STABILITY AND HYDRODYNAMICS OF THE REEF ENHANCING BREAKWATER: A PHYSICAL MODEL STUDY

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Abstract: This study presents the stability and hydrodynamics of the Reef Enhancing Breakwater (REB) based on a physical model study. The REB is an innovative shoreline protection solution that uses interlocking ReefBlocks designed to enhance marine life while ensuring structural stability. Through three physical model testing campaigns conducted in 2020, 2023, and 2024, the hydrodynamic performance and stability of the REB were evaluated for different setups and under varying wave conditions. The hydrodynamic results were compared with the wave transmission equations for submerged rock breakwaters, as described in the Rock Manual (2012), showing comparable wave transmission values to conventional rock structures, and a root mean square error (RMSE) of 0.072 between the equations and the data. The wave transmission formula for permeable structures, as described by van Gent et al. (2023), achieved an RMSE of 0.044, providing a precise tool for detailed designs. The transmission, dissipation, and reflection coefficients are compared to values reported in natural coral reefs, with the aim of biomimicking hydrodynamics for reef crest restoration projects. Stability was assessed for setups with depth limited waves, deep water waves, and under direct impact of plunging breakers. Stability numbers ($N_s = H_{m0}/(\Delta * D_n)$) of up to 1.65 were found with no units being removed from the structure. When subjected to direct plunging wave impacts, lower stability numbers were observed. The findings support that the REB performs as an effective coastal defence technology designed to be stable and an effective wave attenuator while at the same time enhancing the marine ecosystem.

Keywords: breakwater; artificial reefs; reef enhancing breakwater; building with nature; coastal protection; green infrastructure; living breakwaters; eco-engineering; coastal resilience; climate adaptation; engineering with nature; hybrid engineering; biodiversity; ecosystem restoration; beach protection

Introduction

The demand for coastal infrastructure is growing rapidly. Presently over 39% of the global population lives within 100 km of the coast (Cesar et al. 2003). This rapid growth and changes of our coastlines can have a large scale impact on the environment. Key species, such as oysters and coral are vulnerable to coastal modifications. The four main local stressors to coral reefs are physical damage from coastal development, pollution, overfishing, and coral harvesting (U.S. Environmental Protection Agency 2024). Studies have estimated that we could lose up to 90% of all coral reefs by 2050 (UN Environment 2018), and 85% of oyster reefs have been lost already (Beck et al. 2011). The loss of reefs together with a devastating effect on biodiversity, also poses a potential safety risk for coastal areas around the world as coral and oyster reefs play an important role in coastal protection. Coral reefs can reduce up to 97% of wave energy, of which 86% is dissipated at the reef crest alone (Ferrario 2014). Additionally, reefs' coastal dynamics and their ability to be a sediment source make them effective against shoreline erosion. Beaches shielded by coral reefs experience 97% less beach volume loss compared to those without such protection (U.S. Geological Survey 2024).

Traditional solutions for coastal protection, such as groynes and breakwaters, can attenuate wave energy but are not designed with nature in mind. They can have a negative impact on the environment, are expensive to maintain due to sea level rise, and may interrupt the flow and paths of wildlife. By not including nature, the potential benefits of a natural source of sediment to the coast, water quality, and ecosystem services are not necessarily included. Consequently, there has been interest in alternatives that can support nature accretion, like artificial reefs. This interest is supported by previous research in wave attenuation (Armono 2004, Fauzi et al. 2007, Buccino et al. 2014, Del Vita 2016, Osorio-Cano 2019). However, most of the studies on artificial reefs focus mainly on nature enhancement, often omitting their stability in storm conditions. Stability is key both for the succession of a natural reef and for the use of these technologies as infrastructure. The study from Lokesha et al. (2013) describes a study of wave interaction with artificial reefs in the shapes of cubes and pipes. Results showed that 365 out of 720 cases tested were unstable, emphasizing the importance of stability research for the effectiveness of artificial reefs. A literature review by Blacka et al. (2013), on the effectiveness of previous projects of artificial reefs reported that half of the 29 projects reviewed had no significant accretionary impact on the shoreline

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alignment compared to the predicted morphological response and that most structures settled or suffered from scour. This highlights the importance of a holistic eco-engineering approach considering local ecosystems, wave attenuation for shoreline response, stability, and scour protection.

Modular artificial reefs have been explored as nature-enhancing beach protection (Mendoza et al. 2019), demonstrating the potential for combining coastal defence with ecological benefits. Building on this approach, a new type of breakwater was developed for coastal protection and climate adaptation considering nature enhancement, stability, wave dissipation, and constructability; The Reef Enhancing Breakwater (REB). The REB consists of patented ReefBlocks, as shown in Figure 1, which contain an interconnected system of tunnels that reduce pressure, allows water to flow, enhances abiotic conditions for biodiversity, and provides textured surfaces for epifauna such as reef building species, as described by van den Boogaart (2024). The ReefBlock is designed to be stable by its own weight and interlocking system, which also allows for the construction of different configuration of breakwaters and mimicking the hydrodynamics of a reef for shoreline protection. The REB can be used as a submerged breakwater as well as an emerged low-crested structure in tropical or temperate environments.

