

Evaluating the Impact of Degrees of Freedom on the Hydrodynamic Performance of Sloped Floating Breakwaters: An Experimental Study

Sahel Sohrabi¹, Mohammad Ali Lotfollahi Yaghin¹, Alireza Mojtahedi¹ and Mehran Dadashzadeh¹

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Abstract

This study experimentally examines the hydrodynamic performance of a sloped floating breakwater under two distinct configurations one involves a single degree of freedom (1-DOF) system, which is restricted to heave motion; the other involves a three DOF (3-DOF) system, which allows heave, surge, and pitch motions. The main objective is to investigate the effect of DOF on wave attenuation, which particularly explores reflection, transmission, and dissipation mechanisms. Experiments were performed in a wave flume at a geometric scale of 1:15 and under regular and irregular wave scenarios covering various wave heights and periods. Results indicate that the 1-DOF configuration presents superior wave attenuation performance at shorter wave periods, with transmission coefficients up to 14% lower than those of the 3-DOF system. By contrast, at longer wave periods, the 3-DOF configuration exhibits better wave energy dissipation, which achieves 4%–10% lower transmission coefficients. Analysis of Response Amplitude Operators suggests that the decreased heave motion detected in the 3-DOF system at longer wave periods is due to mooring-induced constraints and the interaction among multiple DOFs. This reduction in the heave response considerably contributes to enhanced wave energy dissipation. These outcomes emphasize the vital role of structural flexibility and DOFs in optimizing floating breakwater designs, which offer practical guidance for tailored solutions under diverse wave scenarios.

Keywords Sloped floating breakwater; Degrees of freedom; Hydrodynamic performance; Experimental analysis; Transmission coefficient; Reflection coefficient; Dissipation coefficient

1 Introduction

Floating breakwaters have become a cost-effective and environmentally sustainable alternative to traditional bottom-mounted breakwaters, specifically in deep waters or areas with complex seabed environments (Kar et al., 2019; Li et al., 2024). These structures float at the water surface where the majority of wave energy is concentrated, which makes them efficient in attenuating wave forces while diminishing con-

struction costs and environmental impact (Aleman and Constantin, 2020; Dai et al., 2018). Different from traditional breakwaters, they do not obstruct subsurface water flow, which improves circulation and reduces sedimentation and pollution within protected areas; thus, they offer environmental benefits (Ji et al., 2016; Liang et al., 2022; Vishwakarma and Karmakar, 2024).

The growing demand for larger and deeper marine facilities has further raised interest in floating breakwaters, as the construction of massive bottom-mounted systems becomes increasingly challenging and costly (Christensen et al., 2018; Sepehri et al., 2024). Their versatility and adaptability make them an attractive option for modern coastal protection implementations, especially under dynamic environmental conditions.

However, while floating breakwaters present several advantages, their hydrodynamic performance greatly relies on their structural configuration, material properties, and the nature of the external forces acting upon them, such as waves (Ren et al., 2017; Sohrabi et al., 2024). Several works have examined the performance of floating breakwaters under different conditions, particularly on geometric designs, mooring configurations, and material properties. Despite these advances, the effect of the degrees of freedom (DOFs)—

Article Highlights

- Experimental study comparing 1-DOF and 3-DOF sloped floating breakwaters under regular and irregular wave conditions.
- 1-DOF excels in wave attenuation at short wave periods, while 3-DOF performs better at longer periods.
- Mooring constraints and DOF interactions reduce heave motion, enhancing energy dissipation in 3-DOF systems.
- Results provide practical guidance for optimizing floating breakwater designs under varying wave conditions.

✉ Mehran Dadashzadeh
mehrandadashzadeh@tabrizu.ac.ir

¹ Department of Water Resources Engineering, Faculty of Civil Engineering, University of Tabriz, Tabriz 5166616471, Iran

the number of independent motions a structure can experience in response to wave action—on the hydrodynamic efficiency of floating breakwaters has not been explored yet.

Floating breakwaters can present multiple DFOs, such as heave, surge, sway, pitch, roll, and yaw. In most practical applications, breakwaters are typically constrained to fewer DOFs, with the most common configurations being 1-DOF (heave only) and 3-DOF (heave, surge, and pitch). The effect of individual motion modes on wave attenuation has been extensively examined, but the combined effects of multiple DOFs on the overall performance of floating breakwaters remain poorly understood.

