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WAVE TRANSMISSION ACROSS STEEP SUBMERGED REEFS

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ABSTRACT: This study presents a laboratory study on wave transmission across steep submerged reefs, aiming at further understanding of wave hydrodynamics and establishing empirical formulations of spectral wave parameters along the reef flat. In terms of major mechanism of wave energy dissipation, wave transmission on the reef flat could be split into two regions: the reef-edge surfzone (energy dissipated by wave breaking due to the sudden depth reduction) and the one behind the surfzone (energy dissipated by bed friction). The relative submerged depth $d/H_{\mathrm{m0,i}}$ reflecting the reef shallowness and the fore-reef slope are factors that governs the wave hydrodynamics across the surfzone, e.g. wave breaking and wave spectral transformation. However, the effect of the fore-reef slope is found secondary only. Behind the surfzone the wave height is shown to gradually attenuate with the distance away from the surfzone boundary. Two sets of empirical formulations of the spectral wave parameters (H_{m0} and $T_{m\text{-}1,0}$) are eventually derived for the surfzone and the region behind the surfzone, 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 submerged reefs.

Keywords: Wave transmission, steep submerged reefs, reef flat, wave breaking.

1 INTRODUCTION

Submerged reefs off the coast of Vietnam are a few hundred meters to several kilometres wide at the flat top level. The fore-reef water depth (at the reef foot) is often more than 100m, while only 5 – 20m on the reef flat. The transitional slope from the deep water part to the shallow reef flat typically consists of a steep deep foot (slope ~ 1 /1-1/2) and a milder flank (slope 1/5 – 1/15). Compared to the situation on shallow beaches, the abrupt bed transition over steep fore-reef slopes from deep water to (horizontal) shallow flat tops results in unique wave hydrodynamics across submerged reefs. Particularly, wave breaking on the reef due to sudden depth reduction differs substantially from that on a relatively gentle beach with gradual depth variation. For instance, Nelson (1994) noted that the maximum individual wave height to water depth ratio on a horizontal reef flat (behind the reef-edge surfzone) should not exceed 0.55, far below the commonly accepted value of 0.80. For the design of engineering works on reef flat tops it is required to reliably estimate the design wave heights (extreme conditions) at various locations across the reef flat. Unfortunately, a few studies exist in the literature for the wave hydrodynamics under extreme (design) conditions, but rather for environment-related issues under relatively calm sea states (see e.g. Lowe et al., 2005).

The main objective of the present study is to establish empirical formulations of wave spectral parameters on the reef flat, needed as the input to a wave height distribution model such as by Tuan and Cuong (2019) for determining design characteristic wave heights on steep submerged reefs. The measured wave data can also be used for validation of numerical wave models.

2 EXPERIMENTS

The experiments were carried out at the hydraulic laboratory of Thuy Loi University (Vietnam). These are the follow-up to the first experimental series focusing on the distribution model of wave heights by Tuan and Cuong (2019). The flume is 45 m long (effective), 1.0 m wide and 1.2 m high, equipped with an automated system of Active Reflection Compensation (ARC) and capable of generating both regular and irregular waves up to 0.25 m in height and 2.5 s in peak period.

Figure 1 illustrates the setup of the experiments, in which the smooth and impermeable model reef is 50cm high above the flume bottom. The model length scale selected according to prototype and laboratory conditions is 1/40. The flat top width B is 8.0m, sufficiently wide to accommodate both the reef-edge breaking zone and the transmitted region (behind the surfzone) for observation of the entire progress of wave transformation over the reef. For the effect of the reef slope, two typical fore-reef slopes of 1/5 and 1/10 are considered, respectively. A gentle riprap slope is placed at the other end of the flume to absorb the remaining wave energy.