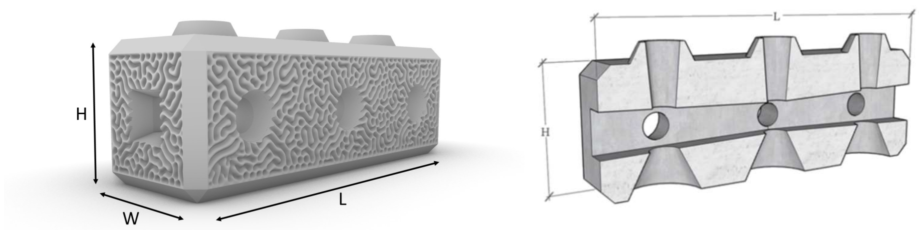

Figure 1. left: Render of the ReefBlock with texture for nature enhancement (van den Boogaart 2024). Right: lengthwise cross section of the ReefBlock, showcasing the interconnected tunnel system.

The ReefBlock has a ratio of 1:1:3 (H:W:L). The ReefBlock can be cast with cementitious or alternative materials in a mold. The dimensions and weight of the ReefBlock can be scaled to fit specific project sites with the parameters shown in Table 1.

Table 1. Geometric parameters of the ReefBlock

Dimensional proportions (H:W:L)	1:1:3
Material volume (m^3)	H*W*L*0.8
Nominal diameter (m)	H*1.33

In early 2023, a section of the Reef Enhancing Breakwater was built in the Netherlands as a demonstration project, as shown in Figure 2. For this demonstration project, 17 ReefBlocks were installed, the location is in an area with active sediment transport and therefore the structure was placed on top of an underlayer and scour protection.

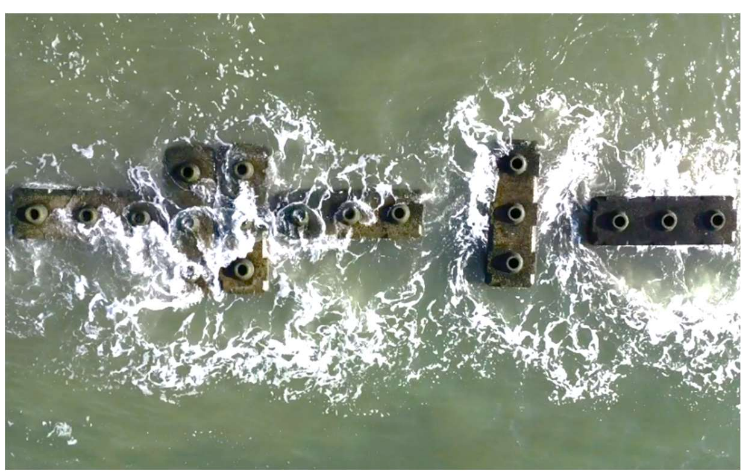

Figure 2. The Rotterdam Reef demonstration project, 6 months after installation.

Three experimental campaigns on the REB were performed at Deltares and Delft University of Technology in 2020, 2023, and 2024. To gain insights into the physical processes in this breakwater and provide guidelines for engineers, the system was tested in physical models. While the focus of the research was broader, the scope of the current work is on investigating the stability of the structure, developing guidelines for design, and determining wave reflection, dissipation, and transmission.

Literature

The transmission coefficient K_t is the ratio of the transmitted to the incident significant wave height, as shown in Equation (1). And can be used to compare natural reefs to artificial coastal defences. From meta-analysis on coral reefs, the estimated value for the wave transmission coefficient is between 0.51 to 0.74, with an average of 0.64 (Ferrario 2014). The transmission coefficient used in this research is defined as the ratio of the transmitted wave height behind the structure to the incoming wave height in front of the structure:

$$K_t = \frac{H_{m0,transmitted}}{H_{m0,incident}} \quad (1)$$

Where: K_t is the transmission coefficient, $H_{m0,transmitted}$ is the transmitted significant wave height behind the structure and $H_{m0,incident}$ is the significant wave height before the structure.

The reflection coefficient is defined as the ratio of the reflected significant wave height to the incident significant wave height, as described by van Seelig et al. (1981).

$$K_r = \frac{H_{m0,reflected}}{H_{m0,incident}} \quad (2)$$

Where $H_{m0,reflected}$ is the reflected significant wave height, and $H_{m0,incident}$ is the incoming significant wave height. While K_t and K_r are common coefficients used to study breakwaters attenuation, the wave dissipation coefficient (K_d) of the structure can be used to understand the dissipative effect of the structure and can be determined using the following equation based on the energy balance (Seelig et al. 1981):

$$K_d = (1 - K_t^2 - K_r^2)^{0.5} \quad (3)$$

Where K_t is the transmission coefficient and K_r is the reflection coefficient. Energy dissipation at the Limones coral reef crest in Mexico was reported to be around 75%, as described by Mendoza et al. (2019), who compared the performance of an artificial reef structure to that of a natural reef.

The Rock Manual (2012) provides an equation to determine the transmission coefficient for traditional low crested rock structures. The wave transmission coefficient can be described by Equation (4), providing a very simple method for preliminary design. The upper and lower bounds of the data considered were given by the ± 0.15 K_t lines compared to the mean fit as described by equation (4).

$$\begin{aligned} -2.0 < \frac{R_c}{H_s} < -1.13 &\quad : \quad K_t = 0.80 \\ -1.13 < \frac{R_c}{H_s} < 1.2 &\quad : \quad K_t = 0.46 - 0.3\frac{R_c}{H_s} \\ 1.2 < \frac{R_c}{H_s} < 2.0 &\quad : \quad K_t = 0.10 \end{aligned} \quad (4)$$

