# Hydrodynamic Performance of Half Pipe Breakwaters Experimentally and Numerically

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The main objective of constructing barriers is to safeguard harbours and shores from waves and sea currents. This paper aims at presenting a study on innovative and non-traditional alternatives to breakwaters, experimentally and numerically, to assess the hydrodynamic efficiency of the suggested models in order to choose the most appropriate one. Two models of semi-submersible-type breakwaters have been studied, in the form of a cross-section of a half pipe with an internal diameter and thickness of 30.00 and 1.00 cm, respectively. Model (a) is a circular half-pipe with an upward concave, whereas model (b) has a sideways concave towards the water. Several scenarios for the breakwaters suggested in this study have been simulated using FLOW 3D. The results indicate that the transmission coefficient (Tc), provided by model (b), is 3-7% lower than model (a), while the reflection coefficient (Rc) values for model (b) are 4-8% higher than model (a). The results show that model (b) has a 10% lower (Tc) at d/h = 0.80 compared to d/h = 0.60, while (Rc) is 8% higher at d/h = 0.80 than at d/h = 0.60 for the same model. The suggested breakwater reduces inclined waves' energy more quickly than perpendicular waves. Regarding the hydrodynamic performance, the proposed breakwater in model (b) is shown to be more efficient and effective than the breakwater in model (a), so it is recommended to use it due to its effectiveness in providing protection for coastal wave zones and benefiting from the energy of waves to generate electricity.

**KEY WORDS**
~ Breakwater
~ Coastal
~ Half pipe
~ Hydrodynamic
~ Numerical model
~ Waves

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## 1. INTRODUCTION

The coastline area is one of the most vital and significant in every nation. The coastal zone and harbours have significant repercussions for the economy since they support a number of activities, such as increasing, revitalising coastal tourism, fostering the development and stabilisation of urban districts [1, 2, 3, 4, 5]. The construction of fishing ports will improve fisheries. However, various natural phenomena, like tides, waves, and sea currents, have a negative effect on the shores and the surrounding environment [6, 7, 8, 9]. A breakwater offers an area in calm waters where ships can dock safely, as well as offering momentary security during building and mineral and oil exploration [10]. The breakwaters significantly reduce the energy of the waves [11]. Conventional barriers like moraine ridges, caissons, and gravity barriers are used to create a safe and tranquil marine area [12, 13, 14]. Some breakwater types must be wider under deep sea conditions, which necessitates the use of more building materials [15, 16, 17]. Such breakwaters also prevent littoral drift, which causes serious erosion or accretion. They restrict water movement, which lowers the quality of the water and upsets the environment [18, 19]. Additionally, the construction of traditional structures calls for trained workers and particular foundation specifications. Everything has combined to result in an unaffordable construction expenditure [20, 21]. In recreational ports, waves are permitted as long as they do not endanger or inconvenience visitors. Consequently, some of these waves are permitted to pass past the barrier since it offers a stunning view of the shore [22, 23, 24, 25]. Numerous studies have been done in the past to suggest new breakwater configurations, enhance their functionality, and look at how their hydrodynamic characteristics may influence wave reduction. An attempt has also been made to understand the performance of mobile breakwaters, using a variety of numerical modelling studies. In order to assess barriers' hydrodynamic effectiveness, the reflection of waves and transmission through the barriers have been examined. To evaluate wave dispersion by vertical breakwaters, numerous mathematical models are created, together with physical hydraulic testing [26, 27, 28, 29, 30, 31, 32, 33]. Breakwaters have been the subject of several studies. The two wave-reflecting surfaces of the floating barrier act as a wave dissipation structure. A stationary floating barrier's hydrodynamic properties have been examined under the influence of waves that are both regular and erratic [34]. To evaluate the effect of breakwater height on different water depths, nine experimental models have been used. Numerical data has been used to assess the hydrodynamic effectiveness around breakwaters. The experimental and numerical results have been found to be very similar [35]. Regular waves' transmission and reflection factors through thin, perforated walls have been investigated. The pores have been recreated by moving the thin perforated plexiglass pane that transmits incident waves while limiting wave overrun and by altering the perforation pattern of the sheets by adding extra holes to them [36]. The efficiency of breakwater caissons supported by pile systems has been investigated [37, 38]. Therefore this paper aims to present a study of innovative and non-traditional alternatives to barriers, experimentally and numerically, for the purpose of evaluating the hydrodynamic effectiveness of the suggested models and selecting the most appropriate alternative.

### 1.1. Problem Statement

Breakwaters with curves are usually used for the following purposes:

- An important solution is common in deep-water cases.
- Suitable for coastal regions with limited soil-carrying capacity.
- Effectively useful in low and medium-wave energy applications.
- Permits the water masses around coastal areas to be constantly refreshed, which lowers pollution.
- It takes up little space so that organisms on the sea bed are not affected.

## 1.2. Study Objectives

- Suggesting types of breakwaters suitable for protecting beaches and ports, taking into account efficiency and cost.
- Examine the efficiency of the two suggested barrier models experimentally and numerically.
- Make use of the energy that waves dissipate to generate electricity.