Several works have determined the role of DOFs in the performance of floating breakwaters, which provides valuable insights into the design and optimization of these structures. For example, Neelamani and Rajendran (2002) and Nakamura et al. (1999) analyzed the performance of floating breakwaters under varying degrees of flexibility and mooring configurations. These studies underscored the role of structural flexibility in improving wave attenuation, specifically in relation to the mooring system and wave interaction. More recent works by Chen et al. (2023) and Guo et al. (2024) demonstrated that enabling floating breakwaters to move in multiple directions—including heave, surge, and pitch—can greatly enhance their ability to dissipate wave energy. However, although these studies have improved our understanding of the influence of DOFs, the particular dynamics of these interactions under real-world conditions remain unclear.

The dynamic behavior of floating breakwaters in response to wave action is difficult, and the interaction between multiple DOFs plays an essential role in their hydrodynamic performance. For example, Ozeren et al. (2011) performed laboratory tests on cylindrical floating breakwaters, which demonstrated that the efficiency of these structures is strongly affected by the draft ratio and mooring configuration. Their study highlighted that partially restrained models—those with reduced vertical restraint—are more efficient in wave dissipation. Therefore, the ability of floating breakwaters to adapt to wave motion is improved when the structure is permitted to move more freely. This result aligns with the findings of Guo et al. (2022), who compared the performance of taut, slack, and hybrid mooring systems. Their results demonstrated that hybrid mooring systems, which integrate taut and slack elements, offer more effective wave attenuation, specifically in varying tidal conditions.

Recent works such as He et al. (2023) and Wan et al. (2025) further determined the role of DOFs in multi-float and hybrid systems. He et al. (2023) studied multi-float structures using SPH models, which underscored the importance of module flexibility and the dynamic response of the system. Their study revealed that multi-float systems with increased DOF can considerably improve wave attenuation and enhance the overall stability of the structure under

various sea states. Similarly, Wan et al. (2025) established a hybrid raft-type system that incorporates wave energy conversion with breakwater functions. Their findings suggested that multi-raft systems with increased flexibility (including additional DOFs) perform better in terms of energy dissipation, specifically when resonant wave modes are considered.

The demand for further studies on the influence of DOFs on floating breakwater performance has been emphasized by recent studies, which highlight the dynamic nature of wave–structure interactions and their dependence on the number of DOFs available to the structure. Recent innovations, such as Ji et al. (2018) and Panda et al. (2024), displayed the importance of structural flexibility in energy dissipation. However, they did not conclusively determine the influence of the interaction among heave, surge, and pitch motions on the overall hydrodynamic performance.

This gap in the literature forms the basis for the current study. This research aims to experimentally evaluate the hydrodynamic performance of sloped floating breakwaters under two configurations: 1-DOF (heave only) and 3-DOF (heave, surge, and pitch). By comparing the two configurations under varying wave scenarios (regular and irregular waves), we aim to offer new insights into the influence of the DOFs of the structure on wave reflection, transmission, and dissipation. This study seeks to fill the gap in the current literature and provide a more comprehensive understanding of the effect of structural flexibility on the performance of floating breakwaters in real-world conditions. The results from this work are expected to contribute to the optimization of floating breakwater designs, specifically in implementations where adaptability and efficient wave energy dissipation are crucial. Furthermore, this work will offer valuable insights into the design and performance trade-offs between 1-DOF and 3-DOF configurations, which will help engineers make more informed decisions when selecting the most appropriate design for different coastal and offshore environments.

2 Experimental investigations

In this study, multiple hydrodynamic experiments were performed to investigate the performance of a sloped floating breakwater with a gap between floaters while considering the influence of different DOFs on its hydrodynamic behavior. The experiments aimed to evaluate the wave attenuation efficiency and dynamic response of the breakwater under various wave scenarios. The design parameters of the breakwater and wave scenarios were chosen based on practical engineering applications to guarantee the applicability of the results. The subsequent subsections offer a detailed description of the experimental setup and testing conditions adopted in this work.

2.1 Test facility

The experiments were conducted in a wave flume at the Hydraulic Laboratory of the Soil Conservation and Watershed Management Research Institute (SCWMRI), Iran (Figure 1). The flume measured 33 m in length, 1 m in depth, and 1 m in width. A geometric scale factor of 1:15 was used for the research, which corresponded to a wave height scale of 1:15 and a wave period scale of 1:3.87, based on Froude modeling. A piston-type wavemaker was installed at one end of the flume, while a wave-absorbing beach was positioned at the opposite end to minimize wave reflection. The floating breakwater was positioned 17.2 m from the wavemaker, which was either secured by mooring lines or anchored by piles, as displayed in Figure 2.