A new expression for wave transmission at submerged coastal structures and artificial reefs was introduced by van Gent et al. (2023). Five structures with varying permeability were simulated in a physical model to represent artificial reefs. The test results were used to calculate the wave transmission (K_t). It was found that existing expressions for wave transmission were not able to represent the measurements accurately, showing bias and systematic deviations. Therefore, the following equation was proposed:

$$K_t = c_1 * \tanh\left(-\left(\frac{R_c}{H_{m0}} + c_2\left(\frac{B}{L_{m-1,0}}\right)^{c_3} + c_4\right)\right) + c_5 \quad (5)$$

Where K_t is the wave transmission coefficient, R_c is the freeboard, H_{m0} is the significant wave height, B is the width of the top row of the structure, $L_{m-1,0}$ is the wave length based on the spectral wave period ($T_{m-1,0}$) and c_1 to c_5 are coefficients to tune the equation for a specific structure type. Many other studies have examined wave transmission at coastal structures. Given the distinct characteristics of artificial reefs compared to traditional submerged coastal structure, Equation (5) is used in the present work.

Physical model setups

Three physical model campaigns were conducted in 2020, 2023, and 2024, with a total testing time exceeding 200 hours. During these campaigns, more than 20 layouts were tested, and measurements were taken for both hydrodynamics and stability. This section outlines the setup of the three physical model campaigns. For the current work, not all physical model tests were included; a selection was made based on a continuous crest and irregular wave conditions. For the hydrodynamic analysis, data from the 2020 and 2023 test campaigns were selected and analysed as a combined data set. For the stability analysis, data from 2023 and 2024 were selected and analysed as a combined data set.

The first physical model campaign took place in 2020 at Deltares in the Eastern Scheldt Flume, as described by van den Brekel (2020). The wave flume has a length of 55 m, a width of 1 m and a height of 1.2 m, and features a piston-type translatory wave board with active reflection compensation. The model scale was 1:15, based on a prototype of 1x1x3 m^3. The current research focuses primarily on determining the hydrodynamic performance of the Reef Enhancing Breakwater. However, additional experiments were conducted to validate the stability of the REB and individually placed ReefBlocks. This included evaluation of design parameters such as density, shape, and the tunnel system design. Stability tests also included conditions with nature accretion and incorporated velocity measurements. The toe of the structure was positioned at 25.1 m from the wave maker on the flat foreshore, as shown in Figure 3. Three sets of wave gauges (WG) were installed along the flume, additionally, one extra wave gauge and an electromagnetic velocity sensor (EMV) were installed, of which the locations were varied throughout testing.

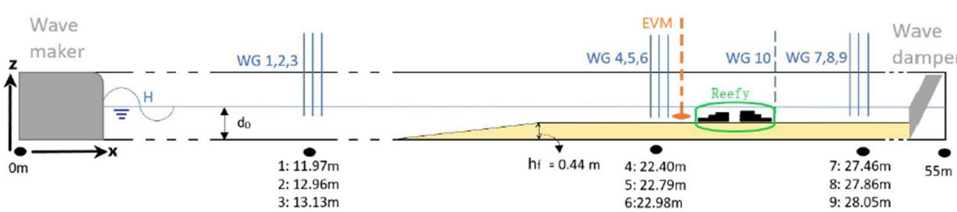

Figure 3. Wave flume setup for the 2020 physical model campaign (van den Brekel 2020).

During the 2020 test campaign, several layouts of the REB were evaluated, as shown in Figure 4, with the goal of identifying the structural design parameters that influence the hydrodynamics of the structure and provide general guidelines for different structure configurations. The water depth d_0 was varied between 0.61, 0.68 and 0.75 m. The significant wave height was varied between 0.01 and 0.12 m, with a wave steepness (s_{0p}) ranging between 2% and 4%. A study was performed to model the wave transmission in Xbeach, as described by Kadoglou (2023).

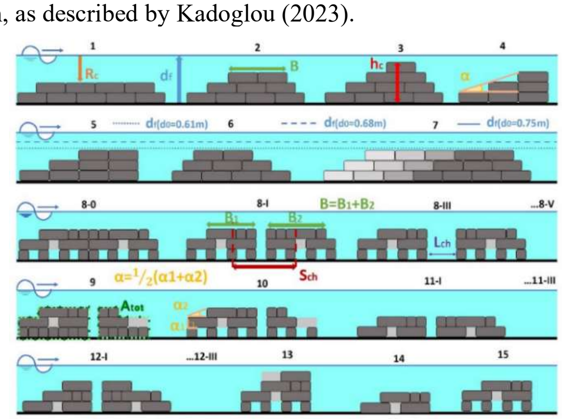

Figure 4. Overview of the cross section for all tested layouts of the Reef Enhancing Breakwater during the 2020 physical model campaign (van den Brekel 2020).