# 2. MATERIALS AND METHODS

## 2.1. Experimental Work

The study experiments have been carried out in the Ports Laboratory, Department of Water Engineering and Water Structures, Zagazig University. The experiments have been performed in wave flume to examine how half pipes, submarine breakwater systems, and regular waves interact. The wave flume description is as follows: length = 12.00 m, width = 2.00 m, height = 1.20 m, and water depth (h) inside the wave flume = 0.40 m, as seen in Photo 1. Two record points have been chosen to measure the heights of incident and reflecting waves. In front of the barrier, the first point ($P_1$) is located at a distance of 0.35 L, while the second point ($P_2$) is located at a distance of 0.70 L, where L represents the wave length. The third point ($P_3$) is to measure the wave heights that are being transmitted, as shown in Figure 1, at a distance of 3.0 m downstream from the breakwater. In order to both absorb and reflect waves, at the end of the flume there is a sloped wall with a slope of 3:1. The sides of the wave flume have been made by reinforced concrete. The wave generator produces regular waves at various frequencies. Two models of semi-submersible-type breakwaters have been studied, in the form of a cross-section of a half pipe with an interior diameter and thickness of 30.00 and 1.00 cm, respectively. Model (a) is a circular half-pipe with an upward concave, whereas model (b) has a sideways concave towards the water, as shown in Figure 2. At the end of the flume a wave generator is located. It consists of two steel bars connected by steel flywheels with a diameter of 0.36 m and a gate made of steel with hinges fixed to the flume. It is powered by a 5.00 horsepower motor that produces a rotation velocity of 1400 rpm. Using a gearbox, the number of rotational motions has been lowered to a range of 20 to 90 rpm, producing waves with durations between 0.60 and 4 seconds. Photo 2 displays the wave generator's whole perspective.

Photo 1. The wave flume

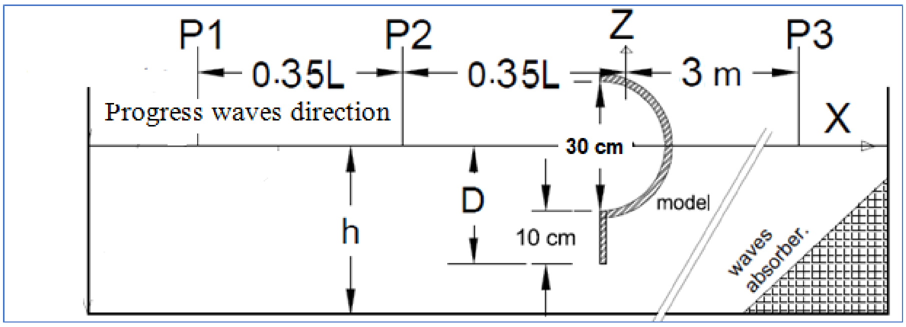

Figure 1. Barrier model dimensions

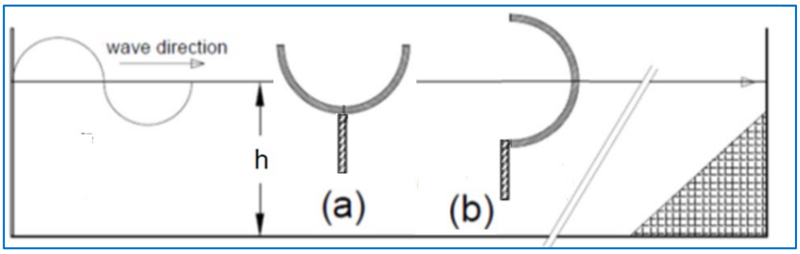

Figure 2. Model (a) and model (b) in the wave flume

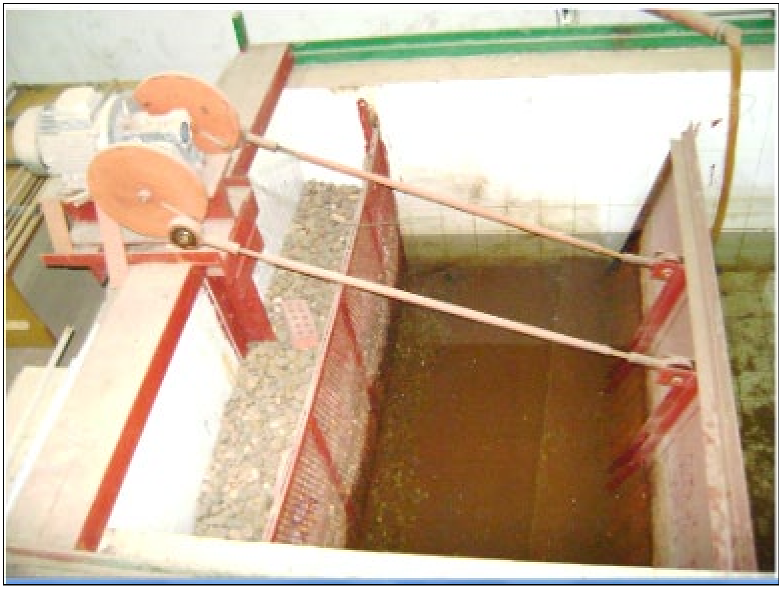

Photo 2. The wave generator

## 2.2. Hydrodynamic Parameter

The hydrodynamic performance of the suggested breakwaters is determined by two study parameters. The first parameter is the reflection coefficient (Rc), which is the quantity of energy that the breakwater reflects and can be determined as follows: [39].

$$R_c = \frac{H_r}{H_i} \qquad (1)$$

Where: $H_r$ is the reflected wave's height, and $H_i$ is the incident wave's height.

The second parameter is the transmission coefficient ($T_c$), which is the wave's height that the incident wave reflects and can be determined as follows: [40].

$$T_c = \frac{H_t}{H_i} \qquad (2)$$

Where: $H_t$ is the wave's height that is transmitted.