Figure 1 Wave flume setup at the SCWMRI hydraulic laboratory

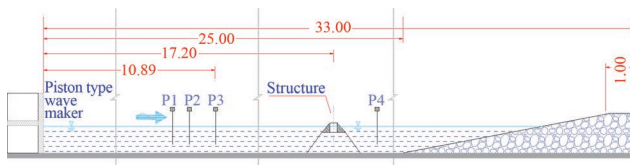


Figure 2 Schematic of the experimental setup

2.2 Model details and test setup

The experimental model adopted in this study was constructed at a 1:15 scale, which adhered to Froude similitude to guarantee precise hydrodynamic representation. The sloped floating breakwater was designed with the following laboratory-scale dimensions: a height of 0.23 m, a draft of 0.15 m, and a total length of 0.808 m for the configuration with a 40° angle. The distance between the two floating sections was 0.26 m, while the length of each floating section was 0.274 m. The model had a total dry mass of 12.07 kg, with its center of gravity located at ($\bar{x} = 0, \bar{y} = 0.063, \bar{z} = 0$). The moment of inertia, I_{yy} , was 1.137 kg·m². A schematic representation of the sloped floating breakwater model used in this work is displayed in Figure 3. The model was fabricated using wood, which was chosen due to its ease of construction and suitability for the required hydrodynamic testing.

The tension in the mooring lines plays a vital role in affecting the motion of the moored floating breakwater,

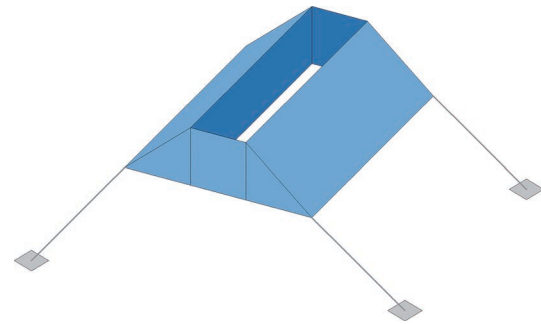


Figure 3 Schematic representation of the sloped floating breakwater model

which greatly influences the structure's ability to attenuate waves. To enhance performance, the floating breakwater was designed to be taut-moored. Four mooring lines were adopted, with two positioned on the seaward side and two on the leeward side of the structure. Each mooring line was attached at one end to the bottom edge of the floating breakwater, while the other end was secured to an anchor fixed to the flume floor. The mooring lines were constructed from stainless steel, with an angle of 45° relative to the flume floor. The length of each mooring line was determined based on this angle and the draft depth of the model. Prior to the formal model tests and wave generation, the initial mooring line tension was carefully modified to ensure a balanced and stable positioning of the floating breakwater. This tension was uniformly set to 5.6 N for each mooring line.

In this work, the sloped floating breakwater was investigated under two conditions: with 1-DOF and with 3-DOF. The breakwater with 1-DOF was only restricted to motion in the heave direction. To model this configuration, four rails were used, which connected the flume wall to the body of the structure. Special attention was given to choosing rails with minimal friction. Figure 4 presents the breakwater with 1-DOF.



Figure 4 Floating breakwater with 1-DOF

For the breakwater with 3-DOF, the structure was connected to the seabed using mooring lines, which could be either cables or chains (Figure 5). This setup enabled the

structure to move freely in six directions: heave, surge, roll, sway, yaw, and pitch. However, given that the experiments were conducted in two dimensions, the movement of the structure was restricted to 3-DOF: heave, surge, and pitch. To exclude the effects of wave diffraction in the experiments, the length of the breakwater should ideally match the width of the channel. In this research, considering that the length of the breakwater was shorter than the width of the flume, waves could pass around the pontoon, which caused diffraction. To mitigate this problem, several polystyrene sheets were placed on the sides of the pontoon. These sheets effectively avoided diffraction without negatively influencing the displacement of the pontoon. Notably, if the length of the breakwater matched the width of the flume, then the movement of the structure would be severely restricted, which would potentially lead to damage during impacts.

