American Journal of Modern Energy
2024, Vol. 10, No. 3, pp. 42-52
https://doi.org/10.11648/j.ajme.20241003.12

Review Article

Research on Breakwater Structure: A Brief Review

Xiaowei Wang[1, 2], Xiaoqun Wang[1, 2, 3, *], Likun Liu[1, 2], Li Xin[1, 2], Kaiming Li[1, 2]

[1]School of Water Conservancy and Hydroelectric Power, Hebei University of Engineering, Handan, China
[2]Hebei Key Laboratory of Intelligent Water Conservancy, Hebei University of Engineering, Handan, China
[3]State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin, China

Abstract

As a kind of protective engineering, breakwater plays a very important role in the safety of the protected objects, and scholars from all over the world have done a lot of research on the characteristics of breakwater. Reviews are a quick way to see how research is progressing. In addition to the traditional breakwaters for the purpose of wave suppression, there are many breakwaters with power generation functions. In order to supplement and enrich the research of breakwater, adapt to the development of The Times, the breakwater is reviewed. In this paper, breakwaters are divided into traditional breakwaters and wave energy converter(WEC) breakwaters according to their functions. The traditional breakwaters for wave absorbing, while the WEC breakwater is breakwater added wave energy converter, which can convert wave energy into electrical energy, so WEC breakwater has two functions of wave dissipation and power generation. According to the fixed type, the traditional breakwater is divided into fixed breakwater and floating breakwater. In addition to adding WEC breakwaters in the classification, this paper takes the transmission coefficient k_t =0.5 as the reference line and compares the optimal transmission coefficient of the corresponding breakwater structure with the reference line. Finally, the structure of the breakwater is summarized and suggested. Hope to play a guiding role in scholars' research and engineering construction.

Keywords

Fixed Type, Floating Type, WEC Breakwater, Transmission Coefficient, Capture Width Ratio

1. Introduction

As a kind of protective engineering, the breakwater is constantly changing with the development of the times, from the earliest fixed breakwater to the floating breakwater, and then the development is combined with the use of wave energy. From a simple rectangular and circular structure to a multi-shape, multi-combination type. From the purpose of wave dissipation to energy conversion, the research on breakwater structures has never stopped. It is very important to summarize the research results of breakwater to grasp the research trends. Some scholars have conducted reviews, such as Rajendra, K et al. [1] reviewed the research on innovative breakwaters in India, the study area was specific but not extensive. Jian Dai et al. [2] reviewed the study of floating breakwaters, the study only focuses on the floating structure, which is one-sided for the breakwater structure. X. L. Zhao et al. [3] reviewed the hybrid floating breakwater-WEC, the study is also one-sided. Y. C. Gu et al. [4] summarized the development of porous membranes and network structures.

*Corresponding author: 1014205052@tju.edu.cn (Xiaoqun Wang)

Received: 29 September 2024; **Accepted:** 18 October 2024; **Published:** 25 December 2024

Jijian Lian et al. [5] reviewed permeable breakwater, categorized permeable breakwater into six types, i. e., row piles, pile foundations, caissons, caissons on pile foundation, horizontal plates, and hybrid structures. The current reviews focused on one aspect, not comprehensive. And with the passage of time and development, there are new types of breakwaters need to be supplemented. In this paper, breakwaters are divided into traditional breakwaters and wave energy converter(WEC) breakwaters according to their functions. The traditional breakwaters are wave absorbing, while the WEC breakwaters are both wave absorbing and power generating. According to the fixed type, the traditional breakwater is divided into fixed breakwater and floating breakwater. In addition to adding WEC breakwaters in the classification, this paper takes the transmission coefficient k_t =0.5 as the reference line and compares the optimal transmission coefficient of the corresponding breakwater structure with the reference line, so as to facilitate readers to better understand the structural characteristics. In order to facilitate understanding, the terms and abbreviations in this paper are explained, see Table 1.

Table 1. *Nomenclature and abbreviations.*

nomenclature	definition	nomenclature	definition	abbreviation	definition
B	breakwater width, m	k	wave number	OWC	oscillating water column
H	breakwater height, m	*R*	radius, m	CWR	capture width ratio
d	Breakwater draft, m	*B*/*L*	relative widths	WEC	wave energy converter
D	submersion depth, m	H_i/L	wave steepness	FBW	floating breakwater
g	gravity acceleration, ms^{-2}	*h/L*	relative depth	BW	breakwater
S	breakwater spacing, m	*h*	depth, m	RAO	response amplitude operator
H_i	wave height, m	H_i/h	relative height		
T	wave period, s	k_t	transmission coefficient		
l	mooring length, m	*d*/*h*	relative draught		
L	wave length, m	ζ	porosity ratio		
δ	thickness, m				

Note: Terms not indicated in the table are subject to the text.

2. The Structural Type of the Breakwater

The structural of the breakwater affects wave abbsorbing, so researchers have never stopped studying the structural. There are many classifications about the structural. For example, Rajendra, K et al. [1] divided breakwaters into fixed and floating breakwaters. Jian Dai et al. [2] divided breakwater into box type, pontoon type, frame type, cushion type, tether float type, horizontal plate type, and other types. This paper divides into traditional breakwater and WEC breakwater according to the function of the breakwater. And breakwater is divided into fixed and floating according to the fixed type. Xuanlie Zhao et al. [6] called the frequency band corresponding to the transmission coefficient k_t<0.5 and the capture width ratio CWR >0.2 as the effective frequency band of OWC breakwater. In this paper, k_t=0.5 is the baseline for qualified wave suppression effect.

2.1. Research on Traditional Breakwater

The traditional breakwater refers to its function of wave dissipation and wave reduction. Usually the transmission coefficient k_t is used to characterize the wave suppression effect, and the higher the transmission coefficient is, the worse the effect is. In addition to the wave absorbing effect, the wave load of the structure is also the focus of research.

2.1.1. Research on Fixed Breakwaters

Fixed breakwater refers to a breakwater fixed on the seabed or coast, and the six degrees of freedom are limited to immobility, and are generally built in shallow sea areas or coasts. The paper dividied fixed breakwater to closed breakwater, permeable breakwater, plate type breakwater and other types.

