ratio of $T_{m-1,0}$ to the event period $T_{m1,0}$ at various sites inside and behind the surf zone. $T_{m-1,0}$ rises in most places on the reef flat, but most significantly in the surf zone. As a result, the duration for these two zones should be chosen separately.

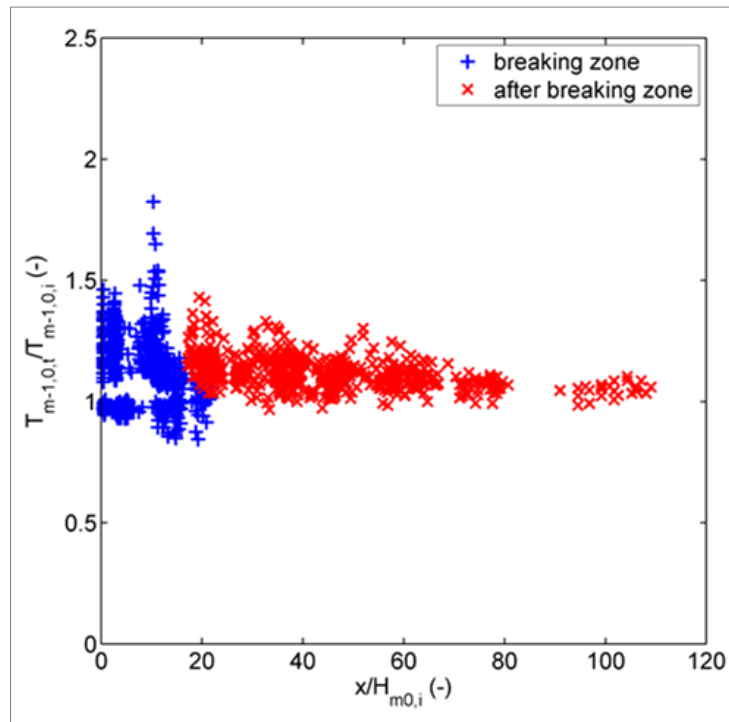


Figure 10. Variations $T_{m-1,0}$ across the coral reef flat

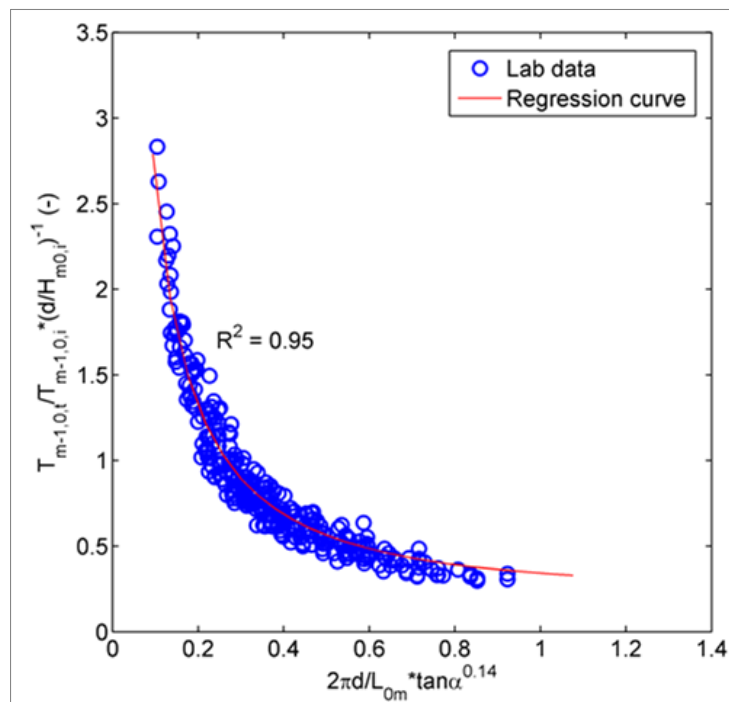


Figure 11. Regression data of $T_{m-1,0,b}$ (based on $T_{m-1,0}$)

The following formulations of the maximum spectral period within the surf zone $T_{m-1,0,b}$ are established (see also Figure 11):

$$\frac{T_{m-1,0,b}}{T_{m-1,0,i}} = 0.26 \frac{d}{H_{m0,i}} \frac{1}{\tanh\left(\frac{2\pi d}{L_{0m}} \tan \alpha^{0.14}\right)} \tag{7-a}$$

$$\frac{T_{m-1,0,b}}{T_{p,i}} = 0.29 \frac{d}{H_{m0,i}} \frac{1}{\tanh\left(\frac{2\pi d}{L_{0p}} \tan \alpha^{0.08}\right)} \tag{7-b}$$

where parameters with subscript (*)_i are associated with the incident wave.

