Laboratory Study of Porosity and Optimal Hole Size in Breakwaters Constructed from Recyscled Materials

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Abstract

One of the primary challenges in the development of coastal areas is the selection of suitable armor to protect coasts with minimum cost and minimal environmental damage. Hole-embedded breakwaters made from recycled materials, as a new generation of permeable structures, provide the possibility of natural water circulation and ecosystem preservation while reducing material consumption. In this research, the hydraulic performance of this type of breakwater was investigated experimentally with emphasis on two key parameters: porosity percentage (open area) and hole diameter. The experiments were conducted in the wave flume of the Marine Engineering Research Center of Nowshahr University of Marine Sciences with dimensions of 36×3×1.25 m. The breakwater models were constructed from recycled polyethylene terephthalate (PET) bottles in two general categories: single-sided perforated and double-sided perforated, with porosity percentages of 7%, 42.78%, and 78.5%, and hole diameters of 2.5, 7.5, and 10 cm (in the model scale), under regular waves with a period of 1.012 s and a height of 23 cm. The results showed that with increasing porosity percentage from 7% to 42.78%, the relative wave run-up (Ru/Hi) decreases by 15% to 20% on average. However, further increase in porosity up to 78.5% not only does not cause a significant reduction in run-up, but in some configurations, it increases wave transmission behind the structure due to increased wave passage. In some configurations, it causes an increase in wave transmission behind the structure. The medium hole diameter (7.5 cm) was identified as the optimal size, such that the breakwater with 42.78% porosity and medium diameter exhibited the lowest run-up and the highest energy dissipation. The findings of this research can serve as a design guide for selecting optimal porosity and hole size in hole-embedded breakwaters made from recycled materials.

Keywords: Hole-embedded breakwater, recycled materials, porosity, optimal hole size, wave run-up, wave transmission, wave energy dissipation.

1. Introduction

One of the most important concerns in coastal engineering has always been wave breakwaters. Coastal protection structures such as breakwaters are responsible for creating tranquility in ports and reducing wave energy. In recent years, rock-fill breakwaters have been proposed as a suitable alternative for rigid breakwaters because these structures, by creating holes in their body (porous), dissipate part of the wave energy and provide the possibility of water exchange between the port and the open sea (Jarlan, 1961; Suh et al., 2006).

The use of recycled materials in the construction of these breakwaters is a further step towards sustainable development. Materials such as PET bottles, which occupy a large volume in nature and remain in the environment for many years, can help preserve natural resources, reduce costs, and reduce greenhouse gas emissions by being used in the construction of these structures (Dhinakaran et al., 2008).

Despite the mentioned advantages, the optimal design of these breakwaters requires precise knowledge of the parameters affecting their hydraulic performance. Two key parameters in this field are porosity percentage (ratio of open area to total area) and hole diameter. To date, limited studies have addressed the simultaneous investigation of these two parameters in breakwaters made from recycled materials. The aim of this research is to determine the optimal porosity and hole size to achieve maximum energy dissipation and minimum run-up and wave transmission.

Recycling polyethylene terephthalate (PET) bottles for breakwater construction presents an alternative approach to incorporating waste materials into coastal infrastructure. Experimental investigations of recycled PET floating breakwaters have also explored the potential of reusing plastic bottles in marine engineering applications [11].

Nevertheless, the hydraulic response of bottle-based perforated breakwaters depends on the opening geometry, the arrangement of the bottles, and the direction from which waves approach the structure.

The present study investigates perforated breakwaters constructed using recycled PET bottles. Particular attention is given to the effects of perforation ratio, opening size, and wave-facing configuration on relative run-up, wave transmission, energy dissipation, and structural displacement.

The specific objectives are:

1. To evaluate the influence of perforation ratio on the hydraulic performance of recycled-material breakwaters.
2. To compare different opening sizes and identify configurations associated with favorable run-up reduction.
3. To examine the effects of structural arrangement and wave-facing orientation.
4. To identify configurations that provide a favorable combination of hydraulic performance and structural stability.

The principal contribution of this study is the experimental comparison of multiple perforation configurations in a recycled-PET breakwater system, with particular emphasis on the combined effects of opening size and structural arrangement.

2. Materials and Methods

2-1. Laboratory Equipment

The experiments were conducted in the wave flume of the Marine Engineering Research Center of Nowshahr University of Marine Sciences with a length of 36 m, width of 3 m, and depth of 1.25 m (Figure 1 and Image 1). A hinged paddle wave maker with a hydraulic jack (Image 2) was used, and a slope-type wave absorber with a angle of 26.28 degrees (Image 3) was placed at the end of the flume. Wave height sensors (Image 4 and Figure 2) were installed at distances of 14 m and 15 m from the wave maker.

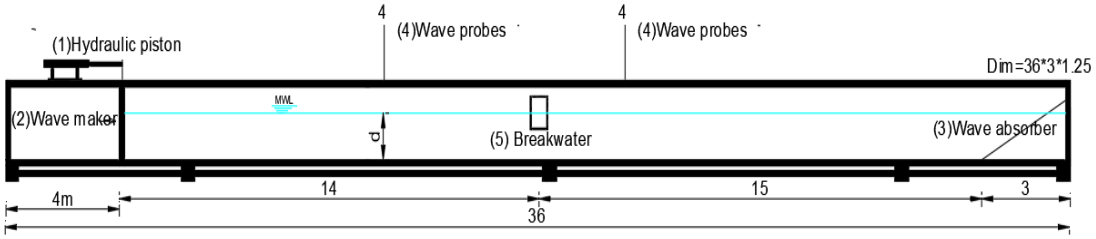

Figure 1. Plan of the wave flume and arrangement of the structure and wave sensors

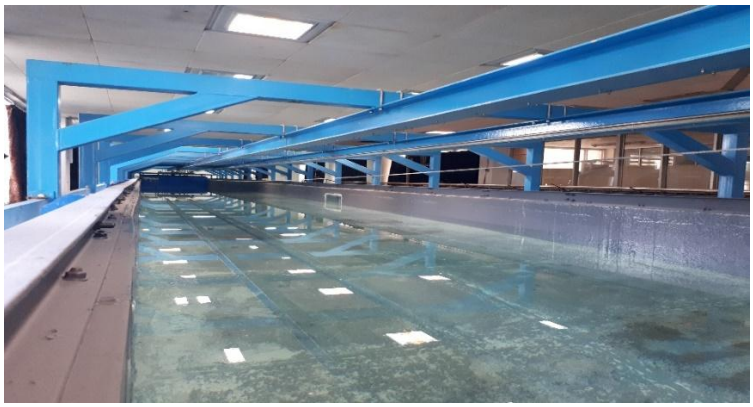

Image 1: Wave flume

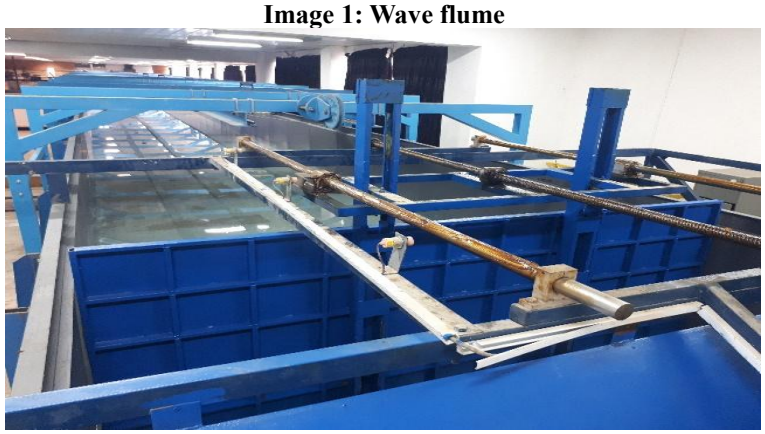

Image 2: Hinged wave maker



Image 3: Wave absorber





Image 4 and Figure 2-2: Wave height sensor

2-2. Construction of the Breakwater Model

The breakwater model was constructed from PET bottles (recycled materials). The bottles were placed inside galvanized mesh frames and connected to each other with rope. The structure was connected to steel weights at the flume bottom through three cables to ensure its stability. To create holes, the beginning and end of the bottles were used. By removing the cap, a small diameter hole (2.5 cm in the model) was created, and by cutting the end of the bottle, a large diameter hole (7.5 cm in the model) was created. The medium diameter (10 cm) was also obtained by combining these two modes (Image 5 and Figure 2).



