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Recent Investigations on Wave Dissipation of New Type Breakwaters

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Abstract: *The performances of wave dissipation, wave force and motion responses for new type breakwater are investigated in the study. Compare with the traditional breakwater, the wave dissipation effect for different new structure type are discussed, including the open plate breakwater, cylinder breakwater, pile breakwater, caisson breakwater, floating breakwater and flexible breakwater. It is found that, the new type breakwaters have advantages on wave damping, lower construction cost, convenient construction and little environment influence. Moreover, the ocean energy such as wave and offshore wind can be captured by optimizing the structure of breakwater. Therefore, it can attain the double effect of wave damping and clean energy utilization.*

Keywords: *breakwater; structure type; wave dissipation; ocean energy*

1. Introduction

Marine economy plays an important role in China's economic development, and the construction of port infrastructure is an important part of marine economy. In recent years, due to the increasing of construction scale, offshore distance, water depth and hydrodynamic conditions, that make it more difficult to built the traditional structure of breakwater. Which may result in the growth of construction difficulty, high construction and maintenance costs, poor water exchange[1-3]. Therefore, many experts have carried out systematic research on the breakwater, and proposed many new type breakwaters with lower construction cost, better wave-damping, little influence on environment, and simple construction, moreover it can capture marine energy[4-6]. Based on previous research, this paper summarizes the wave dissipation, structural stability, dynamic response and wave energy capture of different new type breakwaters, so that the developing direction and related suggestions for new type breakwater are proposed.

2. New type breakwater

2.1 Permeable plate breakwater

By physical model test, Cao [2] studied the wave-damping performance of multi-layer vertical baffle permeable breakwater under different water depth, wave height and baffle spacing. The results show that the wave attenuation coefficient increases with the growth of wave period and wave height, thus the effect of wave dissipation is remarkable. In addition, when the baffle spacing is loosely arranged before and densely after, the wave damping appeared to be more obvious than other conditions. Compared with the results of physical model test and numerical simulation, it is found that the breakwater has better wave dissipation performance for long-wave. Lu et al [4] summarized the effect of wave dissipation for different plate type breakwater, such as single-layer plate breakwater, multi-layer plate breakwater, open-hole plate breakwater. And suggested that the surrounding hydrodynamic, wave absorption mechanism and wave load of open-hole breakwater should be further investigated by numerical simulation. Wang et al.[7] and Cheng et al.[8] investigated the performance of wave dissipation and structural stability for the pile foundation double horizontal plate breakwater and grille plate-type open breakwater using physical model. By analyzing the variation trend of transmission coefficient and reflection coefficient for different wave height, water depth, submersion depth, plate spacing and gap ratio, the dissipation of wave energy caused by breakwater is discussed. The results show that the double-layer plate breakwater has significantly effect on long-period wave dissipating, especially when the water level on the top of breakwater. For the grille plate-type breakwater, when the structure top is higher than water level, the effect of wave dissipation performance is obviously, and the transmission coefficient decreases with the increase of plate spacing, besides the wave dissipation is better when the gap between upper and lower plate attains 0.1.

Tang et al. [9] studied the wave dissipating effect of perforated composite plate breakwater by using the flume experiment. Comparative analysis is conducted for the variation of transmission coefficient, reflection coefficient and dissipation coefficient with different relative structure widths and gap ratios. It is found that the wave force act on the breakwater is smaller, and the effect of wave damping increases with the growth of structure width and gap ratio, moreover, the wave dissipation for the above water case is significantly better than the underwater case. Li et al. [10] proposed a new-type horizontal inclined plate open breakwater, and carried out numerical simulation by VOF method, so as to investigate the variation of transmission coefficient with inclined plate angle, wave steepness, plate spacing, plate width and relative freeboard. The results show that the breakwater has an obvious effect on wave dissipation, furthermore, the transmission coefficient is proportional to the inclined plate angle and plate spacing under the test conditions, but inversely proportional to the relative plate width. The transmission coefficient decreases first and then increases with the growth of steepness and water height.