4.4. Wave Heights in the Transmitted Zone

Wave energy is almost entirely lost by bed friction behind the surf zone. Based on the wave energy conservation equation and the assumption that the linear wave theory is still valid. On a horizontal bed, the wave height decline can be characterized using the following mathematical statement [15]:

$$\frac{H_{m0,x}}{H_{m0,t}} = \frac{1}{1 + \beta \cdot x_t} \tag{8}$$

where $H_{m0,t}$ is the wave height at the wave breaking boundary (or entrance to the transmitted zone), $x_t (= x - x_b)$ is the distance to the breaking boundary of a considered location in the transmitted zone, H_{m0x} is the wave height at the considered location, β is a wave damping parameter due to bed friction. For irregular waves, β can be derived according to the linear wave theory:

$$\beta = f_w \cdot \beta_0$$

$$\beta_0 = \frac{k^2 H_{m0,t}}{\sqrt{2\pi} \sinh(kd)(2kd + \sinh(2kd))} \tag{9}$$

In which, k is the wavenumber, f_w is a wave-related friction coefficient, β_0 is an intermediate wave damping parameter.

The experimental data of the wave height decay as shown in Figure 12 asserts that Equation 8 is indeed applicable. Waves are shown to slowly attenuate because the model reef bottom is smooth and non-porous. Herein, the regression line based on Equation 8 was determined with $f_w = 0.021$ for the best agreement ($R^2 = 0.85$). This small value of the friction coefficient corresponds to the situation of a smooth reef bottom considered in the experiments. However, under field conditions, the reef bottom is often rough and/or porous (e.g., rock or coral), and the decay rate may be considerably larger. In such a situation, the friction coefficient f_w or the decay parameter b in Equation 9 needs to be re-calibrated based on the actual reef bottom conditions. Therefore, for the description of the wave height decay according to Equation 8 in general, it is essential to determine the wave parameters ($H_{m0,t}$ and $T_{m-1,0,t}$) at the entrance of the transmitted zone.

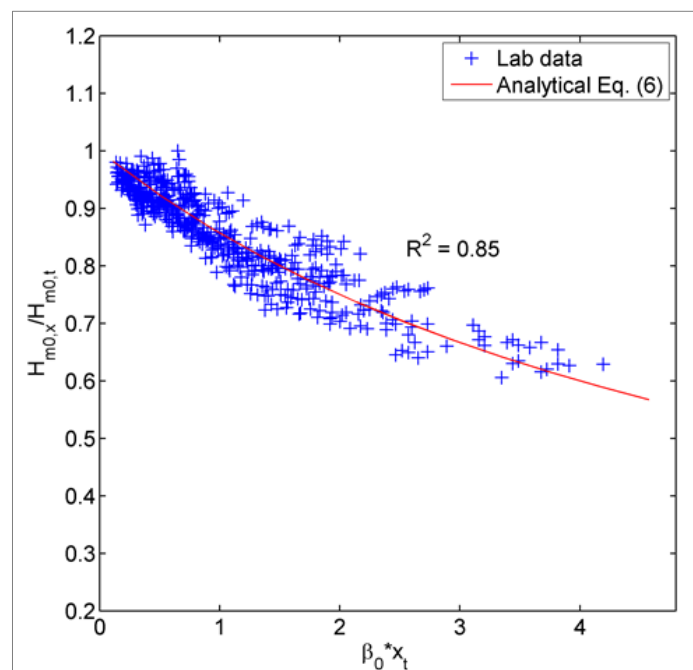


Figure 12. Wave height decay in the transmitted zone

The transmitted wave height at the breaking boundary can be formulated in the same way as for the maximum wave height within the surf zone (see also Figure 13 for the regression data):

$$\frac{H_{m0,t}}{d} = 0.6 - 1.05 \tanh\left(0.31 \frac{2\pi}{L_{om}} d\right) \tag{10-a}$$

$$\frac{H_{m0,t}}{d} = 0.6 - 0.48 \tanh\left(0.81 \frac{2\pi}{L_{op}} d\right) \tag{10-b}$$

Note that the fore-reef slope is absent in Equation 10 because of its negligible effect in the transmitted zone discussed in Section 3.