Image 5: Constructed model of the breakwater structure

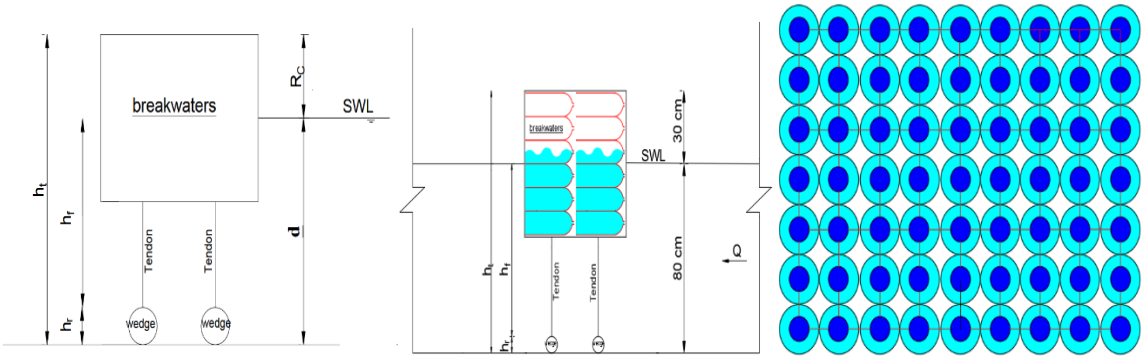

Figure 2: Design of breakwater structure components

2-3. Design of Experiments

In this research, 33 different experiments were conducted on breakwater models with different configurations. Table 1 summarizes the parameters and Table 2 shows the conducted experiments.

Table 1. Governing variables in the investigation of hydraulic performance

Variable	Symbol	Values in the model
Wave height	H	23 cm
Wave period	T	1.012 s
Water depth at the structure	d	80 cm
Wave steepness	H/λ	0.142
Relative depth	d/λ	0.5
Water depth to wave height	d/H	3.478
Paddle stroke	S	14.55 cm
Wave maker frequency	-	0.988 Hz
Scale	-	1/13

Table 2: Table of conducted experiments

NO	type	L_B cm	D_B cm	H_B cm	λ	T	H	h_r	h_f	h_r/h_f	x
1	CBOWFW1	250	30	60	160	1.012	23	10	70	0.143	12
2	CBOWEW2	250	30	60	160	1.012	23	10	70	0.143	12
3	CBOWFEW3	250	30	60	160	1.012	23	10	70	0.143	12
4	HBOWFW4	250	30	60	160	1.012	23	10	40	0.25	11
5	HBOWEW5	250	30	60	160	1.012	23	10	40	0.25	10
6	HBOWFEW6	250	30	60	160	1.012	23	10	40	0.25	10.5
7	HBOWEW7	250	30	60	160	1.012	23	10	40	0.25	9
8	HBOWFW8	250	30	60	160	1.012	23	10	40	0.25	9.5
9	HBOWFEW9	250	30	60	160	1.012	23	10	40	0.25	8.5
10	CBOWSW10	250	triangle	60	160	1.012	23	10	70	0.143	15.5
11	CBOWSW11	250	triangle	60	160	1.012	23	10	70	0.143	16.5
12	HBOWSW12	250	triangle	60	160	1.012	23	10	40	0.25	14.5
13	HBOWSW13	250	triangle	60	160	1.012	23	10	40	0.25	13.5
14	HBOWSW14	250	triangle	60	160	1.012	23	10	40	0.25	13
15	HBOWSW15	250	triangle	60	160	1.012	23	10	40	0.25	12.5
16	CBOWFW16	300	30	60	160	1.012	23	10	70	0.143	12
17	CBOWEW17	300	30	60	160	1.012	23	10	70	0.143	12
18	CBOWFEW18	300	30	60	160	1.012	23	10	70	0.143	12
19	HBOWFW19	300	30	60	160	1.012	23	10	40	0.25	11.5
20	HBOWEW20	300	30	60	160	1.012	23	10	40	0.25	10.5
21	HBOWFEW21	300	30	60	160	1.012	23	10	40	0.25	11
22	HBOWEW22	300	30	60	160	1.012	23	10	40	0.25	9
23	HBOWFW23	300	30	60	160	1.012	23	10	40	0.25	10
24	HBOWFEW24	300	30	60	160	1.012	23	10	40	0.25	8
25	CBOWFW25	250	60	60	160	1.012	23	10	70	0.143	12
26	CBOWEW26	250	60	60	160	1.012	23	10	70	0.143	12
27	CBOWFEW27	250	60	60	160	1.012	23	10	70	0.143	12
28	HBOWFW28	250	60	60	160	1.012	23	10	40	0.25	11
29	HBOWEW29	250	60	60	160	1.012	23	10	40	0.25	10
30	HBOWFEW30	250	60	60	160	1.012	23	10	40	0.25	10.5
31	HBOWEW31	250	60	60	160	1.012	23	10	40	0.25	8.5
32	HBOWFW32	250	60	60	160	1.012	23	10	40	0.25	9
33	HBOWFEW33	250	60	60	160	1.012	23	10	40	0.25	7.5

The breakwater models were tested in three general categories:

1. Breakwater without holes (impermeable) as a reference for comparison.
2. Single-sided perforated breakwater: including states with the beginning facing the wave, end facing the wave, and combined.
3. Double-sided perforated breakwater: including states with the beginning facing the wave, end facing the wave, and combined.

The porosity percentages investigated were: 7% (small holes), 42.78% (medium/combined holes), and 78.5% (large holes). The hole diameters in the model were: 2.5, 7.5, and 10 cm.

2-4. Data Analysis

The relative wave run-up is defined as Ru/Hi, where Ru is the run-up height and Hi is the incident wave height. The wave transmission coefficient is calculated as Ct = Ht/Hi, where Ht is the transmitted wave height. To investigate the effect of wave steepness, the ratio H/L was used.

3. Results and Discussion

3-1. Effect of Porosity Percentage on Wave Run-up

The results show that with increasing relative depth d/L (and consequently decreasing wavelength and period), the run-up decreases. This trend is repeated in all four breakwater dimensions. The reason is that wave energy is directly related to wavelength ($E = \rho g H^2 L/8$), so with decreasing wavelength, wave energy decreases and less run-up occurs.

The run-up in the impermeable breakwater has the highest value and in some cases causes wave overtopping. By creating holes up to 7% of the open surface, the wave run-up decreases. The reason is energy dissipation by the breakwater holes. The results show that in the breakwater with 7% holes, the optimal experimental state is HBOWFW28. Figure 3 (a-d) shows the effect of porosity percentage for double-sided perforated breakwaters.