Wang [11] studied the wave dissipation performance of four kind breakwaters which under different opening positions for horizontal plate and curved plate (as shown in Figure 1). The test results show that the wave dissipation for the square hole on the wave-facing side mode is better than the non-opening case and the hole on back-wave side case. For the submerged condition, the open hole for horizontal plate is better than the curved plate type, conversely, when the breakwater above water, the open hole for curved plate is better than the horizontal plate type. For wave energy dissipation, when the breakwater below the water, the curved plate is better than the horizontal type, however, for the above condition, the horizontal plate type is better than the curved plate. Lv et al. [12] investigated the wave dissipation effect and wave force of the porous I-type plate composition breakwater, and explored the influence of relative wave height and wavelength on the breakwater by physical model tests. It is found that the relative wave height is the main factor impact the wave force of breakwater, the wave force load in the vertical direction is 15 times bigger than the horizontal direction. The total horizontal force increases with the increasing of relative wavelength, when the relative wavelength is greater than 3.617, the total horizontal force trend to be stable.

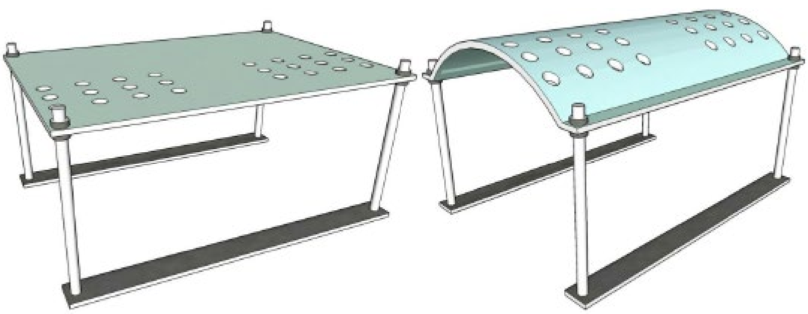

Figure 1: Horizontal plate and curved plate permeable breakwater [11]

2.2 Barrel breakwater

Base on the calculation results of the two-dimensional model, Yang et al.[13] studied the anti-slip stability of bucket breakwater under the ultimate state, and established a stability calculation method for three-dimensional by analyzing the soil pressure on the wall, shear stress at the bottom and self-weight under the influence of rotation. From the viewpoint of practical application, Lian [14] and Zeng et al.[15] take Lianyun Port as an example, systematically introduced the structural design, structural advantages, stability, construction, handling, installation technologies of a new bucket-based breakwater (as shown in Figure 2). And provided technical support for the breakwater application in the fields of coast protection, offshore platform, offshore wind power and other fields.

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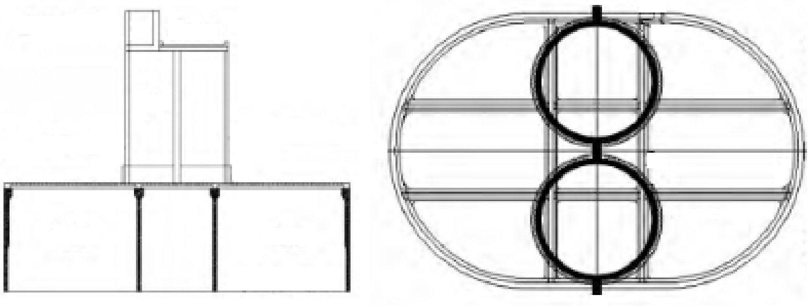

(a) Side view *(b) Plan view*

Figure 2: Cross-section view of a new barrel base structure breakwater[14]

Take Tianjin Port as an example, the structure of horizontal cylindrical breakwater is studied by physical model test and numerical simulation, the stress distribution and damage mode of the breakwater is analyzed, and a stability calculation method is proposed[16]. The results show that the physical model and numerical simulation results can reflect the stability of horizontal cylindrical breakwater. By adjusting the structural parameters such as wing length and cylinder diameter, it can adapt to the construction requirements of different foundation conditions. The breakwater can be well suited to soft ground, and reduce the construction costs.