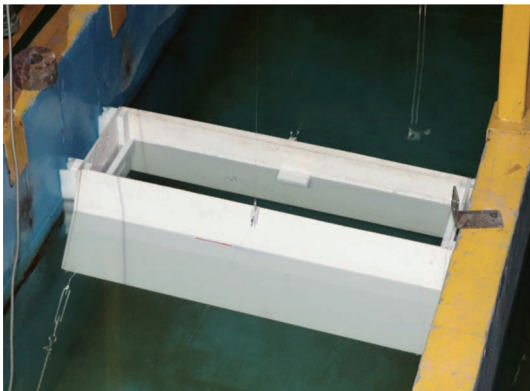


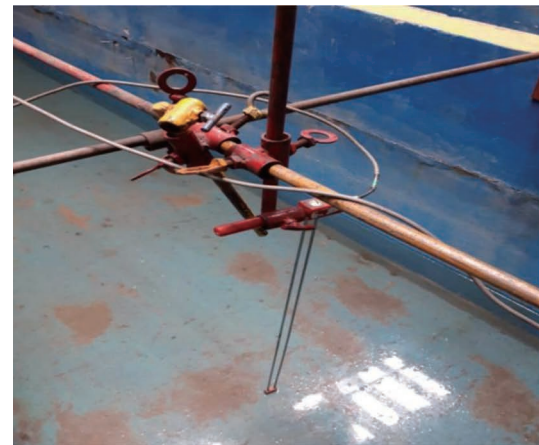
Figure 5 Floating breakwater with 3-DOF

2.3 Instrumentation

Four resistance-type wave gauges, which were manufactured by DHI Denmark, were positioned along the wave flume around the structure to measure the wave surface elevation (Figure 6(a)). The motion responses of the floating breakwater were recorded using ship movement gauges produced by DHI Company, which generated a sampling frequency of 10 Hz and an accuracy of 1 mm (Figure 6(b)).

2.4 Experimental conditions

The experimental study was performed to examine the performance of the floating breakwater models under regular and irregular wave scenarios. All tests were conducted in a wave flume with a constant water depth of 0.67 m. The wave scenarios were generated using a programmable wavemaker, which produced five distinct wave periods and corresponding wavelengths, as summarized in Table 1. Four wave heights were chosen to analyze the hydrodynamic behavior of the breakwater models. For irregular wave scenarios, these heights were regarded as significant



(a) Resistive wave gauges



(b) Displacement sensors for capturing the motion data of the floating breakwater in the laboratory setup

Figure 6 Sensors used in the study

wave heights and adopted as input for the wavemaker. The irregular wave scenarios were simulated using the JONSWAP spectrum to precisely replicate realistic sea states. Before installing the floating body, the incident wave scenarios were calibrated using wave gauges positioned at the designated location of the floating model.

Table 1 Wave parameters utilized in the experiments

Wave Period/ T (s)	0.77	1.00	1.30	1.60	1.80
Wavelength/ L (m)	0.93	1.54	2.46	3.38	3.97
Wave Height/ H (m)	0.043	0.043	0.043	0.043	0.043
	0.056	0.056	0.056	0.056	0.056
	0.066	0.066	0.066	0.066	0.066
	0.080	0.080	0.080	0.080	0.080

2.5 Data analysis

To distinguish incident waves from reflected waves, the three-point method proposed by Mansard and Funke (1980) was used. Four wave gauges were placed along the wave flume surrounding the structure to measure wave surface elevations, with three positioned on the seaward side of

the model and one on the leeward side. The transmission and reflection coefficients were computed using Equations 1 and 2, respectively:

$$C_t = \frac{H_t}{H_i} \quad (1)$$

$$C_r = \frac{H_r}{H_i} \quad (2)$$

where H_t represents the transmitted wave height, H_r denotes the reflected wave height, and H_i indicates the incident wave height. The relationship among the transmission coefficient, reflection coefficient, and dissipation coefficient (C_d) is governed by Equation 3, which is expressed as:

$$C_r^2 + C_t^2 + C_d^2 = 1 \quad (3)$$

The motion responses of the sloped floating breakwater were recorded using the previously mentioned ship movement gauges. The experiments tracked movement in three directions: heave, surge, and pitch. The Response Amplitude Operators (RAOs) for heave, surge, and pitch were computed using Equations 4–6, as outlined by He et al. (2013). The data collected from the gauges were subsequently assessed using Wavepack software:

$$\text{RAO}_s = \frac{A_s}{A_i} \quad (4)$$

$$\text{RAO}_h = \frac{A_h}{A_i} \quad (5)$$

$$\text{RAO}_p = \frac{A_p}{A_i} \quad (6)$$

where A_s , A_h and A_p represent the amplitudes of the surge, heave, and pitch motions, respectively; A_i denotes the amplitude of the incident wave.