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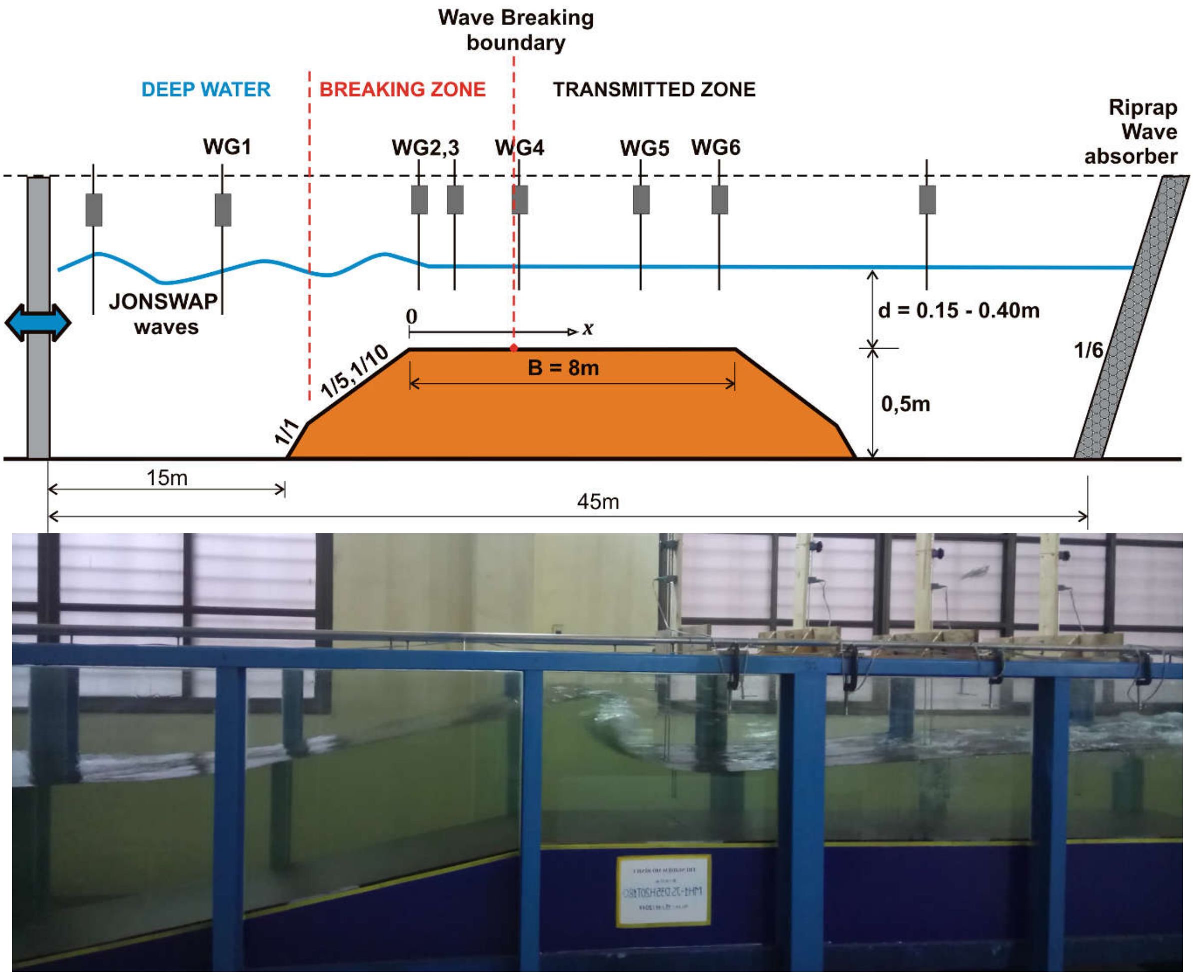

Figure 1 Experimental layout of wave transmission across the submerged reef

Table 1 Summary of the test program

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

Capacitance wave gauges are distributed in three regions across the reef, i.e. deep water, reef-edge breaking zone and transmitted zone, in which positions of those on the reef flat are variable depending on test scenarios so that various wave conditions can be captured. A side video camera is used to record images of the water surface, particularly those with wave breaking, around the reef edge.

The test program as outlined in a matrix of Table 1 is a combination of various submerged depths and wave parameters. The tested waves are JONSWAP spectra with the peak enhancement factor $\gamma = 1.25$ as found most suitable for the deep-sea region off the coast of Vietnam. Note that the wave parameters as shown in Table 1 are nominal (steering) at the wave board boundary only, in which the peak wave periods are derived according to two typical storm wave steepness s_{0p} of 0.03 and 0.04, respectively. Amongst these test combinations, test cases with significant super-elevated water levels behind the reef or with generated largest wave heights in excess of the flume height were excluded. In total, 275 experiments were carried out, each of which lasted approximately 1000 waves to sufficiently cover the main frequency domain of desired wave spectra and allow for stable statistical properties of wave heights.