(i). Research on Closed Breakwaters

Closed breakwater is the earliest studied type, is mostly impermeable. The study focus on the shape of the breakwater. Yonggang Cao et al. [7] studied the wave attenuation characteristics of the double-row trapezoidal underwater breakwater on the flat-bottomed seabed as shown in Figure 1(a), the slope of the trapezoidal side is 1:2, and the slope ratio of the back wave is 1:1, and believed that the structure performs best when the relative spacing S is 12.5~14, but k_t >0.5. Zhenfeng Zhai et al. [8] studied a V-shaped breakwater that penetrates from the bottom to the surface of the sea, as shown in Figure 1(b), and the degree of wave attenuation in the protected area can be satisfactory under certain conditions, but it is difficult to make k_t < 0.5. For Closed breakwater impermeable, it gradually fades from people's view.

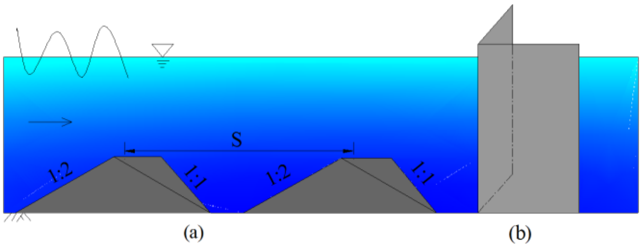

Figure 1. *Closed BWs: (a) Double trapezoidal submerged BW [7], (b) V-shape BW [8].*

(ii). Permeable Fixed Breakwater

Due to the requirements of the sea environment and ecology, the study of fixed breakwaters gradually from impermeable to permeable. Permeable breakwaters are mostly composed of permeable materials or porous structures to relieve the impact on water exchange and dissipate wave. Guoyu Wang et al. [9] proposed an arc-shaped plate breakwater, see Figure 2(a), when the relative width *B*/*L* >0.2, k_t < 0.5. Peihong Zhao et al. [10] studied the effect of different absorber widths on the wave-absorbing performance of the perforated caisson, see Figure 2(b). The width of absorber chamber was a key factor. Ahmed K. Elsheikh et al. [11] experimentally investigated the breakwater effect of pile breakwaters (PB) [11], see Figure 2(c), k_t was reduced 18%~28% by adding horizontal strips, but horizontal strips will increase the investment. K. Qu et al. [12] studied the complex flow phenomenon of the concentrated wave group transformation on submersible permeable breakwater, and concluded that the total wave energy dissipation rate of the permeable breakwater was on average 57.3%, k_t < 0.5 at 19 meters behind the breakwater. Chen Lankun et al. [13] studied the permeable embankment of pile foundation, see Figure 2(e). At the opening rate was 10%, and the relative water depth *h/L* was 0.85, it performe best with -15 °inclination angle.

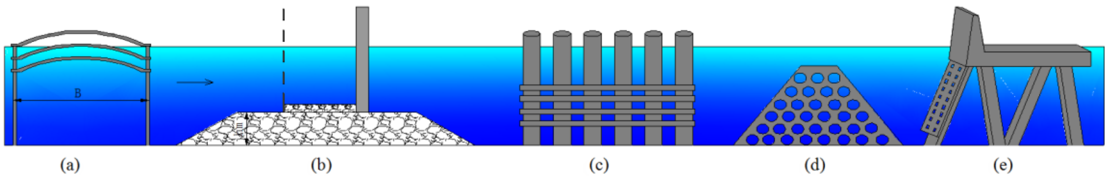

Figure 2. *Permeable fixed BWs: (a) arc plate BW [9], (b) perforated caisson BW [10], (c) piled BW [11], (d) submerged permeable BW [12], (e) pile foundation permeable BW [13].*

(iii). Other Types of Fixed Breakwaters

Yejun Gong et al. [14] proposed a "mountain" type breakwater consisting of two inclined plates and one vertical plate, as shown in Figure 3(a), which consists of three slabs of the same size, the middle slab was placed vertically, the angle between the inclined slab and the horizontal line was 30°. Judging from the experimental and simulation results, the wave-absorbing effect was ideal. Yanxu Wang et al. [15] proposed a combination of pneumatic breakwater and underwater breakwater for wave dissipation, as shown in Figure 3(b). The combination was better than pneumatic breakwater alone or underwater breakwater alone, achieve qualified at *T*<1.6s.

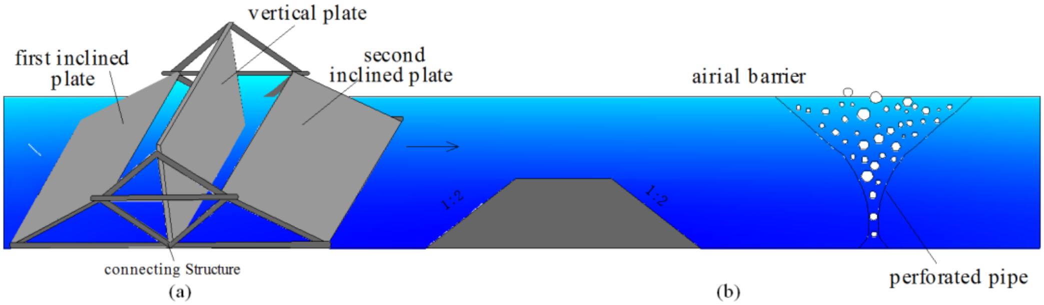

Figure 3. *Other fixed BWs: (a) Mountain-type [14], (b) Pneumatic and submerged combinated [15].*

2.1.2. Research Progress on Floating Breakwaters

Compare to the fixed type, the floating breakwater has no restriction on all six degrees of freedom, and mooring lines/cables are used to connect the buoys to the seabed or other structures. The floating breakwater has good water exchangeability and low cost, which is the current research hotspot, and the research direction of the researchers on the floating breakwater is mainly the shape of the structure, permeable type, flat plate type, net cage type and other types.