For irregular wave scenarios, the analysis approach followed the same fundamental principles as for regular waves, with essential modifications to consider the statistical characteristics inherent in irregular waves. The three-point method remained applicable for separating incident, reflected, and transmitted waves. However, in the context of irregular waves, the wave spectrum was explored to determine the significant wave height and peak period.

An uncertainty analysis was conducted in accordance with the guidelines provided by the International Towing Tank Conference and the Guide to the Expression of Uncertainty in Measurement. This analysis addresses the main sources of uncertainty in the experimental setup, such as wave measurements, motion response data, and derived hydrodynamic coefficients. For wave height measurements obtained using calibrated resistive-type wave gauges, the

manufacturer specifies an accuracy of ± 1 mm. Repeated measurements under identical conditions generated a standard deviation within $\pm 2.5\%$ of the measured wave height. Motion responses (heave, surge, and pitch) were recorded using DHI ship movement sensors, with a resolution of 1 mm and a sampling frequency of 10 Hz. Repeatability tests revealed variations within $\pm 3\%$ for surge and heave, and $\pm 4\%$ for pitch. Furthermore, the uncertainties in the hydrodynamic coefficients were estimated using the law of propagation of uncertainty, which utilized the partial derivatives of the coefficient equations with respect to the measured variables. The combined standard uncertainties for these coefficients were found to be within $\pm 6\%$, which is consistent with values reported in similar experimental works. The uncertainties in the RAOs were examined by propagating the uncertainties from the motion and incident wave measurements, which resulted in uncertainties within $\pm 4\%$. The total uncertainty for each measured and derived parameter was computed using the root-sum-square method, which combines individual standard uncertainties from various sources.

3 Results and discussion

To assess the effect of DOFs on the hydrodynamic performance of sloped floating breakwater, the experimental model was tested under two configurations: 1-DOF and 3-DOF. The structural model, which featured a 40° slope angle and a draft depth of 0.15 m, was subjected to regular and irregular wave scenarios in a controlled wave flume. Figures 7–9 present the transmission, reflection, and dissipation coefficients for the two configurations under the tested wave scenarios. Notably, W represents the width of the structure (in meters), L denotes the wavelength (in meters), and H refers to the wave height (in meters). Consequently, W/L is a dimensionless parameter that signifies the ratio of the width of the structure to the wavelength.

Waves with shorter periods are depicted by shorter wavelengths and more rapid variations. Under these conditions, the structure has limited time to respond, and its dynamic behavior remains restricted, which reduces its ability to adapt effectively. By contrast, waves with longer periods change more gradually, which provides the structure greater opportunity to adjust and interact with the wave motion.

A pile-type structure, which can move freely in the vertical direction, tends to follow the motion of long-period waves by rising and falling with the wave crests and troughs. This behavior leads to a temporary loss of draft, decreases wave reflection, and enables a greater portion of wave energy to transmit through the structure. Meanwhile, a structure with 3-DOF, which was tethered to the flume bed via cables, experiences vertical constraints due to mooring forces. These constraints help the structure main-

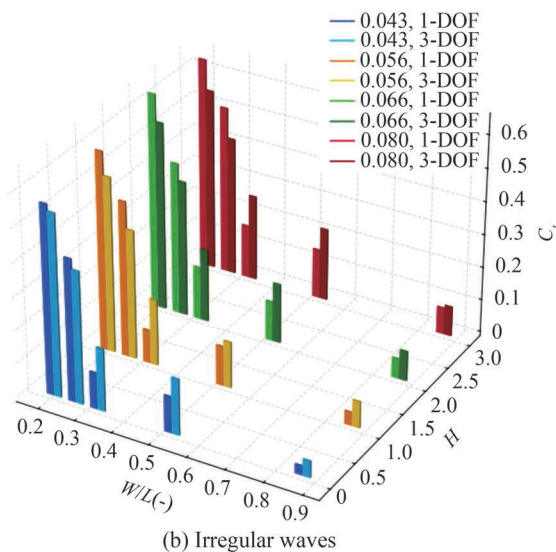
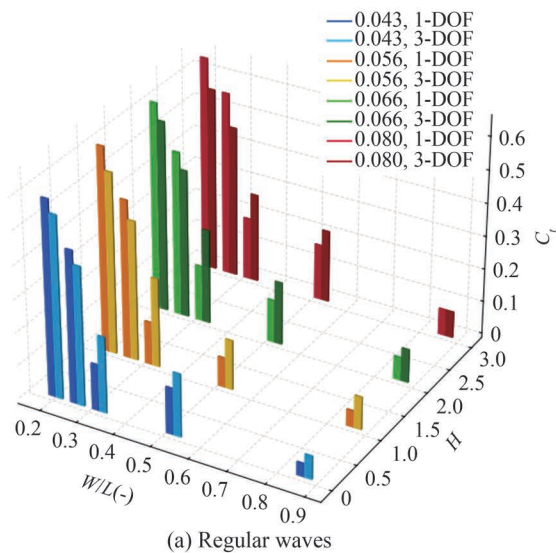