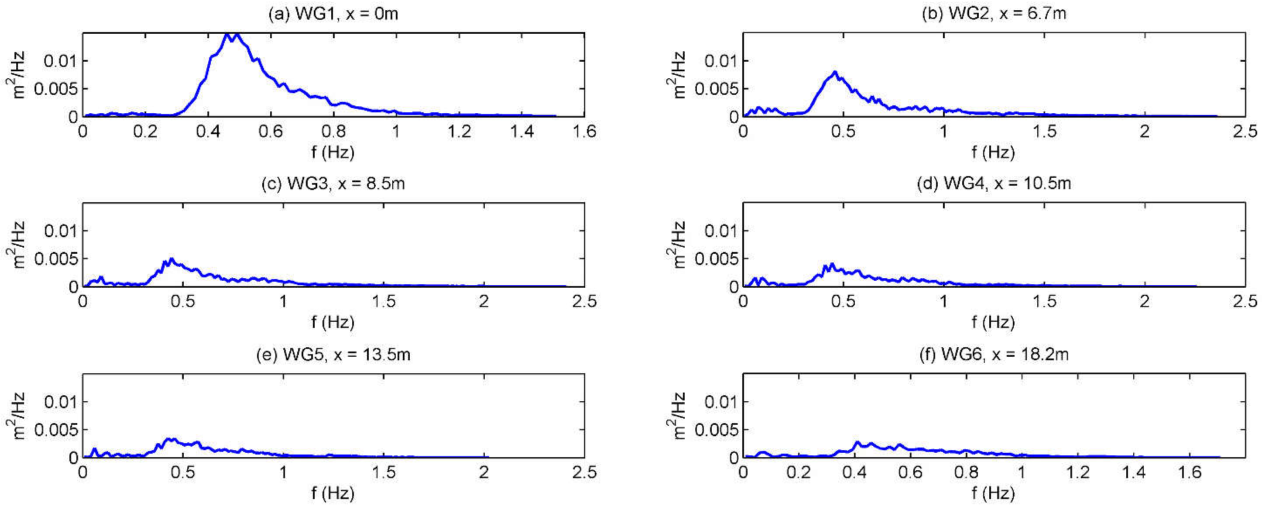

Figure 2 Spectral transformation across the reef

3 DATA ANALYSIS

In this section, behaviour of wave transmission and influences of the reef geometry and of hydraulic conditions are examined in prior to the derivation of empirical formulations.

It can be seen from the measured wave spectral transformation across the reef flat shown in Fig.2 that wave energy is largely dissipated within the reef-edge surfzone (Fig.2a to Fig.2c) whilst remains relatively unchanged after the surfzone (Fig.2d to Fig.2e). This implies that wave transmission in these two regions should distinctly be considered.