(i). Floating Breakwaters with Shapes

Hee Min Teh et al. [16] studied the wave attenuation of two H-type breakwaters, the structure is shown in Figure 4(a). 4(a)-1 is a dissipative breakwater and 4(a)-2 is a reflective breakwater, both of them showed better when encountering steeper waves and are suitable for deep water. Hee Min Teh and H Ismail [17] experimented with the performance of a stepped floating breakwater and designed a trapezoidal barrier with stepped ramp characteristics at both the front and back of the structure. Figure 4(b) is a model of a single-row stepped floating breakwater. Experiments have shown that the k_t <0.2 for double-row trapezoidal, but the mooring system and motion response were not evaluated. Wenjian Dong et al. [18] analyzed the wave attenuation of a semi-submersible permeable tetrahedral breakwater, and Figure 4(c) is an experimental model of the structure. The structure consists of PVC pipes to form a permeable tetrahedron. This structure could dissipate wave well under small period wave conditions. Junqing Ren et al. [19] proposed a parabolic arc breakwater, as shown Figure 4(d). The curvature of a structure is determined by its focal length f. When $\omega \geq 3.0$ rad/s, the parabolic arc breakwater has a better damping effect than the straight breakwater. The parabolic shape of f=10m can focus on bigger waves, which provides favorable conditions for wave attenuation and wave energy extraction. Meysam Rajabi et al. [20] also studied five cross-sectional shapes, namely rectangular, π, "+", triangular, and box-shaped, with the "+" shape being the best in terms of overall performance.

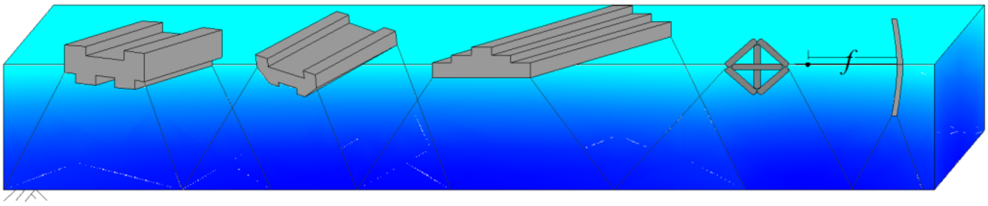

Figure 4. *FBs of different shapes: (a) H-tpye FB [16], (b) A single-row stepped-slope FB [17], (c) Semi-submersible permeable tetrahedron FB [18], (d) Parabolic arc FB [19].*

(ii). Porous Permeable Floating Breakwater

The porous permeable structure is a breakwater with a porous structure added to the pontoon. Use the pores to change the movement of water points to dissipate wave. Il-Hyoung Cho [21] studied a rectangular floating breakwater with vertical porous plates, as shown in Figure 5(a), and found that the larger porosity, the larger k_t, and the appropriate porosity and length can achieve better wave dissipation. Borna Nasri et al. [22] proposed a trapezoidal type floating breakwater with perforated plates, see Figure 5(b), modeled as a trapezoidal box at 60° and a series of perforated iron plates. Small concrete blocks were used inside, and polystyrene foam was extruded around the concrete. Vu Minh Tua et al. [23] proposed a porous semicircular floating breakwater consisting of a box and a porous semicircular, as shown in Figure 5(c). The structure could show satisfactory results at B/L=0.18, better than without porous semicircular in the larger wave. Yufen Cao et al. [24] proposed a permeable multi-floating tube breakwater, see Figure 5(d), and obtained that good wave reduction at the relative chain length is 1:2. Longfei Xiao et al. [25] experimented breakwaters with double-layered perforated walls attached to ring-shaped floating structures, the physical model structure is shown in Figure 5(e). The model is a double-walled perforated wall breakwater (annular VLFS) that forms an inner leeward harbor that can be used to protect vessels.

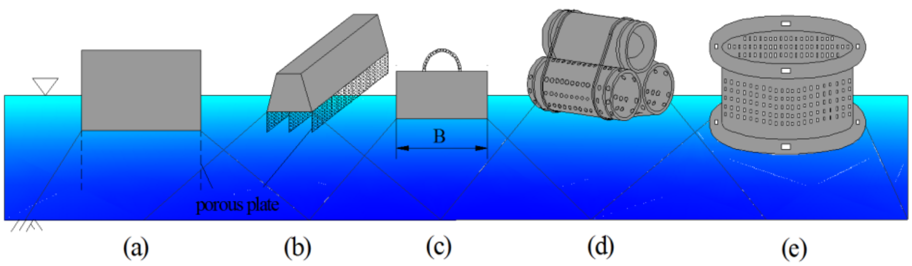

Figure 5. *Porous permeable FBs: (a) A rectangular FB with perforated-wall [21], (b) Trapezoidal cross-section with attached porous plate [22], (c) Perforated semi-circular FB [23], (d) Permeable tri-buoy FB [24], (e) Ring-shaped with double-layered porous side plates [25].*

(iii). Research on Cage-type Floating Breakwaters

The mesh floating breakwater is usually a flexible or rigid network structure added to the pontoon. The network could disturb the movement trajectory of water points to dissipate wave. Chun-Yan Ji et al. [26], Chunyan Ji et al. [27], S. F. Abdullah and A. Fitriadhy [28] analyzed a cylindrical floating breakwater as shown in Figure 6(a). The structure consists of 2 cylindrical pontoons and 9 cylinders. A cage was hung under the double pontoon, in which a rubber hollow ball was placed. Judging from the data results, the wave-absorbing was not particularly ideal, but the response of the sway, heave, and roll motion was small, the maximum mooring force was relatively small. Chunyan Ji et al. [29] studied the cage-type floating breakwater, as shown in Figure 6(b), the main frame was a steel structure, and two hollow rubber buoys are placed in the front and back of the breakwater, which play the role of buoyancy and wave reflection, steel mesh placed between the two buoys to dissipate waves, dissipation effect was better. Jianting Guo et al. [30] studied a three-post floating breakwater, as shown in Figure 6(c). The main body consists of three cylinders. The underwater crate was divided into 6 sub-cages. When the wave period T < 0.9 s, the wave dissipation effect was remarkable, and k_t < 0.4.