Using the numerical simulation technology of finite elements, Ma et al. [17] investigated the bearing capacity and stability of tank-type deepwater breakwater under different length-diameter ratios. It is found that, as the wave load exceeds the critical value, the increasing value of horizontal displacement for a small length-diameter ratio is significantly greater than the large length-diameter ratio. For the high water level, the ultimate bearing capacity of breakwater with a large length-diameter ratio increases significantly. The horizontal displacement decreases with the increasing of insertion depth in soft ground, and the ultimate bearing capacity increases with the growth of foundation depth.

2.3 Pile foundation breakwater

Shang [1] established a three-dimensional finite element model to simulate the inverse T-type breakwater with jackets and pile foundations (as shown in Figure 3), so as to investigate the stability and application of breakwater. By simulating the distribution of soil pressure on pile foundation, the calculation method of soil pressure is further optimized and proposed. Simplified calculation method for anti-slip stability, anti-overturning and foundation bearing capacity analyses are studied, by which the rotation point of instability is determined. In addition, combined with the engineering practice of Tianjin Port, the structural parameter of breakwater is determined. Zhu [18] simulated the wave dissipation effect of the high-pile baffle permeable breakwater with the finite volume method. The variation of transmission coefficient with relative structure width, relative water depth and relative wave height is obtained and the correction formula is further optimized by simulating the flow field around the breakwater. Besides, the numerical simulation results are compared with the experimental value and calculated value of Lapa formula for validation. Fu [19] used a combination of theoretical calculation and physical model test to study the wave dissipation of baffle pile foundation breakwater. By comparing the variation of wave height, wave overtopping and wave force with different submerged depth, it is found that, as the submerged depth increasing, the wave height in the harbor decreases but the horizontal force and wave overtopping rise, which have obvious effect on harbor protection.

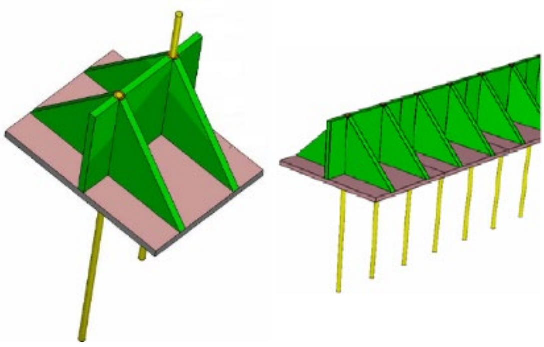

Figure 3: T-type breakwater with jackets and pile foundation [1]

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Take the engineering conditions of Tianjin Port as an example , Zhang et al. [20] proposed a cylindrical jacket and pile foundations breakwater, and calculated the cost of construction according to the relevant standards, the results show that the breakwater had a reasonable cost, laying a foundation for subsequent research and practical application. Using physical model test and numerical simulation, Xia [21] studied the influence of relative structure width and water depth of barrier on the transmission coefficient of the pile foundation permeable breakwater, it is found that the transmission coefficient decreases with the increasing of relative width, when the width is smaller than the critical value (0.35L), and it tended to be stable as the width is bigger than the critical value. Moreover, the transmission coefficient decreases with the increasing of water depth, and it gradually comes to stability when the depth greater than the critical value (1.0H). The wave dissipation increases with the growth of the relative width and the baffle depth, also it is recommended that the design parameters of relative width and relative baffle depth should be 0.25-0.35 times and 1.0 times of wavelength, respectively.

Liu [22] investigated the wave dissipation performance and permeability of 13 pile-based permeable breakwater by using physical model tests and numerical simulation methods, so as to find out the better structural type for application. The variation of transmission coefficient, reflection coefficient and dissipation coefficient with different board opening ratio, structure type, structure width, wave height, wave steepness and water depth are systematical analyzed. The results show that, for the low water level, the board opening ratio and baffle combination play a major role in the wave dissipation. For the double-layer plate case, the wave dissipation increases significantly as the opening rate of front plate increase and rear plate reduce, furthermore, the permeability performance depends on the minimum opening rate. For the high water level, the wave dissipation effect mainly depends on the structural type of wave wall, of which the inverted-arc wave wall can reduce the reflection coefficient by 60% and increase the dissipation coefficient by about 34%, therefore the wave dissipation effect is much better than other types.