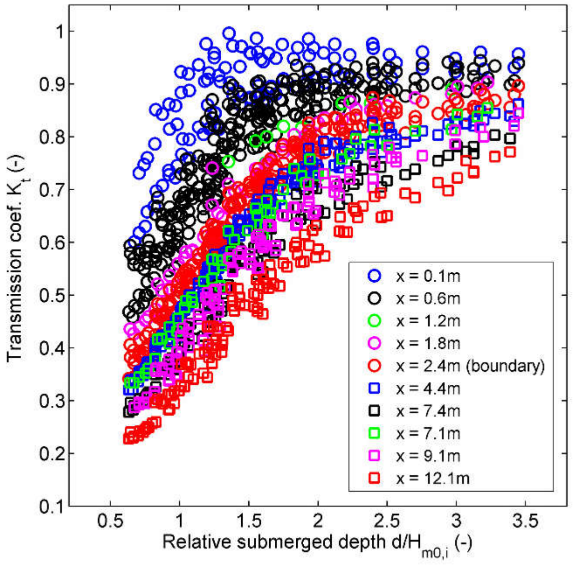

Figure 3 Effects of the relative submerged depth d/H_{m0}

Figure 3 presents the transmission coefficient K_t (= H_{m0x}/H_{m0i}, ratio of the local wave height H_{m0x} to the incident wave height H_{m0i}) at various across the reef flat as a function of the relative submerged depth d/H_{m0}. Like other conventional submerged coastal structures (see e.g. Van der Meer et al., 2005), wave transmission on the reef is clearly proportional to the relative submerged depth, which, however, exhibits different behaviour between inside and behind the surfzone (namely the transmitted zone). Within the surfzone ($x \leq$ 1.8m - 2.4m), the increase of K_t with d/H_{m0} is rather steep for small relative submergence (i.e. until d/H_{m0} < 1.50) and then slows down considerably or even relatively unchanged when d/H_{m0} becomes larger. In the transmitted zone, this increase is generally at a much milder rate.

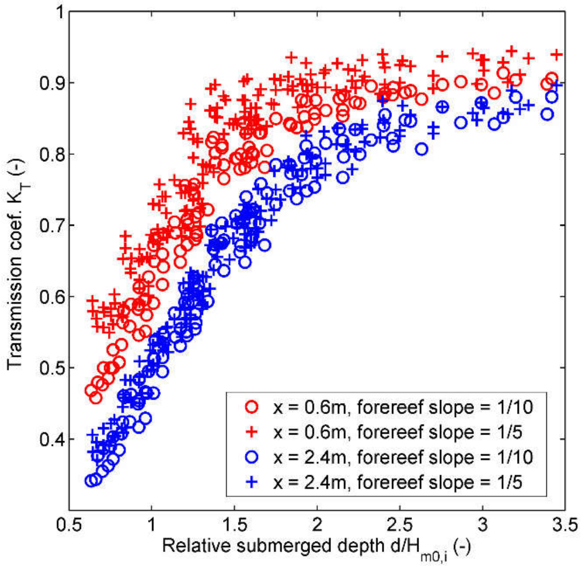

Figure 4 Effects of the fore-reef slope: inside surfzone (x = 0.60m) and transmitted zone (x = 2.4m)

The wave transmission data showing the effects of the fore-reef slope are presented in Fig.4 for one location inside the surfzone (x = 0.6m) and one in the transmitted zone (x = 2.4m), respectively. For each of the locations the data corresponding to two fore-reef slopes are shown (plus signs "+" for slope of 1/5 and open circles "o" for slope of 1/10). Generally speaking, compared to the relative submerged depth, the effect of the fore-reef slope is found secondary only. The effect appears to be considerable in the surfzone, but not in the transmitted zone. A steeper slope generally results in a larger wave height in the surfzone.

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 also Fig.1): the reef-edge surfzone 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.

3 FORMULATIONS

Wave loading is very severe to structures located within the surfzone. It is therefore essential for the engineering design to estimate the wave breaking boundary so that structures can be either safely located well behind the surfzone or proactively designed to sustain such extreme loading conditions in the surfzone. In the following sections, the wave breaking boundary is first statistically estimated from visual observation data from the experiments. Empirical formulations are then derived for estimating design spectral wave parameters (H_{m0} and $T_{m-1,0}$) inside the surfzone. Characteristics of wave transmission behind the surfzone is also addressed.

3.1 Wave breaking boundary

For each of the experiments, images indexed from the video record of wave trains around the reef edge are reviewed to identify the number of breaking waves and determine their corresponding positions x_b measured from the breaking point to the outer edge of the reef flat. As breaking of irregular waves is a random process, the position or distance of a breaking wave is treated as a stochastic variable.

Generally speaking, the breaking point position is related to the maximum individual wave height in the surfzone. Herein we presume a connection between x_b and the maximum spectral wave height that exist within the surfzone $H_{m0,b}$ (see section 3.2 for further details). The relative wave breaking position x_b* is defined as follows:

$$x_b* = \frac{x_b}{d\tanh\left(\frac{2\pi}{L_{op}} d\xi_{op}^{-0.12}\right)} \qquad (1)$$

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

where tanα is the fore-reef slope, L_{0p} and ξ_{0p} are the incident deep-water wave length and the Iribarren number based on the peak spectral period T_p, respectively.