## 2.3. Numerical Simulations

FLOW-3D has been used to numerically simulate the proposed breakwater, which is suitable for the various situations suggested in this study since it offers dependable outcomes, allowing for the economical and time-efficient simulation of numerous variables [41]. It is a quick computational fluid dynamics (CFD) programme that addresses issues with free-surface flow [42]. FLOW-3D mimics both nonlinear and irregular waves in addition to conventional linear waves. Theoretically, Flow-3D uses non-linear, second-order differential equations to describe fluid motion [43]. The development base of the suggested program enables a wide range of applications. Finite volume theory is the foundation for the programme's coding, and Navier-Stokes (RANS) formulas have been utilised to determine the 3D Reynolds mean [44]. The item hydrodynamically analysed in the imposed fluid flow field now has the boundary conditions for hydrodynamics of not sliding and in the unit vector direction (viscosity and vortices; hence applying the RANS equation system). It is specified as having a linear boundary condition upstream. Linear wave theory is implemented in the FLOW-3D surface wave mode, as shown in Figure 3. Non-reflective boundary conditions have been applied at the downstream border to reduce reflection and permit disturbances that originate inside the domain to exit it without altering the interior solution [45]. Figure 4 shows the procedure for numerical simulation. FLOW-3D solves the non-linear transient equations of motion with finite difference and finite volume approximations. A numerical scheme should be implemented to approximate the solution. Using Taylor expansion, the finite difference approximates the continuous to be a linear combination of its derivatives. The greatest derivative order and the separation between two points determine its quality. By using the finite volume method (FVM), the computational domain can be divided into finite control volumes, where the integral forms are satisfied [46]. These methods are derived from flow-suitable conservation equations using an Eulerian description.

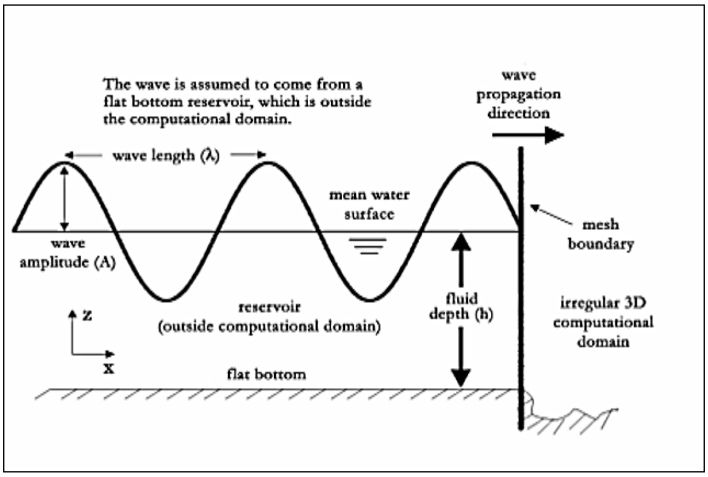

Figure 3. FLOW-3D linear wave characteristic diagram

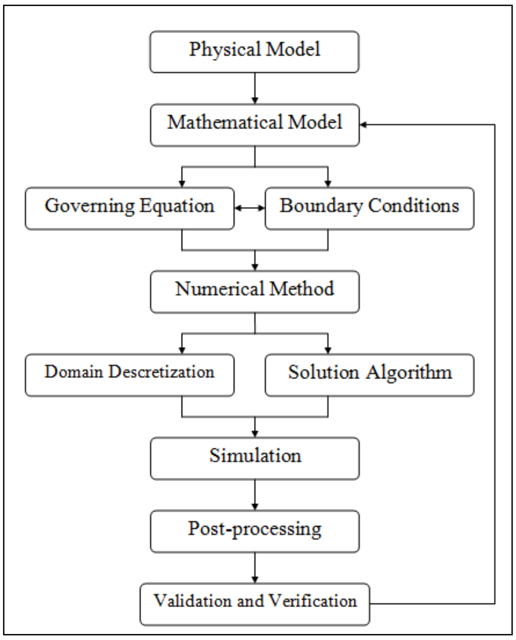

Figure 4. Procedure for numerical simulation.

# 3. RESULTS AND DISCUSSIONS

## 3.1. Experimental Results

In order to establish a set of run circumstances, the following six periodic wave durations (T) have been used: 0.8, 1.00, 1.20, 1.30, 1.60, and 2.00 s. The barriers are exposed to two types of waves. The first type of regular linear wave is orthogonal ($90^0$) on barriers, and the second type of regular linear wave has an oblique angle ($30^0$) on the barriers. In deep water, the waves are unaffected by the bottom, but in intermediate or shallow water, they are. The parameters used for experimentation for the selected model are displayed in Table 1.

| **Parameter** | **Units** | **Water level range** | | | | | |
|---|---|---|---|---|---|---|---|
| Duration of wave (T) | S | 0.80 | 1.00 | 1.20 | 1.30 | 1.60 | 2.00 |
| length of wave (L) | M | 1.18 | 1.62 | 2.10 | 2.30 | 3.10 | 3.70 |
| Wave incident ($H_i$) | Cm | 12.80 | 9.80 | 8.10 | 6.50 | 5.20 | 4.20 |
| Wave number ($k_h$) | 1/m | 5.25 | 3.83 | 2.90 | 2.60 | 2.10 | 1.70 |

Table 1. The chosen model's experimental parameters

Details of the most significant previous studies relevant to this paper are summarised, such as the model type, theoretical model, flume dimensions, and hydrodynamic parameters. Table 2 shows the most significant studies pertinent to the present one.