The second physical model research campaign took place in 2023 at Deltares in the Eastern Scheldt Flume, which has a width of 1 m, a height of 1.2 m, and a length of 55 m, and features a piston-type translatory wave board with active reflection compensation, as described by Geenen (2024). For the current work, both stability and hydrodynamic data were used. Besides this, additional experiments were also conducted, including tests with random placement, increased underlayer roughness, nature accretion, embedded motion sensors, and clogged tunnel systems. A prototype of the ReefBlock measuring 1x1x3 m^3 was considered with a density of 2400 kg/m^3 in salt water. The experiments were scaled using Froude scaling. The ReefBlock was scaled to 1:20, resulting in a nominal diameter D_n = 0.067 m. An underlayer of loose rock d_{n50} = 10 mm with a thickness of 0.05 m was added. The underlayer was included to account for uneven underlayers and installation tolerances in marine construction, where scour protection is needed. The flume features a flat foreshore with a height of 0.3 m, and the front of the foreshore has a slope of 1:5, as shown in Figure 5. Three sets of four wave gauges were added to the flume, to allow for analysis with non-linear wave decomposition methods. The REB was tested at two locations: at the start of the foreshore and at x=38 m. Different configurations were tested, referred to as simple and complex layouts, with both having variants of 2 levels and 3 levels, as shown in Figure 6. Complex layouts are meant to increase turbulent wave dissipation, diversity of abiotic conditions, connectivity between both sides of the structure for water and fauna, and material saving. The water depth d_0 was varied between 0.47, 0.52, 0.57, and 0.62 m. The significant wave height was varied between 0.04 and 0.12 m, with a wave steepness (s_{0p}) set at 2%, 3% or 4%.

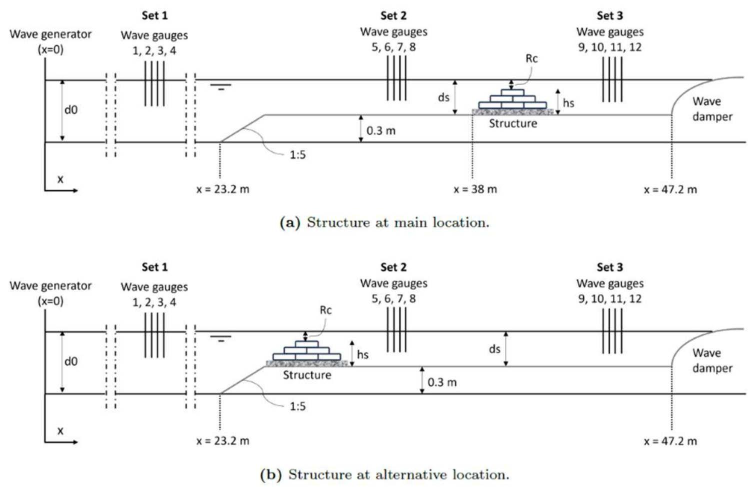

Figure 5. Flume layout of the 2023 experiments, d_0 = offshore water depth [m], d_s = water depth at structure [m], h_s = height of the structure [m], R_c = freeboard. For most of the experiments the structure was tested at location (a) and for some experiments the structure was moved to the alternative location (b) (Geenen 2024).

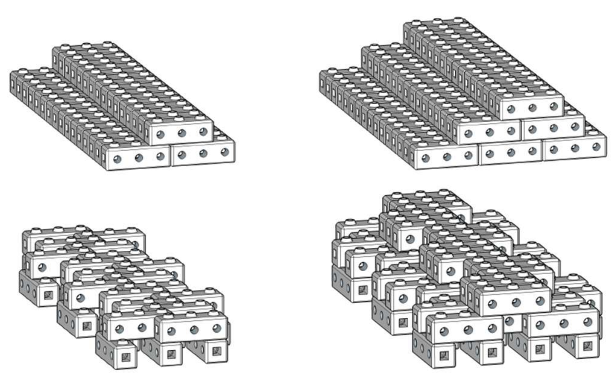

Figure 6. Layouts tested during the 2023 physical model campaign: top left - simple 2-level structure, top right - simple 3-level structure, bottom left - complex 2-level structure, bottom right - complex 3-level structure (Geenen 2024).

The third physical model test took place in the Delft University of Technology Hydraulic Lab in 2024. The flume has a length of 30 m, a width of 0.75 m, and a height of 1.2 m and features a piston-type translatory wave board with active reflection compensation. The same 1:20 physical scale models of the ReefBlocks were used as in the experiments conducted in 2023 at Deltares. The setup simulated the REB placed on top of a straight reef crest with a height of 0.25 m, as shown in Figure 7. The structure was located 26 m from the wave maker. Three wave gauges were positioned in the flume to measure the incoming and reflected significant wave height. Only stability data was collected for the 3-level complex layout, without a rock underlayer. Data from these experiments were solely used for stability research. The water depth d_0 was varied between 0.45 and 0.50 m. The significant wave height was varied between 0.09 and 0.16 m, with a wave steepness (s_{0p}) set at 2%, 3% or 4%.

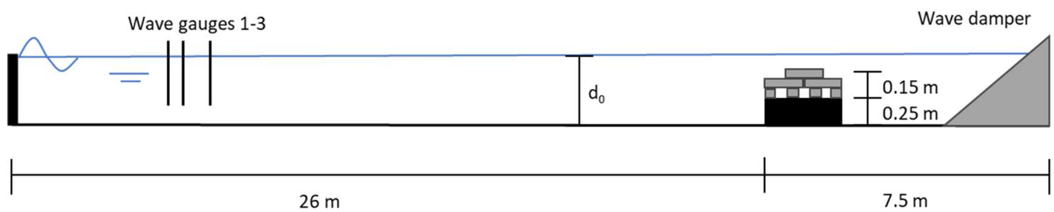

Figure 7. Flume layout for the 2024 experiments, only one group of wave gauges was used to determine the incident significant wave height.

The present work combines data from all three physical model campaigns. For the hydrodynamic analysis, data from 2020 and 2023 were used. For the stability analysis, data from 2023 and 2024 were used. All data used in the current work is based on experiments with irregular waves characterized by a JONSWAP spectrum with a peak enhancement factor of 3.3, the duration of each test was set to a minimum of 1000 waves. The overall porosity of the structures ranged between 20% and 53%.