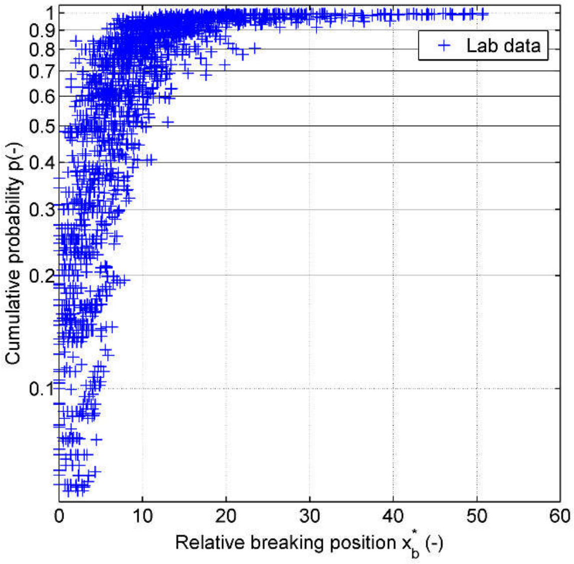

Figure 5 Probability distribution of relative wave breaking position

The non-exceedance probability that a wave break within the reef-edge surfzone, $p(\hat{x}_b \le x_b^*)$, can be calculated from the measured data. Figure 5 presents the measured data of the probability distribution $p(\hat{x}_b \le x_b^*)$ with the breaking position x_b*.

Although there exists no empirical probability distribution yet the surfzone position can be estimated from Fig.5 according to a selected significant level of non-exceedance probability:

Average wave breaking position, p = 50%:

$$x*_{b,50\%} = 10$$

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

Wave breaking position with p = 90%:

$$x*_{b,90\%} = 20$$

$$x_{b,90\%} = 20d\tanh\left(\frac{2\pi}{L_{op}} d\xi_{op}^{-0.12}\right) \qquad (3)$$

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

3.2 Maximum spectral wave height in the surfzone

Unlike the situation on a gentle beach, wave breaking on the reef is drastically concentrated within a narrow reef-edge surfzone. For the design purposes, it is therefore not desirable to determine the spectral wave height H$_{m0}$ across the surfzone. Rather, the maximum spectral wave height within the surfzone is needed. For this, the maximal wave height H_{m0} out of all measuring stations within the surfzone 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 6 shows the data of the maximal wave height plotted against the relative submerged depth d/H_{m0}.

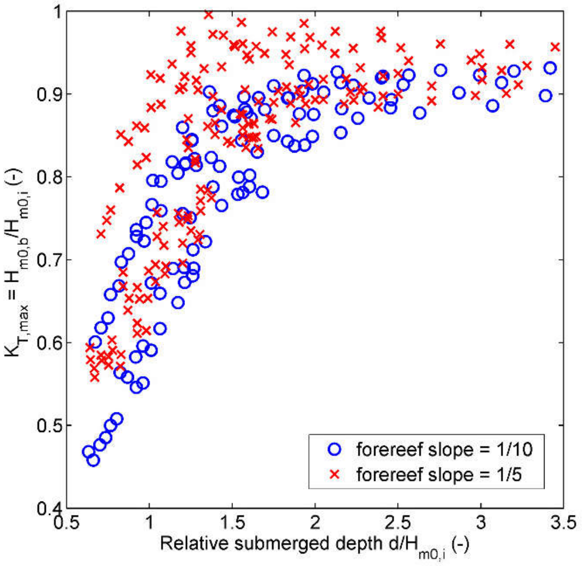

Figure 6 Data of maximal wave height in surfzone

Regression analysis of the data yields the following equations of the maximum spectral wave height in the surfzone (see also Fig. 7):

$$\frac{H_{m0,b}}{d} = 1.0 - 0.80\tanh\left(1.25\frac{2\pi}{L_{om}}d\xi_{om}^{-0.11}\right) \qquad (4a)$$

$$\frac{H_{m0,b}}{d} = 1.0 - 0.76\tanh\left(1.55\frac{2\pi}{L_{op}}d\xi_{op}^{-0.12}\right) \qquad (4b)$$

in which, $H_{m0,b}$ is the maximum spectral wave height within the surfzone, L_{0m} and ξ_{0m} are the incident deep-water wave length and the Iribarren number based on the spectral period $T_{m\text{-}1,0}$, respectively.