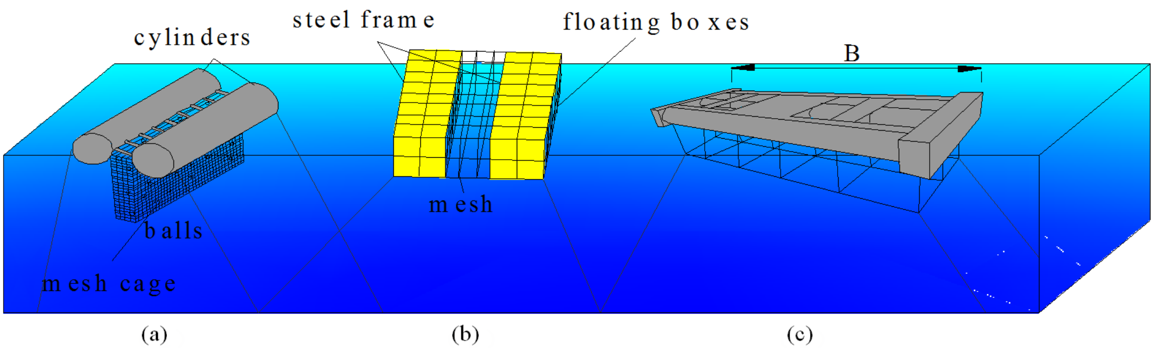

Figure 6. *Mesh floating FBs: (a) Double-pontoon with net FB [26-28], (c) Mesh cage FB [29], (d) Three-cylinders FB [30].*

(iv). Research on Slab-type Floating Breakwater

Zhijie Che et al. [31] numerically calculated the hydrodynamic characteristics of the breakwater with additional horizontal plate structure of the pontoon, see Figure 7(a). The k_t < 0.4 at B/L > 0.25. Zhengzhi Deng et al. [32] studied the floating breakwater with additional lower plate, can be seen in Figure 7(b), a plate under the rectangular wooden box. At normal circumstances, k_t decreases with the increase of B/L. When the number of lower connecting plates n=4 and the relative wire length l/h=1.5, B/L > 0.25, then k_t <0.25. Xiaosong Zhang et al. [33] designed an L-shaped floating breakwater, see Figure 7(c), the L-shaped structure was an improvement on the inverted π structure, and the numerical simulation of the L-shaped floating breakwater had a very promising wave dissipation effect. Zhenqing Liu et al. [34] studied a winged box-type floating breakwater, which is to attach a pair of mutually perpendicular protruding plates to the four corners of the rectangular floating tank, as shown in Figure 7(d), this structure has better performance than the wingless in larger period wave.

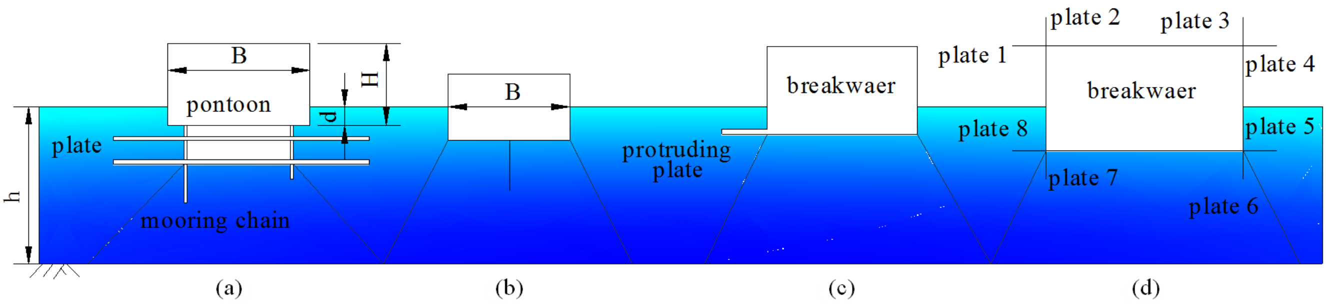

Figure 7. *Plate type FBs:(a) Double slab [31], (b) attached lower plate [32], (c) L-type [33],(d) Winged FB [34].*

(v). Other Floating Breakwaters

In addition to the common breakwater types, there are also ballast type and floating breakwaters with suspended S-blades. Ballast type is a kind of breakwater that fills the body of the breakwater with gas, liquid or flowable particles, and this breakwater can adjust the draft of the breakwater through the filler under the action of waves, thereby improving the efficiency of wave dissipation, and improving the motion response. Mostafa Shahrabi and Khosrow Bargi [35] investigated the use of a tuned liquid column damper (TLCD) to control a floating breakwater structure, called a tuned liquid column damper-breakwater (TLCD+FB), as shown in Figure 8(a). The structure adopts a box pontoon, and the TLCD is placed inside the pontoon. The advantage is that the TLCD was isolated from the direct effects of environmental loads, and the gravitational recovery forces and moments on the displaced liquid in the horizontal and vertical columns of the TLCD greatly inhibit excessive structural movements. With the addition of TLCD, the peak motion response can be reduced by 16% and the mooring force can be reduced by up to 100 kN. Zhiwen Yang et al. [36] and Zhiwen Yang et al. [37] studied the wave dissipation characteristics, motion response and mooring tension of the water ballast floating breakwater, and the structure is shown in Figure 8(b). Fangping Huang et al. [38], Hao Li et al. [39], and Lingjie Bao et al. [40] studied a double-pontoon floating breakwater suspended from Savonius paddles, as shown in Figure 8(c), which consists of twin pontoons, S-shaped resistance vanes, and mooring systems, which can absorb more than 50% waves.

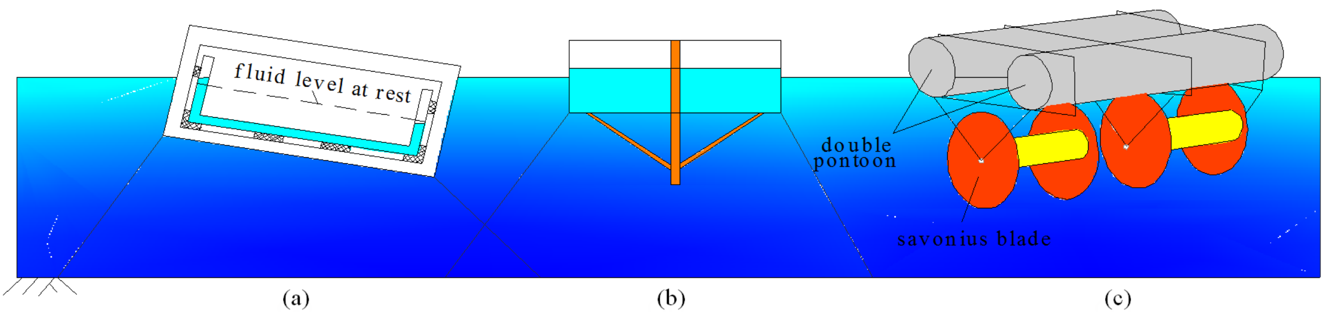

Figure 8. *Other type FBs: (a) Joint TLCD-FB mode FB [35], (b) Water ballast FB [36, 37],(c) S-blade FB [38].*

2.2. Research on WEC Breakwater

By converting wave energy into electrical, the combination of wave dissipation requirements and wave energy generation is a hot topic of research. There is air chamber WEC breakwater, vertical confinement WEC breakwater and other WEC breakwater types.