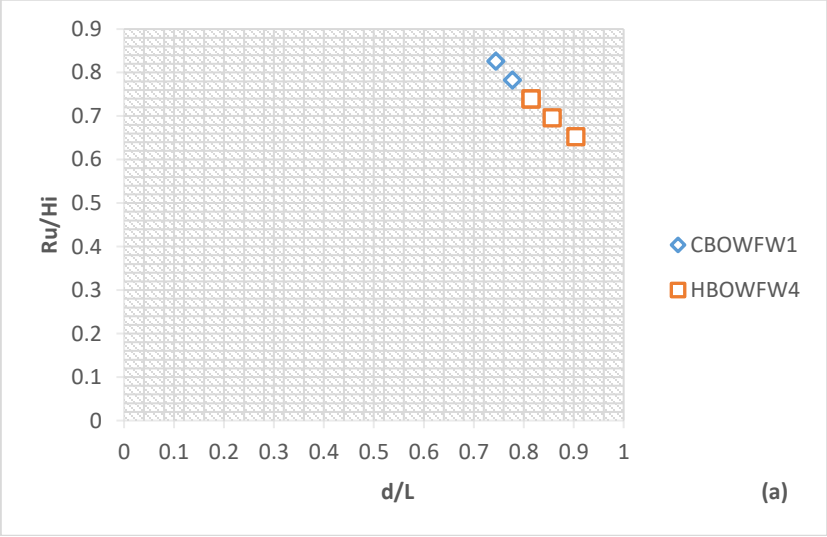

Figure 3 (a): Investigating the effect of perforation percentage on the run-up of a non-perforated breakwater, a one-side perforated breakwater with the perforated end facing the wave, comparing floating and semi-submerged breakwaters with breakwater dimensions of 250×30×60 cm.

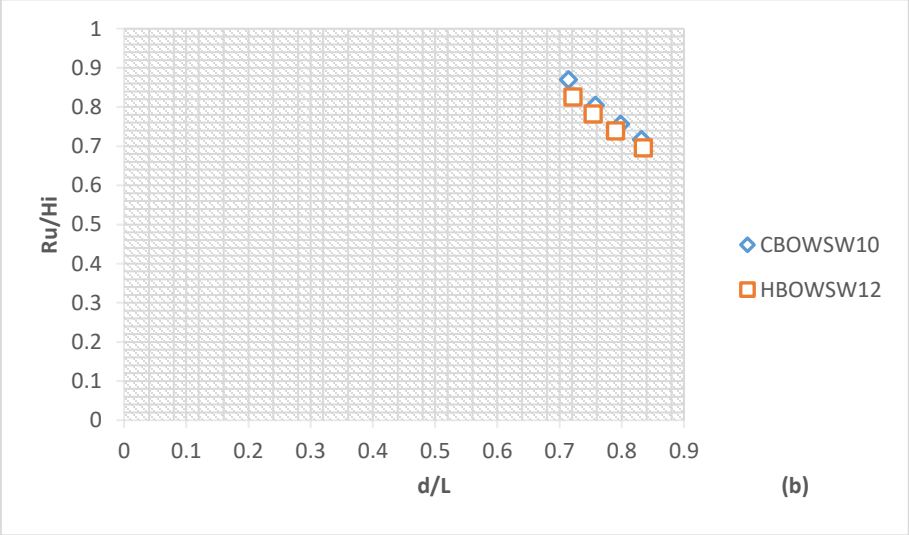

Figure 3 (b): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a one-side perforated breakwater with the side facing the wave, comparing floating and semi-submerged breakwaters with a triangular breakwater.

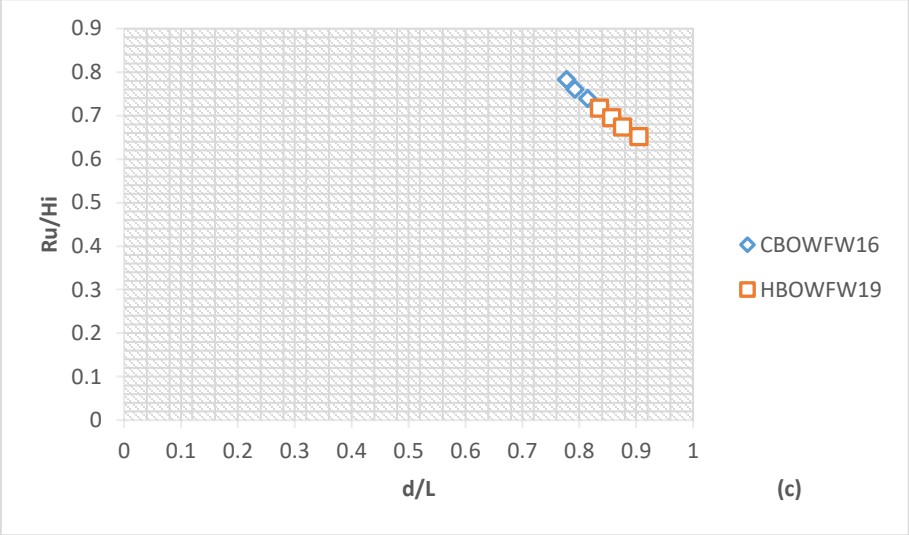

Figure 3 (c): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a one-side perforated breakwater with the perforated end facing the wave, comparing floating and semi-submerged breakwaters with breakwater dimensions of 300×30×60 cm.

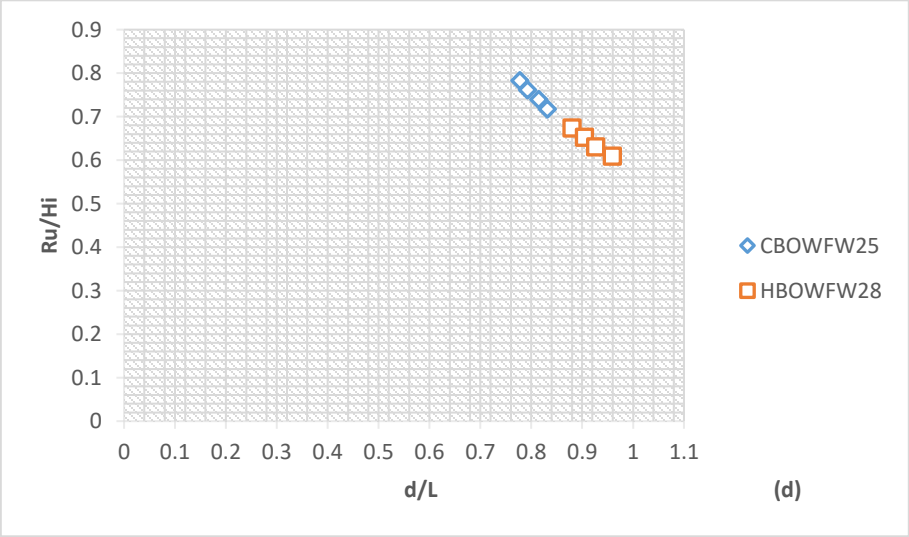

Figure 3 (d): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a one-side perforated breakwater with the perforated end facing the wave, comparing floating and semi-submerged breakwaters with breakwater dimensions of 250×60×60 cm.

In this case also, with increasing d, the run-up decreases. The run-up in the impermeable breakwater has the highest value. By creating holes up to 7% of the open surface, the run-up decreases. The results show that in the breakwater with 7% holes, the optimal experimental state is HBOWFW32.

With increasing porosity percentage from 7% to 42.78%, the relative wave run-up decreases by 15% to 20% on average. However, further increase in porosity up to 78.5% not only does not cause a significant reduction in run-up, but in some configurations, due to increased wave transmission, the run-up behind the structure increases. Therefore, 42.78% porosity is recognized as the optimal porosity.