Note that the use of either Eq. (4a) or Eq. (4b) solely depends on the availability of the spectral period (in fact the use of $T_{m\text{-}1,0}$ 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 surfzone never exceed the water depth over the reef flat.

3.3 Maximum characteristic period $T_{m\text{-}1,0}$ in the surfzone

Due to intensive wave breaking in the surfzone, wave spectra undergo a drastic transformation, e.g. stretching out toward low-frequency bands or exhibiting multiple peaks (see also Fig.2). The peak period T_p is no longer valid in this particular situation and the use of the characteristic spectral period $T_{m\text{-}1,0}$ is found more appropriate instead in many engineering design calculations (see e.g. Hofland et al., 2017).

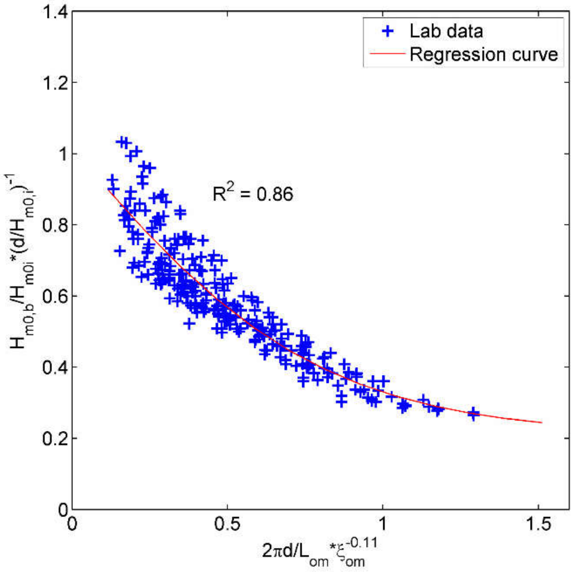

Figure 7 Regression data of H$_{m0,b}$ (based on $T_{m\text{-}1,0}$)

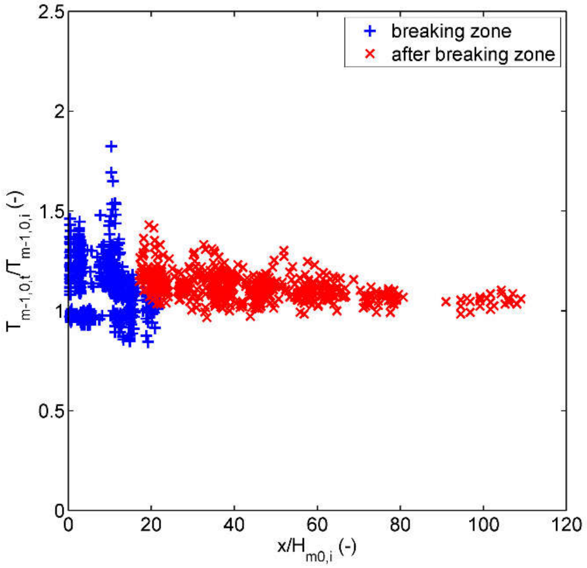

Figure 8 Variations $T_{m\text{-}1,0}$ across the reef flat

Figure 8 shows the ratio of $T_{m\text{-}1,0}$, at various locations inside and behind the surfzone, to the incident period $T_{m\text{-}1,0}$. In general, $T_{m\text{-}1,0}$ is found to increase at most of the locations on the reef flat, but most noticeably in the surfzone. Therefore, the period should distinctly be determined for these two zones.