2.2.1. Air Chamber WEC Breakwater

The air chamber WEC breakwater mainly converts the wave energy into air energy through the air chamber, and then transmit air energy to the shaft through the air turbine, and finally converts to electrical energy through the generator. Fang He et al. [41] improved the wave energy converter floating breakwater and proposed a floating breakwater wave energy converter with an asymmetrical pneumatic chamber like Figure 9(a), constructed a narrow groove opening on the top plate of each pneumatic cavity to simulate the converte. The ratio of the slotted area to the cross-sectional area of each chamber was 1.25%. The experiment results showed that the asymmetric chamber breakwater behaves the same as the symmetrical chamber breakwater in terms of wave propagation and motion response, and when the $B/L > 0.5$, $k_t < 0.5$. Reference [6] studied the effects of the hydrodynamic performance and wave energy extraction efficiency of the three-chamber OWC breakwater, see Figure 9(b), the obtained CWR was > 0.2 and k_t < 0.5, which met the conditions of the wave-energy converter breakwater recognized in the reference.

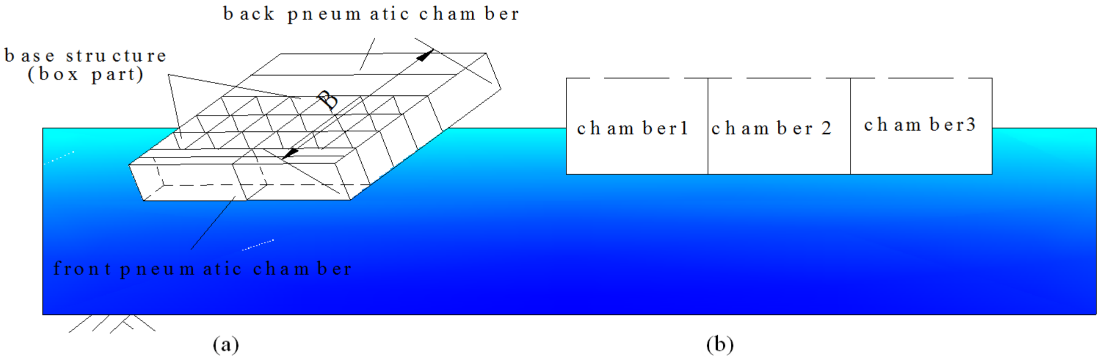

Figure 9. *Pneumatic chamber type WEC BWs: (a) Asymmetric pneumatic chamber [41]; (b) Three-pneumatic chamber [6].*

2.2.2. Vertically Constrained WEC Breakwaters

Vertically constrained WEC breakwater refers to the WEC breakwater with only heave response after confinement, the WEC converts wave energy to mechanical energy by vibration, then transmite the energy to electrical energy through the generator, see Figure 10. Dezhi Ning et al. [42] proposed a pile-confined WEC breakwater, as shown in Figure 10(a), in which the breakwater was connected by two pulleys to the vertical pile, could only heave motion. By properly adjusting the PTO damping force, the CWR is about 24% and k_t < 0.50. Xuanlie Zhao et al. [43], Dezhi Ning et al. [44], Qiang Chen et al. [45], and Xuanlie Zhao et al. [46] also studied the structure, but Xuanlie Zhao et al. [43] mainly analyzes the structural stress, Dezhi Ning et al. [44] numerically simulates two combinations, and concluded that the effective frequency band of the integrated system can be broadened by double pontoons. A numerical model was proposed by Qiang Chen et al. [45] for validation. Xuanlie Zhao et al. [46] analyzed the combination of multiple structures using numerical methods. Similar structures are also studied by Xiaoxia Zhang et al. [47] and Qiaoling Ji et al. [48], who studied floating rectangle-WEC breakwater and inverted L-WEC breakwater (a rectangular breakwater with a vertical curtain wall under it) respectively, as shown in Figure 10(b) and Figure 10(c). For rectangles, the larger coefficients (k_p = 2000) helps the buoy to absorb more wave energy, and the peak absorption efficiency reached 34.2%. For the inverted L type, the CWR > 40% and k_t < 0.35 through reasonable configuration.

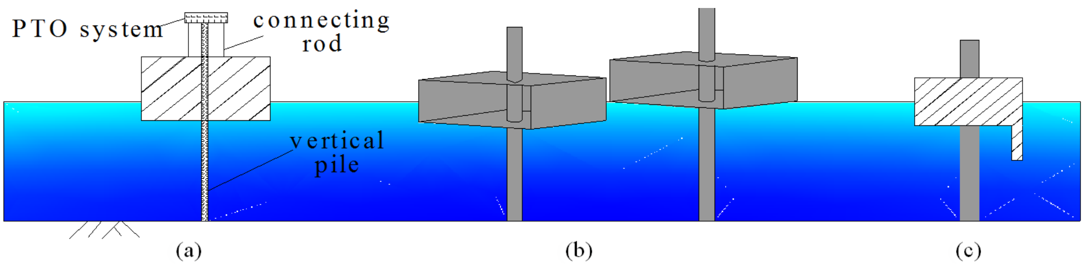

Figure 10. *Vertical constrained WEC BWs: (a) pile-restrained [42], (b) rectangular heaving buoy [47], (c) inverted L-shaped [48].*

2.2.3. Other Types of WEC Breakwaters

Hengming Zhang et al. [49] proposed an asymmetrical bottom WEC breakwater, see Figure 11(a), compared with single WEC, single breakwater, double float system, the conversion efficiency η of the triangular baffle bottom and the square baffle bottom are 78.5% and 76.3% by numerically. Damon How et al. [50] studied a π-type floating breakwater integrated with multiple oscillating water columns (OWC) WECs, as shown in Figure 11(b), and the dimensionless capture width gradually decreases with the increase of wave height. The heave and pitch amplitude of the breakwater was reduced. Siming Zheng et al. [51] studied a plate-wave energy converter (p-WEC) moored in front of a floating breakwater, as shown in Figure 11(c), p-WEC consists of a flexible plate immersed in water, which could heave only. The two sides of were glued with a piezoelectric layer, due to the piezoelectric effect, the elastic motion of the water wave excitation plate can be converted into electrical energy, and the numerical analysis showed that the maximum conversion efficiency η_{ext} can reach a maximum of 0.9, but the effect of wave attenuation of this structure was limited. Yong Cheng et al. [52] investigated an innovative multifunctional platform that combined the functions of floating breakwaters and WECs, as shown in Figure 11(d). The platform used a double cylindrical pontoon-type floating breakwater as the base structure, the two-month pool consists of three connecting walls between two cylinders. When the frequency of the incident wave was close to the natural frequency of the fluid in the lunar pool, the internal fluid will produce violent oscillations, and then collect wave energy in the lunar pool. This structure had a maximum capture efficiency of 21.71%.