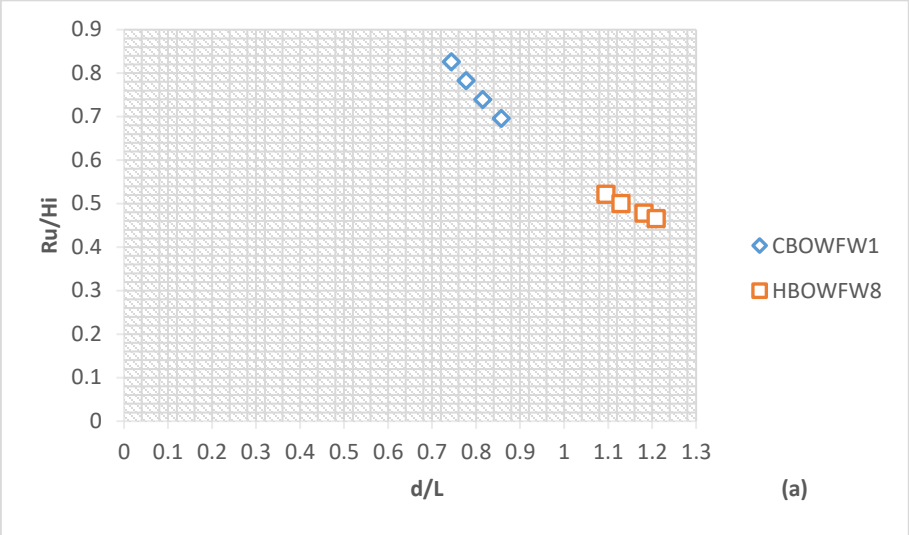

Figure 4 (a): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a breakwater with open ends (both ends open) with the front end facing the wave, comparing floating and semi-submerged breakwaters with breakwater dimensions of 250×30×60 cm.

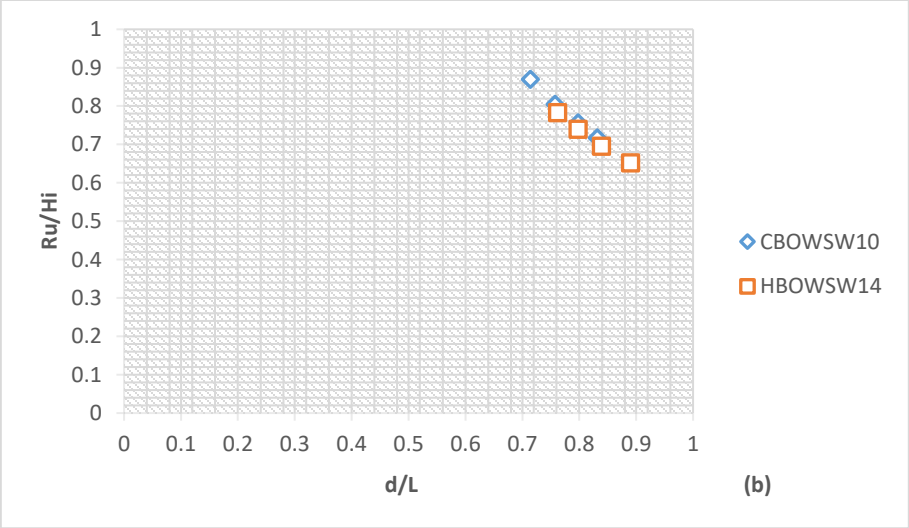

Figure 4 (b): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a breakwater with open ends (both ends open) with the side facing the wave, comparing floating and semi-submerged breakwaters with a triangular breakwater.

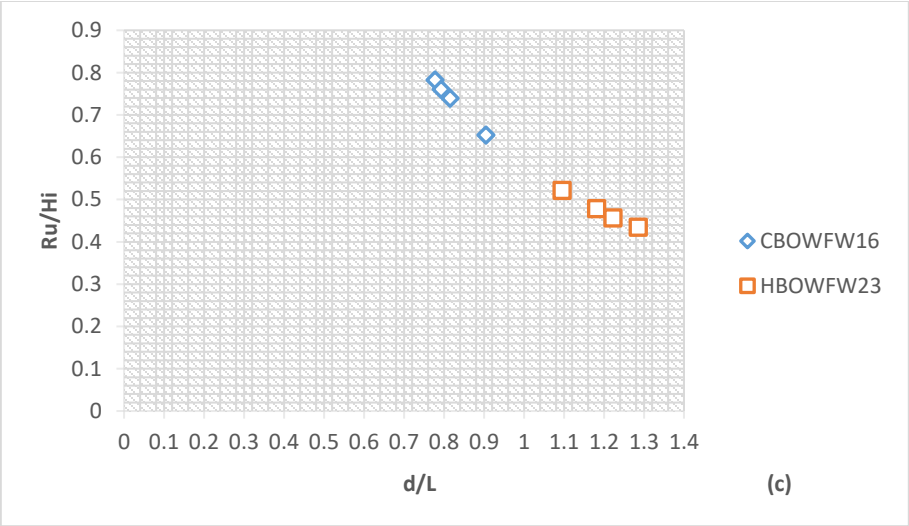

Figure 4 (c): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a breakwater with open ends (both ends open) with the front end facing the wave, comparing floating and semi-submerged breakwaters with breakwater dimensions of 300×30×60 cm.

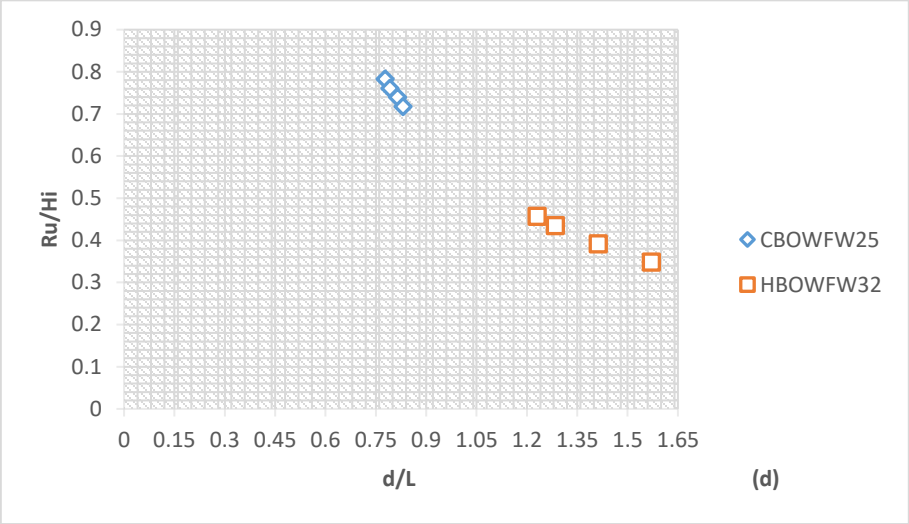

Figure 4 (d): Investigation of the effect of perforation percentage on the run-up of a non-perforated breakwater and a breakwater with open ends (both ends open) with the front end facing the wave, comparing floating and semi-submerged breakwaters with breakwater dimensions of 60×60×250 cm.

3-2. Effect of Hole Diameter on Wave Run-up

To find the optimal hole diameter, the breakwater with 42.78% porosity (which was identified as the optimal porosity in the previous section) was considered. In this case, the porosity percentage was kept constant and only the hole diameters were changed. Figure 5 (a-c) shows the results.

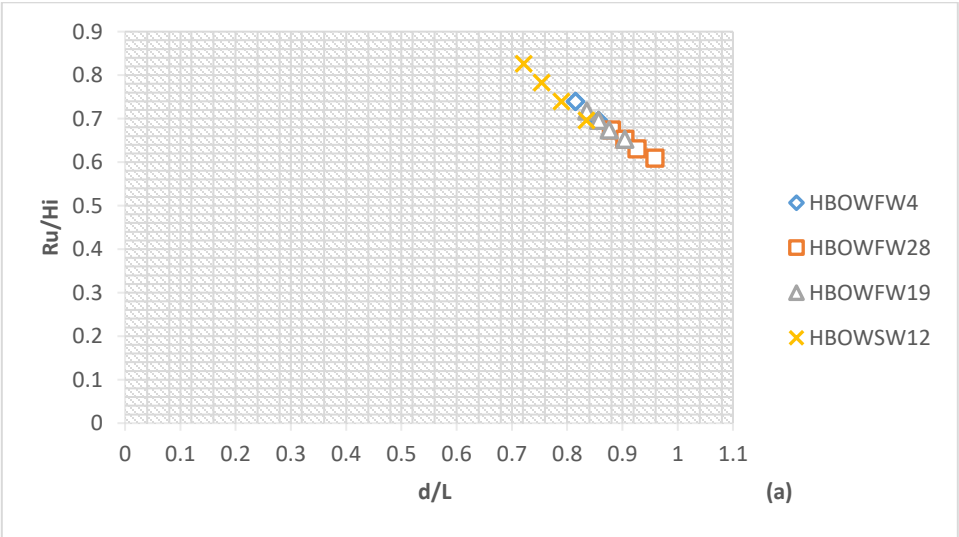

Figure 5 (a): Investigation of the effect of hole size on the run-up of one-side perforated breakwaters with the front end facing the wave, using four types of breakwaters, comparing semi-submerged breakwaters.