Figure 7 Comparison of the transmission coefficients for the 1-DOF and 3-DOF configurations

tain its draft even under long-period waves, which allows it to maintain its efficacy in attenuating wave energy.

For a wave period of 1.3s (equivalent to 5s at prototype scale), the 1-DOF configuration exhibits lower transmission coefficients (14%–19%) than the 3-DOF system (23–28%), which indicates superior wave attenuation at intermediate periods. However, as the wave period increases, the 3-DOF structure begins to outperform the 1-DOF configuration, which achieves transmission coefficients that are 4%–10% lower. This change in performance highlights the improved energy dissipation capacity of the 3-DOF system at longer periods, which is probably attributable to its higher dynamic adaptability and the energy-absorbing contributions of its additional degrees of motion.

The influence of wave period on the transmission coefficient is predominantly significant, as displayed in Figure 7. A notable rise in transmission coefficients is observed with

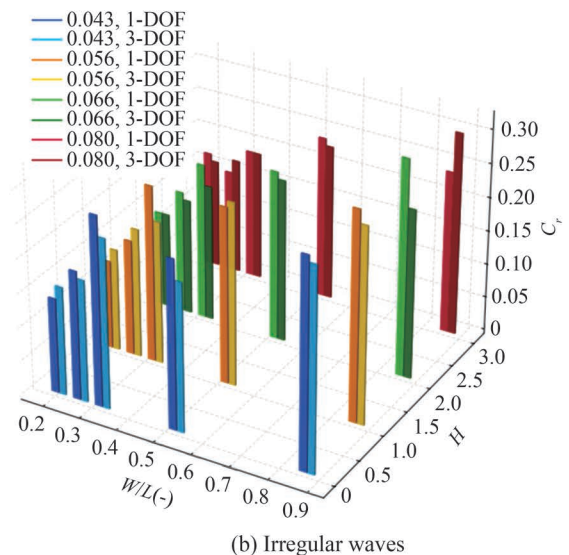
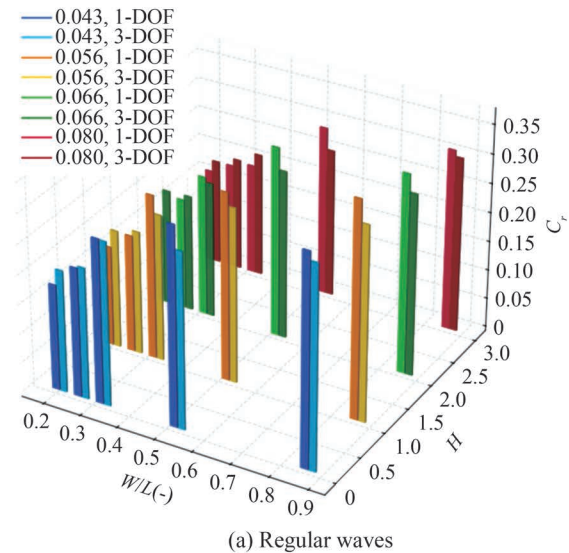


Figure 8 Comparison of the reflection coefficients for the 1-DOF and 3-DOF configurations

extending wave period, which highlights the importance of period-dependent behavior in floating breakwater performance. By contrast, wave height variations have a relatively minor effect on transmission coefficients, which implies that breakwater performance is mainly governed by wave period rather than wave amplitude.

The results obtained for regular and irregular waves do not present significant differences. Specifically, the transmission coefficient for irregular waves is slightly lower than that for regular waves, which is related to the differences in the wave characteristics.