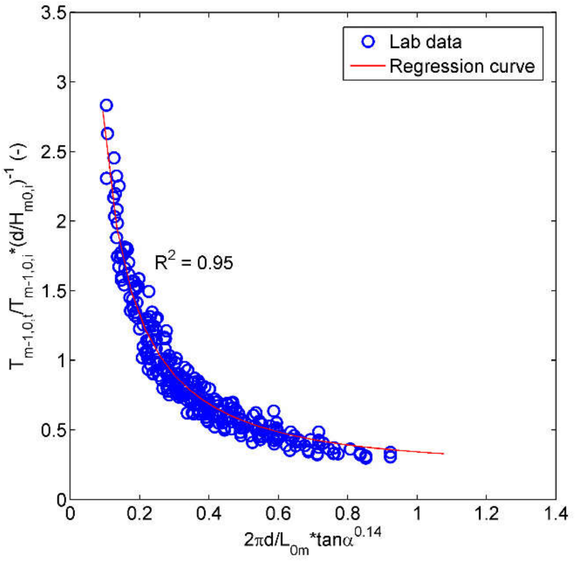

Figure 9 Regression data of $T_{m\text{-}1,0,\mathrm{b}}$ (based on $T_{m\text{-}1,0}$)

The following formulations of the maximum spectral period within the surfzone $T_{m\text{-}1,0,b}$ are established (see also Fig. 9):

$$\frac{T_{m-1,0,b}}{T_{m-1,0,i}} = 0.26\frac{d}{H_{m0,i}}\frac{1}{\tanh\left(\dfrac{2\pi d}{L_{0m}}\tan\alpha^{0.14}\right)} \tag{5a}$$

$$\frac{T_{m-1,0,b}}{T_{p,i}} = 0.29\frac{d}{H_{m0,i}}\frac{1}{\tanh\left(\dfrac{2\pi d}{L_{0p}}\tan\alpha^{0.08}\right)} \tag{5b}$$

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

3.4 Wave heights in the transmitted surfzone

After the surfzone, waves are mainly dissipated by bed friction. From the wave energy conservation equation and assuming that the use of the linear wave theory is still adequate, the wave height decay on a horizontal bed can be described with an analytical expression as follows (see also Dalrymple et al., 1984):

$$\frac{H_{m0,x}}{H_{m0,t}} = \frac{1}{1+\beta\cdot x_t} \tag{6}$$

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:

$$\beta = f_w\cdot\beta_0$$
$$\beta_0 = \frac{k^2 H_{m0,t}}{\sqrt{2\pi}\,\sinh(kd)\left(2kd+\sinh(2kd)\right)} \tag{7}$$

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

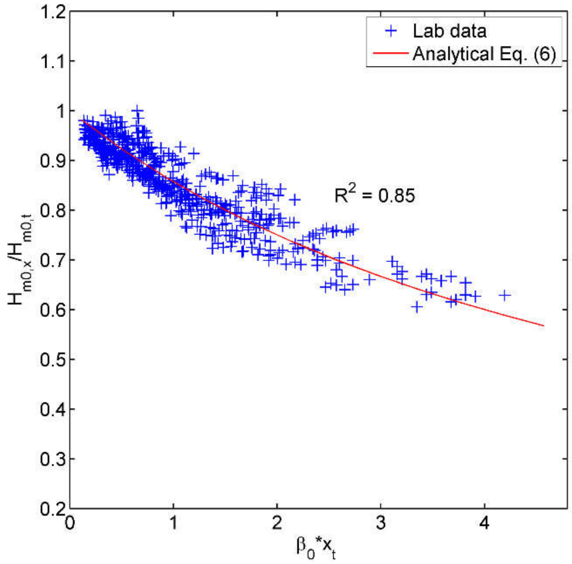

Figure 10 Wave height decay in the transmitted zone

The experimental data of the wave height decay as shown in Fig. 10 assert that Eq. (6) 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 Eq. (6) 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 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 considerably be larger. In such a situation, the friction coefficient f_w or the decay parameter β in E. (7) needs to be re-calibrated based on the actual reef bottom conditions. Therefore, for the description of the wave height decay according to Eq. (6) in general, it is most essential to determine the wave parameters ($H_{m0,\mathrm{t}}$ and $T_{m\text{-}1,0,\mathrm{t}}$) at the entrance of 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 surfzone (see also Fig. 11 for the regression data):

$$\frac{H_{m0,t}}{d} = 0.6 - 1.05\tanh\left(0.31\frac{2\pi}{L_{om}}d\right) \tag{8a}$$

$$\frac{H_{m0,t}}{d} = 0.6 - 0.48\tanh\left(0.81\frac{2\pi}{L_{op}}d\right) \tag{8b}$$

Note that the fore-reef slope is absent in Eqs. (8) because of its negligible effect in the transmitted zone argued earlier.