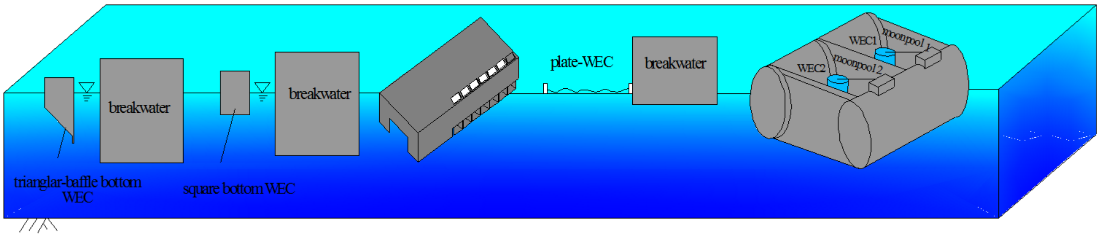

Figure 11. *Other types of WEC BWs: (a) triangular and rectangular bottom WEC BW [49], (b) π type WEC BW [50], (c) plate-wave WEC BW [51], (d) integrated WEC BW [52].*

3. Conclusions and Prospect

3.1. Conclusions

From the research progress on fixed breakwaters, the research direction focuses on the shape and permeability type of the structure. The fixed breakwater has a good wave dissipation effect, but the investment is large, and it is not suitable for the deep-sea area. The shape of the floating breakwater is mainly rectangular, round, triangular, trapezoidal, L-shaped, π-shaped, etc. According to the research results, the rectangular breakwater is better than the circular one, but the force of circular is smaller than rectangular, the "π" type is better than "T ", "L"type and trapezoidal is better than the inverted "π" type, "+" type is the best. Floating breakwaters are highly applicable and can be used in deep-sea areas. WEC breakwaters need to balance wave damping and power generation efficiency, and at present, only numerical results can meet the requirements.

Regardless of whether it is fixed, floating or WEC, the main parameters affecting the function of the breakwater are the width (or B/L), draft d (or relative depth of entry into the water d/h), the number of breakwaters, the spacing of the breakwater and the PTO damping ζ, etc., and the influence on the transmission coefficient k_t is basically the same:

(1) k_t decreases with the increase of B/L, d, d/h, H_i/L and numbers.

(2) k_t increases with the increase of T and ζ, but does not change or increase with the increase of H_i.

(3) The influence of breakwater spacing S on k_t is complex, but there is a certain range that makes k_t tend to be a constant. Different studies have different parameters when meeting the eligibility conditions. B/L > 0.20 of reference [8] can achieve satisfactory results, while studies in reference [41] require $B/L \geq 0.5$ to achieve satisfactory results. For example, the k_t of the "mountain" type breakwater in reference [14] is basically below 0.5. However, the k_t of reference [7], reference [8], etc., needs basically above 0.5. There is also a big gap in the research on the efficiency of wave energy extraction, and the conversion rate can reach more than 80% in theoretical calculations, but the wave energy utilization rate in the experimental is mostly between 0.2~0.3.

3.2. Prospect

Reviewing the research progress of breakwaters, although a lot of research has been done on breakwaters, the ability of breakwater to resist large waves is poor. In this paper, it is suggested that more physical experimental methods should be used to study the wave-dispation and CWR of breakwater or WEC breakwater. The study type should be fixed permeable type, floating type and combined with power generation device breakwater will be the main.

Author Contributions

Xiaowei Wang: Methodology, Writing – original draft, Writing – review & editing

Xiaoqun Wang: Conceptualization, Funding acquisition

Likun Liu: Investigation

Xin Li: Investigation

Kaiming Li: Writing – original draft

Funding

This work was funded by Science and Technology Project of Hebei Education Department (BJK2024016), Hebei Natural Science Foundation (No. E2023402015, E2024402142), National Natural Science Foundation of China (No. U21A20164).

Data Availability Statement

Data are contained within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] K. R, R. B, P. M. Review of Indian research on innovative breakwaters [J]. INDIAN JOURNAL OF GEO-MARINE SCIENCES, 2017, 46(3): 431-452.

[2] DAI J, WANG M C, UTSUNOMIYA T, et al. Review of recent research and developments on floating breakwaters [J]. Ocean Engineering, 2018, 158 132-151. https://doi.org/10.1016/j.oceaneng.2018.03.083

[3] ZHAO X, NING D, ZOU Q, et al. Hybrid floating breakwater-WEC system: A review [J]. Ocean Engineering, 2019, 186 106126-106126. https://doi.org/10.1016/j.oceaneng.2019.106126

[4] GUO Y, MOHAPATRA S, SOARES G C. Review of developments in porous membranes and net-type structures for breakwaters and fish cages [J]. Ocean Engineering, 2020, 200 107027-107027. https://doi.org/10.1016/j.oceaneng.2020.107027

[5] LIAN J., CHEN Y., WANG X., et al. Research progress on structural types of fixed permeable breakwaters for offshore photovoltaic perimeter protection [J]. Acta Energiae Solaris Sinica, 2024, 45(08): 332-341. https://doi.org/10.19912/j.0254-0096.tynxb.2023-0560

[6] ZHAO X, ZHANG L, LI M, et al. Experimental investigation on the hydrodynamic performance of a multi-chamber OWC-breakwater [J]. Renewable and sustainable energy reviews, 2021, https://doi.org/150.10.1016/J.RSER.2021.111512