| Reference | Model type | Theoretical model | Experiment facilities (Length, width, depth), water depth (h) in m | Parameters |
|---|---|---|---|---|
| Present study | semi-submersible curved | A numerical model utilizing the Navier-Stokes equation | (12m, 2 m, 1.2m), h = 0.4 | D/h = 0.6 - .0.8, kh = 1.70 - 5.25, T = 0.8 - 2, Hi = 4.2 - 12.8, L = 1.18 - 3.7 |
| Hussein et al. (2022) [1] | Suspended curved breakwaters | A numerical model utilizing the Navier-Stokes equation | (12m, 2 m, 1.2m), h = 0.4 | D/d = 0.25, Hi = 2.07 - 3.65, L= 2.05 - 4.1, T= 1.2 – 2, d/L= 0.1 - 0.24 |
| Ahmed et al. (2011) [47] | Submerged rectangular impermeable barrier | No theoretical | (21.3 m, 0.76 m, 0.74 m), h = 0.5 m | B/h =1.6, D/h = 0.7 |
| Zhu (2011) [48] | Circle piles arranged in one row | Extension of the Eigen Function | No experiments | Hi/h = 0.08 – 0.37, Kh = 0.5 – 2.5, |
| Rageh et al. (2010) [49] | A vertical barrier including horizontal holes | Extension of the Eigen Function | (15 m, 1 m, 1m), h = 0.5 m | h/L = 0.13 – 0.41, ε = 50% |
| Krishnakumar et al. (2008) [50] | Slot screens are partly Immersed. | Boundary Integral Equation | (72.5 m, 2 m, 2.7m), H = 0.95 | D/h = 0.3, 0.5, 1.0, T = 1 - 2.5 s, ε = 0.17 - .09 |
| Huang et al. (2007) [51] | Completely Immersed slotted breakwaters | Extension of the Eigen Function | (12 m, 0.3 m, 0.5m), h = 0.3 | Kh = 1.0 - 2.5, ε= 0.1 - 0.3, Hi = 0.01 - 0.04 |
| Lin et al. (2007) [52] | Emerging porous rectangular barriers | A numerical model utilizing the Navier-Stokes equation | No experiments | B/h = 0.05 - 0.2, D/h = 1.2, B/L = 0.06 - 0.21, |
| Suh et al. (2007) [53] | A single wall is supported by piles (circular piles) | Extension of the Eigen Function | (104 m, 3.7 m, 4.6m), h = 2.4 | Kh= 0.9 - 4.2, Hi = 0.03, ε = 0.5 |
| Li et al. (2006) [54] | Rectangle and circular holes on a single screen | Extension of the Eigen Function | (56 m, 0.7 m, 1.0), h = 0.35 | Kh= 0.6 – 1.75, ε= 0.1 - 0.4, Hi/L= 0.023 – 0.064 |
| Cokgor et al. (2005) [55] | Permeable Immersed trapezoidal | No theoretical | (22.5 m, 1 m, 0.5 m), h = 0.3m | B/h = 0.67, D/h = 0.83 |

Table 2. Characteristics of the various models that have been compared

## 3.2. Numerical Results

Figure 5 shows a numerical simulation of a case without placing any barriers.

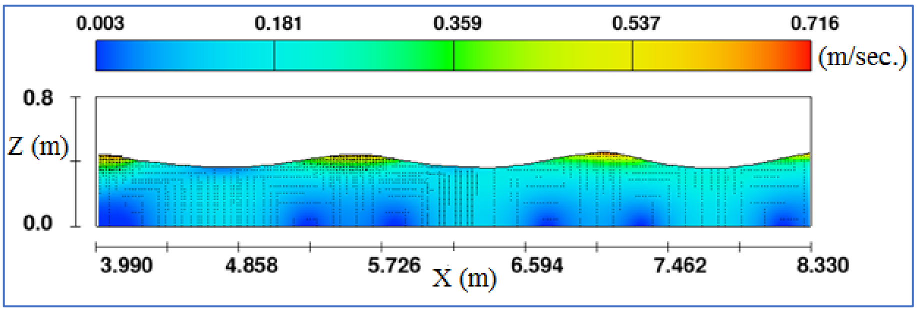

Figure 5. Results of a numerical simulation for a case (without breakwater).

From Figure 5, it is clear that the waves are regular and that their highest speed is at the crest of the wave. Figure 6 displays the comparison between two models of the suggested barriers (model (a) and model (b) for the hydrodynamic performance, transmission coefficient ($T_c$), and reflection coefficient ($R_c$) against ($k_h$), where $k = 2\pi/L$.