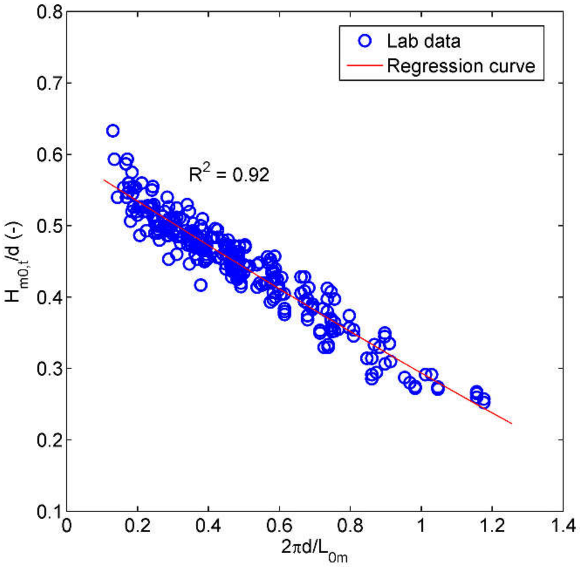

Figure 11 Regression data of $H_{m0,t}$ (based on $T_{m\text{-}1,0}$)

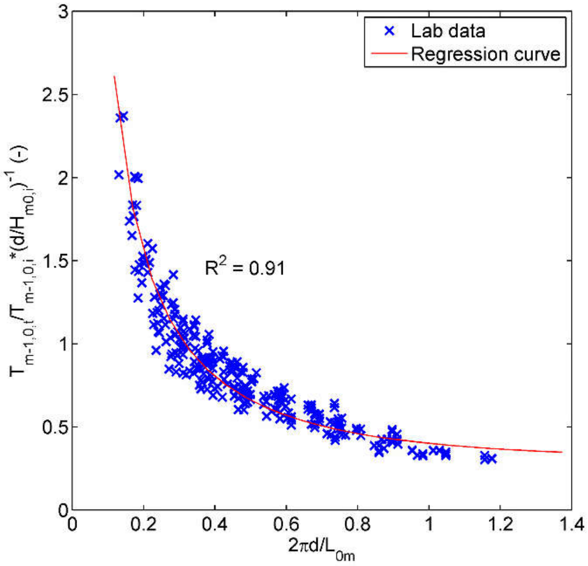

Figure 12 Regression data of $T_{m\text{-}1,0,\text{t}}$ (based on $T_{m\text{-}1,0}$)

Similarly, the average characteristic period in the transmitted zone $T_{m\text{-}1,0,t}$ reads (see also Fig.12):

$$\frac{T_{m-1,0,t}}{T_{m-1,0,i}} = 0.31\frac{d}{H_{m0,i}}\frac{1}{\tanh\left(\frac{2\pi d}{L_{0m}}\right)} \tag{9a}$$

$$\frac{T_{m-1,0,t}}{T_{p,i}} = 0.27\frac{d}{H_{m0,i}}\frac{1}{\tanh\left(\frac{2\pi d}{L_{0p}}\right)} \tag{9b}$$

4 CONCLUSIONS

Laboratory experiments were carried out to investigate wave transmission across submerged reefs with steep fore-reef slopes. The ultimate goal is to derive empirical formulations of wave spectral parameters along the reef flat, needed in the determination of design wave loads to engineering works.

Description of wave transmission is split into two distinct regions, i.e. the reef-edge surfzone and the transmitted zone (behind the surfzone). The wave breaking boundary, which separates these two zones, has been stochastically estimated based on the measured probability distribution of the wave breaking position.

In the surfzone, where wave breaking is the major dissipation mechanism, the relative submerged depth and the fore-reef slope are respectively the primary and the secondary factors that affect wave transmission. Subsequently, for the design purposes, the maximum spectral wave height H_{m0} and the characteristic spectral period $T_{m\text{-}1,0}$ 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.

Future research includes validations of numerical wave models against the laboratory data of this study.

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