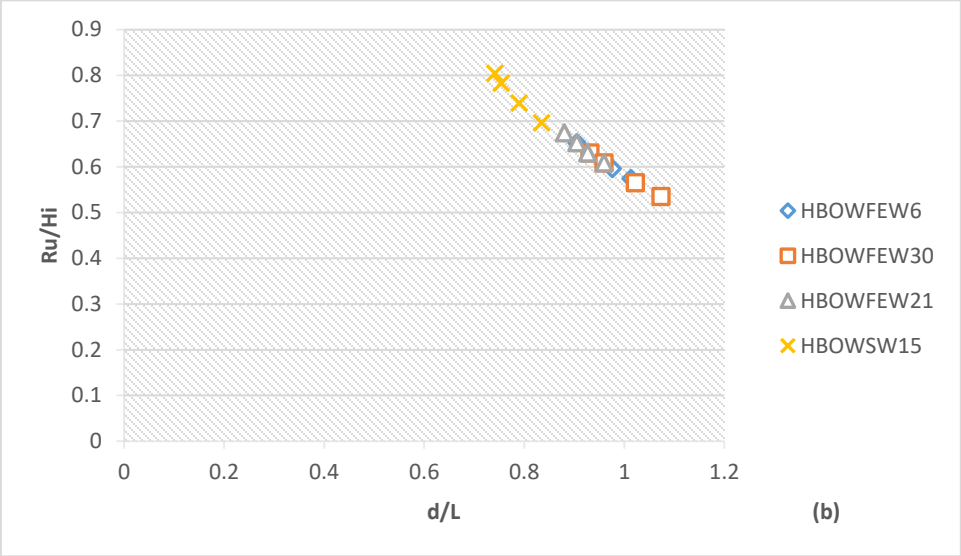

Figure 5 (b): Investigation of the effect of hole size on the run-up of one-side perforated breakwaters with the front end open and the rear end closed, and the front end closed and the rear end open, in a combined configuration facing the wave using four types of semi-submerged breakwaters with breakwater dimensions.

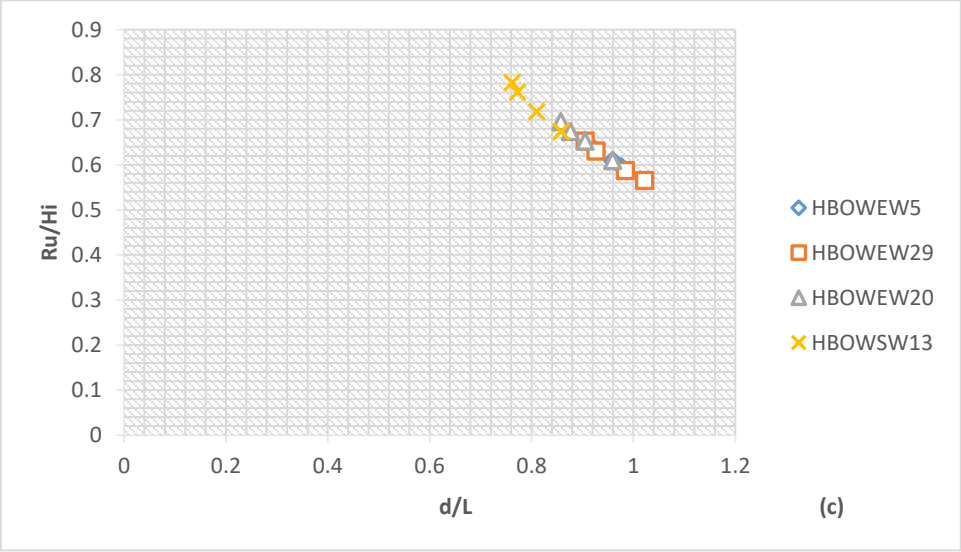

Figure 5 (c): Investigation of the effect of hole size on the run-up of one-side perforated breakwaters with the rear end facing the wave, using four types of breakwaters, comparing semi-submerged breakwaters.

According to the graphs, the run-up in the breakwater with larger hole diameters (10 cm) is higher than the breakwater with medium diameter (7.5 cm). Also, the breakwater with smaller hole diameters (2.5 cm) has a higher run-up than the breakwater with medium diameter. From these graphs, it can be concluded that the breakwater with medium hole size (combined) shows better performance. The reason is greater energy dissipation and consequently reduced run-up.

Physical reason: Smaller holes, although creating more rotational flows, reduce the flow passage cross-section and may lead to increased local pressure and run-up. On the other hand, larger holes, although having a larger passage area, create less turbulence and dissipate less energy. The medium size establishes a suitable balance between creating turbulence and flow passage area.

3-3. Effect of Wave Steepness on Run-up

Figure 6 (a-c) shows the effect of wave steepness (H/L) on relative run-up.

According to the graphs, for all breakwaters, with increasing wave steepness, the relative wave run-up decreases. The decreasing trend of run-up is accompanied by a gentle slope. The reason is that with increasing wave steepness, the wavelength decreases and wave energy decreases.

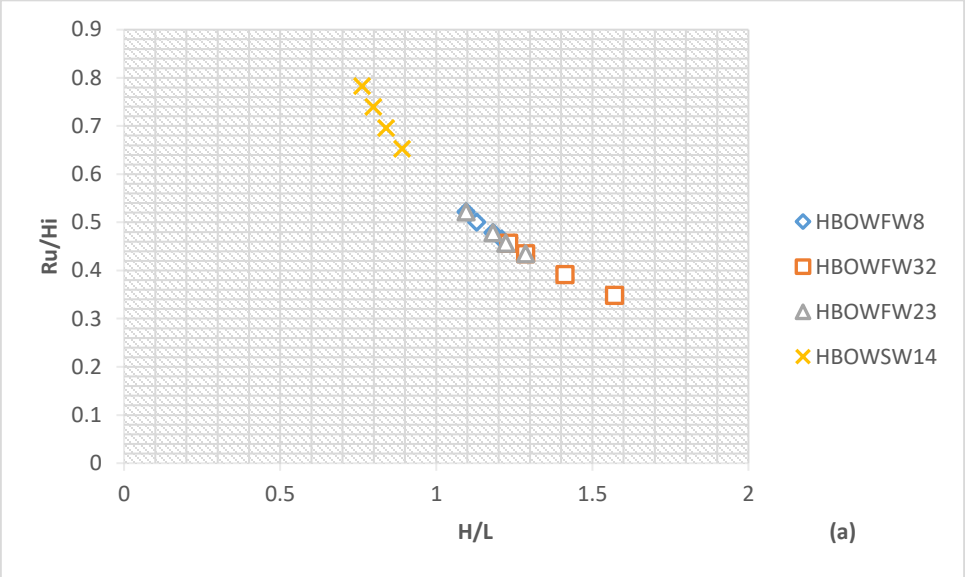

Figure 6 (d): The most suitable configuration in terms of perforation percentage and hole size in double-side perforated breakwaters with the front end facing the wave, using four types of breakwaters.