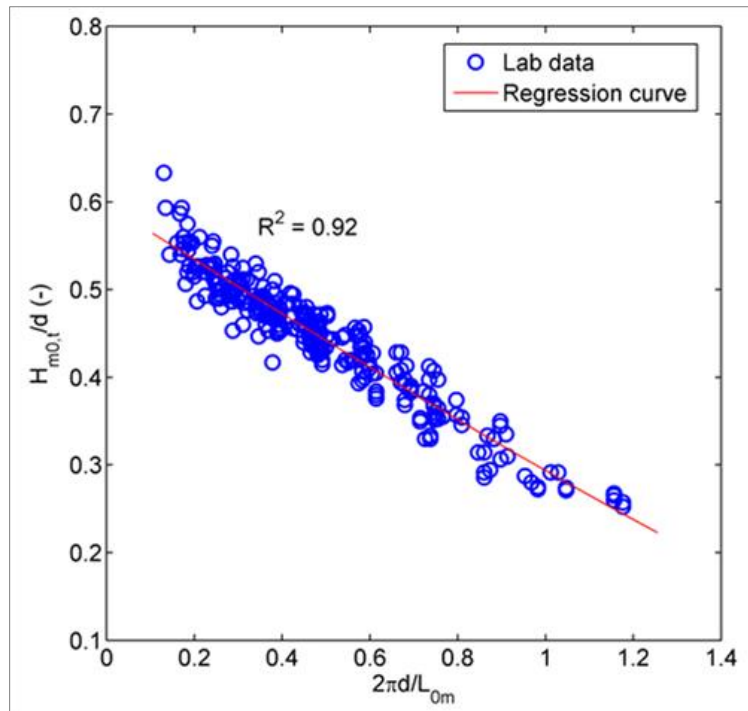


Figure 13. Regression data of $H_{m0,t}$ (based on $T_{m-1,0}$)

Similarly, the average characteristic period in the transmitted zone $T_{m-1,0,t}$ (see also Figure 14):

$$\frac{T_{m-1,0,t}}{T_{m-1,0,i}} = 0.31 \frac{d}{H_{m0,i}} \frac{1}{\tanh\left(\frac{2\pi d}{L_{om}}\right)} \tag{11-a}$$

$$\frac{T_{m-1,0,t}}{T_{p,i}} = 0.27 \frac{d}{H_{m0,i}} \frac{1}{\tanh\left(\frac{2\pi d}{L_{op}}\right)} \tag{11-b}$$

5. Conclusions

Laboratory experiments were carried out to investigate wave transmission across submerged reefs with large steep fore-reef slopes. This study has produced the empirical formulas for the wave spectrum parameters along the reef flat based on the experimental results of the physical model. The design wave loads to offshore structures on submerged reefs with large steep fore-reef slopes require the empirical calculations given in this research. The empirical formulas developed in this paper were used to determine the wave load for the redesign of twenty steel jacket structures on submerged reefs with large steep fore-reef slopes in the continental shelf of Vietnam. This success proves the reliability of the research results published in this paper.

The research results of this paper also show that the reef-edge surf zone and the transmitted zone are the two separate regions in which wave transmission is described (behind the surf zone). The wave-breaking boundary, which separates these two zones, has been stochastically estimated based on the measured probability distribution of the wave breaking position. The relative submerged depth and the fore-reef slope are the primary and secondary parameters that affect

wave transmission in the surf zone, where wave breaking is the dominant dissipation process. Subsequently, for the design purposes, the maximum spectral wave height H_{m0} and the characteristic spectral period $T_{m-1,0}$ within the surfzone have been formulated.

In the transmitted zone, where waves are mainly dissipated by bed friction, the wave height is shown to decay against the travelling distance (to the breaking boundary) and bed friction characterized by the bottom roughness. For use in a general situation with arbitrary reef bottom conditions, wave parameters at the breaking boundary have been formulated based on the experimental data. Validation of numerical wave models against the laboratory results from this work will be a focus of future research.