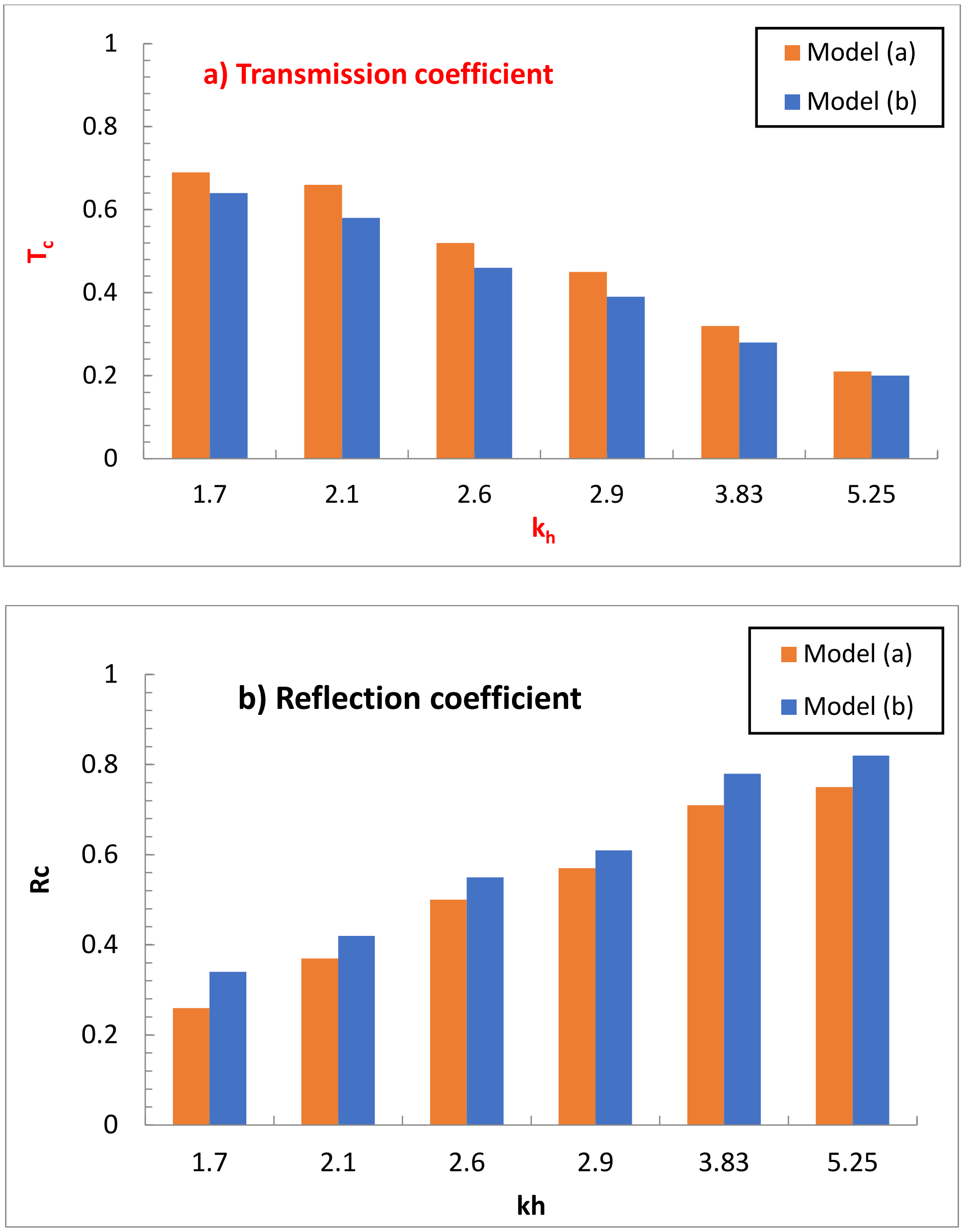

Figure 6. Compares the hydrodynamic performance ($T_c$ and $R_c$) against ($k_h$) for two models of breakwaters

Figure (6a) demonstrates that as ($k_h$) increases, ($T_c$) lowers. The results obtained indicate that the transmission coefficient (Tc) provided by model (b) is 3-7% lower than that in model (a). ($R_c$) rises as ($k_h$) rises, as shown in Figure (4b). ($R_c$) values in model (b) are 4-8% higher than in model (a). The impact of the barrier draft on the hydrodynamic efficiency of performance ($T_c$ and $R_c$) as a function ($k_h$) for model (b) is shown in Figure 7.