2.4 Caisson Breakwater

Niu et al. [23] proposed a comb-type breakwater, and summarized the empirical formula for reduction coefficient of wave force and reflection coefficient of breakwater. Combine with practical application, it is found that the breakwater can reduce the horizontal wave force by 27% and reduce the construction cost by 24.5%. With a combination of physical model test and numerical simulation, Xie [24] and Zhao et al.[25] studied the wave dissipation performance and wave force of inverted-arc breakwater (as shown in Figure 4), and proposed a calculation formula for wave force. It is found that the wave pressure on the breakwater is proportional to the wave height and period, moreover, the horizontal wave force is mainly impacted by the relative wave height, wave steepness, but less impacted by the relative radius and water depth. Furthermore, the total horizontal wave force is reduced by about 10% compared with the vertical breakwater. The reflection coefficient is inversely proportional to the wave steepness, also the magnitude of reflection coefficient at different positions of arc surface is 0< 45<90, and the climbing magnitude is 0<90<45.

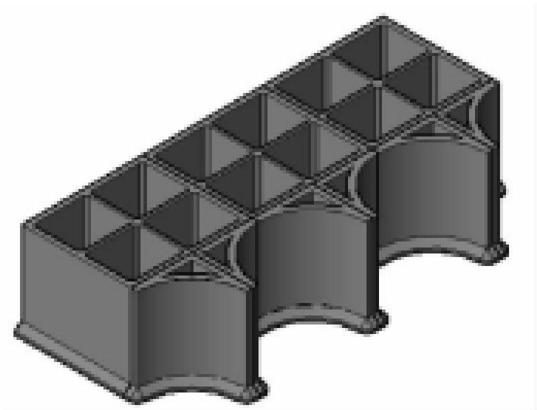

Figure 4: New Type Inverted-arc Breakwater [24]

Zhang [26] combined the advantages of semicircle breakwater, inverted arc breakwater and gravity caisson breakwater, and proposed a new type of semicircular breakwater with open-hole structure. The variation of reflection coefficient and water pressure with wave elements, open porosity and surface cover filler size is investigated in the physical model test. It is found that the variation law of reflection coefficient is not obvious and the water pressure increases with the increasing of wave elements such as wave height and water depth, which is 1-3 times bigger than the semicircular breakwater. Moreover, the maximum position at the contact surface of water and breakwater. Du [27] proposed a permeable caisson breakwater (as shown in Figure 5), and used three-dimensional numerical simulation to investigate the wave dissipation performance of breakwater. The results show that the permeable caisson has better wave dissipation effect, and the wave resonance phenomenon in permeable channel is more obvious for kh=1.25, it is proportional to the wave height and the maximum ratio is about 3. When the opening rate of front plate and side plate of permeable are both 25%, the reflection coefficient can be reduced by 50%-80%, and the resonance wave height can be reduced by 15%-65%.

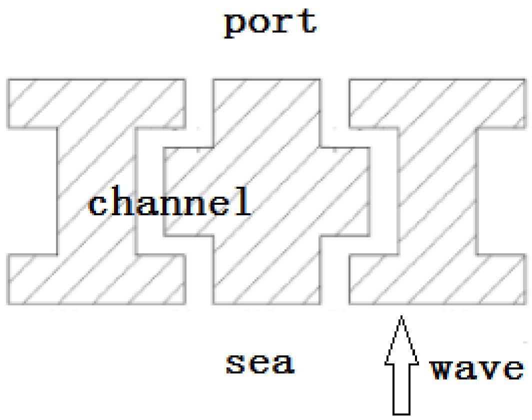

Figure 5: Permeable caisson breakwater [27]