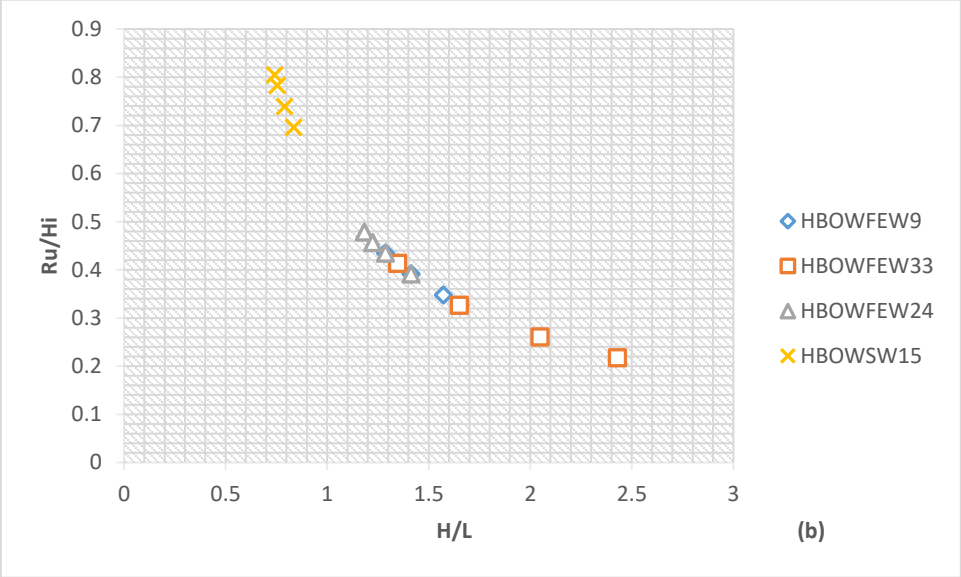

Figure 6 (e): The most suitable configuration in terms of perforation percentage and hole size in double-side perforated breakwaters in a combined orientation facing the wave, using four types of breakwaters.

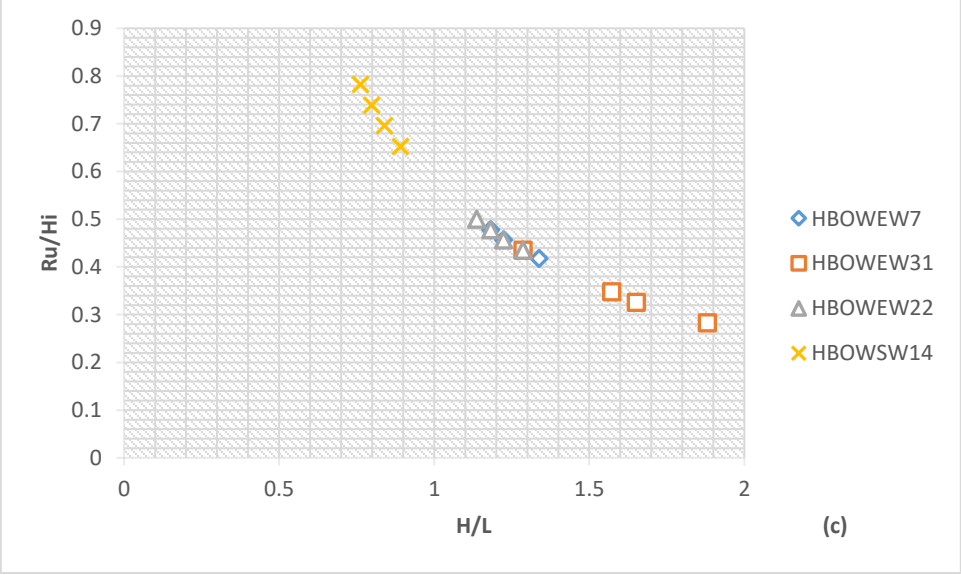

Figure 6 (f): The most suitable configuration in terms of perforation percentage and hole size in double-side perforated breakwaters with the rear end facing the wave, using four types of breakwaters.

4-3. Effect of Porosity Percentage on Wave Transmission

Figure 7 (a-c) shows the effect of porosity percentage on the wave transmission coefficient (Ct).

This trend continues with increasing hole percentage from 7% to 42.78%, the amount of wave transmission through the structure increases. Also, with increasing hole percentage up to 78.5%, the amount of wave transmission through the structure increases. As a result, with increasing hole percentage, the amount of wave transmission through the structure increases. With increasing relative depth and consequently decreasing period and wavelength, the amount of wave transmission decreases. The reason is the reduction of wave energy with decreasing wavelength.

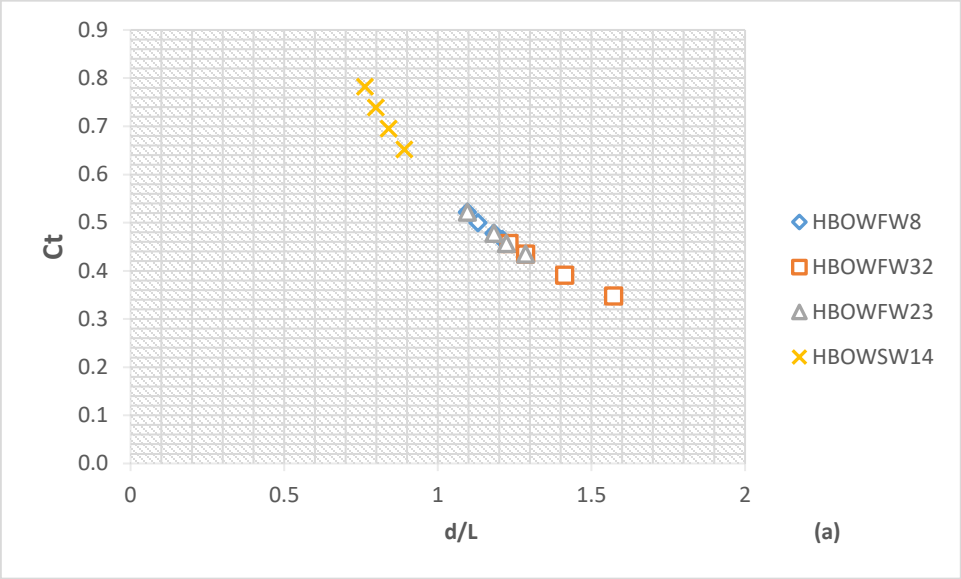

Figure 7 (a): The effect of perforation percentage for wave passage in double-side perforated breakwaters, with the front end facing the wave, using four types of breakwaters.

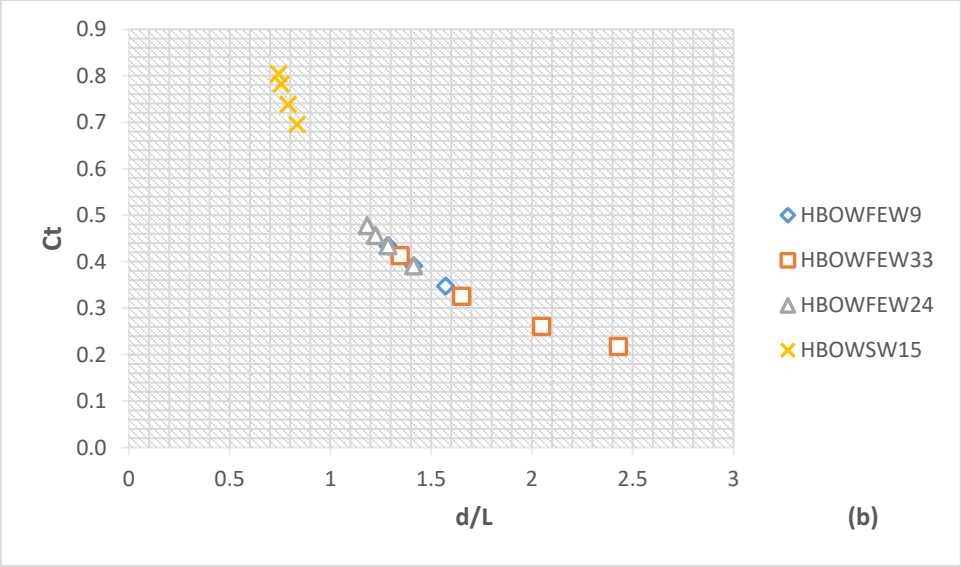

Figure 7 (b): The effect of perforation percentage for wave passage in double-side perforated breakwaters, in a combined orientation facing the wave, using four types of breakwaters.