6. Declarations

6.1. Author Contributions

Conceptualization, D.Q.C.; methodology, D.Q.C.; software, T.Q.T.; formal analysis, D.Q.C.; investigation, T.Q.T.; resources, T.Q.T.; writing—original draft preparation, D.Q.C.; writing—review and editing, T.Q.T.; visualization, T.Q.T.; supervision, D.Q.C.; funding acquisition, D.Q.C. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

7. References

- [1] Nelson, R. C. (1994). Depth limited design wave heights in very flat regions. *Coastal Engineering*, 23(1–2), 43–59. doi:10.1016/0378-3839(94)90014-0.
- [2] Gourlay, M. R. (1994). Wave transformation on a coral reef. *Coastal Engineering*, 23(1–2), 17–42. doi:10.1016/0378-3839(94)90013-2.
- [3] Yao, Y., Huang, Z., Monismith, S. G., & Lo, E. Y. M. (2013). Characteristics of monochromatic waves breaking over fringing reefs. *Journal of Coastal Research*, 29(1), 94–104. doi:10.2112/JCOASTRES-D-12-00021.1.
- [4] Battjes, J. A. (1974). SURF SIMILARITY. *Coastal Engineering Proceedings*, 1(14), 26. doi:10.9753/icce.v14.26.
- [5] Nakaza, E., & Hino, M. (1991). Bore-like surf beat in a reef zone caused by wave groups of incident short period waves. *Fluid Dynamics Research*, 7(2), 89–100. doi:10.1016/0169-5983(91)90062-N.
- [6] Lowe, R. J., Falter, J. L., Bandet, M. D., Pawlak, G., Atkinson, M. J., Monismith, S. G., & Koseff, J. R. (2005). Spectral wave dissipation over a barrier reef. *Journal of Geophysical Research: Oceans*, 110(4), 1–16. doi:10.1029/2004JC002711.
- [7] Demirbilek, Z., Nwogu, O. G., & Ward, D. L. (2007). Laboratory study of wind effect on runup over fringing reefs, Report 1: data report. Technical report, Coastal and Hydraulics Laboratory, Engineering Research and Development Center, Vicksburg, United States.
- [8] Buckley, M. L., Lowe, R. J., Hansen, J. E., & Van Dongeren, A. R. (2015). Dynamics of wave setup over a steeply sloping fringing reef. *Journal of Physical Oceanography*, 45(12), 3005–3023. doi:10.1175/JPO-D-15-0067.1.
- [9] Becker, J. M., Merrifield, M. A., & Yoon, H. (2016). Infragravity waves on fringing reefs in the tropical Pacific: Dynamic setup. *Journal of Geophysical Research: Oceans*, 121(5), 3010–3028. doi:10.1002/2015JC011516.
- [10] Buckley, M. L., Lowe, R. J., Hansen, J. E., Van Dongeren, A. R., & Storlazzi, C.D. (2018). Mechanisms of wave-driven water level variability on reef-fringed coastlines. *Journal of Geophysical Research: Oceans*, 123(5), 3811–3831. doi:10.1029/2018JC013933.
- [11] Tuan, T. Q., & Cuong, D. Q. (2019). Distribution of wave heights on steep submerged reefs. *Ocean Engineering*, 189, 106409. doi:10.1016/j.oceaneng.2019.106409.
- [12] van der Meer, J. W., Briganti, R., Zanuttigh, B., & Wang, B. (2005). Wave transmission and reflection at low-crested structures: Design formulae, oblique wave attack and spectral change. *Coastal Engineering*, 52(10–11), 915–929. doi:10.1016/j.coastaleng.2005.09.005.

- [13] Miche, M. (1954). *Undulatory Movements of the Sea in Constant or Decreasing Depth: Limited Form of the Wave at the Time of Breaking Application to Marine Structures*. College of Engineering, University of California, California, United States.
- [14] Hofland, B., Chen, X., Altomare, C., & Oosterlo, P. (2017). Prediction formula for the spectral wave period $T_{m-1,0}$ on mildly sloping shallow foreshores. *Coastal Engineering*, 123, 21–28. doi:10.1016/j.coastaleng.2017.02.005.
- [15] Dalrymple, R. A., Kirby, J. T., & Hwang, P. A. (1984). Wave Diffraction Due to Areas of Energy Dissipation. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 110(1), 67–79. doi:10.1061/(asce)0733-950x(1984)110:1(67).