Basis on the summarizing research and practical engineering experience, Zhao [28] studied the wave dissipation performance of comb-type breakwater, buttressed breakwater and open-hole caisson breakwater with physical model tests. The results show that, for the low water depth, the wave dissipation effect of open-hole caisson breakwater is significantly better than the comb type, and the buttress structure has the worst effect. With the increase of water depth, the wave dissipation effect of all three structures decrease. Li et al. [29] conducted a physical model test on the vertical breakwater with different arc radius breastwall, and studied the wave dissipation performance by analyzing the variation of wave force with wave height, wavelength and arc radius. The experiments show that the wave force acting on the breastwall is proportional to the relative wave height, and it increases firstly then decreases and then increases again as the relative wavelength increasing. For the same wave condition, the arc wave force is bigger than the vertical breakwater, and the wave force is inversely proportional to the arc radius.

2.5 Floating Breakwater

Liu [3] investigated the wave dissipation performance of the porous floating breakwater (as shown in Figure 6) and the anchor chain force of different mooring modes through physical model test. The variation of transmission coefficient, reflection coefficient and anchor chain force with different wave elements, opening position and mooring mode are discussed. The results show that the wave period has an obvious effect on the transmission coefficient, but has little influence on the reflection coefficient. The wave dissipation effect of floating breakwater on long wave is slightly better than the traditional type, but the effect on short wave is better than long wave. The wave dissipation effect of eight-shaped mooring mode is better than the cross-shaped, and the force of anchor chain is proportional to the wave height and period. For low water level, the force of eight-shaped anchor chain is bigger than the cross type, however, the force difference become small for the high water level. Using the combination of numerical simulation and physical model test, Wang [30] studied the variation of transmission coefficient, reflection coefficient and surrounding flow field of the floating breakwater with anti-arc surface. The results are compared with the rectangular pontoon breakwater, it is found that the dissipation effect of floating breakwater with anti-arc surface is better than rectangular pontoon breakwater, also it has better shielding effect on long-period wave. As the anchor chain partially towed, the length of anchor chain has little influence on the wave dissipation.

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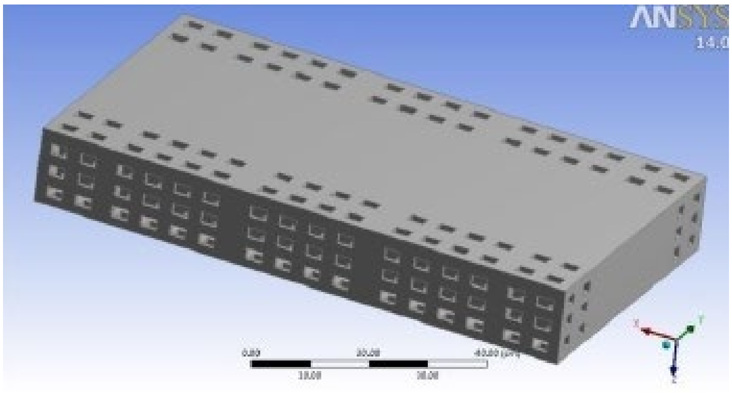

Figure 6: The porous floating breakwater [3]

Yao [31] used theoretical analysis and physical model test to study the wave dissipation performance of three different semi-immersed perforate breakwaters. The changes of reflection coefficient, transmission coefficient and energy dissipation coefficient with different plate spacing and water depth are analyzed, it is found that, under the same condition, the wave dissipation effect of the opening bottom plate structure is better than two others, which the reflection coefficient is smaller and the wave energy dissipation coefficient is bigger. For the small plate spacing condition, the solid floor structure has good wave dissipation effect, for the large plate spacing, the wave dissipation effect of the non-bottom plate structure is better. Leng [32] used AQWA software to simulate the wave force and wave dissipation performance of the multi-body floating breakwater. By comparing the wave dissipation of breakwater in the open sea area and island area, it is found that the presence of the island or reef interferes with the incident wave, which changes the wave force and wave dissipation effect of breakwater. The results show that the mooring line type plays a major role in the influence of breakwater, but the length of mooring line has little influence on the wave force. For different mooring line type, the motion responses of breakwater decreases as the length of mooring line decrease.