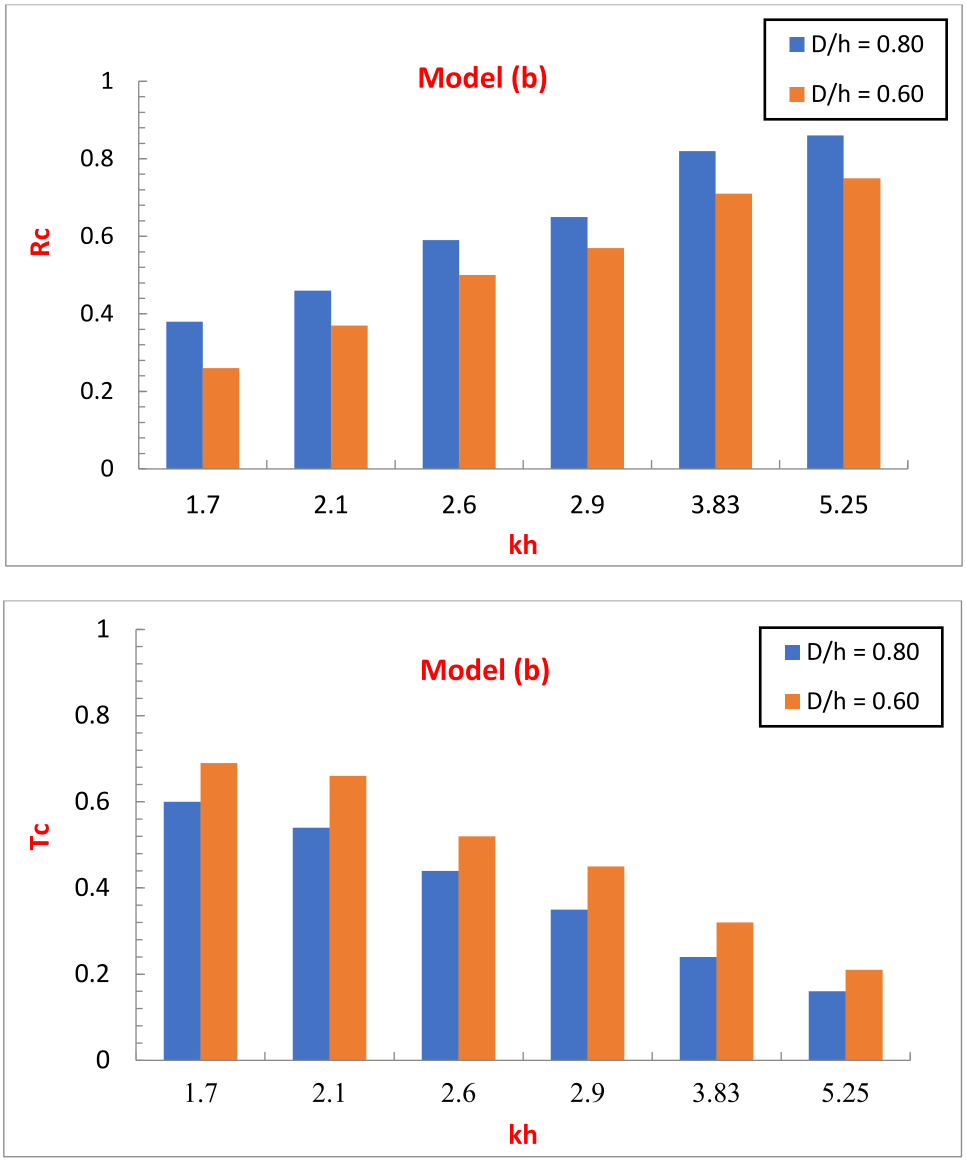

Figure 7. Impact of barrier draft on ($T_c$ and $R_c$) against ($k_h$) for model (b)

Figure (7a) shows that the breakwater of model (b) has a 10% lower ($T_c$) at D/h = 0.80 than at D/h = 0.60, while ($R_c$) is 8% higher at D/h = 0.80 than at D/h = 0.60 for the same model, as shown in Figure (7b). Figure 8 shows the ($T_c$) and ($R_c$) values for the model (a) at regular linear waves orthogonal ($90^0$) on the barrier and oblique ($30^0$) on the barrier.

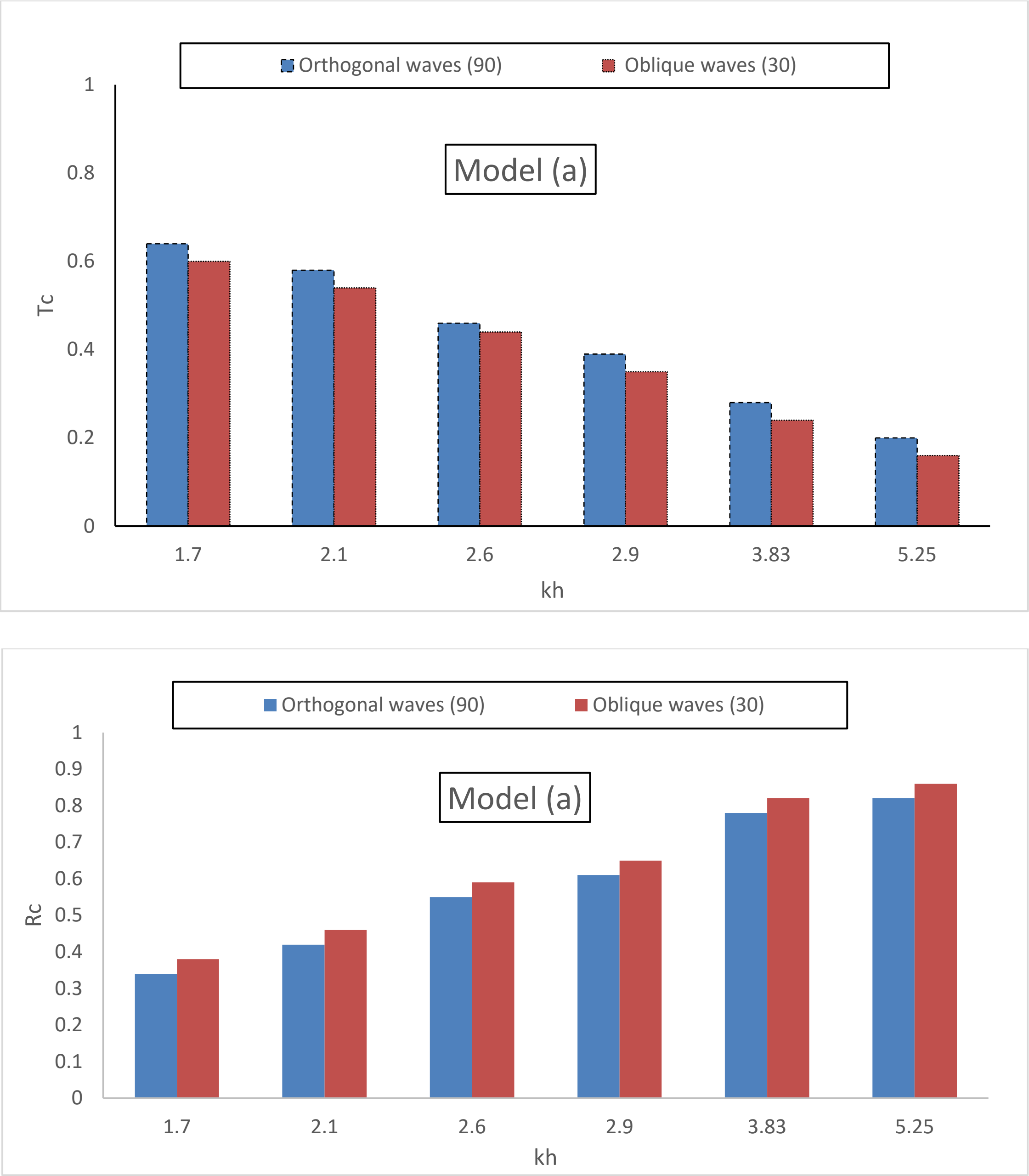

Figure 8. Compares the hydrodynamic performance (Tc and Rc) against (kh) for model (a) at 300 and 900

According to Figure (8a), orthogonal waves have ($T_c$) was 5% higher than an oblique wave with an angle of $30^0$. The $R_c$ of orthogonal waves is 5% less than the ($R_c$) of the wave that is oblique at an angle of $30^0$, according to Figure (8b). A comparison of breakwater draft and speed at 1.1 s wave periods is shown in Figure 9.