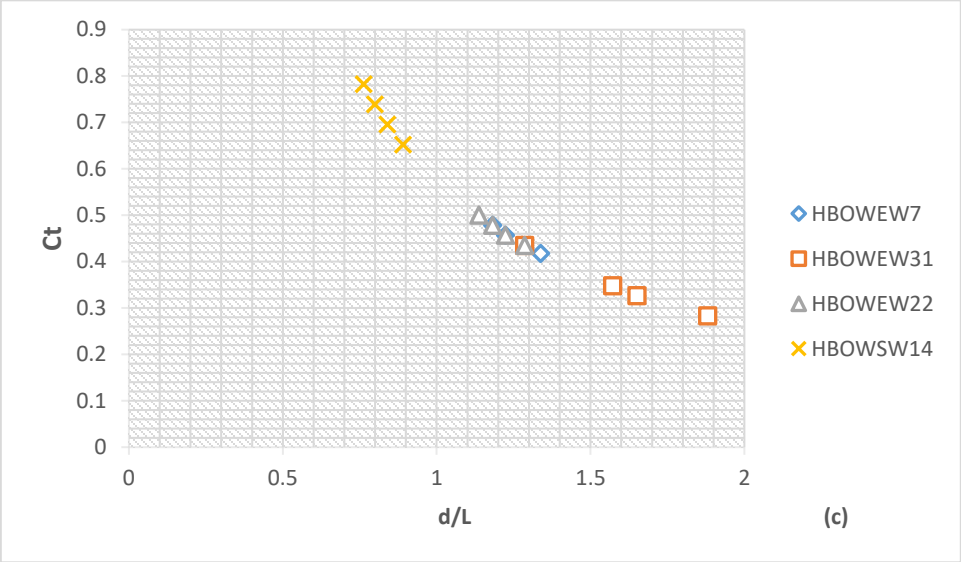

Figure 7 (c): The effect of perforation percentage for wave passage in double-side perforated breakwaters, with the rear end facing the wave, using four types of breakwaters.

3-5. Effect of Wave Steepness on Wave Transmission

Figure 8 (a-c) shows the effect of wave steepness on the transmission coefficient.

With increasing wave steepness, the wave transmission coefficient decreases. This is because with increasing wave steepness, the wavelength decreases and consequently wave energy decreases. It is also observed that the breakwater with 42.78% holes has lower transmission than the other two types.

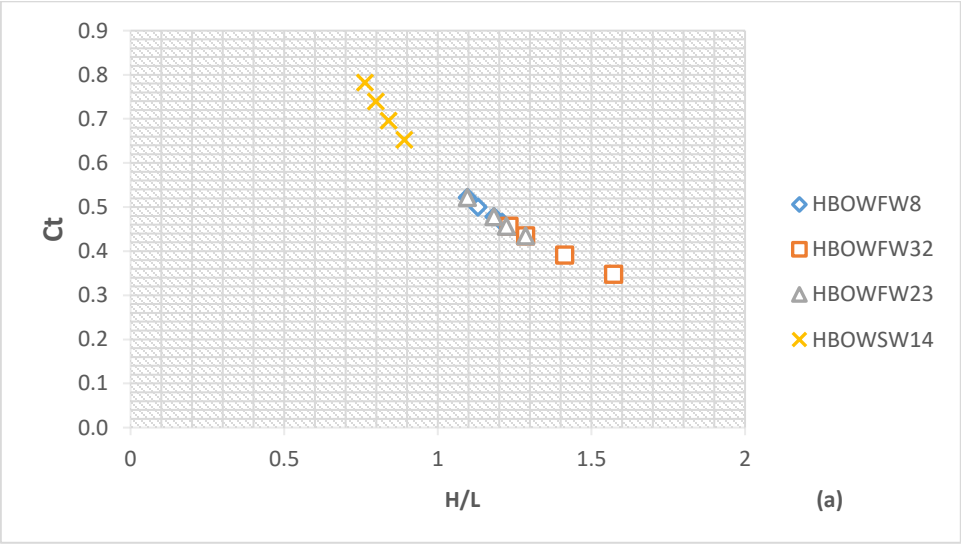

Figure 8 (a): The effect of wave steepness for wave passage in double-side perforated breakwaters, with the front end facing the wave, using four types of breakwaters.

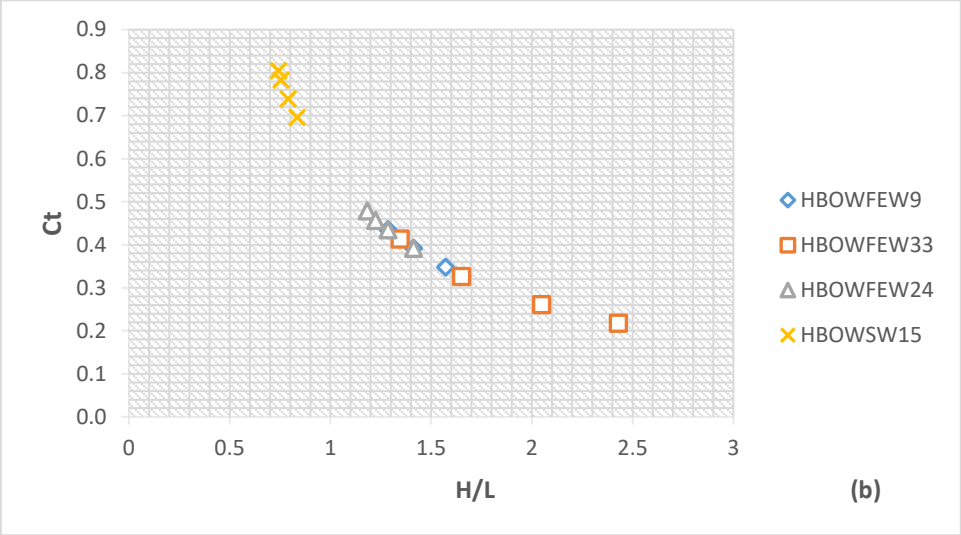

Figure 8 (b): The effect of wave steepness for wave passage in double-side perforated breakwaters, in a combined orientation facing the wave, using four types of breakwaters.

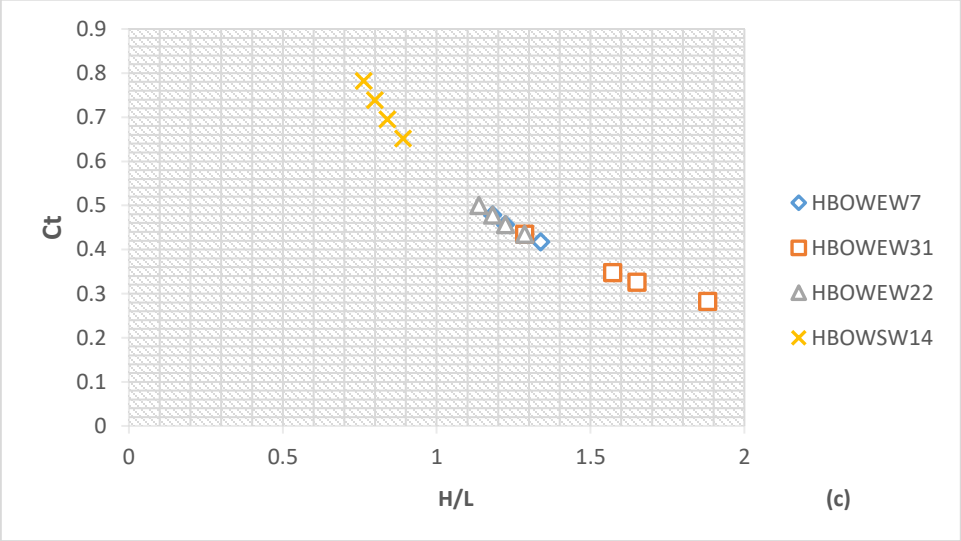

Figure 8 (c): The effect of wave steepness for wave passage in double-side perforated breakwaters, with the rear end facing the wave, using four types of breakwaters.