Zhang [33] proposed two new types floating breakwater, bubble floating and nail-shaped floating breakwater, in order to study the stress situation and wave dissipation performance by numerical simulation (ANSYS-AQWA). Compared with the square box floating breakwater, it is found that the response amplitude is proportional to the stress on anchor chain, wave height and wave period, the nail-shaped structure is better than the bubble floating type, moreover, the arrangement of parallel anchor chain has a higher safety coefficient. The transmission coefficient of three structure is proportional to the wave height and wave period, also the wave dissipation performance of bubble floating structure is better than nail-shaped type. Shen et al.[34] and Jiang [35] used AQWA software and ANSYS software to study the force situation, motion response and wave dissipation effect of floating breakwater. The results show that the increasing of scantling draft can effectively reduce the transmission coefficient, which is obvious than water depth, and the dynamic response is remarkable, therefore the wave dissipation performance is better. Ge et al. [36] investigated the wave dissipation performance of a new raft floating breakwater using physical model tests, and found that the wave dissipation effect is obvious when the relative inclined width increase.

Deng [37] designed three different kinds of cost-effective floating breakwater (as shown in Figure 7), they are rectangular type, circular-rectangular type and oval type, which have the advantages of low costs, convenient assembly and reusability. It is found that the hydrodynamic characteristics and wave dissipation performance for rectangular type are significantly better than two other types, besides, a set of on-site installation technical schemes is proposed. Xie [5] suggested that building double buoyant floating breakwater by using reinforced concrete materials, and studied damage mode for different wave conditions with numerical simulation. The force situation and vulnerable areas of structure were discussed, on that basis the corresponding strengthening measures were studied. Wu [38] used numerical simulation (ANSYS) and physical model tests to study the wave force of double-tube double-plate floating breakwater. It is found that wave height is the main factor impact on wave load, which is proportional to wave height and period. The horizontal wave force is mainly affected by the height of vertical plate, but the immersion depth has little influence. The stress response of the breakwater is analyzed by the finite element model, and an optimization measure to increase the thickness of bottom plate is proposed.

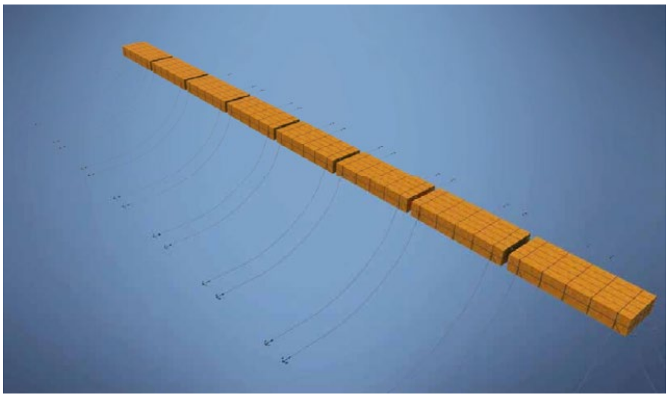

Figure 7: Layout of rectangular type cost-effective floating breakwater[37]

He [39] proposed a new composite pontoon-plate type breakwater, and used AQWA software to study the dynamic response, mooring line force and wave dissipation performance. The results show that the displacement amplitude, mooring line force of floating body are inversely proportional to the relative distance, and the motion response is minimal, when the relative width of breakwater is between 0.6-0.7. In addition, the floating anchorage reaches the most stable condition for the critical value (21m) of plate length. The transmission coefficient is inversely proportional to the relative width, and the influence of plate spacing decreases with the increase of relative width. It is found that the structure has obvious effect on short-period wave. Zou [40], Wen [41] and Yang [42] used physical model test and numerical simulation to study the wave dissipation performance of the new emergency floating breakwater (as shown in Figure 8), and investigate the impact of wave steepness, relative draft, relative width and anchor chain length on the transmission coefficient. The results show that the transmission coefficient is inversely proportional to the wave steepness, relative width and relative draft, and the wave steepness is the main factor. Besides, this structure has obvious effect on wave damping for small wave.