Data processing hydrodynamics

For the analysis of the hydrodynamics, a selection of the data was made to include only structures with a continuous crest. From the 2020 data, 23 tests were included that contained data from layouts: 2, 4, 5, 6, 7, 8, 11, 13, 14, and 15, as shown in Figure 4. From the 2023 dataset, 62 tests were included covering both 2-level and 3-level structures in both the complex and simple forms, as shown in Figure 6. The Zelt & Skjelbreia (1992) method, hereafter Z&S, was used to decompose the surface elevation time series.

Results and analysis hydrodynamics

Figure 9 shows the measured wave transmission, reflection, and dissipation coefficients on the vertical axes, and the relative crest height on the horizontal axis. In this research, the freeboard is defined as negative for a submerged structure. The data are plotted for different crest widths of the structure. Where the crest width is defined as the number of ReefBlocks (lengthwise) in the top row, as shown in Figure 8. Similar to the literature, the relation between the relative crest height (R_c/H_{m0}) and the wave transmission coefficient (K_t) can be observed: as the structure becomes more submerged, the wave transmission coefficient increases. However, for a certain relative crest height, the transmission coefficient (K_t) can vary by approximately ±0.1. This variation could be explained by differences in crest width between the structures, where longer structures provide less wave transmission for the same relative crest height. However, the porosity between structures also varies, which can cause an additional dissipation mechanism caused by interstitial flow as described by Cardenas Rojas et al. (2021). The relation between the wave reflection coefficient (K_r) and relative crest height (R_c/H_{m0}) is less pronounced compared to the transmission coefficient. In general, as the structure becomes more submerged the reflection coefficient decreases. Additionally, a wider structure generally has a lower reflection coefficient for a similar relative crest height. The relation between the dissipation coefficient (K_d) and relative crest height (R_c/H_{m0}) shows that the dissipation coefficient increases as the relative crest height increases. Additionally, structures with a larger crest width result in a higher dissipation coefficient compared to those with a smaller crest width, in literature other effects such as the breaker type and spectral shape also influence the energy dissipation as described by Cardenas Rojas et al. (2021), however, this was not further analysed in the current work.

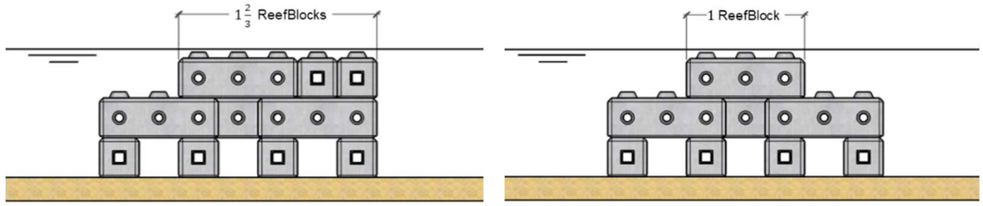

Figure 8. The crest width in terms of the number of ReefBlocks (lengthwise), for layout 15 from the 2020 test campaign and the 3-level complex layout from the 2023 campaign.

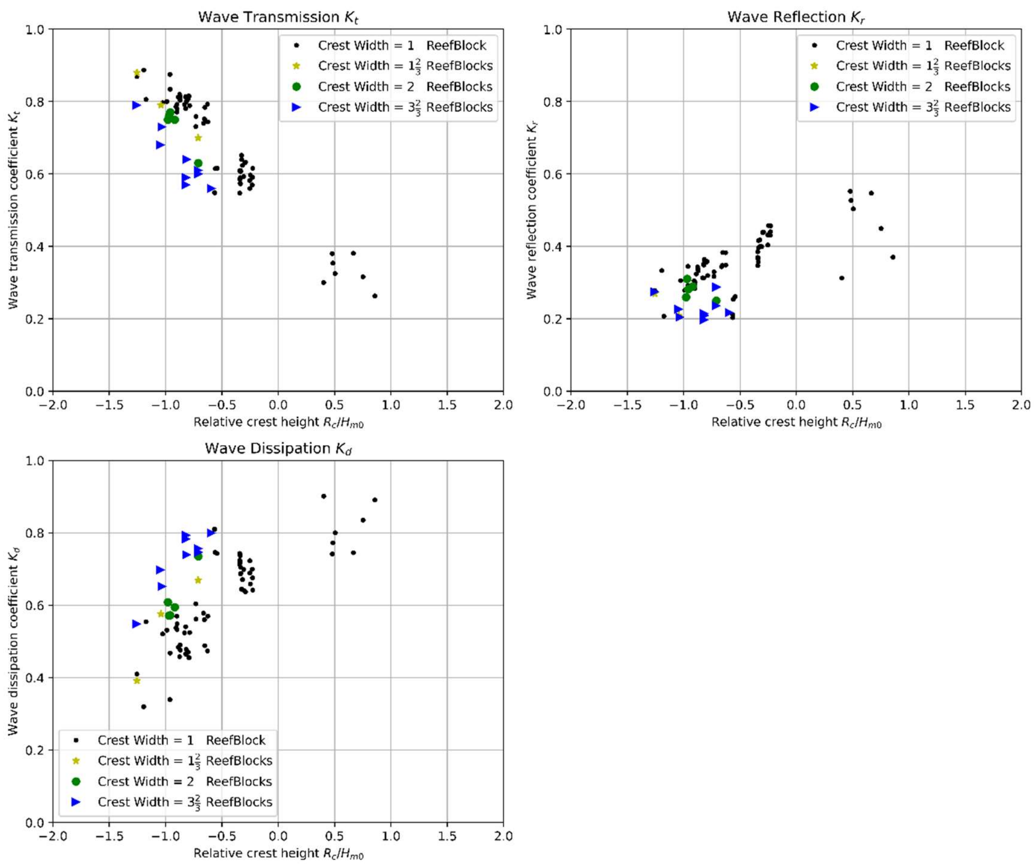

Figure 9. Measured wave transmission, reflection and dissipation coefficients for different crest widths, expressed in terms of the length of a ReefBlock.