As previously discussed, at shorter wave periods, the structure has insufficient time to synchronize with the wave motion, which results in limited heave motion. On the contrary, at longer wave periods, the structure adapts more effectively, which follows the wave motion and loses its

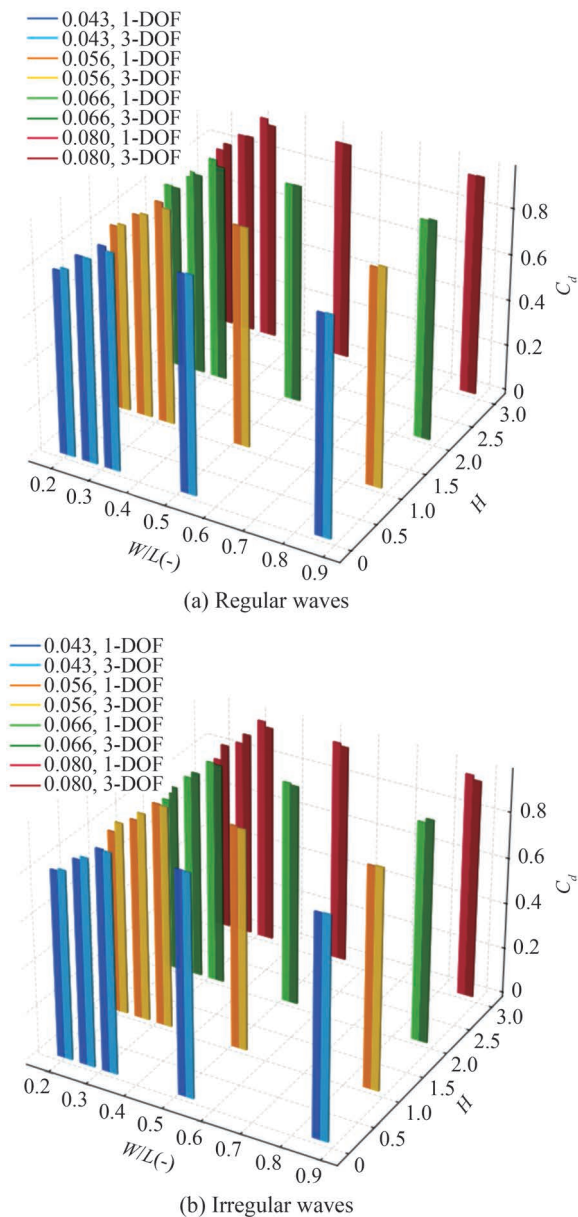


Figure 9 Comparison of the dissipation coefficients for the 1-DOF and 3-DOF configurations

draft. This decreased wave-structure interaction enables more incident wave energy to pass through, which leads to minimal reflection. Consequently, the reflection coefficient for the structure with 3-DOF rises at higher wave periods. However, the sloped breakwater consistently exhibits a lower reflection coefficient than a vertical breakwater configuration.

With regard to the dissipation coefficient, the structure with 3-DOF generally exhibits a slightly higher dissipation coefficient than the 1-DOF configuration. However, at a wave period of 1.3 s, where the transmission coefficient of the 1-DOF structure presents the most significant difference from that of the 3-DOF structure, the dissipation coefficient for the 3-DOF configuration is notably higher. This result indicates that the 3-DOF system is more effective at

dissipating wave energy, specifically at intermediate wave periods.

Figure 10 displays the heave RAOs for the 1-DOF and 3-DOF configurations under regular and irregular wave scenarios. Across all tested wave periods, the heave motion of the sloped floating breakwater with 3-DOF is consistently lower than that of the 1-DOF configuration. This variation in heave motion becomes increasingly pronounced as the wave period extends.