[7] CAO Y, JIANG C, BAI Y. Wave attenuation properties of double trapezoidal submerged breakwaters on flat-bed [J]. Transactions of Tianjin University, 2012, 18(6): 401-410. https://doi.org/10.1007/s12209-012-1880-9

[8] ZHAI Z, HU Q, YE W, et al. Analytical modelling of solitary wave diffraction from a V-shaped breakwater [J]. Ocean Engineering, 2021, 230. https://doi.org/10.1016/J.OCEANENG.2021.109014

[9] WANG G, REN B, WANG Y. Experimental study on hydrodynamic performance of arc plate breakwater [J]. Ocean Engineering, 2016, 111 593-601. https://doi.org/10.1016/j.oceaneng.2015.11.016

[10] ZHAO P, SUN D, WU H. Influence of Wave-Absorbing Chamber Width on the Wave Attenuation Performance of Perforated Caisson Sitting on Rubble-Mound Foundation [J]. Mathematical Problems in Engineering, 2021, 2021. https://doi.org/10.1155/2021/8845331

[11] AHMED K E, YASSER E M, MOSTAFA M M. A comparative study between some different types of permeable breakwaters according to wave energy dissipation [J]. Ain Shams Engineering Journal, 2022, 13(4). https://doi.org/10.1016/J.ASEJ.2021.11.015

[12] QU K, HUANG X J, GUO L, et al. Numerical Study on Hydrodynamics of Submerged Permeable Breakwater under Impacts of Focused Wave Groups Using a Nonhydrostatic Wave Model [J]. Journal of Marine Science and Engineering, 2022, 10(11): 1618-1618. https://doi.org/10.3390/JMSE10111618

[13] CHEN L., PAN X. Wave dissipation performance of new type of pile foundation permeable breakwater based on FLOW-3D [J]. Port & Waterway Engineering, 2022, (01): 59- 65. https://doi.org/10.16233/j.cnki.issn1002-4972.20211227.001

[14] JUN Y G, MIN J Z, QING W H, et al. Wave Dissipation Characteristics of A Mountain-Type Breakwater [J]. China Ocean Engineering, 2021, 34(6): 863-870. https://doi.org/10.1007/S13344-020-0078-5

[15] WANG Y, YIN Z, LIU Y, et al. Numerical investigation on combined wave damping effect of pneumatic breakwater and submerged breakwater [J]. International Journal of Naval Architecture and Ocean Engineering, 2018, 11(1): 314-328. https://doi.org/10.1016/j.ijnaoe.2018.06.006

[16] TEH M H, MOHAMMED I N. Experimental Study on Wave Dampening Ability of Floating Breakwaters [J]. Advanced Materials Research, 2013, 2605(785-786): 1253-1257. https://doi.org/10.4028/www.scientific.net/AMR.785-786.1253

[17] TEH M H, ISMAIL H. Hydraulic Characteristics of a Stepped-slope Floating Breakwater [J]. IOP Conference Series: Earth and Environmental Science, 2013, 16(1): 012060-012060. https://doi.org/10.1088/1755-1315/16/1/012060

[18] DONG J W, SHANGGUAN C Z, WANG L Y, et al. Experimental Study on Wave Dissipation Coefficient for Semi-Submersible Permeable Tetrahedron [J]. Applied Mechanics and Materials, 2017, 4429 357-362. https://doi.org/10.4028/www.scientific.net/AMM.864.357

[19] REN J, JIN P, LIU Y, et al. Wave attenuation and focusing by a parabolic arc pontoon breakwater [J]. Energy, 2021, 217 119405. https://doi.org/ 10.1016/j.energy.2020.119405

[20] MEYSAM R, HASSAN G. Hydrodynamic Performance Improvement of Double-Row Floating Breakwaters by Changing the Cross-Sectional Geometry [J]. Mathematical Problems in Engineering, 2021.1 (2021): 2944466. https://doi.org/10.1155/2021/2944466

[21] Cho I. Transmission coefficients of a floating rectangular breakwater with porous side plates [J]. International Journal of Naval Architecture and Ocean Engineering, 2016, 8(1): 53-65. https://doi.org/10.1016/j.ijnaoe.2015.10.002

[22] NASRI B, MOGHIM N M, BADRI A M. Experimental study on trapezoidal pontoon-type floating breakwaters with attached porous plates [J]. Journal of Ocean Engineering and Marine Energy, 2021, 7(1): 1-17. https://doi.org/10.1007/S40722-021-00185-Z

[23] TUAN V Mi, DUONG B, HUNG V Q., et al. Experimental study on the wave dissipation performance of a perforated semi-circular floating breakwater[J]. Journal of Science and Technology in Civil Engineering (JSTCE)-HUCE, 2022, 16(3): 59-70. https://doi.org/10.31814/stce.huce(nuce)2022-16(3)-05

[24] CAO Y, SHI Y, BAI Y, et al. Numerical Modeling of Permeable Floating Breakwater under the Action of Waves [J]. Journal of Coastal Research, 2018, 85(sp1): 1101-1105. https://doi.org/10.2112/SI85-221.1

[25] XIAO L, KOU Y, TAO L, et al. Comparative study of hydrodynamic performances of breakwaters with double-layered perforated walls attached to ring-shaped very large floating structures [J]. Ocean Engineering, 2016, 111 279-291. https://doi.org/10.1016/j.oceaneng.2015.11.007

[26] SHENG Y S, NING J P, REN Y Z, et al. Experimental Study on Wave Attenuation Performance of A New Type of Floating Breakwater with Twin Pontoons and Multi Porous Vertical Plates [J]. China Ocean Engineering, 2022, 36(3): 384-394. https://doi.org/10.1007/S13344-022-0034-7

[27] JI C, CHENG Y, CUI J, et al. Hydrodynamic performance of floating breakwaters in long wave regime: An experimental study [J]. Ocean Engineering, 2018, 152 154-166. https://doi.org/10.1016/j.oceaneng.2018.01.055

[28] ABDULLAH S F, FITRIADHY A. Application of genetic algorithm for optimum hydrodynamic performance of twin pontoon floating breakwater [J]. Journal of Waterway, Port, Coastal, and Ocean Engineering, 2020, 146(2): 04019040. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000548

[29] JI C, CHEN X, CUI J, et al. Experimental study on configuration optimization of floating breakwaters [J]. Ocean Engineering, 2016, 117 302-310. https://doi.org/10.1016/j.oceaneng.2016.03.002