3-6. Reduction Rate of Run-up Relative to Impermeable Breakwater

Figure 9 shows the percentage reduction of dimensionless run-up for all perforated breakwaters relative to the impermeable breakwater.

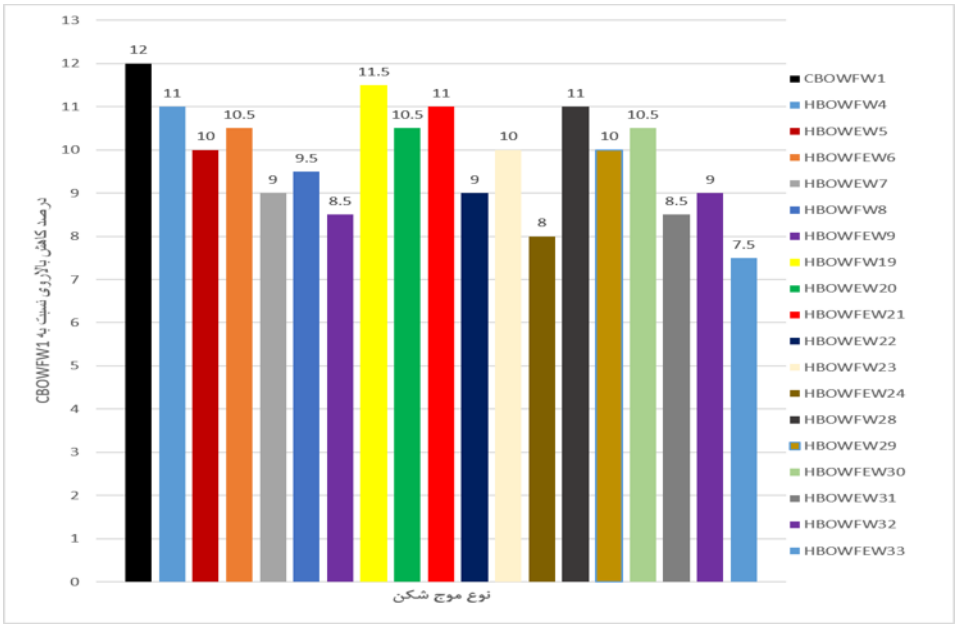

Figure 9. Percentage reduction of wave run-up of perforated breakwaters relative to impermeable breakwater with four types of breakwaters

The highest reduction rate in dimensionless run-up belongs to the double-sided perforated breakwater HBOWFEW24, and the lowest reduction rate belongs to the breakwater HBOWFEW19 with large holes. The performance of some breakwaters is approximately equal.

3-7. Summary of Results

Table 3 presents a summary of the optimal states for each category of breakwaters.

Table 3. Optimal states in terms of porosity percentage and hole size

Optimal Experiment	Optimal Hole Size	Optimal Porosity	Breakwater Type
HBOWFW28	Medium (combined)	7%	Single-sided perforated (beginning facing wave)
HBOWEW29	Medium (combined)	78.5%	Single-sided perforated (end facing wave)
HBOWFEW30	Medium (combined)	42.78%	Single-sided perforated (combined)
HBOWFW32	Medium (combined)	7%	Double-sided perforated (beginning facing wave)
HBOWEW31	Medium (combined)	78.5%	Double-sided perforated (end facing wave)
HBOWFEW33	Medium (combined)	42.78%	Double-sided perforated (combined)

3-8. Comparative synthesis of the dissertation and three related studies

Table 4. Comprehensive comparison of the present dissertation and related studies

Comparison criterion	Present dissertation (Ahmadi)	Kelch Vieira & Gireli (2012)	Mohd Azhar & Mohd Zaki (2026)	Wijesekara et al. (2026)
Structure type	Perforated floating breakwater	Floating breakwater	Floating breakwater	Fixed breakwater (geopolymer-based)
Material	Recycled PET bottles	Reused PET bottles	Recycled PET bottles	Geopolymer incorporating waste materials
Scale / test basis	Laboratory model; scale reported as 1:13 in the dissertation table	Laboratory model; scale reported as 1:25 in the dissertation table	Laboratory experiment; scale not specified in the dissertation table	Laboratory / simulated marine-leaching assessment
Main response or parameter	Wave run-up, transmission, energy dissipation and displacement	Wave-height reduction	Wave-transmission coefficient and submergence	Leaching of metals and environmental safety
Favorable design / reported outcome	Combined opening arrangement; 42.78% porosity (HBOWFEW30 in the dissertation table)	Reported 98% reduction in transmitted wave height	70% submergence; reported wave-height reduction of 25%	GEO-RSiA-RA identified as the favorable geopolymer formulation

Comparison criterion	Present dissertation (Ahmadi)	Kelch Vieira & Gireli (2012)	Mohd Azhar & Mohd Zaki (2026)	Wijesekara et al. (2026)
Wave-height reduction / performance	Configuration-dependent; no single percentage applies to all tested cases	98% reported in the dissertation comparison table	12.5–25% reported in the dissertation comparison table	Not applicable as a direct wave-attenuation metric
Environmental safety	Not assessed directly in the present experiments	Not assessed in the dissertation comparison table	Not assessed in the dissertation comparison table	High environmental-safety performance reported in the dissertation comparison table
Structural stability	Described as good in the dissertation comparison table	Described as weak in the dissertation comparison table	Described as moderate in the dissertation comparison table	Described as high in the dissertation comparison table
Relative cost	Low (as reported in the dissertation comparison table)	Low (as reported in the dissertation comparison table)	Low (as reported in the dissertation comparison table)	Moderate (as reported in the dissertation comparison table)

4. Conclusion

In this research, the hydraulic performance of hole-embedded breakwaters made from recycled materials was investigated experimentally with emphasis on two key parameters: porosity and hole size. The following results were obtained:

Effect of porosity: With increasing porosity percentage from 7% to 42.78%, the relative wave run-up decreases by 15% to 20% on average. However, further increase in porosity up to 78.5% not only does not cause a significant reduction in run-up, but in some configurations, it increases wave transmission. Therefore, 42.78% porosity is recognized as the optimal porosity.

Effect of hole size: Among the three hole diameters investigated (2.5, 7.5, and 10 cm in the model), the medium diameter (7.5 cm) was identified as the optimal size. The breakwater with 42.78% porosity and medium diameter exhibited the lowest run-up and the highest energy dissipation.

Effect of wave steepness: With increasing wave steepness (H/L), the relative run-up and wave transmission coefficient decrease. This is due to the reduction of wavelength and consequently the reduction of wave energy.

Overall performance: Double-sided perforated breakwaters with combined arrangement and 42.78% porosity (HBOWFEW33) showed the best performance in terms of reducing run-up, wave transmission, and structure displacement.
Environmental benefits: The use of recycled PET bottle materials in the construction of these breakwaters, in addition to reducing costs, helps preserve natural resources and reduce environmental pollution.

Design recommendations: Based on the results of this research, for the design of hole-embedded breakwaters made from recycled materials, a porosity of 42.78% and medium hole diameter (combined) are proposed as optimal values. Also, double-sided perforated arrangement with combined configuration is recommended to achieve maximum energy dissipation and minimum wave transmission.

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