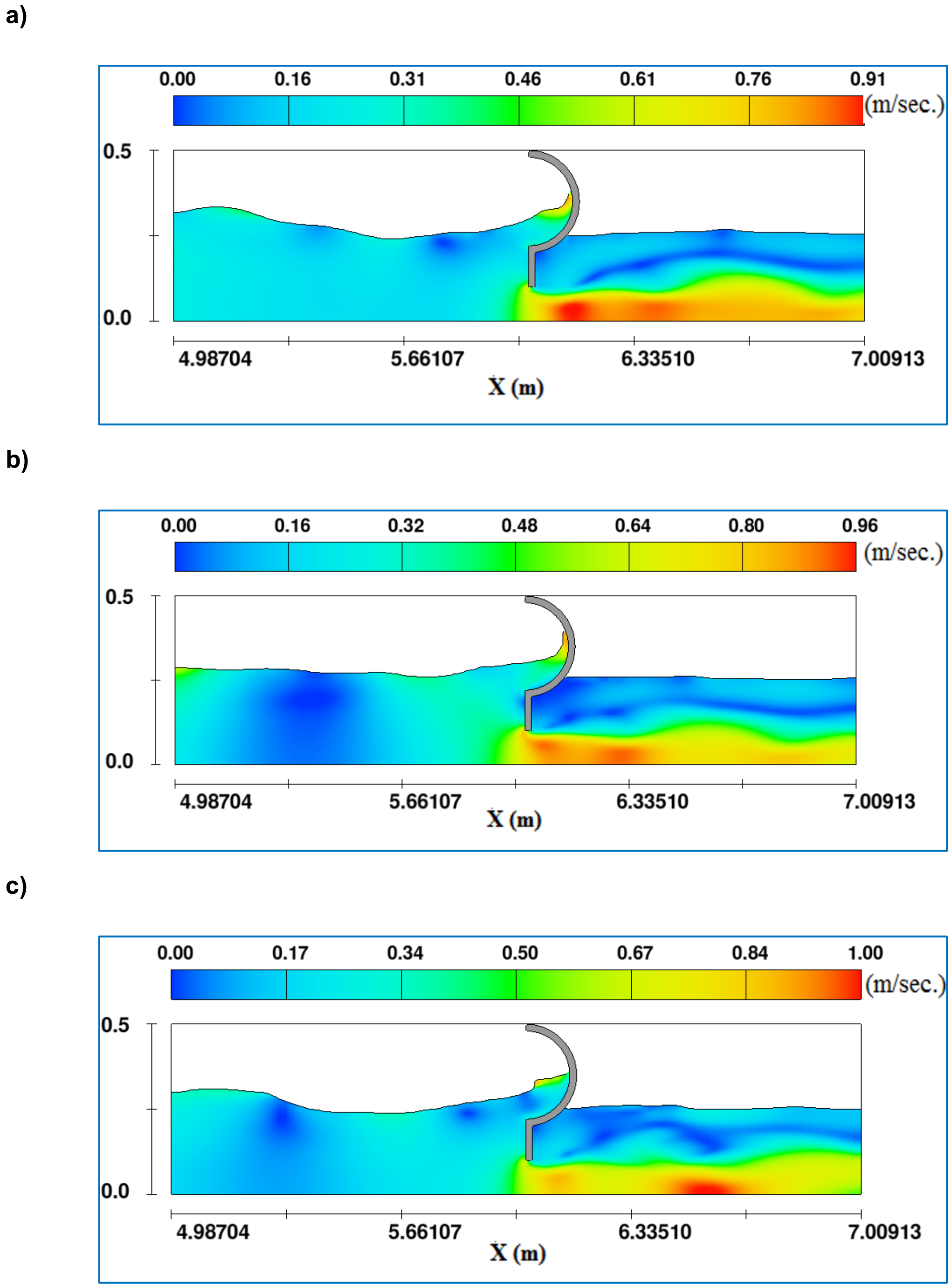

Figure 9. Speed and barrier draft comparison at 1.1 s wave periods.

The maximum velocity rises as the barrier draft increases, as seen in Figure 9. It has been observed that the waves are dispersed at the barrier's edge, which has assisted in reducing the energy of the waves. The Flow-3D simulation, depicted in Figure 10, reveals that the hydrodynamic pressure on the breakwater increases with wave reflection.