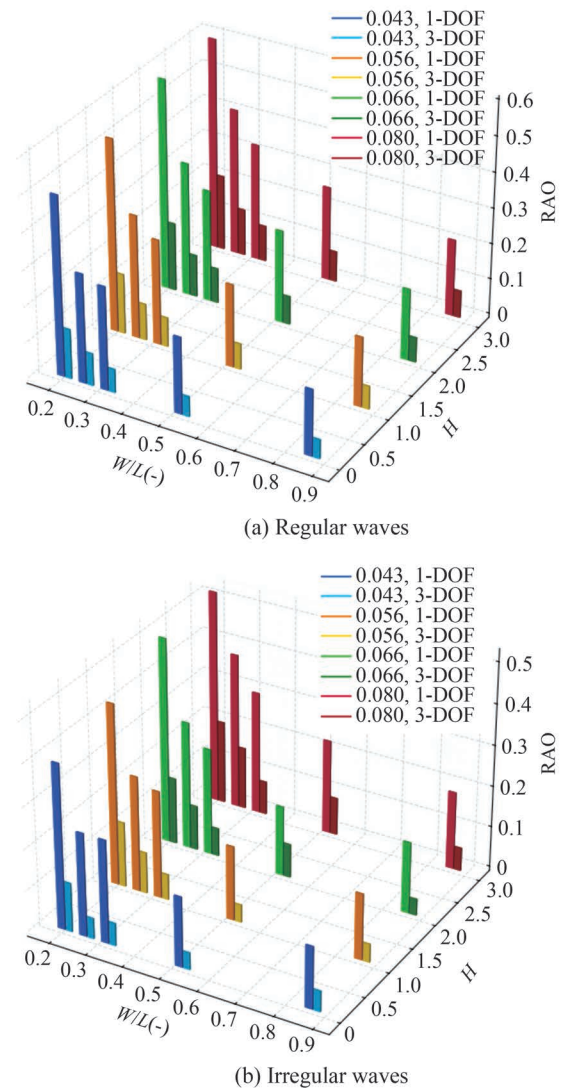


Figure 10 Comparison of the heave RAOs for the model in the 1-DOF and 3-DOF configurations

At higher wave periods (1.6 and 1.8 s), the floating breakwater with 1-DOF presents more significant heave motion, with the structure rising and falling nearly in synchronization with the wave crests and troughs. This synchronized motion results in a decrease in wave reflection from the structure, which leads to higher transmission coefficients. By contrast, the 3-DOF structure, which was tethered to

the bottom of the flume by cables, has a more limited capability to move vertically. As a result, it exhibits less displacement during these wave periods.

In lower wave periods, the structure with 1-DOF presents greater vertical motion than the 3-DOF structure, although this difference becomes less pronounced at higher periods. However, the 3-DOF structure, in addition to vertical motion, also experiences surge and pitch movements. Consequently, although the heave motion is lower than that of the 1-DOF structure, the additional movements result in a lower overall reflection coefficient. Ultimately, a higher transmission coefficient is observed at these periods.

4 Conclusion

This study experimentally evaluated the hydrodynamic performance of a sloped floating breakwater under regular and irregular wave scenarios, with a focus on the effect of DOFs on wave attenuation behavior. The experiments were performed using a 1:15 scale model featuring a 40° slope and a draft depth of 0.15 m. Two structural configurations were investigated: a 1-DOF system restricted to heave motion and a 3-DOF system capable of heave, surge, and pitch motions.

The results reveal that, at shorter wave periods, the 1-DOF structure exhibits better wave attenuation performance than the 3-DOF configuration. This advantage is highly pronounced at a prototype wave period of approximately 5 s, where the 1-DOF setup achieves up to 14% lower transmission coefficients. As the wave period extends to 5.8 and 7 s, the structure has additional time to synchronize with the wave motion, which results in increased vertical movement. This improvement leads to a decreased capability to block wave transmission, which diminishes the performance of the 1-DOF configuration. Under these scenarios, the 3-DOF structure outperforms its counterpart, with transmission coefficients 4%–10% lower.

Furthermore, at longer wave periods, the amplified vertical motion of the 1-DOF structure leads to higher reflection coefficients than those of the 3-DOF system. This contrast highlights the role of motion constraints in modulating the hydrodynamic response of the structure. Across all wave periods, the heave motion is consistently greater in the 1-DOF configuration than in the 3-DOF configuration. This difference becomes increasingly pronounced as the wave period extends. While the 3-DOF system exhibits less vertical motion, the combined effects of surge and pitch contribute to a redistribution of energy, which improves its performance. At shorter wave periods, this multi-directional response results in slightly higher transmission coefficients. However, at longer wave periods—specifically around 6.2 and 7 s—the improved vertical motion of the 1-DOF structure significantly decreases its effectiveness, which allows

the 3-DOF system to outperform it in terms of wave energy dissipation.

The findings also emphasize the dominant role of wave period in determining breakwater performance. Transmission coefficients rise notably with wave period, while wave height variations have comparatively minimal influence. This trend underscores the importance of considering period-dependent behavior in the design and analysis of floating breakwater systems.

Overall, this study reveals that the structural configuration and the number of DOFs significantly affect the hydrodynamic performance of floating breakwaters. Further work on additional DOF combinations and their interactions under various wave scenarios could offer deeper insights and guide the establishment of more efficient and flexible breakwater designs.

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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