[30] GUO J, ZHANG Y, BIAN X, et al. Hydrodynamic Performance of a Multi-Module Three-Cylinder Floating Breakwater System under the Influence of Reefs: A 3D Experimental Study [J]. Journal of Marine Science and Engineering, 2021, 9(12): 1364-1364. https://doi.org/10.3390/JMSE9121364

[31] CHEN Z J, WANG Y X, DONG H Y, et al. Time-domain hydrodynamic analysis of pontoon-plate floating breakwater[J]. Water Science and Engineering. 2012, 5(3): 291-303. https://doi.org/10.3882/j.issn.1674-2370.2012.03.005

[32] DENG Z, WANG L, ZHAO X, et al. Hydrodynamic performance of a T-shaped floating breakwater [J]. Applied Ocean Research, 2019, 82: 325-336. https://doi.org/10.1016/j.apor.2018.11.002

[33] ZHANG X, MA S, DUAN W. A new L type floating breakwater derived from vortex dissipation simulation [J]. Ocean Engineering, 2018, 164 455-464. https://doi.org/10.1016/j.oceaneng.2018.06.059

[34] LIU Z, WANG Y, WANG W, et al. Numerical modeling and optimization of a winged box-type floating breakwater by Smoothed Particle Hydrodynamics [J]. Ocean Engineering, 2019, 188 106246-106246. https://doi.org/10.1016/j.oceaneng.2019.106246

[35] SHAHRABI M, BARGI K. Structural control of the floating breakwaters by implementation of tuned liquid column damper: [J]. Advances in Structural Engineering, 2020, 23(8): 1587-1600. https://doi.org/10.1177/1369433219898081

[36] YANG Z, XIE M, GAO Z, et al. Experimental investigation on hydrodynamic effectiveness of a water ballast type floating breakwater [J]. Ocean Engineering, 2018, 167 77-94. https://doi.org/10.1016/j.oceaneng.2018.08.030

[37] YANG Z, JI Xinran, XIE M, et al. Experimental study on the dynamic response of a water ballast type floating breakwater [J]. Ocean Engineering, 2021, 233. https://doi.org/10.1016/J.OCEANENG.2021.109012

[38] PING F H, KAI G, SHI Z L, et al. Experimental Research on A New Type of Floating Breakwater for Wave-Absorbing and Energy-Capturing [J]. China Ocean Engineering, 2021, 34(6): 817-827. https://doi.org/10.1007/S13344-020-0074-9

[39] LI H, CHEN J, BAO L, et al. Research on Wave Attenuation Performance of Floating Breakwater [J]. Energies, 2021, 14(24): 8316-8316. https://doi.org/10.3390/EN14248316

[40] BAO L, WANG Y, JIANG C, et al. Research on Wave and Energy Reduction Performance of Floating Breakwater Based on S-Shaped Runner [J]. Energies, 2022, 15(14): 5148-5148. https://doi.org/10.3390/EN15145148

[41] HE F, HUANG Z, LAW W A. An experimental study of a floating breakwater with asymmetric pneumatic chambers for wave energy extraction [J]. Applied Energy, 2013, 106 222-231. https://doi.org/10.1016/j.apenergy.2013.01.013

[42] NING D, ZHAO X, GÖTEMAN M, et al. Hydrodynamic performance of a pile-restrained WEC-type floating breakwater: An experimental study [J]. Renewable Energy, 2016, 95 531-541. https://doi.org/10.1016/j.renene.2016.04.057

[43] ZHAO X, NING D, GÖTEMAN M, et al. Effect of the PTO damping force on the wave pressures on a 2-D wave energy converter [J]. Journal of Hydrodynamics, Ser. B, 2017, 29(5): 863-870. https://doi.org/10.1016/S1001-6058(16)60798-9

[44] NING D, ZHAO X, ZHAO M, et al. Analytical investigation of hydrodynamic performance of a dual pontoon WEC-type breakwater [J]. Applied Ocean Research, 2017, 65 102-111. https://doi.org/10.1016/j.apor.2017.03.012

[45] CHEN Q, ZANG J, BIRCHALL J, et al. On the hydrodynamic performance of a vertical pile-restrained WEC-type floating breakwater [J]. Renewable Energy, 2020, 146 414-425. https://doi.org/10.1016/j.renene.2019.06.149

[46] ZHAO X, XUE R, GEN J, et al. Analytical investigation on the hydrodynamic performance of a multi-pontoon breakwater-WEC system [J]. Ocean Engineering, 2021, 220. https://doi.org/10.1016/J.OCEANENG.2020.108394

[47] ZHANG X, ZENG Q, LIU Z. Hydrodynamic Performance of Rectangular Heaving Buoys for an Integrated Floating Breakwater [J]. Journal of Marine Science and Engineering, 2019, 7(8): 239-239. https://doi.org/10.3390/jmse7080239

[48] JI Q, XU C, JIAO C. Numerical investigation on the hydrodynamic performance of a vertical pile-restrained reversed L type floating breakwater integrated with WEC [J]. Ocean Engineering, 2021, 238. https://doi.org/10.1016/J.OCEANENG.2021.109635

[49] ZHANG H, ZHOU B, VOGEL C, et al. Hydrodynamic performance of a dual-floater hybrid system combining a floating breakwater and an oscillating-buoy type wave energy converter [J]. Applied Energy, 2020, 259(C): 114212-114212. https://doi.org/10.1016/j.apenergy.2019.114212

[50] HOWE D, NADER J, MACFARLANE G. Performance analysis of a floating breakwater integrated with multiple oscillating water column wave energy converters in regular and irregular seas [J]. Applied Ocean Research, 2020, 99. https://doi.org/10.1016/j.apor.2020.102147

[51] ZHENG S, MEYLAN M, ZHANG X, et al. Performance of a plate-wave energy converter integrated in a floating breakwater [J]. IET Renewable Power Generation, 2021, 15(14): 3206-3219. https://doi.org/10.1049/RPG2.12230

[52] CHENG Y, XI C, DAI S, et al. Performance characteristics and parametric analysis of a novel multi-purpose platform combining a moonpool-type floating breakwater and an array of wave energy converters [J]. Applied Energy, 2021, 292. https://doi.org/10.1016/J.APENERGY.2021.116888