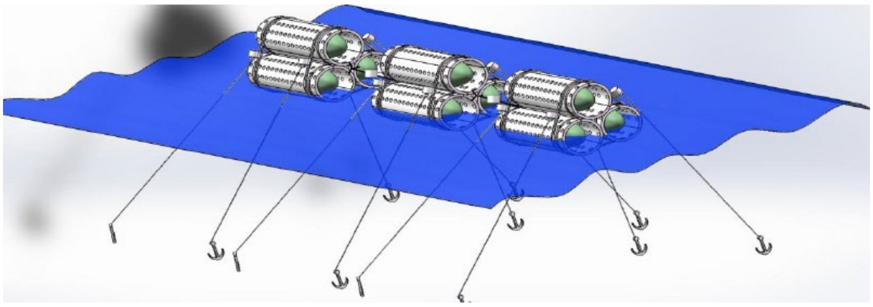

Figure 8: New type of floating breakwater for emergency [40]

2.6 Flexible breakwater

Using physical model test, Wang et al. [43] studied the wave dissipation performance of flexible floating breakwater, and discussed the variation of transmission coefficient with wave height, wave period and breakwater width. The tests reveal that the damping structure can reduce the wave energy effectively, and its transmission coefficient is between 0.4-0.7, which has obvious effect on long-wave and short-wave dissipation. Xu [44] proposed a vertical curtain flexible floating breakwater, and its wave dissipation performance is studied by physical model test. The variation of transmission coefficient, reflection coefficient and diffraction coefficient with different breakwater width, wave steepness and floating plate are analyzed. It is found that the effect of relative width on wave dissipation is obviously, when it reaches the critical value (0.3). This breakwater has obvious wave dissipation effect on long wave and diffraction, which is much better than the floating plate. Qiu [45] studied the wave dissipation performance of cylindrical flexible floating breakwater and investigated the transmission coefficient, reflection coefficient, attenuation coefficient by physical model test. It is found that the relative width is the main influencing factor of wave damping. This breakwater has a significant effect on short-wave dissipation, but has less effect on long-wave.

Yang [46] designed a layered flexible floating breakwater (as shown in Figure 9), and conducted a physical model test to study the relationship between transmission coefficient, reflection coefficient,

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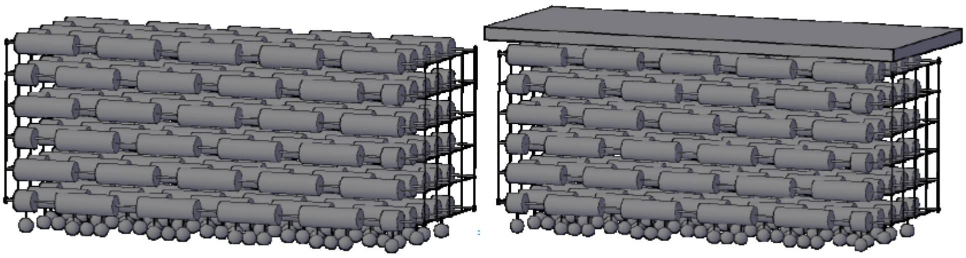
diffraction coefficient and structure width, wave steepness, floating plate. The results show that the wave dissipation effect is obvious for the relative width of 0.3, which the damping structure reduce the wave energy effectively. The diffraction area is mainly concentrated in the end of the embankment, and the presence of floating plate decreases the motion response significantly. The mooring force of anchor chain shows a large difference with the changes of wave height and wave period, and the presence of floating plate increases the mooring force of anchor chain significantly.



(a) without floating plate *(b) with floating plate*

Figure 9: Now layered flexible floating breakwater [46]

Liu et al. [47] analyzed the problems of traditional floating breakwater, on this basis, proposed four kinds of breakwater, including tow-box type, arc-shaped type, double-cylinder-single-plate type, double cylinder-double-plate type, which are composed of high-density polyethylene float and plastic blind ditch. The structural form and wave dissipation mechanism of various breakwaters are introduced, and the applications are summarized, also it is found that the breakwater has obvious effect on short-wave damping. Wang et al. [48] studied the influence of structure width, wave height and incidence angle of flexible multi-pontoon breakwater on the motion response by numerical simulation. It is found that the motion response is proportional to the wave height, and the pitching motion response is proportional to the wave incidence angle. When the embankment width is greater than 0.65, the motion response is stable. Ran et al. [49] combined with physical model test and numerical simulation (AQWA software) to study the wave dissipation performance of V-shaped flexible floating breakwater. The results show that the breakwater has obvious effect on short-period wave reduction, and the wave dissipation effect is significant when the angle is 60°.