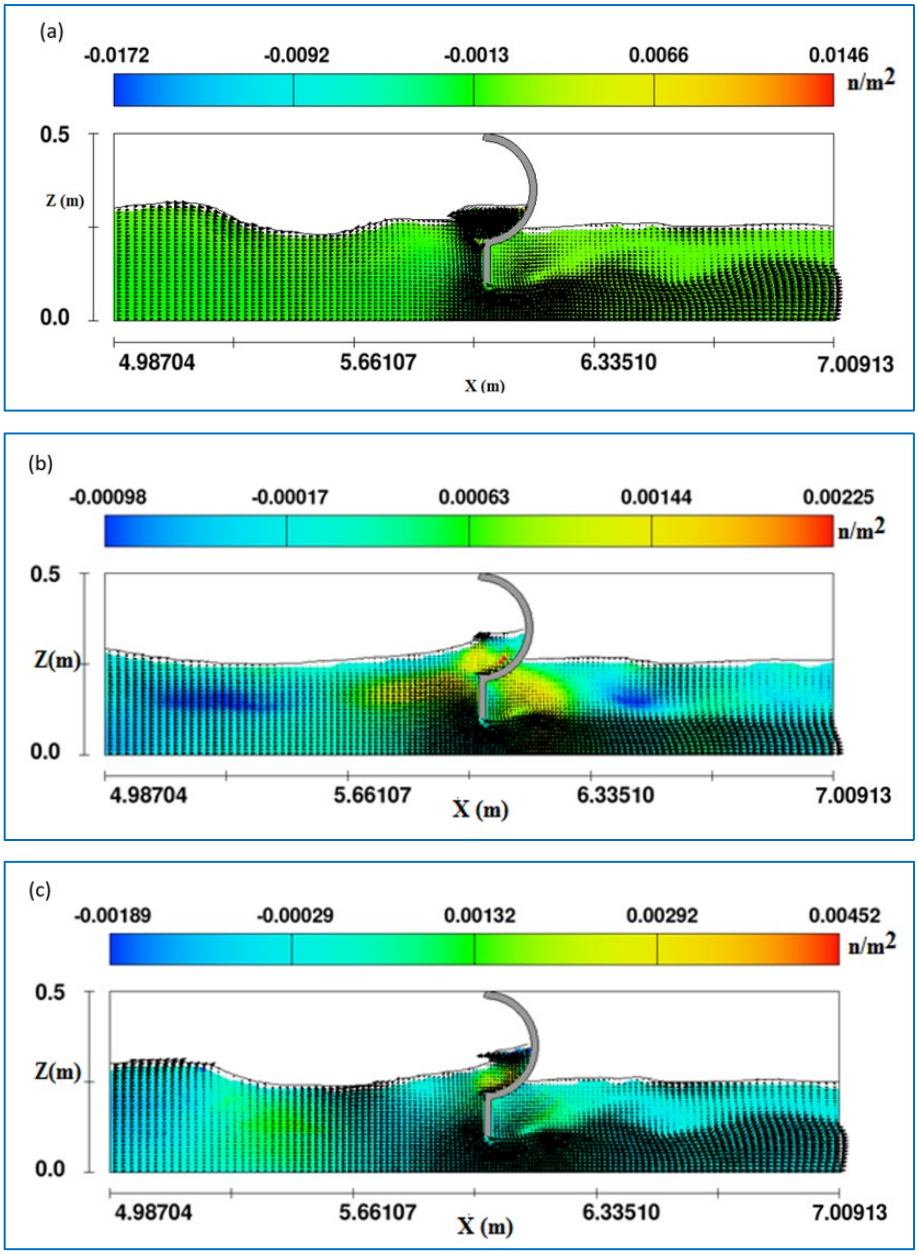

Figure 10. The relationship between breakwater draft and pressure

As may be seen in Figure 10, it turns out that the draft has an inverse relationship with the hydrodynamic performance ($T_c$ and $R_c$). When compared to orthogonal waves, the tested barrier dissipates oblique waves' energy more quickly. The height of the wave behind the barrier lowers as the velocity rises below and behind the barrier. Table 3 shows a statistical comparison of the hydromechanical efficiency between model (a) and model (b) in terms of wave transmission and reflection.

| Parameter | Model (a) | Model (b) |
|---|---|---|
| Wave number ($k_h$) | 2.6 | 2.6 |
| Transmission coefficient ($T_C$) | 0.5 | 0.45 |
| Reflection coefficient ($R_C$) | 0.47 | 0.52 |

Table 3. Statistical comparison of the hydromechanical efficiency of the proposed models

The suggested breakwater in model (b) seems to be more effective and efficient than the breakwater in model (a) in terms of hydrodynamic performance. It is therefore advised to utilise model (b) since it is efficient in shielding maritime wave regions and utilising wave energy to produce electricity.

## 4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions may be drawn after analysing the study results, as follows:

- The suggested breakwater in model (b) is more efficient and effective than the breakwater in model (a) regarding hydrodynamic performance.
- The transmission coefficient of breakwaters decreases as their draft depth increases, whereas the reflection coefficient rises.
- The suggested breakwater reduces wave energy more in the inclined case than in the case of perpendicular waves.
- The draft gets deeper, causing the wave behind the barrier to lower.
- As the wave's reflection height grows, so does the hydrodynamic pressure on the breakwater.
- The pressure and velocity around a breakwater can be determined using a numerical model.
- Most of the essential elements of experimental data, as well as theoretical results, can be effectively reproduced by the numerical model.
- It is recommended to use wave energy as an alternate, sustainable, and clean method of electricity generation.

Based on the conclusions reached from this study, the following recommendations are proposed:

- Implementation of the proposed barrier (model b) evaluated within the criteria examined.
- In the future, it will be important to study more different angles of the wave.
- More dimensions of the half-pipe breakwater must be simulated.
- Studying the effect of irregular and random waves in the proposed models.
- Semi-submersible concave barriers are low-cost and easy to install, particularly on beaches used for recreational purposes.

## LIST OF SYMBOLS

- $D$ = barrier draft [L].
- $h$ = water depth [L].
- $H_i$ = wave incident [L].
- $H_r$ = the height of the reflected wave [L].
- $H_t$ = wave height transmitted [L].
- $k_h$ = number of waves [-].
- $L$ = length of wave [L].
- $P_1$ = The first point at a distance of 0.35 L in front of the breakwater [-].
- $P_2$ = the second point at a distance of 0.70 L in front of the breakwater [-].
- $P_3$ = The third point at a distance of 0 m downstream the breakwater [-].
- $R_c$ = the coefficient of reflection [-].
- $T$ = duration of wave [T].
- $T_c$ = the coefficient of transmission [-].

## CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

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