In terms of mimicking the hydrodynamic functions of a natural reef, the results presented in Figure 9 can be used to determine the design geometry of the structure. In the Mesoamerican Barrier Reef, the dissipation coefficients are around 75% (Mendoza et al. 2019).

Wave transmission Rock Manual

To further analyse the wave transmission coefficient, a comparison was made with conventional submerged rock structures, as shown in Figure 5.17 of the Rock Manual (2012). In Figure 10, Equation (4) is plotted along with the ± 0.15 K_t offset and the measured wave transmission data. The equation and ± 0.15 K_t bounds represent the measured data quite well and could indeed be used for an initial estimate. The equation generally overestimates the wave transmission coefficient for structures with a wider crest width and underestimates it for structures with a smaller crest width. The root mean square error (RMSE) of the data relative to Equation (4) is 0.072. A comparison with Figure 5.17 from the Rock Manual shows that the REB has a similar performance compared to traditional rock infrastructure.

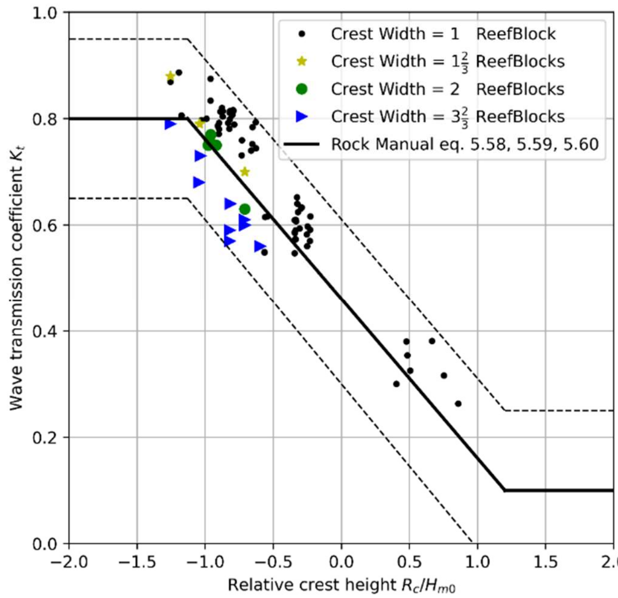

Figure 10. Measured wave transmission coefficient compared to those shown in Figure 5.17 of the Rock Manual (2012).

Wave transmission formula

A new expression to calculate the wave transmission coefficient of artificial reefs and submerged structures that includes the effect of the crest width was proposed by van Gent et al. (2023), as shown in Equation (5). The expression contains five parameters, c_1 to c_5, which vary for each structure type and are used to tune the equation for the dataset used in this study. The equation has been optimized using the five parameters to describe the wave transmission coefficient data. The root mean square error (RMSE) method has been employed to assess the performance. The optimized parameters and RMSE are provided in Table 2.

Table 2. Optimized coefficients from Equation (5) for the Reef Enhancing Breakwater and the RMSE between calculated and measured data.

c_1	0.386
c_2	0.941
c_3	0.750
c_4	-0.150
c_5	0.497
RMSE	0.044

Figure 11 shows the measured wave transmission coefficient and the calculated K_t based on Equation (5), plotted against the relative crest height. On the right, the deviation between the calculated and measured K_t is plotted. The performance of Equation (5) and the optimized coefficients, show a good agreement with the data and can be used for a more detailed design approach compared to Equation (4).

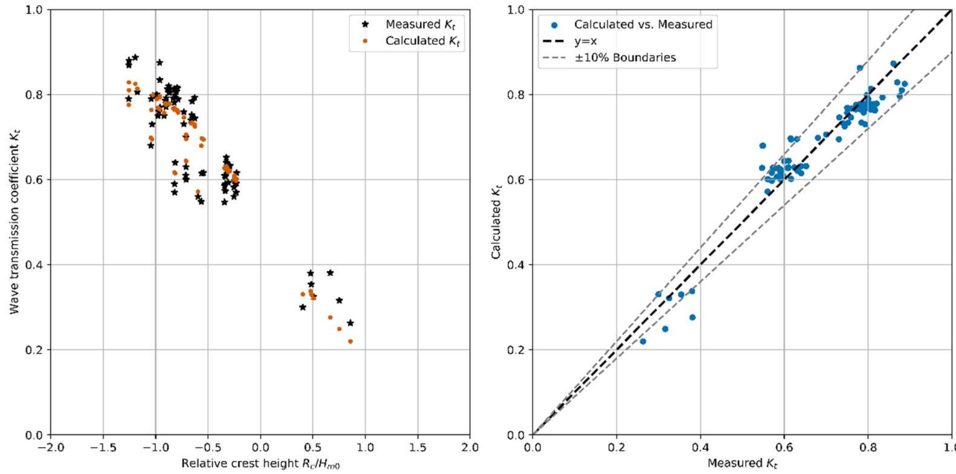

Figure 11. Measured and calculated wave transmission coefficient (K_t) and parity plot.