3. Application of wave energy by new breakwaters

Shi et al. [50] designed a caisson breakwater as an OWC wave energy device and studied the feasibility of device by physical model tests. The results show that the wave surface in caisson gas chamber increases with the increasing of wave period, which directly influence the power generation efficiency of breakwater. Wu [51] studied the coupling floating breakwaters with wind turbines (as shown in Figure 10), using the established numerical model to simulate the motion response and power generation under the action of wind and wave, it is found that the device has better wave resistance and wave dissipation effect. Besides, it has lower cost compared with the traditional floating fans. Bian [52] proposed two new types of water turbine floating breakwater and the wave dissipation, hydrodynamic characteristics, power generation performance is simulated by CFD technology. The results show that the performance of pile-restrained type is more significant, among which the wave dissipation and power generation of single-channel type are directly proportional to the main size of breakwater.

Figure 10: Coupling floating breakwaters with wind turbines [51]

On the basis of traditional slope embankment structure, Yang et al. [53] proposed a new type breakwater with function of wave dissipation and power generation, which provides a reference for future marine energy utilization. Zhong [54] proposed a flexible floating breakwater with savonius rotor as the main body, and studied the dynamic response, wave dissipation performance by physical model tests. The experiment tests show that the wave dissipation effect is significant, when the breakwater is placed in a V-shaped shape at an angle of 60°. And the breakwater width is the main factor impact the wave dissipation, which the wave damping effect is the best as the relative width is 0.4. In addition, wave height is the main factor affecting the mooring force of anchoring, the force is proportional to the wave height and angle, furthermore the force on facing wave side is greater than the back side. Bao et al. [55] studied the wave dissipation and energy absorption effects of floating breakwater (as shown in Figure 11) by physical model tests and numerical simulations. It is found that the energy absorption effect is obviously, when the blade rotation frequency close to wave frequency, moreover, the wave dissipation of parallel arrangement is better than the vertical type. Yu et al. [56] used numerical simulation to study the wave dissipation performance, motion response and anchor force of double-pontoon suspended savinious propeller-blade floating breakwater. The simulation show that, as the pontoon spacing is close to wavelength, the wave dissipation effect is obviously, and the tension on the wave side increased significantly. The transmission coefficient decreases with the increasing of relative distance between pontoon and propeller. In addition, the wave dissipation performance increases with the decrease of the blade height-diameter ratio.

Figure 11: Paddle floating breakwater[55]

Sun [6] proposed a backward-curved tube floating breakwater with air turbine, and conducted experimental studies on its wave dissipation performance, hydrodynamic, power generation performance. It is found that, for the relative width is 0.4 case, the transmission coefficient is reduced by 10%, the anchor chain tension is reduced by 20%, and the wave dissipation effect is obviously which is benefit for extend the service life of anchor chain. Yu et al. [57] proposed a pile-based permeable breakwater with integrated oscillating water column power generation (OWC), so as to study its wave dissipation effect and wave energy-kinetic energy conversion rate by physical model tests. It is found that the structure has good wave dissipation effect and wave energy conversion amount when the wave period is 5s.

4. Conclusions and Suggestions

Through the studies of wave dissipation effect and wave load for different structure breakwaters, it is found that the new breakwater have obvious advantages on low cost, convenient construction, small ecological impact, less occupation of sea, and good wave dissipation performance. Therefore it should actively strengthen management from the aspects of construction subsidies, quality system, industrialization promotion, simplified approval process, innovative supervision mode[58], so as to promote the using of new breakwater in practical engineering application.

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