Data processing stability

For stability research, the wave height in front of the structure has been measured and analysed using the Z&S method. The stability of the structures was recorded using visual observations, cameras and smart ReefBlocks with embedded motion sensors. For stability analysis, only data from the 2023 and 2024 test campaigns were used.

Results and analysis stability

To analyse the stability data, the following definitions have been used. Unstable conditions are defined as conditions where one single ReefBlock or multiple units are removed from the structure or when the base of the structure has been displaced. Stable conditions are defined as conditions where no ReefBlocks were removed and the base of the structure is in the same position at the beginning and end of the test. This can be compared to a zero damage design criterion. The analysis is based on data from the 2023 and 2024 experiments. The three different setups were analysed separately as each location has different conditions that influence the type of wave attack. To present the data, the stability number $N_s = H_{m0}/(\Delta * D_n)$ is used. An overview of the stability results are shown in Figure 12.

The main location from the 2023 experiments, as shown in Figure 5, has a flat foreshore where the highest waves were limited by the water depth, which was varied during the experiments. The significant wave height (H_{m0}) ranges between 0.04 and 0.12 m. The water depth in front of the structure (h) was varied between 0.17 and 0.32 m. The significant wave height to local depth ratio H_{m0}/h in front of the REB, ranged from 0.14 to 0.41. The deep water wave steepness s_{0p} varied between 1.7% and 4.2%, the input values set at 2%, 3% or 4%. At this location, both the simple and complex forms of the 2- and 3-level structures were tested. No instabilities were observed at this location; this can be attributed to the depth limited waves. In an effort to reach the limits of the structure, the water depth was increased. This led to an increase in the significant wave height but also made the structure more submerged without reaching instabilities.

The alternative location from the 2023 experiments, as shown in Figure 5, involved placing the REB in both the 2-level simple and complex layouts on top of the 1:5 slope. No wave gauges were present around this location. Therefore, the results presented for this location are based on the deep water wave height H_{m0}, which ranged from 0.07 to 0.12 m. During testing, shoaling on the slope was observed, increasing the wave height and resulted in plunging breakers. As a result, the calculated stability number is an underestimation of the actual stability number based on local conditions. The deep water wave steepness s_{0p} ranged between 2.3% and 3.7%. At this location, several instabilities were observed, the first of which occurred due to scour of the underlayer at N_s = 1.12. The erosion of the front of the underlayer removed the support of the ReefBlocks and made the ReefBlocks prone to uplift leading to the removal of units. After this experiment, the thickness and diameter of the toe protection were increased. The next instabilities were observed direct impact of plunging breakers led to removal of multiple units above a stability number (N_s) of about 0.9. The Iribarren number for this location was between 1.1 and 1.5, confirming the observed plunging breakers.

During the 2024 campaign, the 3-level complex layout was placed on top of a vertical wall, as shown in Figure 6. This setup was chosen to achieve a larger significant wave height ranging from 0.09 to 0.16 m. At this location, the ratio between significant wave height and the local depth at the structure H_{m0}/h ranged from 0.36 to 0.63. The deep water wave steepness s_{0p} ranged between 1.9% and 3.8%. For this setup, another instability mechanism was observed, at a stability number of N_s = 1.78, the base of the structure began to shift backward for the largest waves during the test. Which can be explained because the friction between the 3D printed ReefBlocks and the smooth bottom was low, as further described by Geenen (2024).

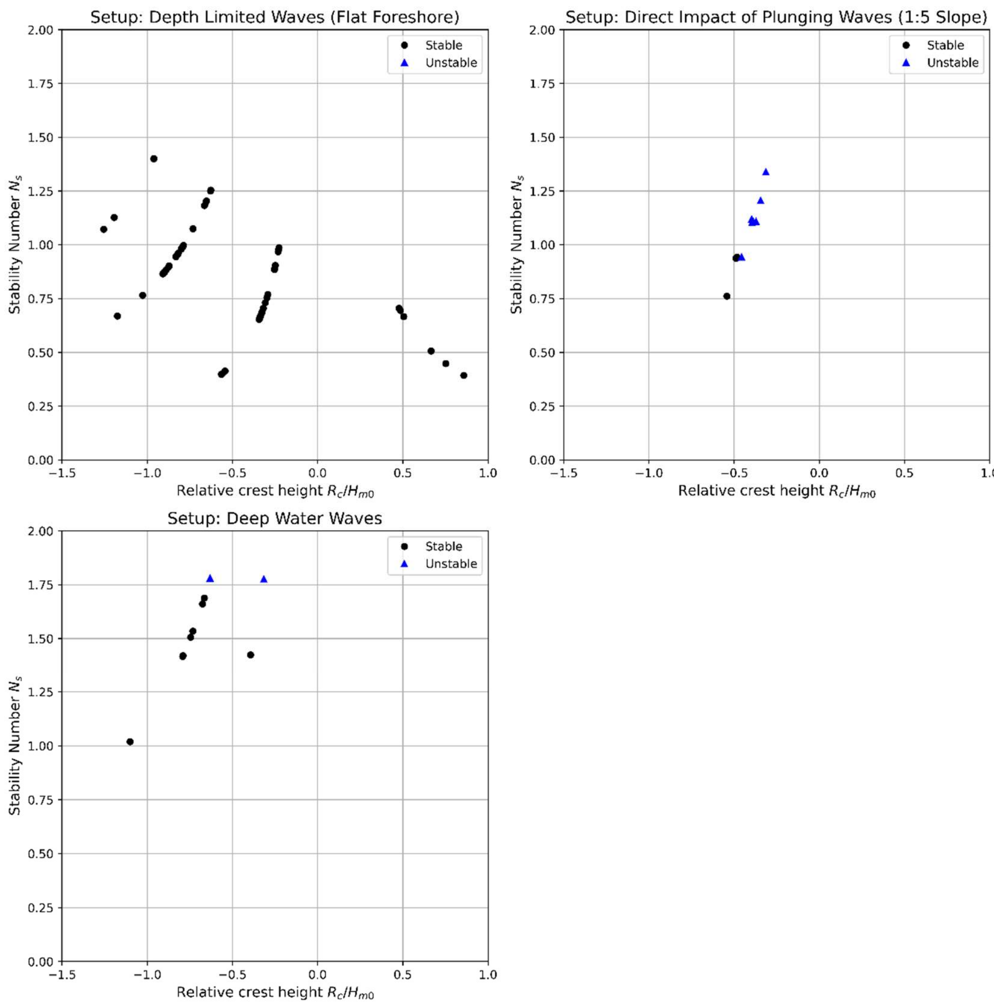

Figure 12. Stability results, showing the stability number (N_s) and relative crest height for each location, representing a different type of wave climate.

During stability testing, several small movements of ReefBlocks within the REB were observed. Mainly, small sliding motions of the upper blocks were observed, which were possible due to small spaces between the protrusion and the opening of the upper block, meant for marine installation tolerances. These movements did not lead to instabilities but could give some loads on the protrusions. Two smart ReefBlocks, with motion sensors were used during testing, the sensor design was based on the sensor design as described by Hofland et al. (2023) and Houtzager et al. (2024). These data, in combination with the number of movements can be used to determine the dimensions of the protrusions and the strength of the material needed for the design life of the structure.

Discussion

The stability number for the ReefBlock is not comparable to conventional armour units designed for slopes. This is due to the definition of damage, in this work a zero damage criterion has been used. Furthermore, the definition of the nominal diameter is not suited for an elongated shape, like the ReefBlock. Because the stability number, $N_s=H_s/(\Delta D_n)$, uses the nominal diameter, $D_n = V^{1/3}$. For the ReefBlock the nominal diameter is relatively large compared to its height. For example, a ReefBlock with a height of 1 m ($D_n = 2.4^{1/3} = 1.34$ m) could be considered an efficient alternative to three cubic ReefBlocks, each with a height of 1 m and with a $D_n = 0.8^{1/3} = 0.92$. Under identical loading conditions, the ReefBlocks stability number would be 0.92/1.34 = 0.69, or 30% lower than that of three cubic equivalents, resulting in a comparatively lower stability number for the ReefBlock. Assuming that the response to the loading would be the same, which is not expected since the weight of a cubic ReefBlock would be one third of the weight of a ReefBlock.

Conclusion

Reef Enhancing Breakwater

The Reef Enhancing Breakwater is a system of interlocking ReefBlocks that provides the same wave transmission coefficient compared to conventional low crested and submerged breakwaters as was shown by the comparison with the Rock Manual (2012). Two design methods are proposed to calculate the wave transmission, a first indication can be made using Equation (4) from the rock manual. To optimize this indication, design choices in crest width and freeboard can be made using Figure 10. The second method, is to use the equation proposed by van Gent et al. (2023) in combination with the optimized coefficients as shown in Table 2. Providing a more detailed approach and result. The stability results, presented in Figure 12, can be used to determine the size of the ReefBlock needed for a certain location based on the stability number.

Hydrodynamics

The wave transmission coefficient (K_t) was calculated using measurements from physical model testing. The measurements cover a range of structures with variations in porosity (20% to 53%) and crest width (1 to 3.67 ReefBlock lengths), as well as for varying conditions with a relative crest height (R_c/H_{m0} = -2.5 to 0.9) and wave steepness (s_{0p} = 1.5% to 5.4%). The results were found to be consistent with the wave transmission coefficient for low-crested structures, as described in Figure 5.17 of the Rock Manual (2012). Equation (4) provides a basic description of the data and can be used as a preliminary estimate of performance, where the width of the crest or the relative crest height can be adjusted to achieve the desired effect. The root mean square error (RMSE) of 0.072 indicates a close fit. Van Gent et al. (2023) describes a new expression, Equation (5), to calculate K_t for submerged coastal structures, and artificial reefs, this expression features five coefficients that can be used to tune the type of structure. For the REB, the optimized coefficients c_1 to c_5 can be found in Table 2, and result in a RMSE of 0.044 when comparing the calculated values to the measurements. Equation (5) provides a design tool that can be used to evaluate wave transmission of a detailed design. In terms of the wave transmission coefficient, the Reef Enhancing Breakwater has similar performance as rock reefs, the data follows a similar behaviour as described by the Rock Manual (2012).

Stability

The stability of the Reef Enhancing Breakwater has been researched using physical modelling. Three different setups were tested, each with different types of waves and for a range of conditions. Figure 12 provides an overview of the results and can be used to determine the stability and size of the ReefBlock for a certain location. For locations with depth limited waves or deep water waves no units were extracted from the structure for a stability number N_s up to 1.65. To understand damage mechanisms and progression, the structure was positioned on top of a 1:5 slope and loaded by the direct impact of plunging waves, creating damage for lower stability numbers. This highlights the importance of breaker type and the evaluation of conditions with the surf similarity parameter of the project location, as this can affect the stability of the structure.

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